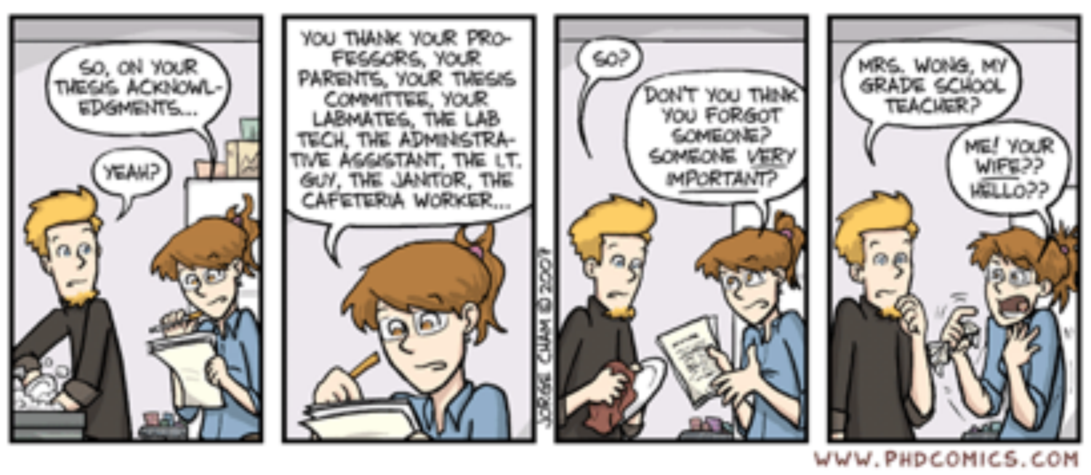
Ingrid-Maria Gregor, DESY

STRIP TRACKER OVERVIEW

**10th International “Hiroshima” Symposium
on the Development and Application of
Semiconductor Tracking Detectors
Xi’An, China
September 25th - 29th 2015**

OUTLINE

- Introduction
- Strip Tracker Upgrade during LS2
  - LHCb
- Strip Tracker Upgrade during LS3
  - CMS
  - **ATLAS**
- Conclusions



Duccio Abbaneo

Tim Jones

Thomas Bergauer

Andreas Mussgiller

Phil Allport

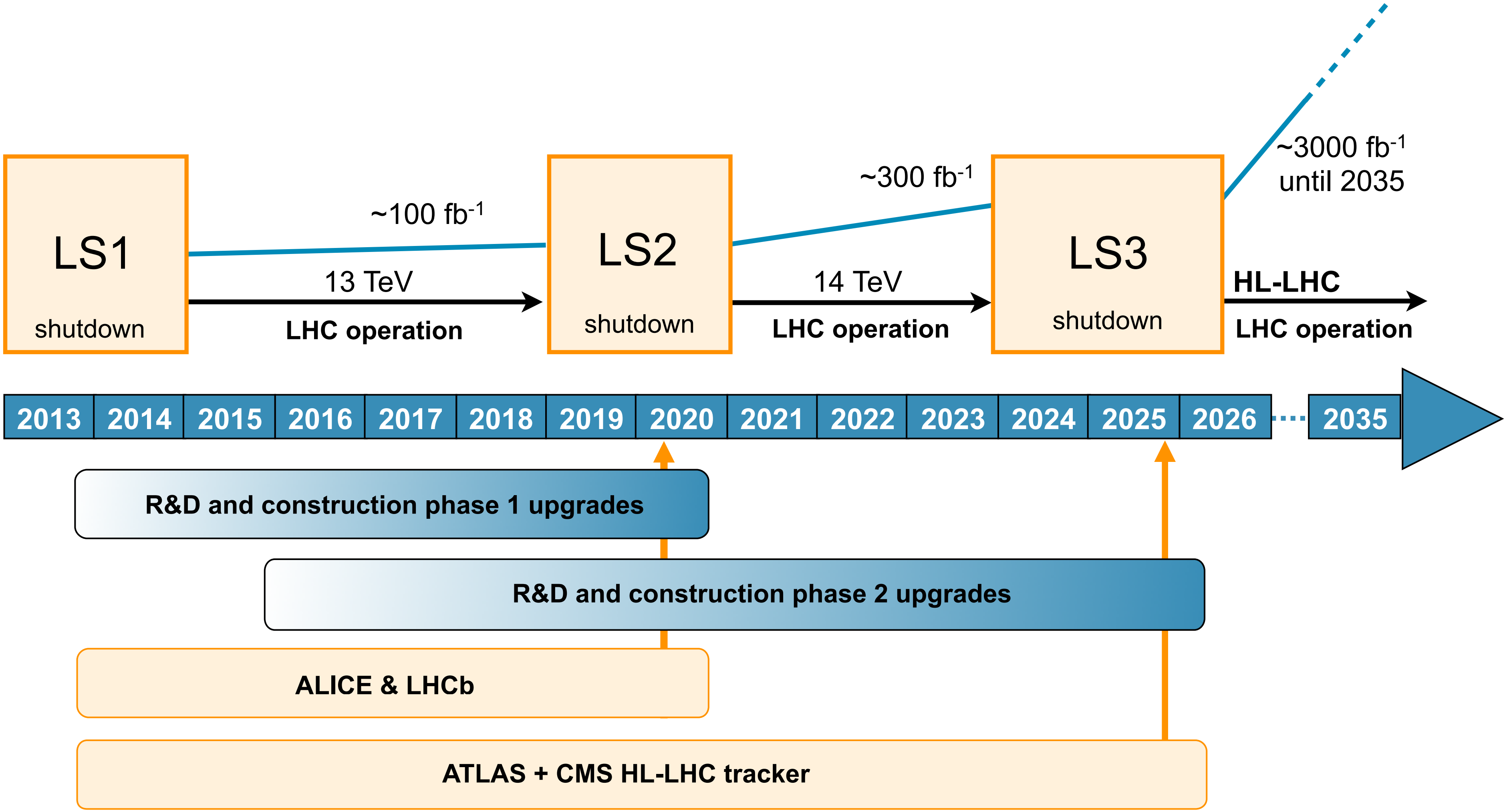
Tony Affolder

Nick Styles

… and more !!

INTRODUCTION

LHC SCHEDULE



LS1

shutdown

~100 fb^{-1}

13 TeV

LHC operation

LS2

shutdown

~300 fb^{-1}

14 TeV

LHC operation

LS3

shutdown

~3000 fb^{-1}
until 2035

HL-LHC

LHC operation

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 …… 2035

R&D and construction phase 1 upgrades

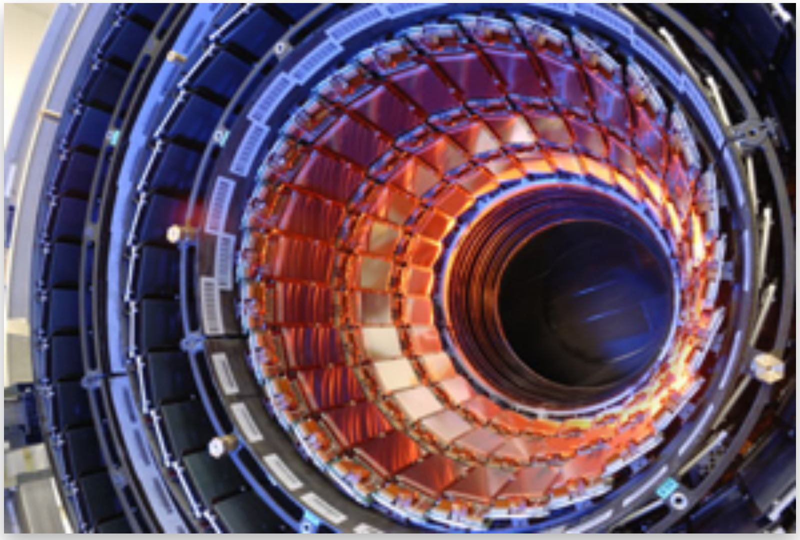
R&D and construction phase 2 upgrades

ALICE & LHCb

ATLAS + CMS HL-LHC tracker

INTRODUCTION

- The challenging physics program and environment require excellent tracking capabilities for all four LHC experiments.
  - Current trackers are performing outstandingly well.
- Improvements/replacements of the trackers will be necessary for the running after LS2 and LS3.
- Two main considerations:
  - Bandwidth saturation and occupancy: current front-end electronics designed to accommodate occupancies of up to 50 pile-up events.
  - Radiation Damage: Current detectors not designed to withstand the expected fluences beyond LS3.
- All four experiments will upgrade their tracking systems in the next decade
  - LS2: ALICE, **LHCb**
  - LS3: **ATLAS, CMS**



Current CMS Strip Tracker

Performance Improvement

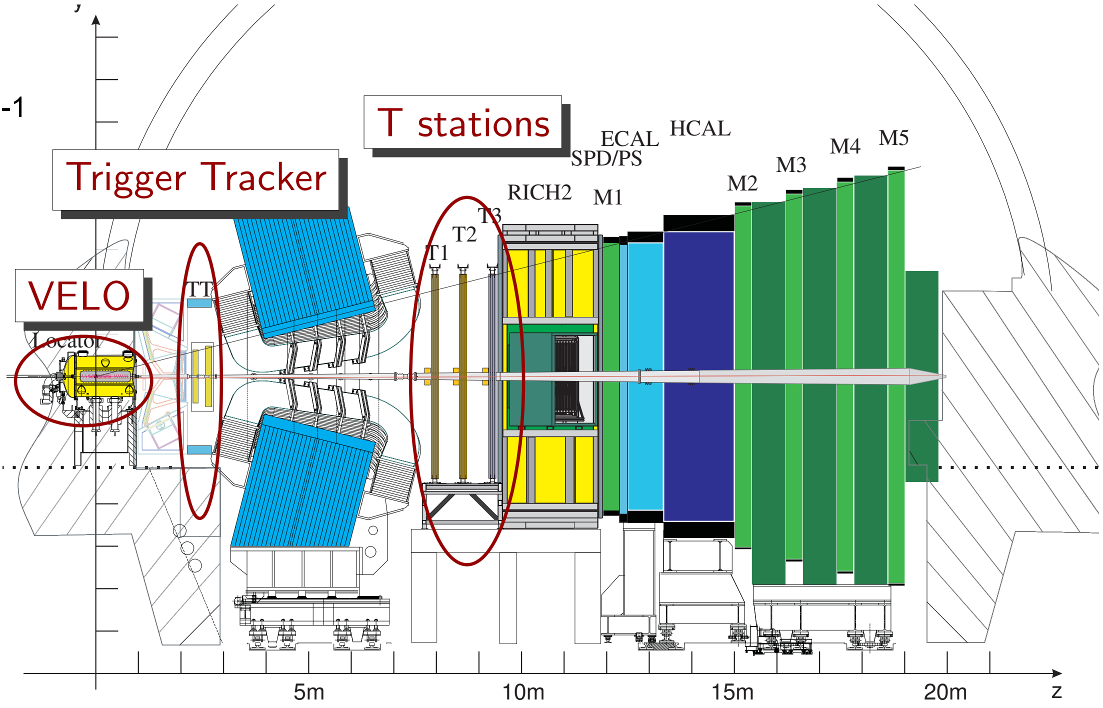
	Increase granularity at large radii	Increase granularity close to the IP (small pixels)	Increase number of pixellated layers	Reduce material
Fast and efficient pattern recognition in high pileup	X	X	X	
Improve momentum resolution at low pT				X
Improve momentum resolution at high pT	X			
Improve tracking efficiency	X			X
Improve impact parameter resolution		X		
Improve two-track separation		X		
Reduce photon conversions				X

- All four LHC experiments work on a combination of those measures.

LS2 STRIP TRACKER UPGRADES
LHCb

LHCb Tracker Upgrade

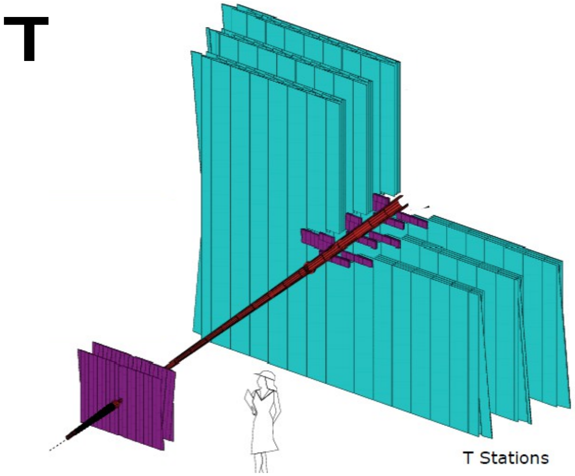
- Increase luminosity to L=2x10^{33} cm^{-2}s^{-1} to reach 10fb^{-1} per year
    - Better event selection at 40MHz readout and software trigger
- Event topology is more complex
    - More primary vertices
    - Increased track multiplicity
    - Detector occupancy



- Excellent momentum, time, and vertex resolution
- Keep or improve current detector performance under more challenging conditions
- Maintain high track efficiency (~90% when p≥5GeV)

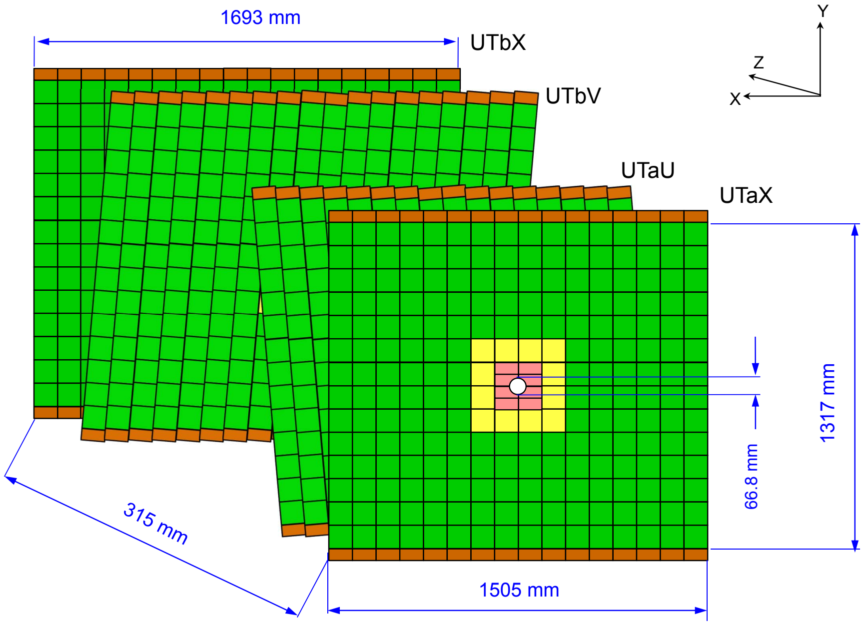
- Planned LHCb tracker upgrades during LS2
    - replace Vertex locator (VELO)
    - Trigger tracker: replace by Upstream Tracker
    - T stations: redesign high occupancy regions
- Upgrade of all electronics to cope with 40MHz readout

LHCb Upstream Tracker UT



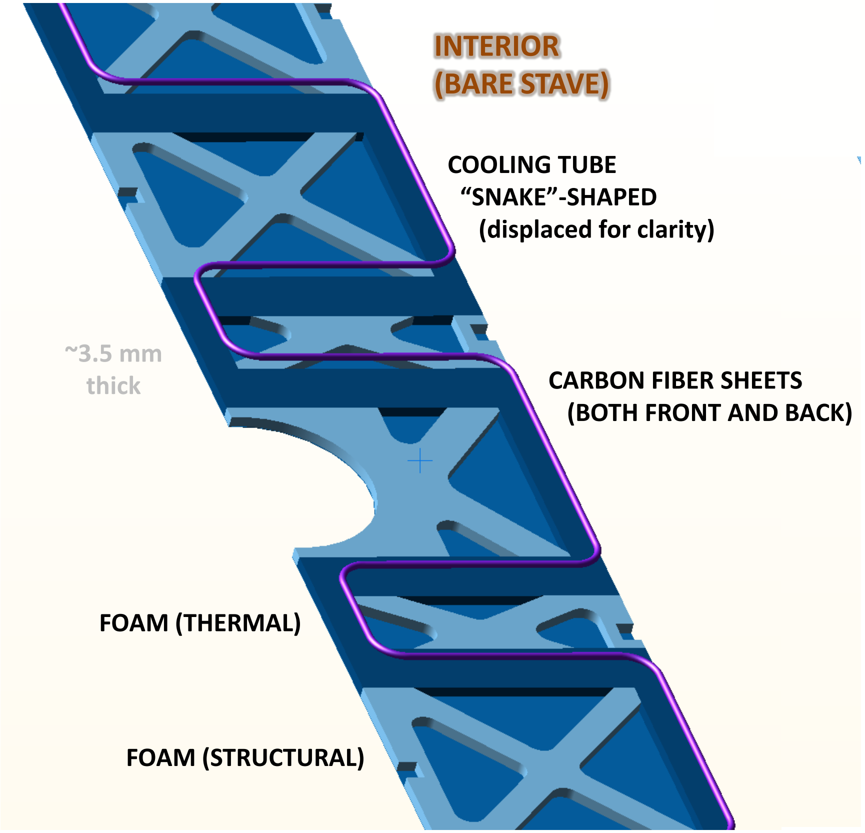
- Upgrade of Trigger Tracker station (UT) in front of magnet
  - Challenges: low mass, cooling and segmentation to reduce occupancy
  - New more granular silicon sensors to cope with occupancy
  - Reduce gaps and minimize material in acceptance

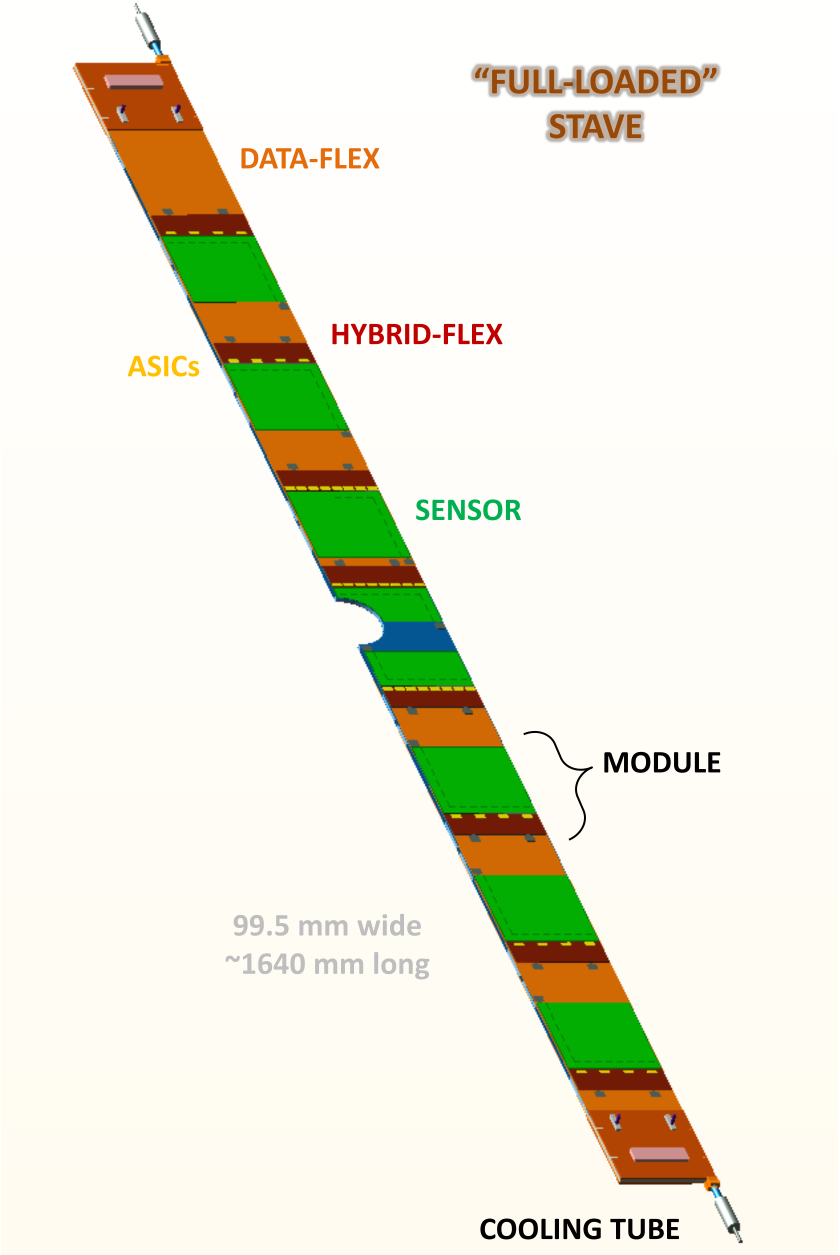
- Four planes of silicon strip detectors constructed using “staves” with silicon on both sides, partially overlapping in the x-direction to ensure 100% coverage
- Single sided sensors with various pitch and length
- 68 staves, ~0.5M channels



Details: Mark Tobin, this session

LHCb Stave Details





- Very light stave structure based on Carbon Foam, Carbon Facings and Titanium Tubes
- Some developments based on ATLAS ITK strips developments

LS3 STRIP TRACKER UPGRADES
ATLAS & CMS

BASIC REQUIREMENTS FOR NEW TRACKER

ttbar event with 140 pile-up events (ATLAS simulation)

Radiation hardness

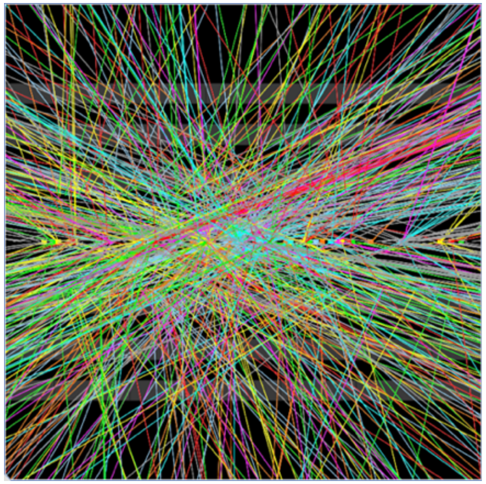
- Ultimate integrated luminosity considered ~ 3000 fb^{-1}
- Annual integrated luminosity of 250-300 fb^{-1} with levelled operation at $7*10^{34}$ $cm^{-2}sec^{-1}$
- Radiation hard sensor material required
- New readout electronics required

Granularity

- Efficient pattern recognition and tracking with pile-up of >200
- Maintain detector occupancy below % level
- Requires much higher granularity

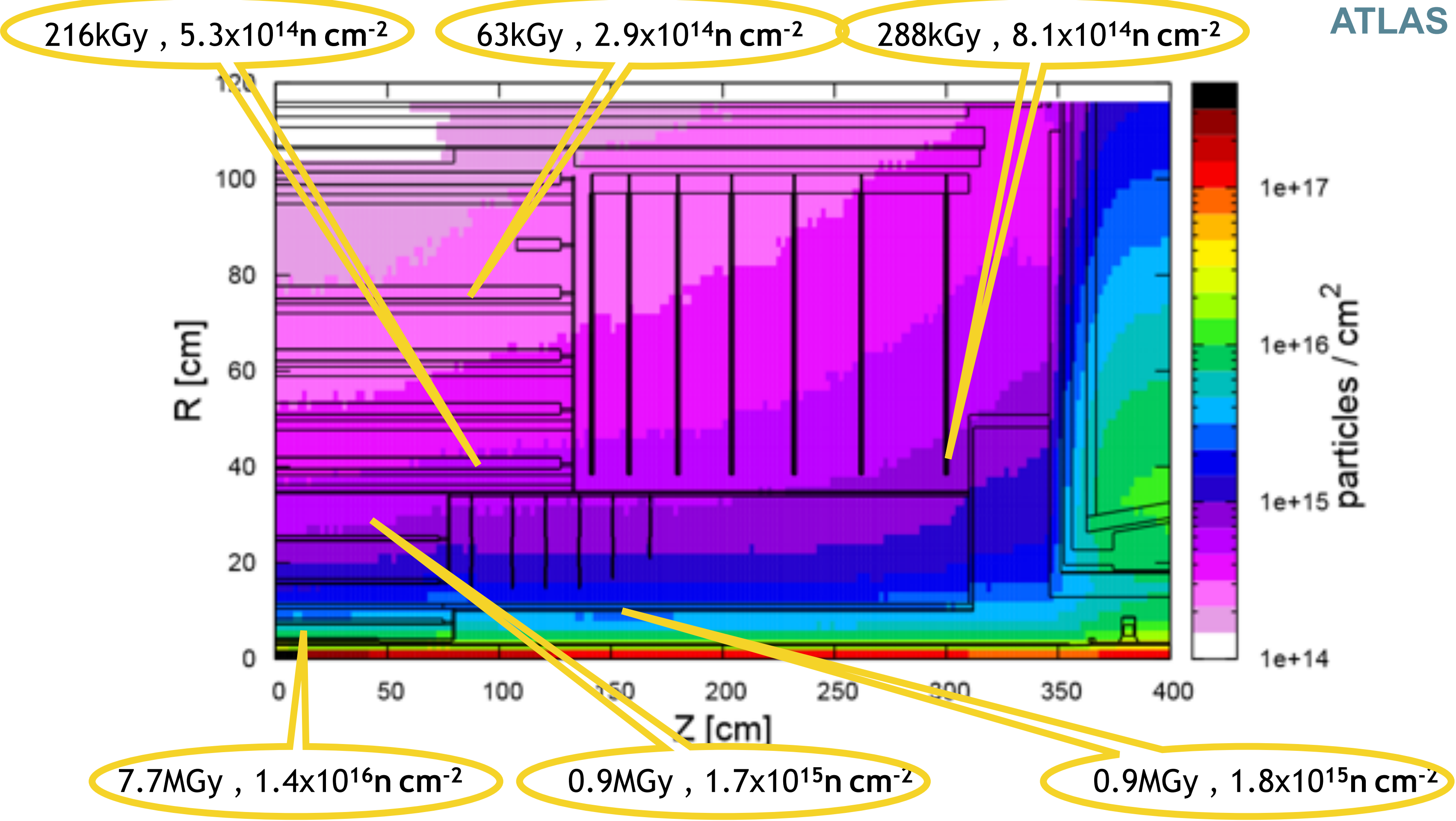
Improve tracking performance

- Reduce material in the tracking volume
  - Improve performance at low p_T
  - Reduce rates of nuclear interaction, photon conversions, Bremsstrahlung…
- Reduce average pitch
  - Improve performance at high p_T



BIGGEST CHALLENGE: RADIATION

Example:
ATLAS ITK


216kGy , 5.3×10^{14}n cm^{-2}

63kGy , 2.9×10^{14}n cm^{-2}

288kGy , 8.1×10^{14}n cm^{-2}

7.7MGy , 1.4×10^{16}n cm^{-2}

0.9MGy , 1.7×10^{15}n cm^{-2}

0.9MGy , 1.8×10^{15}n cm^{-2}

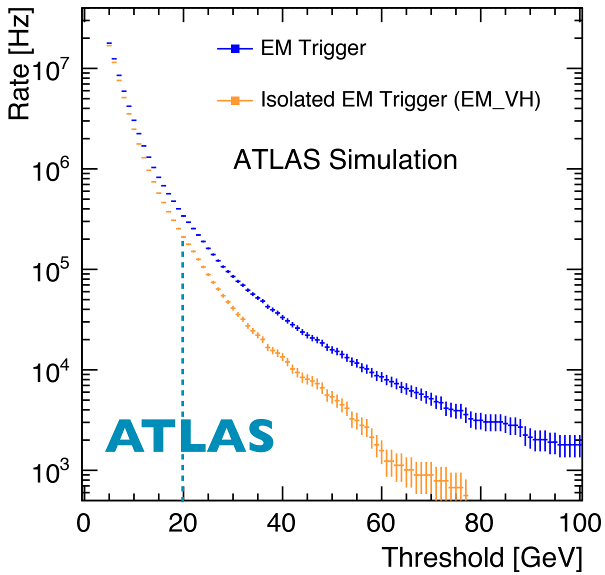
- Radiation levels need to be carefully simulated to avoid unknown “hot-spots”
- Change of geometry and material can change radiation map

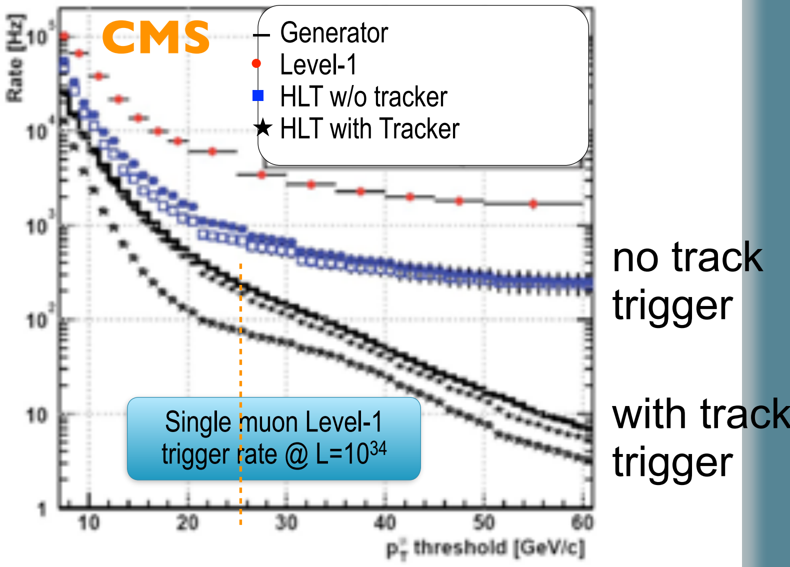
NEW TRIGGER SCHEMES REQUIRED

- Tracker input to Level-1 trigger
  - μ, e and jet rates would exceed 100 kHz at high luminosity
  - Increasing thresholds would affect physics performance
    - Muons: increased background rates from accidental coincidences
    - Electrons/photons: reduced QCD rejection at fixed efficiency from isolation

- Implement changes on different levels
  - Make existing triggers more granular
  - Use tracking information in trigger

- Add tracking information at Level-1
  - Move part of High Level Trigger reconstruction into Level-1
  - Challenge: squeeze into existing latency

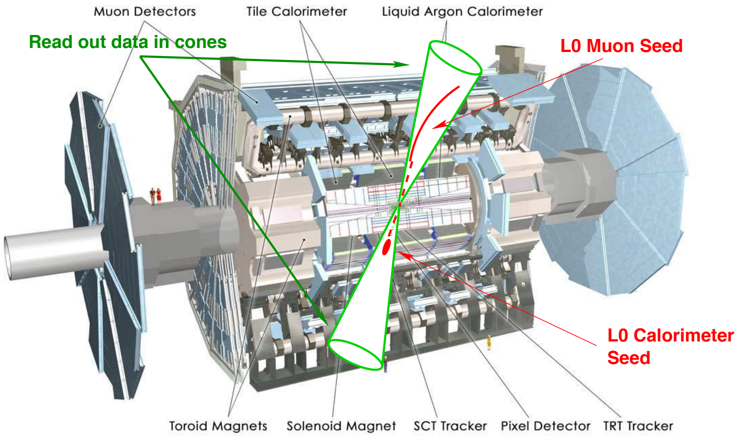




TRACK TRIGGER

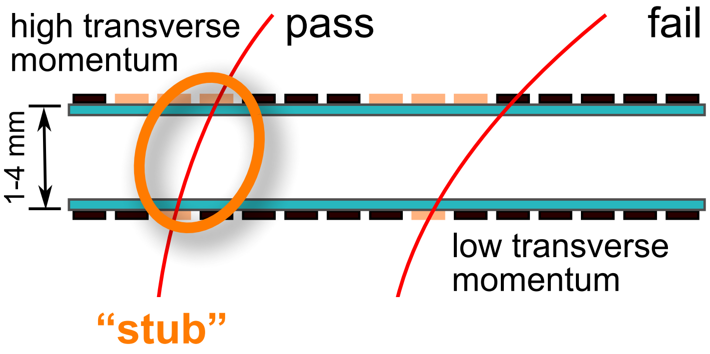
ATLAS - Region of Interest Trigger:

- ‘**pull** architecture’
- first level trigger (Calo/Muon) reduces rate within ~6us to ~1MHz and defines ‘regions of interest’ (RoIs)
- track trigger extracts tracking info inside RoIs from detector



CMS - self triggered trigger:

- ‘**push** architecture’ for outer tracker
  - track segment selection at front-ends all tracks with $p_T > 2$ GeV
  - ~1mm primary vertex resolution
  - pattern recognition and track fit at L1 in off-detector electronics (AM+FPGAs)



Combination of multiple layers

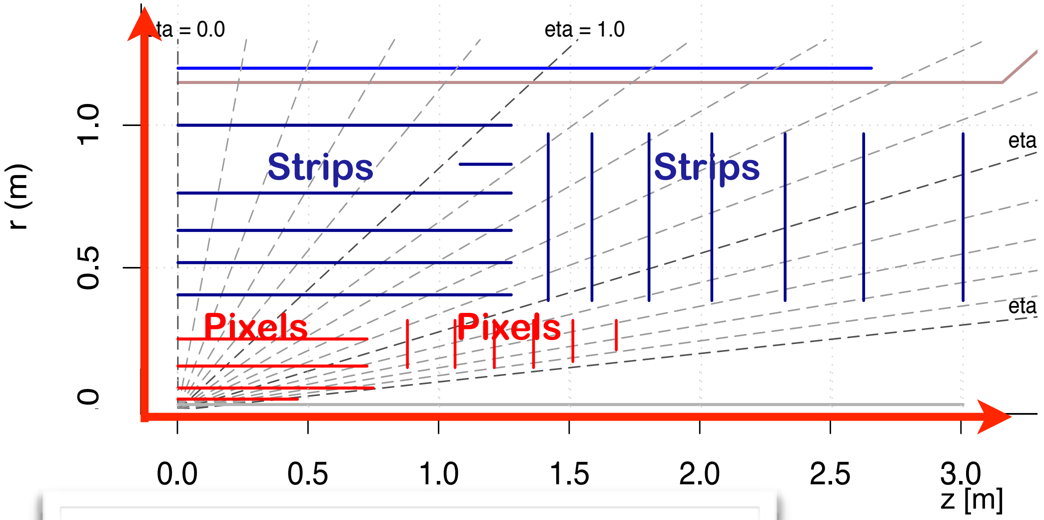
Difference in trigger choice defines differences in detector design !

ATLAS AND CMS HL-LHC TRACKER

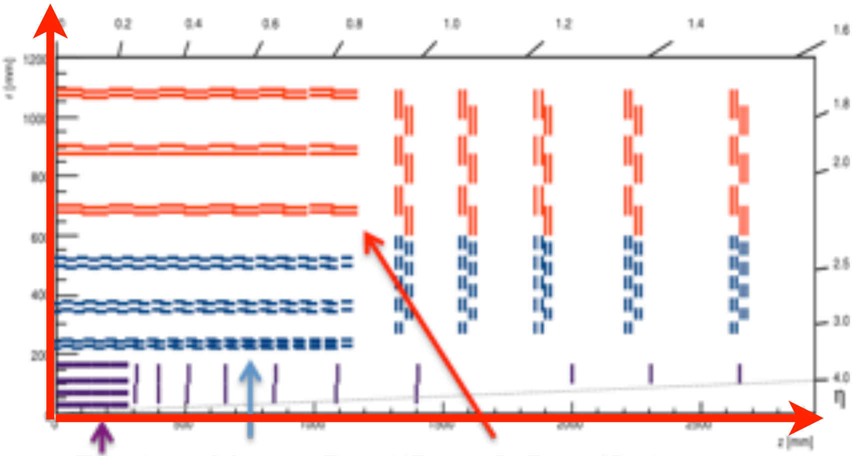
- ATLAS&CMS plan for ~200 m^2 silicon strip detector
- Commonalities:
  - 20000 modules to be produced
  - choice of sensor technology (n-in-p)
  - radiation level (O(10^{15} n$_{eq}$/cm^2))
- Similar granularity
  - strip pitch ~ 70-90 μm & length ~ 2.5 to 5 cm
  - pixel pitch ~ 50 μm and ~ 100 μm length

		ATLAS	CMS
Pixels	Layers (B+EC)	4 + 6	4 + 10
	Area	8.2 m^2	4.6 m^2
	Channels [10^6]	638	380
Strips	Layers (B+EC)	5.1 + 7	6 + 5
	Area	**193 m^2**	**218 m^2**
	Channels [10^6]	74	250

ATLAS



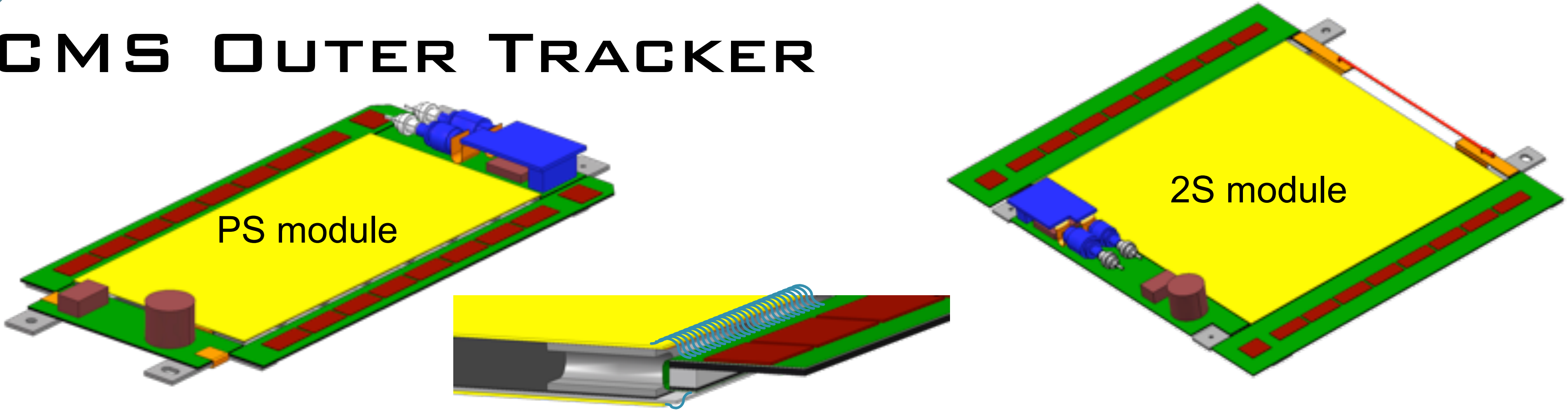
CMS



Pixels - Macro-Pixel/Strip & Strip/Strip modules

Both trackers similar on first view but in details rather different.

CMS OUTER TRACKER



- Modules discriminate low-p_T tracks in the FE electronics
- Hybrid is key element: Wire-bonds from the sensors to the hybrid on the two sides
  - FE chips bump-bonded onto hybrid
- Overall 216 m^2 with 47 M strips, 215M long pixels
- All modules send out data for track reconstruction at Level-1

PS Module

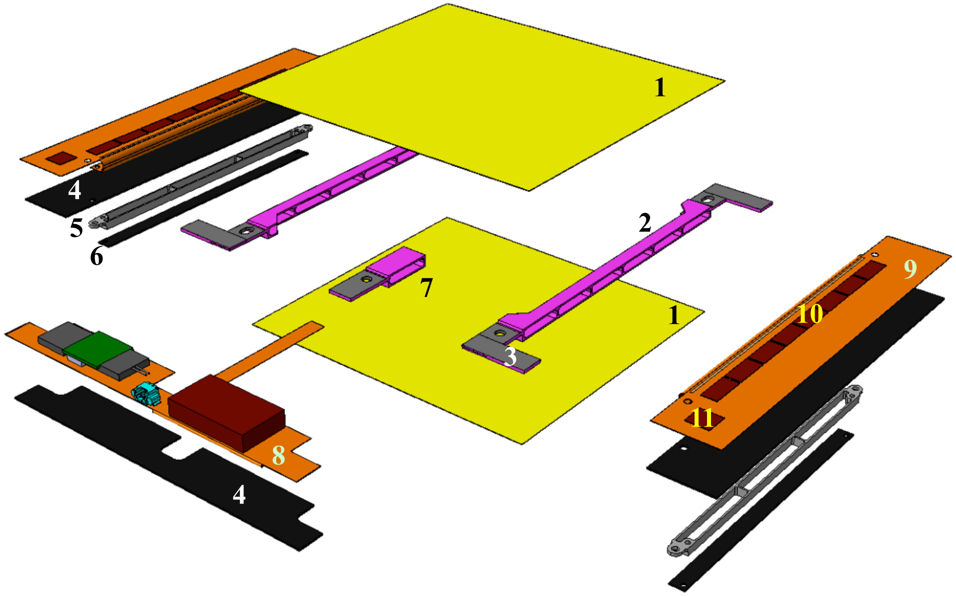
- Three inner layer (R>20cm) of Pixel-Strip modules
  - Top sensor: strips 2x25 mm, 100 μm pitch
  - Bottom sensor: long pixels 1.5 mm × 100 μm
- z-information from pixel sensor

2S Module

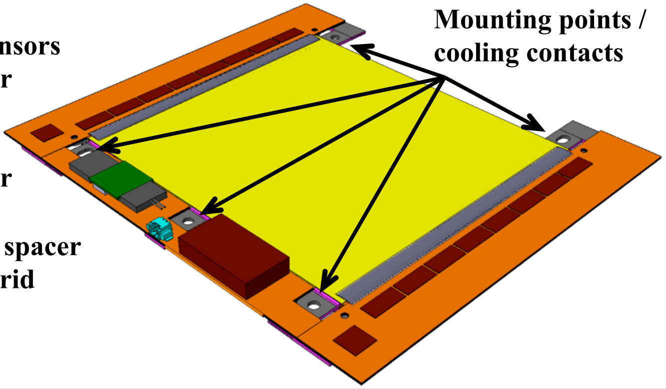
- Three outer layer (R>60cm) of 2-Strip modules
  - Strip sensor 10x10 cm^2 with 2x5cm long strips, pitch of 90 μm
  - light and “simple”
  - no z-information

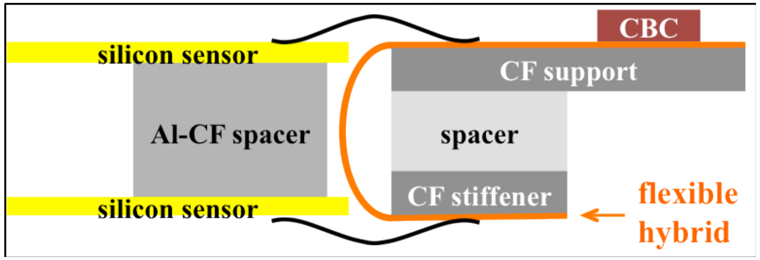
CMS 2S-MODULE

- Five mounting/cooling points – peripheral cooling
  - Concept similar to modules of the present tracker
- Al-CF spacers provide good thermal conduction, and enable simple, high-precision assembly minimising CTE mismatch
  - choice of Al-CF composite material was breakthrough in pT-module design
- Hybrids are laminated on the CF supports in industry



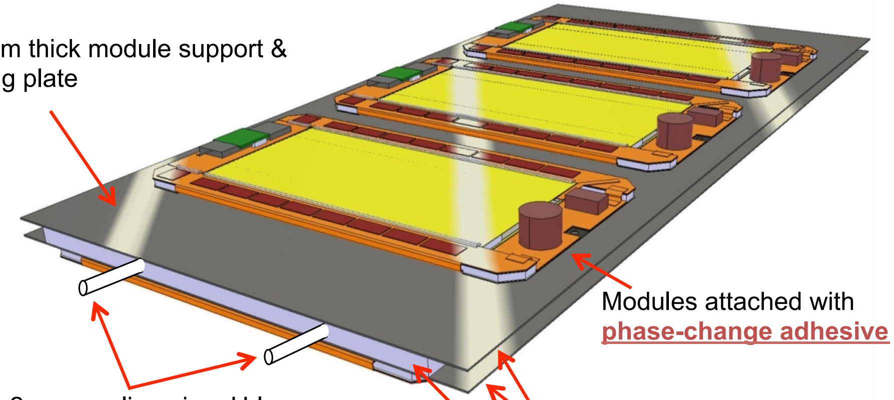
1. 2S silicon sensors
2. Al-CF spacer
3. Al-CF tab
4. CF support
5. Al-CF spacer
6. CF stiffener
7. Al-CF short spacer
8. Service Hybrid
9. FE Hybrid
10. CBC
11. CIC





Picture: CMS collaboration

CMS Module Support

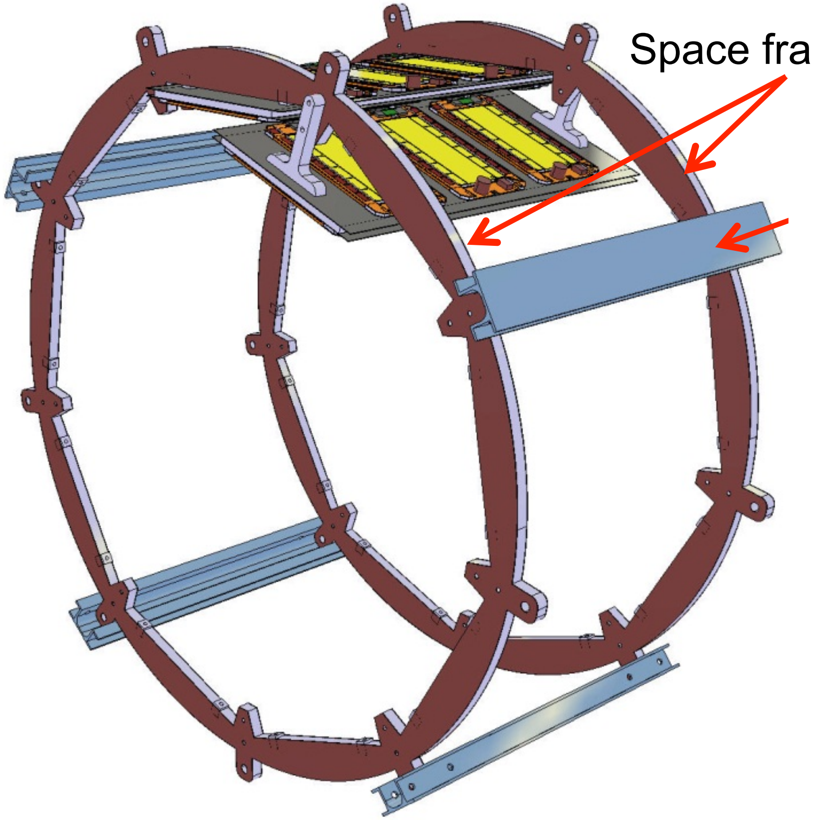


4-6 mm thick module support & cooling plate

Modules attached with **phase-change adhesive**

Diam ~2 mm cooling pipe, U-loop
Carbon foam or aluminium/carbon-fibre block next to cooling pipe

~0.5 mm high-conductivity carbon-fibre composite skins
Foam core

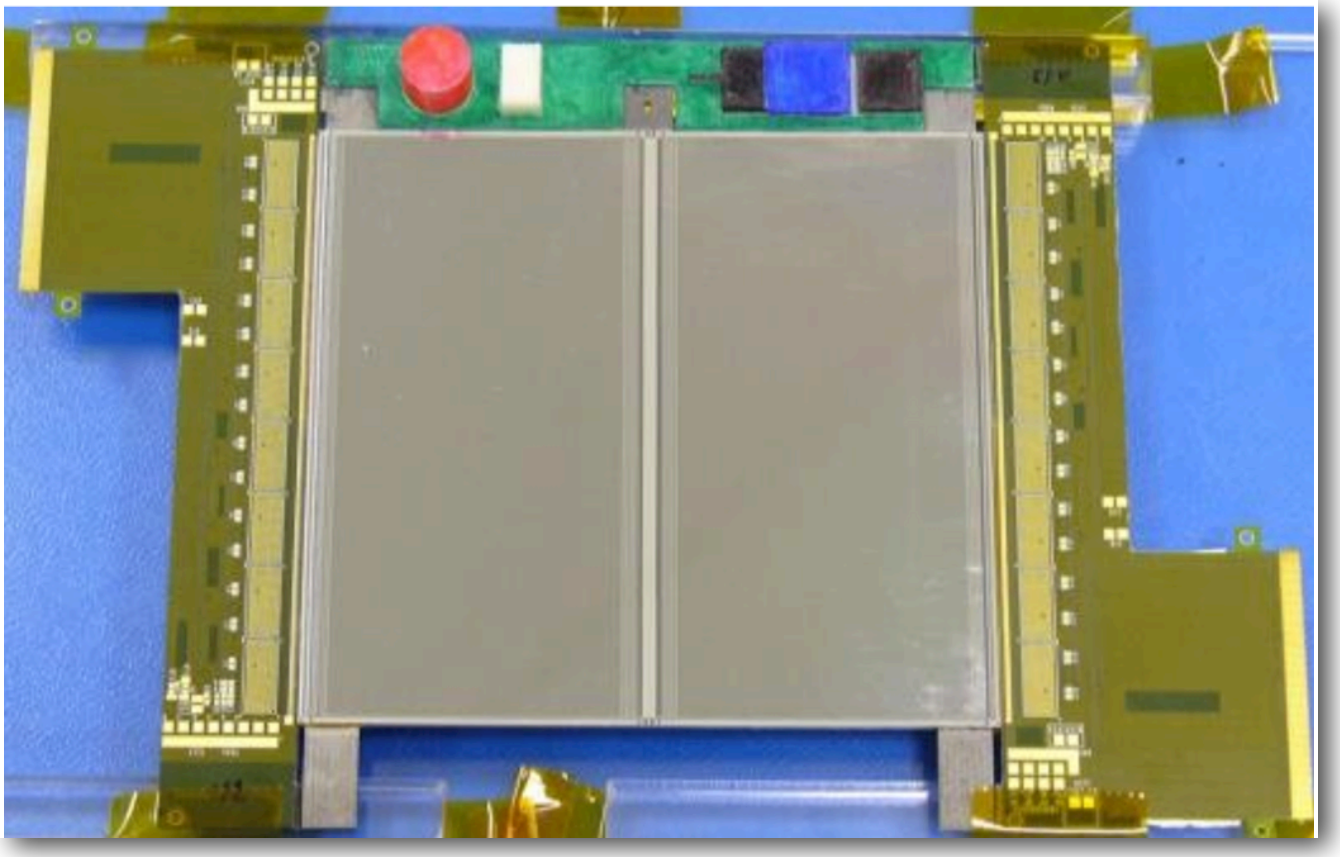


Space frame

- Investigating various structures for optimal module placement
- Long structures with either purely straight or inclined sections to build the barrel

CMS PROTOTYPE 2S MODULE

- Dummy module built for assembly studies
  - Prototype readout hybrids with 8xCBC2 Inactive dummy sensors
  - 3d-printed service hybrid dummy

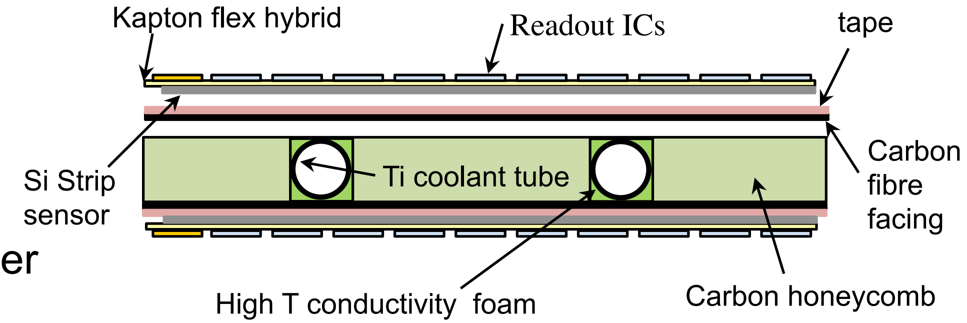


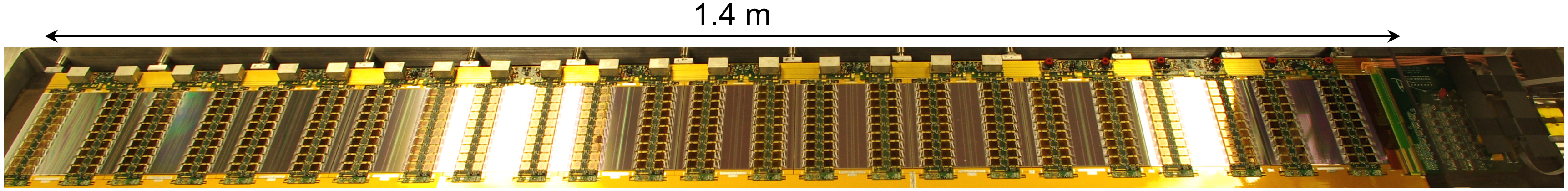
ATLAS Silicon Strip Tracker

- Outer tracker is a silicon strip detector with n-in-p sensors
  - LOI layout: 5 barrel layers, 7 discs EC, “stubs”
- Double-sided layers with axial strip orientation and rotated by 40mrad on other side (z-coordinate)
  - Short (23.8 mm) and long strips (47.8 mm) with 74.5 μm pitch in barrel
  - End-Cap with radial strips of different pitch (6 different module designs)

- Silicon Modules directly bonded to a cooled carbon fibre plate.
- A sandwich construction for high structural rigidity with low mass.
- Services integrated into plate including power control and data transmission.
- R&D already in full swing

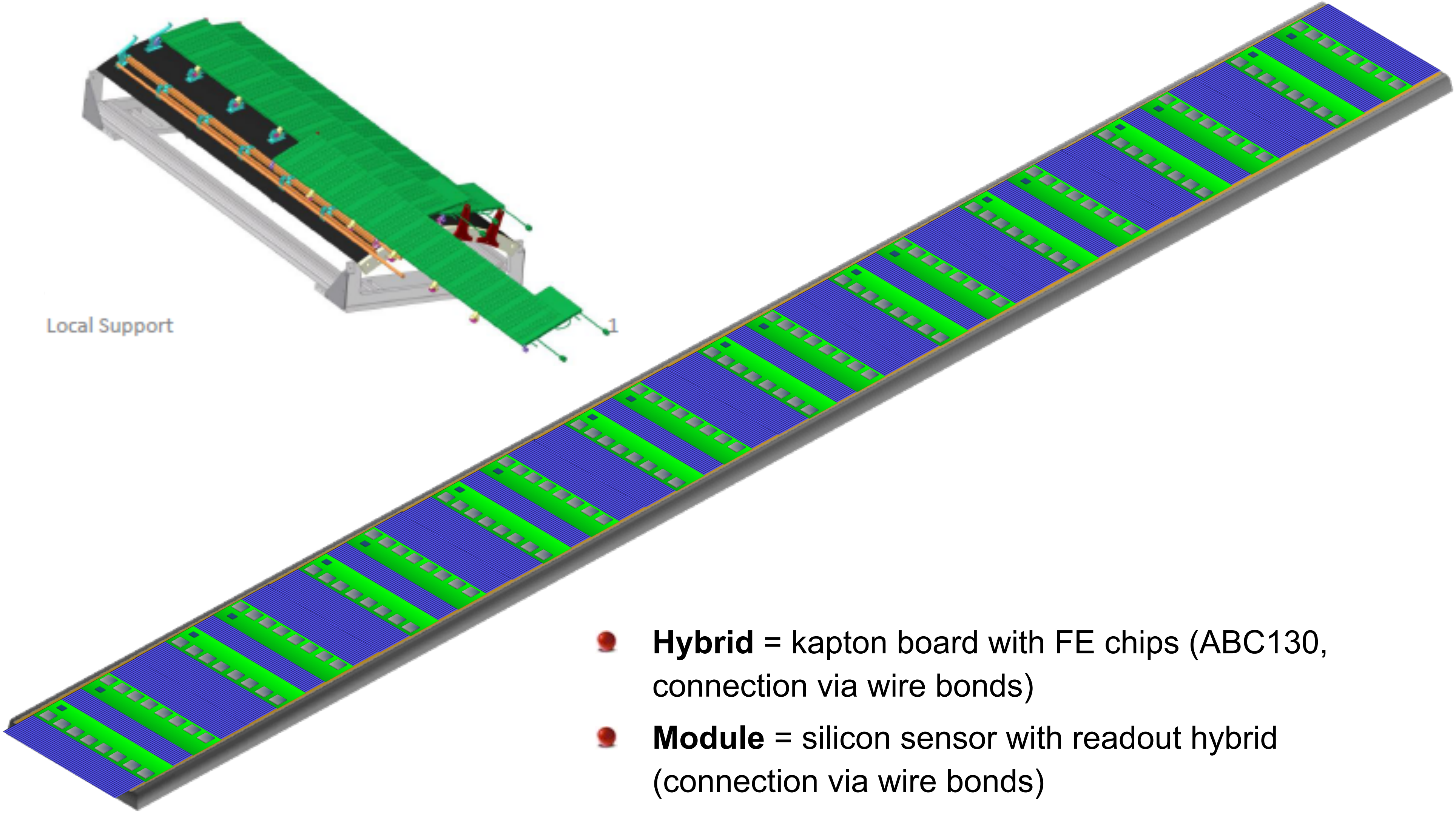
Stave cross-section:





ATLAS Prototype for barrel strip stave

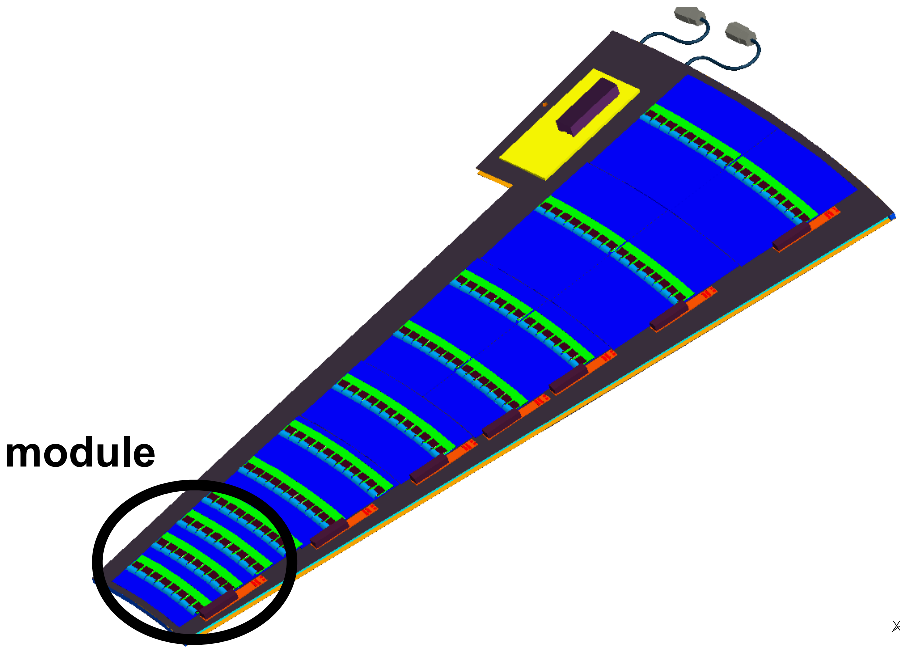
ATLAS STRIPS: STAVE/PETAL CONCEPT



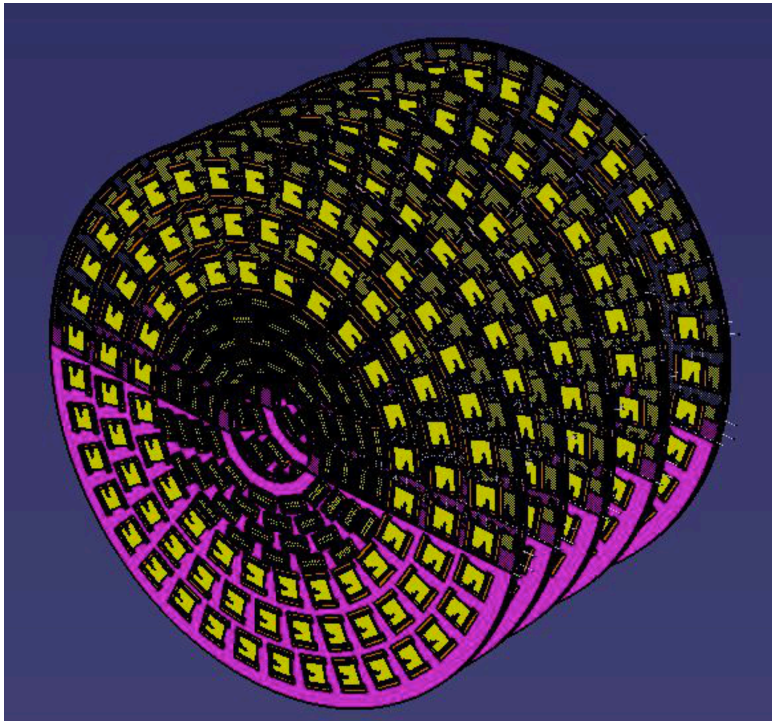
- **Hybrid** = kapton board with FE chips (ABC130, connection via wire bonds)
- **Module** = silicon sensor with readout hybrid (connection via wire bonds)
- **Stave/petal** = core structure + cooling + electrical services (power, data, TTC) + modules

END-CAPS - COMPLICATED GEOMETRY

ATLAS

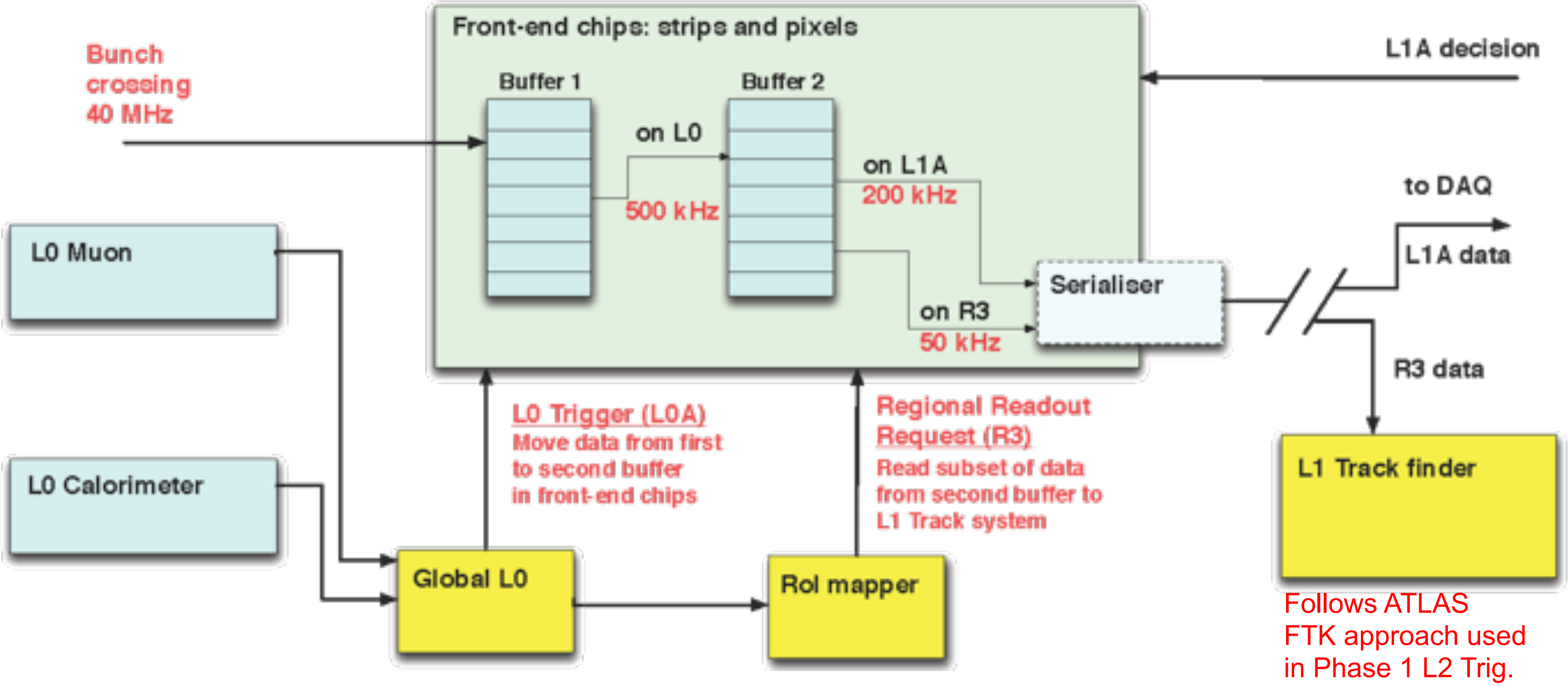


CMS



- End-caps are a problem due to their geometrical constraints
  - **ATLAS**: following stave concept -> build disks out of wedge shaped petals covered by six different sensor shapes
  - **CMS:** same rectangular module type as barrel strip detector
- Both designs have their advantages and disadvantages: material budget and production steps

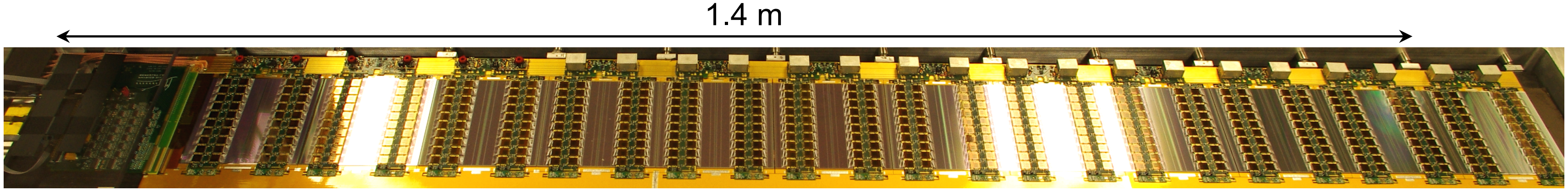
ATLAS Double Buffer Trigger

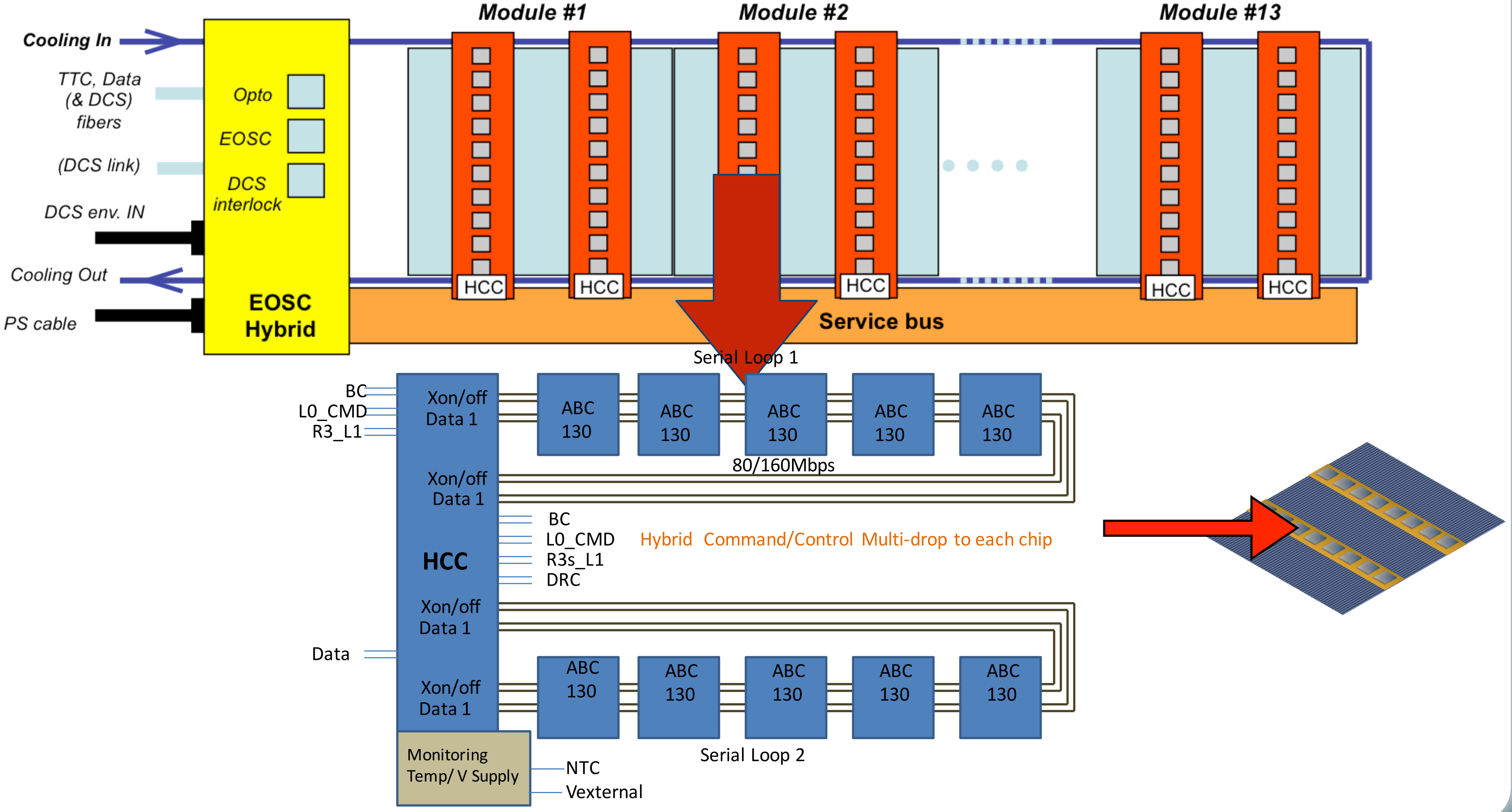


Follows ATLAS FTK approach used in Phase 1 L2 Trig.

- Level 0 trigger accept rate (1 MHz)
- On an L0 accept, copy data from primary to secondary buffer
- Identify "Regions" in detector (1-10% of the detector on each L0 accept) like L1 RoI
- Generate "Regional Readout Request" (R3) - modules in "Region" read out subset of their data
- On an L1 accept (≥ 200 kHz), all modules read out event from Secondary buffer
- Since only ~10% of the detector (the "Regions") will be read out on the Level 0 accept,
- R3 request rate for any specific part of the detector will be ≥ 50 kHz

ATLAS: ON-STAVE DATA FLOW





Module #1

Module #2

Module #13

Cooling In

TTC, Data
(& DCS)
fibers

(DCS link)

DCS env. IN

Cooling Out

PS cable

Opto

EOSC

DCS
interlock

EOSC Hybrid

HCC

Service bus

Serial Loop 1

BC
L0_CMD
R3_L1

Xon/off
Data 1

ABC 130

80/160Mbps

BC
L0_CMD
R3s_L1
DRC

Hybrid Command/Control Multi-drop to each chip

HCC

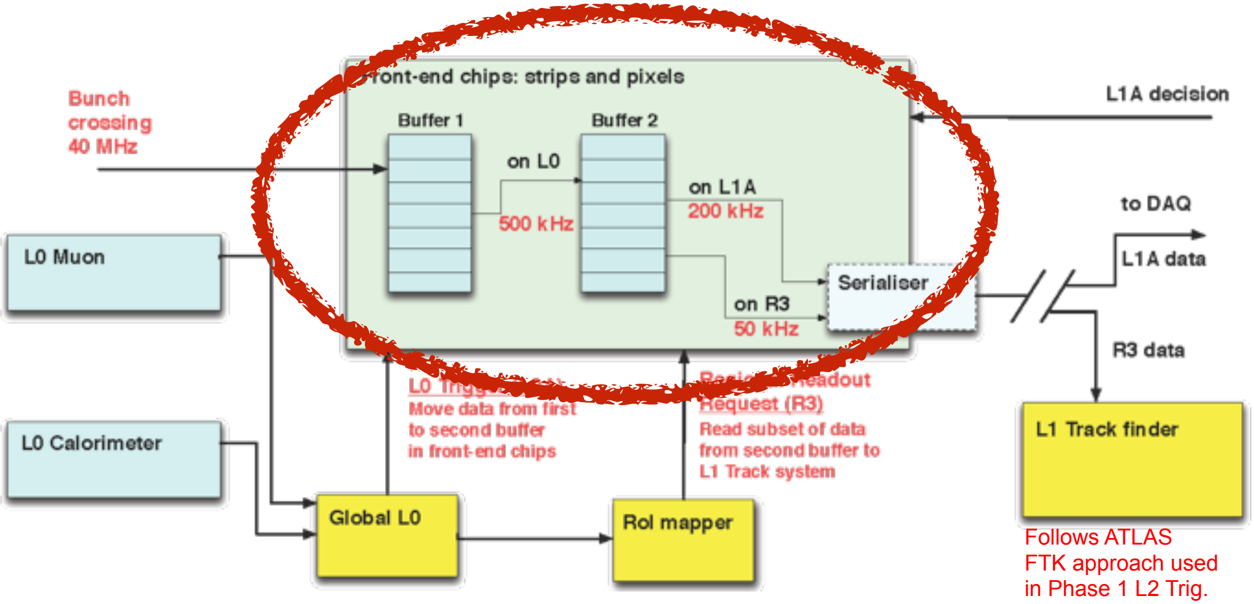
Data

Serial Loop 2

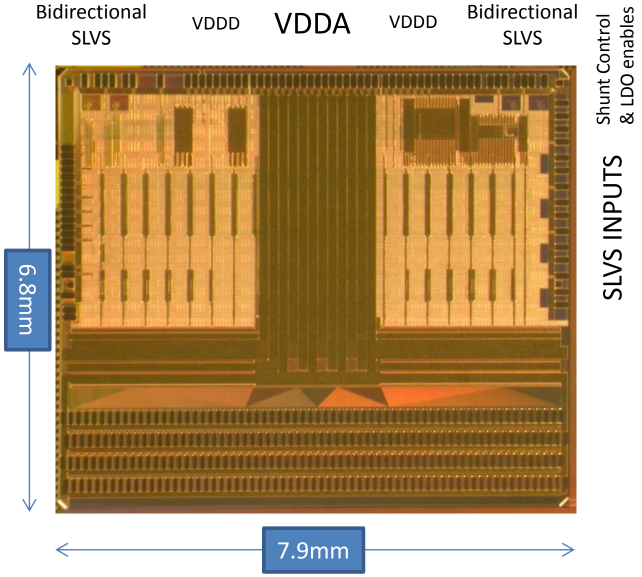
Monitoring
Temp/ V Supply

NTC
Vexternal

THE FRONT - END CHIP ABC130



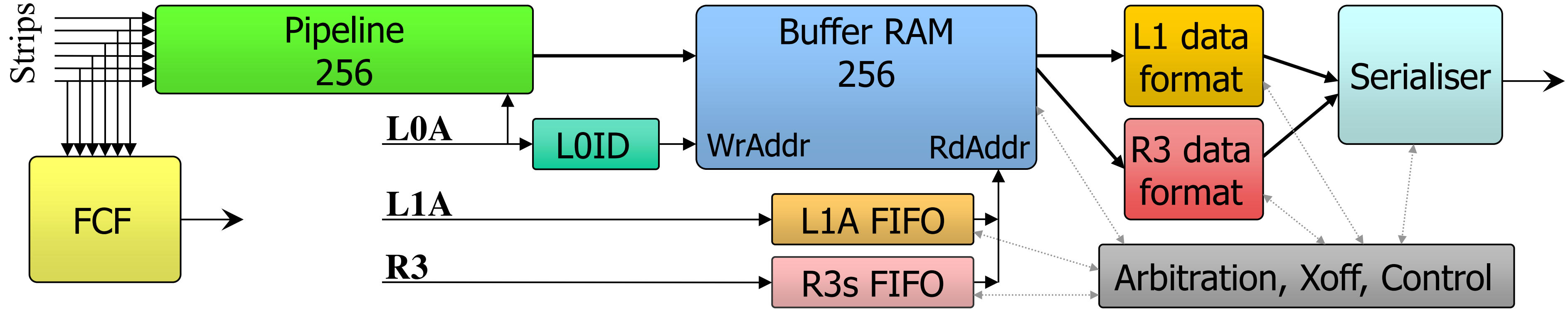
Follows ATLAS
FTK approach used
in Phase 1 L2 Trig.



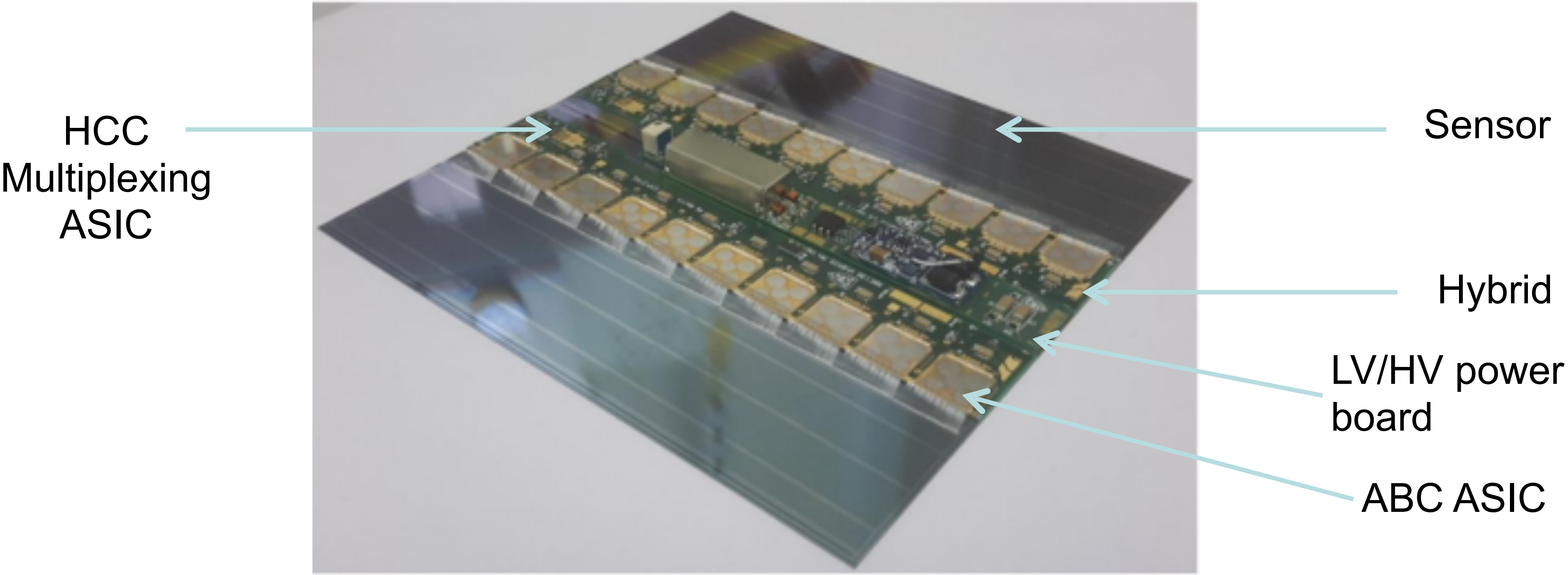
- ABC= ATLAS Binary Chip
- 256 channel chip processed in 130nm technology
- FE geometry suits direct sensor bonding
- Some key features
  - Fixed length data packets
  - Programmable LDOs for Analogue/Digital power
  - Shunt to support Serial Powering

ABC130 Track Trigger Architecture

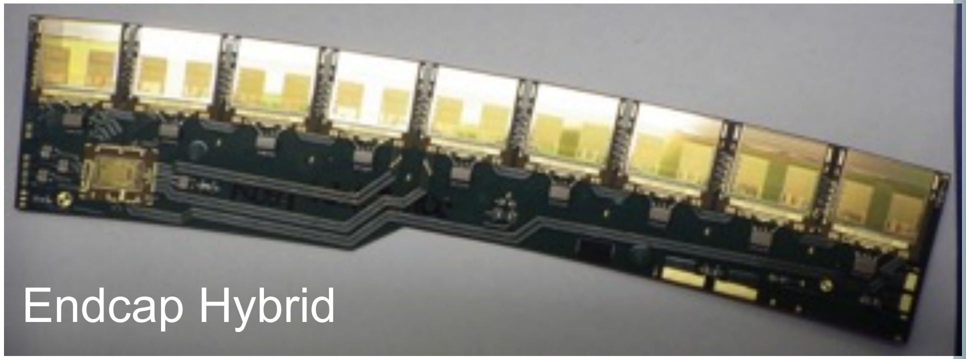
- **Additional track-trigger function**
  - Regional Readout (R3)
    - A special trigger sent only to modules inside a Region of Interest
    - L0-trigger identified regions of interest
  - L0A copies data from pipeline to RAM – L0ID counter used as address
    - L1A and R3 requests have independent FIFOs
      – Stores L0IDs - locates event in buffer
      – Arbiter ensures ordered data handling - R3 has priority – Effective as a de-randomiser
  - Data is formatted by dedicated blocks and serialised to HCC



ATLAS Strip Module Components



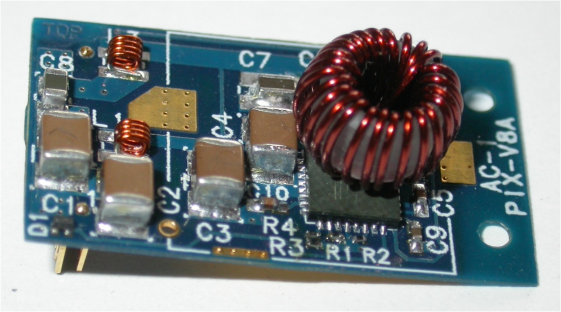
- Short Strip Barrel Module: Composed of 2 Hybrids, 1 sensor, and 1 power board
- Each Hybrid:
  - 10 x ABC130 readout chips
  - 1 x HCC multiplexing chip
- R&D programme in full swing - produced already a few fully equipped staves



COMMON: POWER AND COOLING

Novel Powering Concepts

- More power dissipation is expected (more channels)
- Cabling cannot be changed and overall material needs to be reduced
- Two options have been invested in the last years: DC-DC and serial powering
- CMS: decided on DC-DC powering (pixels and strips)
- ATLAS:
  - strips: DC-DC is baseline
  - pixels: serial powering is baseline

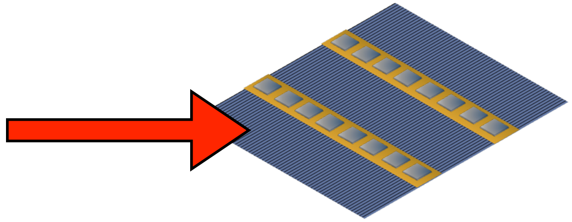


CO_2 Cooling

- Evaporative system + excellent thermodynamic properties of CO_2 can provide low-mass, high-efficiency cooling
- Foreseen for Phase-0/ Phase-I upgrade projects
- The technology in principle allows scaling to full tracker

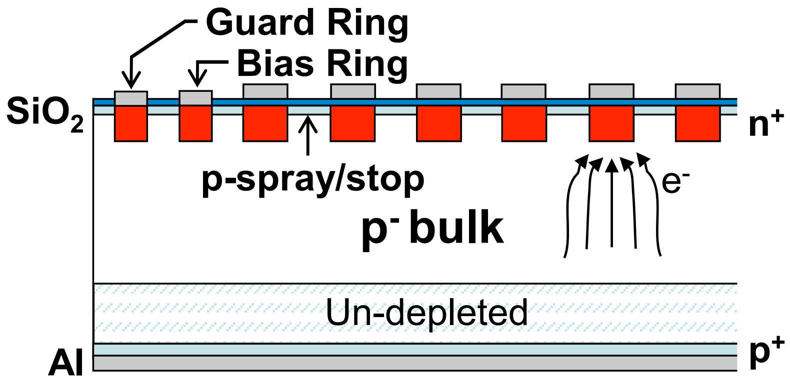
picture: CERN

BASELINE SENSORS



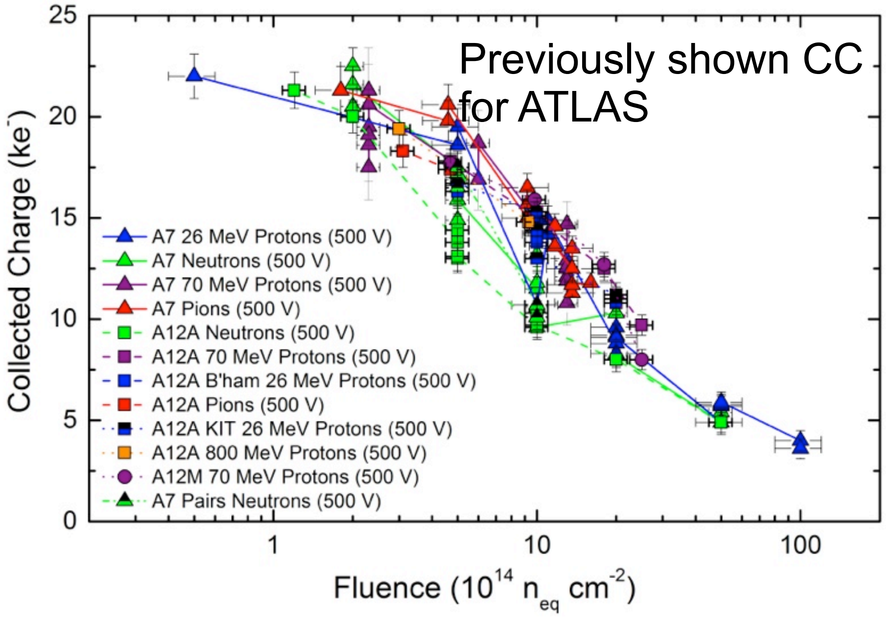
- Sensor parameters basically defined for ATLAS and CMS: **n-in-p with p-stop isolation**
  - Collects electrons like current n-in-n pixels -> faster signal, reduced charge trapping
  - Always depletes from the segmented side: good signal even under-depleted

See talks from:
Thomas Bergauer
Bart Hommels
Kazuhiko Hara
Marcela Mikestikova
Riccardo Mori



- ATLAS: investigating the option to replace classic planar sensor by a CMOS solution

See talk from:
Vitaliy Fadeyev


Previously shown CC for ATLAS

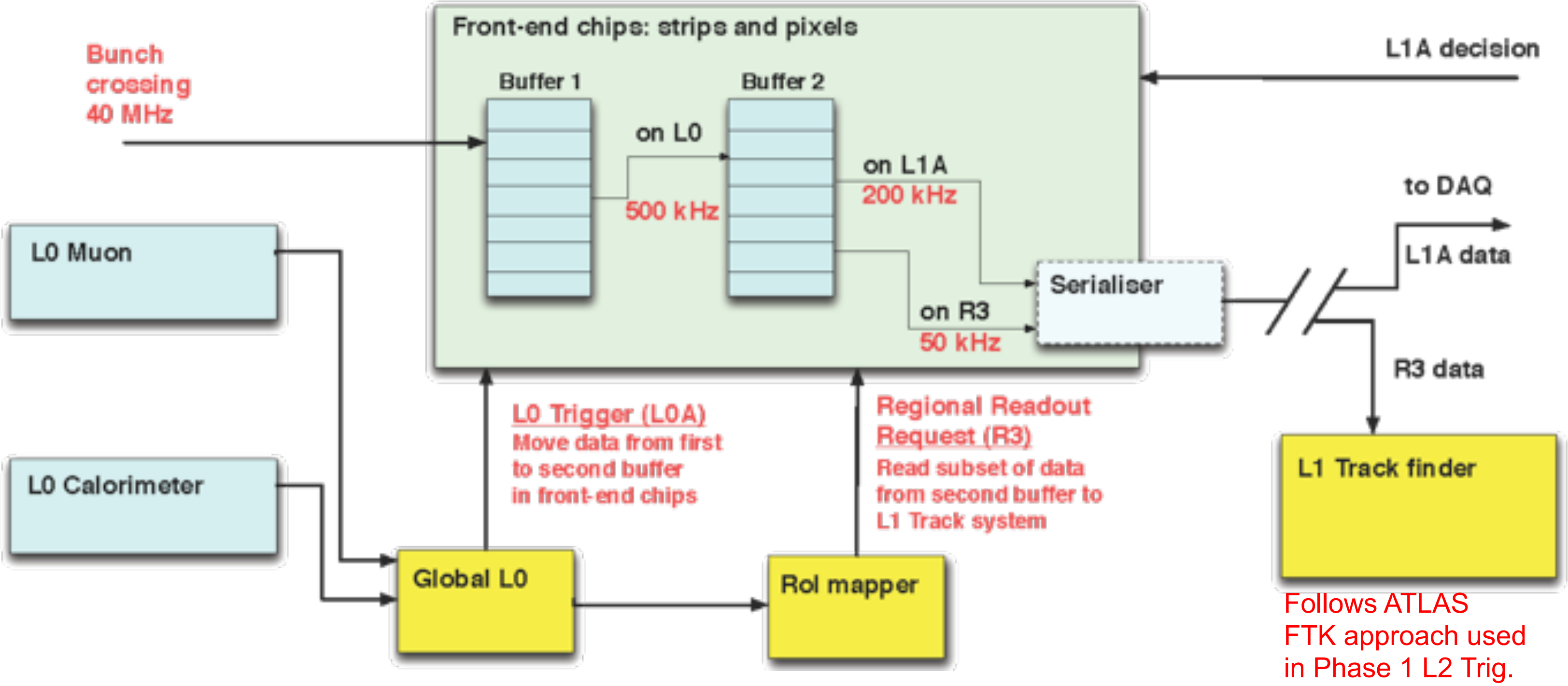
CONCLUSIONS

- Strip detectors are a important tracking detector used in many high-energy physics detectors
- LHC upgrades also includes strip systems for LHCb, ATLAS and CMS
- Commonalities in many areas: choice of sensor technology, concept of readout …
- Specifications by experiment pushes differences in details

System	ATLAS	CMS
Trigger	Track Trigger with ROI	Self seeded with pt modules
Strip Layout	Barrel + End-cap	Barrel + End-cap
Silicon Strip	n-in-p FZ	n-in-p MCz (or FZ)
Barrel Strip	stave concept	pt modules
End Cap Strip	petal concept: many different module types	square module type as in barrel
Read out	binary (ABC)	binary (CBC)

BACKUP SLIDES

ATLAS Double Buffer Trigger



Follows ATLAS FTK approach used in Phase 1 L2 Trig.

- Level 0 trigger accept rate ≥ 500 kHz
- On an L0 accept, copy data from primary to secondary buffer
- Identify "Regions" in detector (1-10% of the detector on each L0 accept) like L1 RoI
- Generate "Regional Readout Request" (R3) - modules in "Region" read out subset of their data
- On an L1 accept (≥ 200 kHz), all modules read out event from Secondary buffer
- Since only ~10% of the detector (the "Regions") will be read out on the Level 0 accept,
- R3 request rate for any specific part of the detector will be ≥ 50 kHz