University of BRISTOL

LHC UPGRADES

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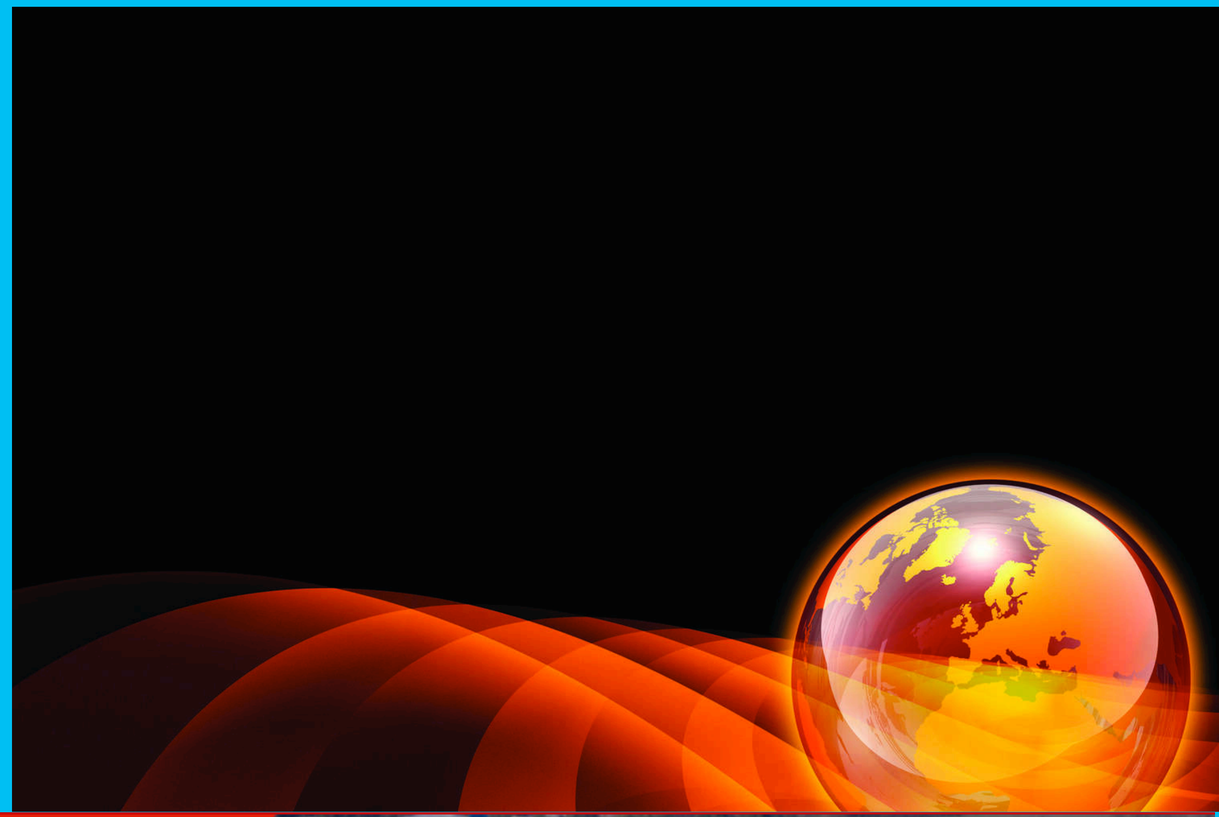
IOP APP/HEPP 2022
Rutherford Appleton Laboratory, UK

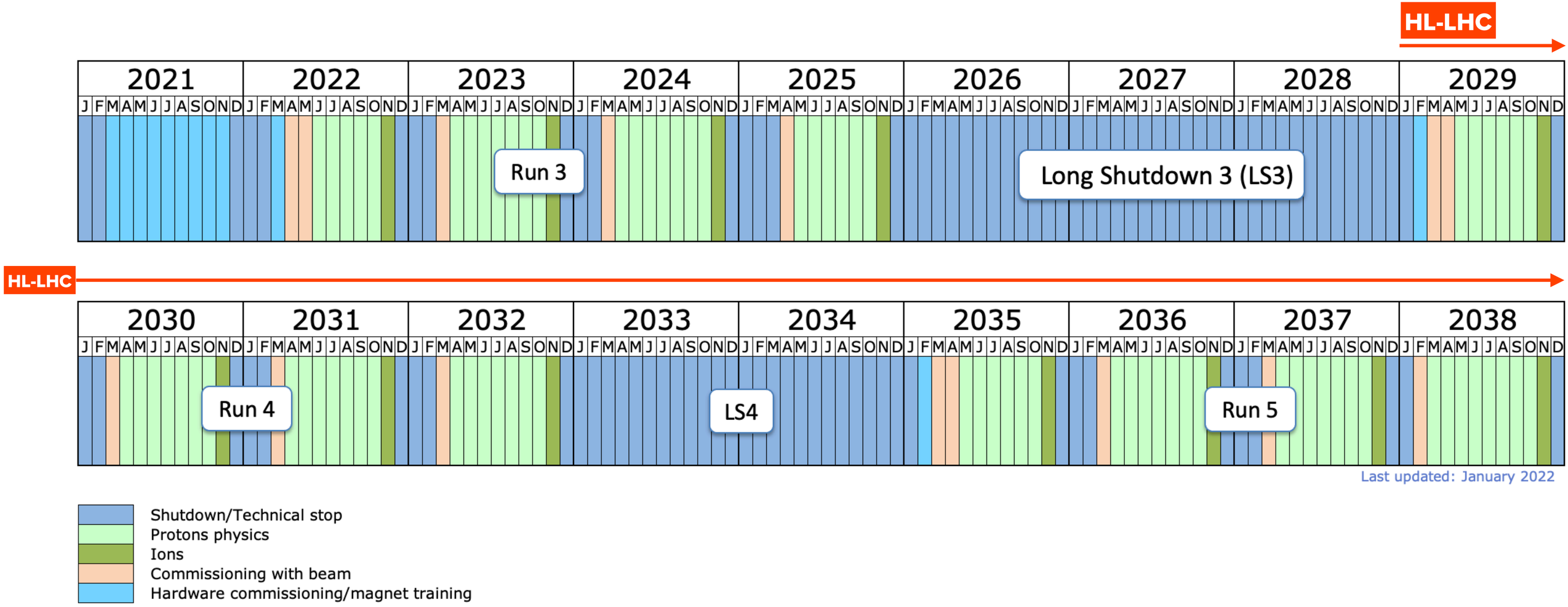


IOP Institute of Physics

HEPP & APP Annual Conference 2022

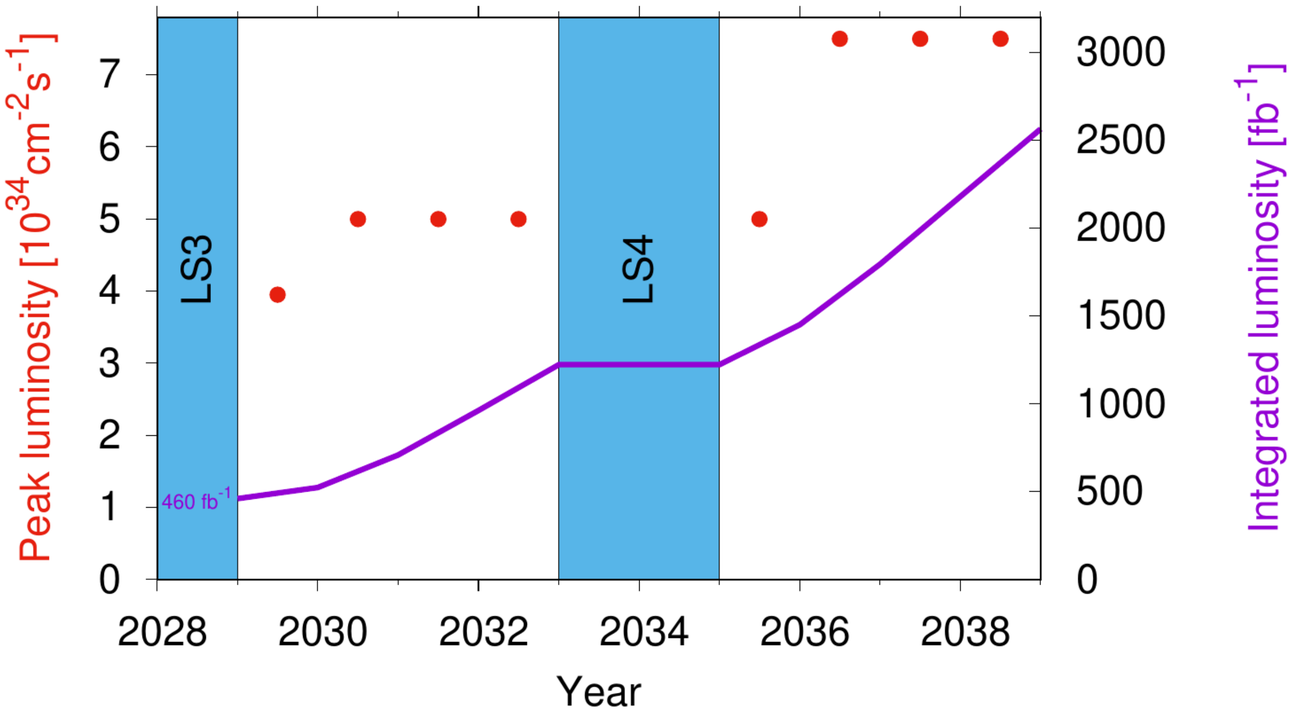
3-6 April 2022, Rutherford Appleton Laboratory STFC, Oxfordshire, UK

INTRODUCTION - SCHEDULE



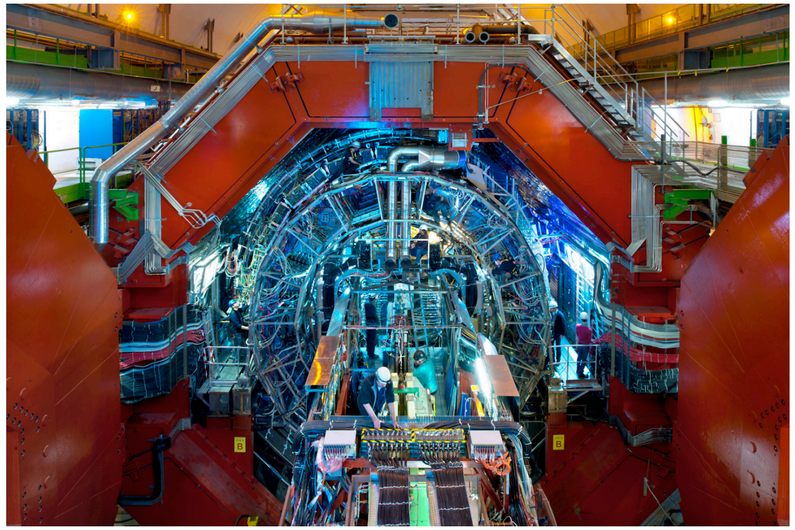
HL-LHC

- Upgrade the LHC to provide increased luminosity to the detectors
- Many key measurements will benefit from increased statistical precision
- Simultaneous pp collisions (aka pile-up) represents a big challenge to detectors
- Note the “virtual luminosity” provided by LHC is expected to be higher than 5e34, so luminosity levelling will be used to limit the Pile-up in the experiments.

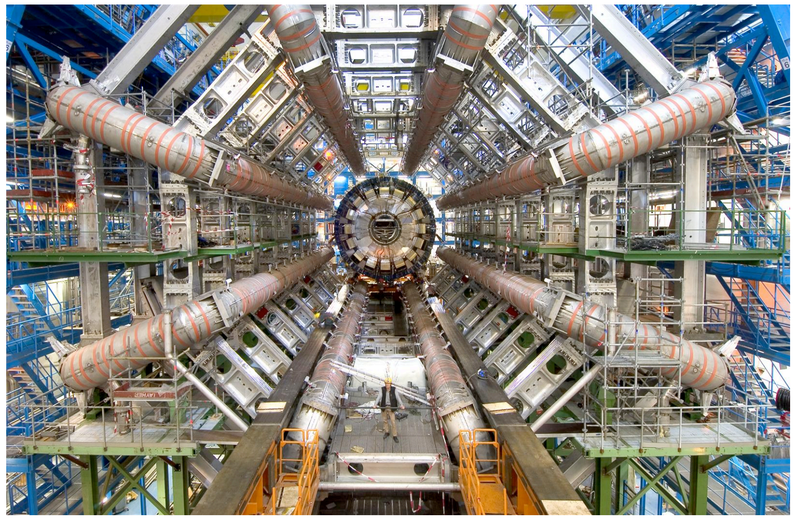


LHC EXPERIMENTS

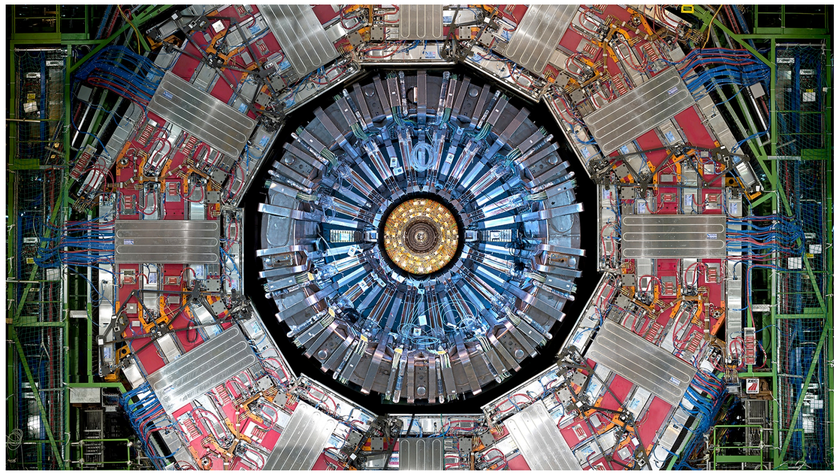
ALICE



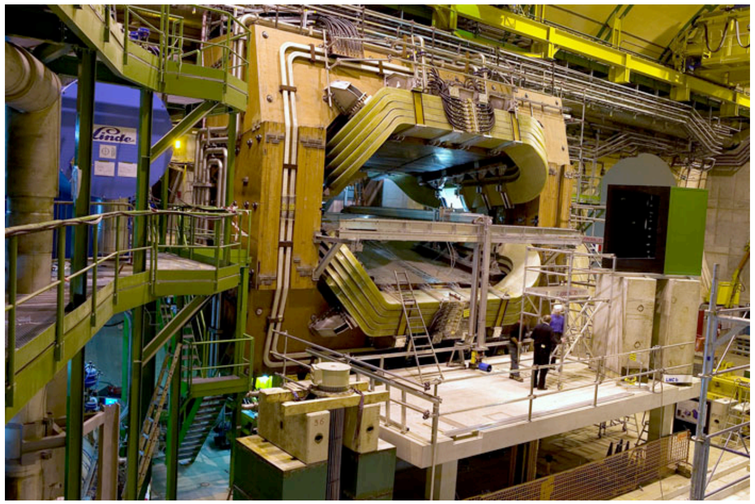
ATLAS



CMS



LHCb

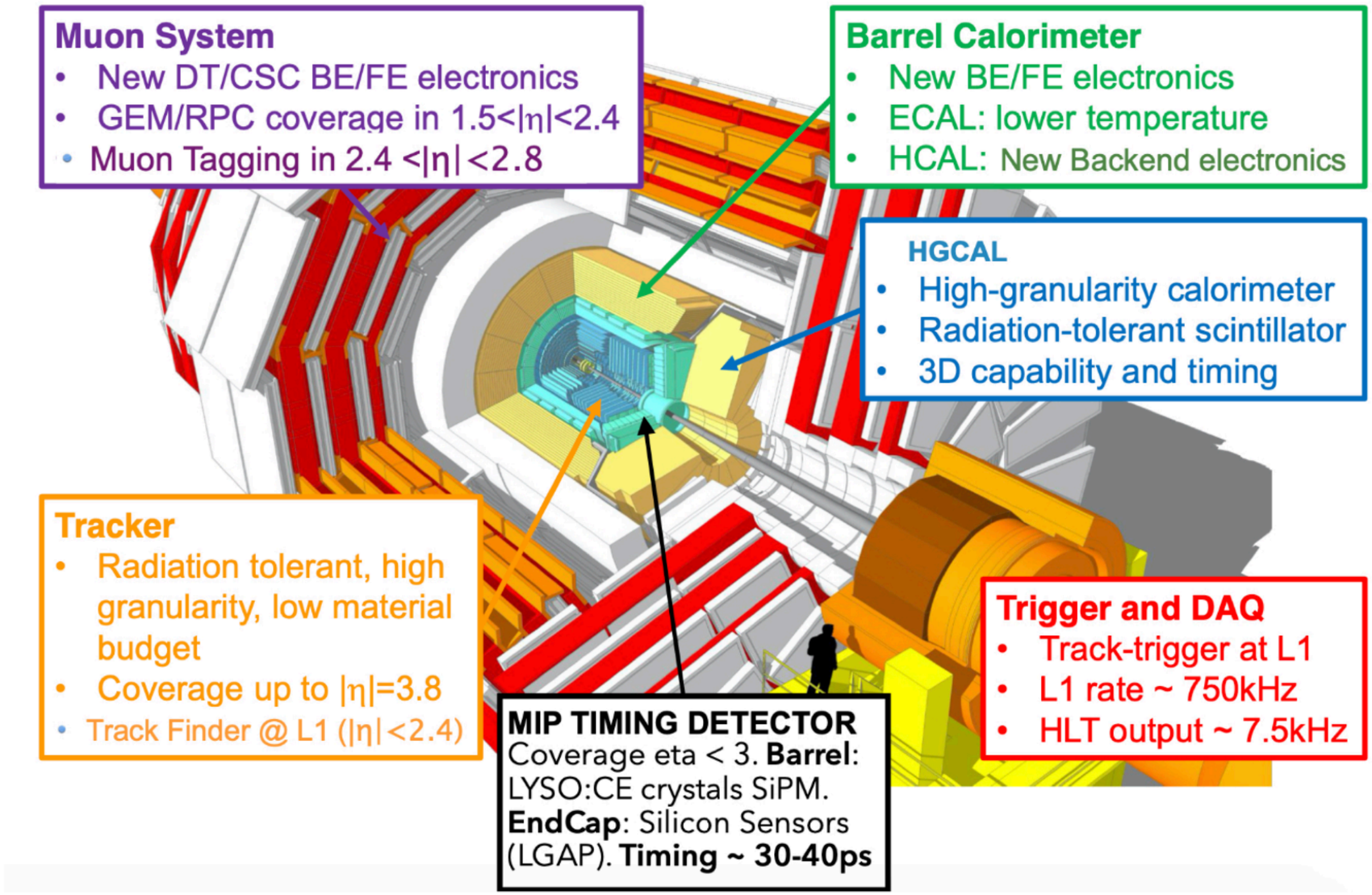


CMS Upgrades

Phase 1 completing now (though majority in LS1)

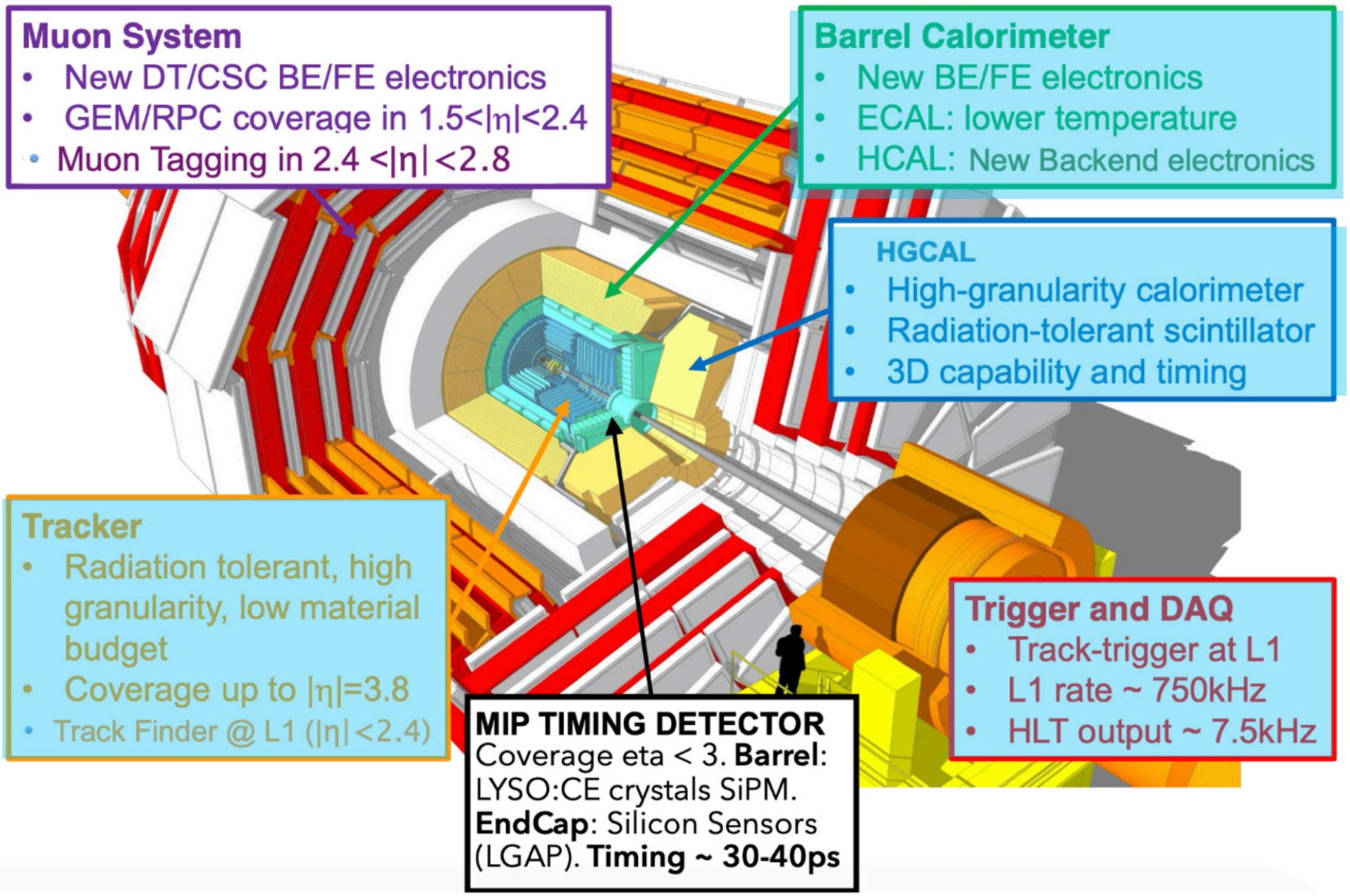
Phase 2 for HL-LHC in 2029 - install in LS3

CMS HL-LHC UPGRADE (PHASE 2)



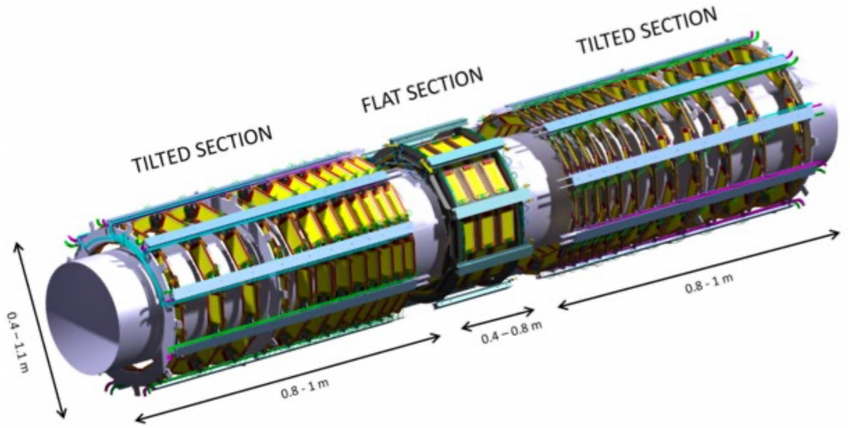
CMS HL-LHC UPGRADE (PHASE 2)

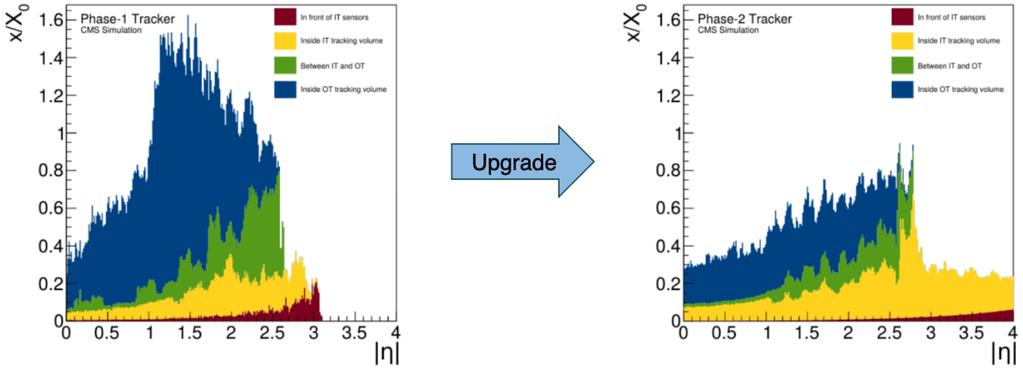
UK INVOLVEMENT

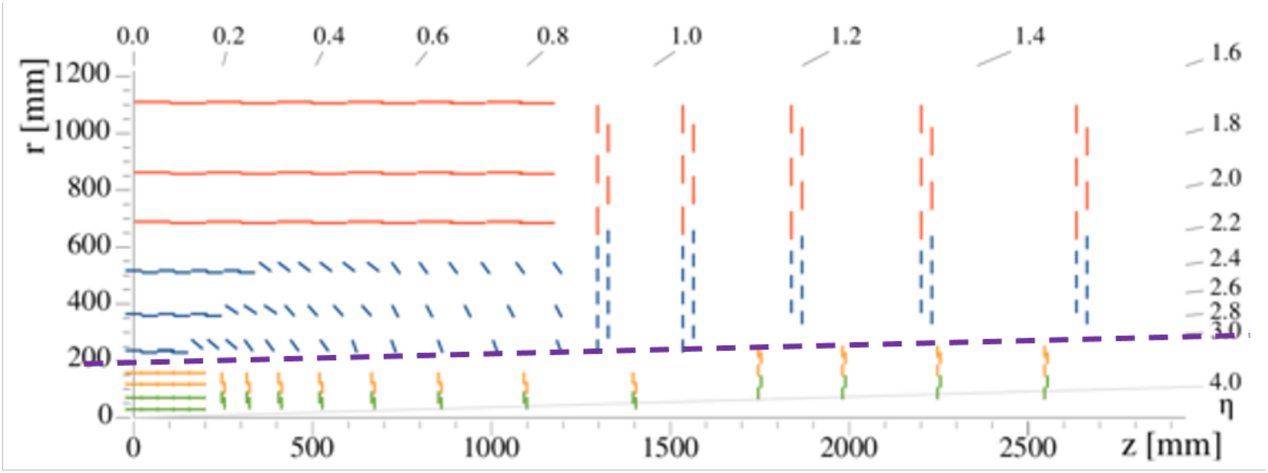


CMS HL-LHC UPGRADE - TRACKER

- Increased granularity
- Lower material budget
- Extended coverage
- Tracks being included in L1 for first time



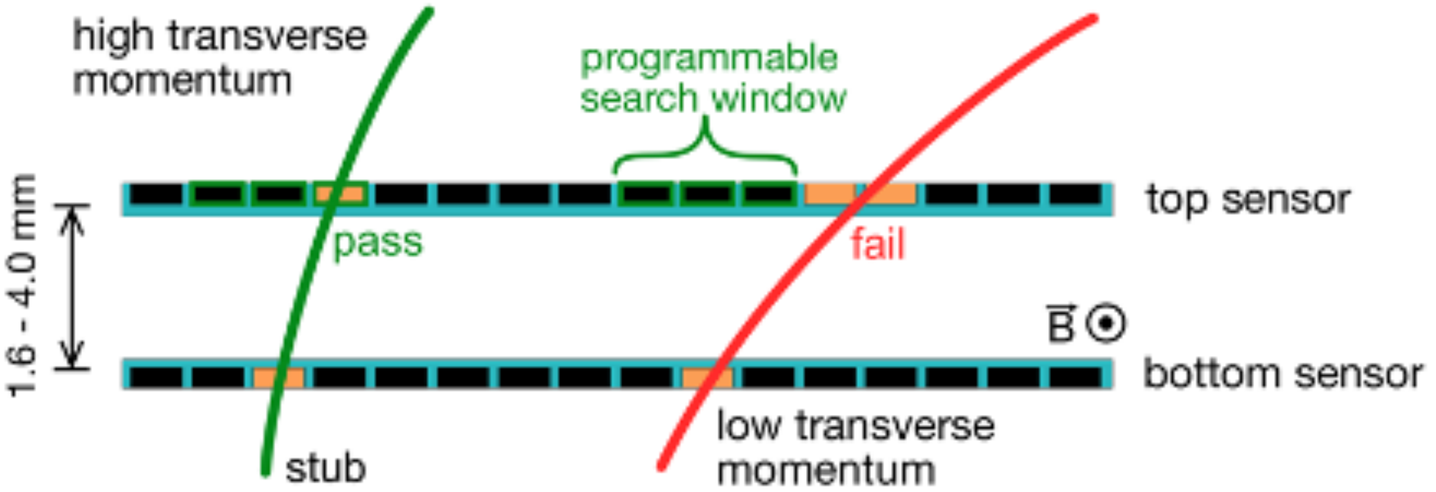




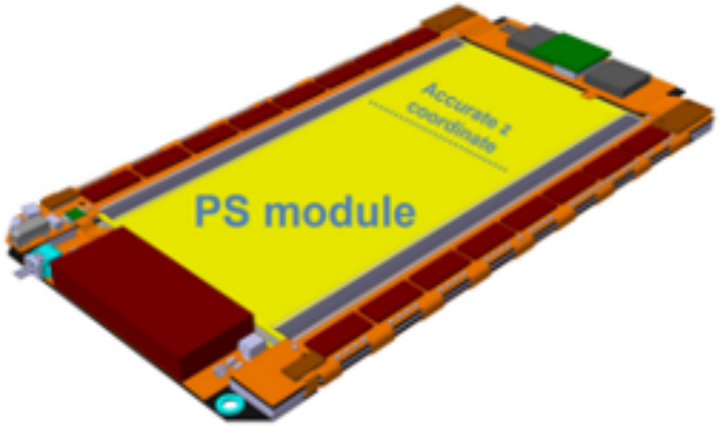
- Outer Tracker:
  - 200m2 of silicon
  - 9.5 million channels
  - Light-weight mechanics and modules

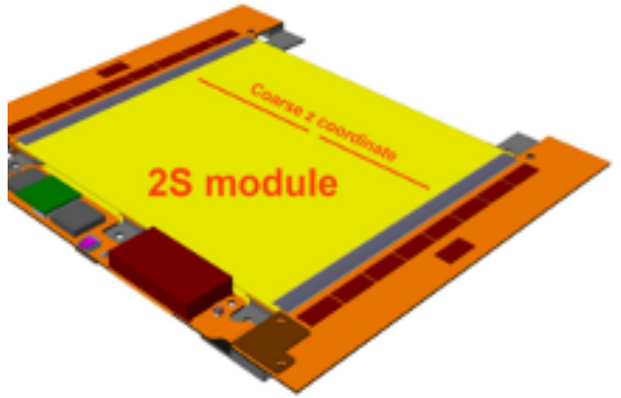
CMS HL-LHC UPGRADE - TRACK-TRIGGERING

- Local rejection of low-pT tracks
- Exploit bending in CMS 4Tesla magnetic field
- Correlate hits from 2 closely spaced sensors to form stubs with track pT > 2 GeV



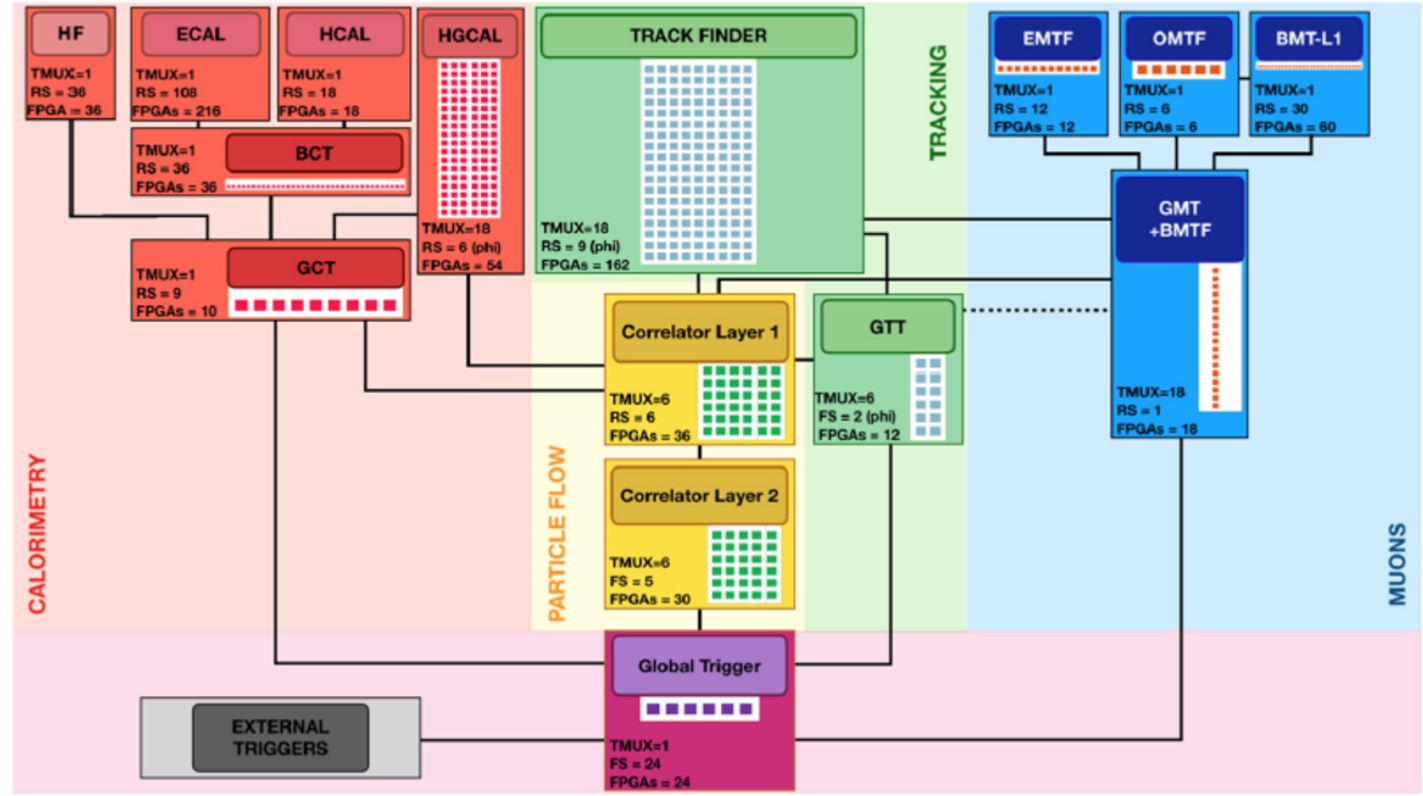
- Strong UK involvement
  - development of concept of pT module including design and production of the ASIC to be used in the 2S module (CBC-130nm ASIC)





CMS HL-LHC UPGRADE - L1 TRIGGER

- Calorimeter, Muon, and Tracking info come in to the L1 at 40 MHz.
- The information is combined in the Correlator Trigger, but also maintain independent stand alone triggers.
- Latency increased from 3.8 to 12.5us and rate from 100kHz to 750 kHz.
- Time-multiplexed (developed by UK for Phase 1, now implemented across whole trigger for Phase 2)
- Test-stands now built and operational - firmware testing in progress

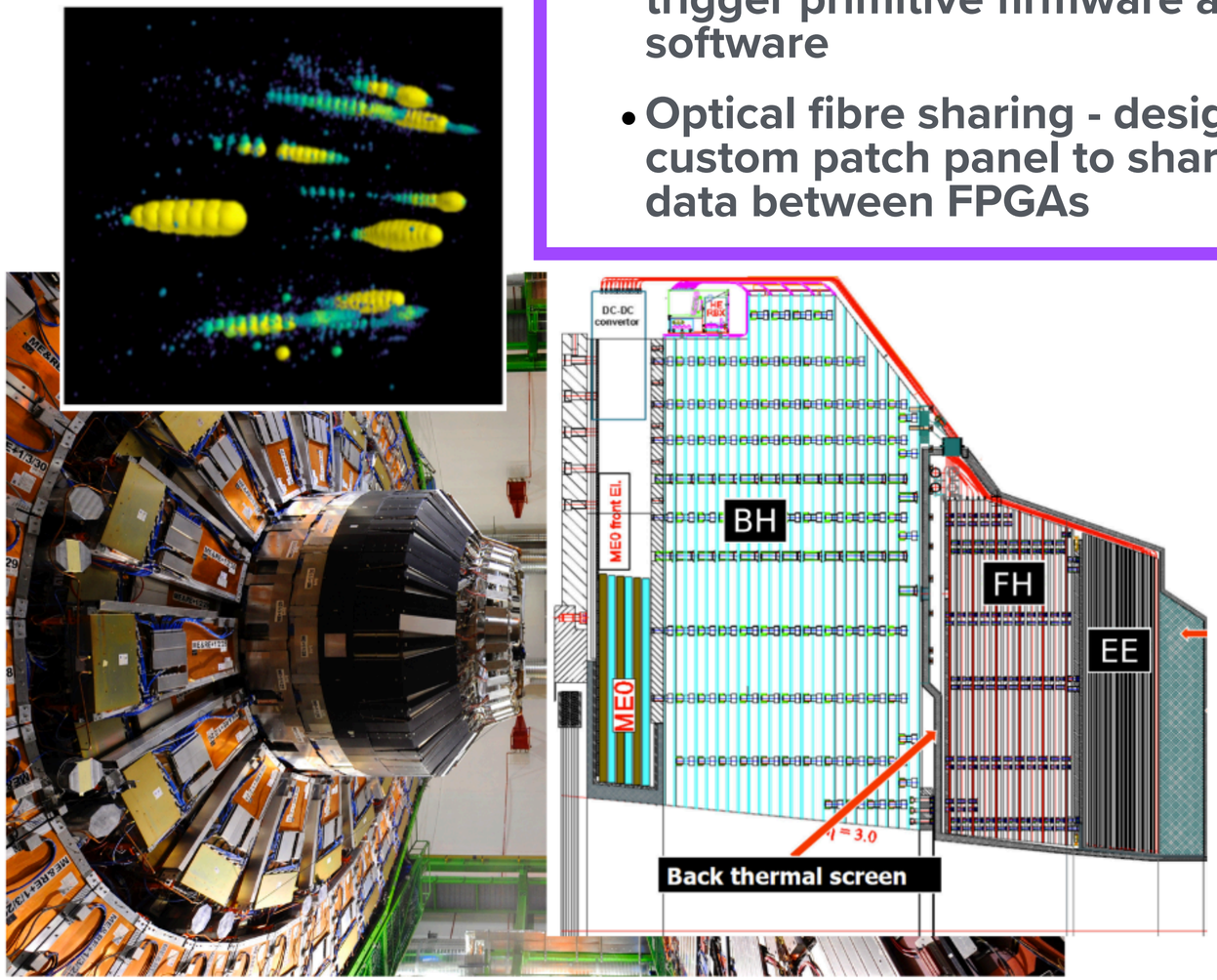


CMS HL-LHC UPGRADE - CALORIMETRY

- High Granularity Calorimeter with 4D reconstruction of shower development
- Sampling calorimeter with silicon sensors optimised for high PU environment
- Idea developed in UK, and now have leadership in electronics, TP firmware, and simulation.

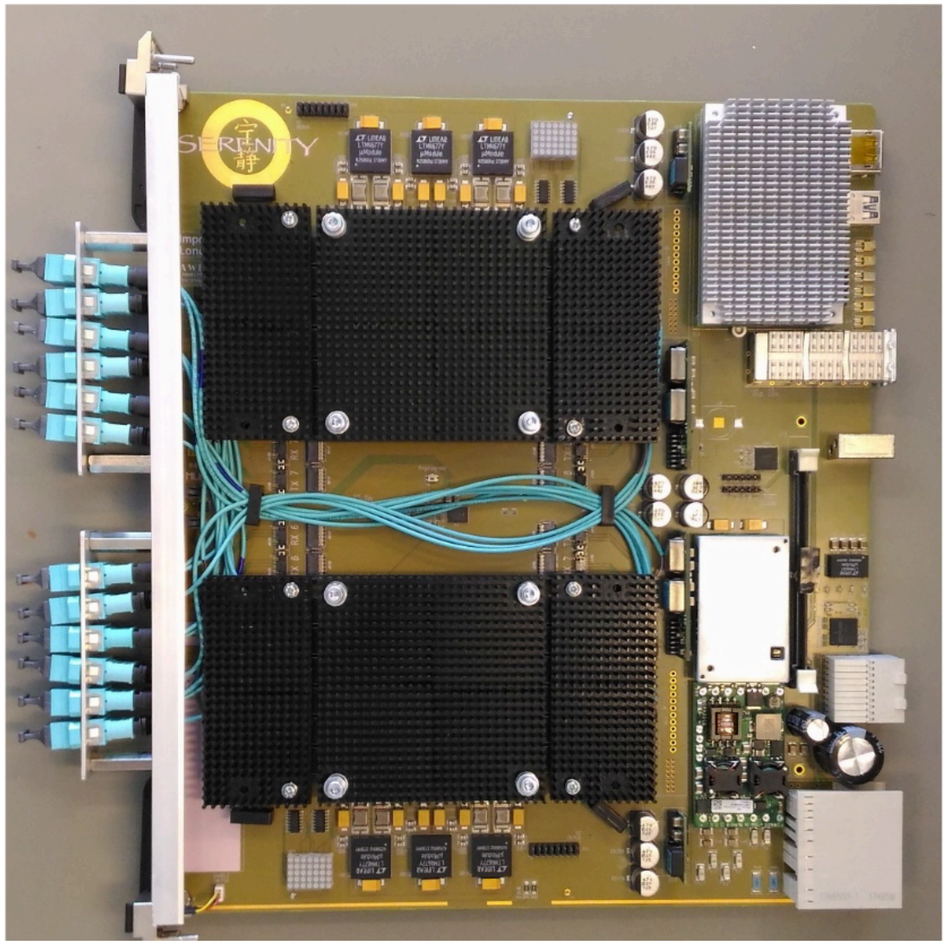
- Silicon sensors on track to complete version 2 validation and make production order in Sept.
- Trigger firmware making good progress, first integration tests with L1 to start this month
- ASICS: Front-end ASIC testing well advanced
  - Concentrator ASIC of Trigger - prototype received - looks good.

- ECAL Barrel upgrade UK involvement:
  - UK involved in developing trigger primitive firmware and software
  - Optical fibre sharing - designing custom patch panel to share data between FPGAs



CMS HL-LHC UPGRADE - TECHNOLOGY

- Advanced TCA board developed in UK - Serenity
- Board will be used across CMS for trigger and back-end
- Flexible dual-FPGA card
- Prototype cards currently being used in test systems at CERN
- UK providing firmware, software, integration etc



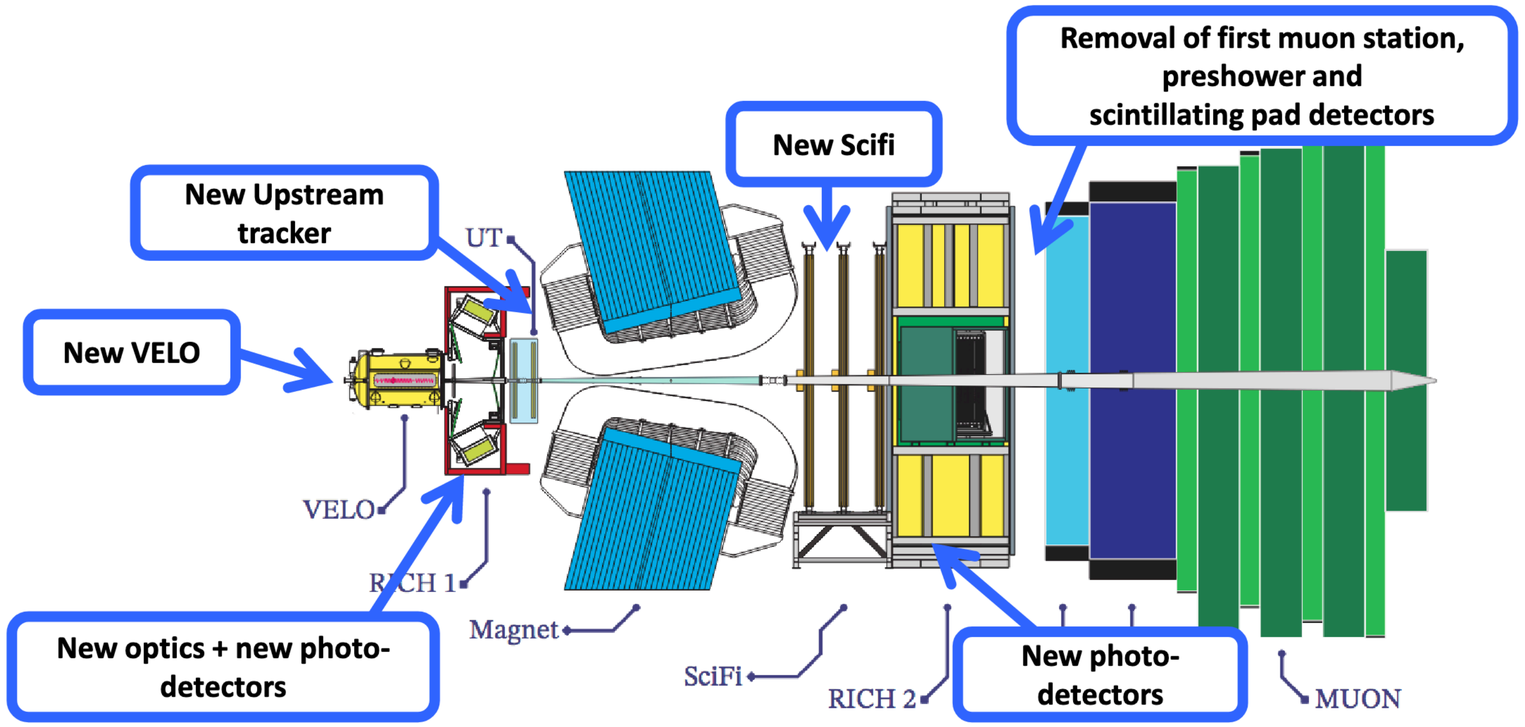
LHC-b Upgrades

Upgrade 1 completing now

Upgrade 2 for Run 5 (2035) - install in LS4

UPGRADE I

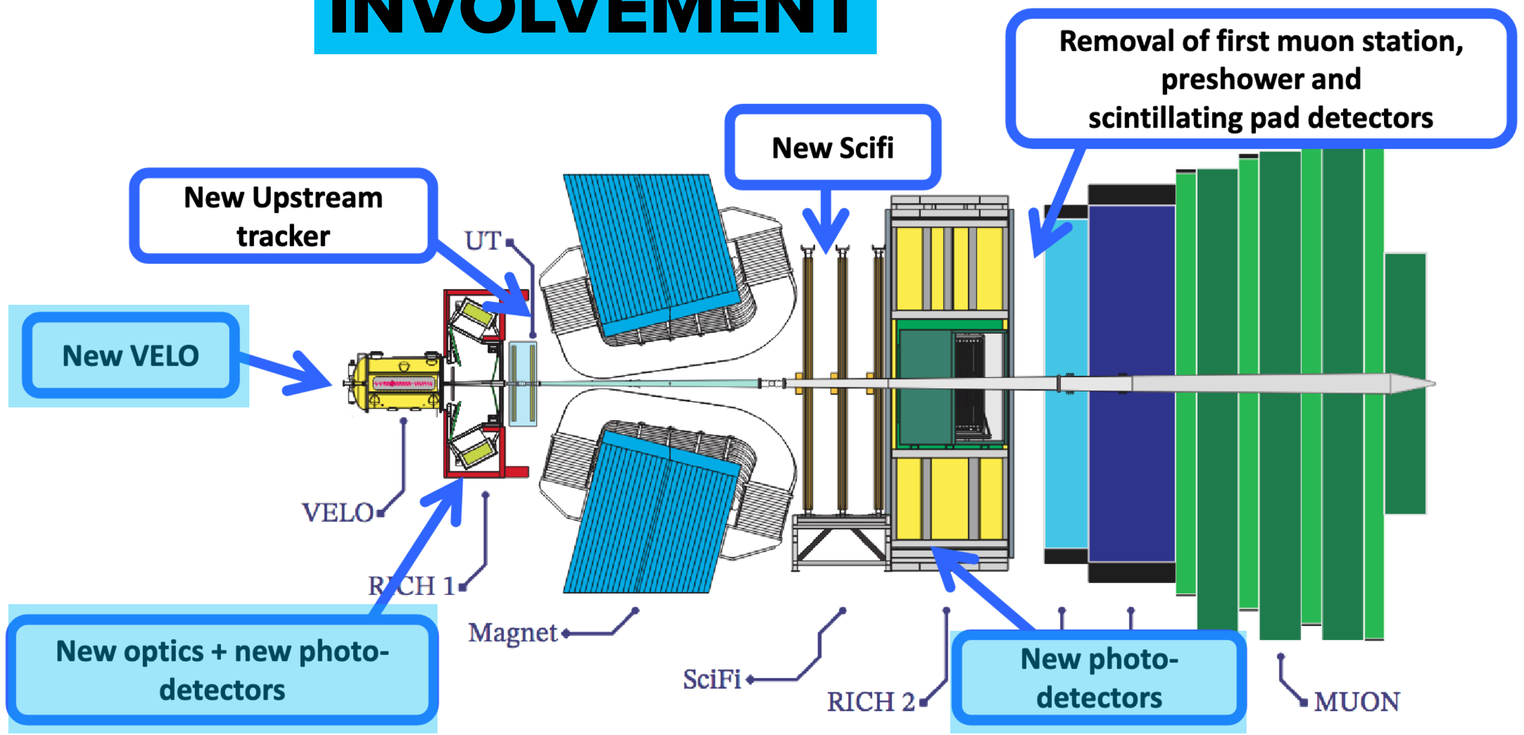
- Completing now in time for Run 3
- Software-only trigger (first of its kind at LHC)
  - 30 MHz readout
- All electronics replaced
- Increasing average pile-up capability from 1.5 to 6



UPGRADE I

- Completing now in time for Run 3
- Software-only trigger (first of its kind at LHC)
  - 40 MHz readout
- All electronics replaced
- Increasing average pile-up capability from 1.5 to 6

UK INVOLVEMENT



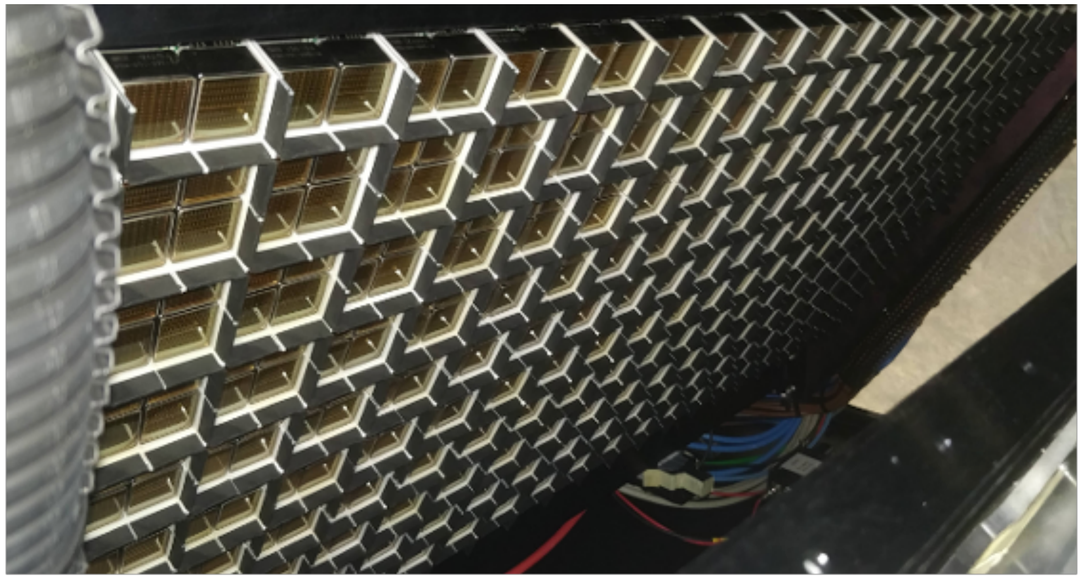
UPGRADE I - VELO

- Vertex Locator
  - Silicon Pixel sensors
  - Increase in channels from 170k to 42m
  - Going even closer to the beam axis - some active pixels 3.5mm from the beam
  - Reduced material budget
  - Improved vertex resolution

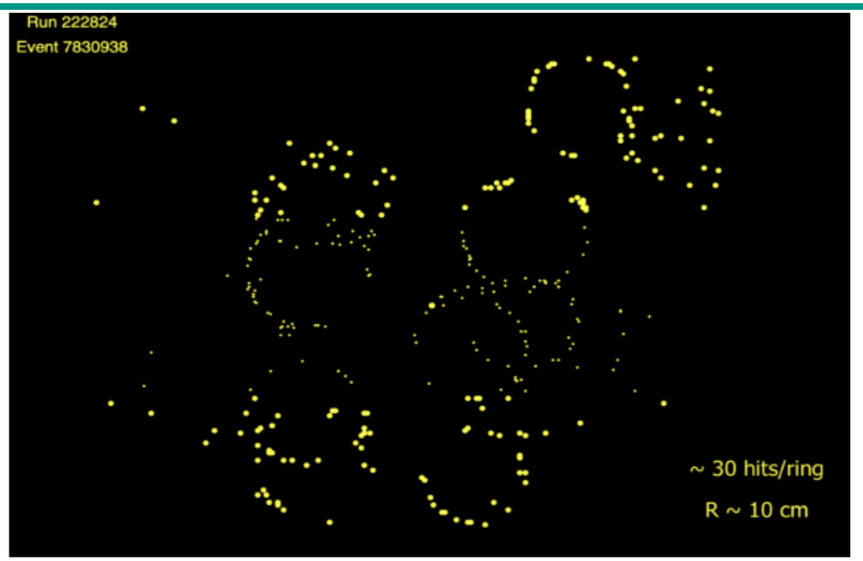
- Installation
  - Side C arrived safely at CERN end of January
  - Detailed inspection, then installation March 1-2
  - Commissioning now underway
  - Side A currently finishing assembly - shipping and installation planned to take place in April - prior to LHC intensity ramp-up

UPGRADE I - RICH

- Ring-Imaging Cerenkov detector
  - Particle ID detector - k/pi/p separation using the phenomenon of particles traversing through media faster than light.
  - RICH1 upstream of the dipole magnet
  - RICH2 downstream of the dipole magnet
  - Excellent k/pi separation up to 100 GeV/c



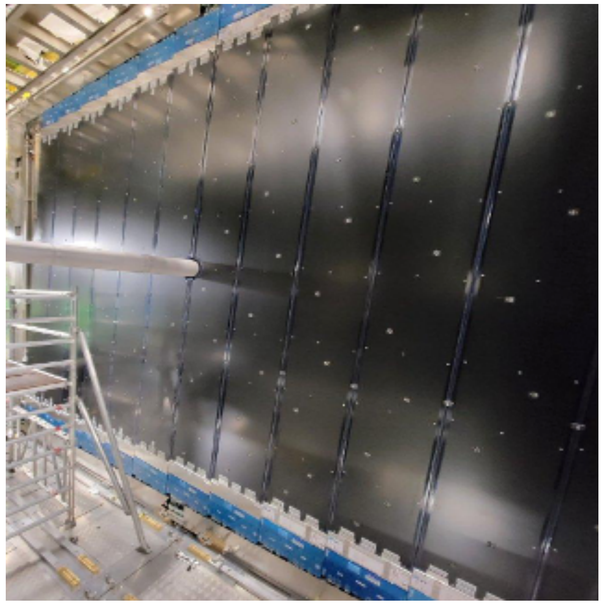
- Upgrade
  - RICH1 optics replaced to handle increased occupancy
  - RICH1 and 2 to use multi-anode PMTs with high granularity.
  - RICH2 installed last year
  - RICH1: last PMT column installed end of Jan, magnetic shielding installed earlier this month
  - Currently commissioning both RICH detectors.



UPGRADE I - TRACKERS

- UT: Upstream Tracker
- Silicon Microstrip sensors
- 537k channels readout using custom ASIC
- Decision taken in Dec not to install before cavern closure
- Complete Service and Mechanics before closure
- First side sept, second YETS

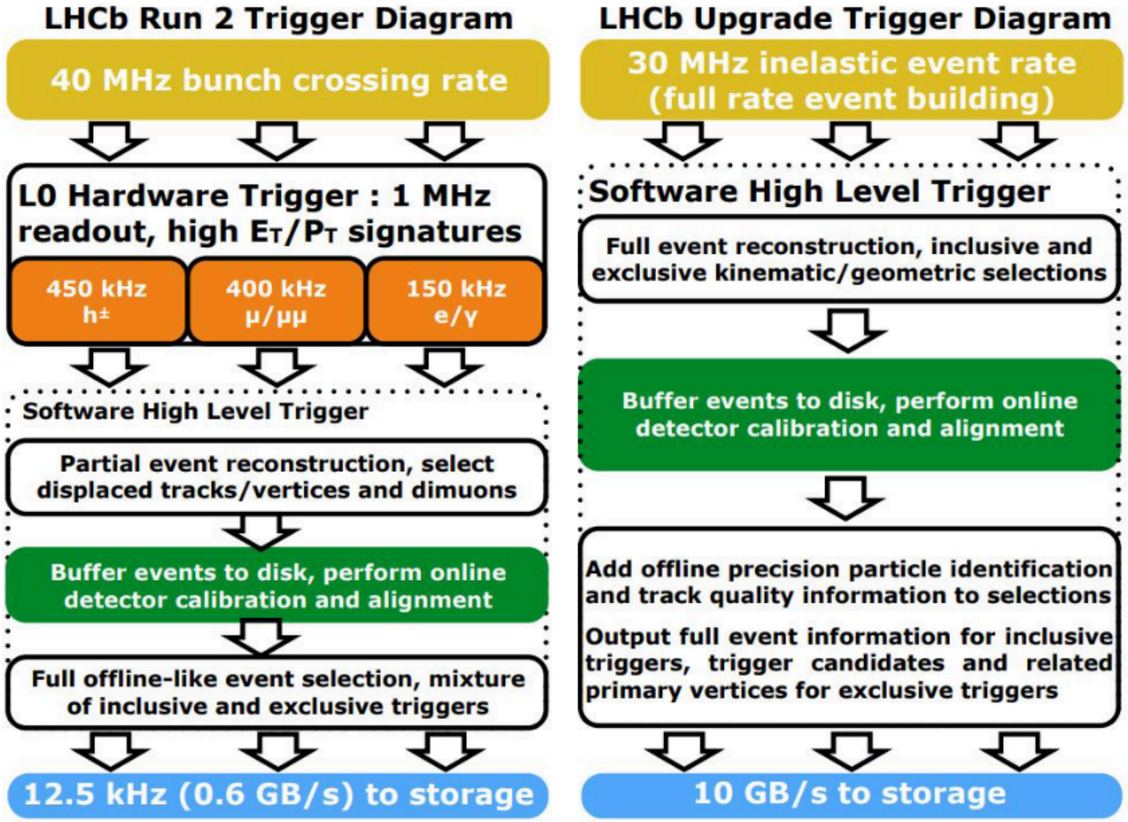
- Sci-Fi: Scintillating Fibre Tracker
- 6 scintillating fibre mats with 6 layers of 2.5m long fibres with 250um diameter.
- Installation of frames finished end of Jan
- Commissioning of detector on-going
- Alignment/closure of frames underway



UPGRADE I - SW ONLY TRIGGER

- Run 3 trigger
  - Full rate fed through to SW only trigger
  - Two stages:
    - HLT1: 30MHz to 1Mhz
    - HLT2: 10GB/s to permanent storage

- Status:
  - Most GPUs for HLT1 installed
  - Disks/servers for HLT1 buffer arrived and installed, for HLT2 on-going now
  - Preparing for data-taking - checking transfer from LHCb to storage sites



UPGRADE II

- To fully realise the flavour physics potential of the HL-LHC, need to be able to accept higher inst. luminosity
- Aiming for 1.5e34 - Average Pile-Up ~50
- Will enable LHCb to have a dataset of 300fb-1 up to the end of HL-LHC
- The idea is to replace all existing spectrometer components to increase granularity, reduce material budget, exploit new technologies.
- Installation in LS4 - 2033/34

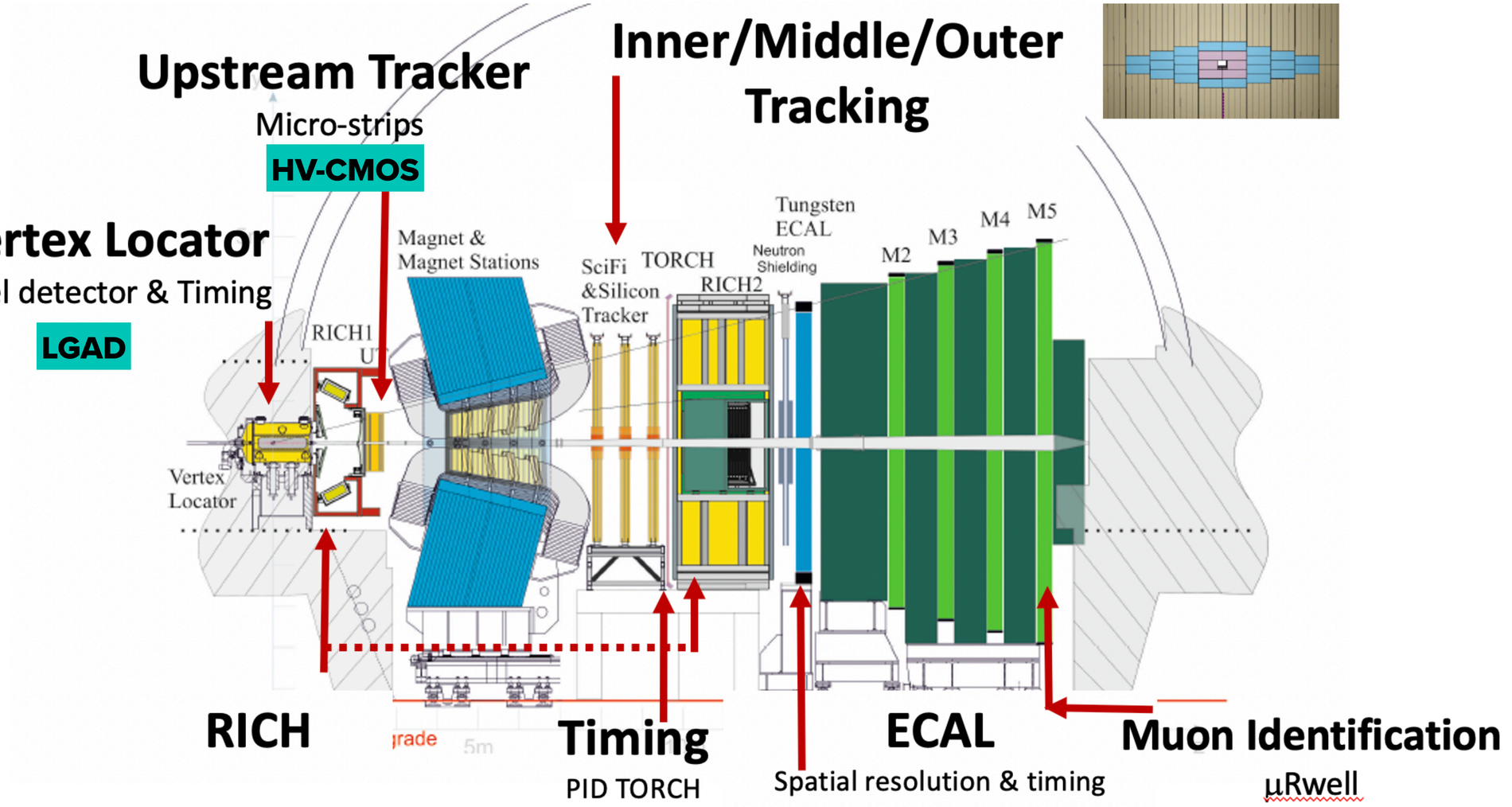
https://cds.cern.ch/record/2776420?ln=en

UPGRADE II

- Simulation has shown that precision timing could play a crucial role in vertex separation - will be required across several subdetectors.
- Significant UK involvement:
  - Charged Hadron ID - RICH and TORCH. TORCH - Time of Internally Reflected Cerenkov light installed between RICH2 and Calorimeter
  - Vertexing and Tracking - VELO and Mighty Tracker. New trackers to deal with increased occupancy and ability to handle larger radiation doses.
  - Data processing - investigating novel technologies and architectures (GPUs and IPUs)
- LS3 will be used to consolidate Phase I detector and commission new technologies for Phase II

UPGRADE II

CANDIDATE TECHNOLOGIES



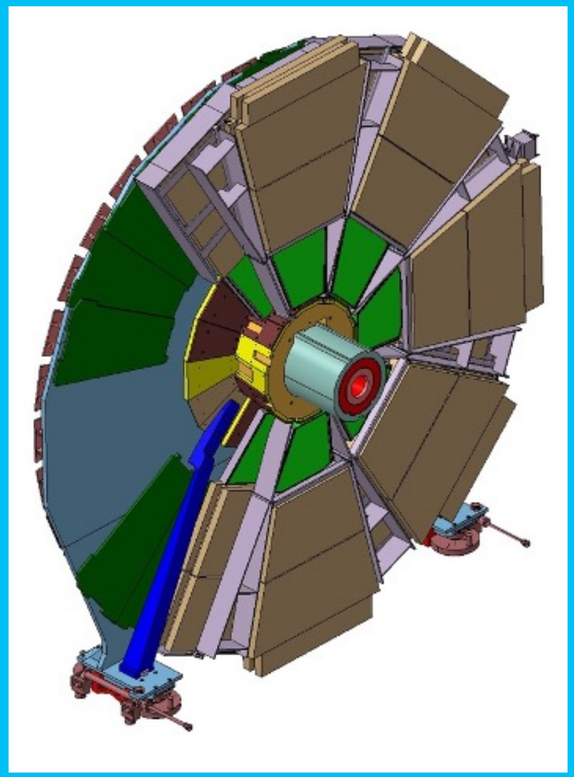
ATLAS Upgrades

Phase 1 completing now

Phase 2 for HL-LHC in 2029 - install in LS3

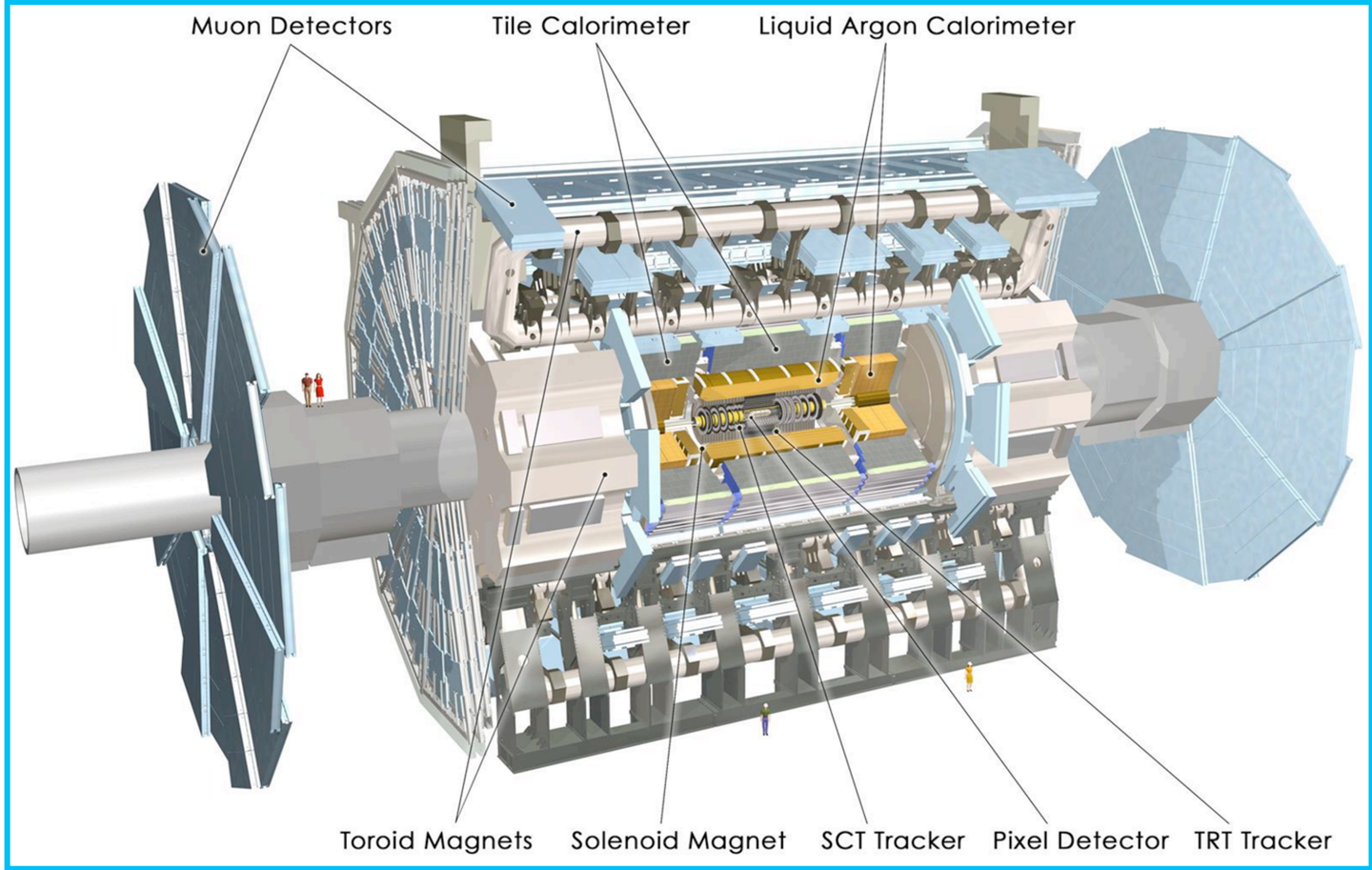
ATLAS PHASE I

- Upgrades to Calorimeter electronics and triggering - significant UK involvement
  - includes increased granularity information coming from LAr
  - Larger FPGAs - more sophisticated algorithms
- Muon New Small Wheels
  - Major construction project to replace first layer of End-Cap muon
  - Both wheels now installed and being commissioned
  - Have seen parts of the detector already integrated into the ATLAS DAQ system



ATLAS PHASE II

- Full replacement:
  - Inner Tracking detectors (Pixel and Strips)
  - Trigger and DAQ
- Electronics upgrades:
  - Liquid Argon (LAr) calorimeter
  - Tile calorimeter
  - Muon systems
- New detector:
  - High Granularity Timing Detector

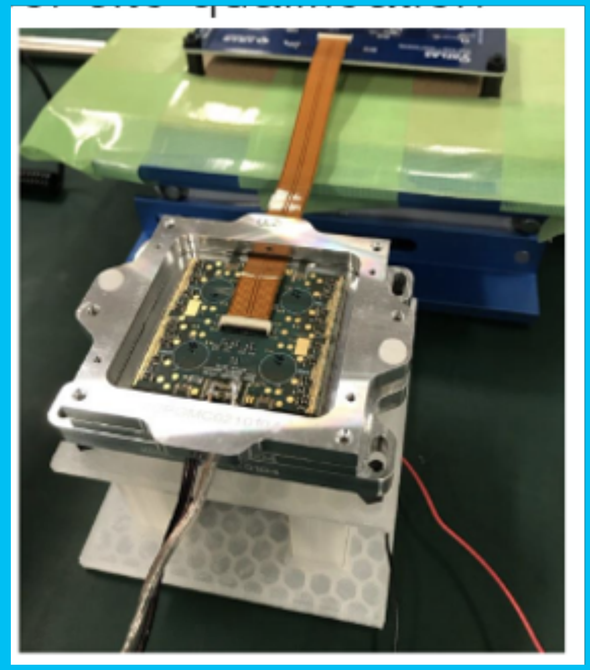


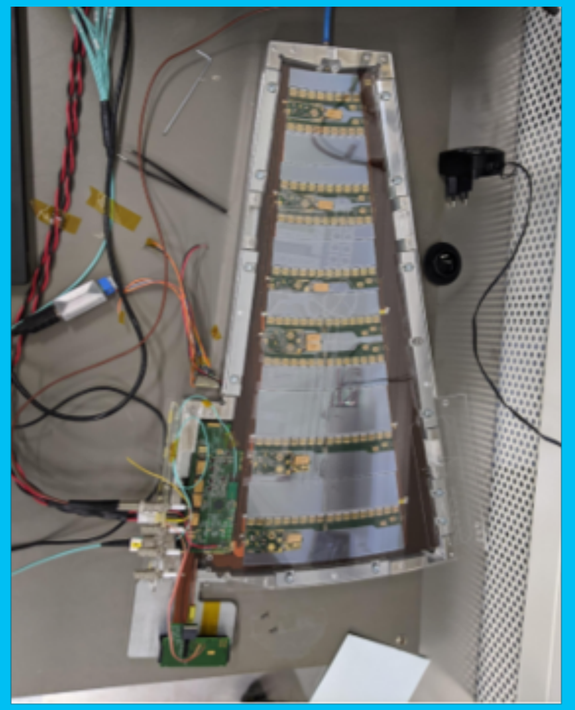
ATLAS PHASE II - INNER TRACKER

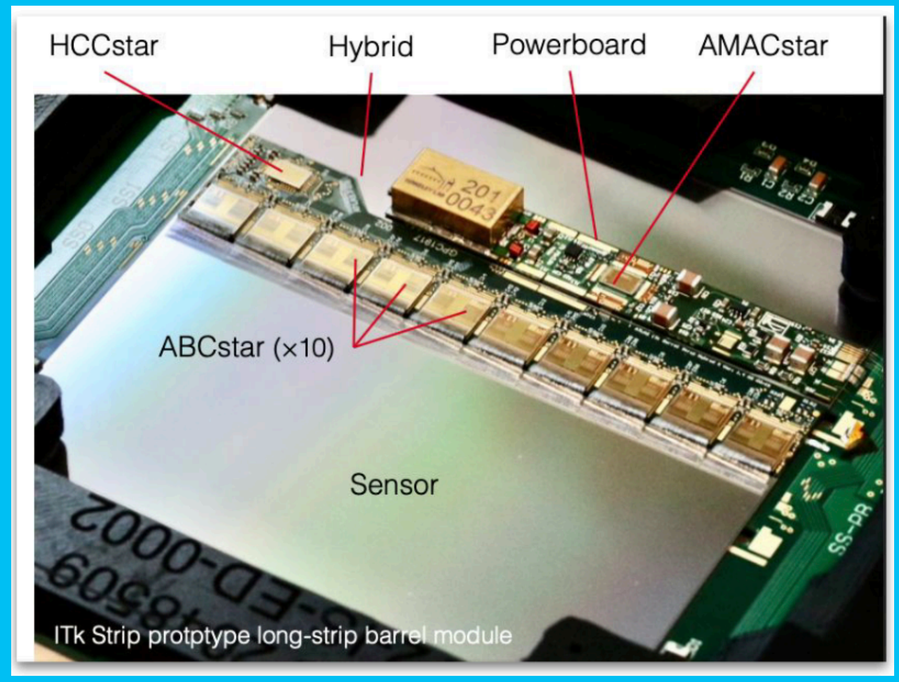
- Pixels:
  - 5 flat barrels at small eta, inclined layout at intermediate eta, ring geometry at large eta
  - Eta range extended from 2.5 to 4.0
  - Reduction in material and silicon area

STRONG UK INVOLVEMENT

- Pixels status:
  - 3D and Planar sensors in pre-prod.
  - FE ASIC testing overall successful
  - Final Design Reviews (services, mechanics, in 2022)





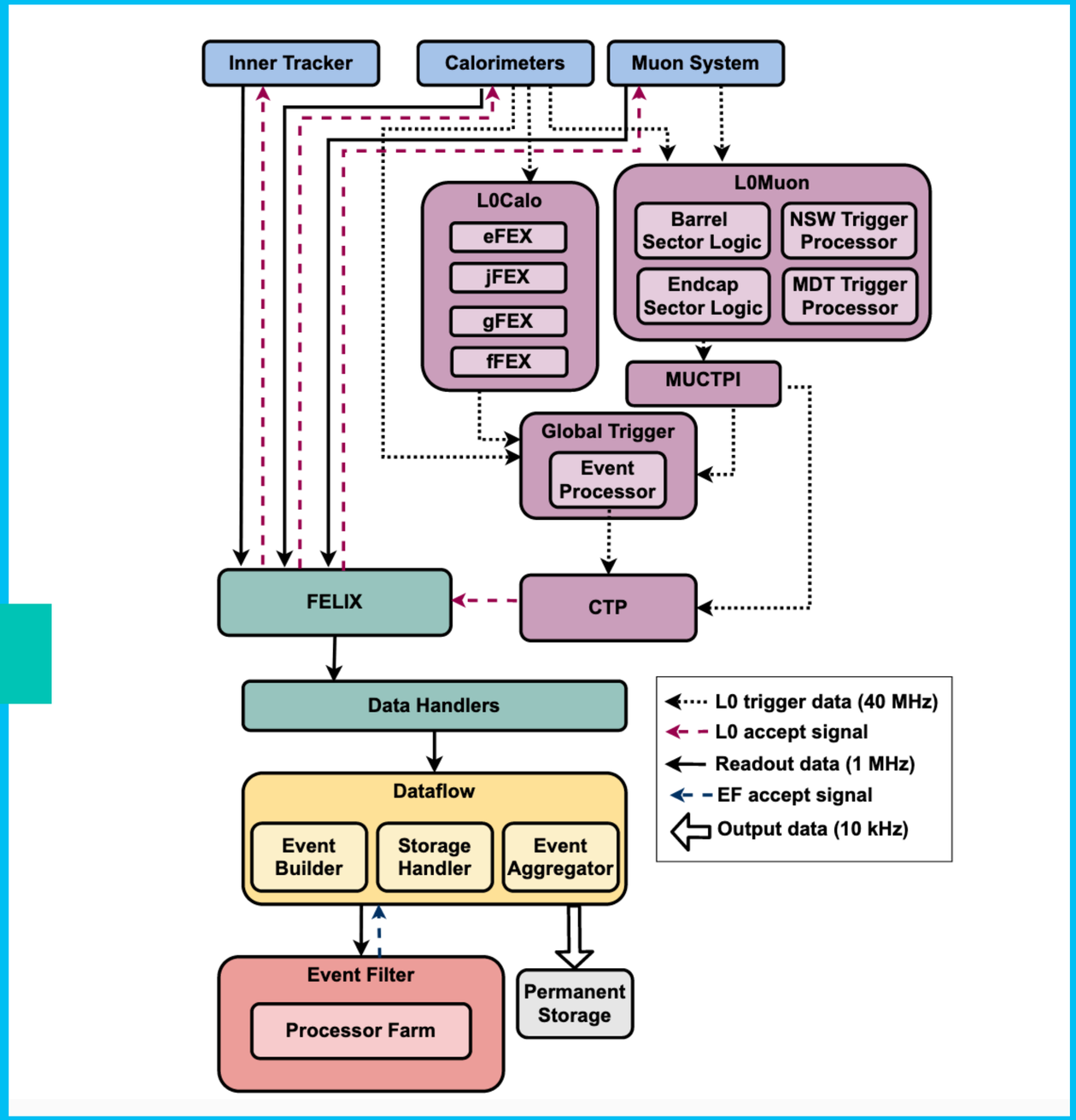


ATLAS PHASE II - TDAQ

- Need to keep thresholds low for Physics program
- Single-level hardware trigger (L0) running at 1 MHz
- Input from Calo and Muons
- Event Filter Farm performs offline-like reconstruction
- Output to tape 10 kHz

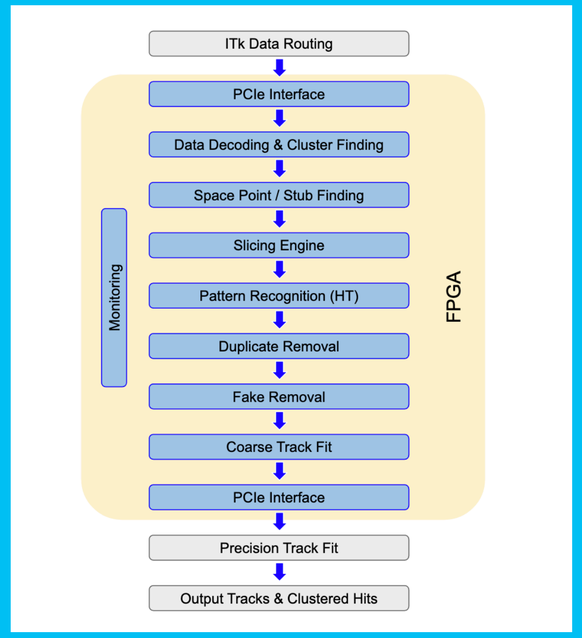
STRONG UK INVOLVEMENT

- First versions of hardware (Global Common Module, Muons) being tested currently.
- Decision to move away from a Hardware Track Trigger changed the assumptions for the Event Filter Tracking originally made - re-examined.



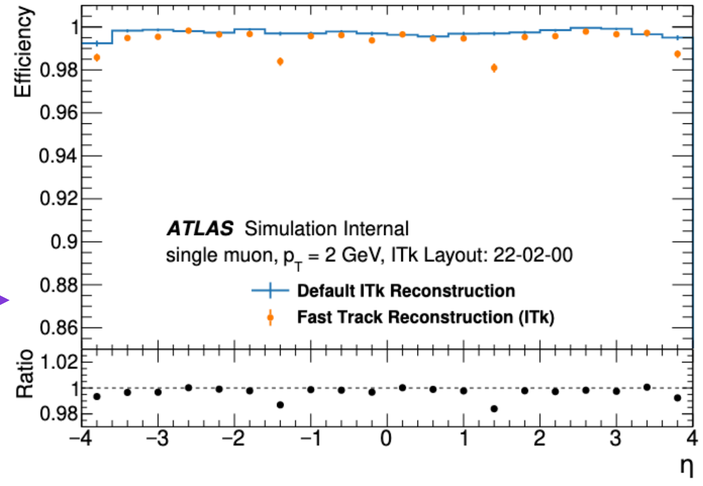
ATLAS PHASE II - TRACK TRIGGERING

- Event Filter Tracking
  - FPGA-based demonstrator
    - XiLinx Alveo U250
    - A full ITk event can be processed by each FPGA-accelerator
    - Concluded the system could be built with these cards.



STRONG UK INVOLVEMENT

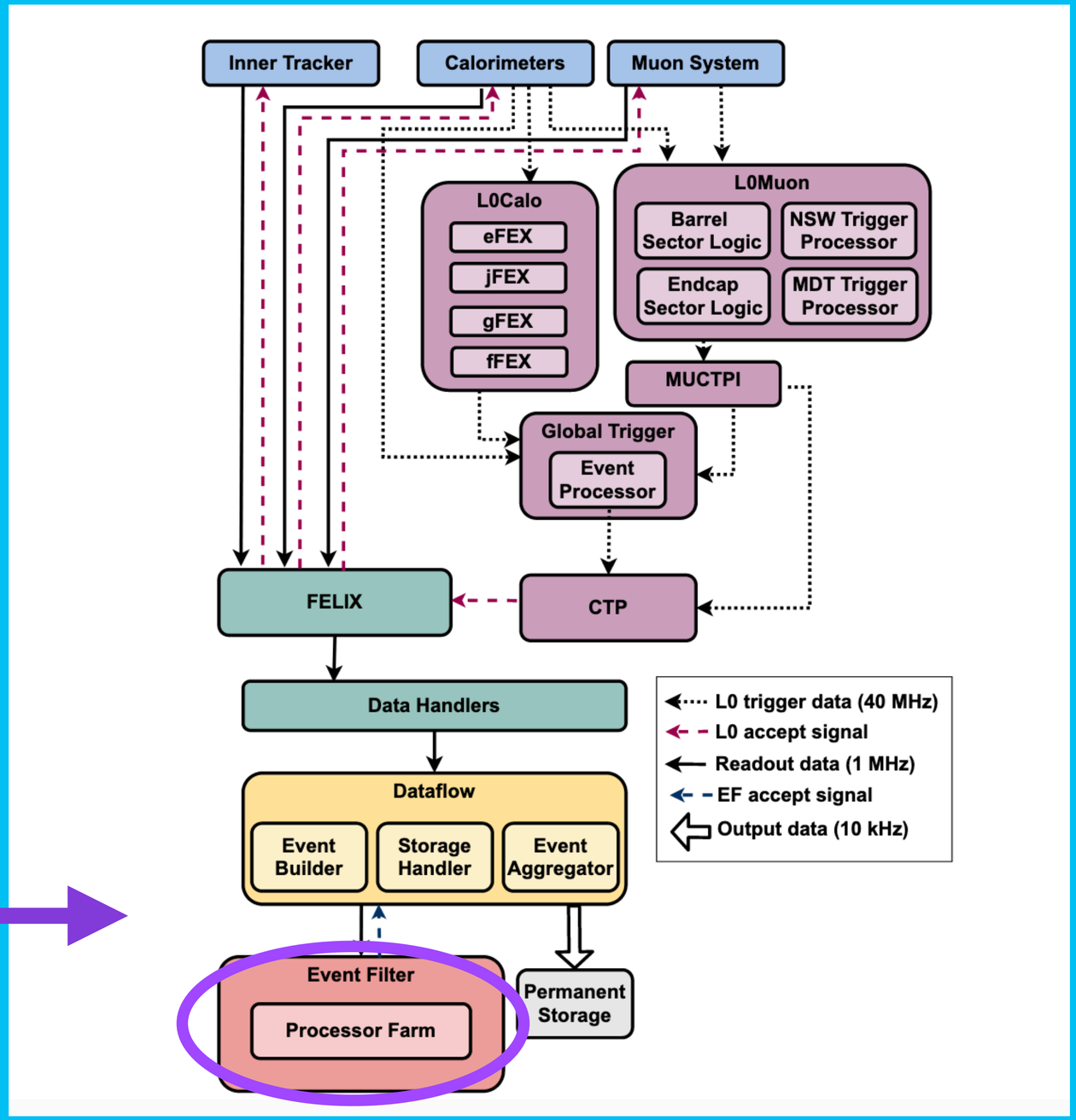
- Event Filter Tracking
  - CPU-based demonstrator
    - Fast version developed
    - Benchmarked with Intel Xeon E5-2620 v4 2.1 GHz CPUs with 16 cores



$\langle\mu\rangle$	Tracking	Release	Byte Stream Decoding	Cluster Finding	Space Points	Si Track Finding	Ambiguity Resolution	Total ITk
140	default	21.9	2.2	6.4	3.5	31.6	43.4	87.1
	fast			6.1	1.0	13.4	-	22.7
200	default	21.9	3.2	8.3	4.9	66.1	64.1	146.6
	fast			8.1	1.2	23.2	-	35.7

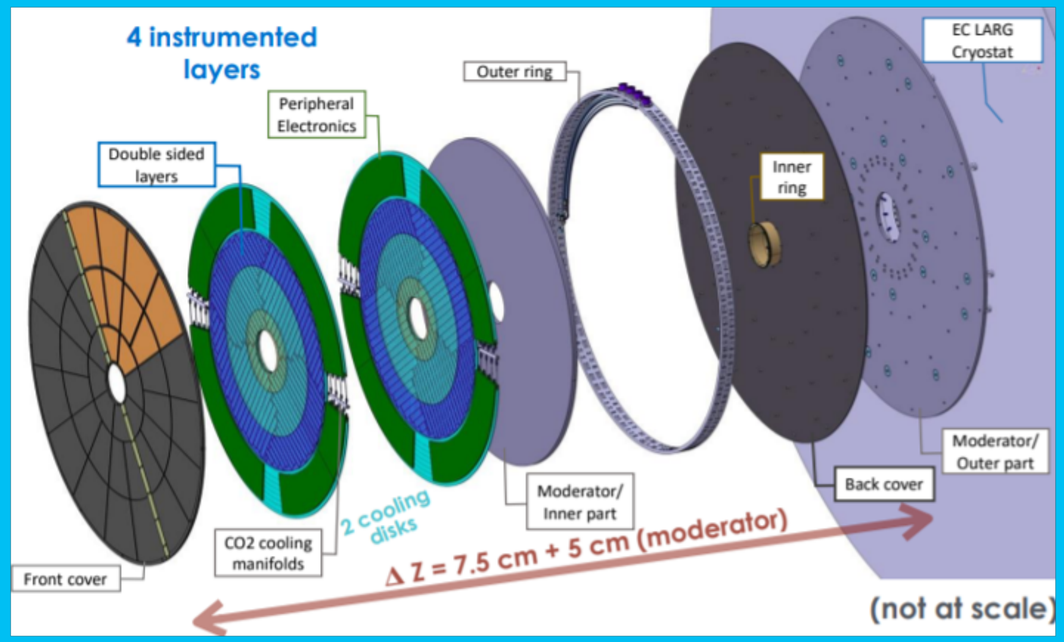
ATLAS PHASE II - TRACK TRIGGERING

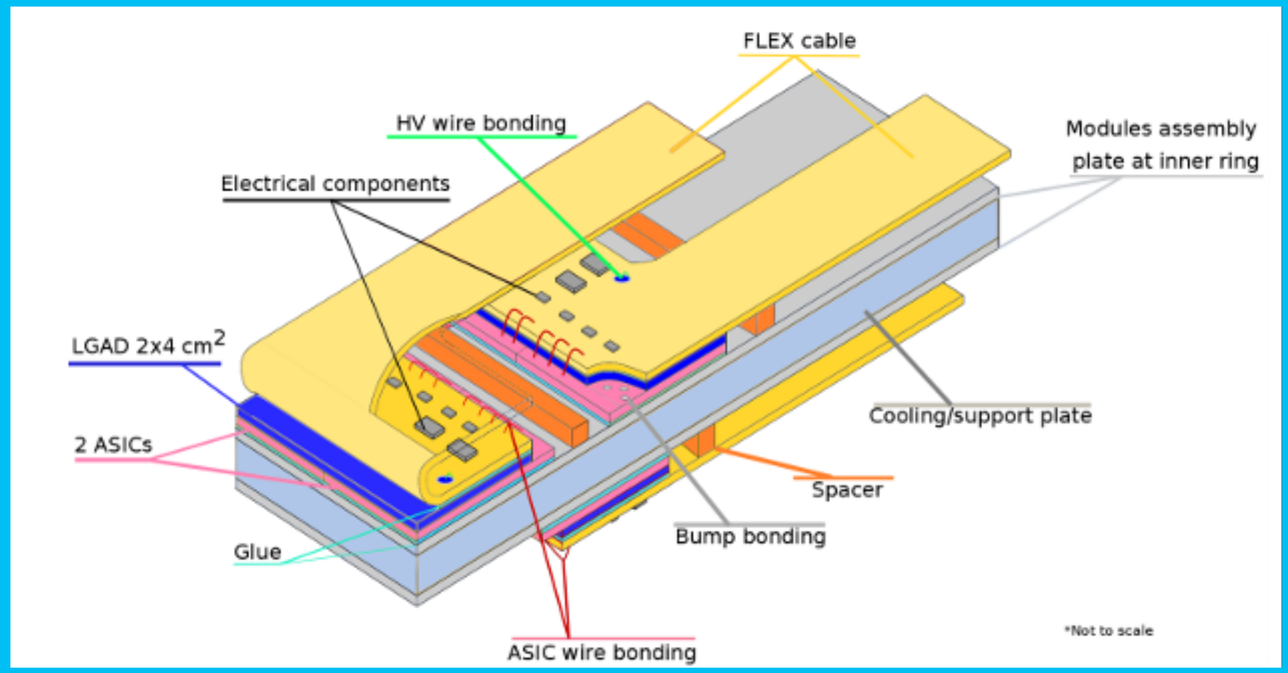
- Recent amendment to TDR - Event Filter Tracking
- Recommendation: Commercial solution - software-based - but concurrently pursuing accelerator-based components to augment system
- New system architecture



ATLAS PHASE II - HGTD

- Timing detector that can be used to help identify primary vertices coming from overlapping pp interactions
- Will cover region of eta between 2.4 and 4.0.
- 30ps timing resolution - using low-gain avalanche detectors.
  - large signal-to-noise ratio
  - excellent time resolution





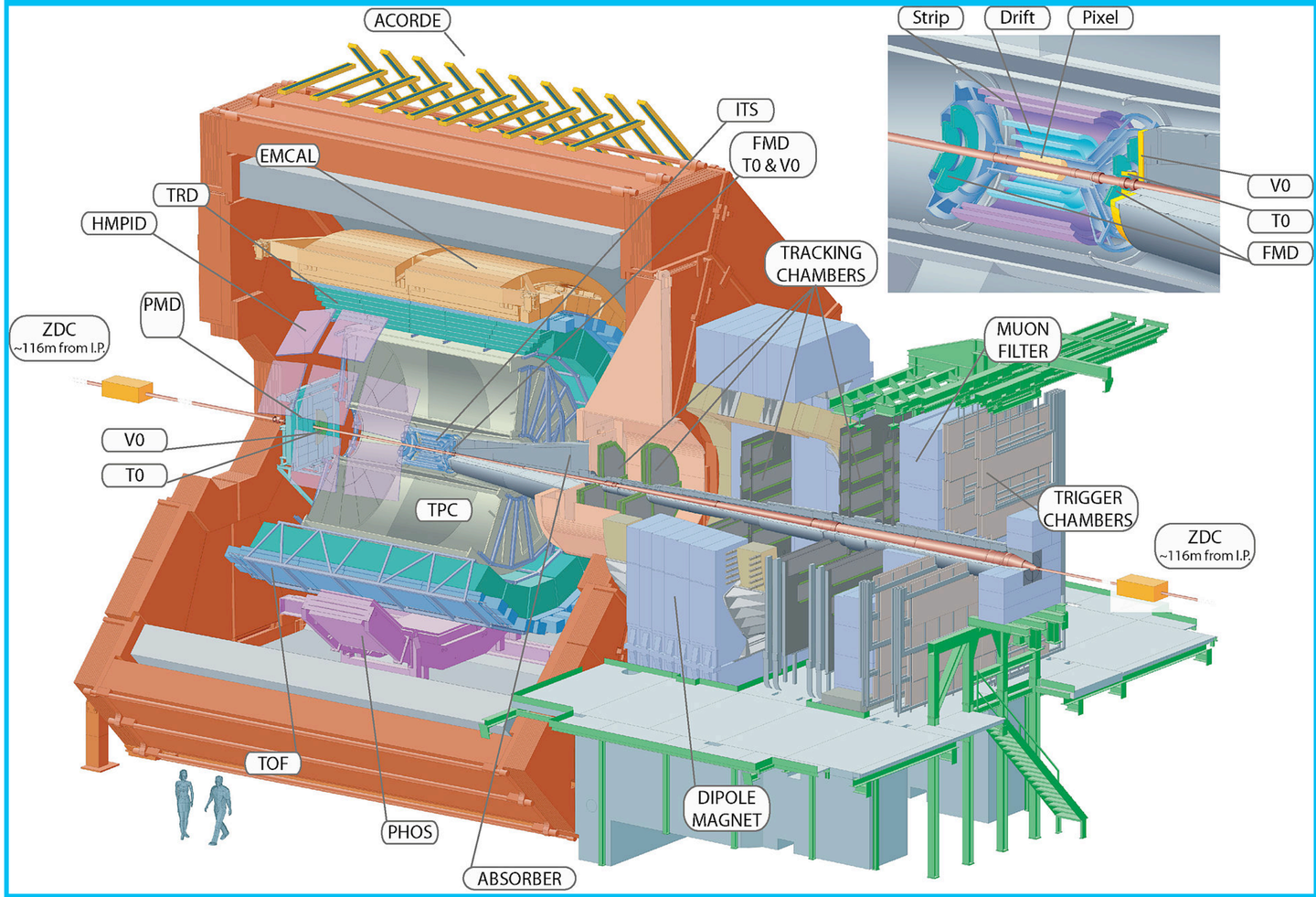
ALICE Upgrades

Upgrade to ALICE 2 completing now

Upgrade to ALICE 3 for Run 5 (2035) - install in LS4

ALICE

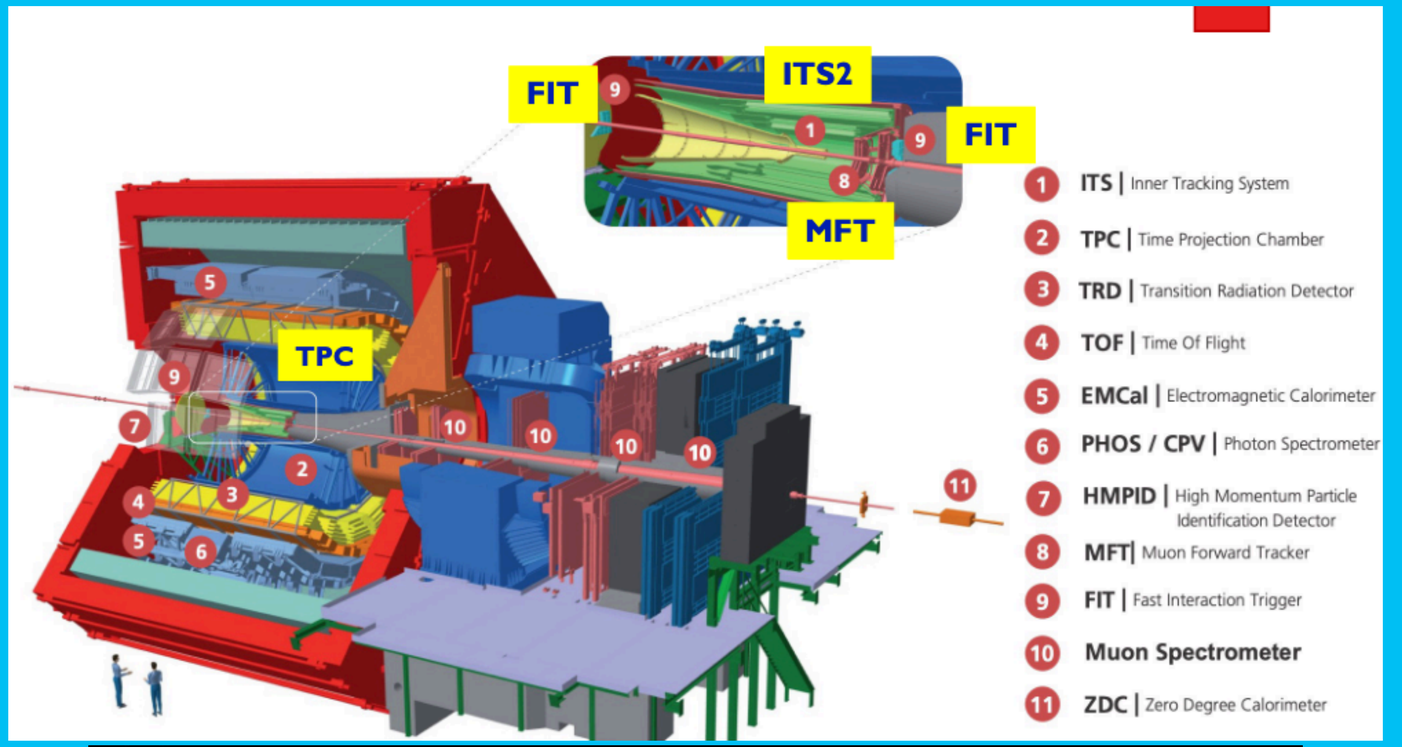
- ALICE is designed to study heavy-ion collisions at a centre-of-mass energy of 5.02TeV
- Can exploit the temperatures and densities of these collisions to investigate the quark-gluon plasma.
- UK is playing a leading role in the Trigger and the Inner Tracking System
- Upgrade to ALICE2 occurred during LS2 in time for Run 3

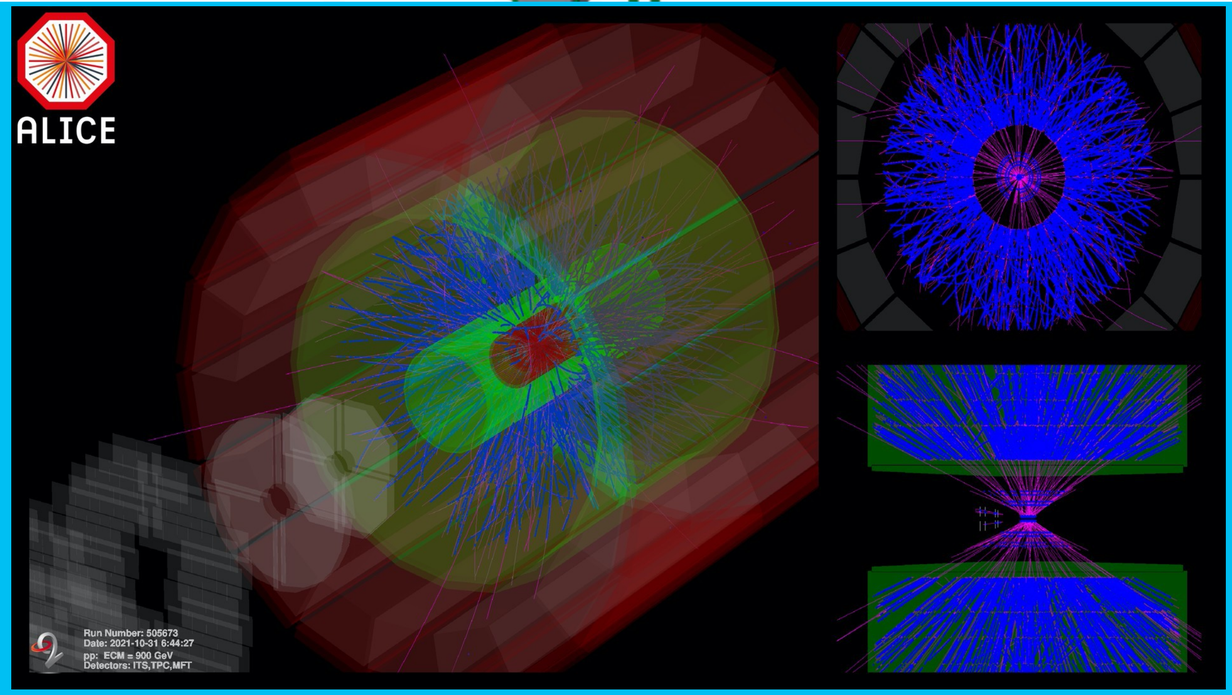


ALICE 2

- New silicon tracker
- TPC readout using GEM
- Fast interaction trigger
- Continuous readout and online data reconstruction
- Plan to inspect ALL minimum bias Pb-Pb collisions at 50kHz.
- Collect 13nb^{-1} of data (x50 increase of many observables compared to Run 1 and 2).

- UK had leading role in Central Trigger Processor and Inner Tracking System

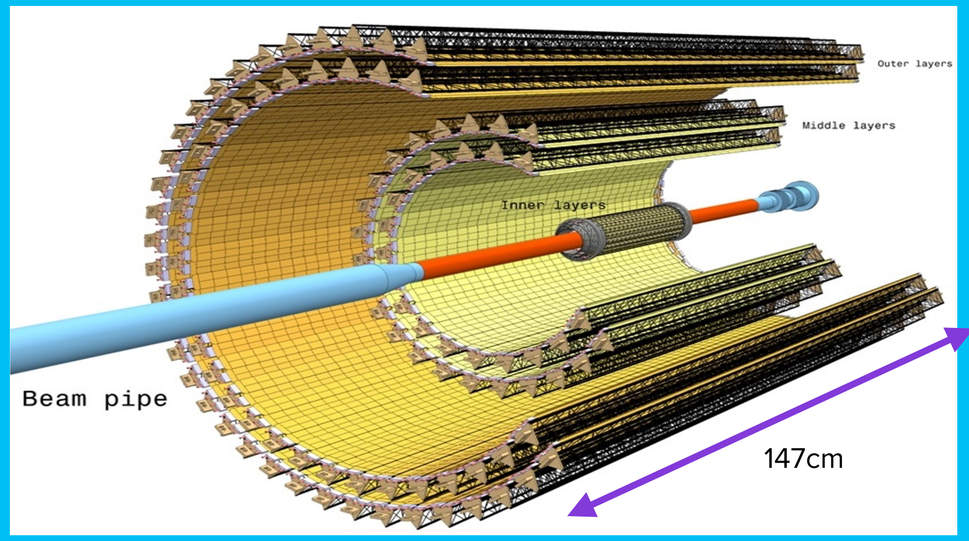


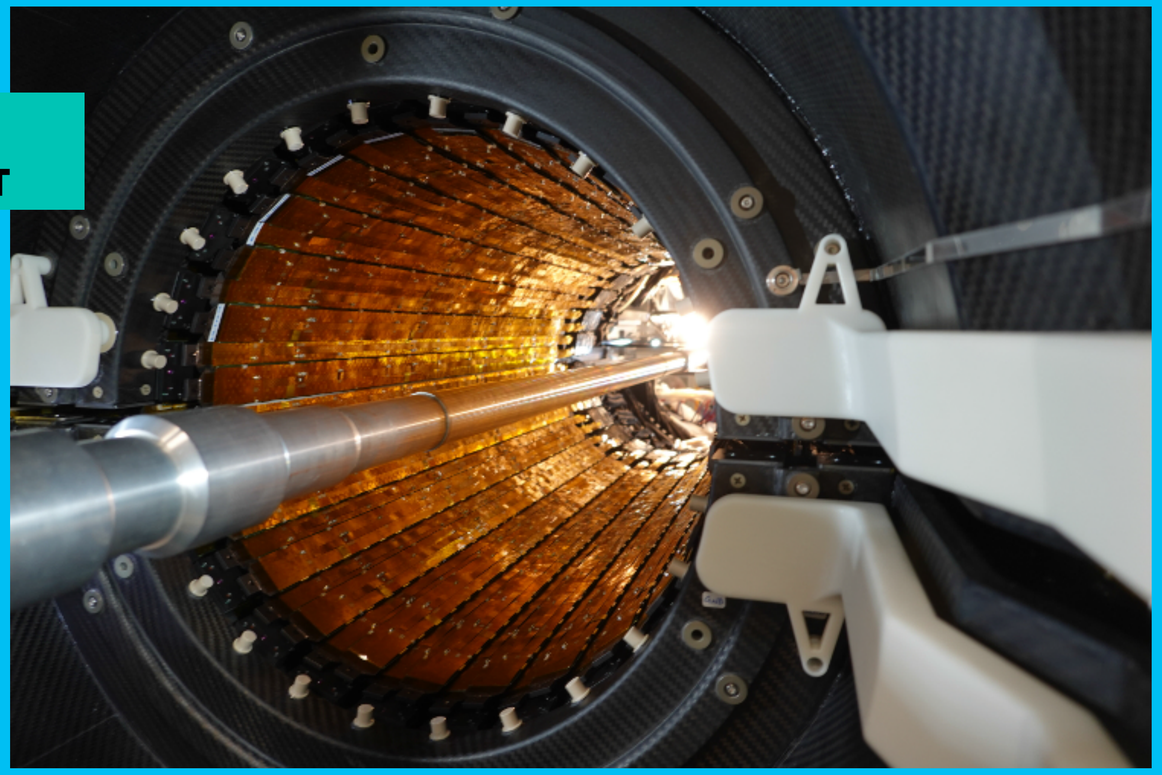


ALICE 2 - ITS2

- First large Silicon tracker entirely composed of CMOS Monolithic Active Pixel Sensors (MAPS)
  - improved tracking efficiency and pT resolution - increased granularity
  - improved impact parameter resolution
    - closer to IP, new beam pipe
    - reduce material budget
    - reduce pixel size
  - Improved readout capability x100
  - Fast removal/insertion for maintenance
- 7 concentric layers -split into Inner Barrel (3 layers) and Outer Barrel (2 middle layers and 2 outer layers)
- ITS2 Outer Barrel installed March 2021

STRONG UK INVOLVEMENT



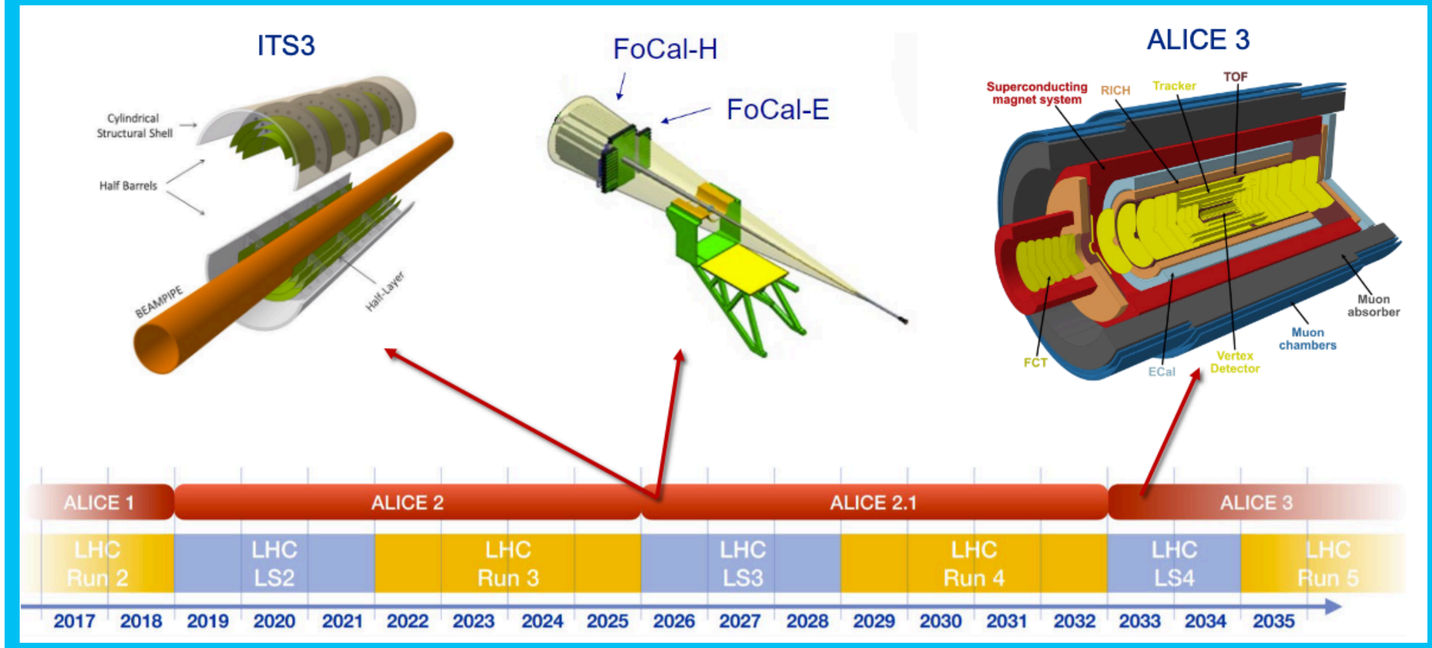


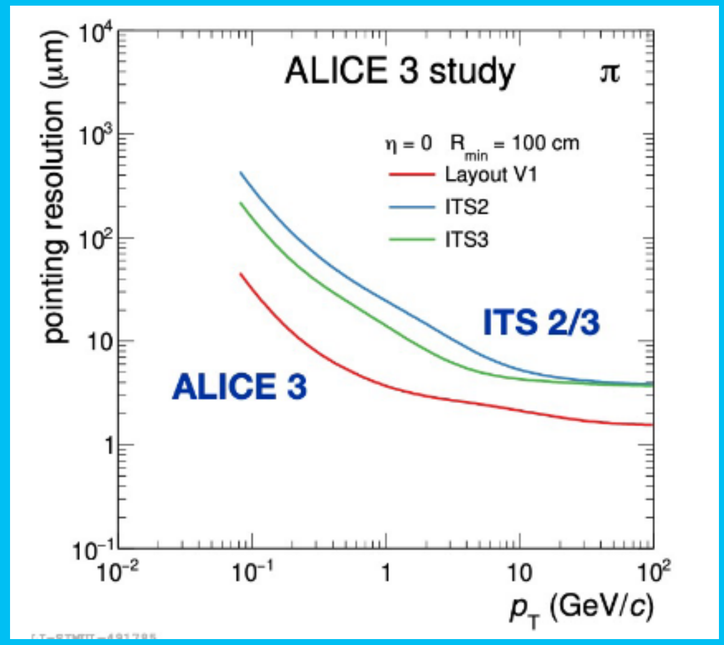
ALICE INTO THE FUTURE

- Plan to upgrade ITS and install Forward Calorimeters in LS3/Run4
- Then plan large upgrade - ALICE3 for installation in LS4. Letter of Intent has been reviewed by LHCC
- pp, pA, AA collisions at luminosities 20-50 higher – electromagnetic probes at ultra-low pT, precision physics in the charm and beauty sector
  - LoI now publicly available

HTTPS://CDS.CERN.CH/RECORD/2803563/FILES/LHCC-I-038.PDF

- Complete overhaul of detector including
  - Compact all-silicon tracker with high resolution vertex detector
  - Superconducting magnet system
  - Particle ID over large acceptance
  - Fast read-out and online processing





Summary

SUMMARY

- The LHC experimental upgrade program is vast in scope, technologically complex, and designed to get the absolute best out of the collisions from LHC and HL-LHC.
- The next set of upgrades planned for LS3 are well underway, several prototyping efforts and test stands are built and in operation
- The UK is firmly embedded in all 4 major experiments, with leadership roles across detector projects
- We have key expertise in Trigger/DAQ, Particle ID, Tracking, Calorimetry, including all aspects of electronics systems (software, firmware, hardware)
- We can continue to build on these efforts and develop further novel technologies and systems over the next 10-20 years…