Detector upgrade at Run3 and HL-LHC

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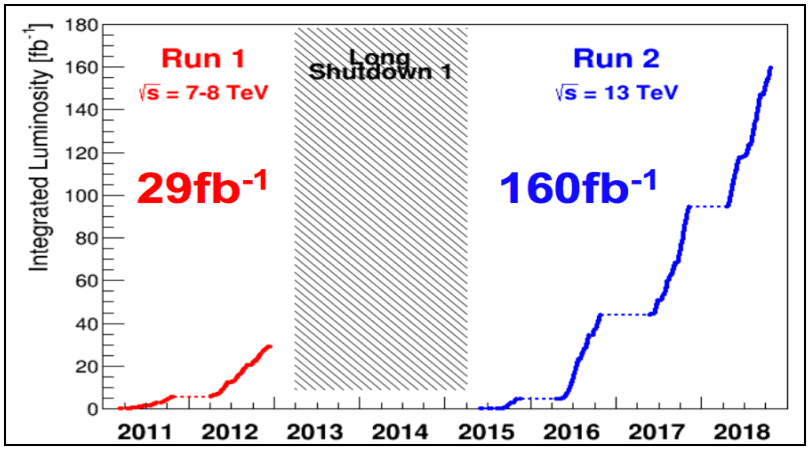
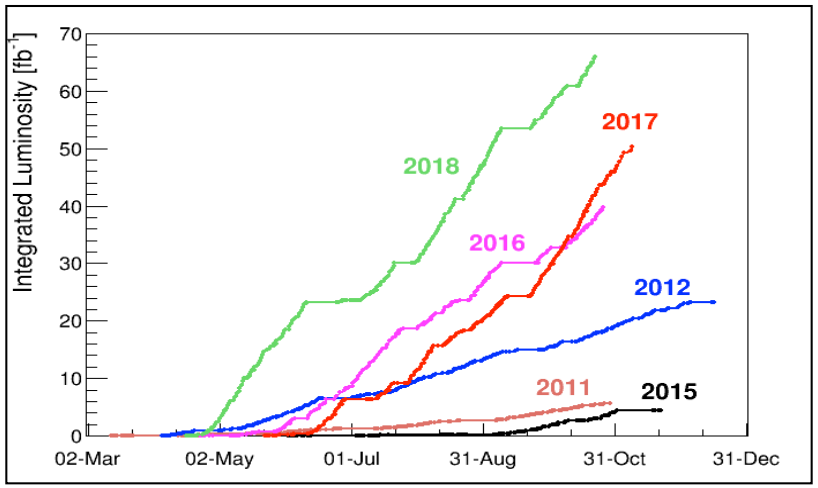
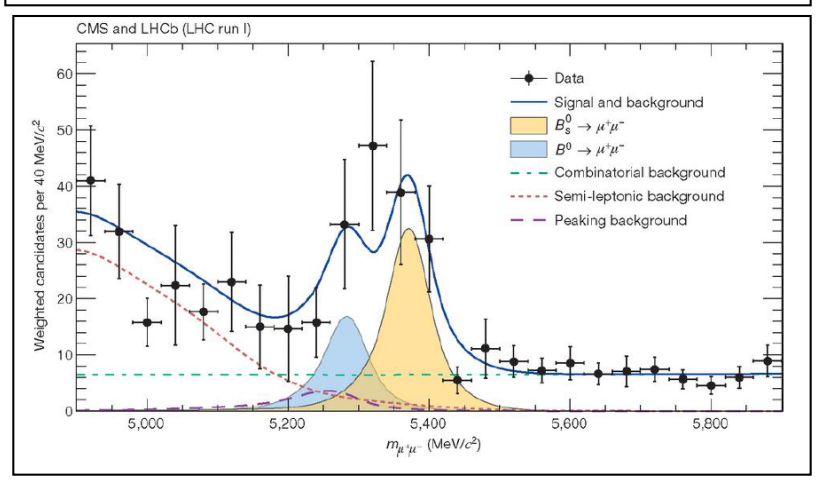
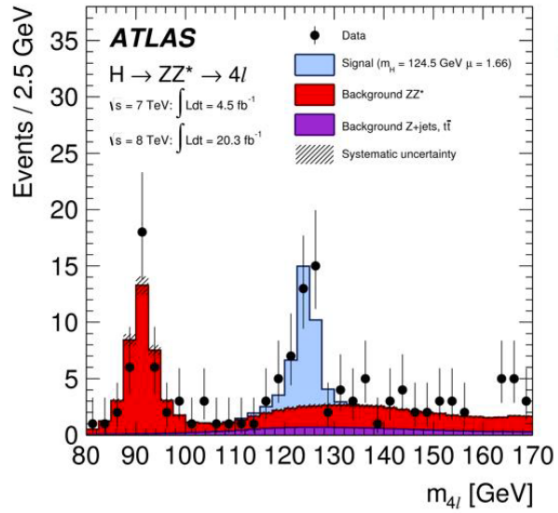
Legacy (Run 1 and 2)

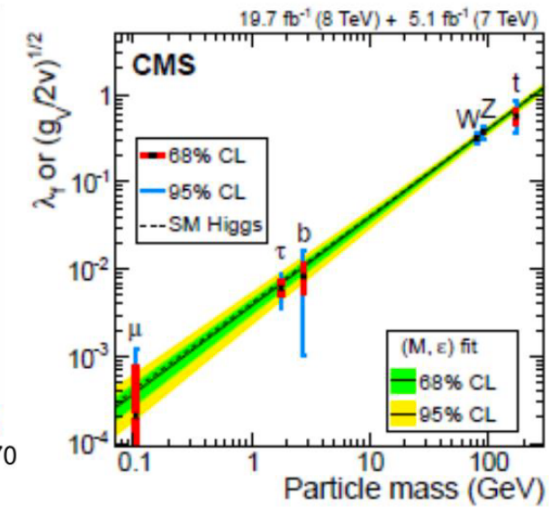
Source: https://twiki.cern.ch/twiki/bin/viewauth/LhcMachine/LhcCoordinationMain





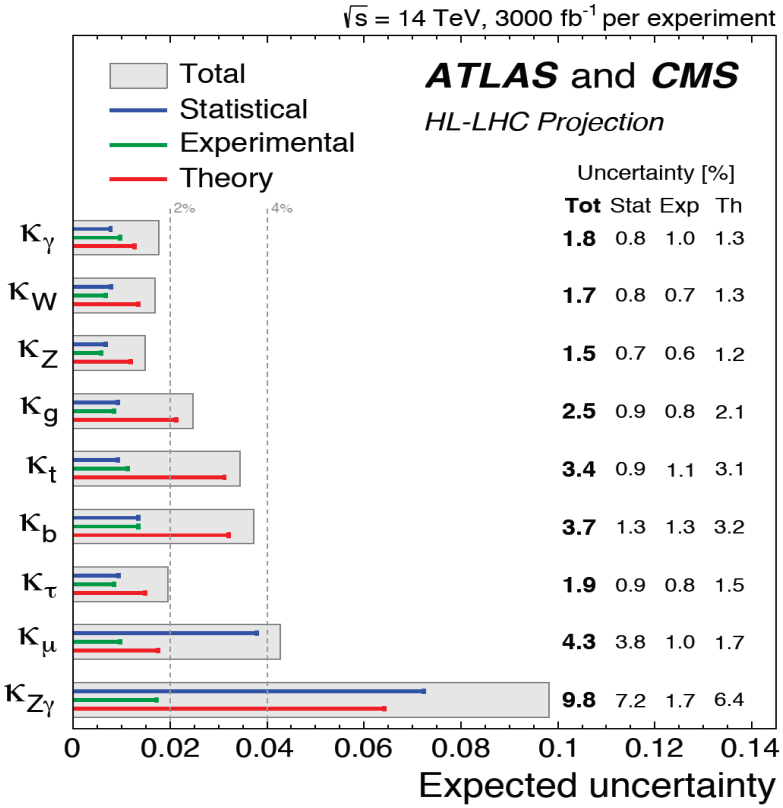




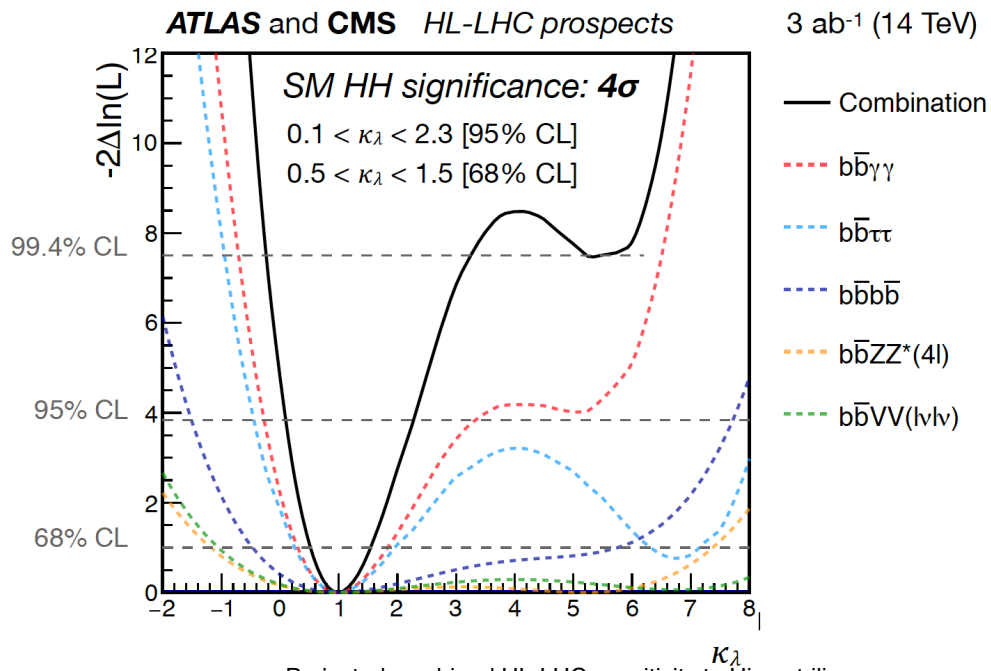


- Integrated Luminosity
  - CMS and ATLAS (total) ~ 190 fb^{-1},
    LHCb: 10.1 fb^{-1} (total) , ALICE 1 nb^{-1} (Run 2/Pb-Pb))
    (http://acc-stats.web.cern.ch/acc-stats/#lhc/overview-panel)
- Higgs boson coupling to the heaviest, third generation of quarks and leptons
- Precise masses of the Higgs boson, top quark W boson, $B_s \to \mu\mu$ branching ratio - constraining the Standard Model
- Target Long Lived Particle searches
  https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.122.131801

Physics potential HL-LHC



Projected uncertainties on κ_i , combining ATLAS and CMS: total (grey box), statistical (blue), experimental (green) and theory (red).



Projected combined HL-LHC sensitivity to Higgs trilinear coupling from direct search channels

- Run 1 and 2 legacy underscores need the for the High-Luminosity LHC, and full design energy of 14 TeV
  - precise measurement - Higgs boson properties and SM phenomena
  - Higher sensitivity for both direct and indirect searches for new physics

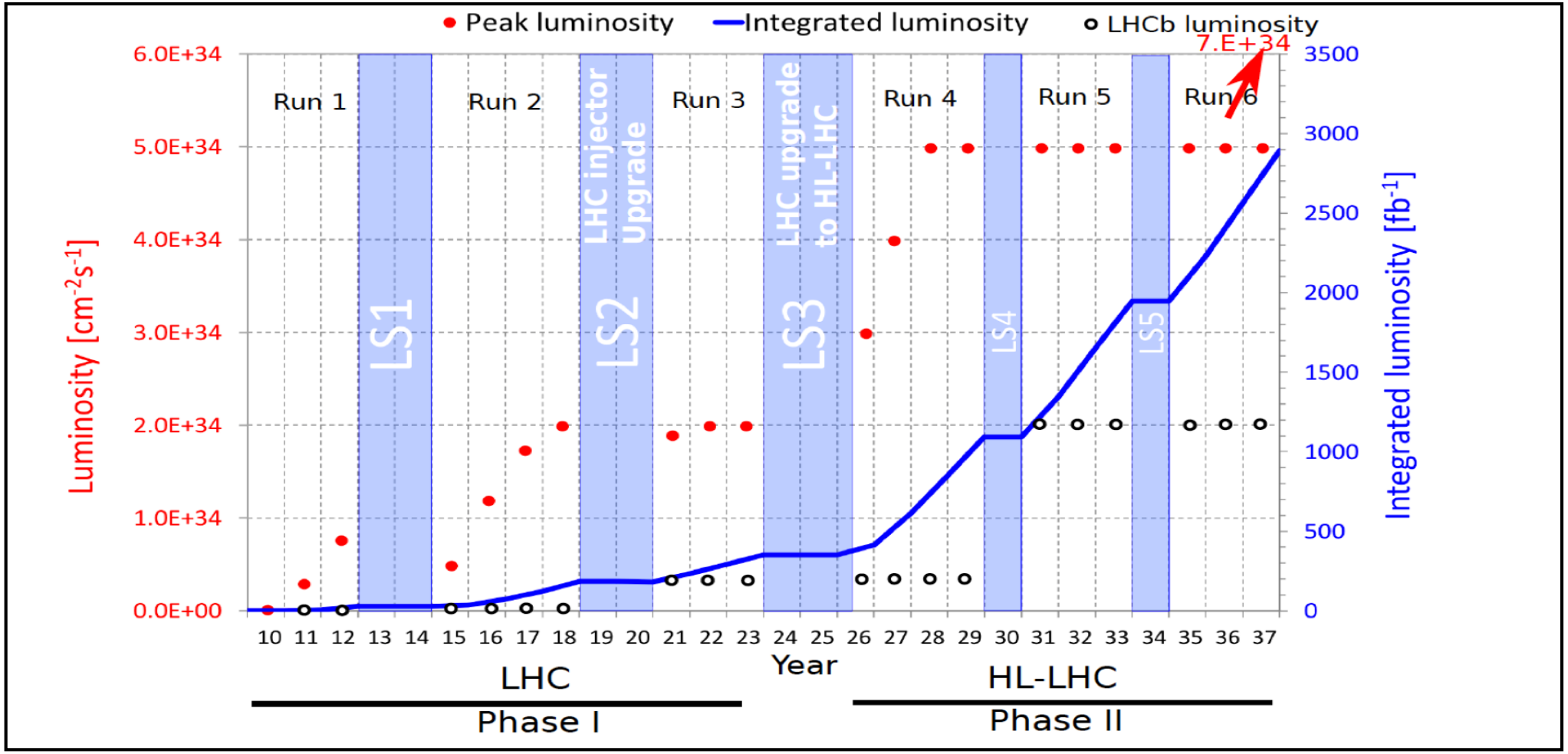
- Higgs coupling rate measurements in κ-framework

  $H \to \gamma\gamma, ZZ^*, WW^*, \tau^+\tau^-, b\bar{b}, \mu^+\mu^-$ and $Z\gamma$.
- uncertainties reduced by a factor of two

- Higgs pair production
- Combined observation sensitivity of 4 s.d. for HH signal

HL-LHC European Strategy input: https://indico.cern.ch/event/765096/contributions/3295995/attachments/1785339/2906404/HLLHC.pdf

Timeline (LHC/HL-LHC) - Long Shutdowns, Runs, Upgrades



Run 3

- ATLAS and CMS will run at just slightly higher inst. lumi than 2018, significant upgrades in the detector and upgrade systems
- LHCb will undergo a major detector upgrade, pile up ~5
- ALICE major upgrade

Run 4

- Marks officially the start of HL-LHC
- ATLAS and CMS will undergo major detector upgrades, pileup up to ~ 140 (200)
- LHCb undergoes consolidation upgrades (phase Ib)
- LHCb phase II upgrade for Run 5

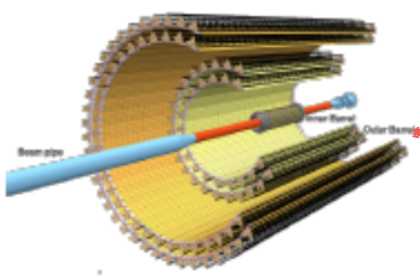
Run 3 ALICE Detector

- Improvements in readout bandwidth and trigger capability
- Goal is to register all Pb-Pb collisions (3kHz -> 50 kHz)

New Detector

Inner Tracking System

- Improve impact parameter resolution by a factor of 3 in (r-phi) and ~5 in (z); reduce material budget, increase granularity, fast insertion/removal to fix parts

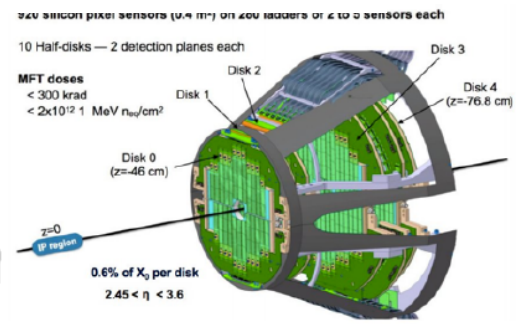


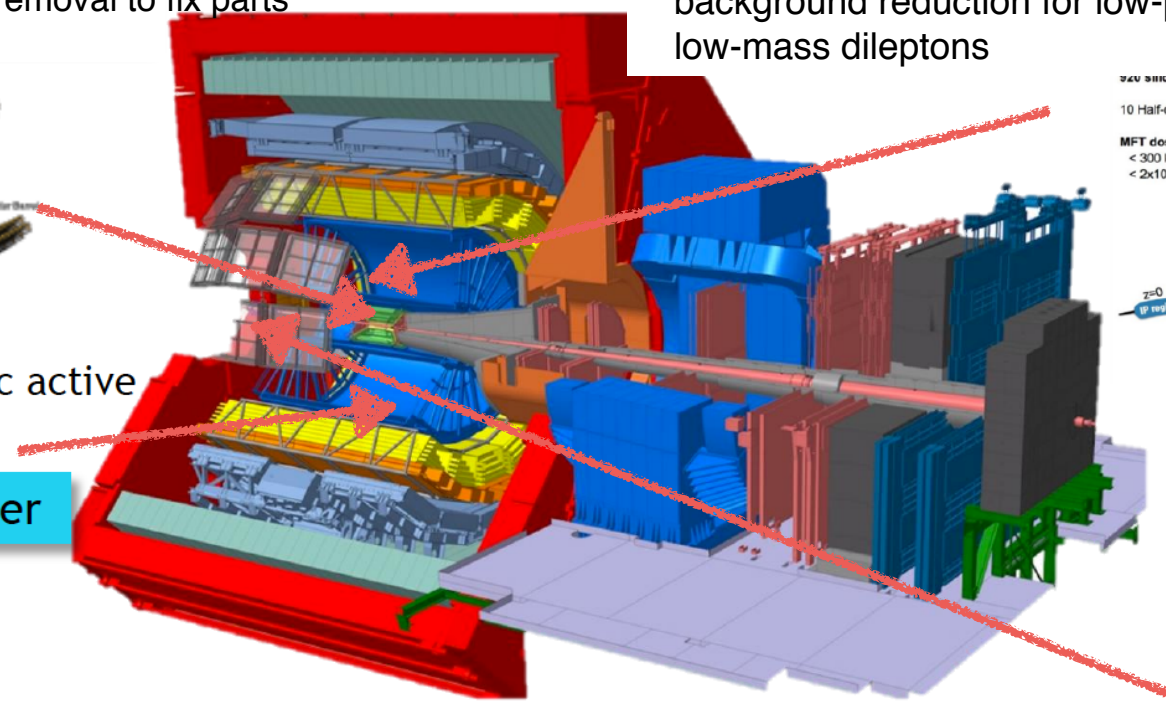
10m² of CMOS monolithic active pixel sensors

New Detector

Muon Forward Tracker

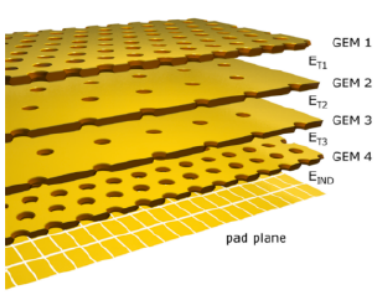
- New silicon detector in front of muon absorber
- Add secondary vertexing for heavy-flavour and background reduction for low-p_T quarkonium and low-mass dileptons





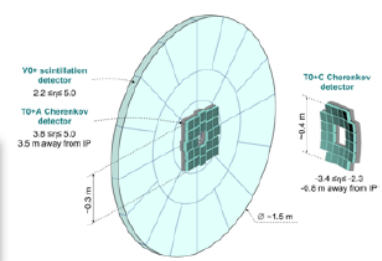
Time Projection Chamber

New Detector



- GEM: Micro-pattern gas detector with high electric field for electron multiplication in small holes of a thin polymer sheet
- Proven to work reliably in high-rate environments and high rate capability

Fast Interaction Trigger



- Upgrade of existing V0 and T0 detectors to improve acceptance and timings

Integrated Online-Offline system (O²)

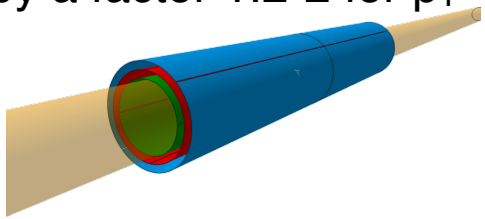
- Record minimum-bias Pb-Pb data at > 50kHz (currently ~ 1 kHz)

+ new readout for all detectors

ALICE upgrade proposal (LS3) for Run 4 and beyond (LS4)

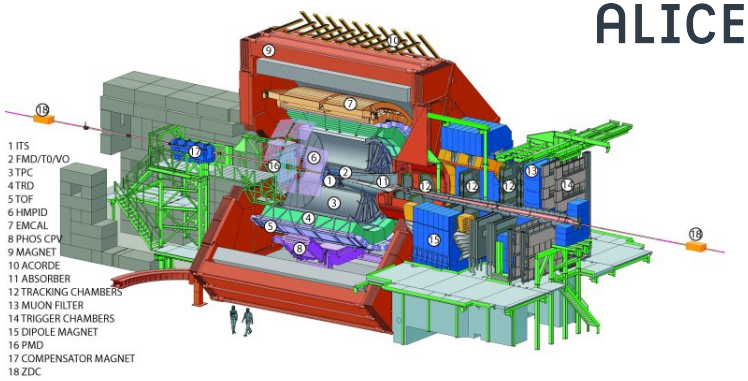
- **Fully cylindrical tracking detector**
- Reduce the material budget
- Resolution improves by a factor 2 in the full p_T range
- Efficiency increases by a factor 1.2-2 for p_T < 100MeV/c

Sensors arranged with a perfectly cylindrical shape -> sensors thinned to ~30μm can be curved to a radius of 10-20mm

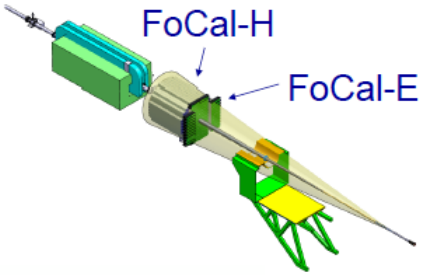


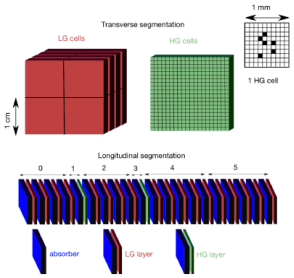
Stitching technique -> wide area sensors

- **New Beam Pipe**
  IR = 16mm, ΔR = 0.5mm



- **The FoCal Proposal**
- high-granularity Si-W calorimeter for photons and π_0
- measurement of direct photon production at forward rapidity in p-Pb

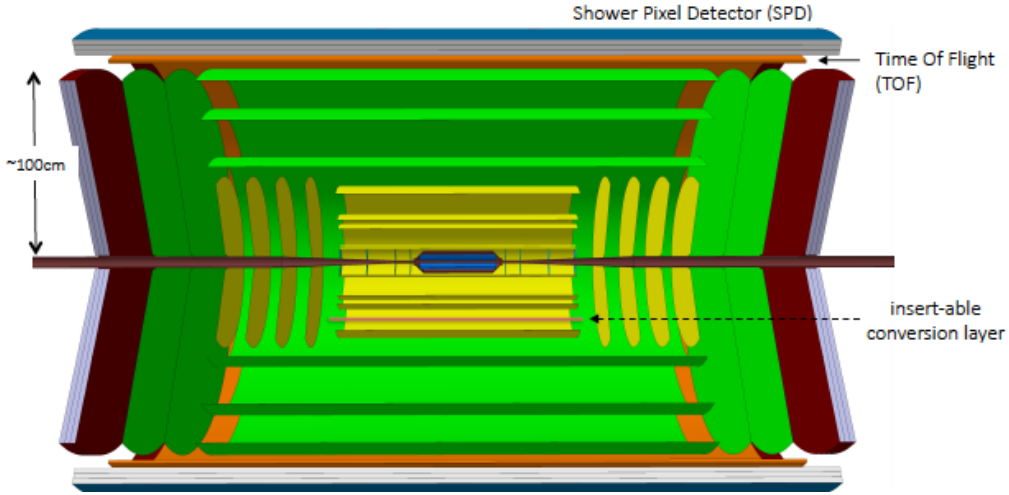




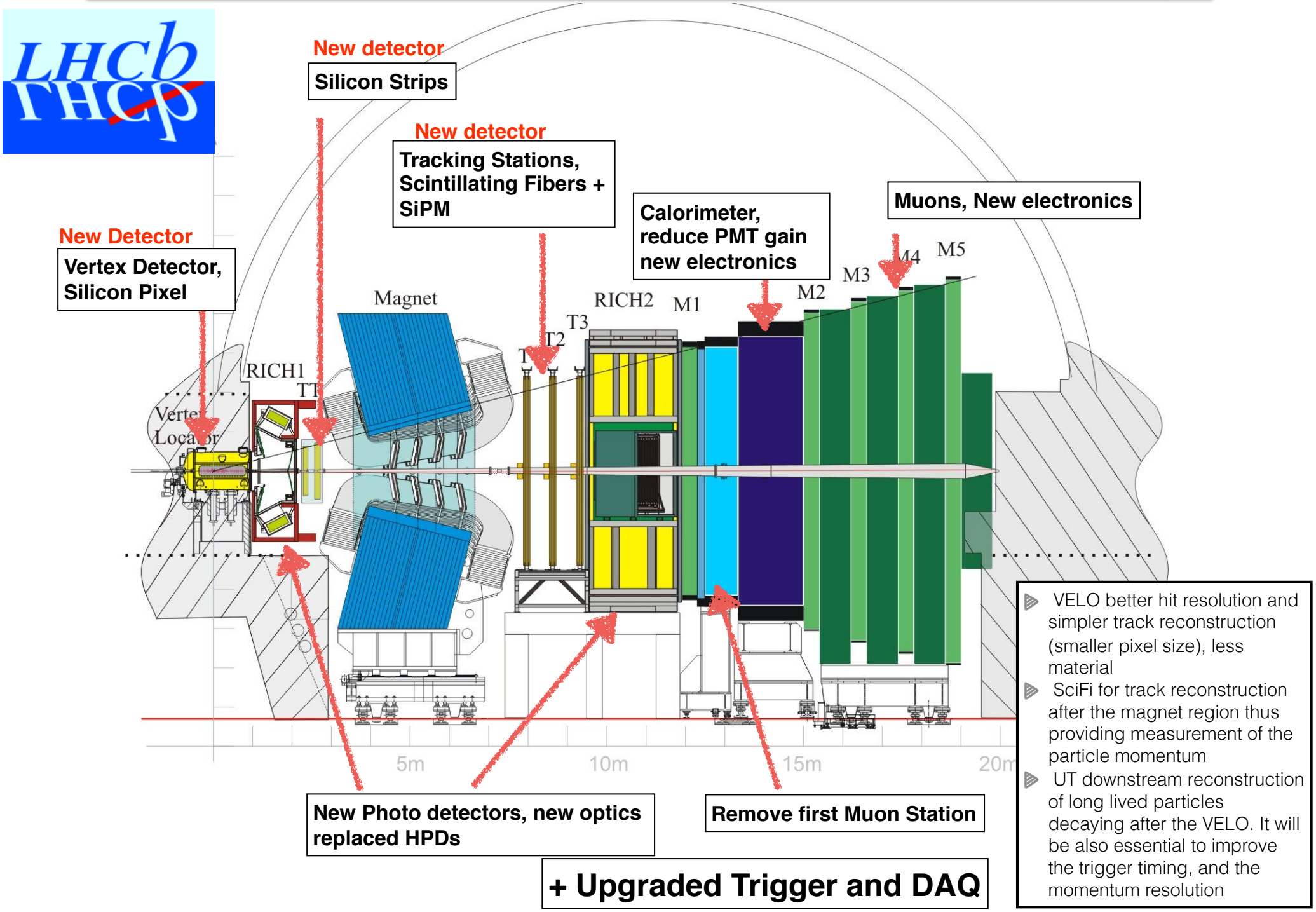
- **The E-Cal Proposal**
- Instrument forward region
- Separate γ/π_0 at high energy in pp and pPb
- Si-W calorimeter with effective granularity ≈ 1mm^2

Beyond LS4

- a completely new detector without TPC
- All-silicon detector (CMOS)
- enhanced performance (very high spatial and time resolution)

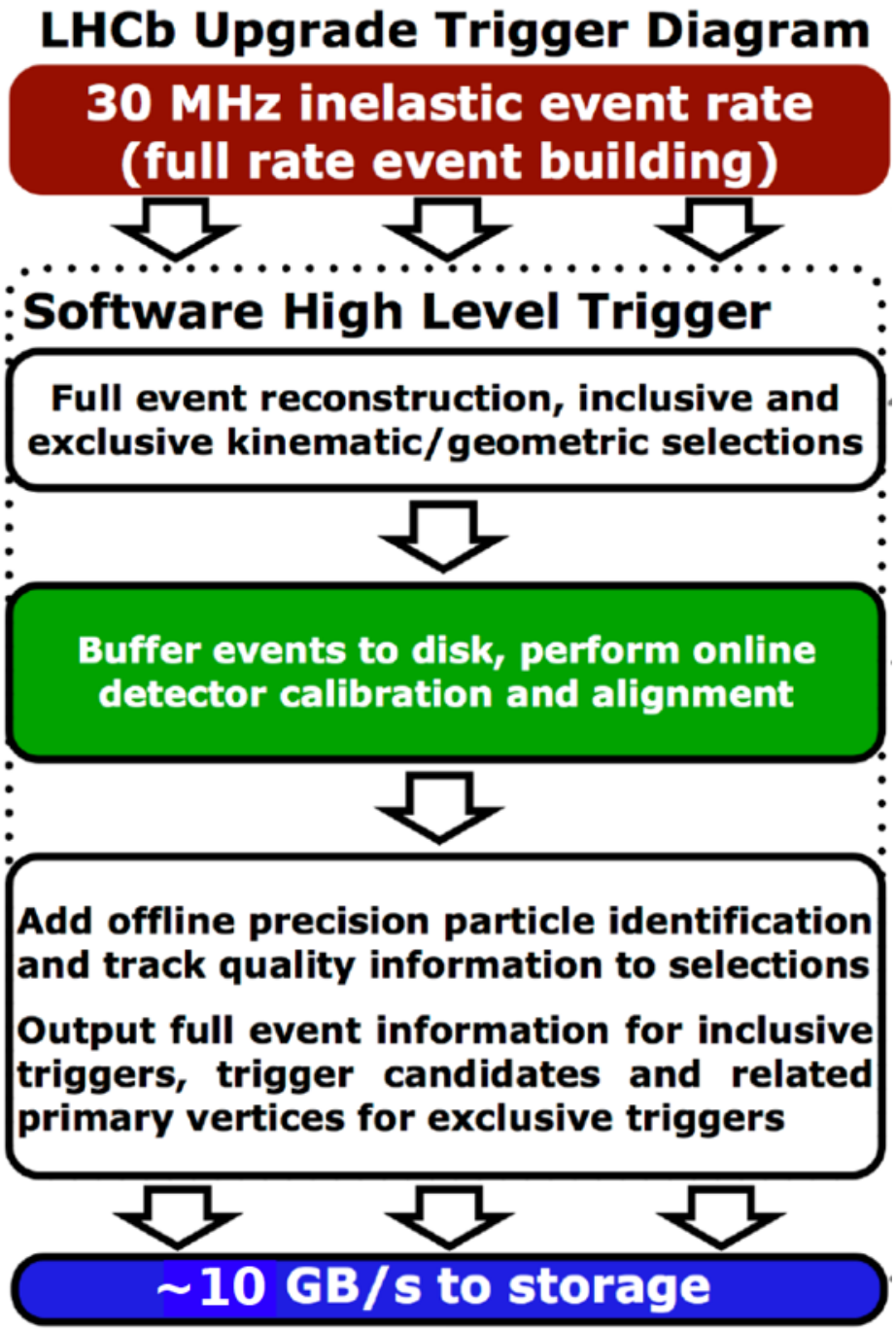


Run 3 LHCb Detector (Upgrade I)



- VELO better hit resolution and simpler track reconstruction (smaller pixel size), less material
- SciFi for track reconstruction after the magnet region thus providing measurement of the particle momentum
- UT downstream reconstruction of long lived particles decaying after the VELO. It will be also essential to improve the trigger timing, and the momentum resolution

Run 3 LHCb Detector (Upgrade I) - Trigger



CERN-LHCb-DP-2016-001, arXiv:1604.05596

Current Trigger and Limitations

- The current trigger strategy at LHCb - L0 40 MHz up to 1 MHz (calorimeters and the muon based)
- HLT performs partial event reconstruction at the rate of 1 MHz
- Selected events are stored at a rate of 12.5 KHz.
- current readout and triggering scheme is a limiting factor for the trigger
- trigger yield on many hadronic channels already saturates at the current luminosity

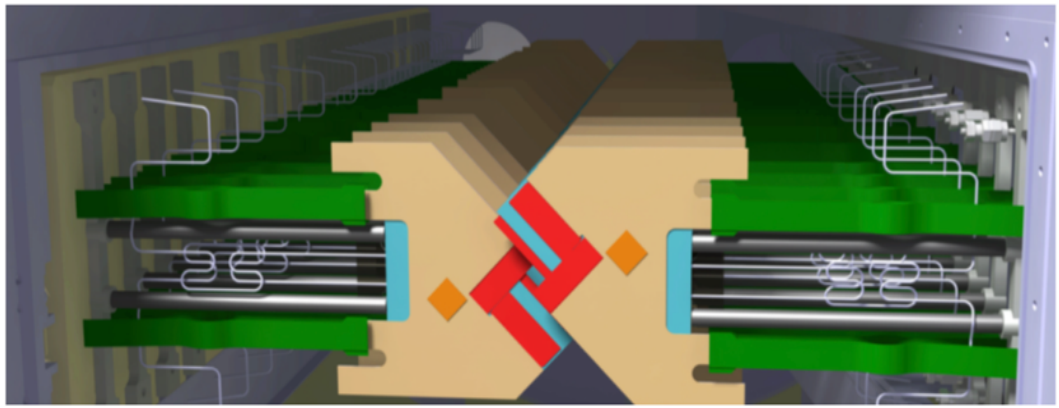
Upgrade I - trigger

- 40 MhZ readout
- Remove hardware trigger
- Tracking followed by high efficiency displaced tracks inclusive sections
- Perform a fast reconstruction for real-time alignment and calibration
- Online quality= offline quality
  - no need for further processing
- Increased output rate to storage
- Analysis on Trigger Objects, only save what is necessary from event

CERN-LHCC-2018-007 ; LHCB-TDR-017

Run 3 LHCb Detector Tracking System

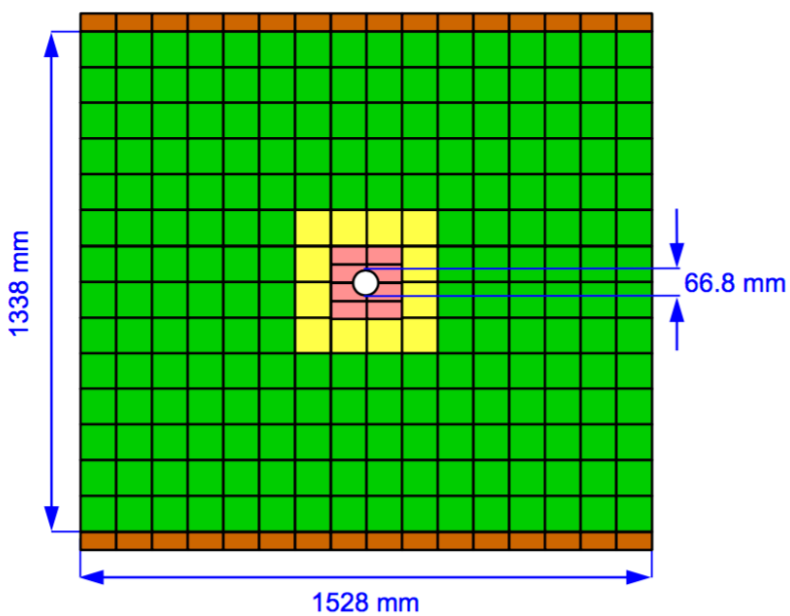
VELO



(a)

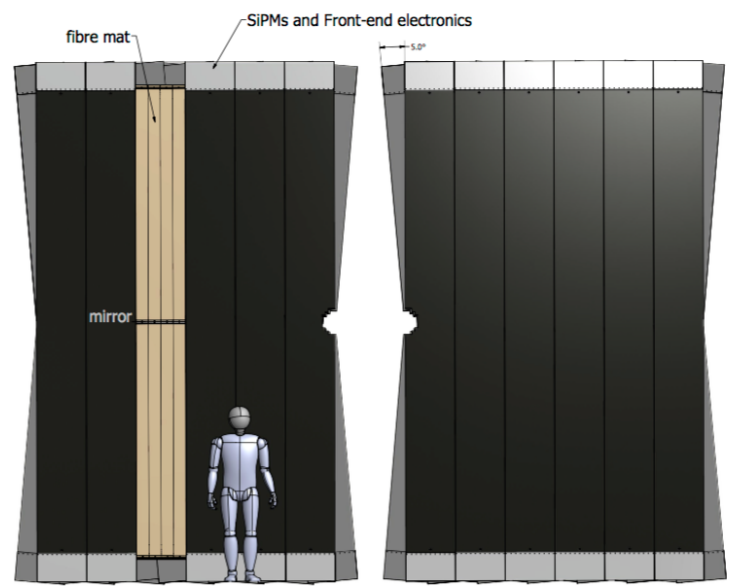
- better p_T resolution
- drastic reduction in ghost rate
- large gain in reconstruction time

UT



(b)

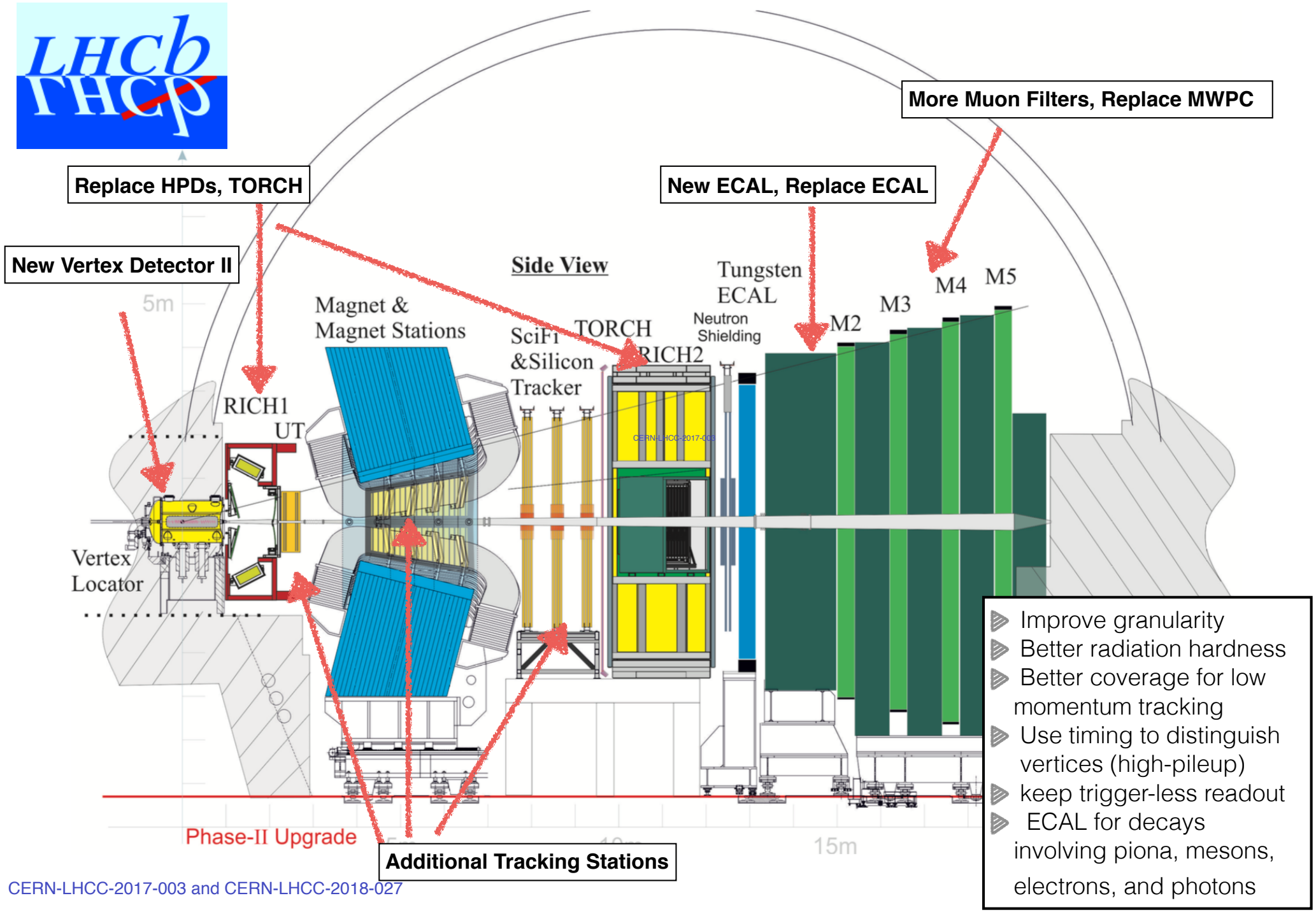
SciFi



(c)

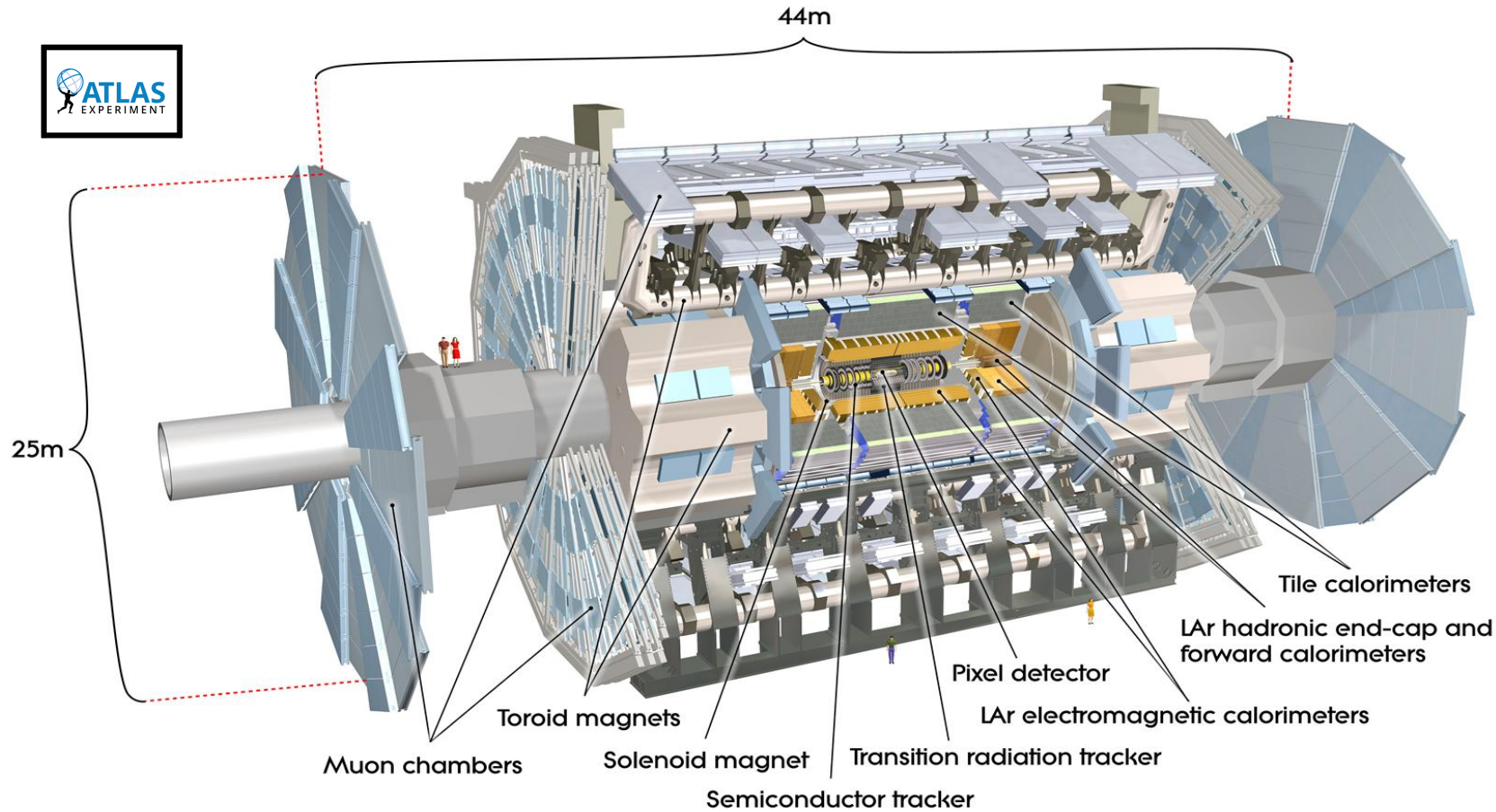
CERN-LHCC-2013-021 and CERN-LHCC-2014-001

LHCb Upgrade II



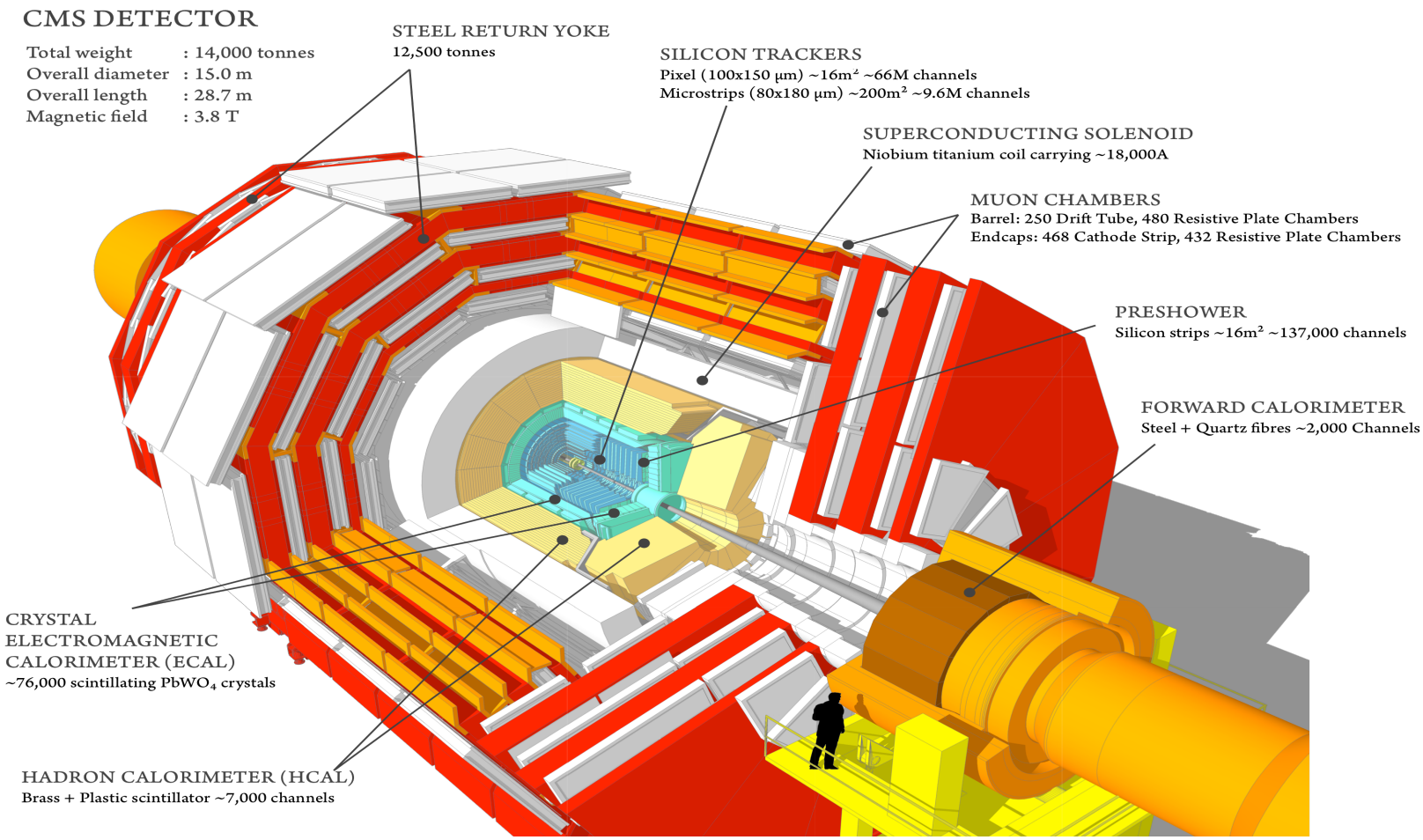
CERN-LHCC-2017-003 and CERN-LHCC-2018-027

ATLAS Upgrade I - LS2



- Consolidation of LHC ATLAS - Preparation for HL-LHC ATLAS
- Better trigger capabilities (efficiency, fake rejection)
- Maintain same acceptance/p_T thresholds with higher pileup.
- Fast Track Trigger (FTK) HW based tracking of Si-tracking layers at “Level 1.5”
- High Granular L1 Calorimeter Trigger
- Muons: New Small Wheel (NSW), sTGC + MicroMegas (trigger & precise tracking)
- Trigger/DAQ Phase I Upgrade
  - L1Calo - improved lepton triggering,MET…
  - L1Muon - new/improved sector logic

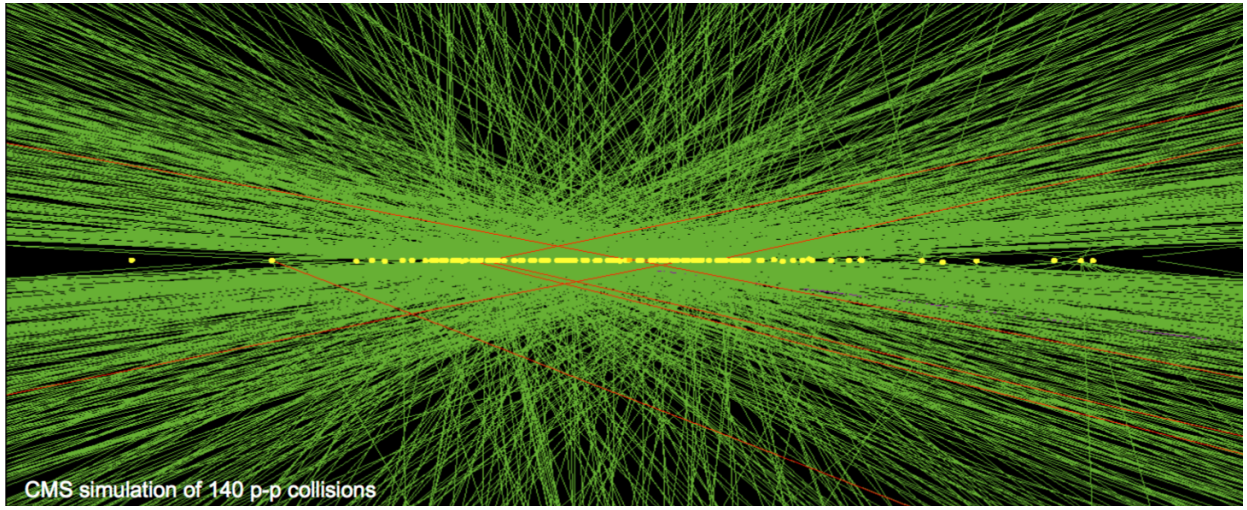
CMS Upgrade I - LS2



- Consolidation of LHC CMS - Preparation for HL-LHC CMS
- Phase-1 Pixel Detector installed in YETS (early 2017)
- HCAL Upgrade HPD—>SiPM End-cap done in 2017/2018
- CSC endcap muon chamber New front-end
- Installation of GEM chamber GE1/1
- Installation of Phase2 beam pipe
- Trigger modification to accomodate Muon and Calo changes

Phase II - Challenges and Strategy

- Luminosity of up to 7.5×10^{34} $cm^{-2}s^{-1}$
- up to 200 events/ 25 ns bunch crossing
- Higher pile-up, higher occupancy



Simulation of the reconstruction of 140 pileup p-p collisions in the CMS tracker

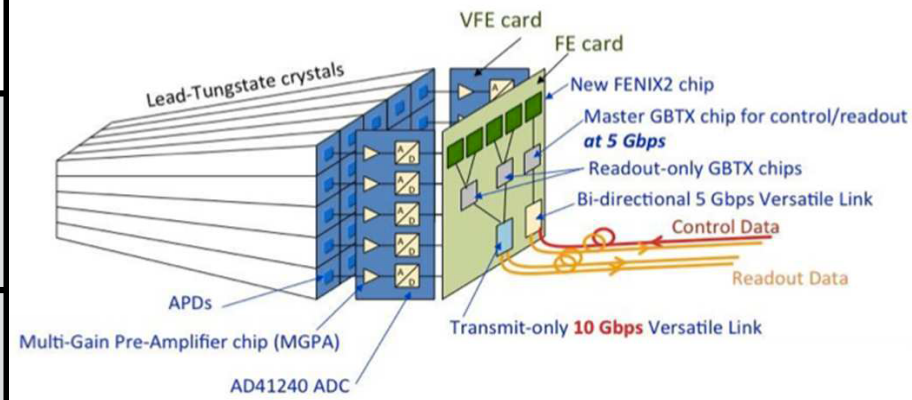
ttbar event with 140 pile-up events (ATLAS simulation)

- Major modification of the detector, trigger and DAQ system.
- Need higher detector granularity
- Increase HW trigger latency and enhanced processing capabilities to maintain good efficiency
- Hardware tracking to provide track information to the trigger
- Timing and fine granularity (tracker, calorimeters) to mitigate pile-up

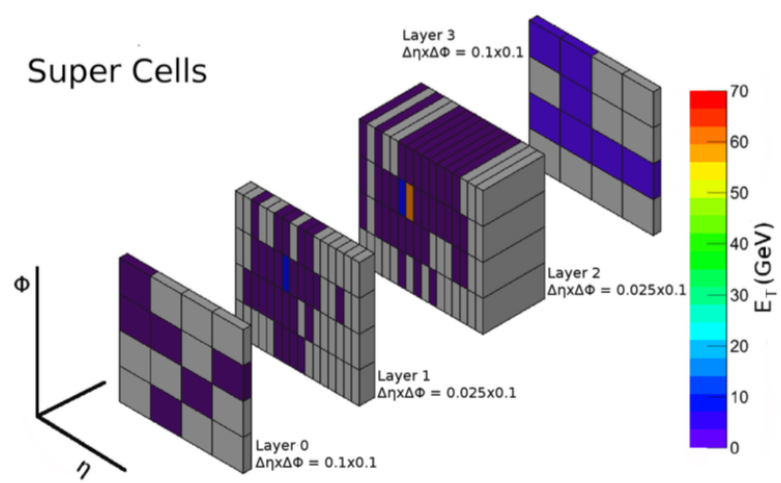
ATLAS and CMS Phasell Upgrades at a glance

	ATLAS EXPERIMENT	CMS
Pixel Detector	New, Radiation tolerant - higher granularity, extended coverage forward region	New, Radiation tolerant - higher granularity, extended coverage forward region
Tracker	New, all silicon, extended coverage forward region high granularity timing detector	New, all silicon, extended coverage forward region
Calorimeters	New FE electronics for Tile and LAr (trigger), replace FCAL if required	replace full endcaps (longevity), FE electronics in ECAL barrel for trigge
Muon system	additional forward chambers - new FE electronics in DT chambers (longevity & trigger)	new FE electronics for trigger
Timing	New, track-to-vertex association, pile up mitigation, Coverage 2:4 < η < 4	New, track-to-vertex association, pile up mitigation, Coverage η < 3
Trigger/DAQ	Upgrade, add tracking at Level 1, new back-end electronics	Upgrade, add tracking at Level 1, new back-end electronics

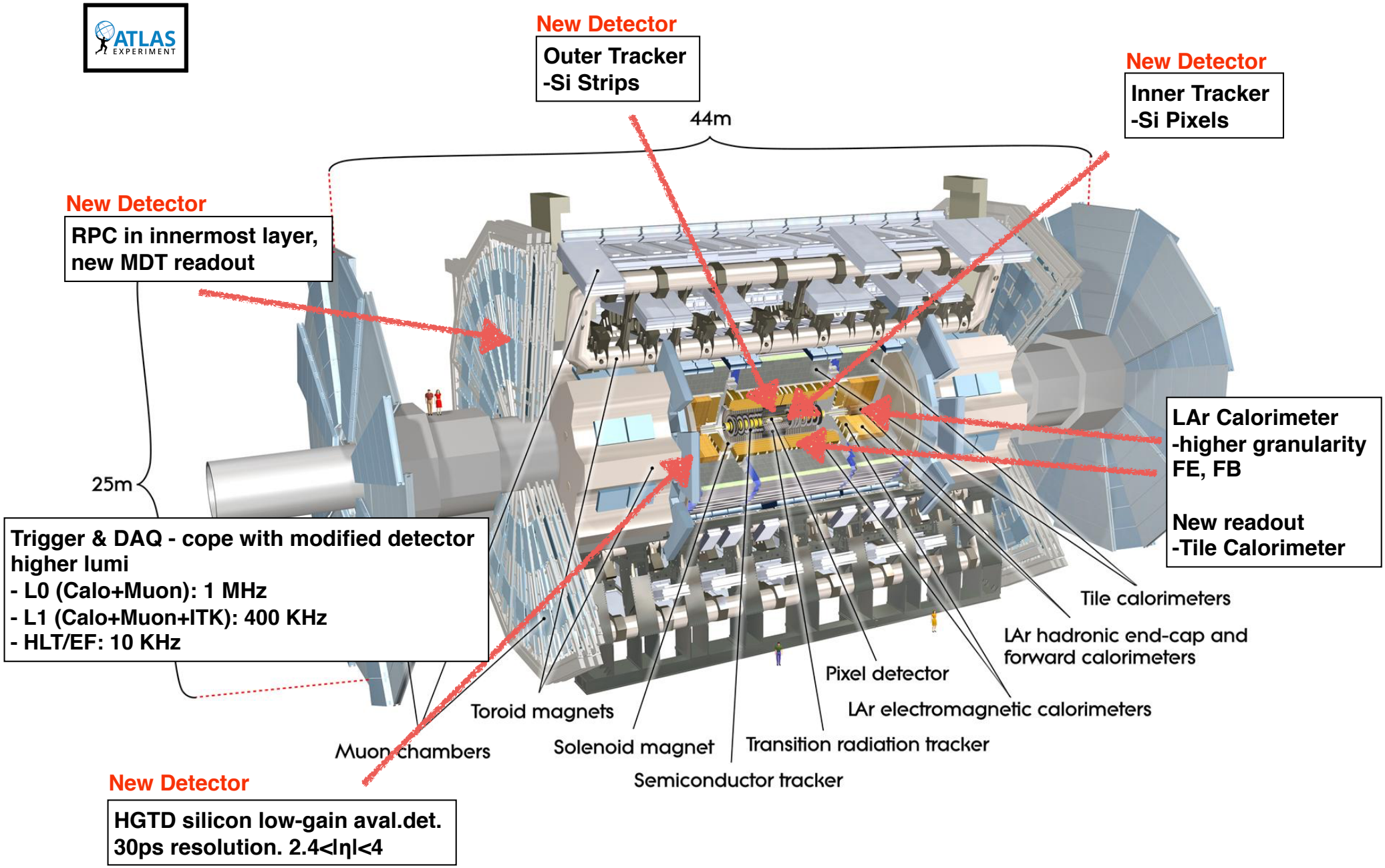
CMS - Barrel Calorimeters crystal readout



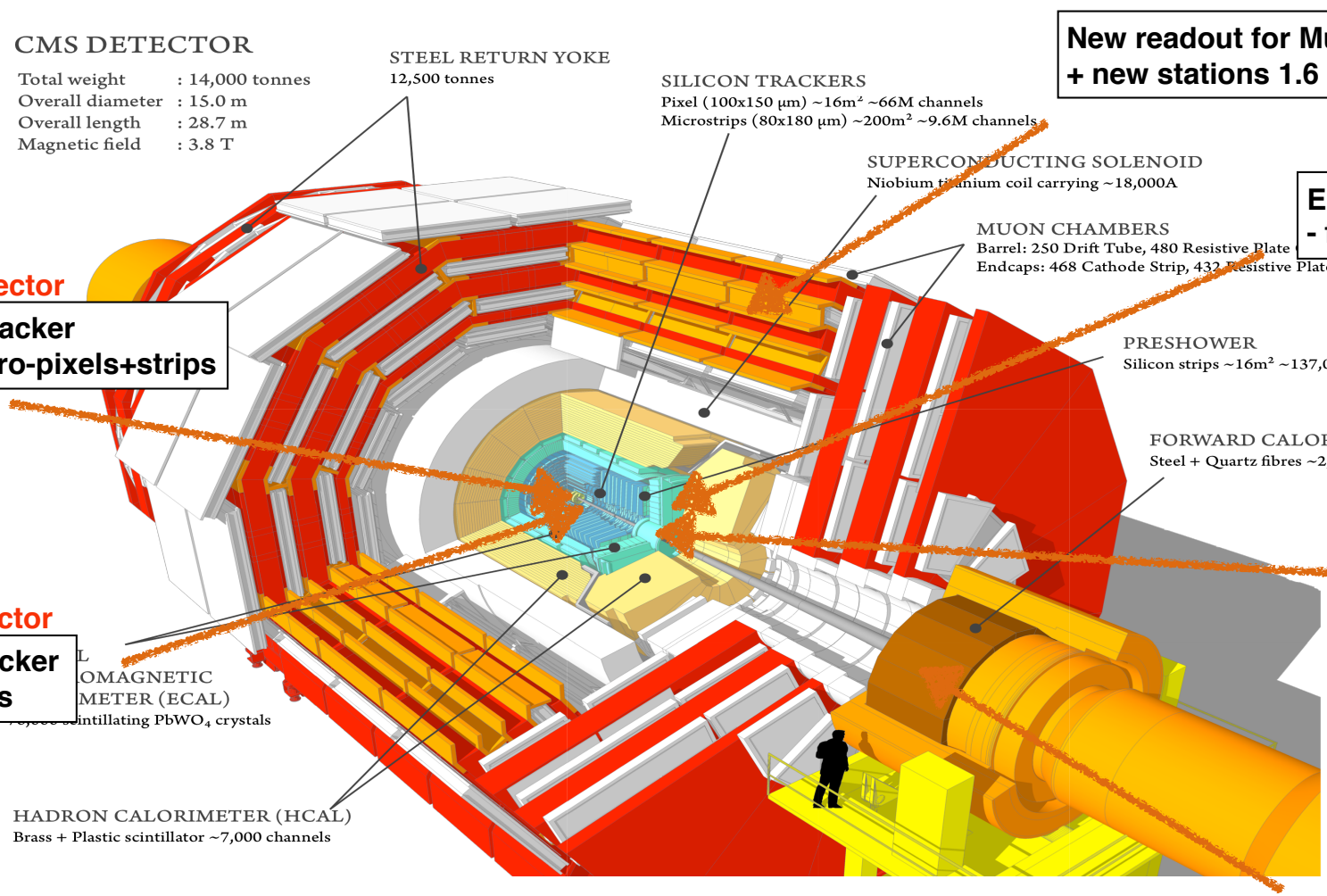
ATLAS - Super Cells designed for LAr trigger upgrades



ATLAS Phase II upgrades



CMS Phase II upgrades



New readout for Muon system + new stations 1.6 < η <2.4

ECAL barrel readout - full granularity @ 40 MHz

New Detector

Outer Tracker - Si macro-pixels+strips

New Detector

MIP timing σ_t= ~30 ps

New Detector

Inner Tracker - Si Pixels

New Detector

Endcap Calorimeter 4D showers, σ_t= ~20 ps

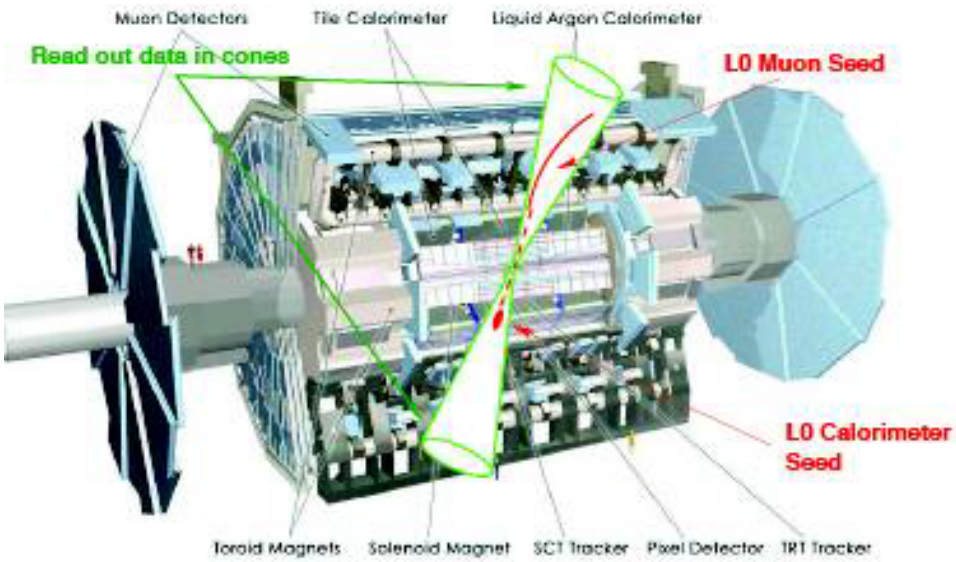
L1-Trigger/HLT/DAQ - cope with modified detector higher lumi
- **Tracks in L1-Trigger at 40 MHz**
- **PFlow-like selection 750 kHz output**
- **HLT output 7.5 kHz**

ATLAS and CMS Phase II Trigger

- Tracks in Trigger, high granularity, improve single lepton trigger, sensitive to EW scale
- Pileup mitigation techniques using tracks in the trigger, improve hadronic triggers

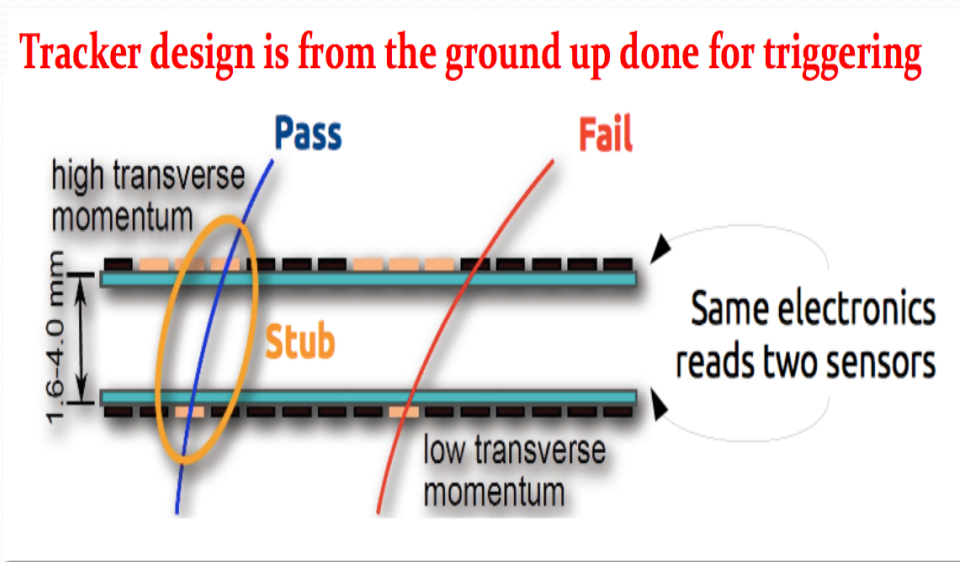
ATLAS [CERN-LHCC-2017-020]

- Being installed:Fast TracK Trigger (FTK) at L2, 25μs, pattern recognition with associative memories (AM), track fitting in FPGAs
- 'Pull architecture'
- HL-LHC: L0 trigger (Calo/Muon) reduces rate within ~6 μs to ≳ 500 kHz and defines 'regions of interest' (RoIs)
- L1 track trigger extracts tracking info inside RoIs from detector FEs
- HW trigger accept 1 MHz (10 μs)
- z-resolution < ~10 mm
- Data storage 10kHz



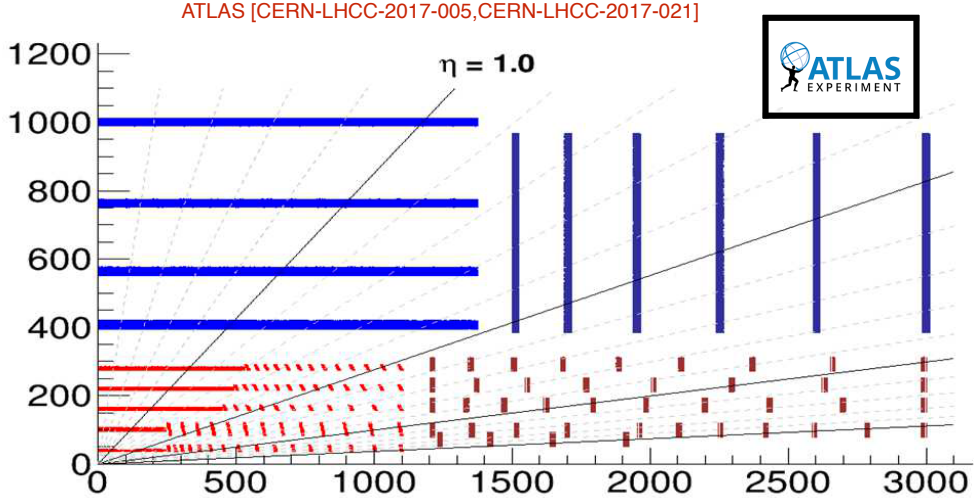
CMS [CERN-LHCC-2017-013,014]

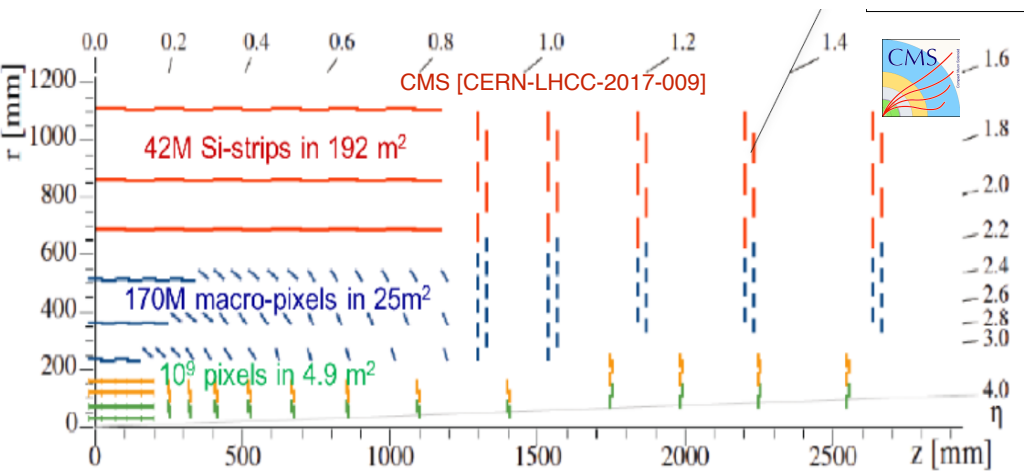
- 'Push architecture' for outer tracker
- Track segment selection at front-ends based on pt measurement (at 40 MHz)
- ~1mm primary vertex resolution
- Pattern recognition and track fit at L1 in off-detector electronics (AM+FPGAs)
- HW trigger accept 750 kHz (12.5 μs)
- Data storage 7.5 kHz
- Explore 'pull architecture' for pixel b tags at L1



ATLAS and CMS Phase II Tracker

ATLAS [CERN-LHCC-2017-005,CERN-LHCC-2017-021]





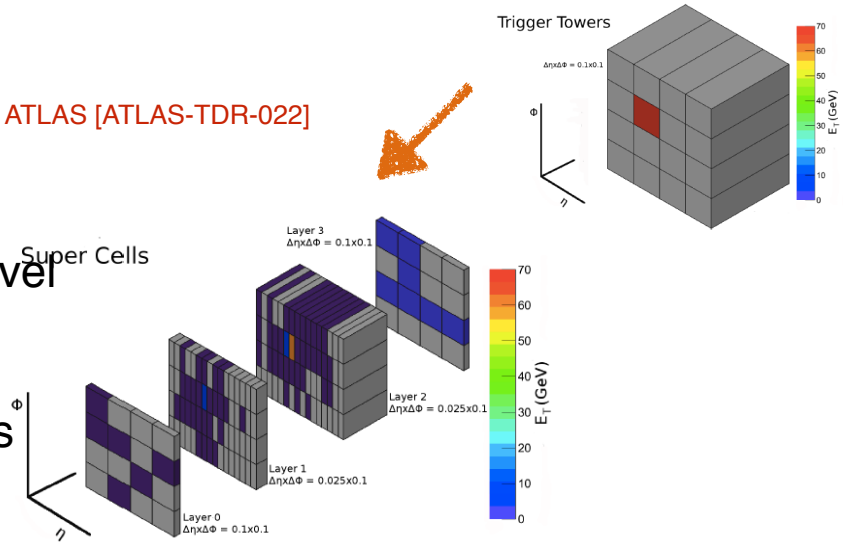
Tracker		ATLAS	CMS
Inner (Pixels)	Layers (B+EC)	5 + 9	4 + 12
	Area	~13 m^2	4.9 m^2
Outer	Layers (B+EC)	4 + 6	6 + 5
	Area	163 m^2	192 m^2

- Reduced material in active volume wrt Phase I
- Improved IP and vertex resolution
- Extended coverage
  - $|\eta| < 2.5 \rightarrow |\eta| < 4.0$
  - VBF processes and improved association of tracks to jets for PU mitigation
- Pixel: mix of technologies
  - planar n-in-p, 3D, CMOS 50 x50 and 25 x100μm²
- Strip: pitch ~ 60-90 μm & length ~ 2.5 – 5 cm
  - CMS: back-to-back sensors, p_T measurement in the readout
  - ATLAS: stereo-angle between sensors on double sided structure.
- A lot of optimisation to minimize the pile-up influence (computing time, b-tagging, jet-reco, ...)

ATLAS and CMS Phase II Calorimetry

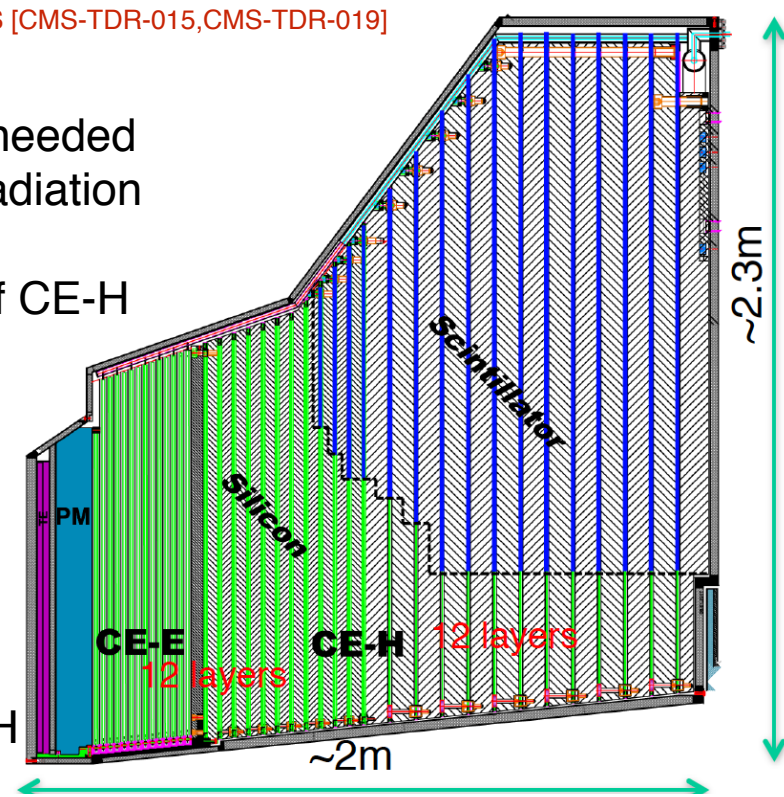
- Exploiting the higher resolution and longitudinal shower information from the calorimeter for better energy resolution / signal discrimination at trigger level
- LAr Calorimeter - higher granularity FE, FB
  - High Granular L1 Calorimeter Trigger
- Tile Calorimeter: replace HV, FE and BE electronics

ATLAS [ATLAS-TDR-022]



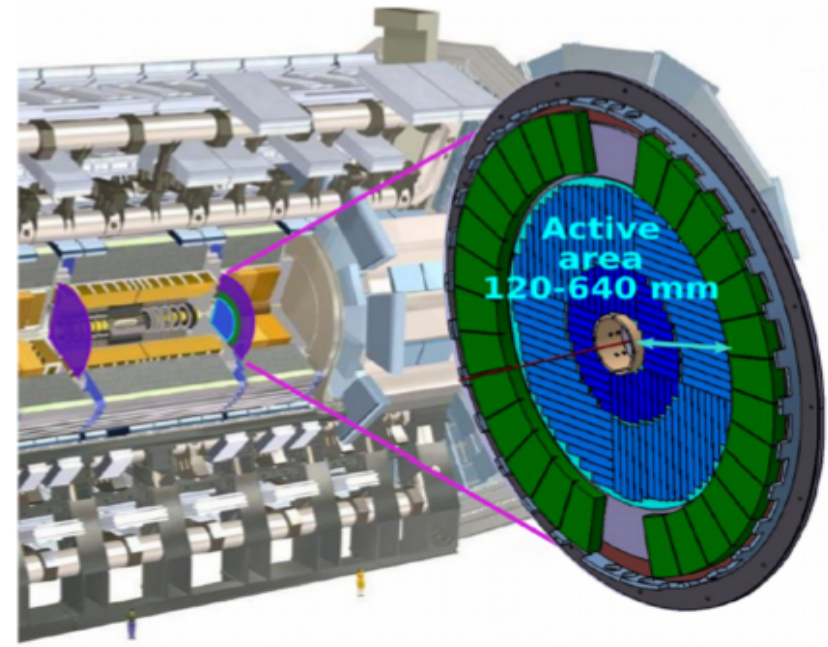
- High granularity calorimeter for particle flow
- VBF identification and hadr. tau-jets, PU rejection
- High fluence, especially at $|\eta| > 3$ —> Rad. hard Si + SiPMs needed
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H
- HGCAL covers $1.5 < \eta < 3.0$
- Full system maintained at -30°C
- ~600m^2 of silicon sensors
- ~500m^2 of scintillators
- 6M Si channels, 0.5 or 1.1 cm^2 cell size, 400k scint-tile channels ($\eta-\phi$)
  - Data readout from all layers
  - Trigger readout from alternate layers in CE-E and all in CE-H

CMS [CMS-TDR-015,CMS-TDR-019]



ATLAS and CMS Phase II Timing

- Timing layer needed as track-to-vertex association is ambiguous when tracking z-resolution is larger than separation between vertices
- Key component for pile-up mitigation techniques, in particular for jet reconstruction. Compliment calorimeter timing informations
- Unique discovery potential for Long Lived Particles
  - https://indico.cern.ch/event/793591/
  - https://indico.cern.ch/event/792346/contributions/3426226/attachments/1852203/3041097/14_TimingLLP_ZhenLiu_CERNLLP2019.pdf
- Different strategy for timing layer
  - ATLAS forward
  - CMS central



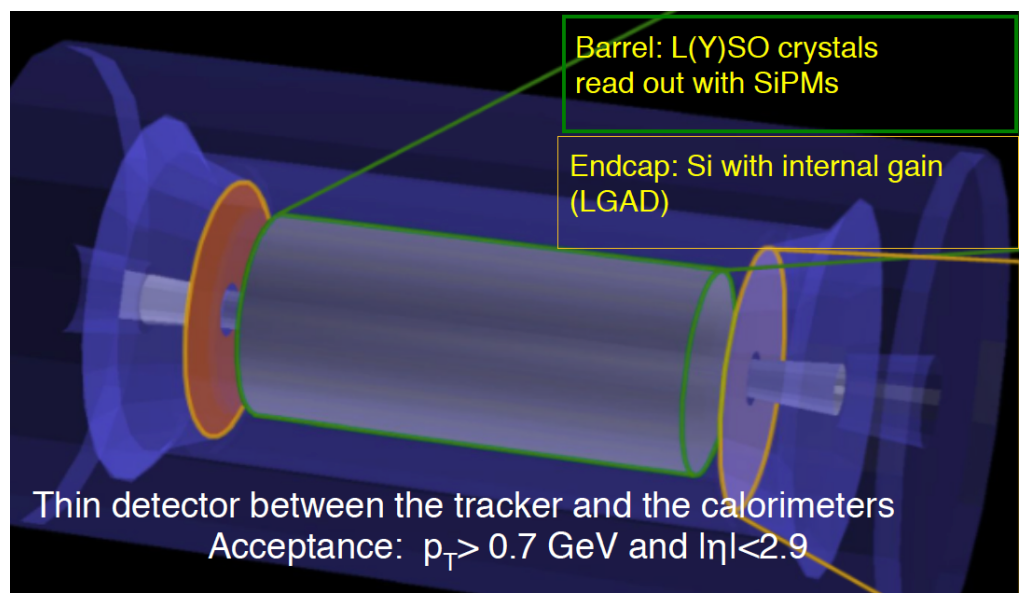
- Scintillators (LYSO:Ce) and SiPM for lower irradiation areas

ATLAS EXPERIMENT

- LGAD Silicon sensors , O(mm^2) channels
- 30 ps per tracks
- Coverage 2:4 < η < 4

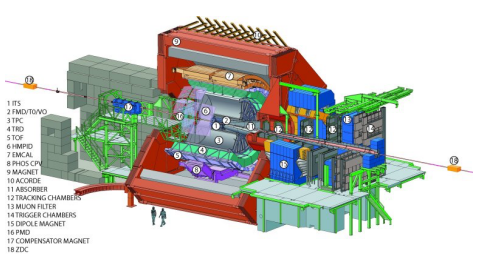
CMS

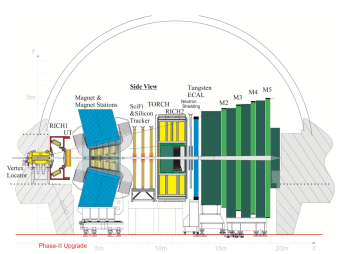
- LYSO:Ce crystals with SiPM (Barrel), *O*(cm^2) channels
- LGAD Silicon sensors (Endcaps), *O*(mm^2) channels
- 30-40 ps per tracks
- Coverage η < 3

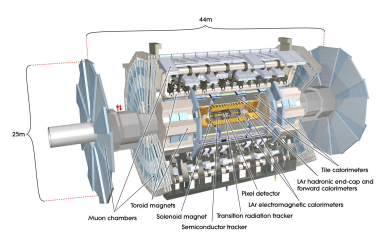


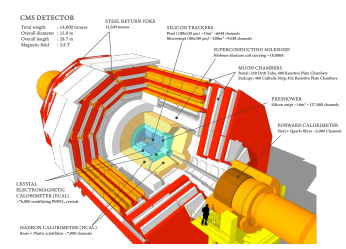
Run 3 and HL-LHC Outlook

- HL-LHC: 7.5×10^{34} $cm^{-2}s^{-1}$, 200 pileup, 3000 fb^{-1}
- Great physics potential, very challenging environment
- Comprehensive Upgrade programs for ATLAS, LHCb, CMS
- Currently TDRs are being published or have been published for the subsystems
- ALICE undergoing a major upgrade completed in 2020 for Run 3
- Another 150fb^{-1} to be collected by ATLAS CMS phase I detectors and more upgrade proposals in view of Run 4
- LHCb Upgrade I soon to be installed, 50 fb^{-1} by 2029, 300 fb^{-1}1 by 2036 if Upgrade II.
- ATLAS and CMS will be fully upgraded by 2026, expect 3000 fb^{-1} by 2037
- A matching collaborative computing and software effort to meet HL-LHC challenging experimental conditions (not covered in this talk) https://indico.cern.ch/event/651352/contributions/2960318/attachments/1630863/2599645/WLCG_Strategy_towards_HL-LHC.pdf, arXiv:1712.06982
- The hardware modifications opens new possibilities for LLP community
- Busy and exciting years ahead of us!



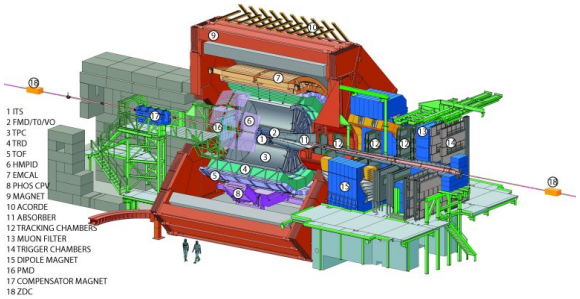






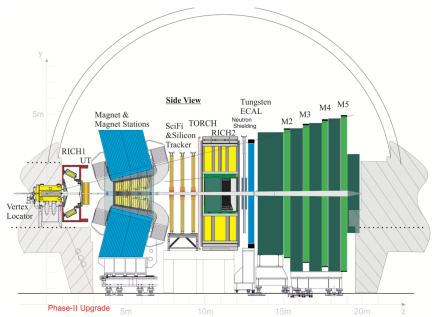
Thanks to colleagues - a lot of material borrowed from their slides

Public available Links to referred and further information on Phase-2 upgrade



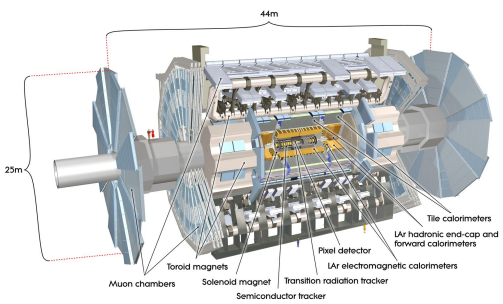
ALICE

CERN-LHCC-2012-012, LHCC-I-022
CERN-LHCC-2013-014, LHCC-I-022-AOD-1
CERN-LHCC-2012-005, LHCC-G-159, 2012
CERN-LHCC-2013-024, ALICE-TDR-017
CERN-LHCC-2013-020, ALICE-TDR-018
CERN-LHCC-2013-018, ALICE-TDR-015
CDS ALICE-PUBLIC-2018-013
arXiv:1812.06772, arXiv:1902.01211



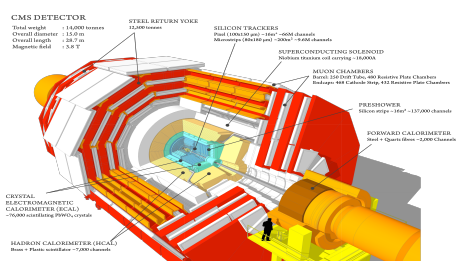
LHCb

Software and Computing (Run 3) CERN-LHCC-2018-007
Velo (Run 3) CERN-LHCC-2013-021
EOI Phase-II CERN-LHCC-2017-003



ATLAS EXPERIMENT

ITk Pixel TDR CERN-LHCC-2017-021
ITk Strip TDR CERN-LHCC-2017-005
LAr TDR CERN-LHCC-2017-018
Tile TDR CERN-LHCC-2017-019
Muon TDR CERN-LHCC-2017-017
TDAQ TDR CERN-LHCC-2017-020
Timing Detector CERN-LHCC-2018-023



CMS

Tracker CERN-LHCC-2017-00
Muon CERN-LHCC-2017-012
Barrel CERN-LHCC-2017-011
Endcap CERN-LHCC-2017-023
MTD CERN-LHCC-2017-027
L1 Trigger (Interim TDR) CERN-LHCC-2017-013
DAQ/HLT (Interim TDR) CERN-LHCC-2017-014

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