The tracking detectors of the ATLAS and CMS experiments for the High-Luminosity LHC

Seminar at the University of Geneva

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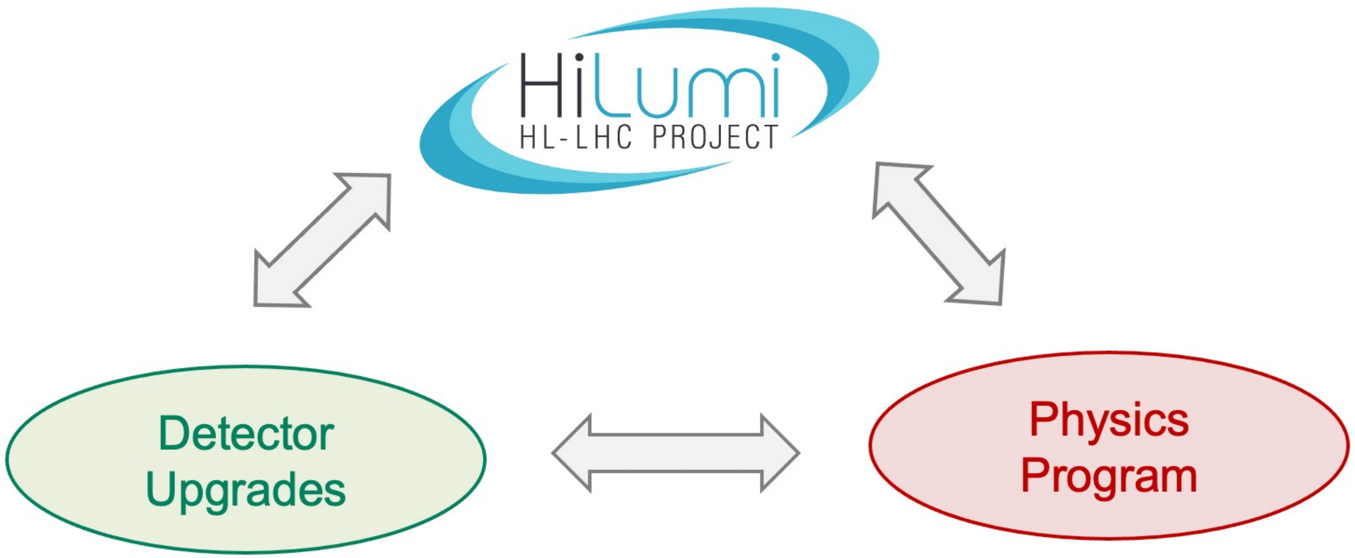
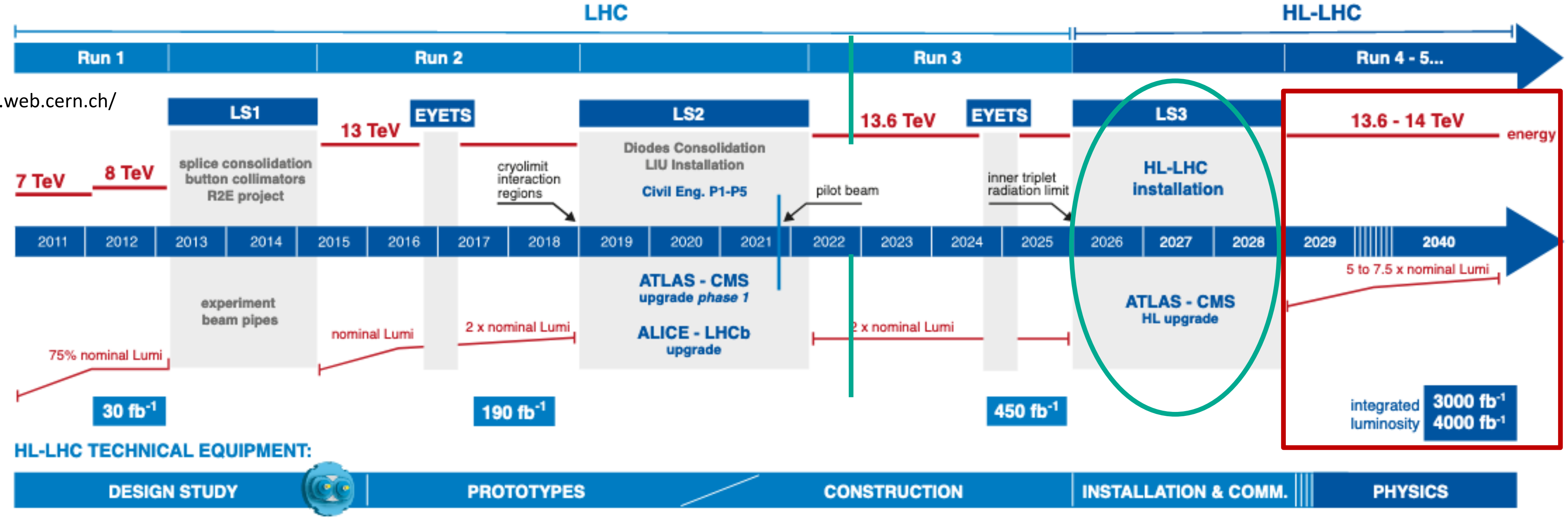
Overview

- The High-Luminosity LHC and challenges for the experiments
- The upgrade plans of the tracking detectors of the ATLAS and CMS experiments
- Layout of the new silicon tracking detectors
- Technology choices and results of prototyping of
  - the new Inner Tracker (ITk) of ATLAS
  - the new Inner Tracker and Outer Tracker of CMS
- Summary



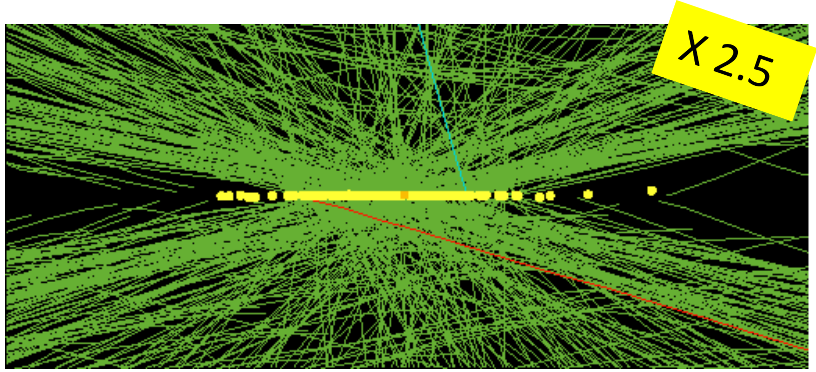
Phase-II Upgrade of the LHC

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



From LHC to HL-LHC

- Proton-proton collisions with up to 14 TeV at higher intensity
- Instantaneous nominal luminosity x5-7.5
- Integrated luminosity x10



High pile-up fill in 2017: 78 reconstructed vertices in event from high pile-up CMS-PHO-GEN-2012-002

Challenges for the experiments at the HL-LHC

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

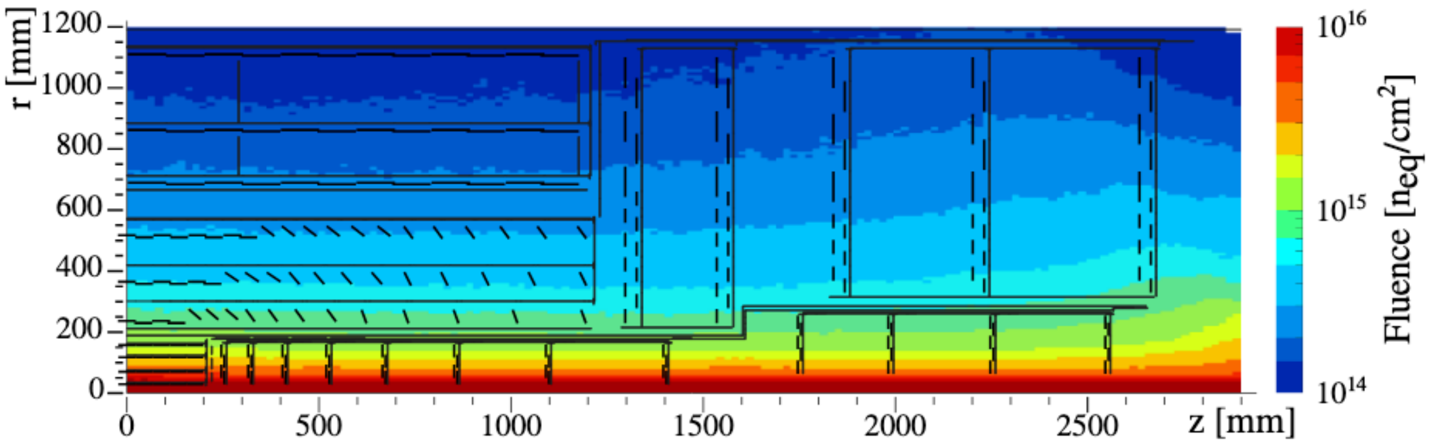
- Instantaneous nominal luminosity x5-7.5 → Increased particle densities
- Integrated luminosity x10 → Increased radiation damage, radiation levels up to 2×10^{16} n_{eq}/cm^2 or 1 GRad
  - Impact on detector technologies (silicon planar and 3D-sensors), electronics (deep sub-micron technologies and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

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

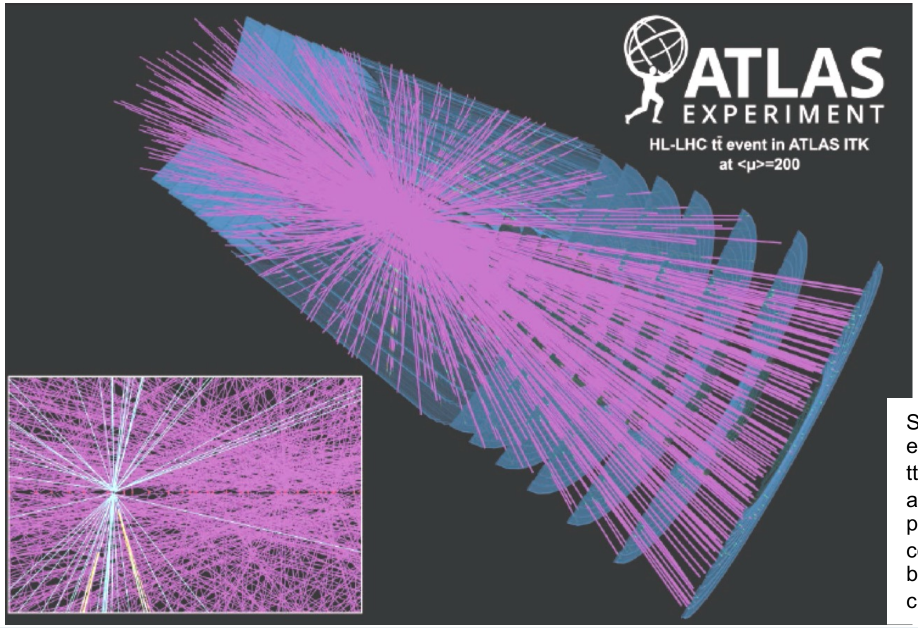
- Accumulation of "pile-up" jets especially in forward region

→ Hit rates x8, up to 3 GHz/cm^2

- Higher rate of fake tracks

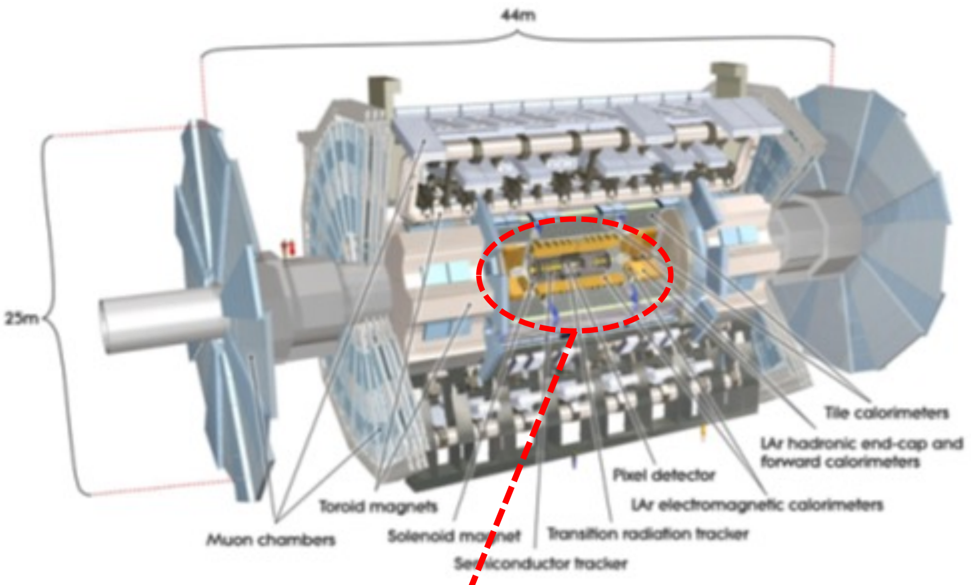


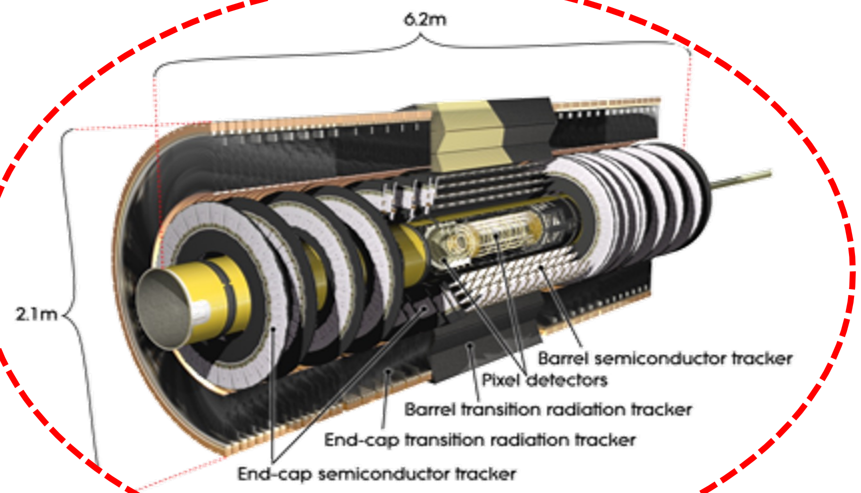
Integrated particle fluence in 1 MeV-neutron equivalent fluence for CMS tracker for pp collisions at 14 TeV (FLUKA 3.7.2.0 CMS-TDR-17-001, LHCC-2017-009)



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

The ATLAS and CMS experiments

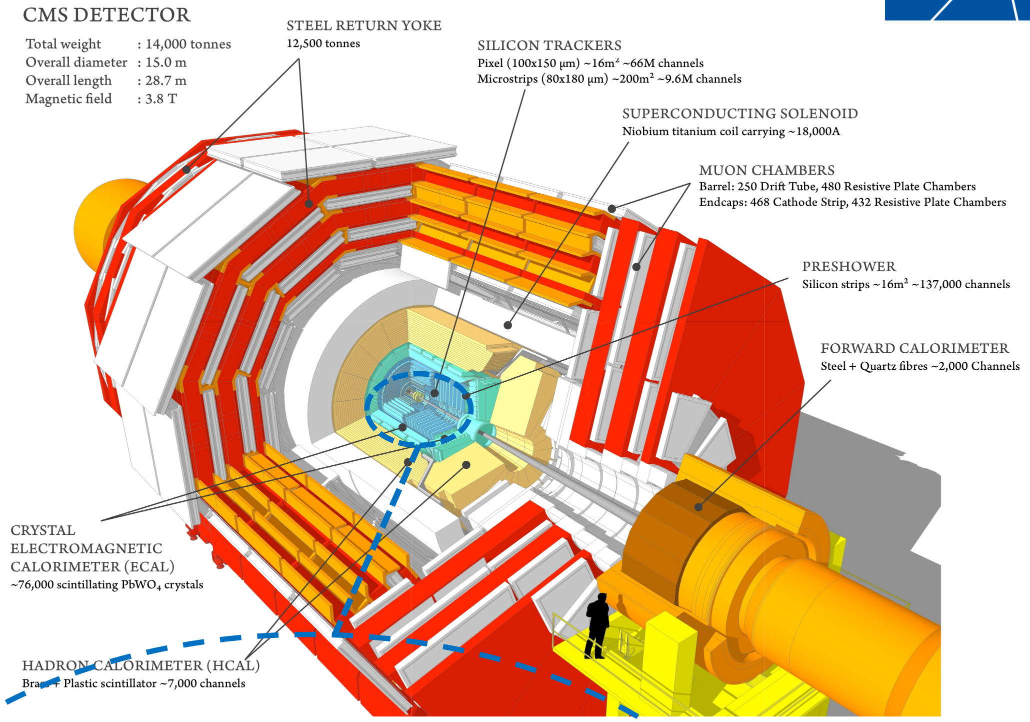


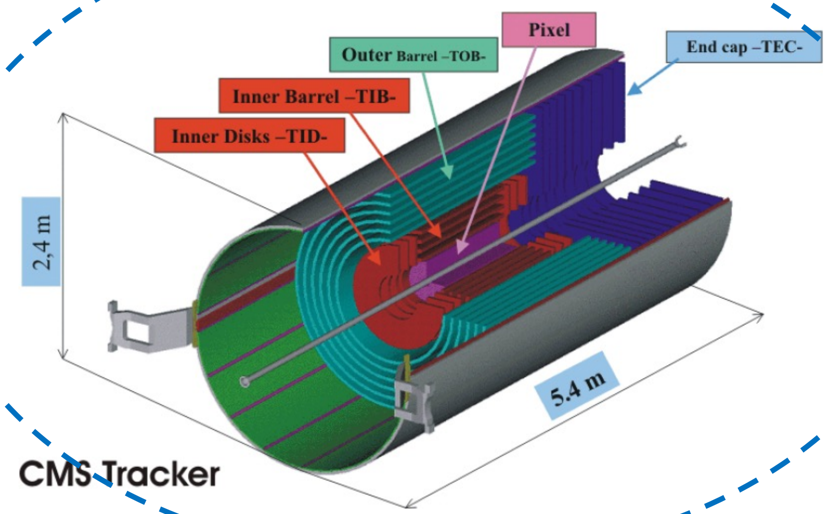


ATLAS Inner Detector

Target for HL-LHC:

At least the same performance of the ATLAS and CMS experiments as in Run-2/Run-3



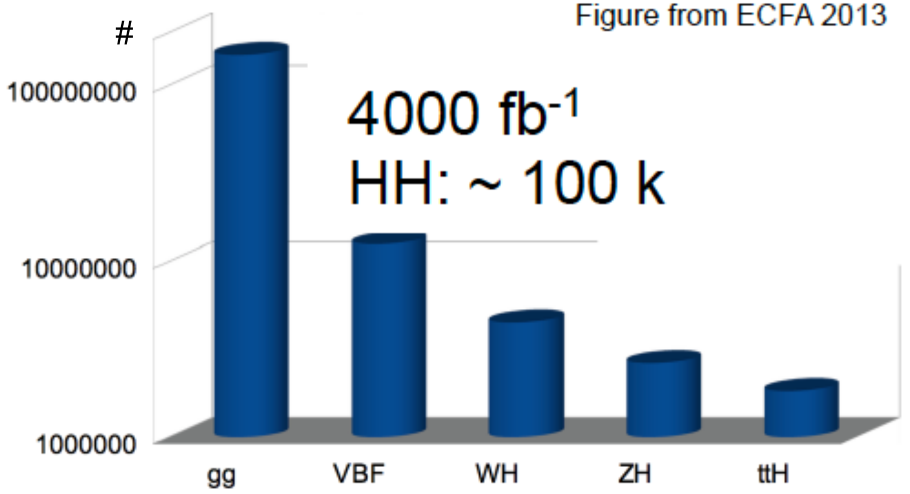


Phase-II Upgrade: Physics Program

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

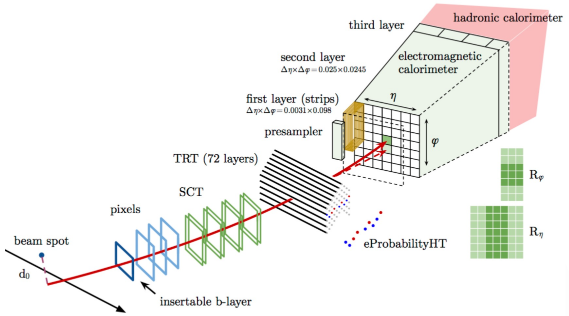


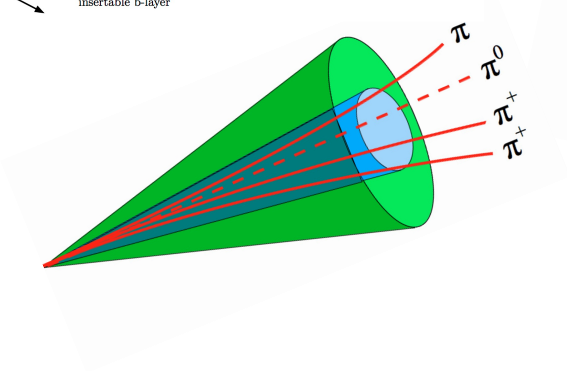
HL-LHC offers increased dataset → Reduced uncertainties both statistically and experimentally (large calibration datasets)

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

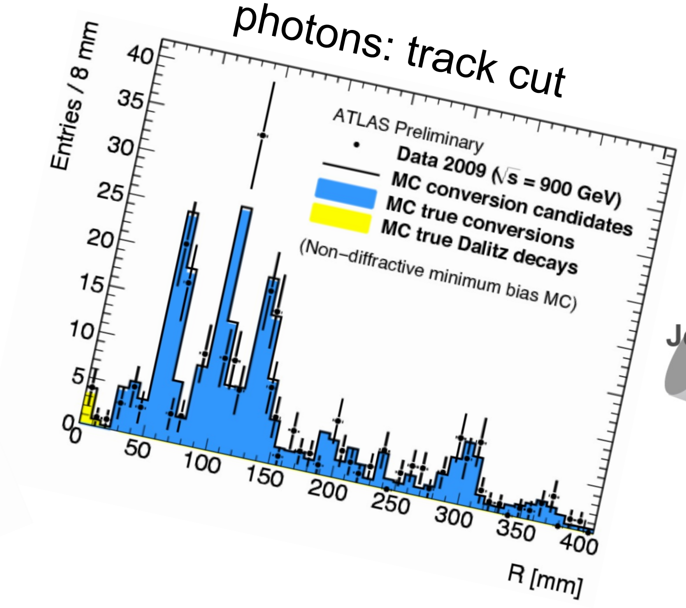
Tracks are everywhere

leptons: e/mu/tau

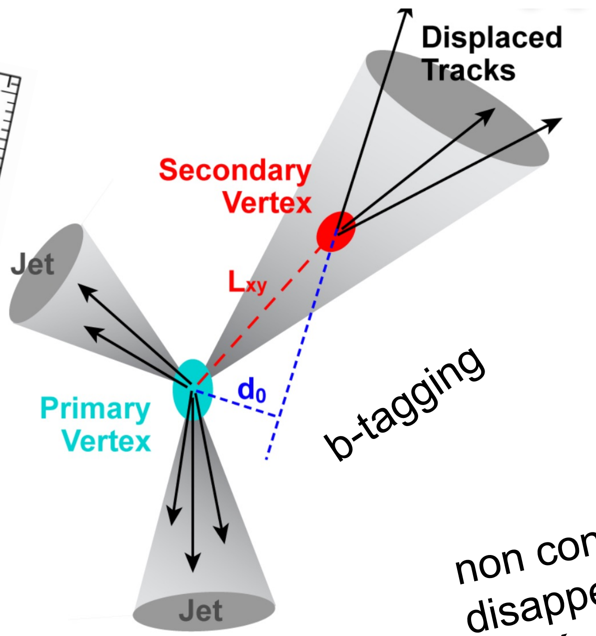




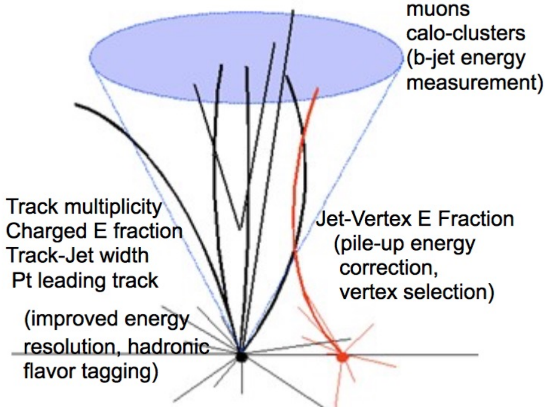
photons: track cut



b-tagging



jets: calibration/pile-up suppression



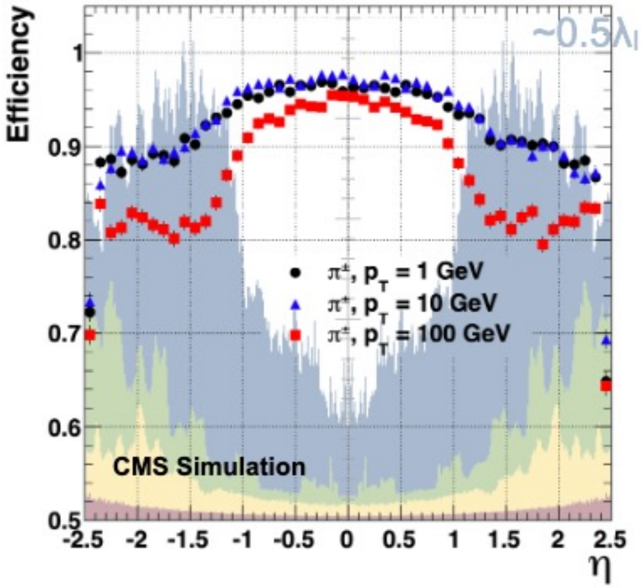
non conventional signatures:
disappearing tracks in SUSY
EWK … → missing E_T

- Many challenges for reconstruction:
  - High multiplicity events and highly boosted jets require **improved granularity and resolution**
  - VBS/VBF forward jets: **forward tracker** for pile-up rejection by jet-vertex association
  - Rare events: **improvements in coverage and reconstruction efficiency**

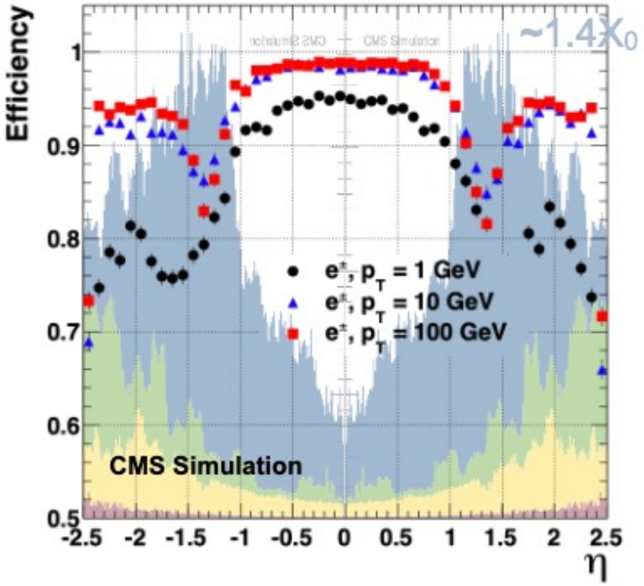
→ **Detector upgrades**

Further motivations for detector upgrades

- Efficient tracking with small fake rates



Track reconstruction efficiencies for pions



Track reconstruction efficiencies for electrons

The tracker material profile (in λI and X_0 respectively) is superimposed 2014 *JINST* **9** P10009

→ **Radiation tolerance, high granularity and low material budget essential in tracking detectors**

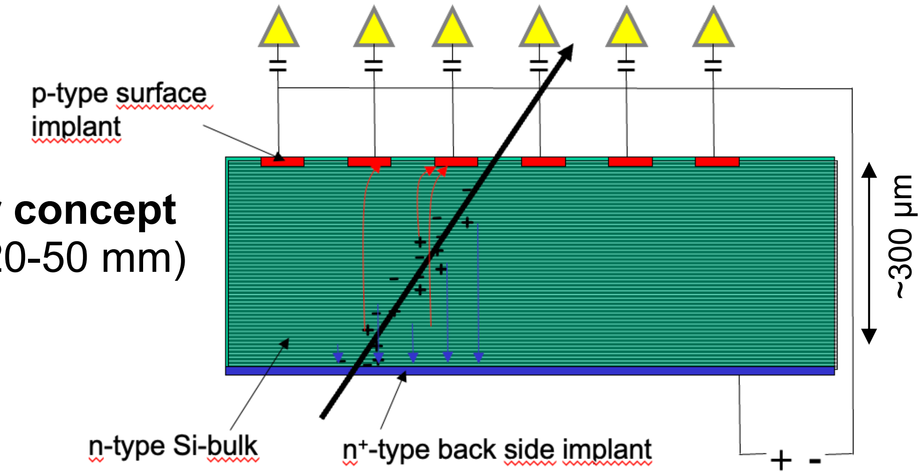
+ current trackers can't withstand radiation and rates beyond LHC

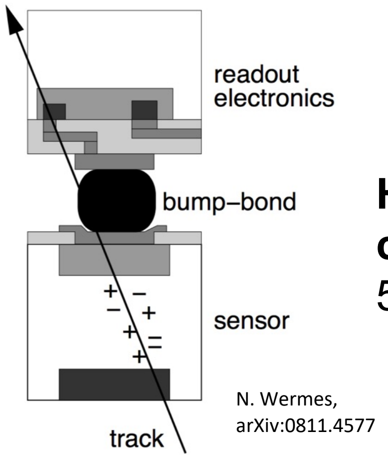
→ **New all-silicon tracking detectors for ATLAS and CMS experiments with extended coverage to |η| < 4**

Silicon strip and pixel detectors

- **P-N diode in reverse bias capacitively coupled to a charge-sensitive amplifier**

Strip detector concept
(strip lengths 20-50 mm)

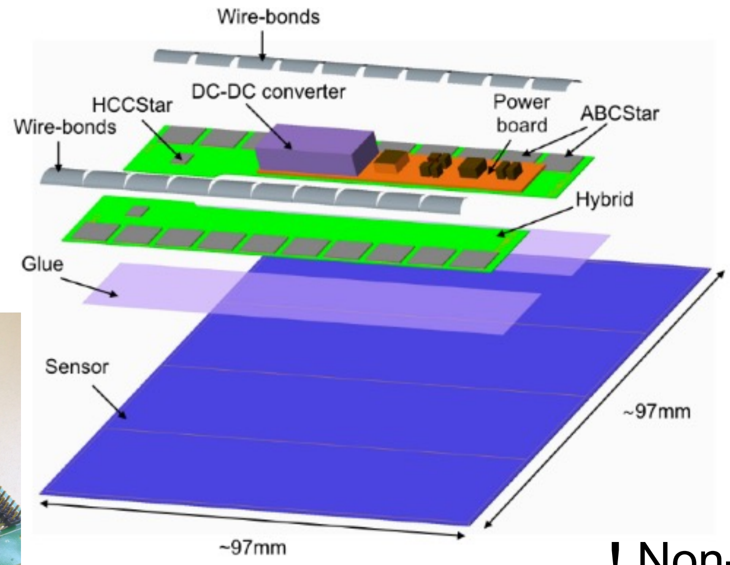


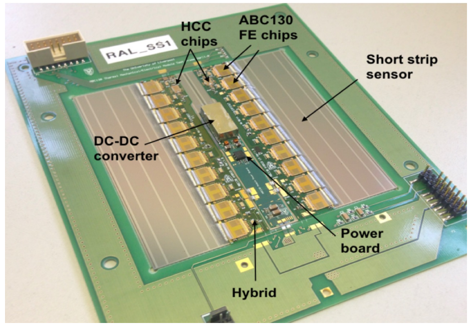


Hybrid-pixel detector concept (pixel sizes 50x50 µm^2 - 25x100 µm^2)

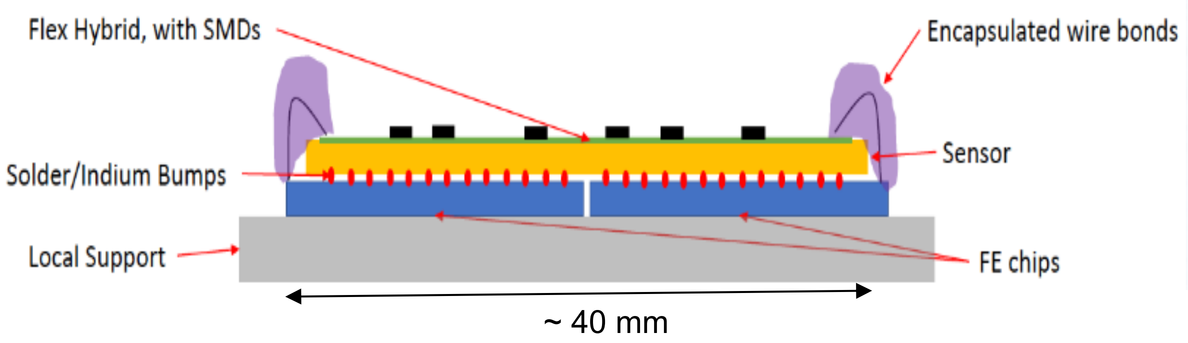
CMOS detector concept

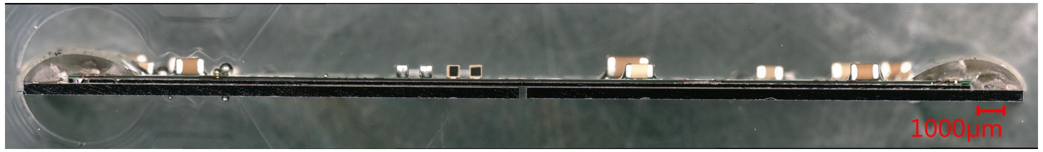
- Modules





ATLAS strip module

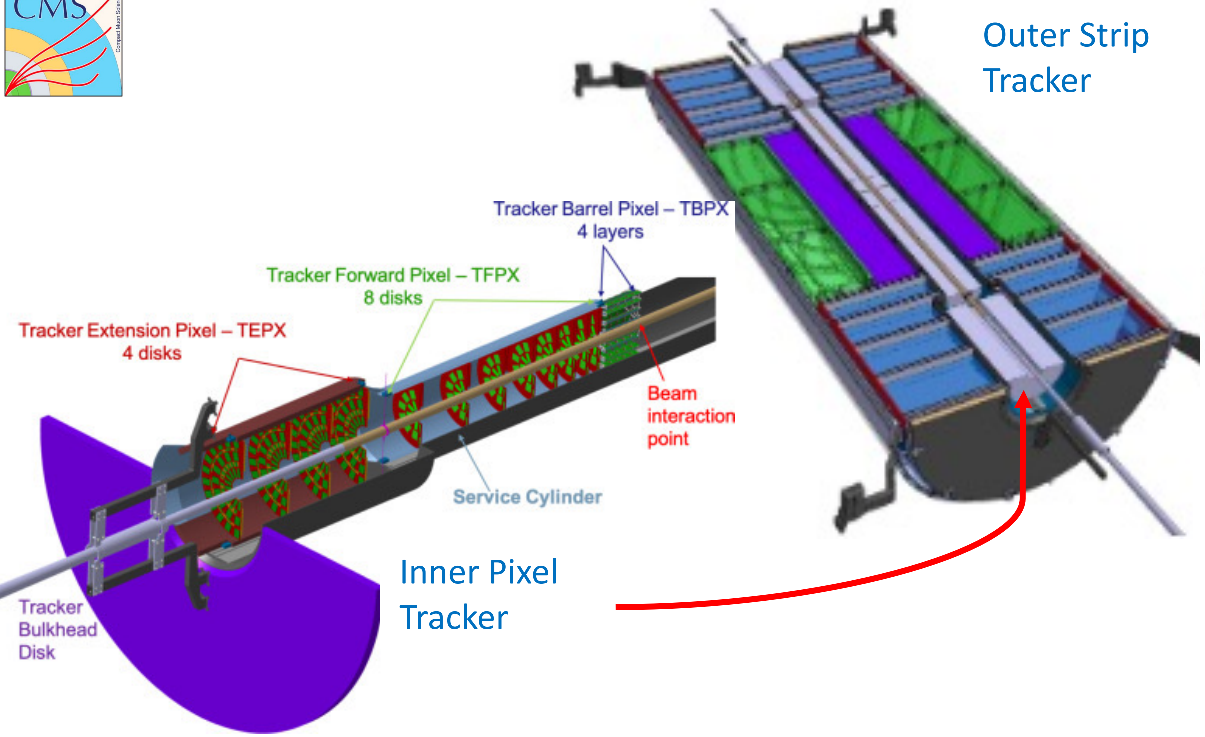


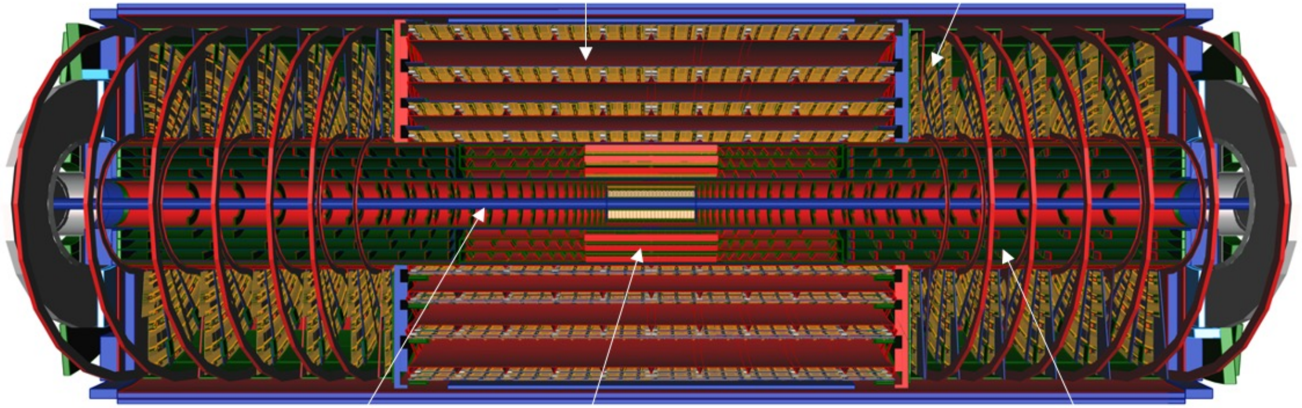


Cross section of ATLAS pixel quad module

! Non-ionizing energy loss of charged and neutral particles damages the silicon bulk → Performance degradation!

The upgrade tracking detectors



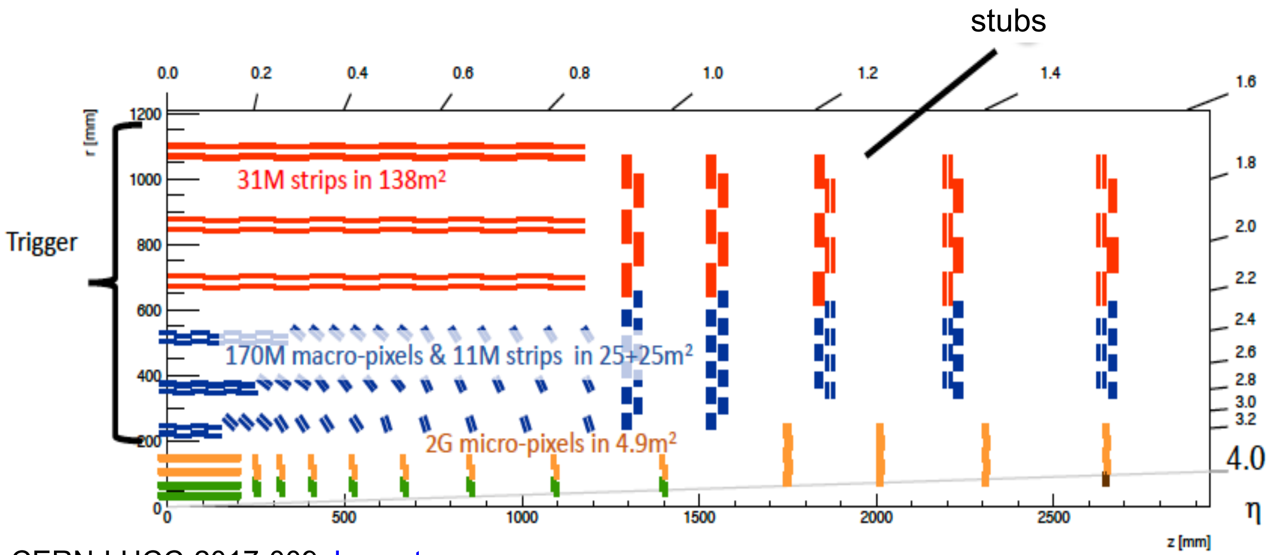


- **n-in-p silicon sensors** (planar or 3D for radiation hardness)
- Extended coverage to forward region
- Fast data transmission with low power giga-bit data transmission
- Serial powering of pixel detectors, DC-DC converters for strip detectors
- CO_2 cooling (thinner pipes)
- Carbon structures for mechanical stability

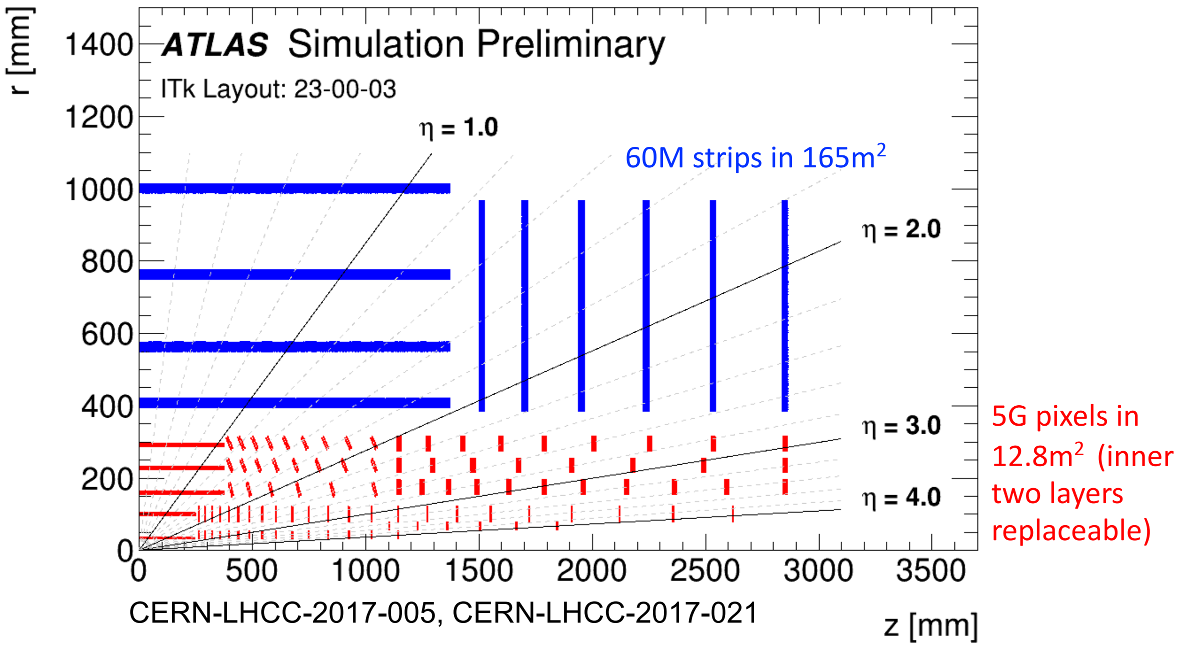
→ **low material budget (< 2 X_0) and efficient powering**

The layout of the tracking detectors

- Layout of the upgrade tracking detectors



CERN-LHCC-2017-009, Layout



CERN-LHCC-2017-005, CERN-LHCC-2017-021

	CMS	ATLAS
Strip pitch (μm)	90-100	70-85
Strip length (cm)	2.5-5	2.5-8
Strip thickness (μm)	290	300
Pixel size (μm²)	25x100, 1.5 mm macro-pixels	50x50 (planar L1-L4), L0 3D in rings 50x50, 25x100 in flat
Pixel thickness (μm)	≤ 150	≤ 150

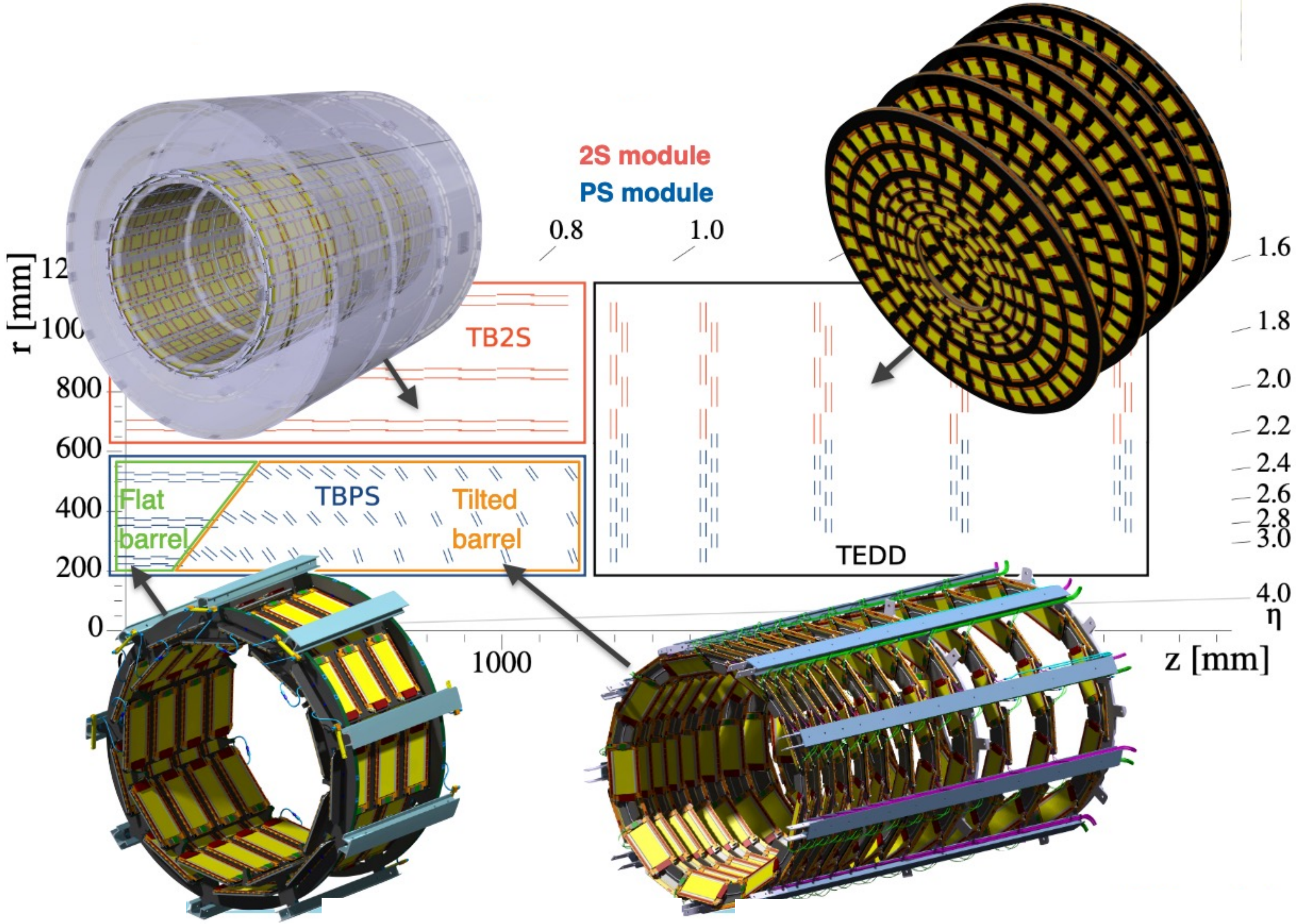
The CMS Strip detector upgrade

The CMS OUTER tracker foresees two type of modules

Concept: Every **module** is a **functional unit individually** connected to the power source and to backend system for data, trigger and control

- 7608 Strip-Strip modules – 2S
- 5592 Macropixel-Strip modules – PS

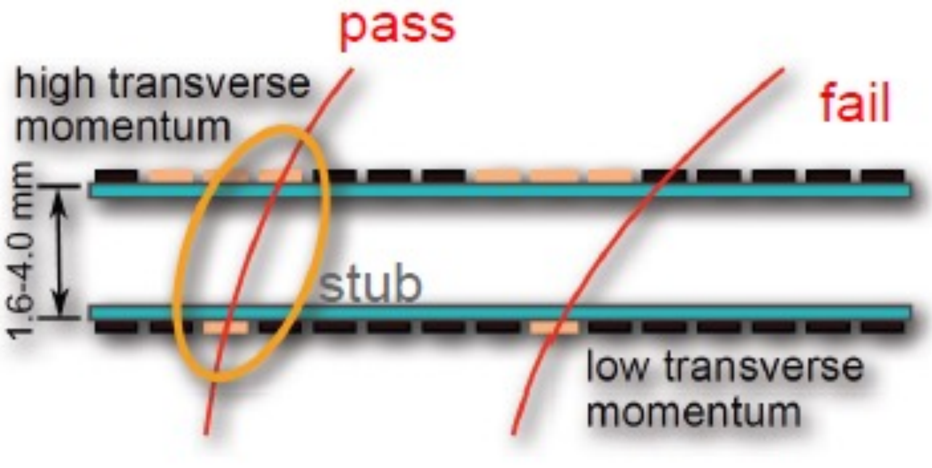
- Cabling to service area (power supplies) defines the optimal powering group: 12 modules per group → 12 modules mounted on various carbon fibre/foam support structures for precise placement and with cooling pipes for cooling

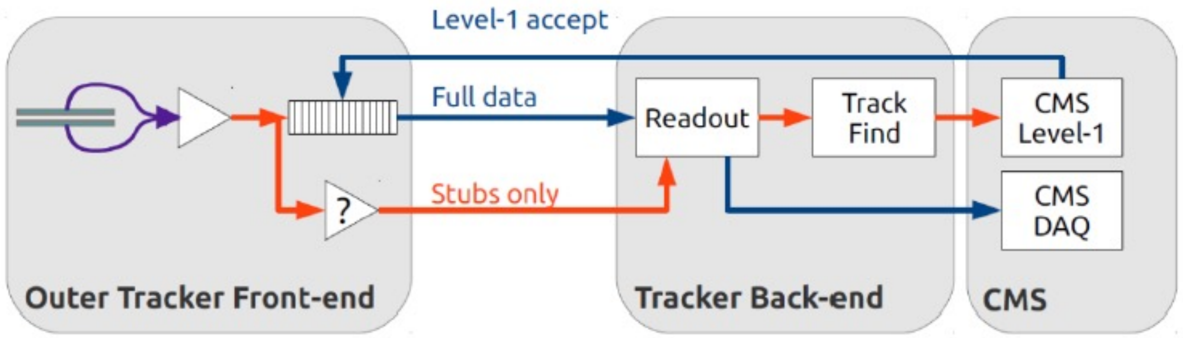


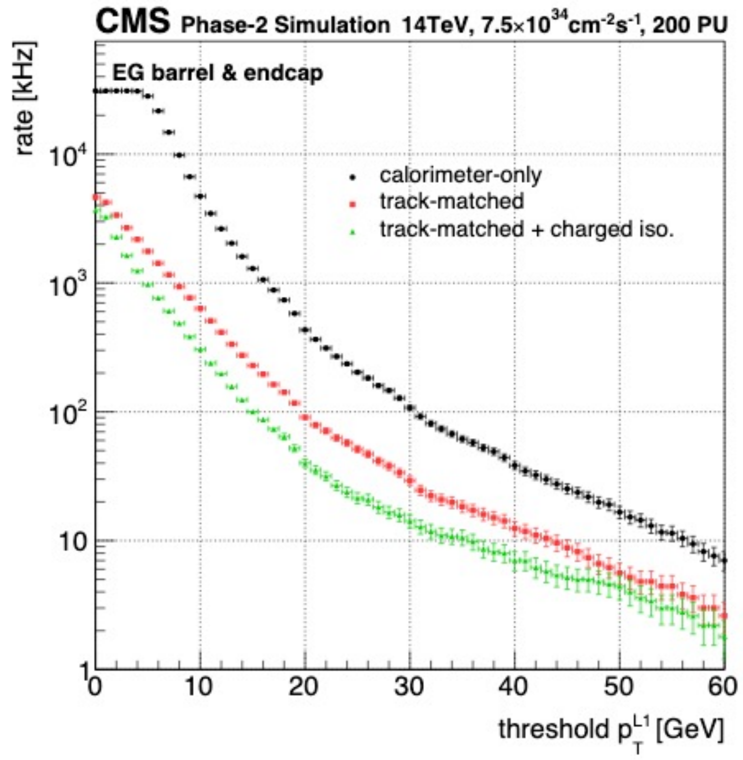
Track information for triggering in CMS

A. Dierlamm, S. Mersi

Key point in CMS Outer Tracker: include tracking information with fast readout → **2-sensor module concept for tracker**





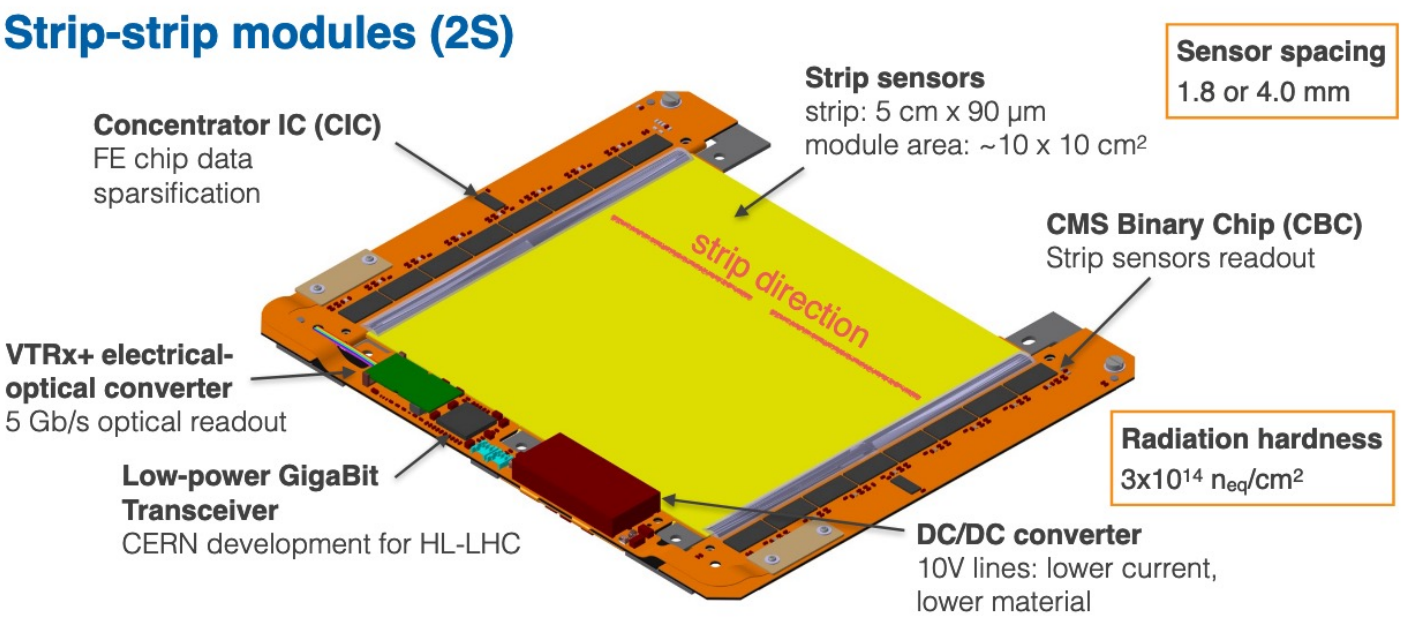


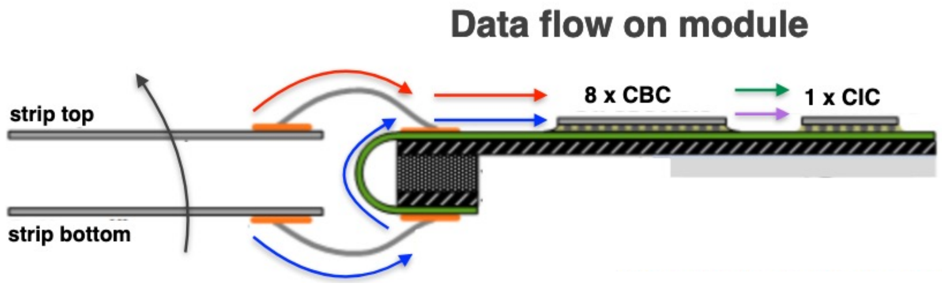
- → Correlation on module level (@ 40 MHz) to form stubs is sent out if within p_T > 2 GeV
- → Latency ~12 μs
- → Rate reduction (factor 10) due to sharp thresholds (leptons) and isolation (multi-jet background reduction)
- → Muon+calo+tracks combined give capability to particle-flow selections
- → Expected results achieved with prototype modules

CERN-LHCC-2020-004, CMS-TDR-021

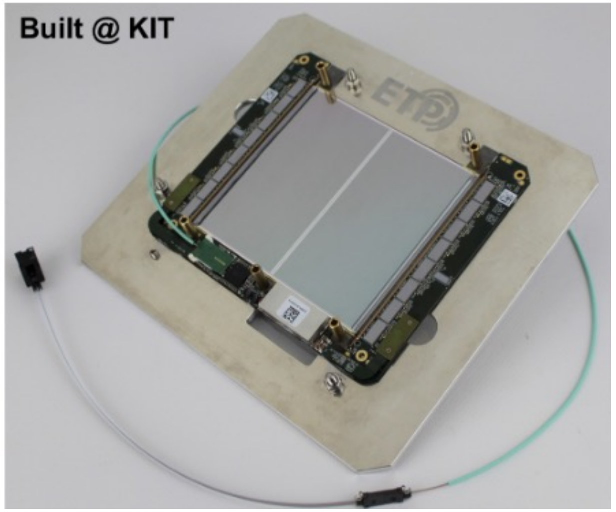
Strip-Strip (2S) modules in CMS

F. Ravera





- Sensor production started in Summer 2020, progressing smoothly
- Module production ongoing in 7 production centres in Europe, US, India and Pakistan



Integration prototype for central section (TB2S):

- Ladders from carbon fibre frame and cooling tubes
- 12 modules per ladder

Pixel-Strip (PS) modules in CMS

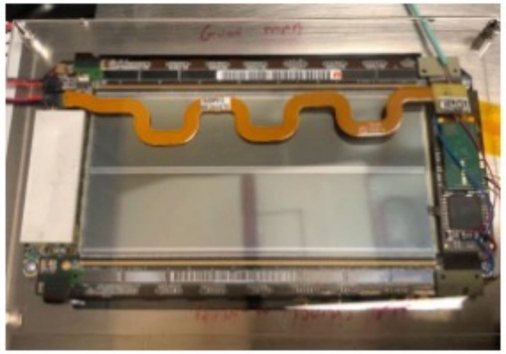
K. Damanakis

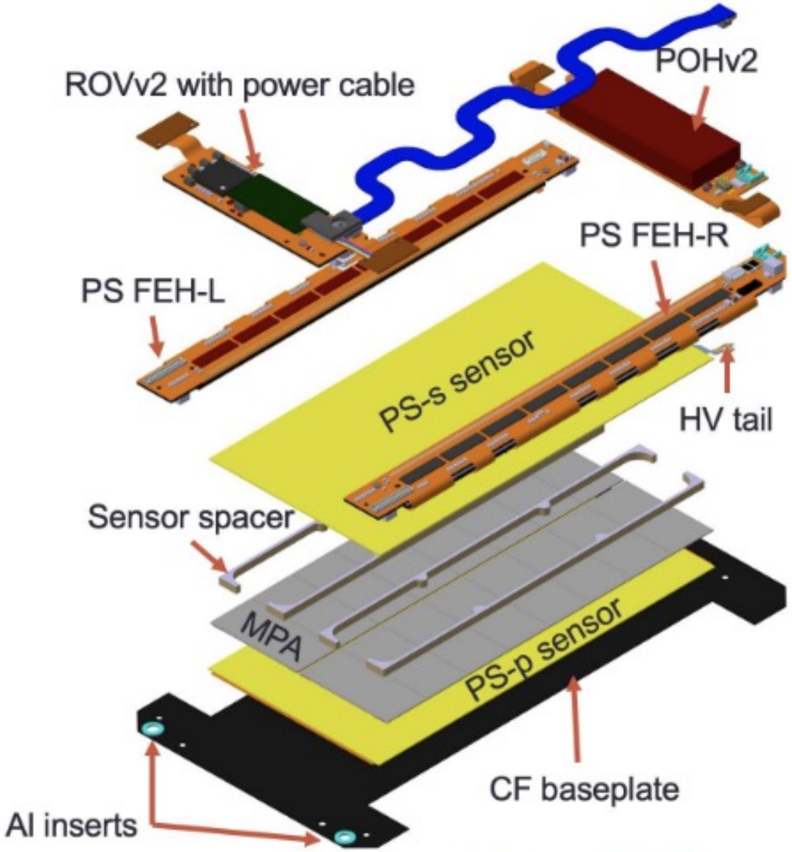
Macro-pixel sensor:

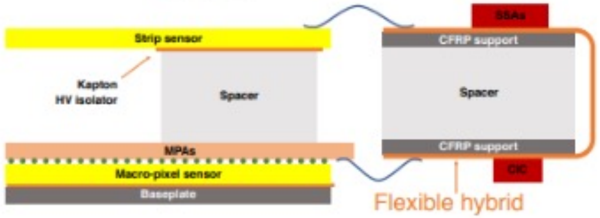
- **PS-p sensor**
  - Size : 5 x 10 cm^2
  - Pitch : 100 μm
  - Length : 1.5 mm
  - No. of strips : 32x960

Strip sensor:

- **PS-s sensor**
  - Size: 5 x 10 cm^2
  - Pitch: 100 μm
  - Length: 2.5 cm
  - No. of strips: 2x960



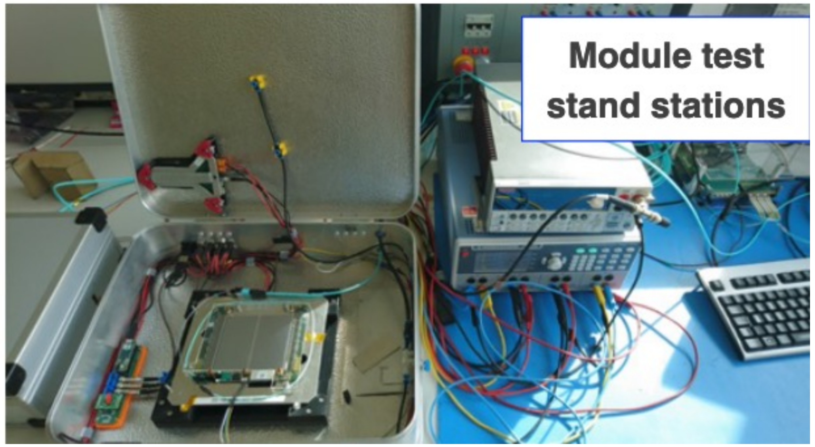




Sensor spacing 1.6, 2.6 or 4.0 mm
Radiation hardness $1\times10^{15}\ n_{eq}/cm^2$

5 module production centres are getting ready for pre-production

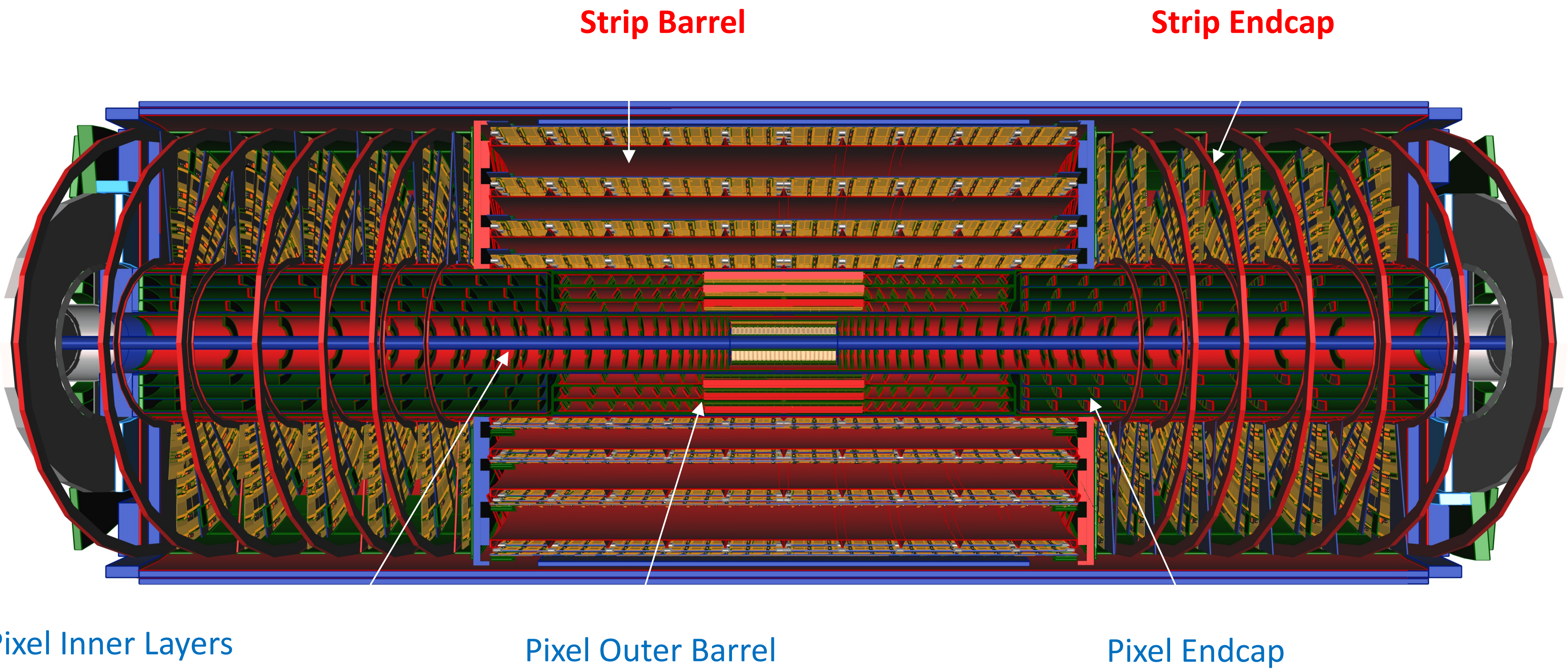
- Several prototypes successfully assembled and qualified (good hit efficiencies)
- Pre-production: spring 2023 - winter 2024
- Production: spring 2024 - spring 2026



Test results with irradiated modules:

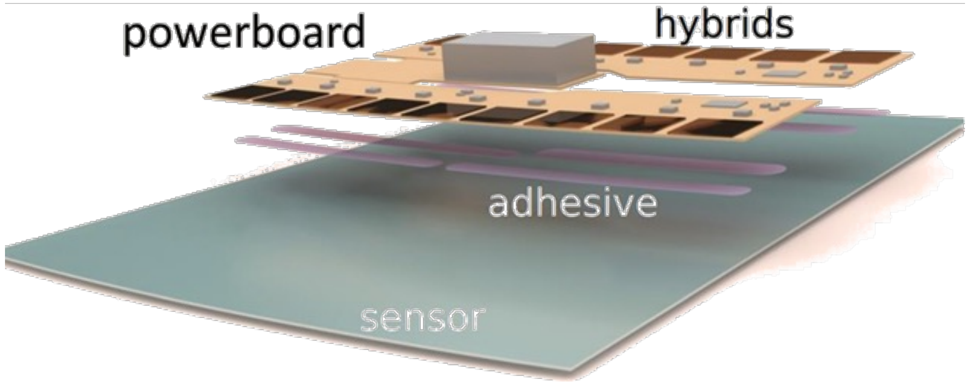
- Ladder cooled with 2S and PS modules cooled with CO_2. Test-box flushed slightly with dry air.
- Variations of CO_2 cooling set value: No thermal runaway observed below -18°C (potential convection contribution)

The strip detector of the new Inner Tracker ITk of ATLAS

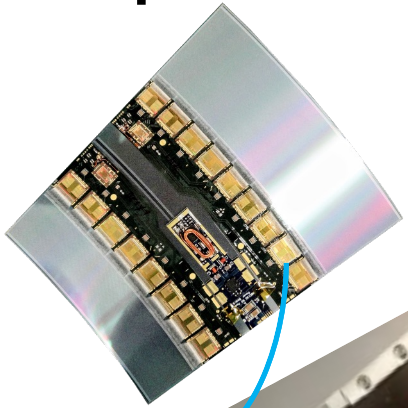


Concept of the ITk Strip Detector

- ~3x size and ~5x modules compared to current SCT strip detector in ATLAS
- **Similar concept of modularity of components**
  - Assembly and testing at multiple sites
  - Simplifies final assembly
  - Earlier test of full system
- 10,000 modules in 8 flavours with 2560 or 5120 channels/module

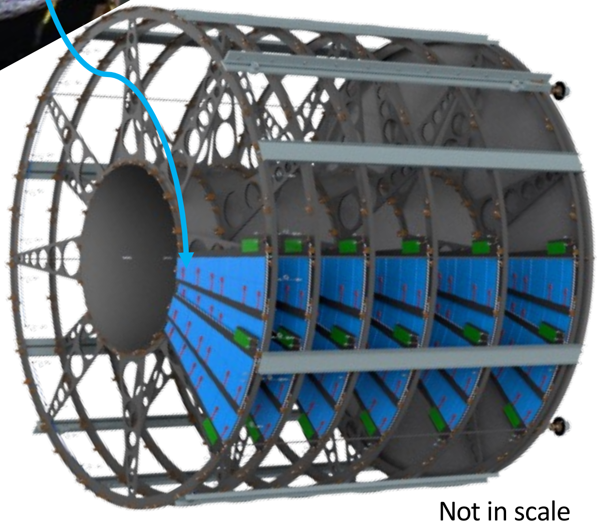


- Parallel powering scheme with DC/DC converters and on-module power control and monitoring chips



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



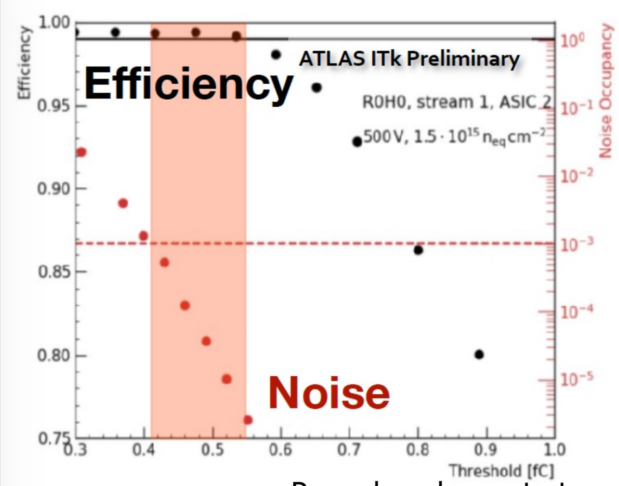
Endcap global support

- **More details on supports and cables in spare slides**

Not in scale

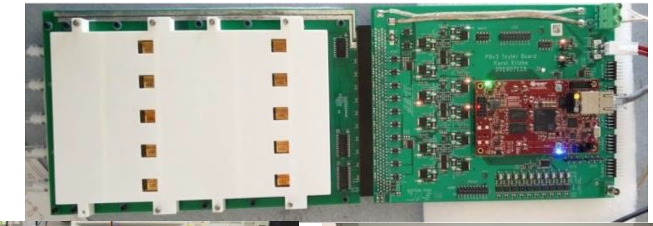
ITk Strip module production and performance

- **n-in-p float-zone sensors with p-stop isolation and ~320 µm thickness**
- Measurements in test beam show results meeting the operation range (>99% efficiency, <0.1% noise occupancy requirement, signal-to-noise ratio >10)

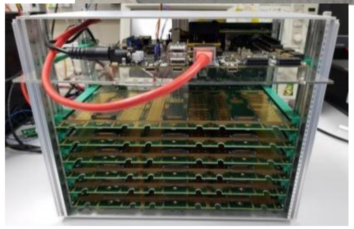


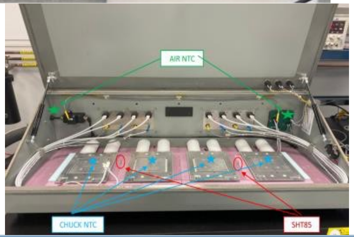
- **Preproduction ongoing**
  - ~20 assembly sites across 4 continents

Power board mass-tester



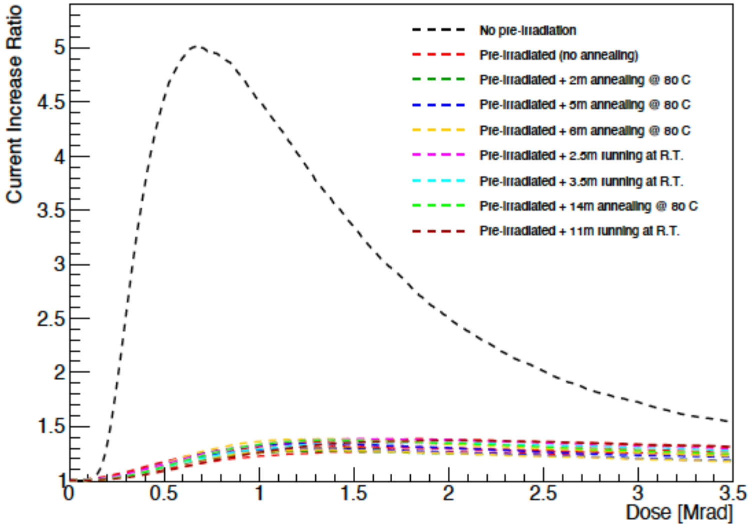
Hybrid Burn-in Crate





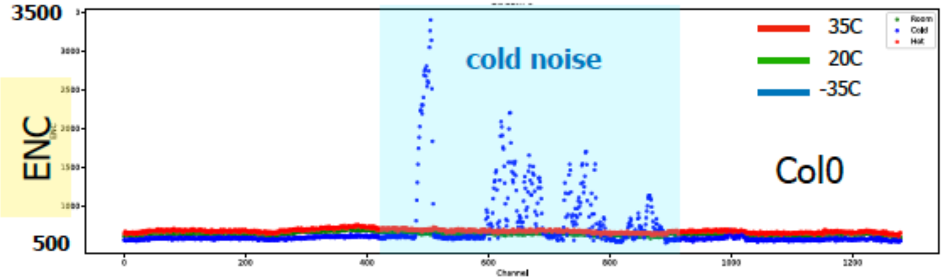
Module Thermal Cycler

- **Binary readout chip and controller chips** (130 nm CMOS) Improved design for radiation hardness but still power usage increase vs. ionizing dose (known for this CMOS process)



→ pre-irradiation of ASICs to 5 Mrad in production (DOI: 10.22323/1.313.0094)

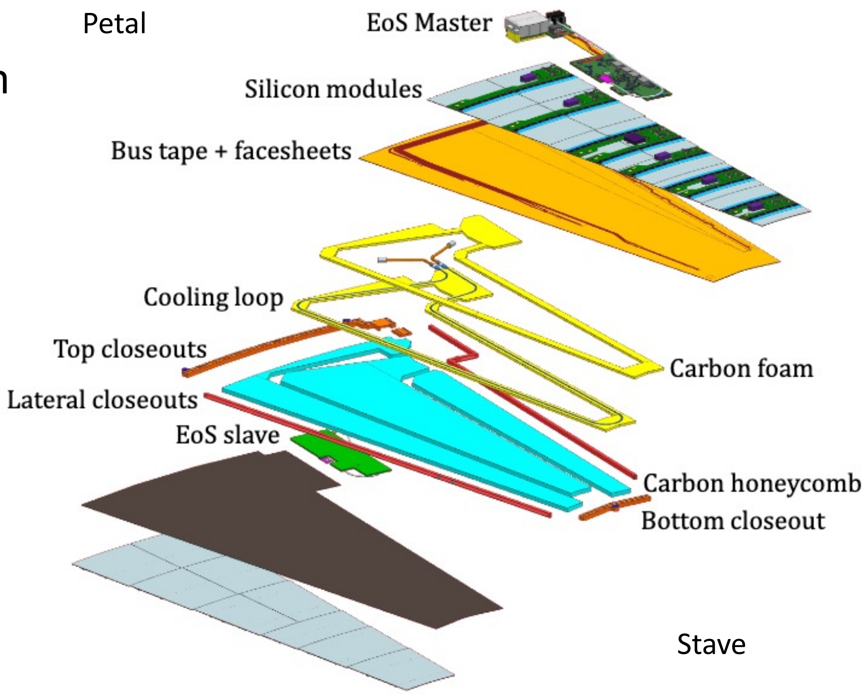
- Increase in noise was observed in modules at cold operation, mainly in strips below hybrid

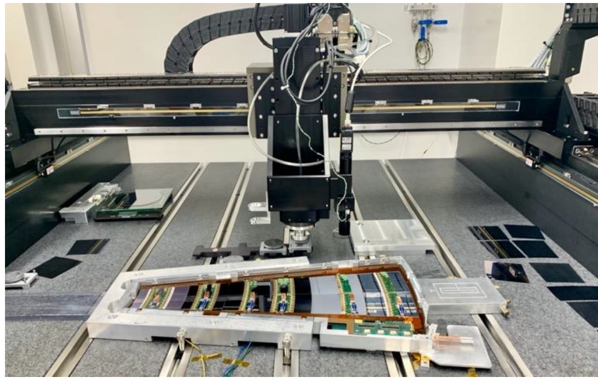


→ Investigation actively ongoing

ITk Strip local supports

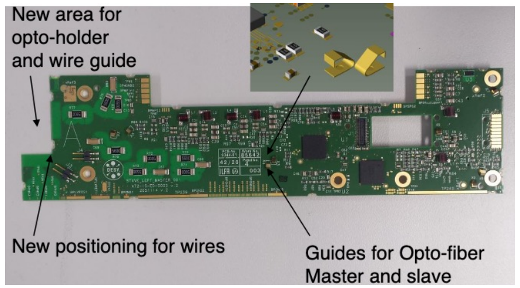
- **Carbon-fibre composite structures** with co-cured polyimide-copper **bus tapes** have **modules** glued on top of both sides with a stereo angle between both sides
  - In central region (barrel): staves with 14 modules on each side (392 staves in total)
  - In endcaps: petals with 9 modules on each side (384 petals in both endcaps)



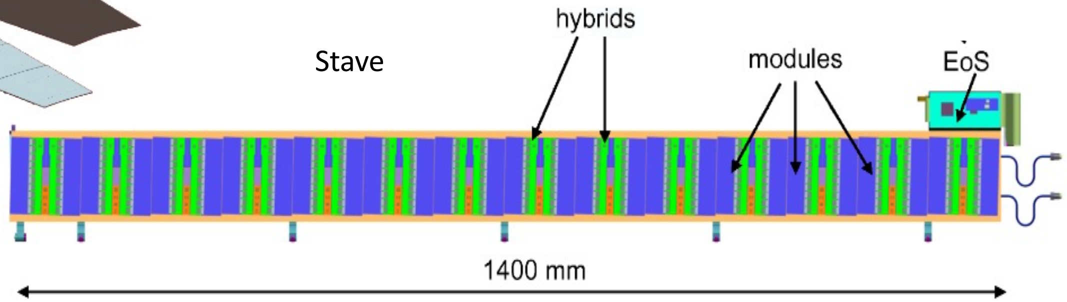


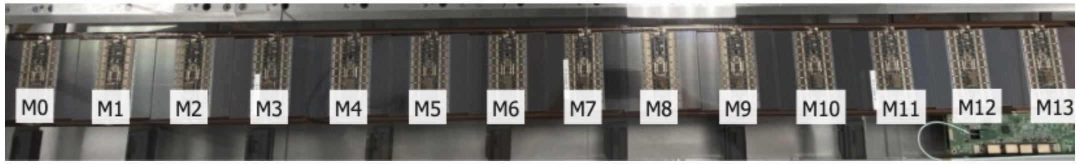
Loading of modules to better than 40 µm accuracy with gantry systems

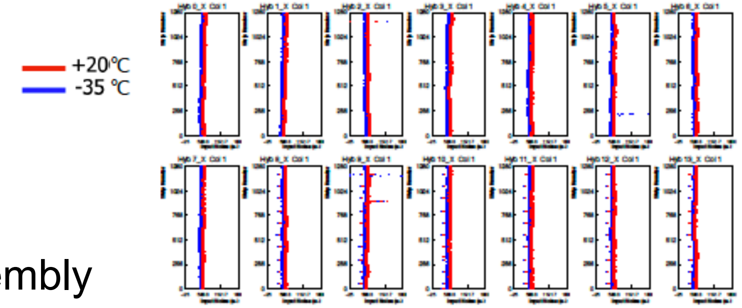
- **End-of structure cards service the electrical to optical transmission** (lpGBT and VTRx+ links) **and to the outside world**



End-of-strucure card



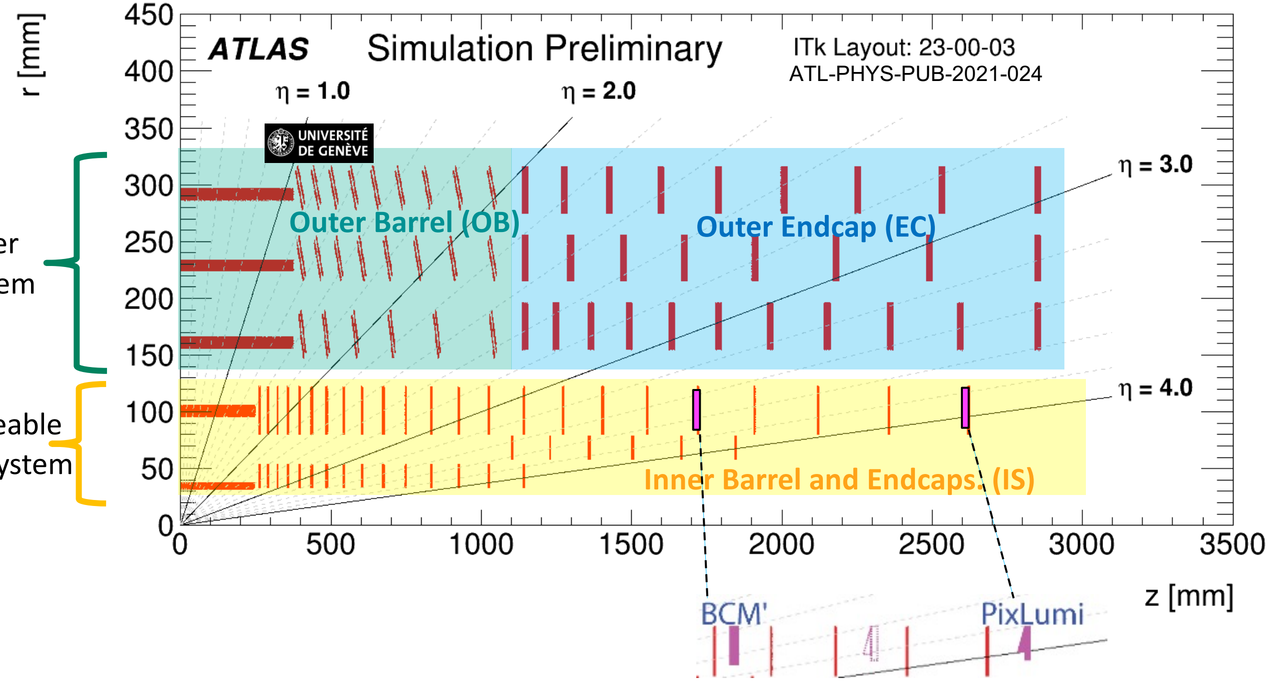




Noise and leakage current values as expected after assembly

- Good electrical and thermal performance achieved, pre-production running

Overview of the ATLAS ITk Pixel detector

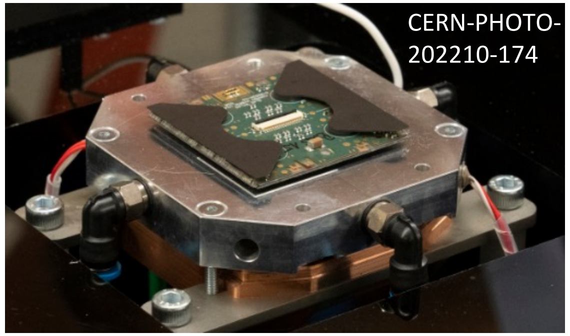


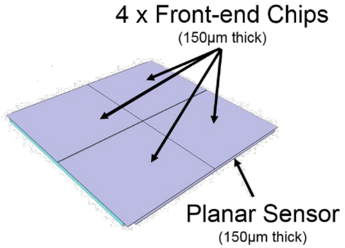
	Surface [m²]	# Channels	# modules
Pixel	13 **(x7)**	5 G **(x60)**	8.5 k

OB 53.5% of the pixel detector

Uni GE team plays a key role in the Outer Barrel!

4-chip module on test jig





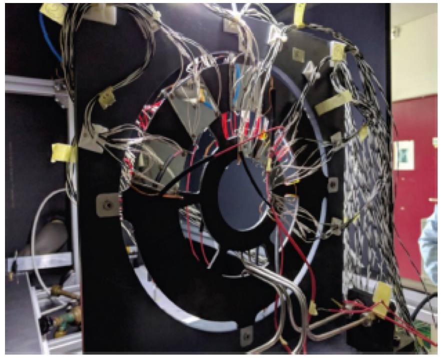
- **Different sensors types and technologies depending on distance from interaction point**
  - Modules assembled with 3D-sensors in triplet, 3 chips (Layer 0), planar quads, 4 chips with 100 µm (L1), planar quad sensors with 150 µm thickness (L2, L3, L4)
  - Pixel size 50x50 µm² (L1-L4, rings of L0), 25x100 µm² (barrel of L0)
  - Modules plan soon to start pre-production with current version of front-end chip

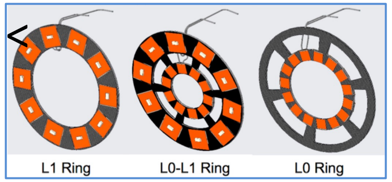
- **Front-end chip** developed in **RD53** Collaboration (ATLAS+CMS) (see later slides on CMS)
- **Reduction of material by deploying serial powering and CO_2 cooling**
- Fast readout with max. 1 MHz trigger rate and data transmission with 1.28 Gbps (electrical) to lpGBT and VTRx+ link (optical) to FELIX readout

Local support mechanics of the ITk Pixel detector

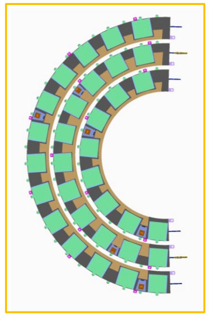
Principle: Local support structures from carbon-fibre composites get modules attached

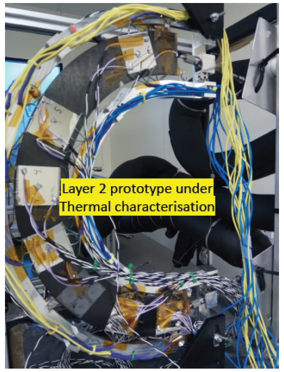
- Inner System: staves, rings



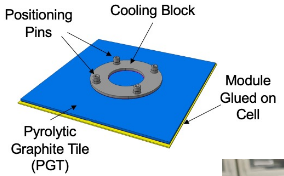


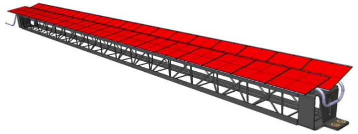
- Endcap: half-rings

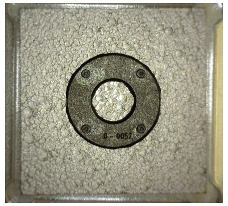


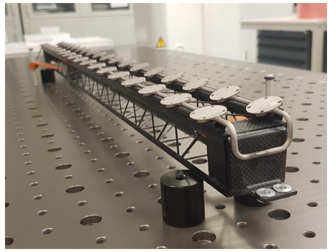


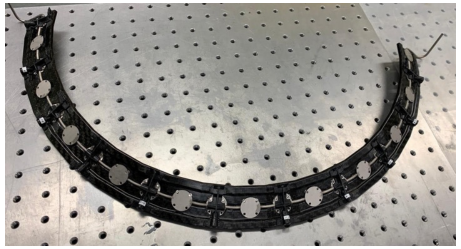
- Outer Barrel: cells, longerons and inclined half-rings







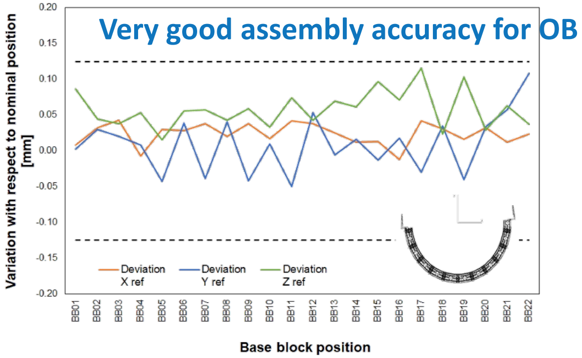




- **Layout differs in detector areas:** varying serial powering chain lengths, varying mechanical solutions to achieve high thermal and electrical performance for stable and safe operation

→ **Successful evaluation of thermal performance and manufacturing variability for OB local supports**

→ **Pre-production ongoing**

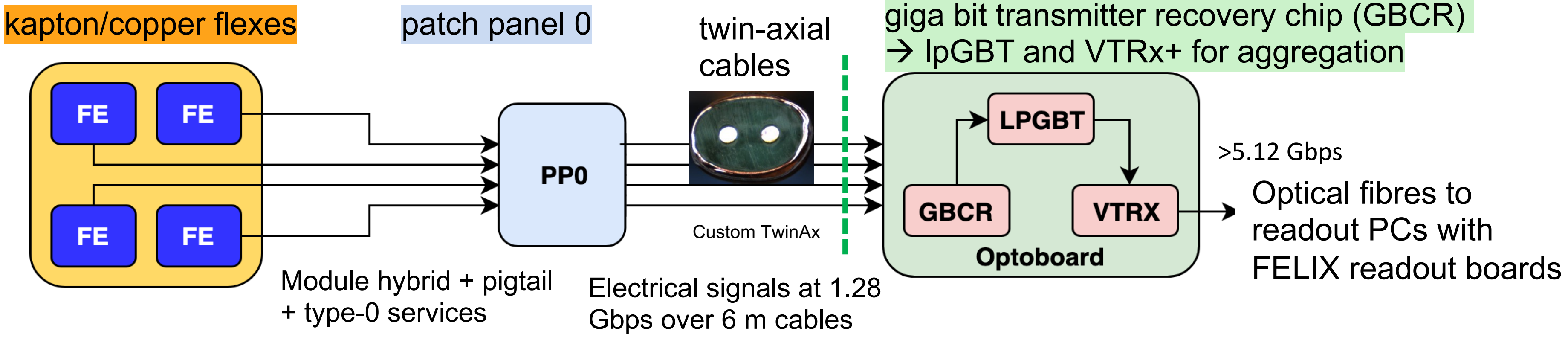



OB inclined half-ring in UniGE clean room

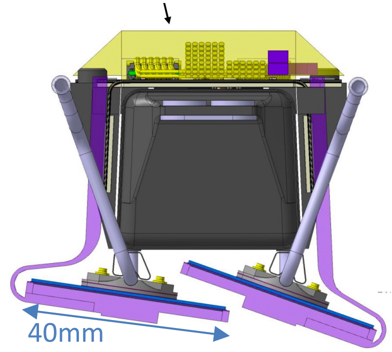
Manufacturing of components and assembly for OB in-house at CERN, the University of Geneva and the University of Bonn

Readout of the ITk pixel detector

- On-detector readout with 1.28 Gbps (up to 4 lanes per front-end chip) and conversion to optical signals at > 5.12 Gbps
- Uplink sharing for all layers to reduce material (320 MHz)



L2 Barrel: envelope for twinax cables

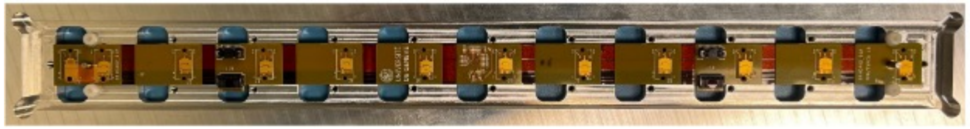


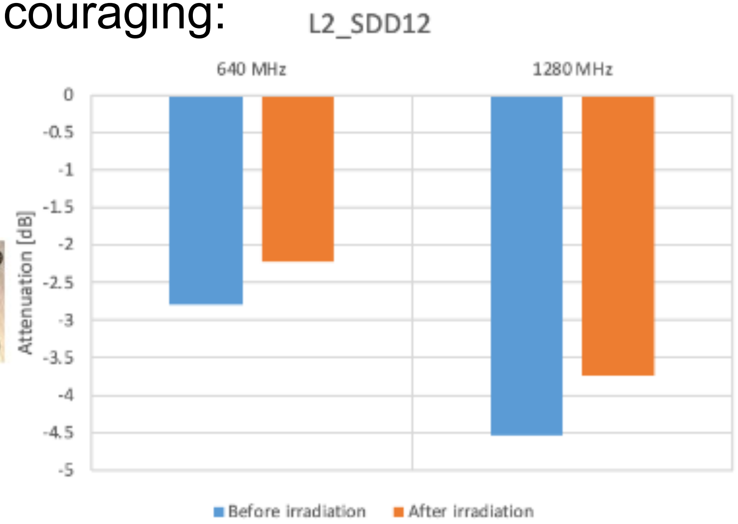
Further challenge are space constraints for routing of services

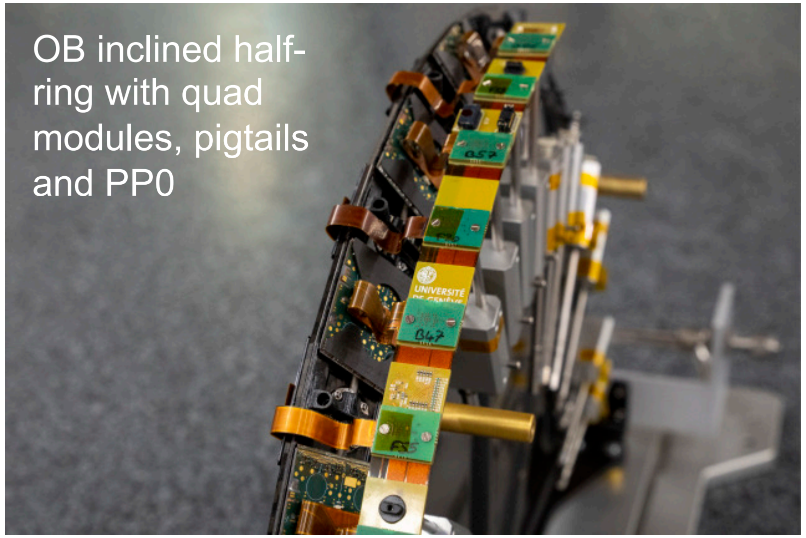
Losses to be kept below 20 dB → Verification of full chain to be achieved!

First results on single components are encouraging:

Inclined PP0 layer 3 developed and successfully tested at UniGE



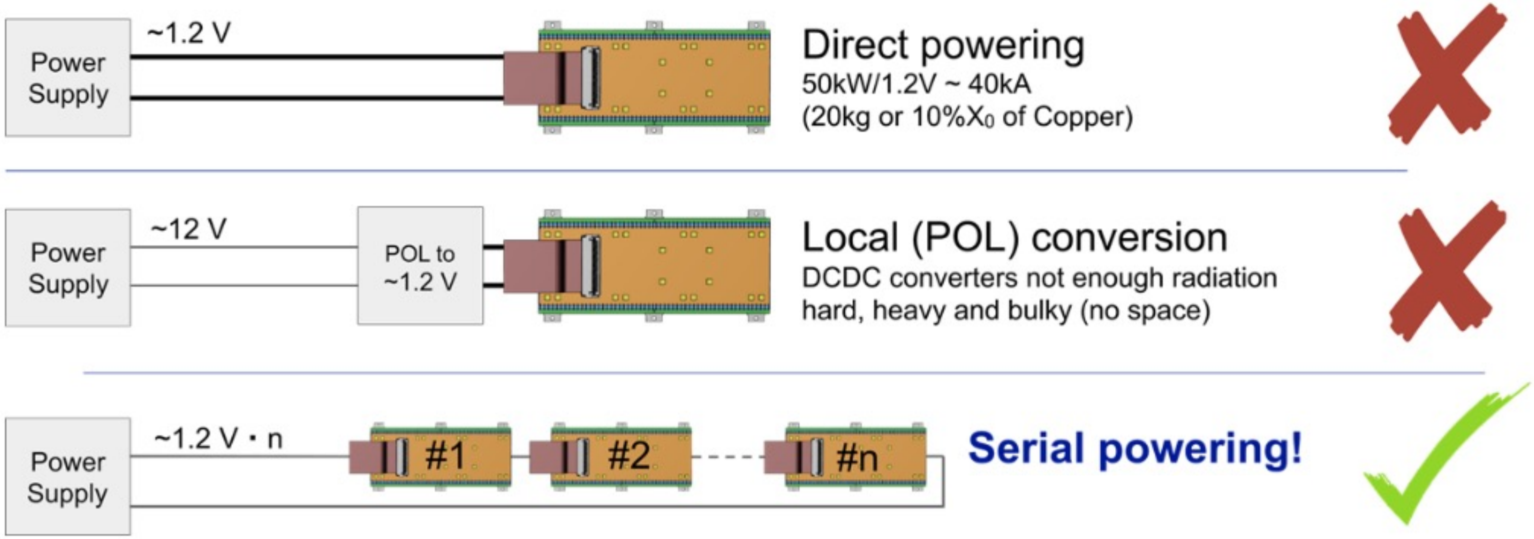




Powering of the ATLAS and CMS Pixel detectors

G.Sguazzoni, T. Senger

- **Powering modules serially with chains of up to 12 quad modules**

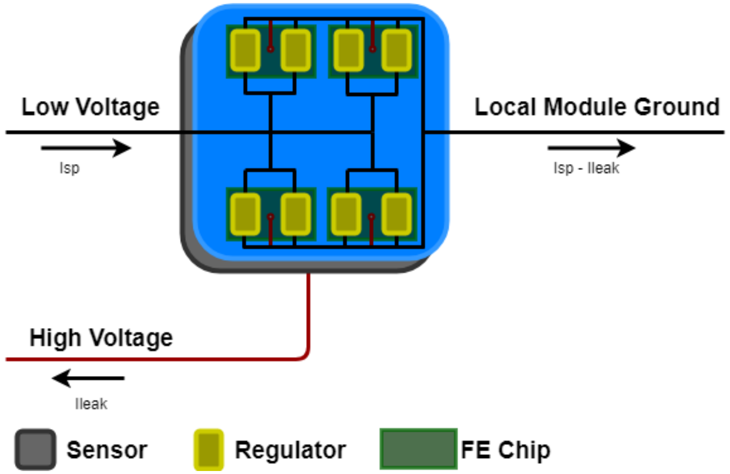


Serial powering:
T. Stockmanns et al., NIM A511 (2003) 174-179
D. Bao Ta et al., NIM A557 (2006) 445-459
L. Gonella et al., JINST 5 (2010) C12002

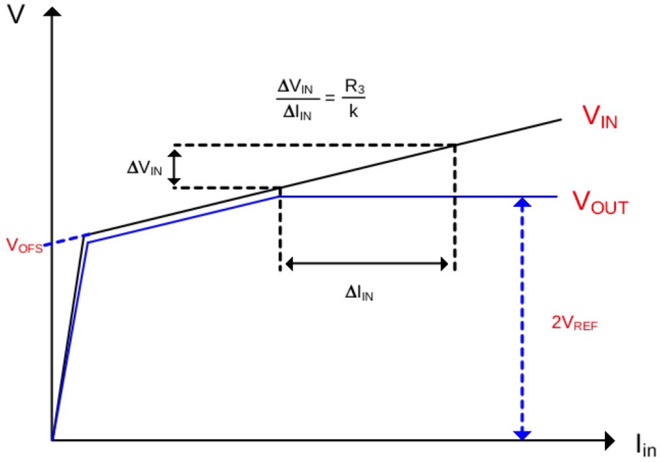
→ Radiation hard on-chip shuntLDO converts input voltage to constant front-end chip supply voltage. Slope & offset can be regulated.

→ Reduced number of supply lines, less material

→ Less power dissipation on services than with parallel powering



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



- Several HV lines per chain (at least 2 per SP-chain foreseen)
- Each module on different potential → AC-coupling of data lines
- Challenge: Has never been used on large scale, configuration and heat dissipation in ShuntLDOs

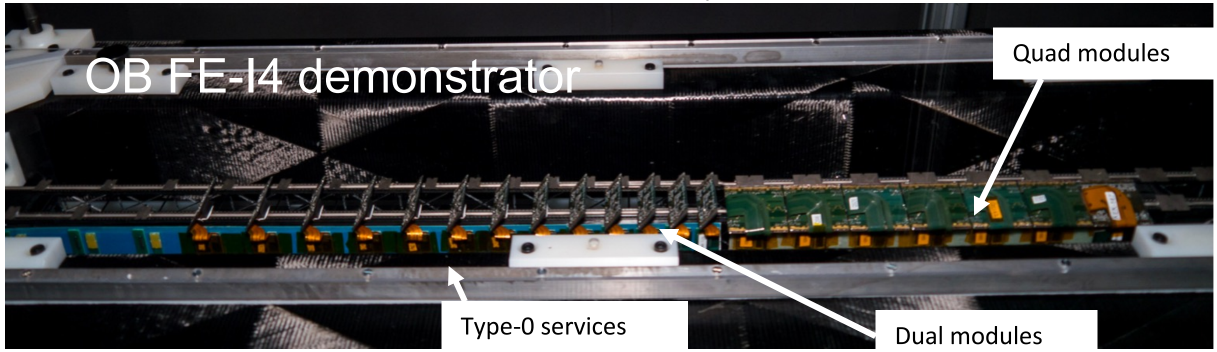
In ATLAS ITk Pixel:

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

Results of electrical prototypes in ITk Pixel

- **Outer Barrel demonstrator program** based on previous front-end chip version **successfully finished** (Up to 120 FE-I4 ASICs in 6 SP-chains)
  - Power fluctuations indicated necessity of improved shuntLDOs compared to FE-I4, implemented in ITkPixV1 FE (current FE)
- Test of **serial powering chain of standalone modules** before and after irradiation → modules fully functional but features at start-up seen (studying fast load changes in the serial chain)

https://cds.cern.ch/record/2661761



- **OB demonstrator with current front-end chip RD53A** recently installed and both inclined half-ring (11 modules) and first part of longeron (6 modules) **being evaluated** in OB System Test with CO_2 cooling

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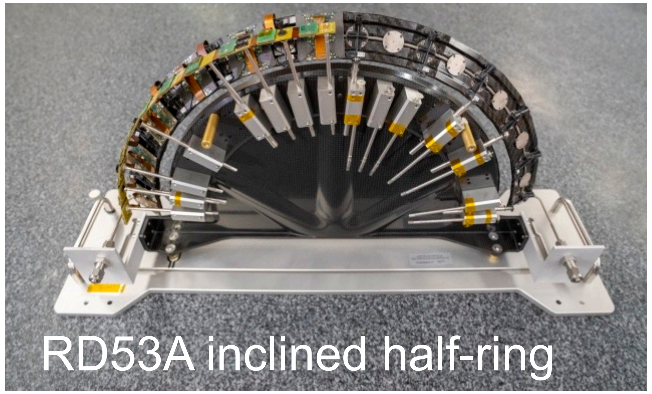
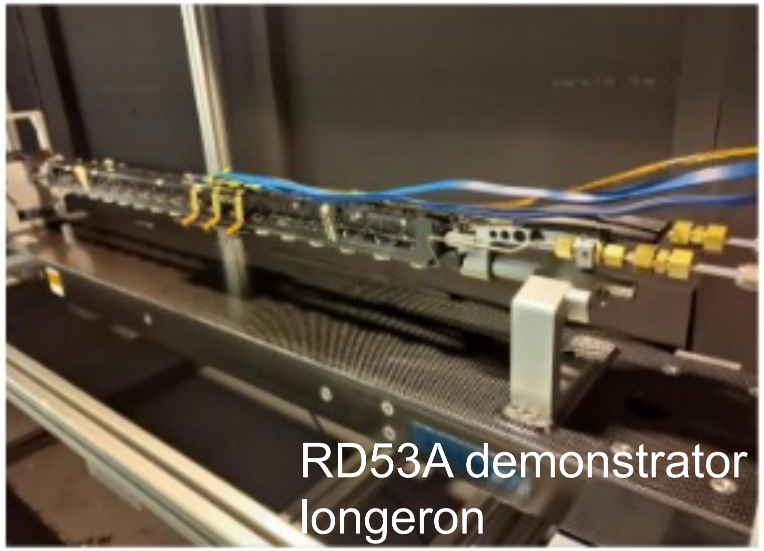
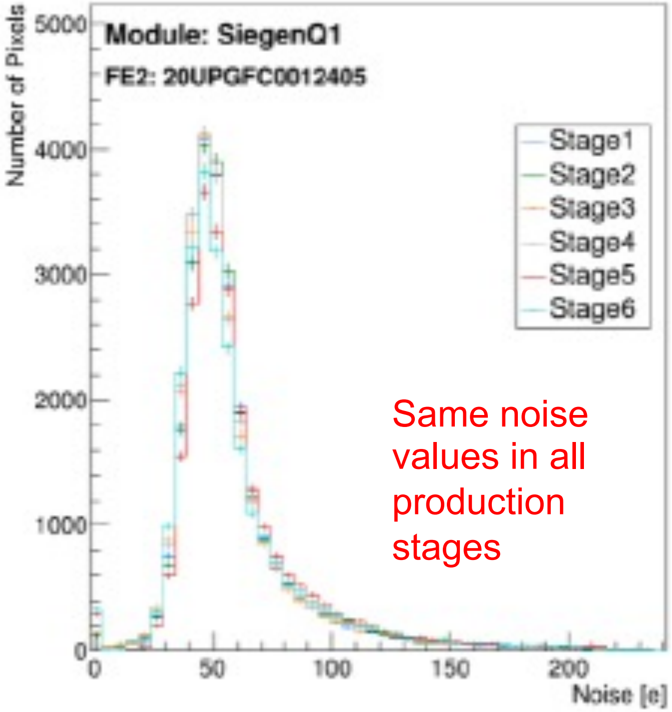






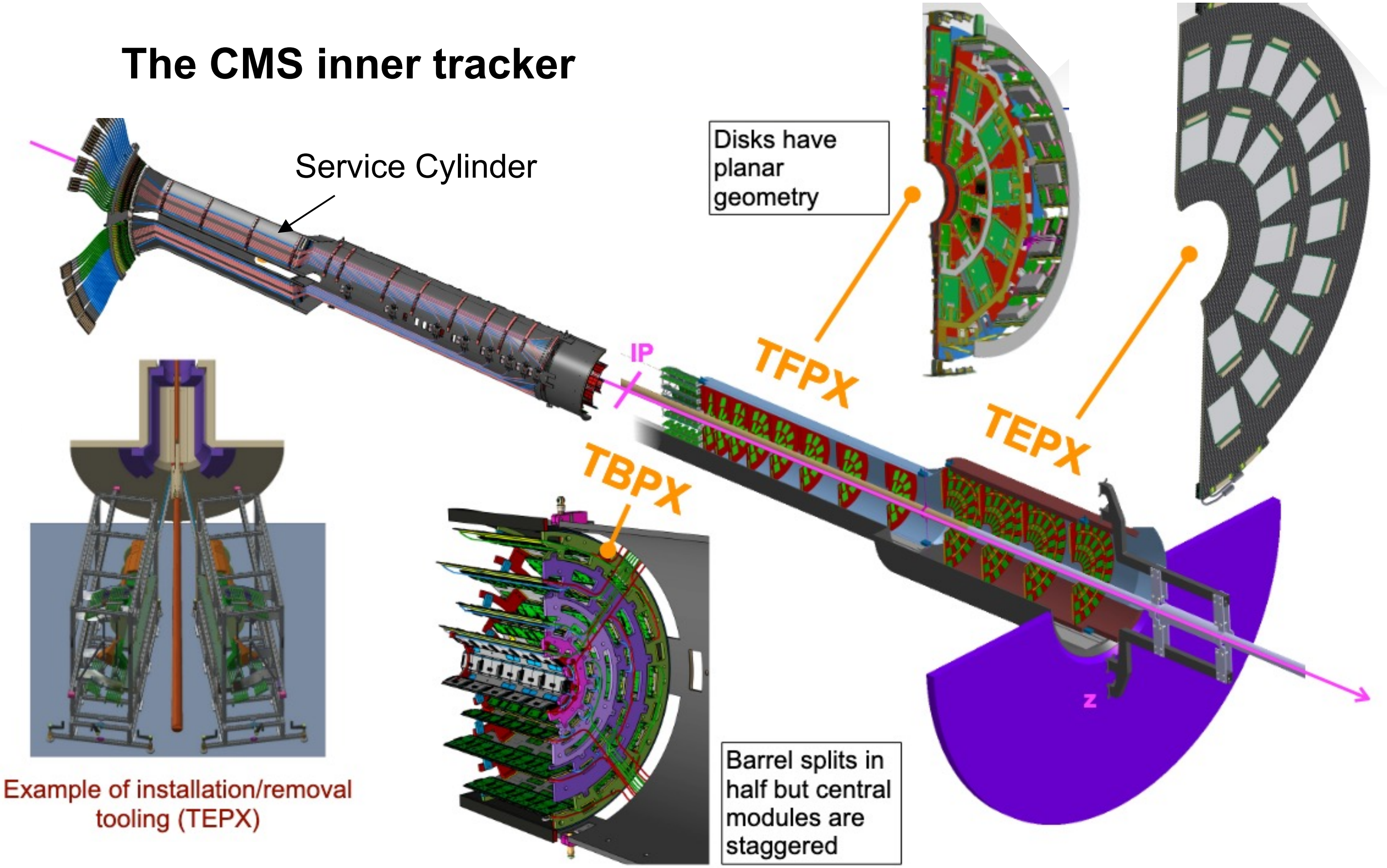
Same noise values in all production stages

Stages: 1 Module QC, 2 Thermal cycling, 3 Cell Loading, 4 Tab cutting, 5 Final Pigtail, 6 On demonstrator

The new CMS Pixel detector

G.Sguazzoni

The CMS inner tracker



- **Planar n-in-p sensors with pixel size: 25x100 μm².** 3-D sensors in barrel layer 1
- 3900 modules, 4.9 m² (~50% modules less than in ATLAS ITk Pixel)
- Powering in serial chains and cooling with CO_2 . Cooling pipes below front-end periphery in innermost layers.
- Service Cylinder to route cables on-detector. Specific boards for electrical-optical conversion inside the detector volume (see spare slide)

- Relatively simple removal/ installation (smaller Layer 1 radius since beam pipe bake out can be done without IT in place) → Maintenance possible in long shutdowns

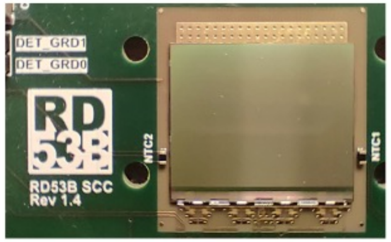
Front-end and module concept in CMS Pixels

- **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 were collected and show good results. Cold-start up of ShuntLDO problematic**
  - ITkPixv1 (ATLAS) and CROC-1 (CMS) produced and being tested
  - Verification of ATLAS ITkPixv2 ongoing to submit for production at the end of November 2022, then design of CMS CROC-2 to submit in April 2023

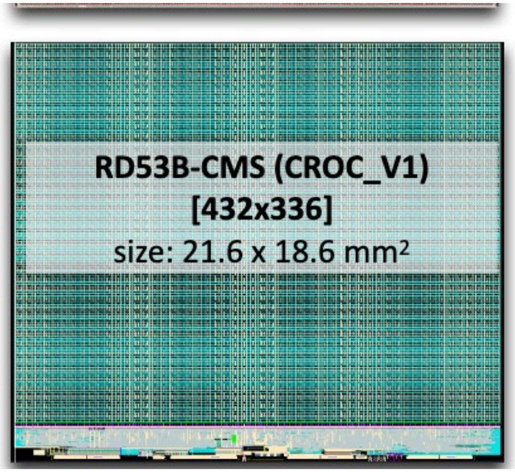
Cell size	50x50 μm²
Technology	CMOS 65 nm
Hit rate	3.5 GHz/cm²
Trigger rate	750kHz
Trigger latency	12.5 μs
Min. threshold	600 e-
Radiation tolerance	> 500 Mrad* @ -15 °C
Power	< 1W/cm²

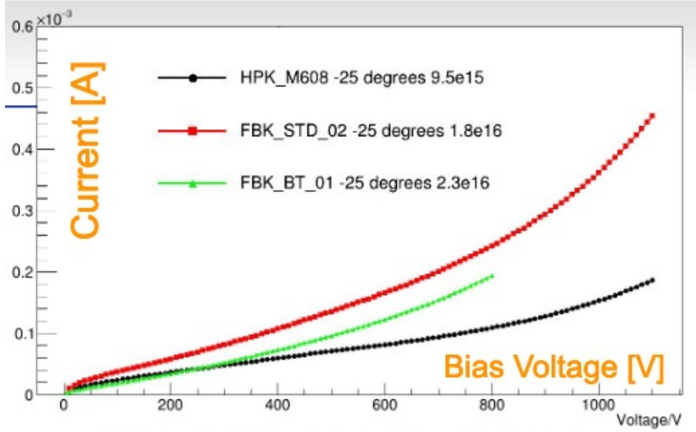
*but demonstrated working up to ~1.1Grad

architectures



CMS prototype w/ final size and linear FE





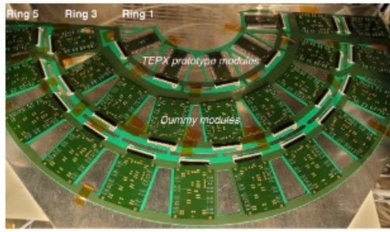
Post-coating, post-irradiation IV of HPK and FBK single chip modules

→ Evaluation of performance after irradiation and in test beams ongoing

- **Module** flavours with 1x2 and 2x2 front-end chips. Assembly performed with jigs and templates (10-20 μm precision achieved)
- Parylene-N foreseen for encapsulation of wirebonds and for HV insulation

A prototype ladder

A prototype small disk



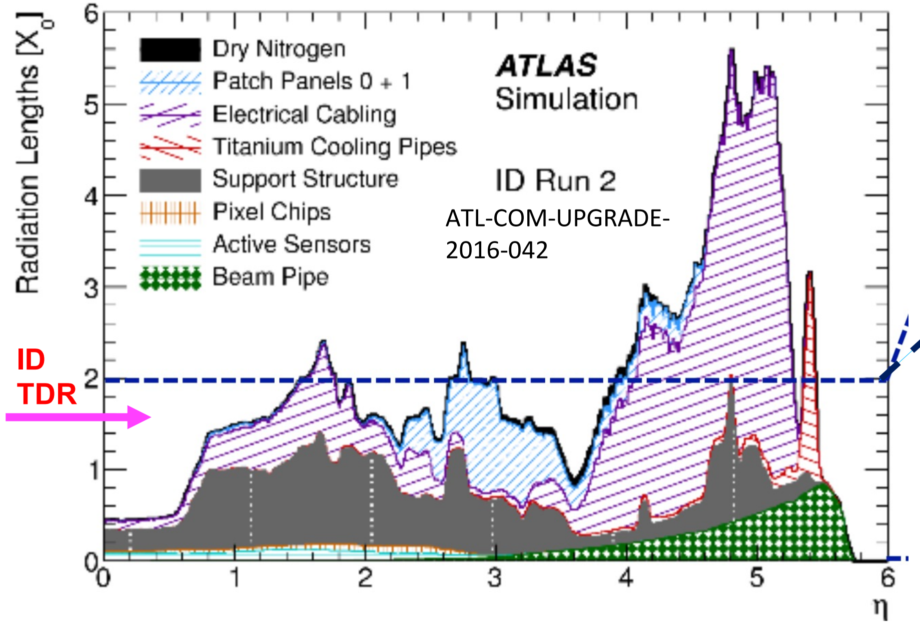
A prototyoe large disk

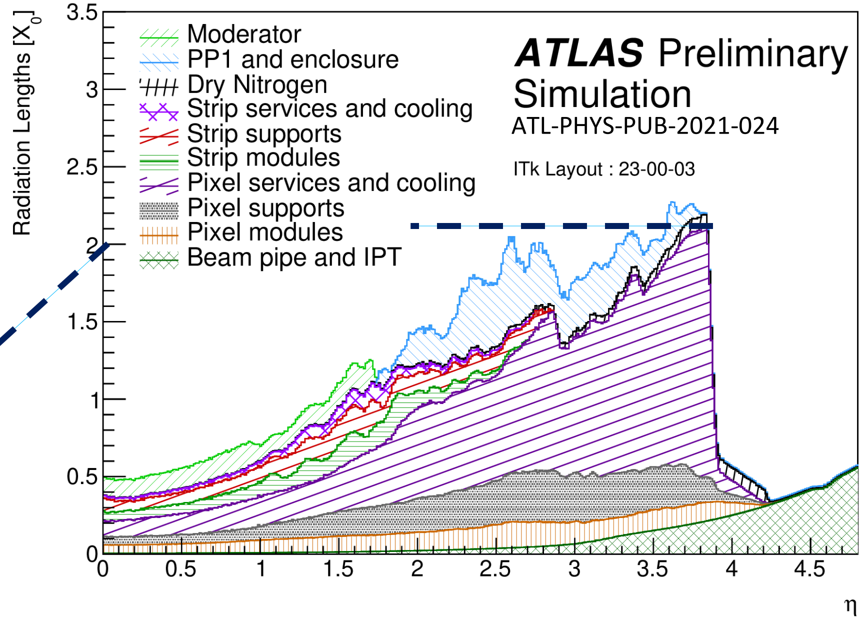
System test ran cooling and mechanics prototypes being tested

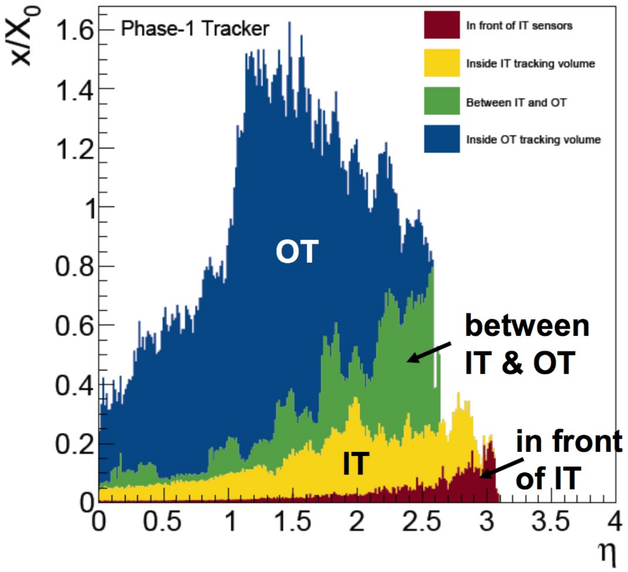
Material estimates for the upgrade tracking detectors

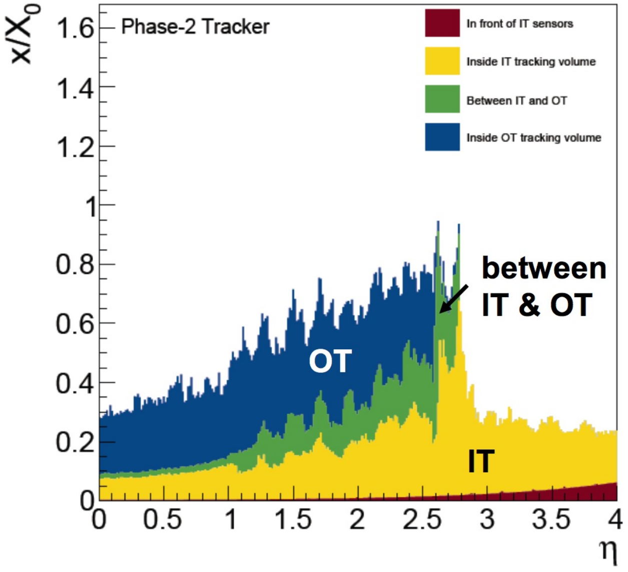
Design aiming for reduction of material

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





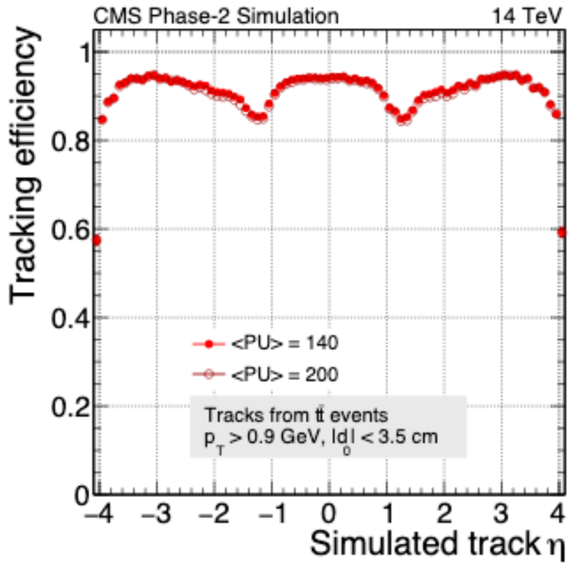


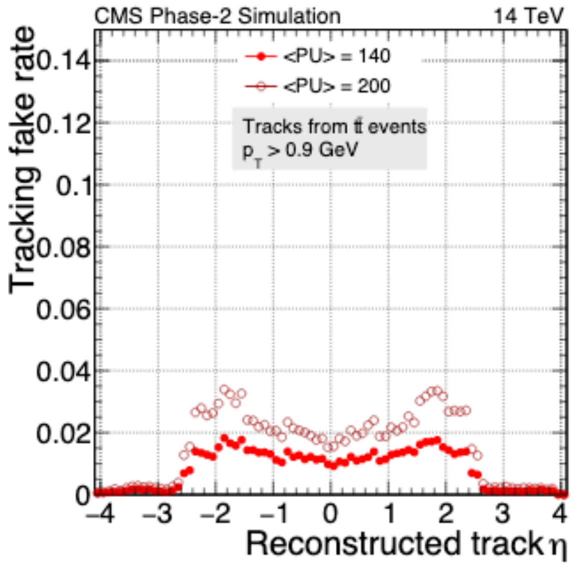


CMS CERN-LHCC-2017-009

Tracking performance

- High tracking efficiencies and low fake rates





- For ATLAS reconstruction efficiency
  > 90% in central region
  > 80% in forward region

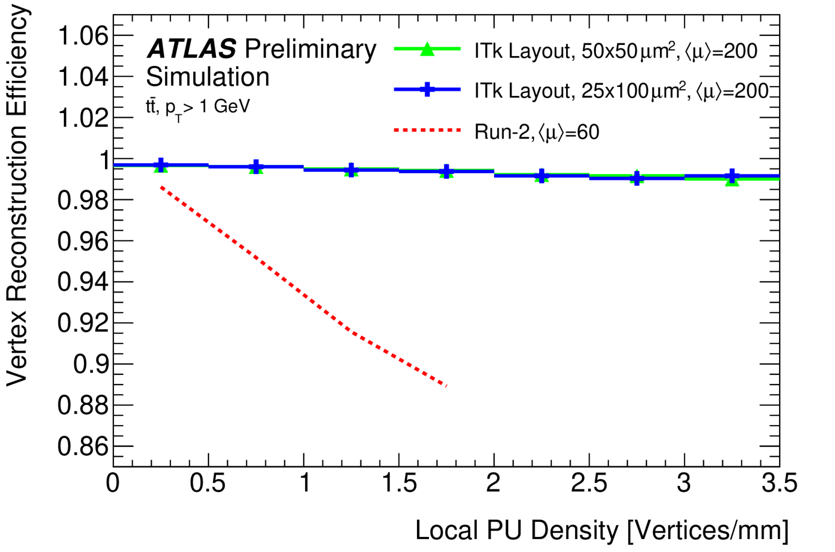
Reduced material → less interactions

Increase in hit counts → tighter track selections

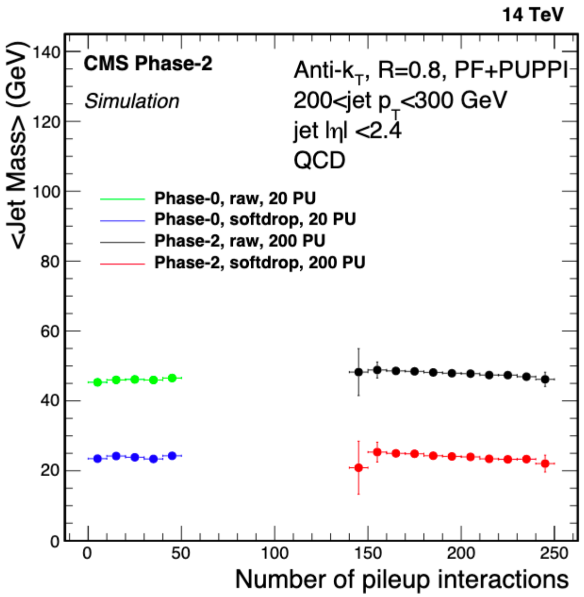
Improved hermeticity → more hits and fewer holes

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

ATL-PHYS-PUB-2019-014

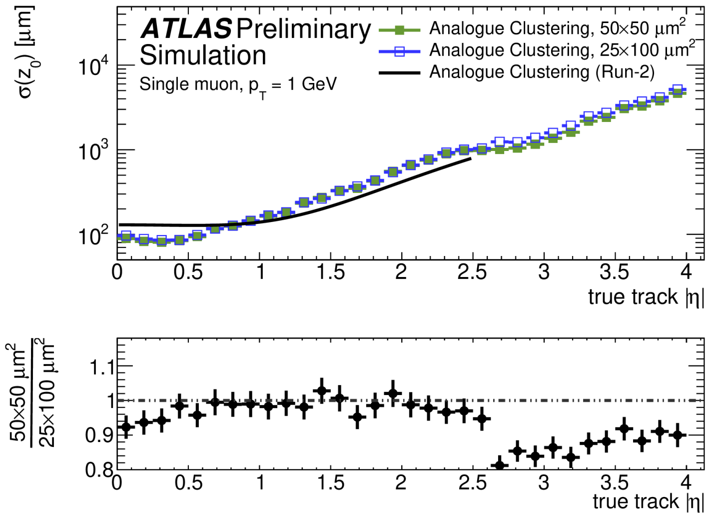


- Jets robust to pile-up

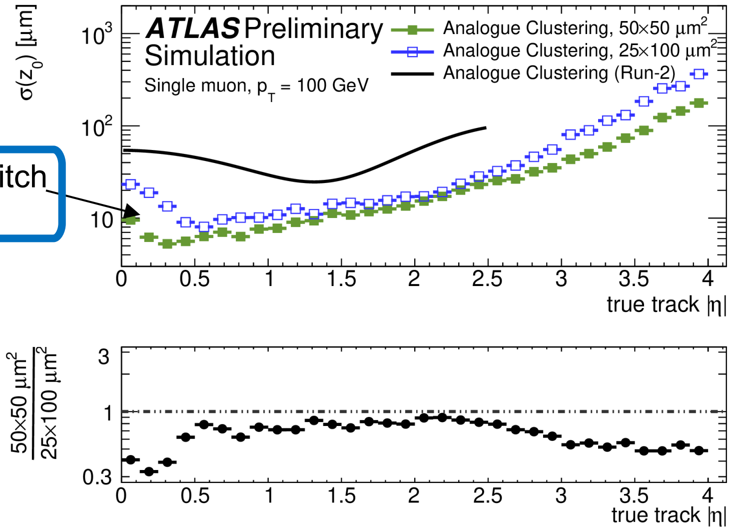


Tracking performance

- Longitudinal impact parameter z_0 resolution crucial for pile-up suppression

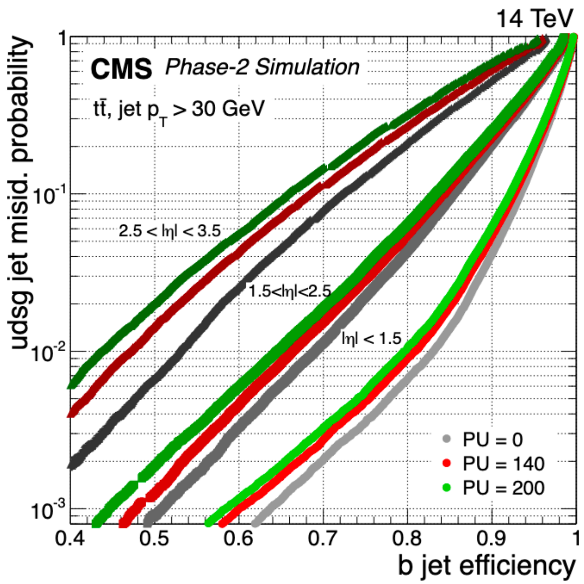


smaller pitch
in ITk

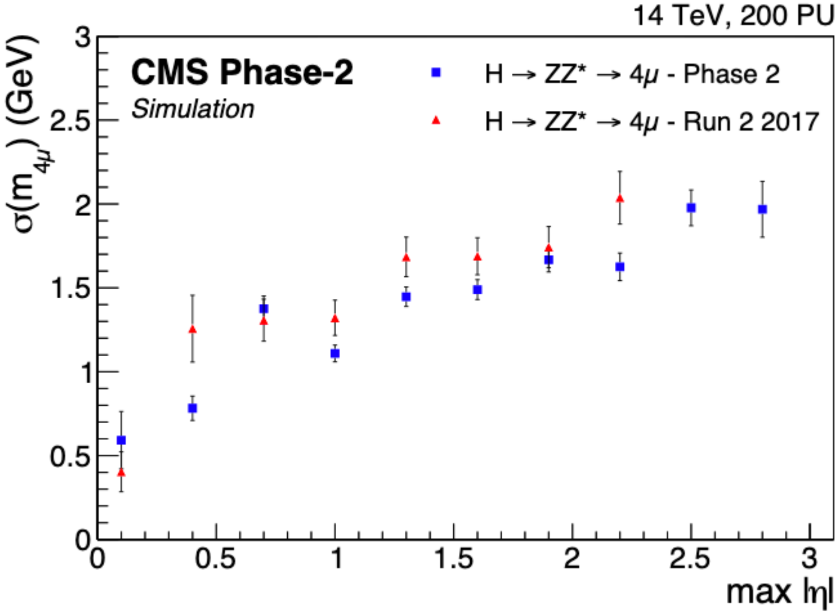


- For low p_T dominated by multiple scattering
- For high p_T dominated by intrinsic detector resolution
- Improvement due to reduced material and better resolution of strip tracker than current TRT

- B-tagging performance and light-jet rejection robust to pile-up → important to discriminate between VBF and tt in forward regions



- Extrapolation for Physics case H→ μμ



Summary

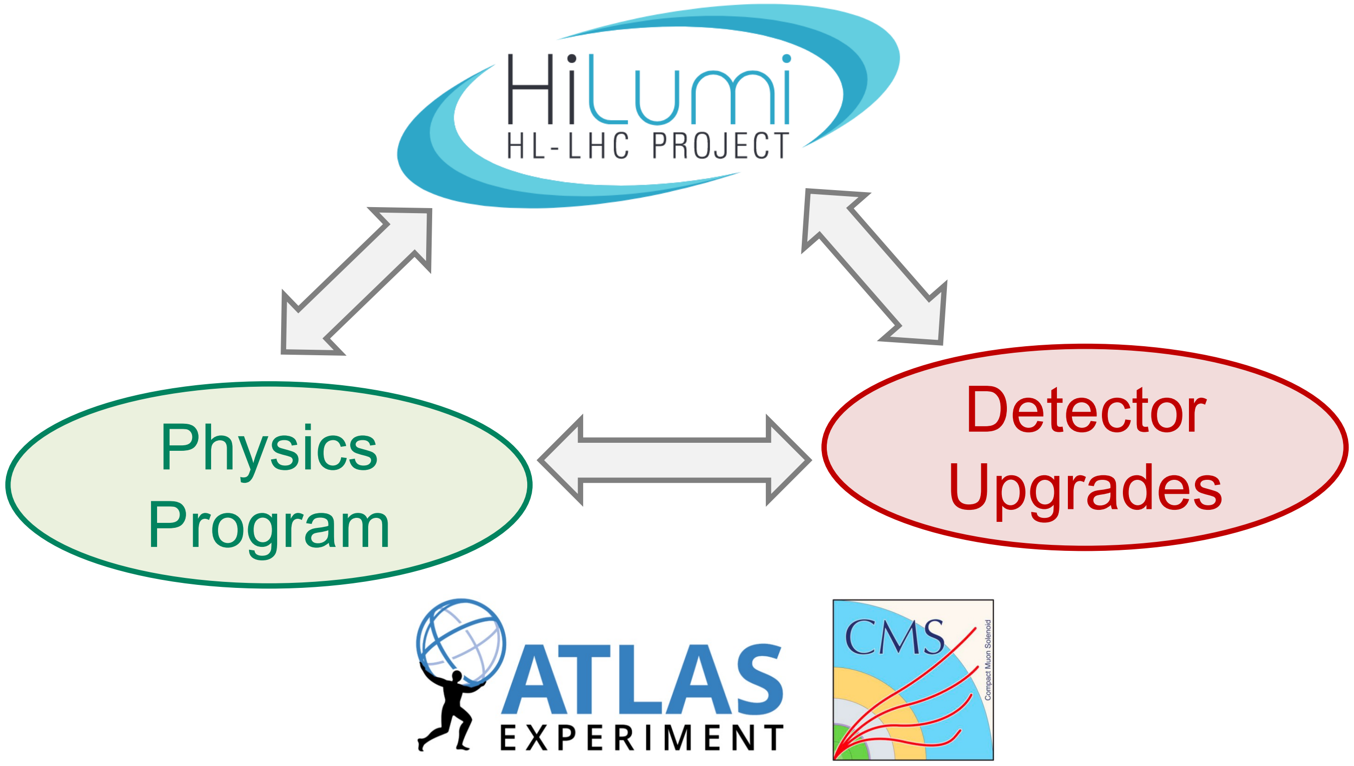
- HL-LHC will increase physics reach of the ATLAS and CMS experiments
  - Improved precision for several processes (Higgs-couplings, …) and several rate-limited processes get available (VBS, Di-Higgs, …)
- ATLAS and CMS experiments have to tackle challenges of high pile-up, particle rates and radiation dose

  → New all-silicon tracking detectors for both experiments
- In ATLAS: ~4-layer strip detector with about 10,000 strip modules and ~5-layer pixel detector with about 8,500 pixel-hybrid modules
  - Strips: Design verified and many final design reviews passed. Deep into pre-production and starting production. Unexpected effect of cold noise being investigated.
  - Pixels: Prototypes of several components being tested and first parts (sensors) in pre-production. Main challenges are front-end chip submission, module production and validation of data transmission concept.
- In CMS: ~6-layer strip detector with about 13,000 strip modules and ~4-layer pixel detector with about 4,000 pixel-hybrid modules
  - Outer Tracker: Production of modules ongoing. Mechanics to go in production next year
  - Inner Tracker: Module concept prototyped, System slice test successfully ran. Main challenges: front-end chip submission next year
- Common effort essential to make it for installation in 2027

Thank you!

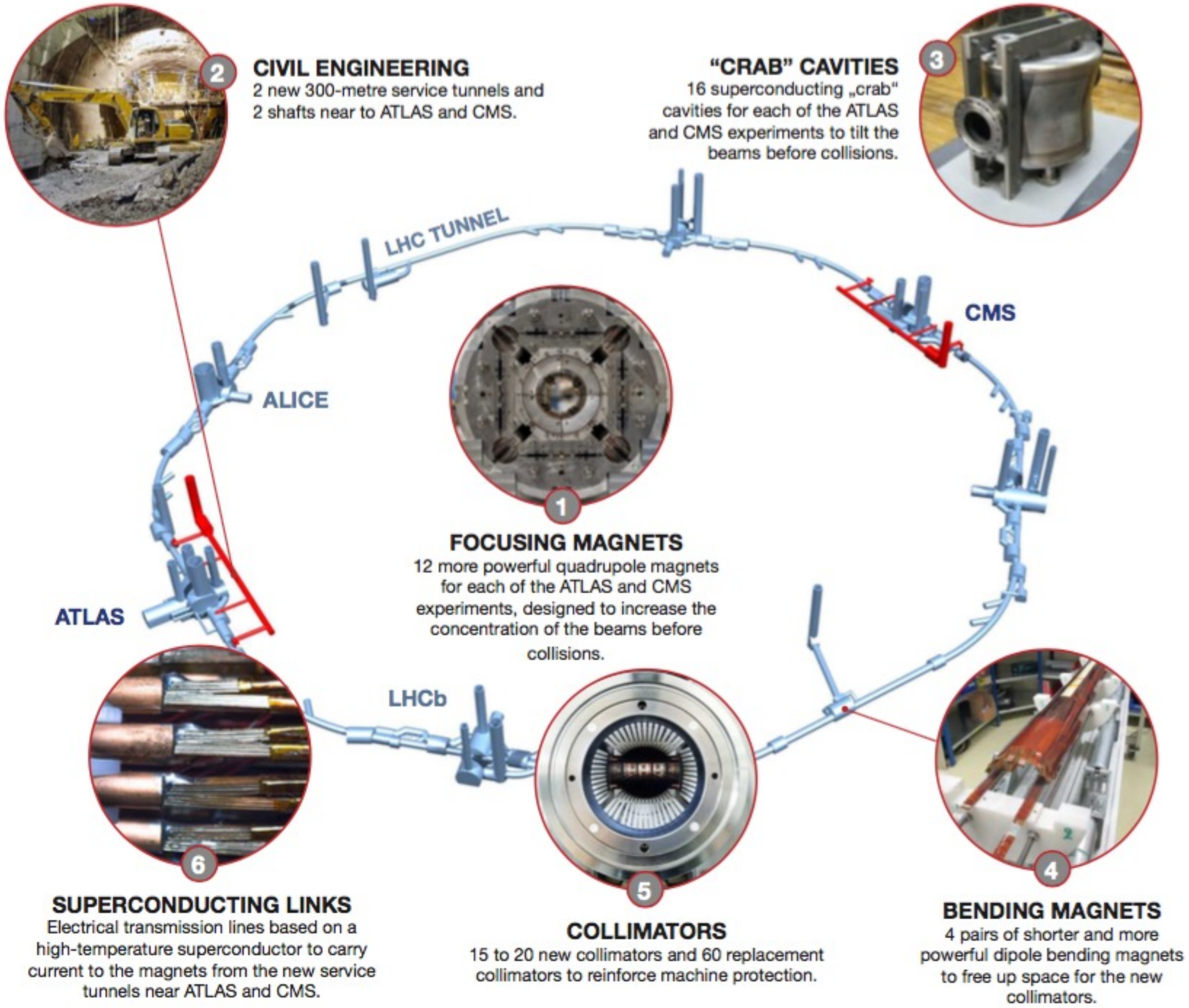
Acknowledgment

Matthias Hamer, Antonio Cassese, Didier Contardo, Konstantinos Damanakis, Didier Ferrere, Frank Hartmann, Helen Hayward, Anna Sfyrla, Felix Sefkow, Thomas Senger, Giacomo Sguazzoni, Stefaniana Stucci, Benedikt Vormwald



SPARE

The HL-LHC



CIVIL ENGINEERING
2 new 300-metre service tunnels and
2 shafts near to ATLAS and CMS.
"CRAB" CAVITIES
16 superconducting „crab"
cavities for each of the ATLAS
and CMS experiments to tilt the
beams before collisions.
LHC TUNNEL
CMS
ALICE
ATLAS
FOCUSING MAGNETS
12 more powerful quadrupole magnets
for each of the ATLAS and CMS
experiments, designed to increase the
concentration of the beams before
collisions.
LHCb
SUPERCONDUCTING LINKS
Electrical transmission lines based on a
high-temperature superconductor to carry
current to the magnets from the new service
tunnels near ATLAS and CMS.
COLLIMATORS
15 to 20 new collimators and 60 replacement
collimators to reinforce machine protection.
BENDING MAGNETS
4 pairs of shorter and more
powerful dipole bending magnets
to free up space for the new
collimators.

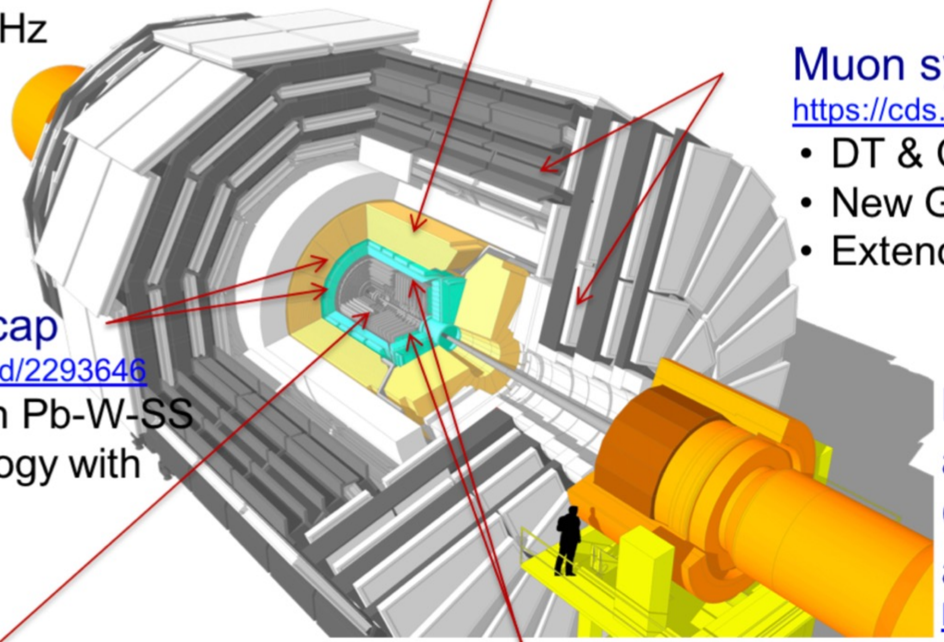
Phase-II Upgrade: Detector Upgrades – CMS

NEW READOUT

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

https://cds.cern.ch/record/2714892



Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

NEW DETECTOR

Calorimeter Endcap
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

NEW DETECTOR

Tracker
https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612 https://cds.cern.ch/record/2667167
- $\simeq$ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

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.

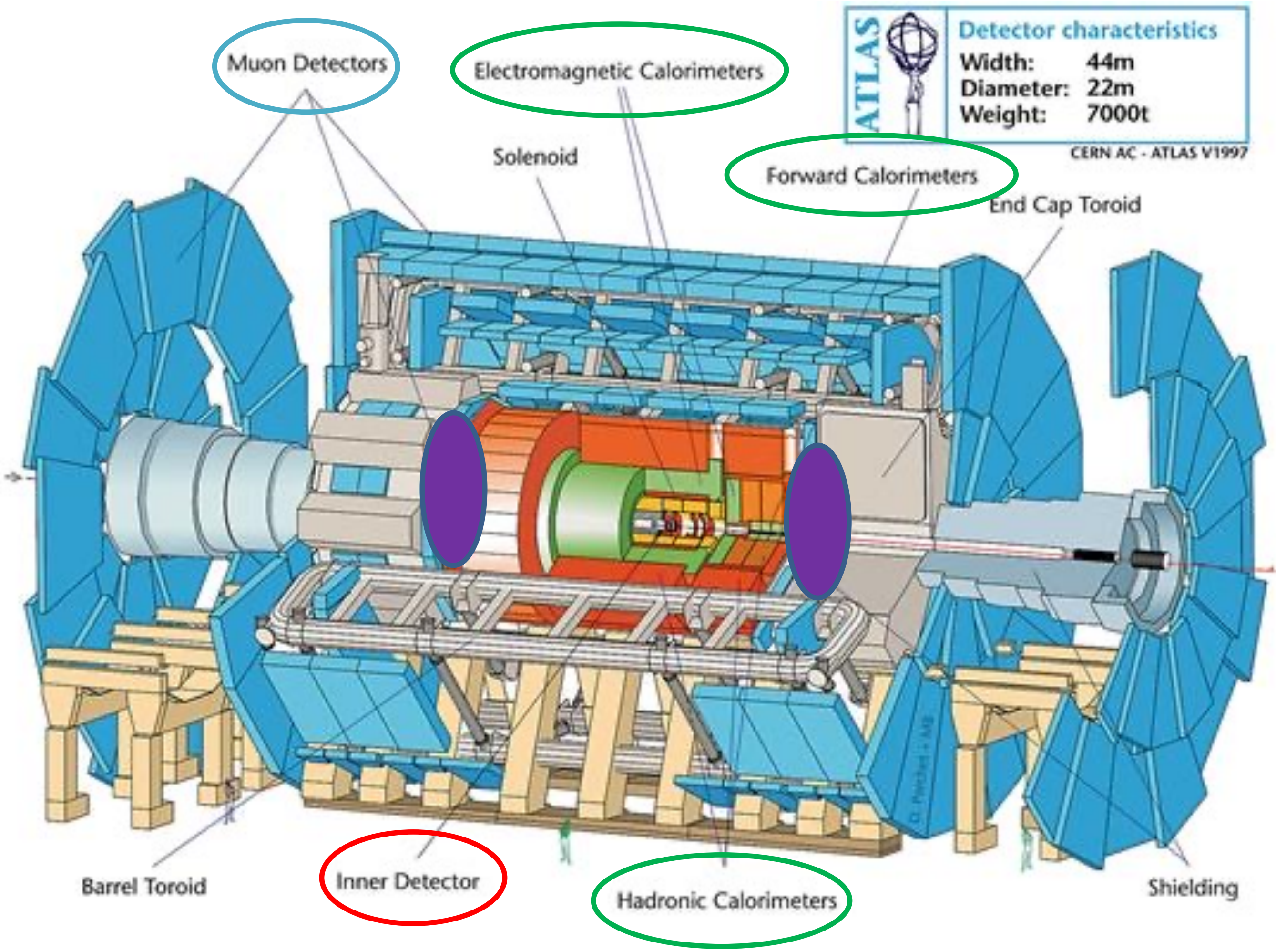
HGTD: new high granularity timing detector with forward coverage from LGADs, 30-50 ps resolution for MIPs
CERN-LHCC-2020-007 ; ATLAS-TDR-031.

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-2017-020 ; ATLAS-TDR-029.



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 for ATLAS and CMS with extended coverage to $|\eta| < 4$

Timing detectors:
High granularity timing detector in forward region in ATLAS and timing layer for MIPs around trackers in CMS

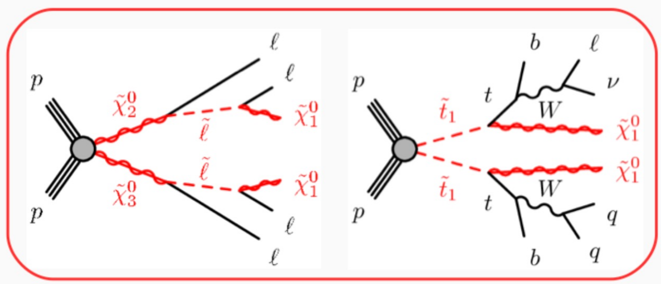
Calorimetry:
ATLAS: New FE electronics for Tile and LAr calorimeter (increase granularity)
CMS: Replace endcaps and replace electronics in electromagnetic calorimeter

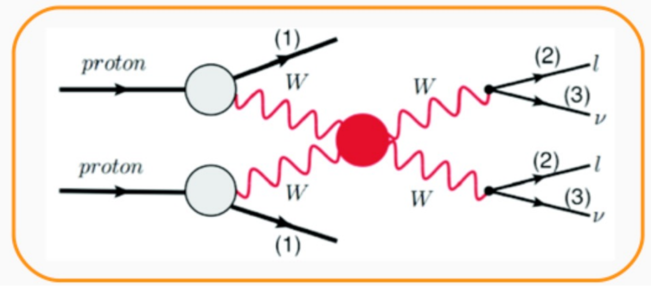
Muon system:
ATLAS: New FE electronics and additional units in muon spectrometer
CMS: Extend forward chambers and replace electronics

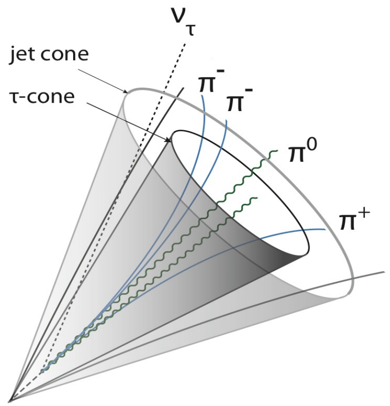
Motivations for detector upgrades

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



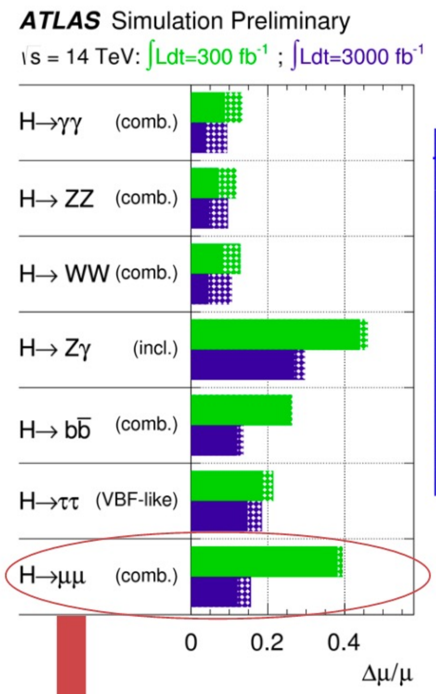




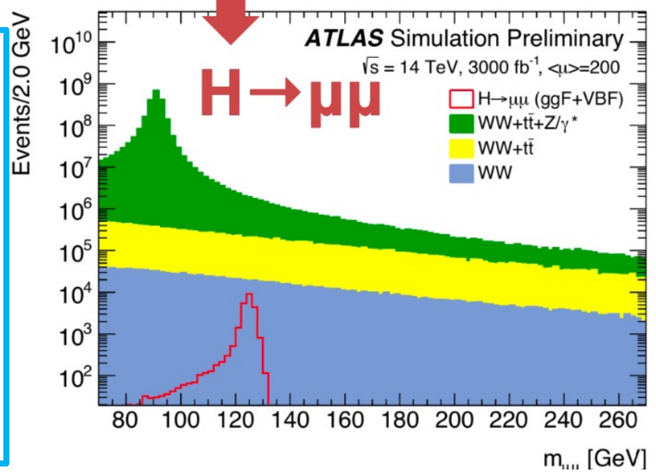
+ current trackers can't withstand radiation and rates beyond LHC

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



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

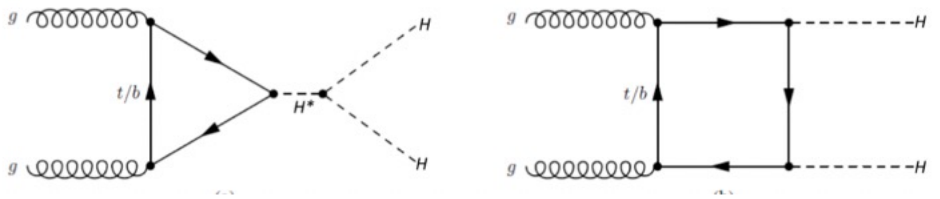


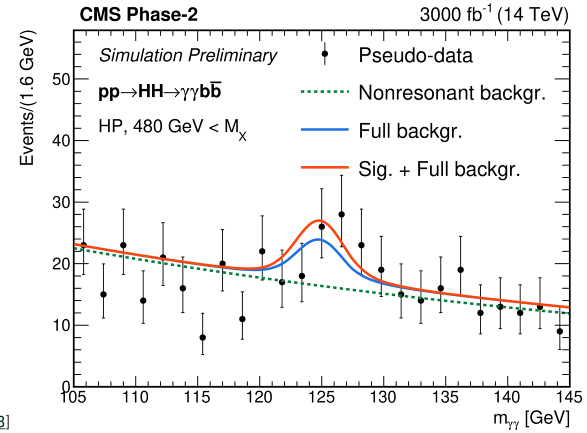
https://cds.cern.ch/record/2319741

- **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)

https://arxiv.org/1910.11775

- Di-Higgs Production → **direct handle on Higgs self coupling**





CMS-PAS-FTR-18-019

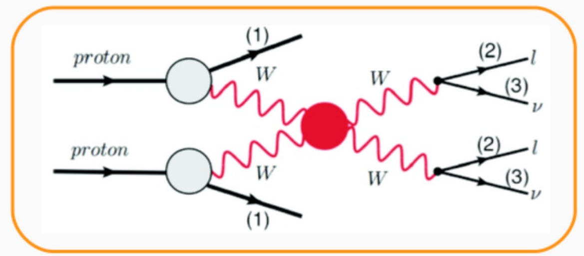
[ATL-PHYS-PUB-2018-053]
[CMS-PAS-FTR-18-019]

SM HH Signal Significances	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau^+\tau^-$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV^*$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4\ell)$	-	0.37	-	0.37
Combination	3.5	2.8	3.0	2.6
	4.5		4.0	

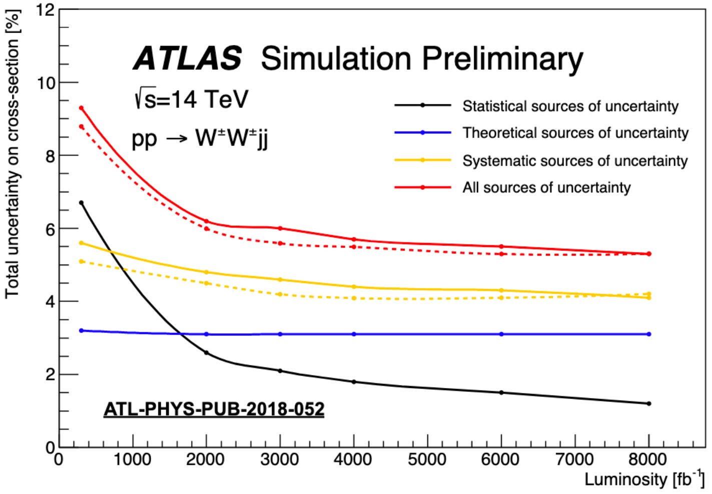
Combining all channels yields to sensitivity of 4σ

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

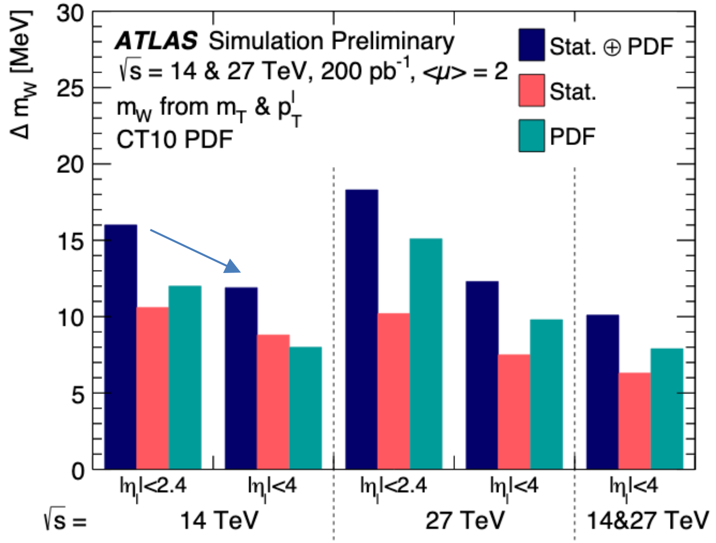


- Despite major improvements with forward tracking and jet-tagging capabilities, WW analysis will be systematically limited

see also: CMS-PAS-FTR-18-005/-014/-029/-038/-023

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



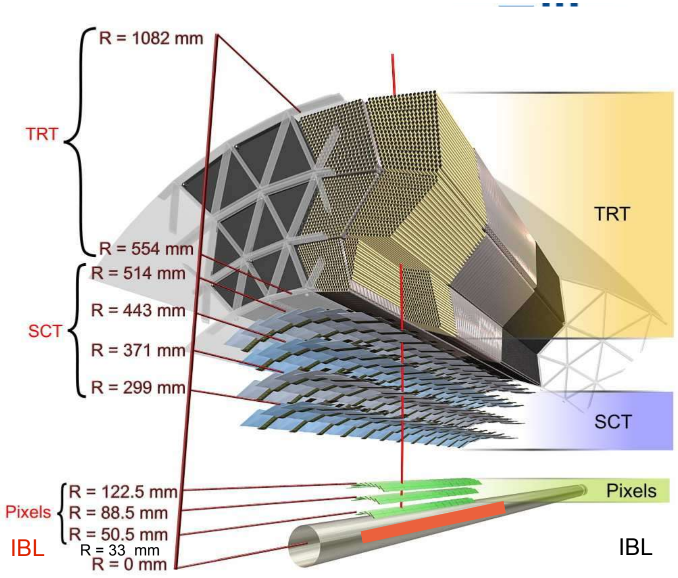
For 200 pb^{-1}

$\sqrt{s}$ [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)

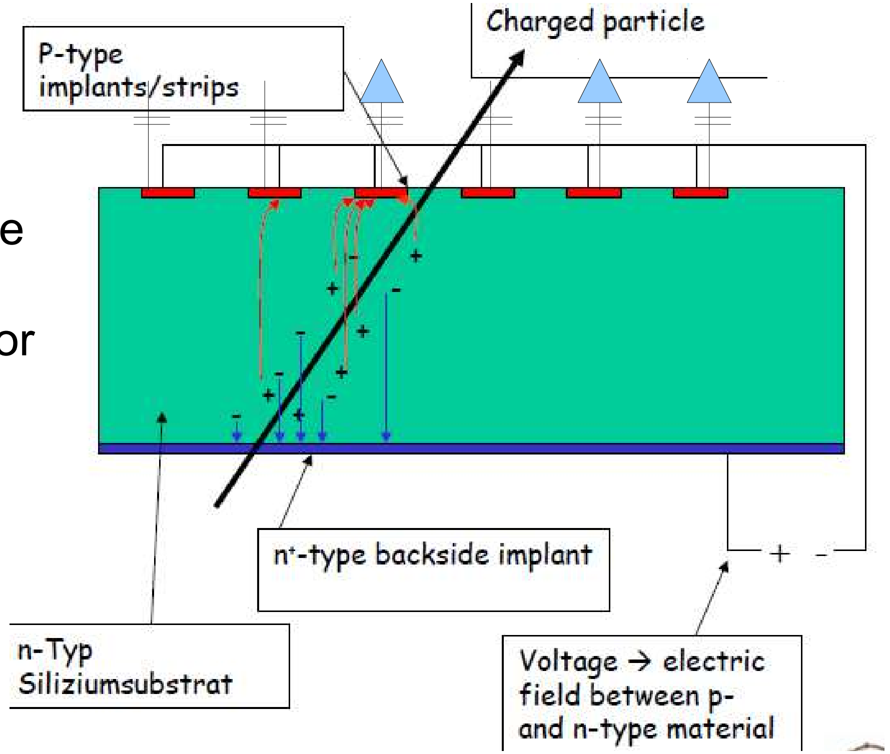
https://cds.cern.ch/record/2703572

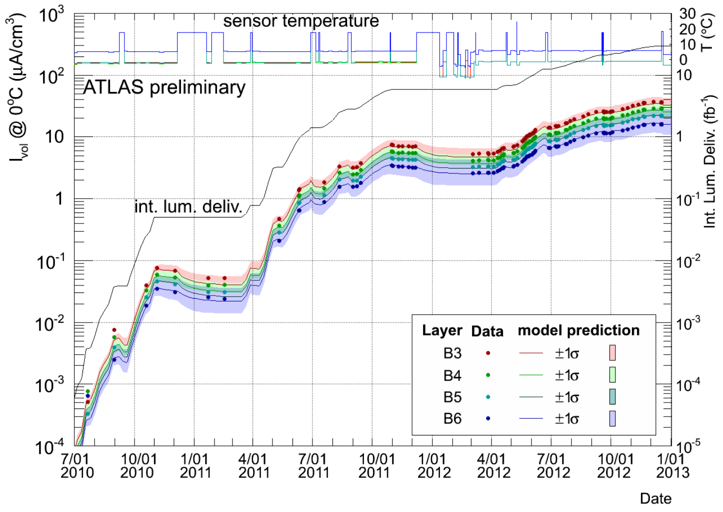
Current ATLAS tracker

- Current silicon strip tracker in ATLAS performing very well and lead to great physics results, Run 2 just successfully started
- Radiation damage occurring
- ATLAS silicon strip tracker planned for maximal dose of $2*10^{14}$ Neq/cm^2



n-type strip sensor

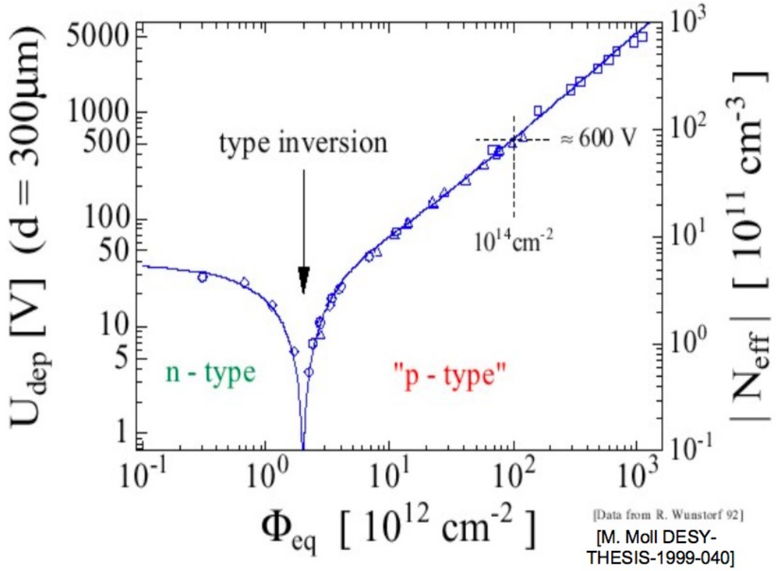




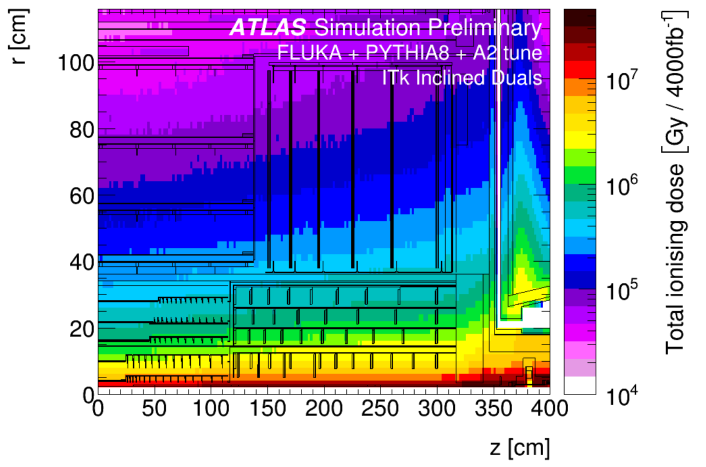
Radiation damage in silicon sensors

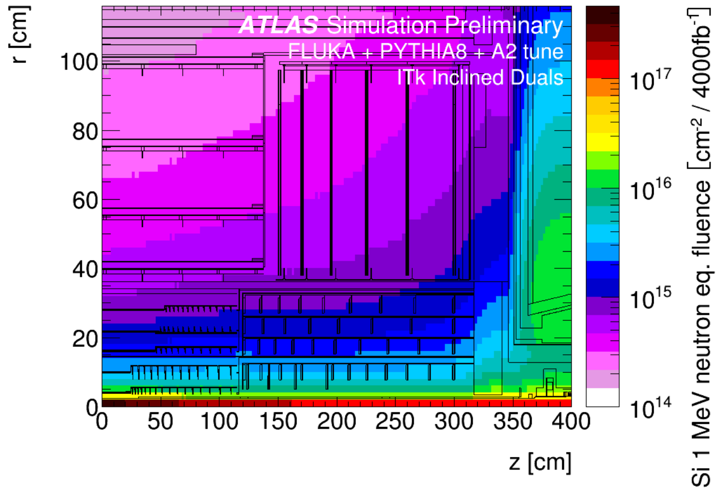
Radiation damage: non-ionising energy loss of charged and neutral particles
→ damage in silicon bulk

Effects:
- Increase of leakage current
- Change of effective doping concentration
- Increase of depletion voltage
- Defects act as trapping centres affecting the charge collection efficiency



[Data from R. Wunstorf 92]
[M. Moll DESY-THESIS-1999-040]



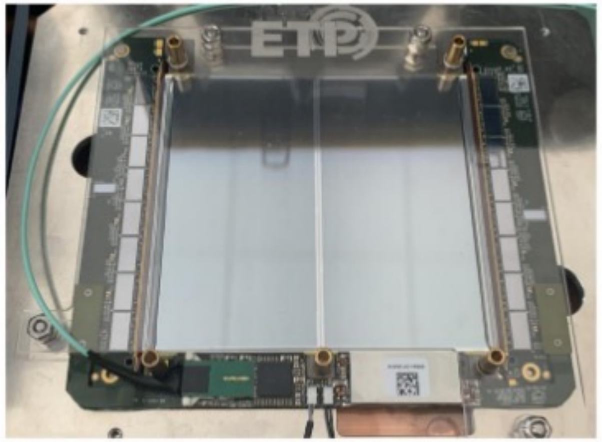


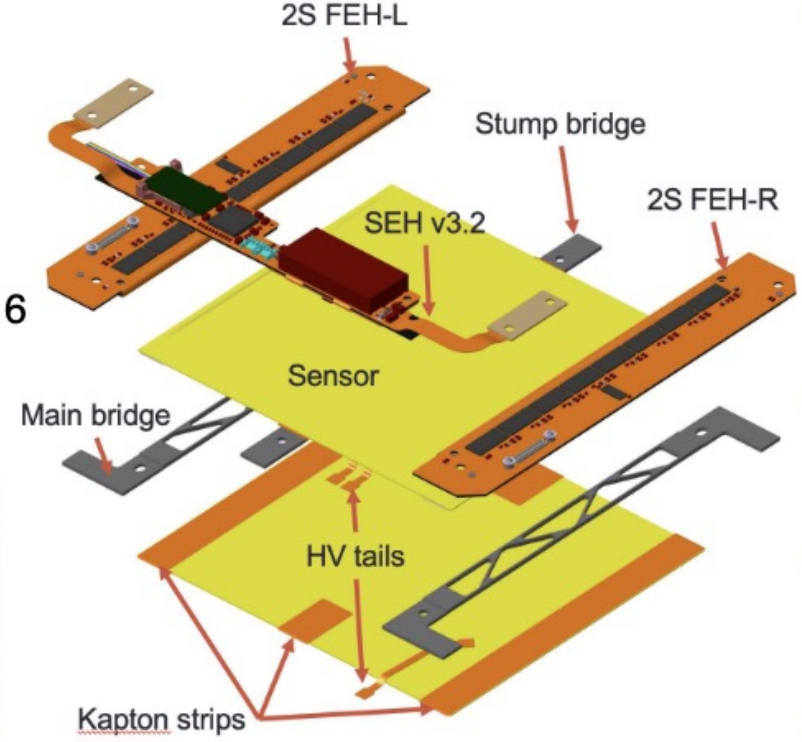
→ Radiation damage degrades the detector performance and limits the life time

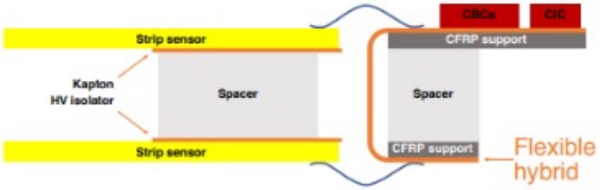
Strip-Strip (2S) modules in CMS

- **2 x Strip sensors**

2S sensor
- Size : 10 x 10 cm^2
- Pitch : 90 μm
- Length : 5 cm
- No. of strips/sensor : 2x1016





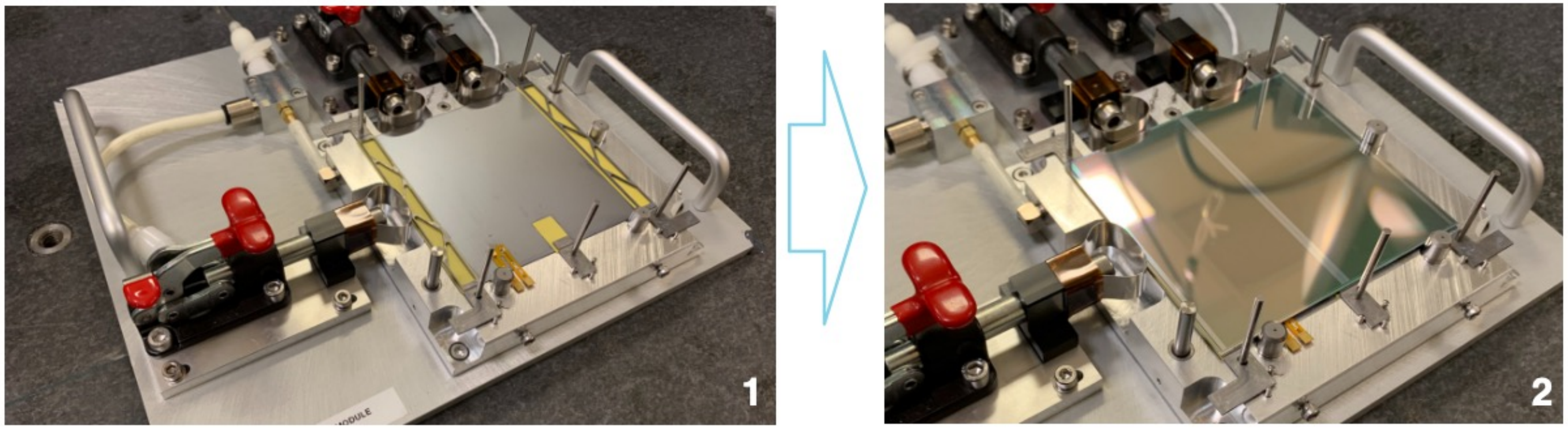


- **2 x 8 CMS Binary Chip (CBC)**
  - 2x127 channels per chip
  - Bump bonded to flexible hybrid
  - Connects to top and bottom sensors
  - Inter-chip communication via hybrid
- **Concentrator ASIC: CIC**
  - collects data from 8 CBCs (half module)
- **Low Power GigaBit Transceiver**
  - *lpGBT + VTRx+*
- **2-stage DCDC powering**
  - 12 V to 2.5 V (opto)
    1.25 V (ASICS)

Strip-Strip (2S) modules in CMS

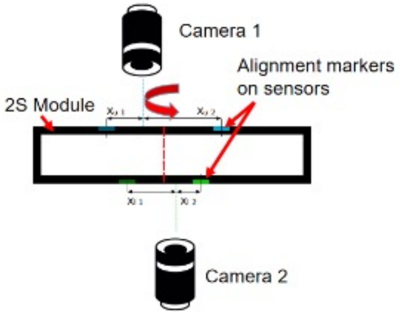
2S assembly - sensor alignment

Sensor-sensor gluing

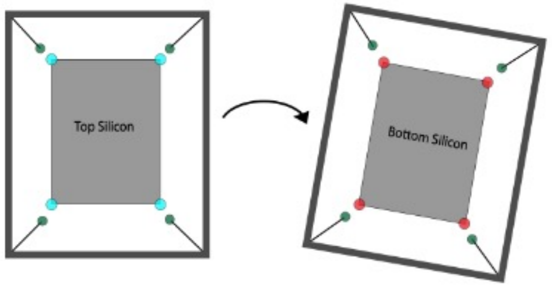


Sensor-sensor alignment measurement

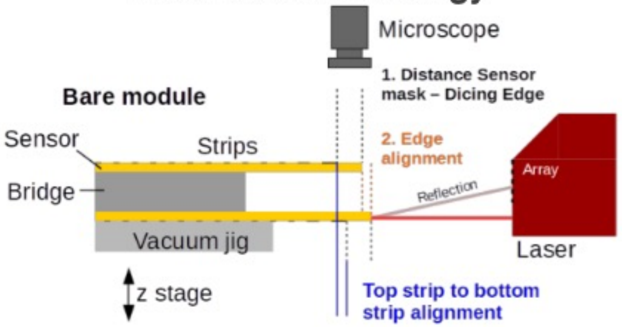
Double-sided metrology



Needle-based metrology



Laser-based metrology

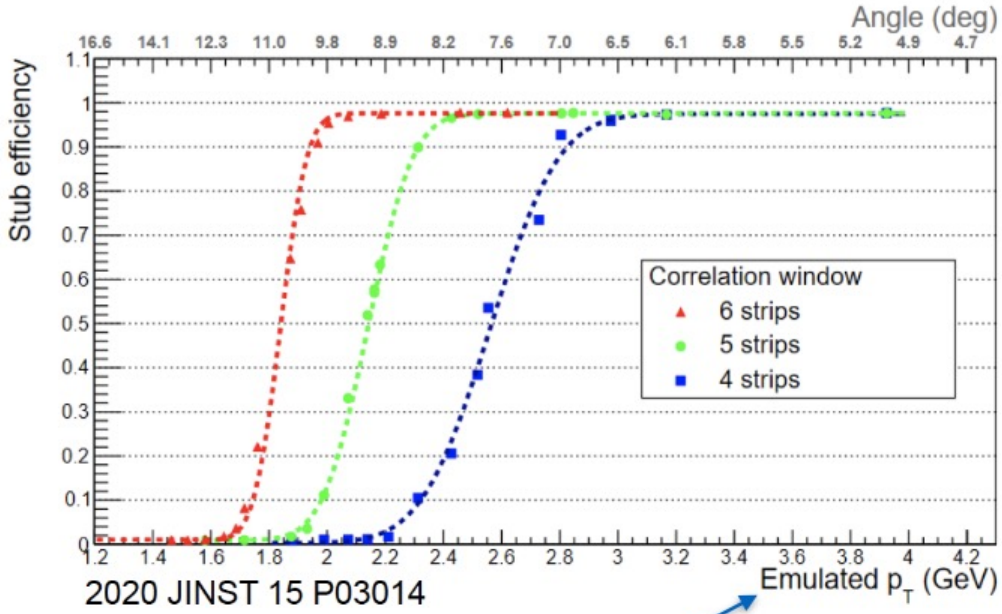


- Specs: rotation < 400 µrad, strip parallel (perpendicular) offset < 100 (50) µm

Strip-Strip (2S) modules in CMS

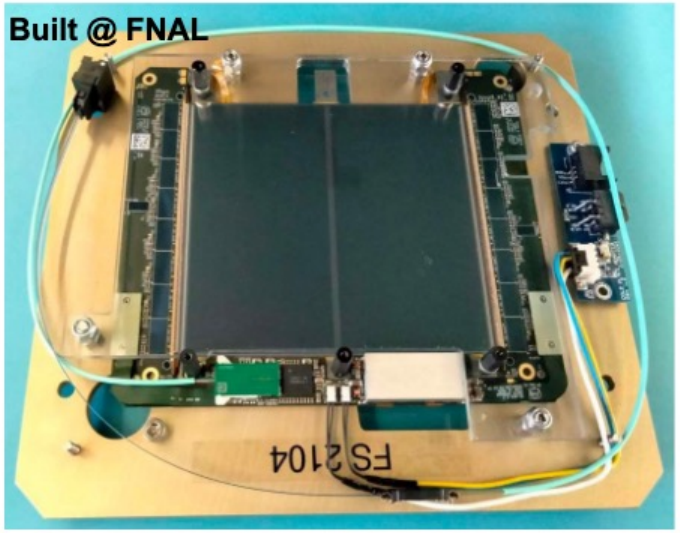
2S module prototypes

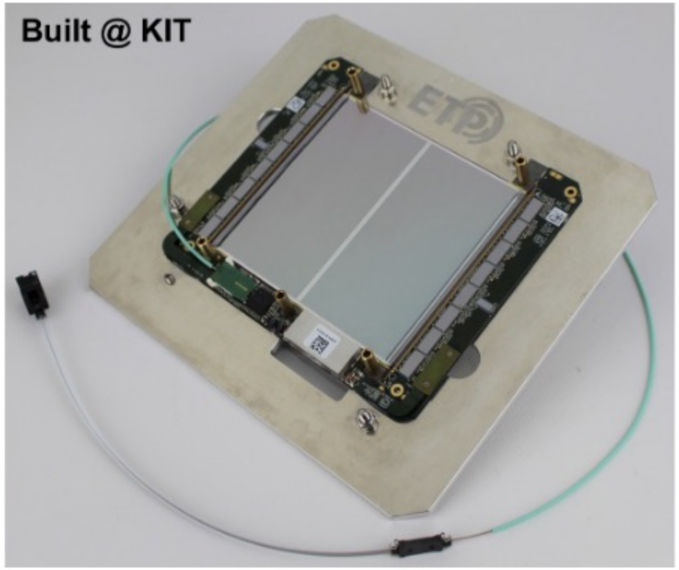
- More than 30 modules build across the various production centers
- Several laboratory and beam tests carried out before and after irradiation, expected performance confirmed



2020 JINST 15 P03014

Emulated by rotating the module wrt to the beam





Pixel-Strip (PS) modules in CMS

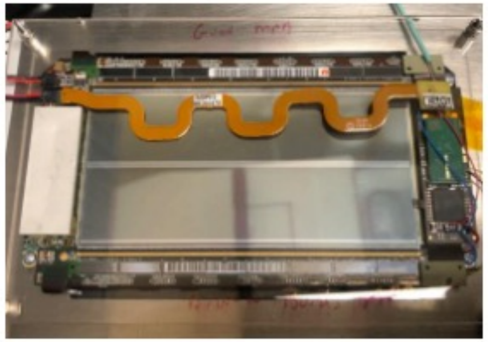
K. Damanakis

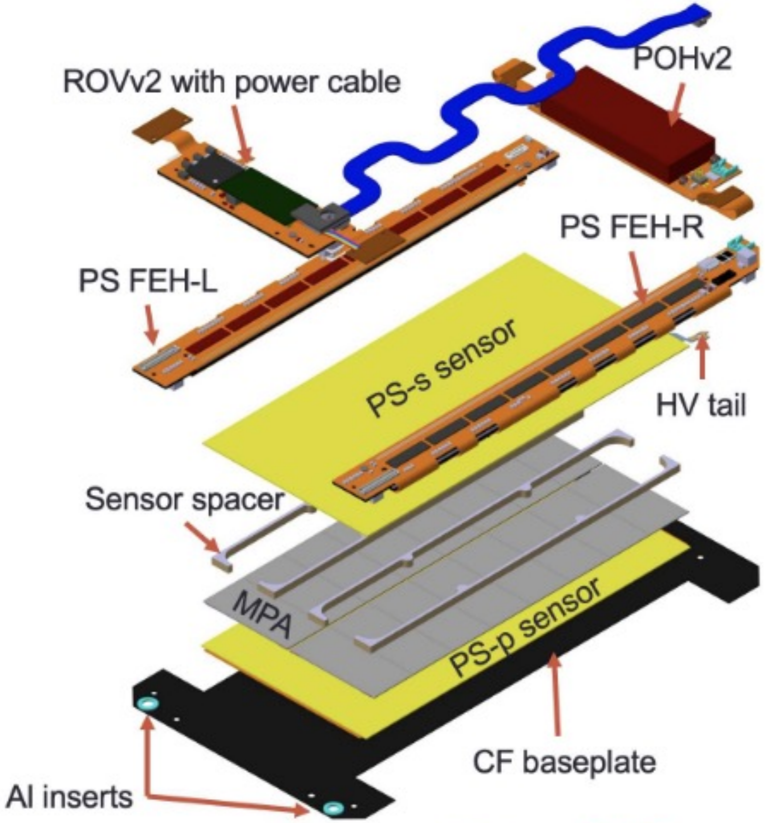
Macro-pixel sensor:

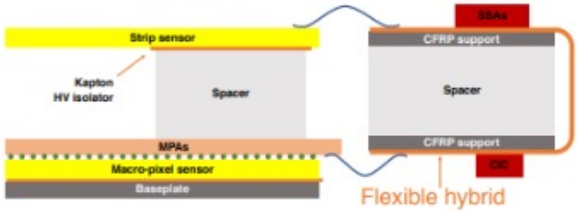
- **PS-p sensor**
  - Size : 5 x 10 cm^2
  - Pitch : 100 μm
  - Length : 1.5 mm
  - No. of strips : 32x960

Strip sensor:

- **PS-s sensor**
  - Size: 5 x 10 cm^2
  - Pitch: 100 μm
  - Length: 2.5 cm
  - No. of strips: 2x960





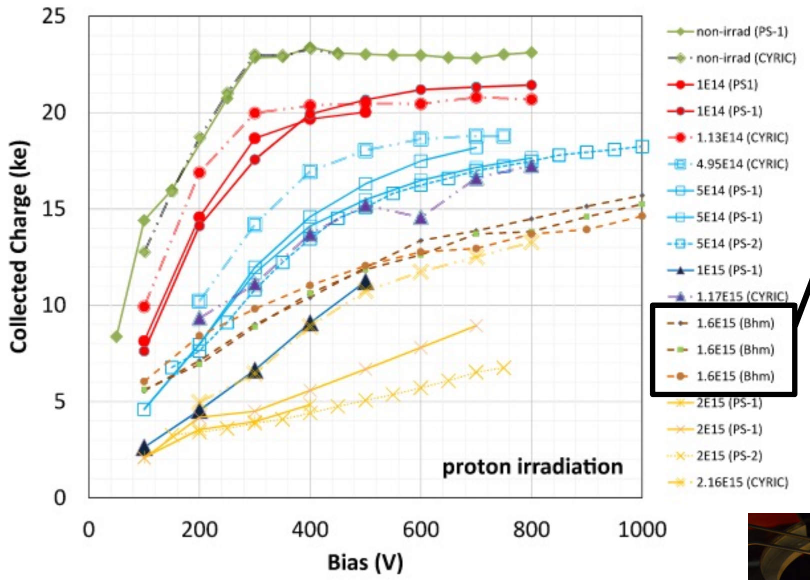


Sensor spacing 1.6, 2.6 or 4.0 mm

- **2 x 8 Short Strip ASIC (SSA)**
  - 120 channels per chip
  - Sends hits to MPA
  - Bump bonded to flexible hybrid
- **16 MacroPixel ASIC: MPA**
  - 120 x 16 pixels per chip
  - Bump bonded to Macro-Pixel sensor
  - Includes correlation logic
- **Concentrator ASIC: CIC**
  - collects data from 8 MPAs
- **Low Power GigaBit Transceiver**
  - *lpGBT + VTRx+*
- **2 stage DCDC powering**
  - 12 V to
    - 2.5 V (opto)
    - 1.25 V (ASICS)
    - 1.05 V (MPA digital)

ATLAS ITk Strip sensors and electronics

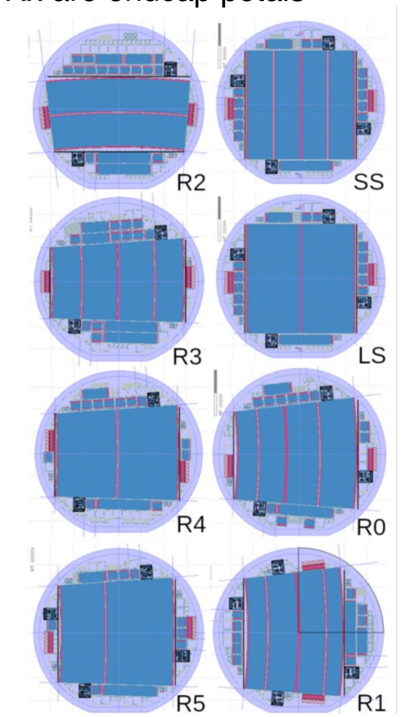
- **n-in-p float-zone sensors with p-stop isolation and ~320 µm thickness**
  - 8 sensor types (2 for barrel, 6 for endcap)
  - bias voltage: 100V to 500V
  - ~24% wafers delivered for production. Few percent rejected due to too low quality

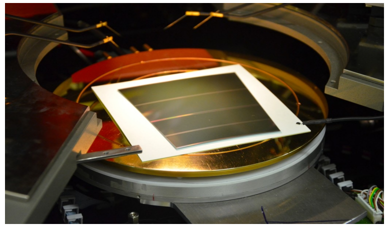


Max expected + safety: $1.6 \times 10^{15}\ n_{eq}/cm^2$

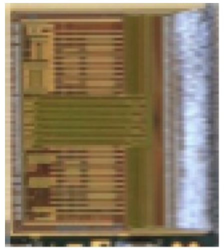
Nucl. Inst. Meth, A 983 (2020) 164422

SS, LS are barrel
Rx are endcap petals





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

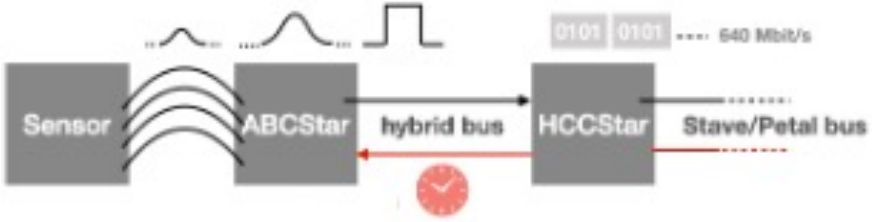


HCCStar (Hybr. controller)
- Connects 10x ABC to stave
- SEE mitigation

- All three chips were extensively modified to improve SEE protection and validated
- In production stage for detector

ABCStar (front-end chip)
- Binary readout with 256 channels

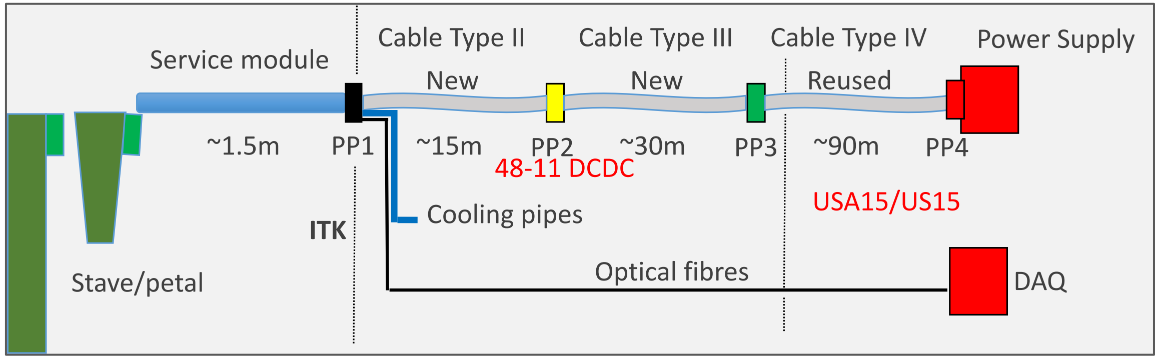
AMACStar (Power control and environmental monitoring)
- On the same wafer as HCC



https://arxiv.org/pdf/2009.03197

Services of the strip detector

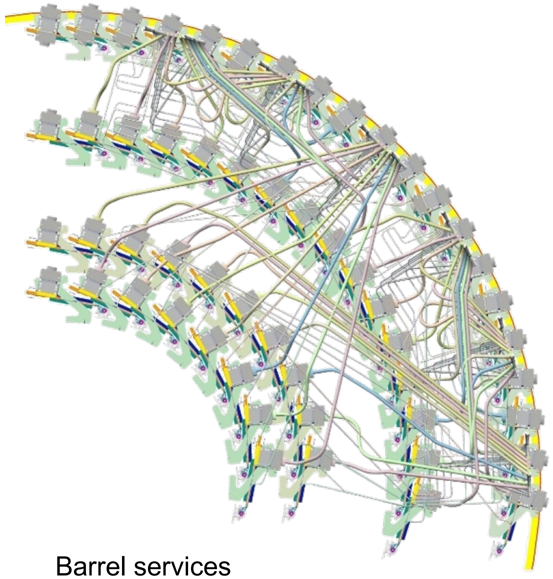
- Full chain defined and services purchased for larger system tests



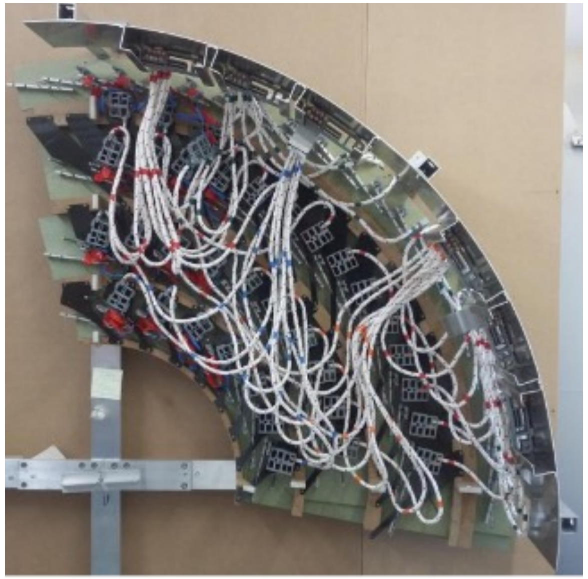
Type-1 Cable Connectors

Type-3 cables

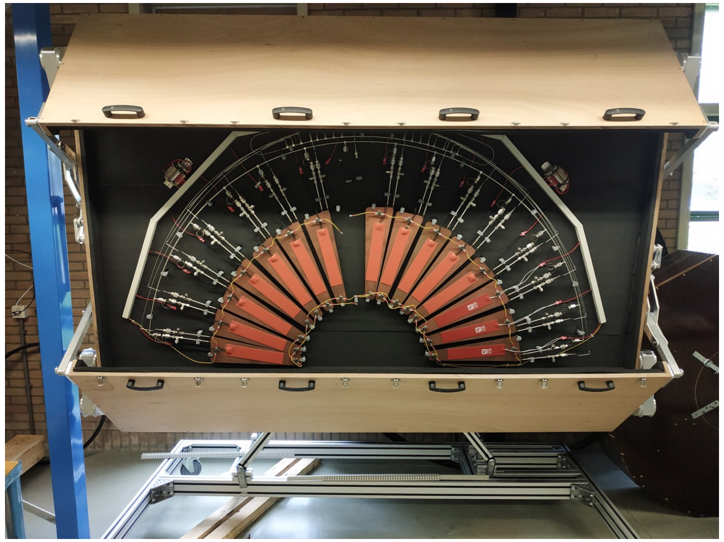
- Services on the detector sorted in service modules



Barrel services



Mockup of services



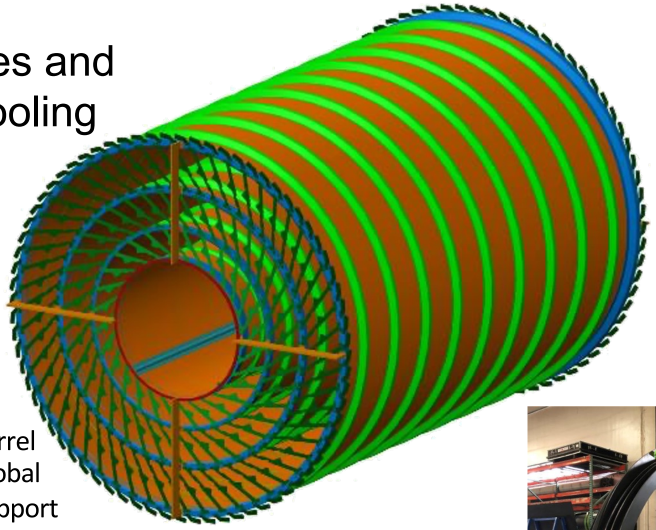
EC cooling manifold tested with in CO_2 plant at CERN

Global mechanics and integration of ATLAS ITk Strips

- Loaded local support structures (staves and petals) are end-insertable including cooling and cabling
  - Fire-tests of components passed

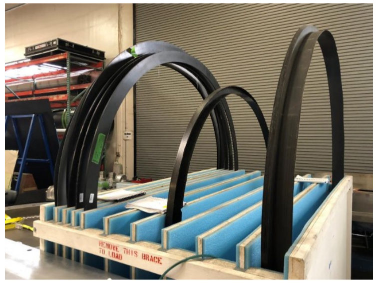
- For barrel: carbon cylinders for each layer in which staves are inserted.
  - Tests with mock-ups well advanced

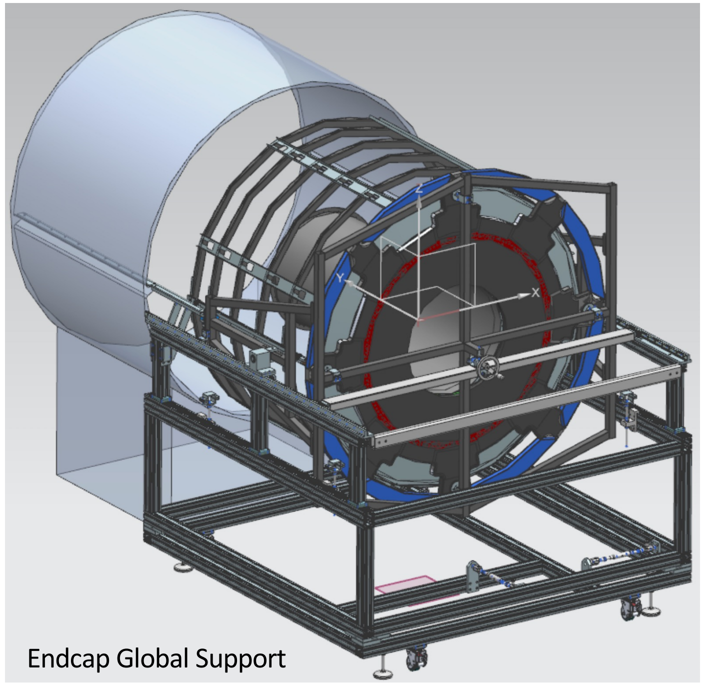
- For endcaps: carbon wheels with blades for each disk mounted in endcap structure
  - Tests with mock-ups well advanced



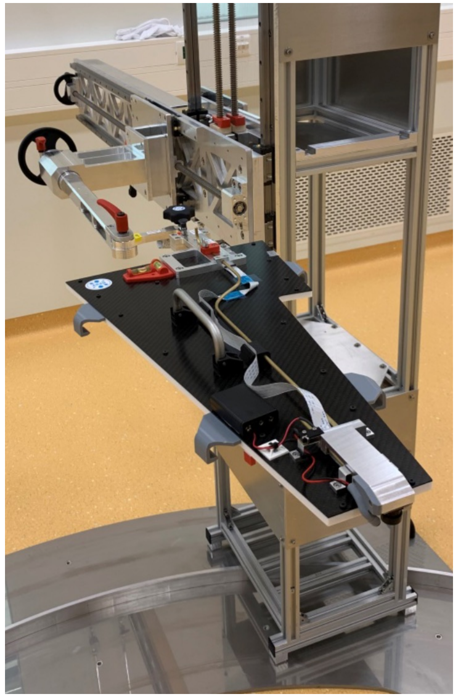
Barrel Global Support

Shell flange prototypes

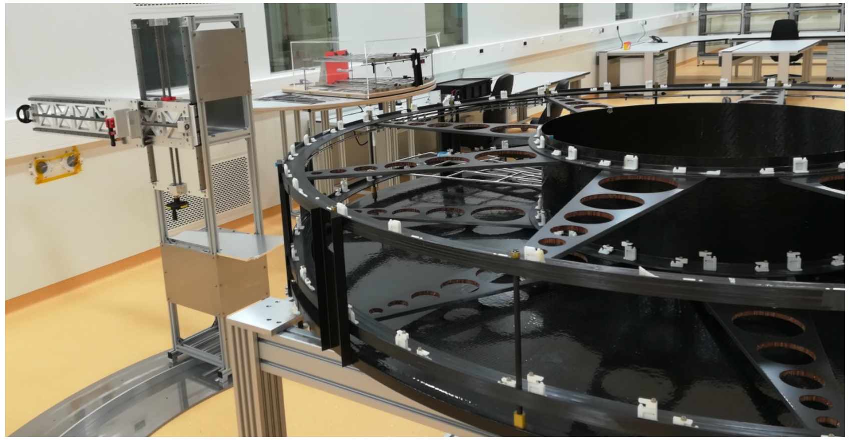




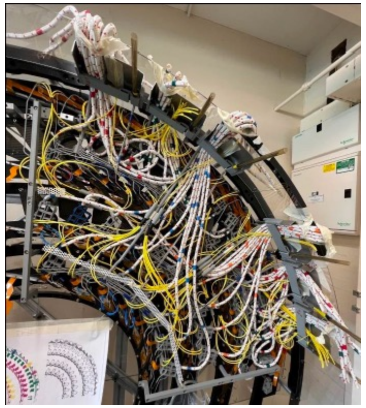
Endcap Global Support



Prototype Wheels (w/ blades)



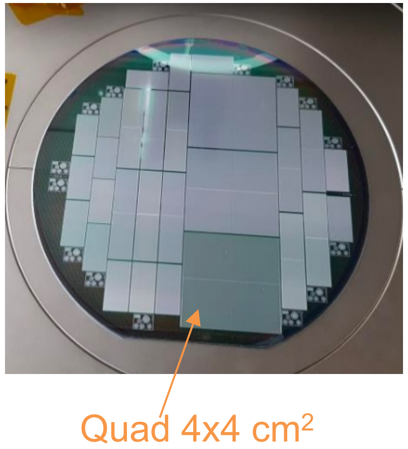
Mockup of services, interlinks and end flanges



ATLAS ITk planar and 3D pixel sensors

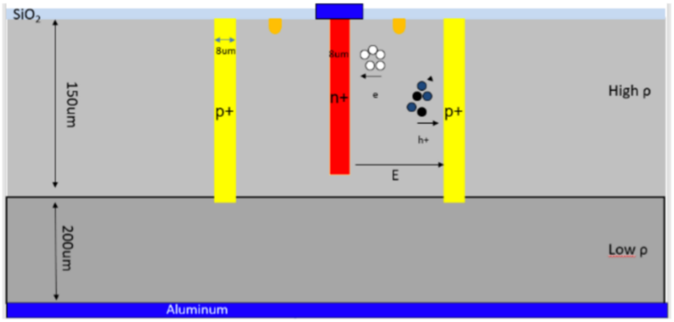
Thin n-in-p planar sensors

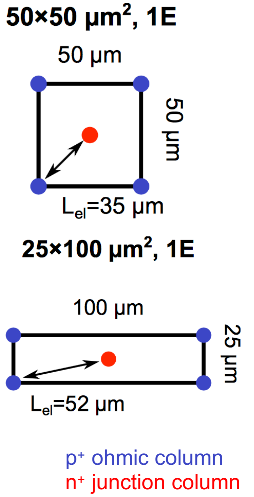
- **Dies of 4x4 cm²**
- 100/150 µm thick
- Bias voltage up to 600/400 V (at end of life-time)
- Signal: ~10000 e^- (~6000 e^- after HL-LHC dose)
- **Production about to start after production readiness review in Nov. 2022**



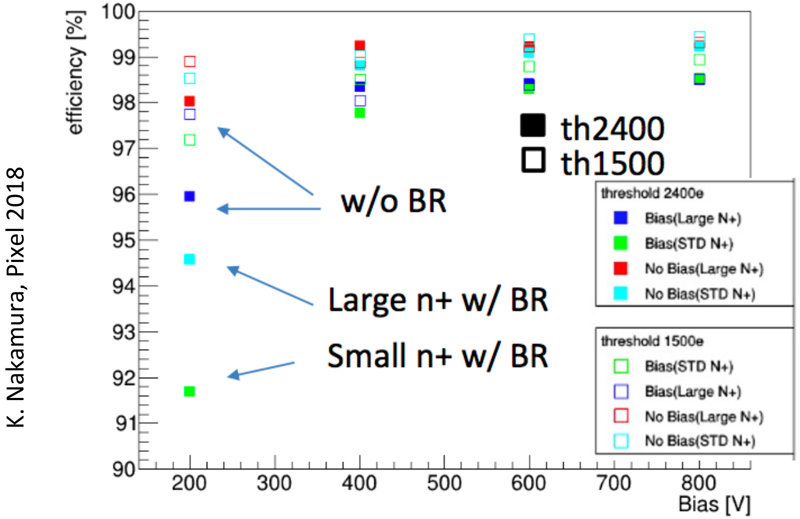
3D sensors

- For innermost layer: 1.3×10^{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
- **Pre-production ongoing**



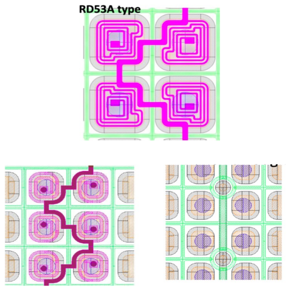


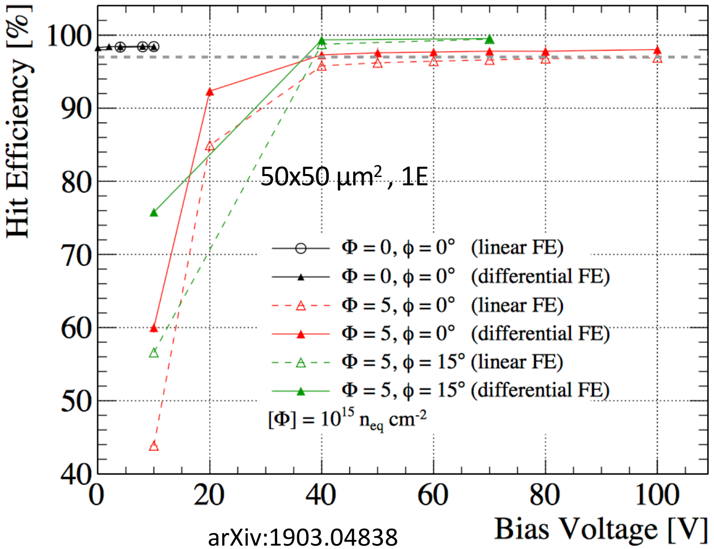
Test beam results for 50x50 µm² planar modules with varying bias structures irradiated with 70 MeV protons to $3*10^{15}$ n_{eq}/cm^2



Biasing solutions

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



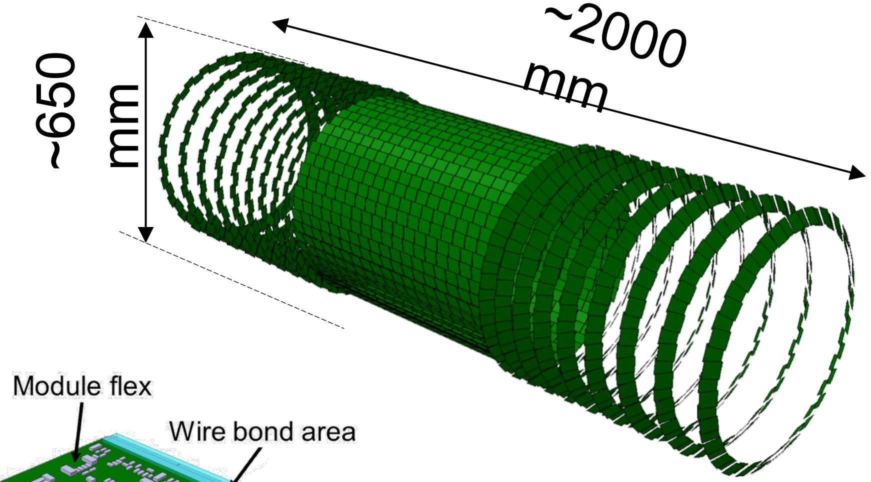


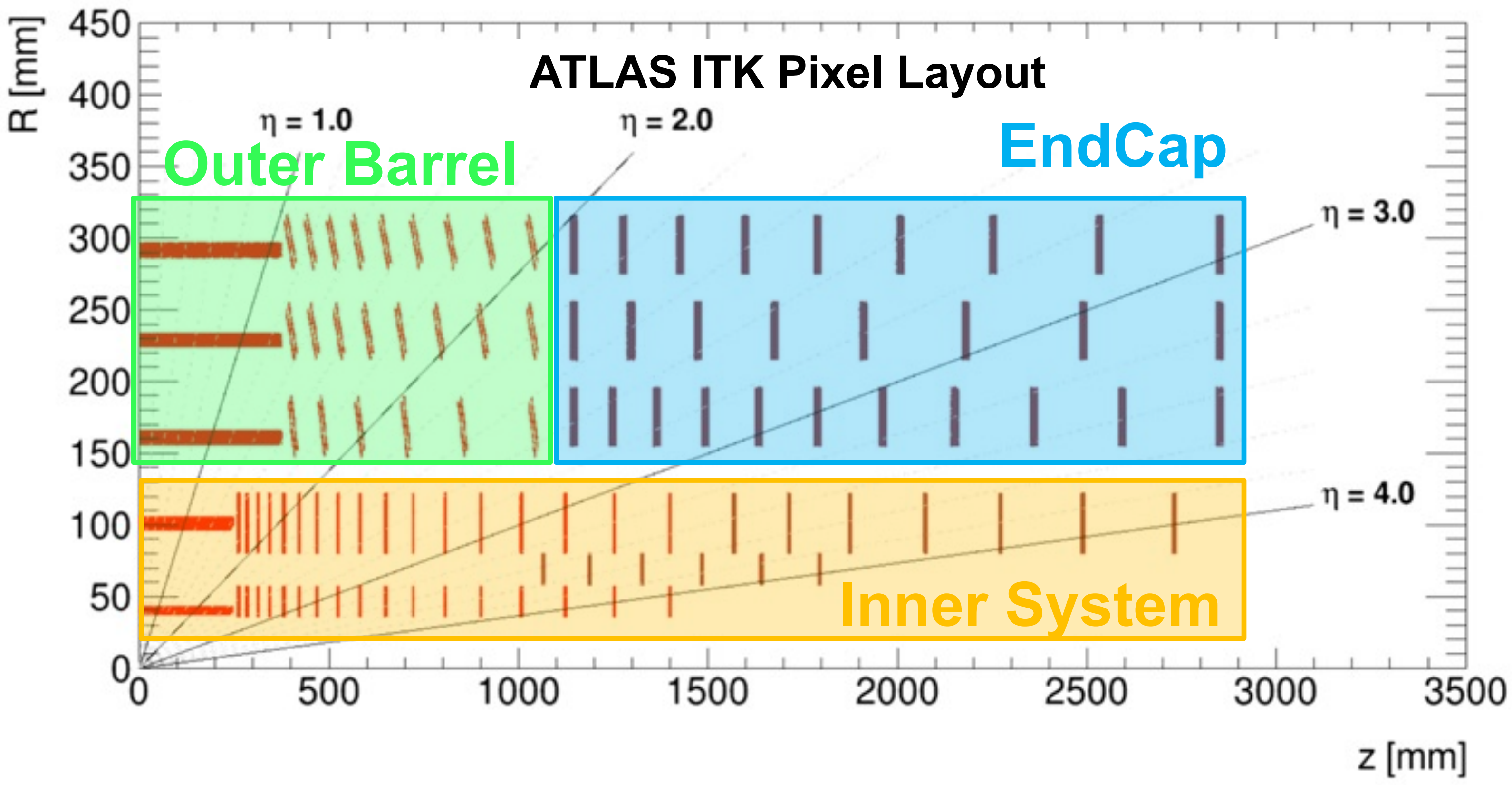
arXiv:1903.04838

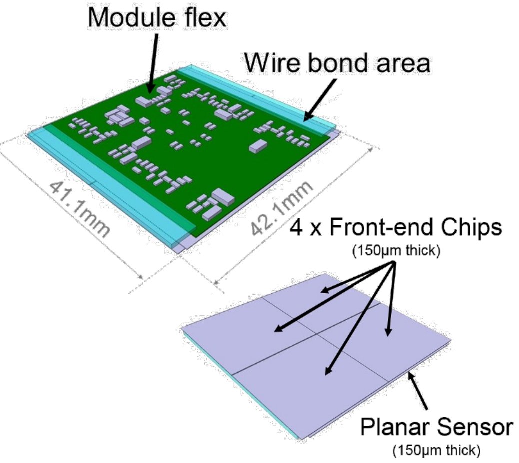
- >97% efficiency at perpendicular track incidence
- Power consumption at the operational voltage: <10 mW/cm²
- Maximum operational voltage: 250 V

ITK Pixel Outer Barrel

- ATLAS ITK Pixel Upgrade
  - Active area ~13m^2
  - First pixel detector with inclined layout
  - TDR approved in 2018







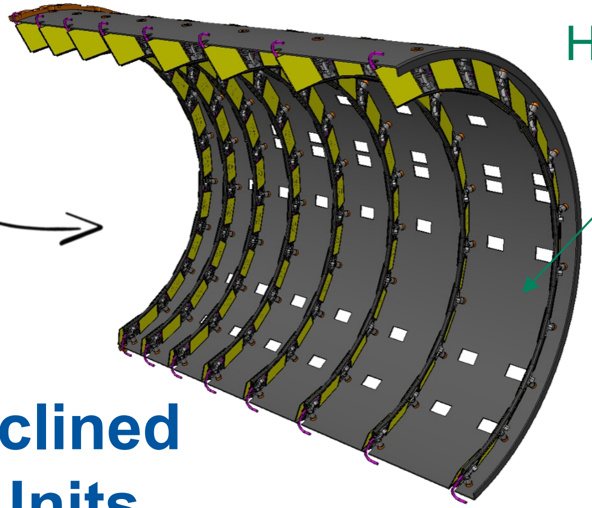
- 4472 Pixel modules
- Active area: 6.94m^2 (53.5% of Pixel Detector)
- >14 Institutes from six different funding agencies

<u>4 times</u> the area of the current ATLAS Pixel Detector!!

ITk Pixel OB Global Structures

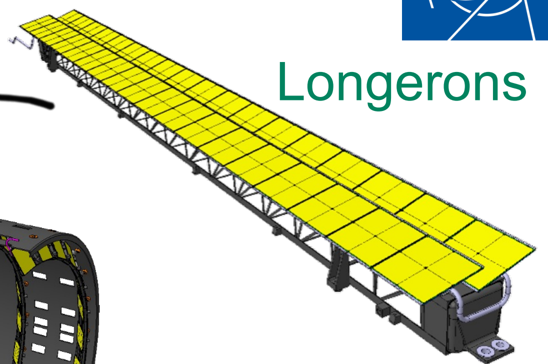
D. Alvarez Feito

Inclined Half Rings

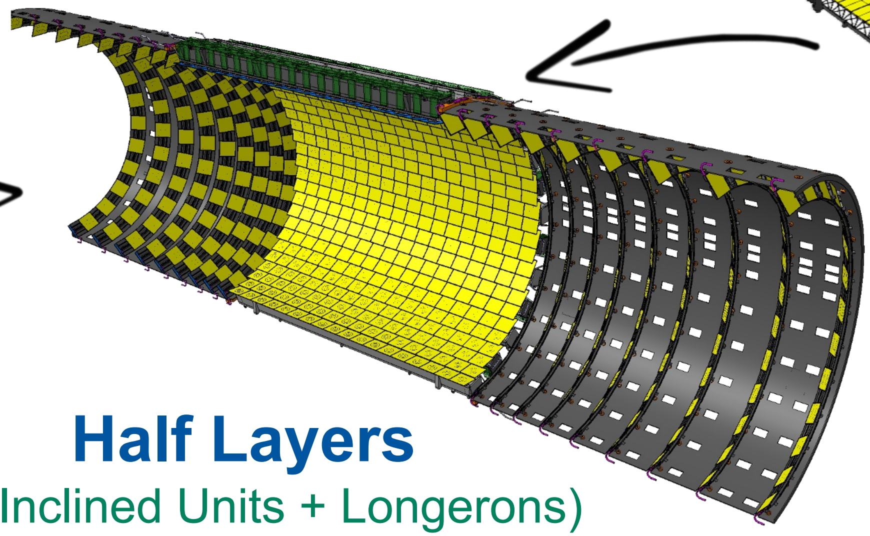


Half Layer Shell

Inclined Units

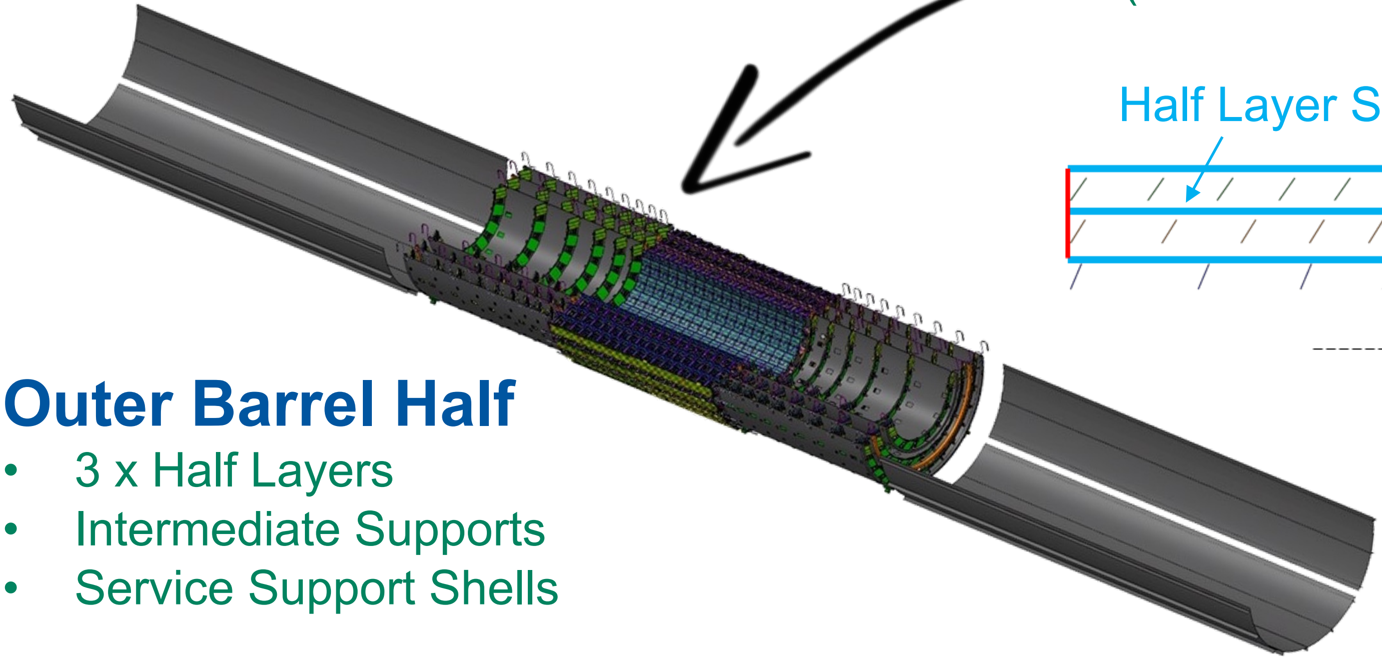


Longerons



Half Layers

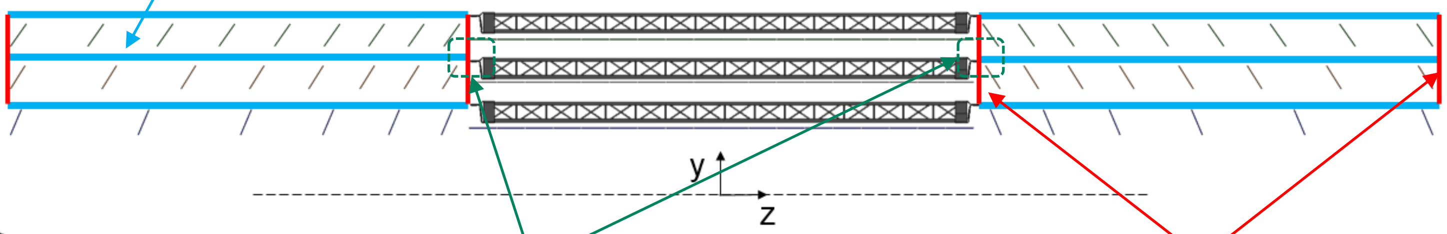
(2 x Inclined Units + Longerons)



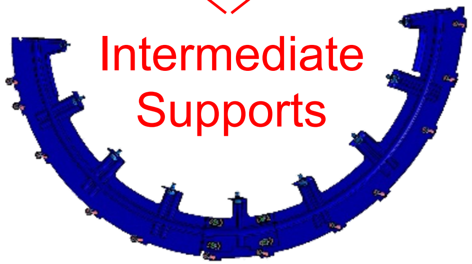
Outer Barrel Half

- 3 x Half Layers
- Intermediate Supports
- Service Support Shells

Half Layer Shells



Bolted connections



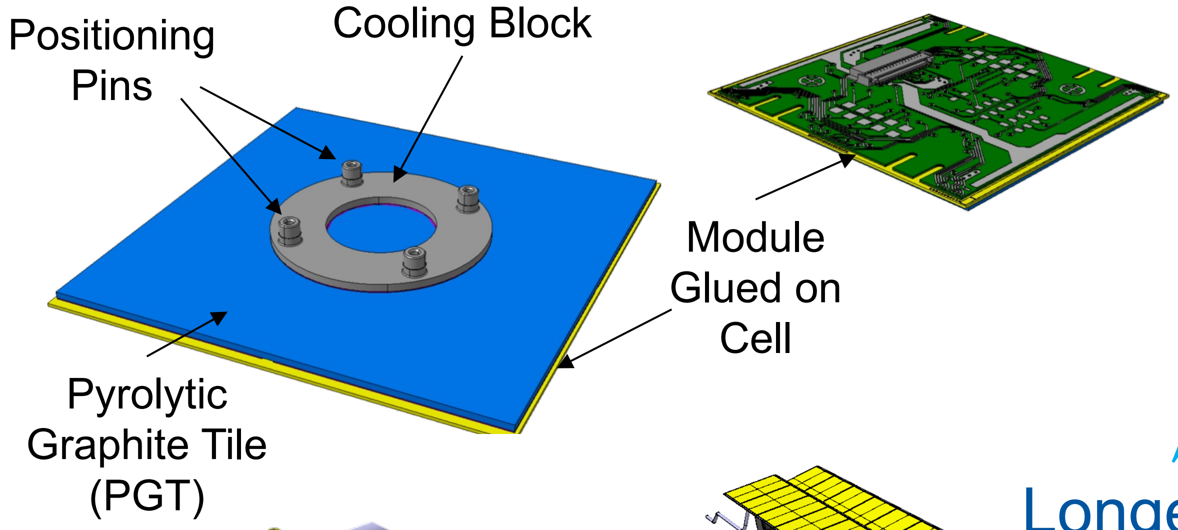
Intermediate Supports

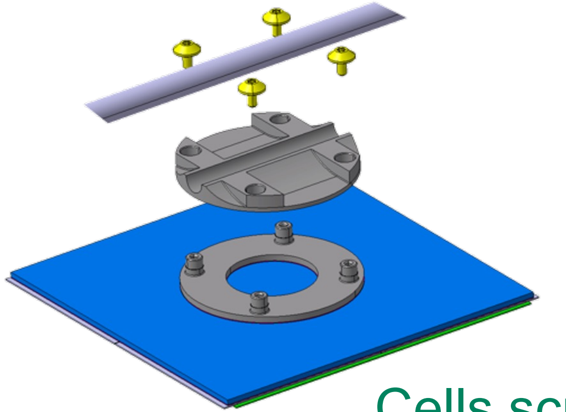
ITk Pixel OB Local Supports

D. Alvarez Feito

Module Cells

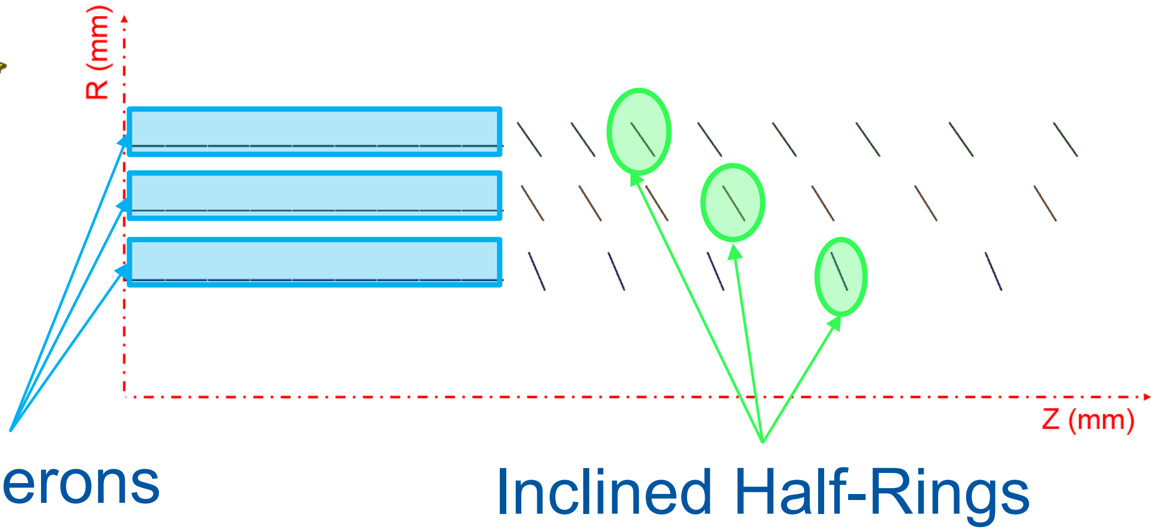
(Module + PGT tile + Cooling Block)

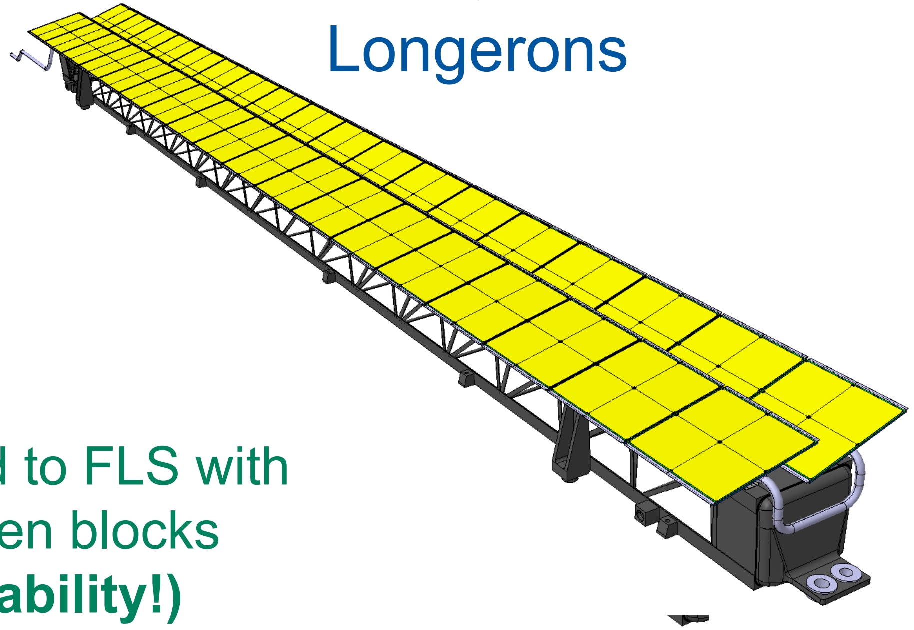




Functional Local Supports (FLS)

(Base Blocks + Cooling Pipe + CFRP Support Structure)

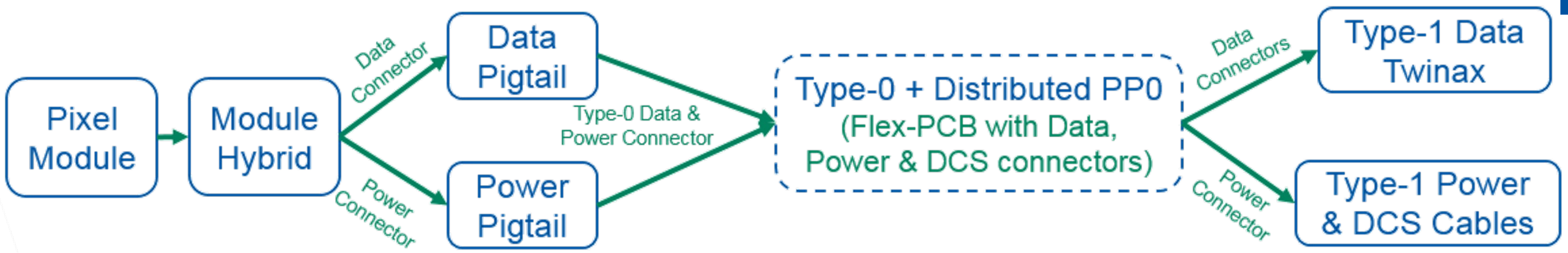


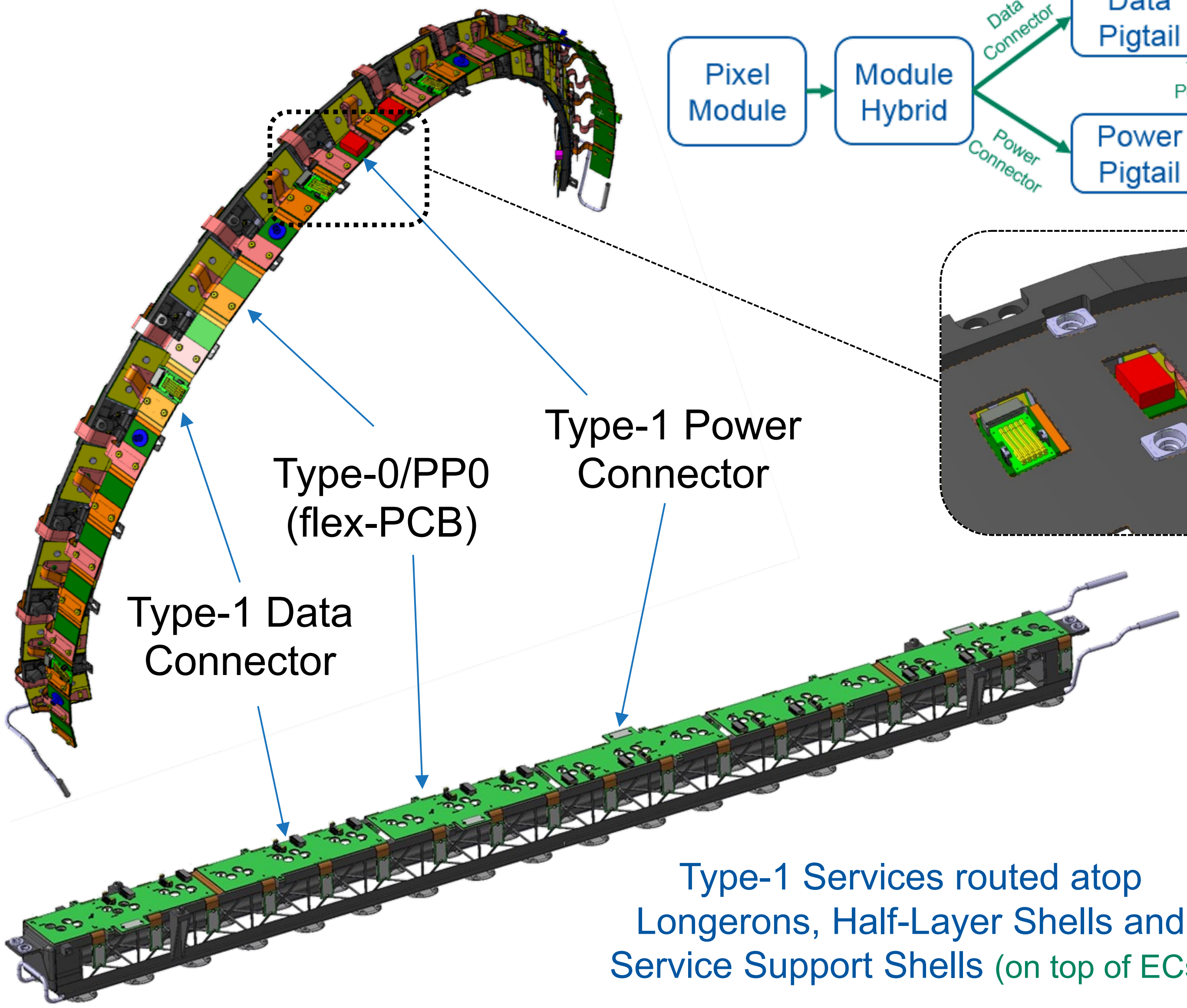


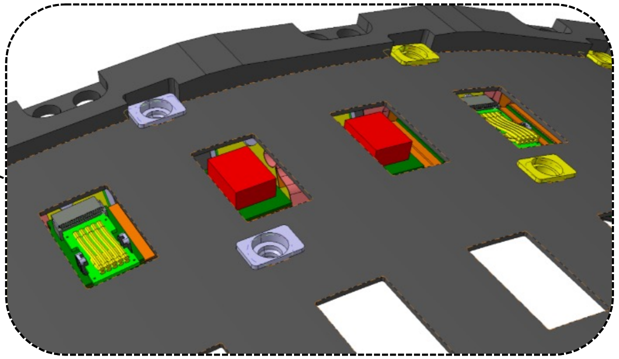
Cells screwed to FLS with
TIM between blocks
(re-workability!)

ITk Pixel OB Service Scheme & Routing

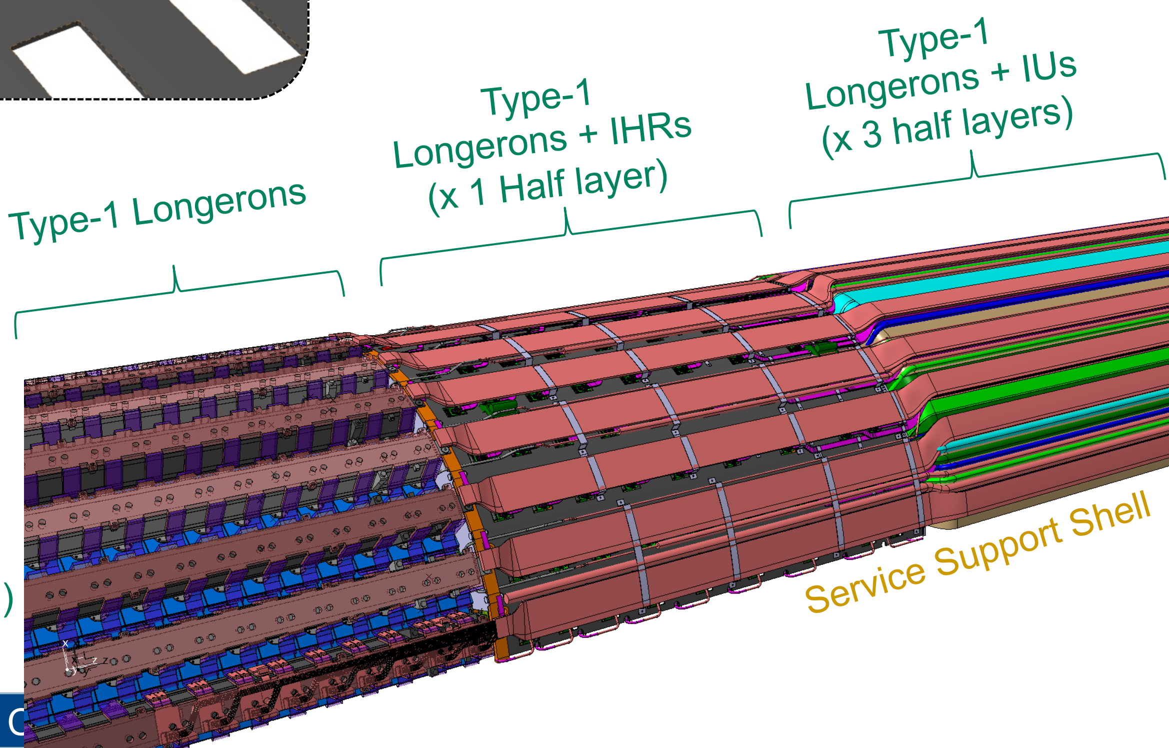
D. Alvarez Feito







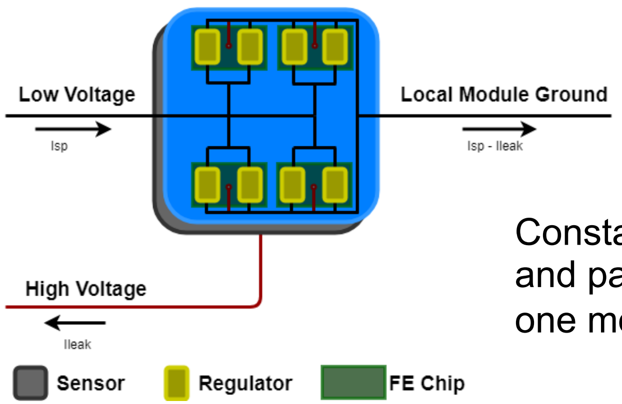
IHR Flex-PCB installed on the inside of the Half-Layer Shells (Openings in the CFRP shells to connect the Type-1 services)



Type-1 Services routed atop Longerons, Half-Layer Shells and Service Support Shells (on top of ECs)

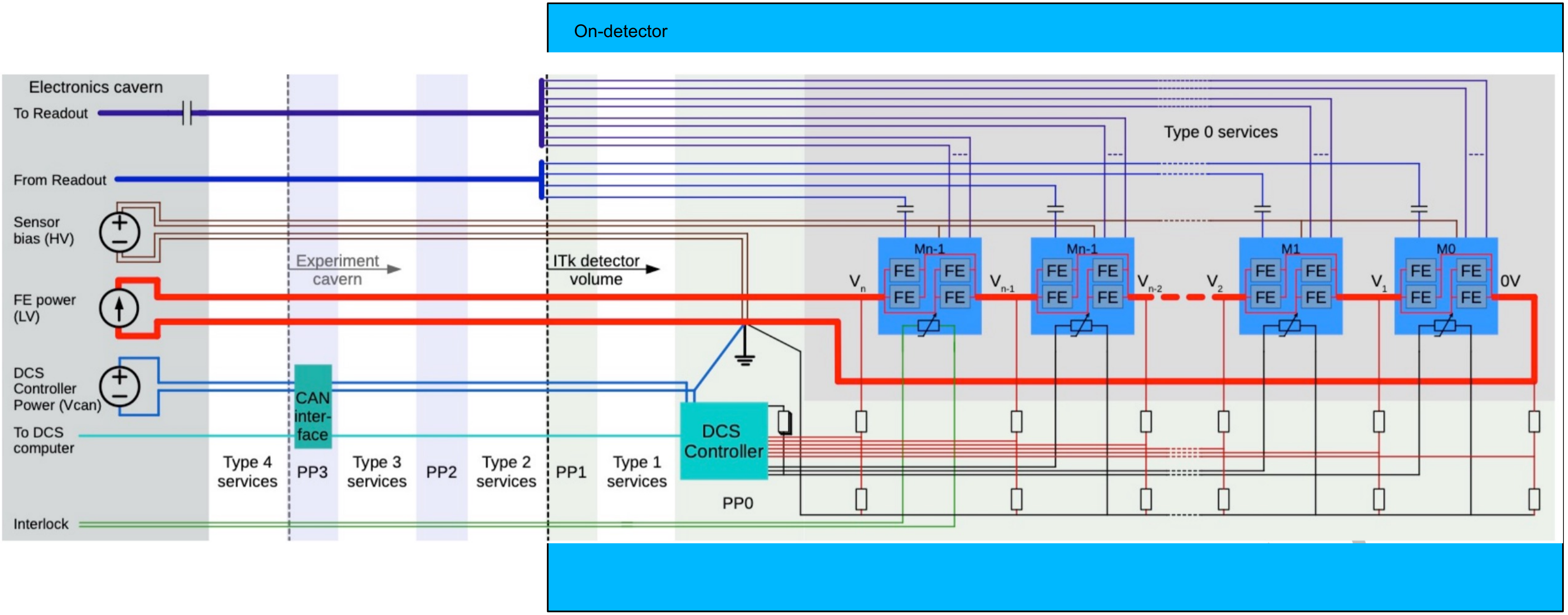
Powering of the ITk Pixel detector

- **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



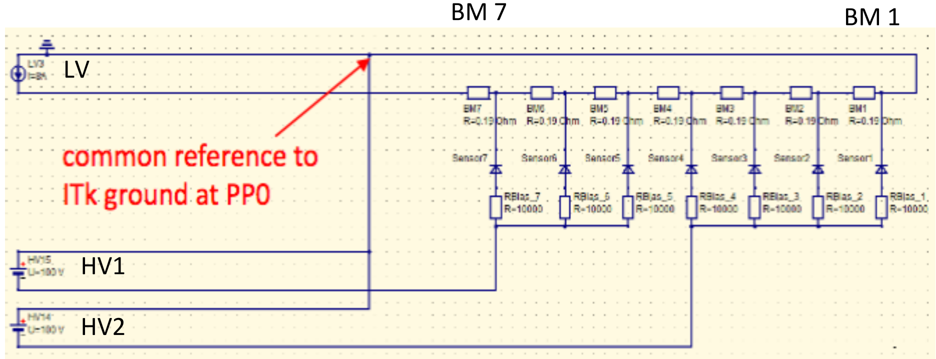
Serial powering:
T. Stockmanns et al., NIM A511 (2003) 174-179
D. Bao Ta et al., NIM A557 (2006) 445-459
L. Gonella et al., JINST 5 (2010) C12002

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



Results of ITk Pixel electrical prototypes

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

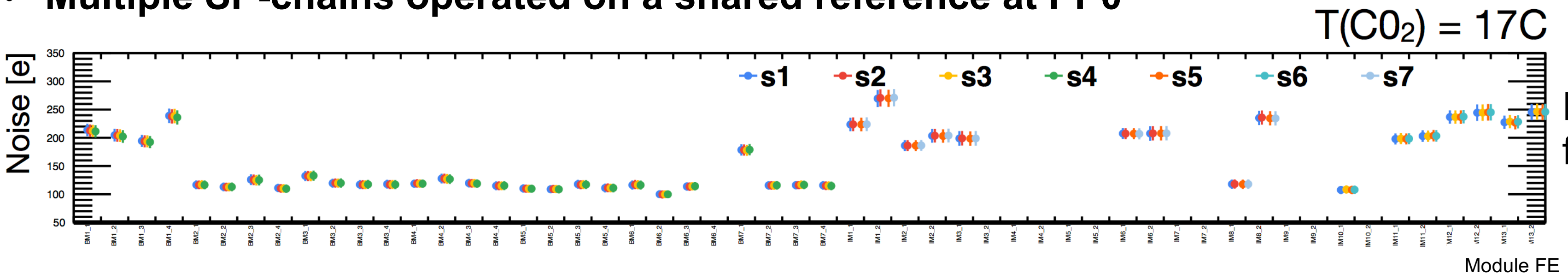


- **Serial powering features**
  - Measurements with realistic power supplies and services scheme → Leakage current return through **HV power supply with low-ohmic off-mode required** to avoid forward bias on module with lowest ground level in chain → **Input to PSU specifications**

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**



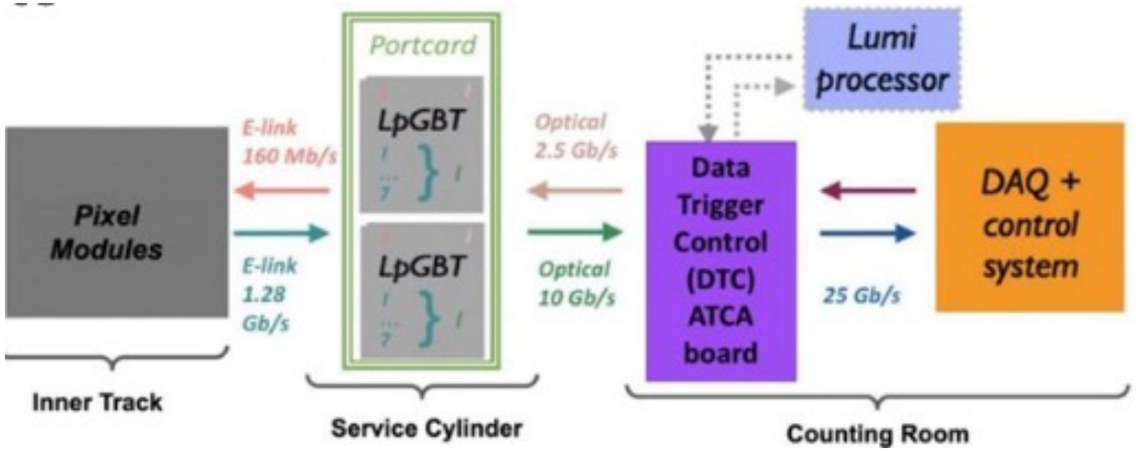
Fully functional

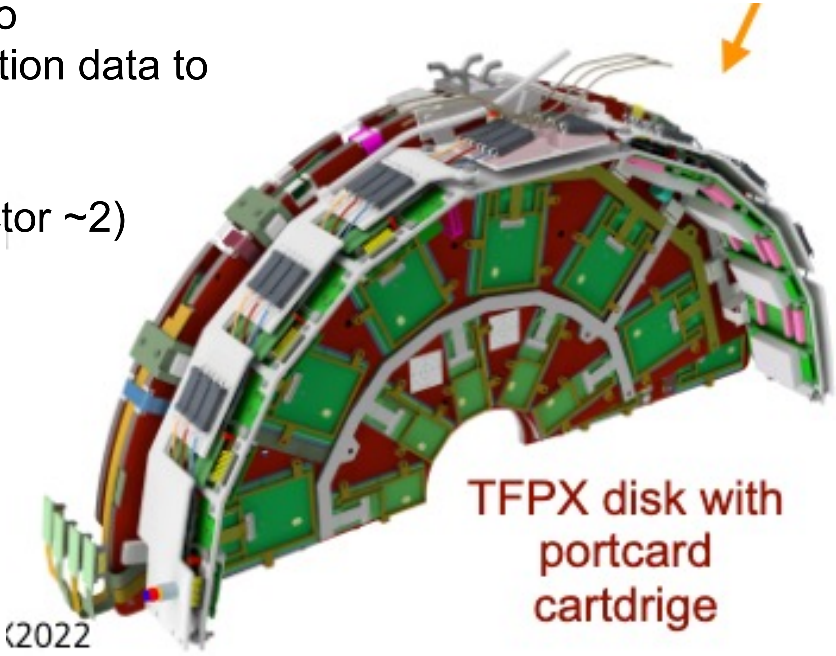
Scenario	powering scheme SC1	SC2	SC3
1	1	1	1
2	1	1	0
3	1	0	1
4	1	0	0
5	0	1	1
6	0	0	1
7	0	1	0

CMS Pixel readout architecture

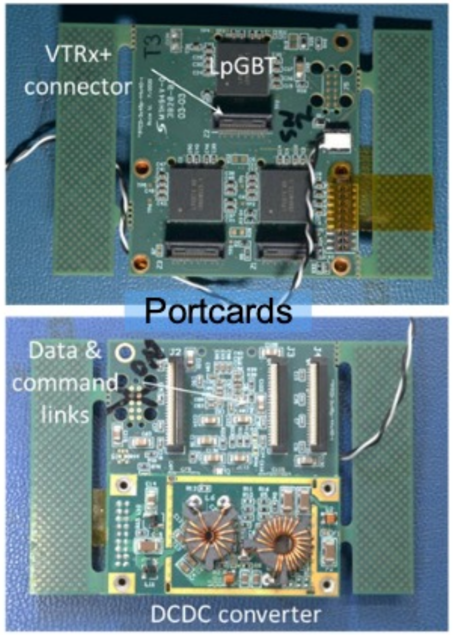
- Communication electronics hosted on dedicated board
  - Detached from the modules
  - Portcards optoelectronic service card (~ 700)
  - Positioned around IT support cylinder (TBPX) and on “Dee” structures (TFPX, TEPX)
  - Opto-converter boards: Portcard houses 3x lpGBTs and VTRx+ links, powered via cascaded DC-DC converters (1 bPOL12V DC/DC converter 1 bPOL2V5 DC/DC converter)
  - Up to 6 electrical up-links at 1.28 Gb/s → module to LpGBT
  - Rates reduction achieved with data formatting. One electrical down-link at 160 Mb/s → LpGBT to module clock, trigger, commands, configuration data to modules

- Efficient data formatting to reduce data rates (factor ~2) / 25% bandwidth headroom on e-link occupancy
- Back-end electronics
  - 28 DTC (Data Trigger Control) boards
  - Lumi processors

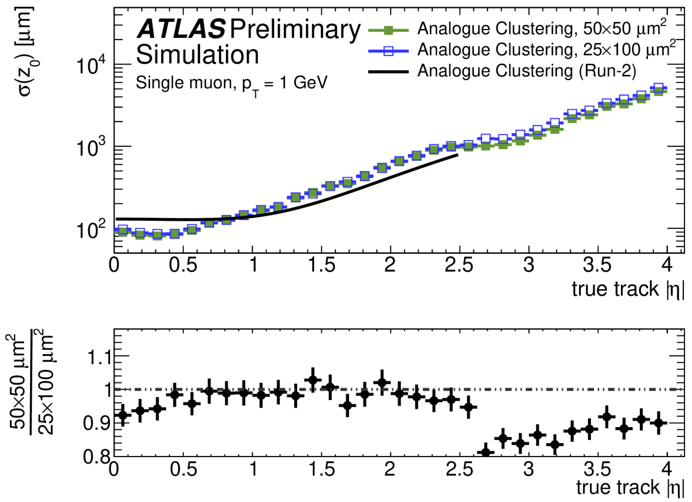


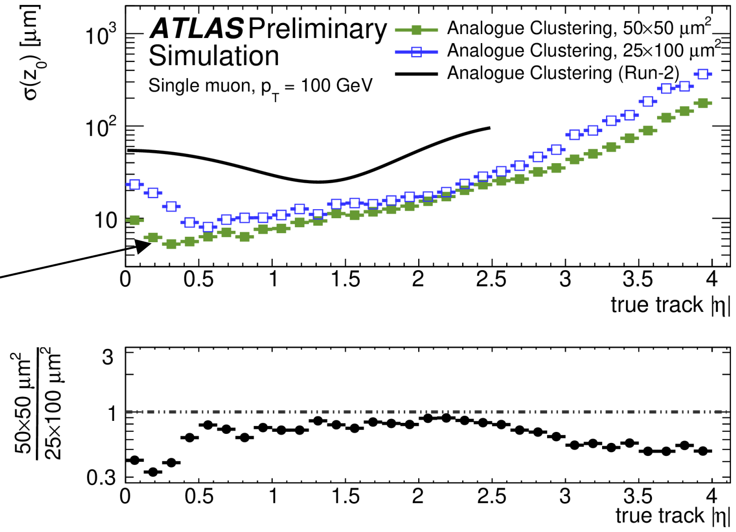


TFPX disk with portcard cartdrige

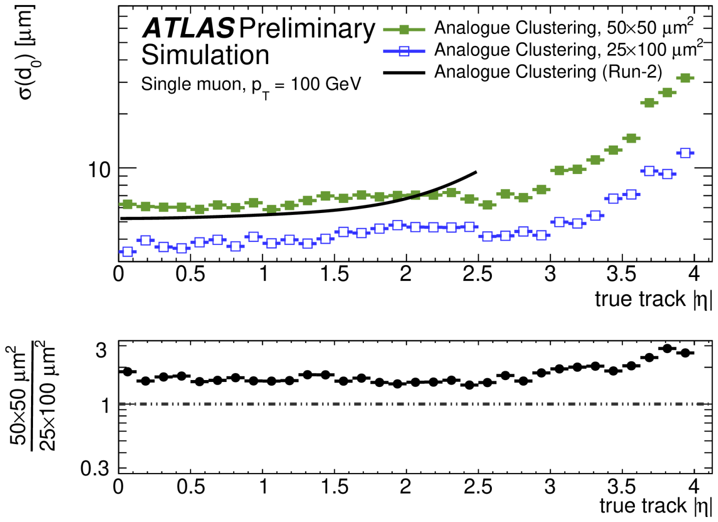


Tracking performance: impact parameter resolution

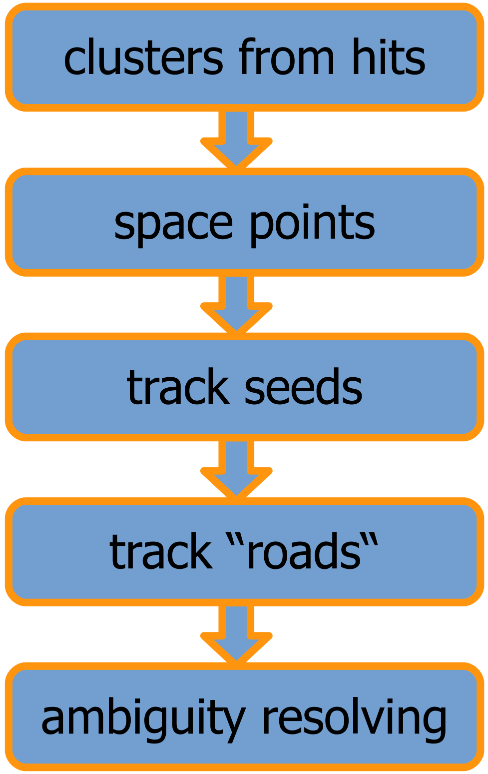




smaller pitch in ITk



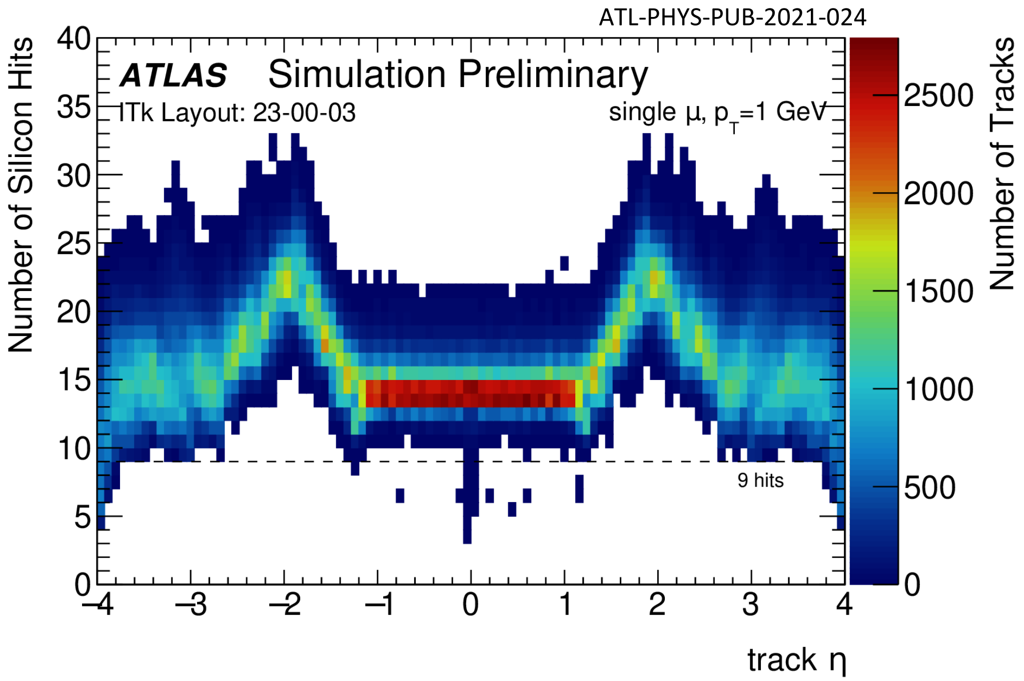
- Longitudinal z_0 resolution crucial for pile-up suppression
- For low p_T dominated by multiple scattering
- For high p_T dominated by intrinsic detector resolution
- Improvement due to reduced material and better resolution of strip tracker than current TRT



Conservative estimate for performance of ATLAS ITk: algorithms not fully optimized

Tracking performance

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

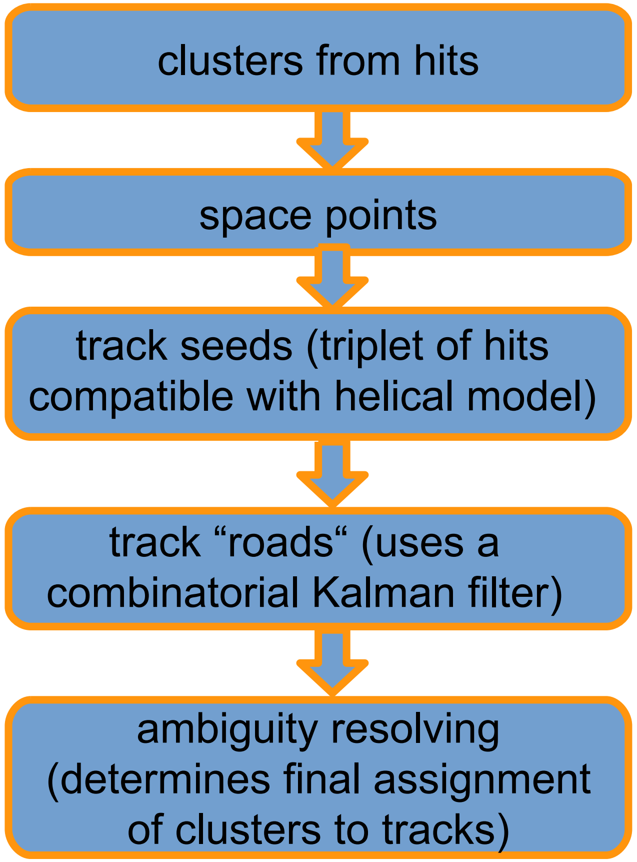


ITk provides at minimum **9 hits** in the barrel and **13 hits** in the forward or all particles with p_T> 1 GeV within $|z_{vertex}|$ < 150 mm

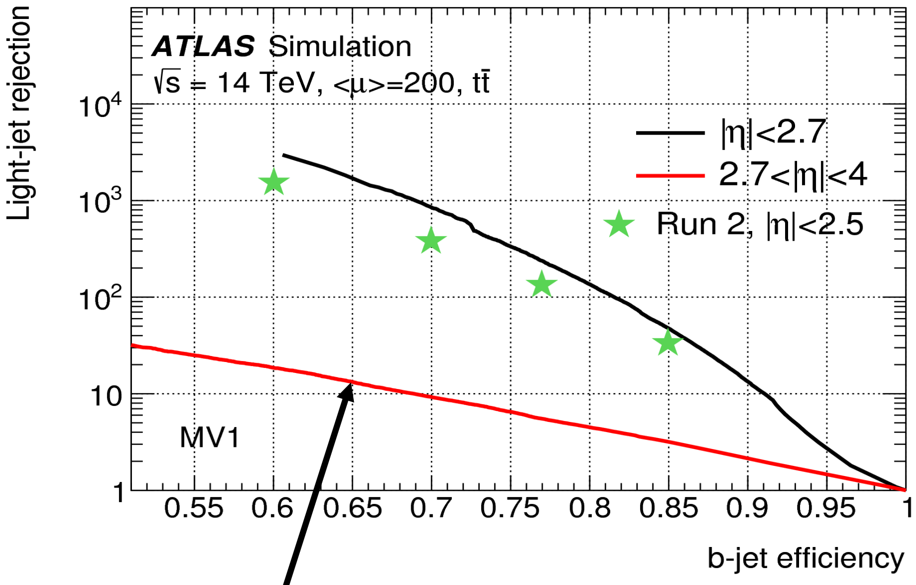
Redundancy is very important to clean combinatorics in reconstruction

Track Reconstruction: From detector readout to physics objects

Reconstruction chain steps:

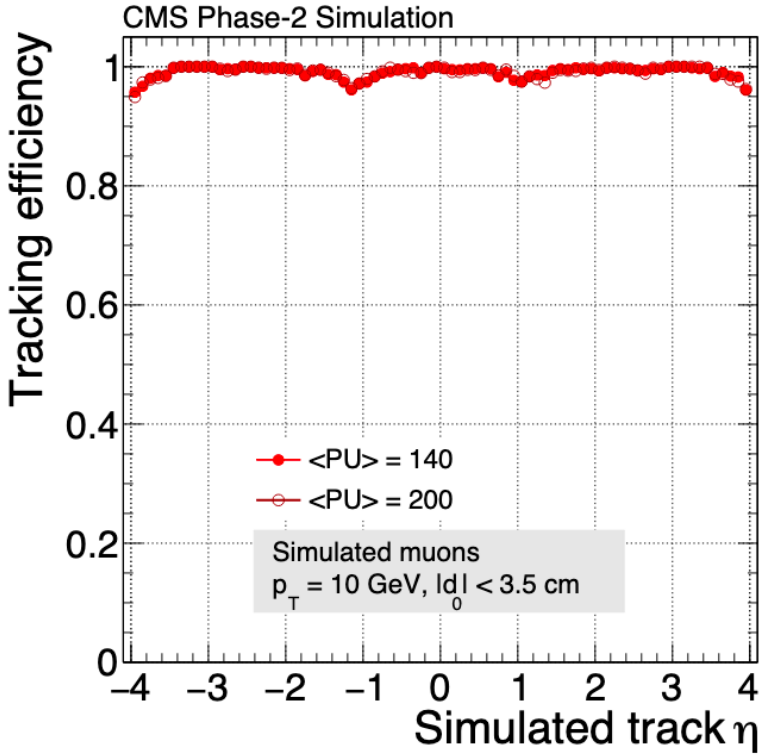


More tracker performance



→ **not optimised!**
→ **important to discriminate between VBF and tt in forward regions**

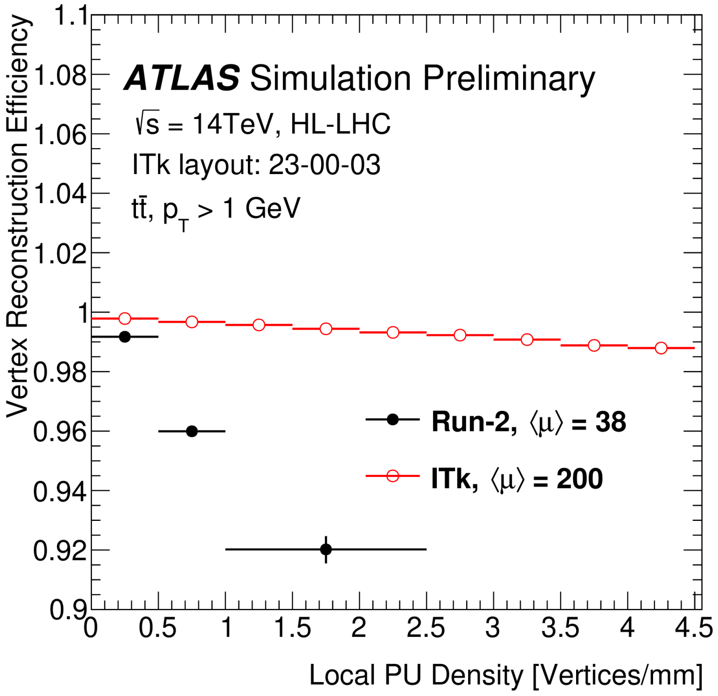
- b-tagging
→ evaluated using tt sample with parton-jet matching
→ Run-2 algorithms without dedicated tuning used

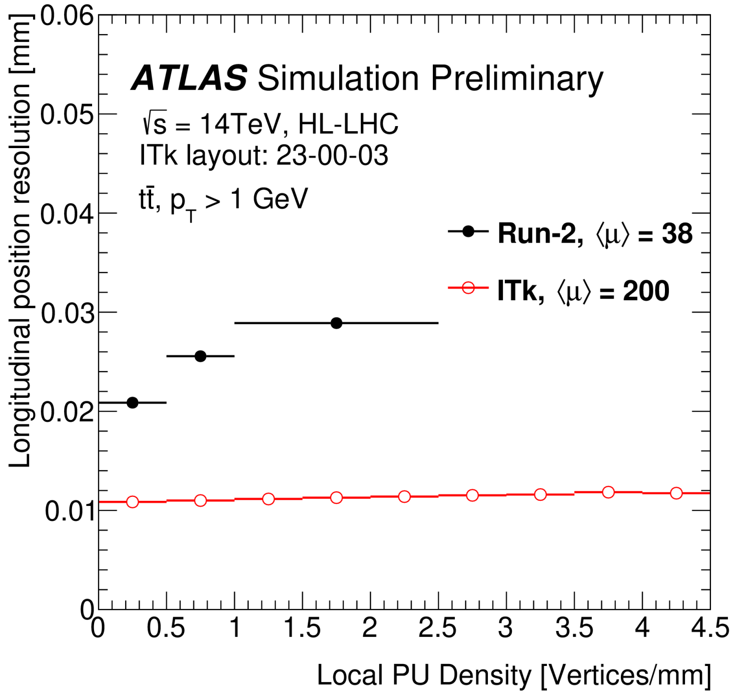


- Tracking efficiency with muons in CMS

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



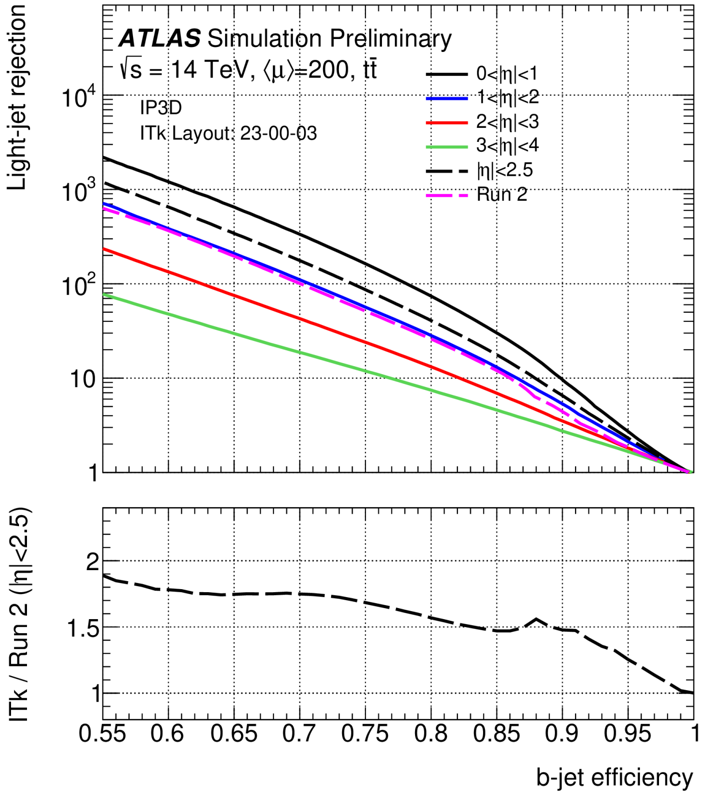


- Vertex reconstruction efficiency shows **robust performance** even up to <μ> ~ 200
- **Longitudinal position resolution** improved by factor of 2-3 and exhibits strong **robustness against pile-up**

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

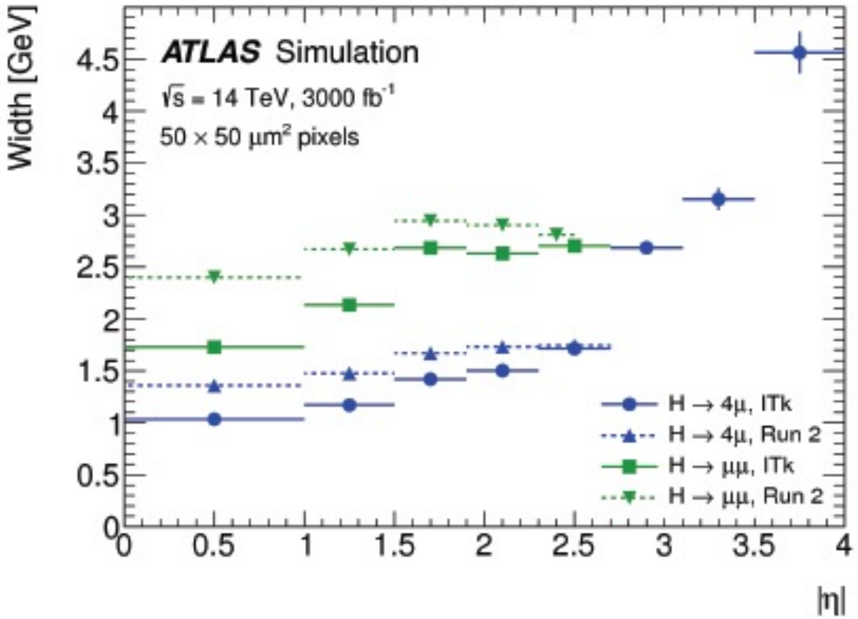
Jet Flavour Tagging and Physics Case

- 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