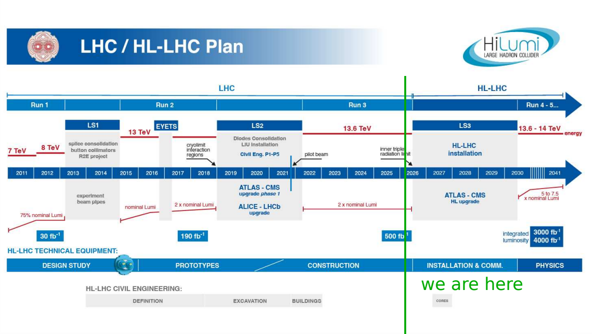
LHC Upgrades

Silvia Gambetta

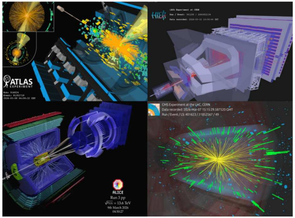
IOP Joint APP and HEPP Annual Conference 2026

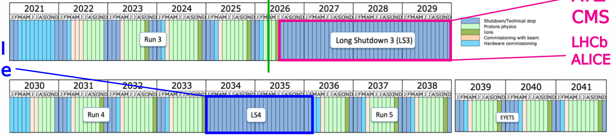
LHC Upgrades: when? Timeline of High Lumi projects



we are here

Event displays from
7 March, "last first injection"
of Run3





ATLAS CMS } **Phase-II Upgrade**

LHCb ALICE } **Enhancements**

LHCb ALICE } **Phase-II Upgrade**

Last months of Run 3 data taking ongoing: end of Run foreseen on the 30 June

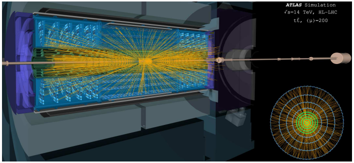
Last dance for many sub-systems with major Phase-II Upgrade foreseen for ATLAS and CMS, plus enhancement programmes in LHCb and ALICE [2026-2030]

Next major Upgrade foreseen in LS4 with Phase-II Upgrade foreseen for ALICE and LHCb [2034-2036]

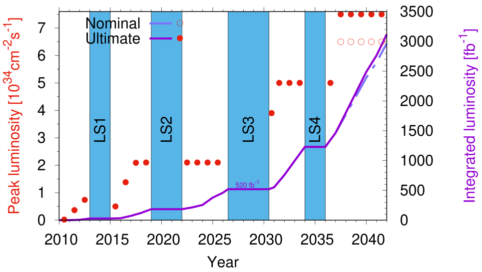
LHC Upgrades: what? A data driven era

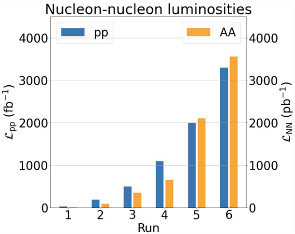
> “The full exploitation of the physics potential of the LHC and the HL-LHC and the completion of the high-luminosity upgrade remain the highest priorities of European particle physics.” [CERN-ESU-2025-002]

- Unprecedented pile-up conditions and track density
- Challenging radiation doses
- Huge volume of data to handle



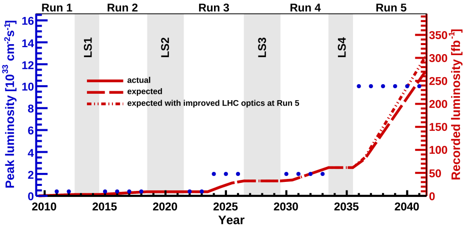
ATLAS and CMS ↓





←ALICE

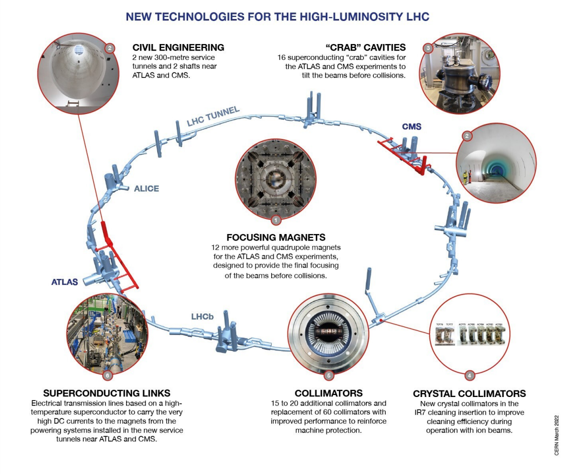
LHCb→



Huge volume of data to probe the Standard Model, perform precision measurements reaching theoretical uncertainties and search for New Physics

LHC Upgrades: how? Build a new machine

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



NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC

CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near ATLAS and CMS.

“CRAB” CAVITIES
16 superconducting “crab” cavities for the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for the ATLAS and CMS experiments, designed to provide the final focusing of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry the very high DC currents to the magnets from the powering systems installed in the new service tunnels near ATLAS and CMS.

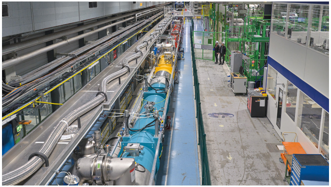
COLLIMATORS
15 to 20 additional collimators and replacement of 60 collimators with improved performance to reinforce machine protection.

CRYSTAL COLLIMATORS
New crystal collimators in the IR7 cleaning insertion to improve cleaning efficiency during operation with ion beams.

CERN March 2022

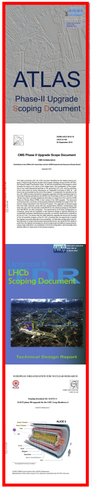
Crab cavities

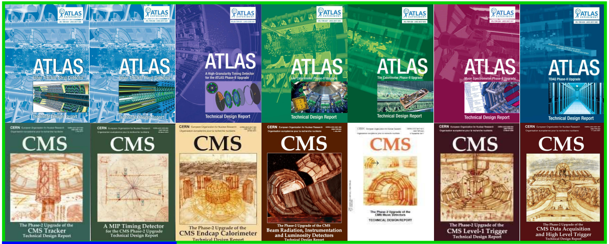
95 m long test stand



Preparation of a magnet and transfer of the beam screen to a movable bench

LHC Upgrades: but how? Build new experiments





R&D → Technical Design reports

↓

Technology consolidatoin and production

↓

construction and commissioning

Enhancements and Anticipation

Physics motivations and Scoping scenarios

Preparation for Upgrades takes over a decade

Our mantra: "Measure what is measurable and make measurable what is not so." G. Galilei

Intensity and precision frontier at High Lumi LHC still has a lot to deliver: less than 20% of the LHC data will be collected by the end of Run3

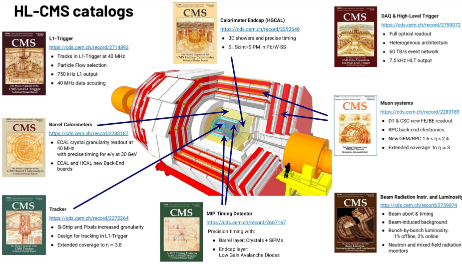
LHCC-G-166
ATLAS-TDR-025
ATLAS-TDR-030
ATLAS-TDR-031
ATLAS-TDR-022
ATLAS-TDR-028
ATLAS-TDR-026
ATLAS-TDR-029

LHCC-G-165
CMS-TDR-014
CMS-TDR-020
CMS-TDR-019
CMS-TDR-023
CMS-TDR-016
CMS-TDR-021
CMS-TDR-022

LHCB-TDR-026
LHCB-TDR-024
LHCB-TDR-025

LHCC-G-185
ALICE-TDR-022
ALICE-TDR-021

LHC Upgrades: The challenge



HL-CMS catalogs

L1-Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting

Calorimeter Endcap (HGCAL)
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

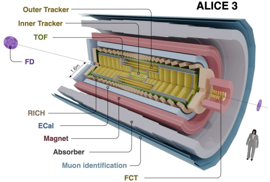
Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz
  with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

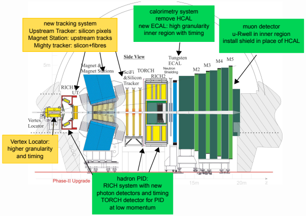
Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

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/2667167
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer:
  Low Gain Avalanche Diodes

Beam Radiation Instr. and Luminosity
http://cds.cern.ch/record/2759074
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity:
  1% offline, 2% online
- Neutron and mixed-field radiation monitors





new tracking system
Upstream Tracker: silicon pixels
Magnet Station: upstream tracks
Mighty tracker: slicon+fibres

calorimetry system
remove HCAL
new ECAL: high granularity
inner region with timing

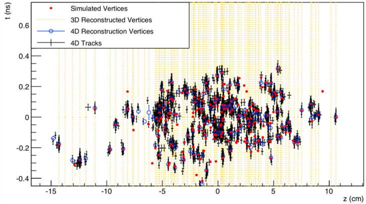
muon detector
u-Rwell in inner region
install shield in place of HCAL

Vertex Locator:
higher granularity
and timing

hadron PID:
RICH system with new
photon detectors and timing
TORCH detector for PID
at low momentum

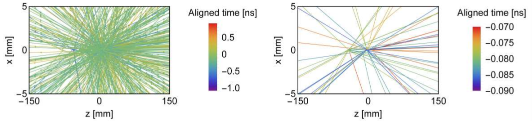
Faster: Introduction of timing; higher granularity coupled with timing in tracking and in Particle Identification, to cope with peak occupancy and improve reconstruction
Higher: Increase coverage; increase instrumented areas with strategic technology
Stronger: Cope with unprecedented radiation level; handle huge volume of data and increasing bandwidth

Faster: Timing



From MIP TDR

Exploit the separation in both time and space of the *pp* collisions: separation in time corresponds essentially to the time-of-flight for the length of a bunch



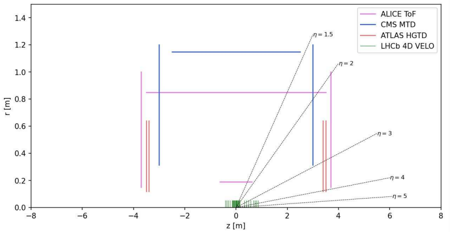
From LHCb Framework TDR

$\sigma_t = \sigma_{\text{bunch}}/\sqrt{2}c \sim 180\,\text{ps} \Rightarrow$ time resolution tens of ps $\ll \sigma_t$

- ALICE 3 Time Of Flight (TOF) ~ 20 ps
- ATLAS High Granularity Timing Detector (HGTD) ~ 50 ps
- CMS MIP Timing Detector (MTD) $\sim 30 - 50$ ps
- LHCb 4D VErtex LOcator (VELO) < 20 ps

See excellent review of timing in trackers by G. Pizzati at LHCP 2025

Timing is a key technique in LHC Upgrades also beyond tracking

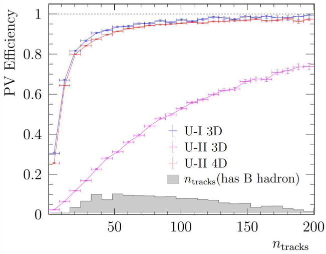


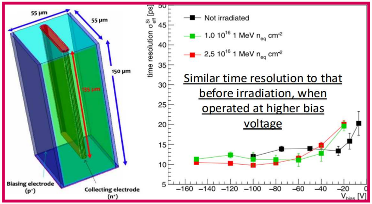
Detector	Acceptance	Technology	Pitch	Layers
HGTD	$2.4 < \lvert\eta\rvert < 4.1$	Silicon/LGAD	1.3 mm	4+4
Barrel TOF	$\lvert\eta\rvert < 1.75$	Silicon	1 →5 mm	1+1
Forward TOF	$1.75 < \lvert\eta\rvert < 4$	Silicon	1 →5 mm	1+1
BTL	$\lvert\eta\rvert < 1.45$	LYSO+SiPM	~ 3 mm	1
ETL	$1.6 < \lvert\eta\rvert < 3.0$	Silicon/LGAD	1.3 mm	4+4
VELO	$2 < \eta < 5^*$	Silicon	$\leq 55\,\mu$m	> 26 ?

Faster: LHCb Velo

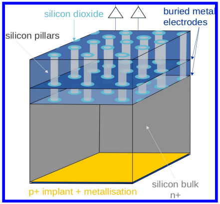
4D VErtex LOcator in LHCb for time stamping of Primary Vertexes Run 5

- Introduction of timing essential to retain PV reconstruction efficiency in LHCb Upgrade II conditions
- 3D Sensors: ideal solution for both timing and radiation-tolerance
- Timing and radiation tolerance proven with trench-type silicon sensors [TimeSpot]
- R&D at early stage on Silicon Electron Multiplier to study potential for high electric field [SiEM]



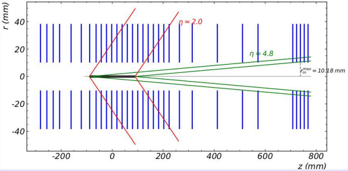


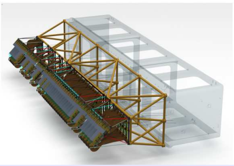
Similar time resolution to that before irradiation, when operated at higher bias voltage

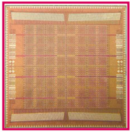


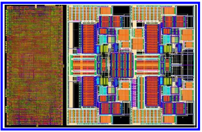
Two ASICs considered (28nm CMOS)

- IGNITE: 3D integration (one ASIC for analog, one for digital)
- Picopix: On-pixel analog power drop compensation



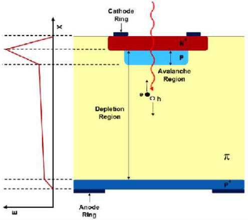


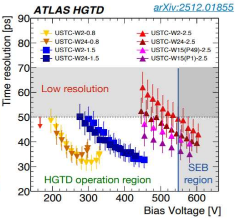




Faster: ATLAS HGTD

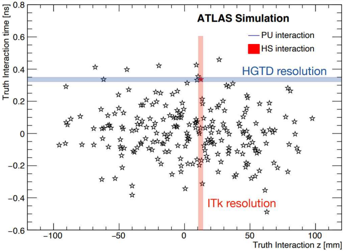
High Granularity Timing detector in ATLAS for time stamping tracks Run 4





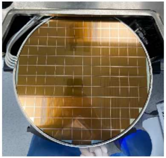
Vertex time information as new dimension to identify pileup

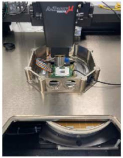
Instruments the forward region: 3.6M channels

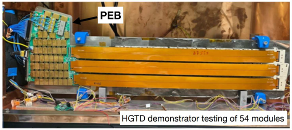


LGAD selected as sensors [characterisation on beam]

(15x15 pads, 1.3x1.3 mm^2 pad size, 775 μm device thickness, 50 μm active region)



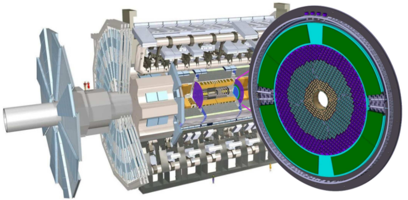




HGTD demonstrator testing of 54 modules

HGTD assembly stand

ALTIROC as ASIC: 17 wafers ∼2000 ASIC probed for preproduction

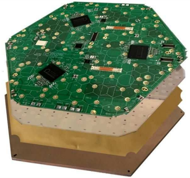


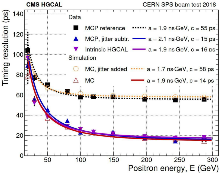
Faster: CMS HGCAL

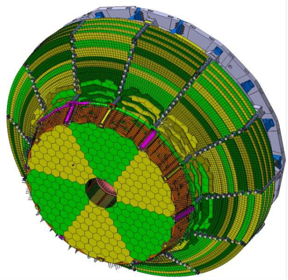
High-Granularity Calorimeter in CMS for timing of showers

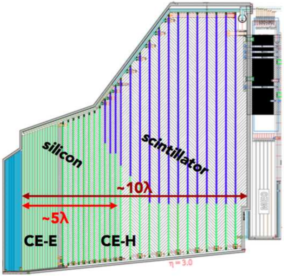
Run 4

- Electromagnetic section: Silicon with Pb and CuW absorbers, 6M silicon pads (620 m^2)
- Hadronic section: Silicon + scintillator with Cu absorbers, 240000 plastic scintillator tiles + SiPM (370 m^2)

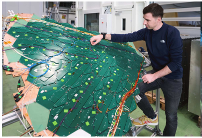


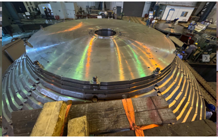






8" Silicon sensors embedded in Hexagonal silicon modules
SiPMs read out by variant of HGCROC ASIC
Timing performance verified on testbeam [see results]

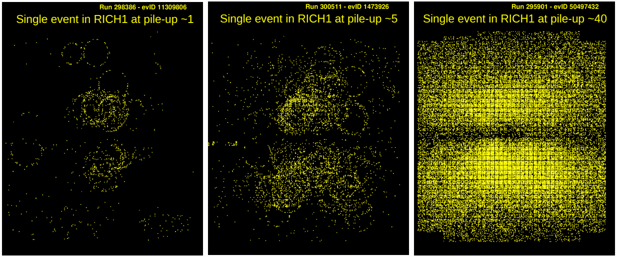


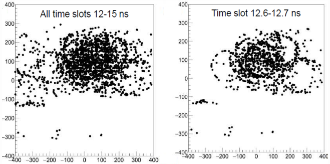


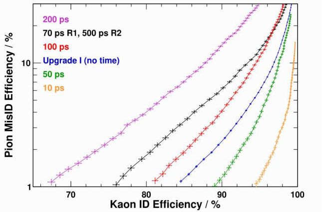
Faster: LHCb RICH

Ring Imaging Cherenkov detectors at LHCb for timing of Cherenkov rings   Run 4-5

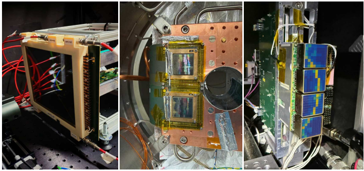
- new optics and layout to reduce peak occupancy
- timing as key ingredient to retain the Particle Identification performance

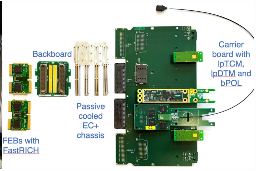






LHCB-TDR-023





FastRICH ASIC already design and version 0 being validated for the RICH LS3 Enhancement programme (replacement of FE electronics to anticipate time-resolved RICH and introduction of timing in LHCb)

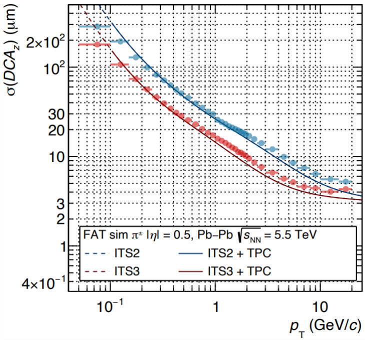
LHCB-TDR-024

Higher coverage: ALICE ITS3

Inner Tracker System 3 at ALICE

- move closer to the beam-pipe (24 mm → 19 mm)
- minimise material budget ($0.36 \to 0.07 X/X_0$ per layer)
- improve pointing resolution

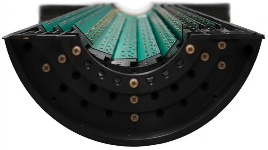
ALICE-TDR-021



Can bent silicon work?

[Operations on beam]

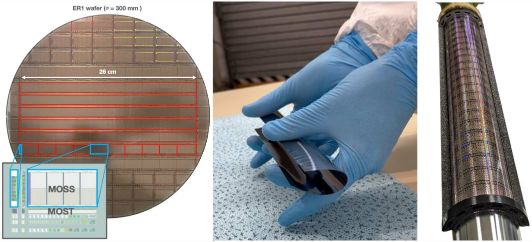
Run 4



ITS2

ITS3

First MOnolithic Stitched Sensor (MOSS) for HEP: 14x259 mm^2, 6.72 Mpixel
MOSAIX: ITS3 scale, 3 ASICs stitched together → full scale prototype



Engineering Run 2 wafers received

Higher coverage: CMS tracker

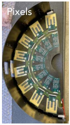
CMS-TDR-014

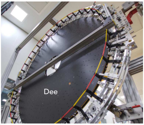
Inner Tracker

- 4 barrel layers,
- 8 small disks, 4 large discs per side
- Pixel size: 25 x 100 μm2
- 2 x 109 channels

Outer Tracker

- 6 barrel layers
- 5 discs per side
- 44 million strips
- 174 million macropixels

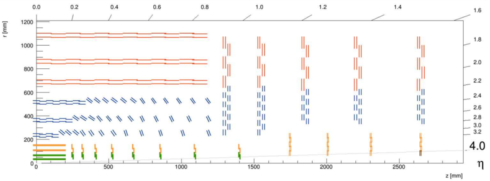


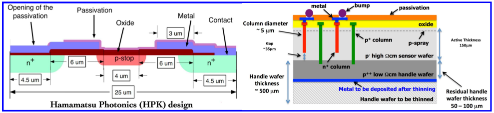


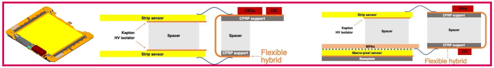
A. Canepa, LHCP 2025

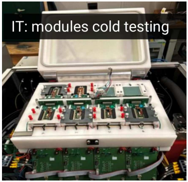
Module in production stage: assembly ongoing for both IT and OT in production centres

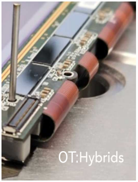
Run 4

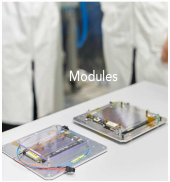








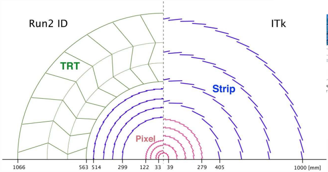


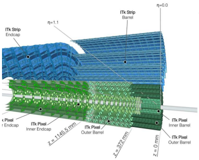


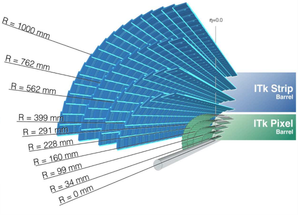
Higher coverage: ITK

Inner Tracker at ATLAS

Run 4







Pixel detectors (inner part)

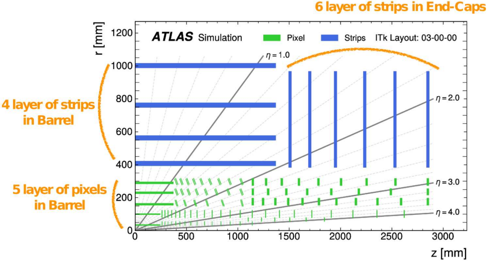
[ATLAS-TDR-030]

- 5 billion channels
- 5 layers of pixels in Barrel
- Many disks in End-Cap

Strip detectors (outer part)

[ATLAS-TDR-025]

- 60 million channels
- 4 layers of strips in Barrel
- 6 layers of strips in End-Cap



6 layer of strips in End-Caps

4 layer of strips in Barrel

5 layer of pixels in Barrel

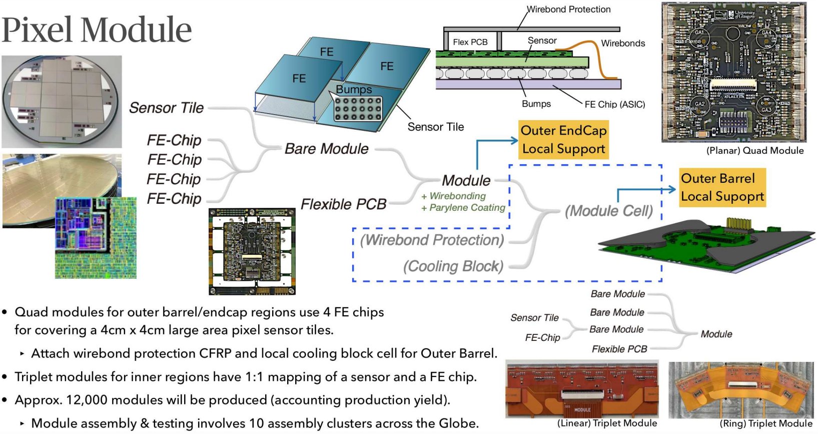
Compared to current detector (ID): Improved tracking acceptance from $|\eta| < 2.5$ to $|\eta| < 4$

	Area (in m^2)	# modules	# channels (in M)
ID Pixel	~ 2	~ 2000	~ 92
ITk Pixel	~ 13	~ 8400	~ 5100

Unprecedented scale of massive silicon detector production

ITK Pixel

[H. Oide LHCP 2025]

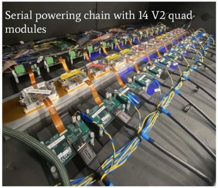


Pixel Module

- Quad modules for outer barrel/endcap regions use 4 FE chips for covering a 4cm x 4cm large area pixel sensor tiles.
  - Attach wirebond protection CFRP and local cooling block cell for Outer Barrel.
- Triplet modules for inner regions have 1:1 mapping of a sensor and a FE chip.
- Approx. 12,000 modules will be produced (accounting production yield).
  - Module assembly & testing involves 10 assembly clusters across the Globe.

Cylinder 3 insertion (CERN)

IS pixel integration mock-up

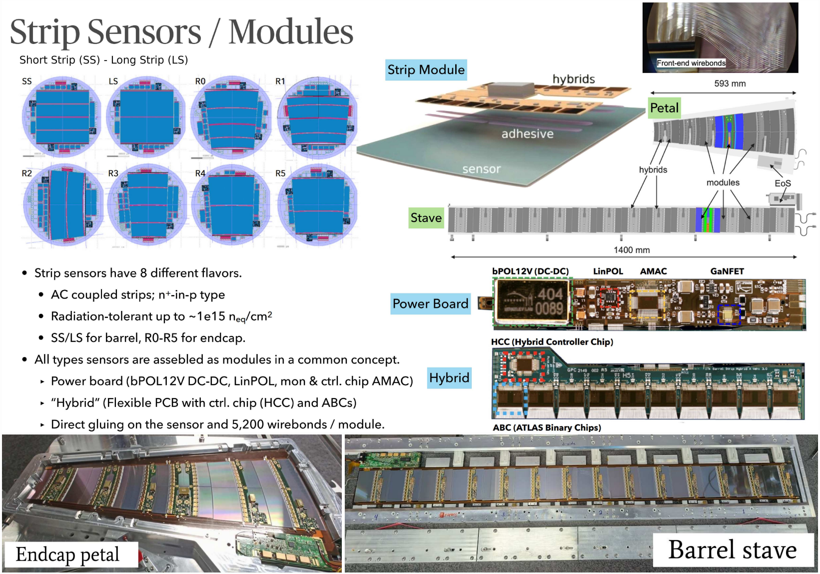


Serial powering chain with 14 V2 quad modules

[LHCC Open session]

ITK Strip

[H. Oide LHCP 2025]



Strip Sensors / Modules

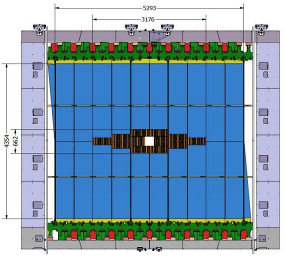
Short Strip (SS) - Long Strip (LS)

- Strip sensors have 8 different flavors.
  - AC coupled strips; n^+-in-p type
  - Radiation-tolerant up to ~1e15 n_{eq}/cm^2
  - SS/LS for barrel, R0-R5 for endcap.
- All types sensors are assebled as modules in a common concept.
  - Power board (bPOL12V DC-DC, LinPOL, mon & ctrl. chip AMAC)
  - "Hybrid" (Flexible PCB with ctrl. chip (HCC) and ABCs)
  - Direct gluing on the sensor and 5,200 wirebonds / module.

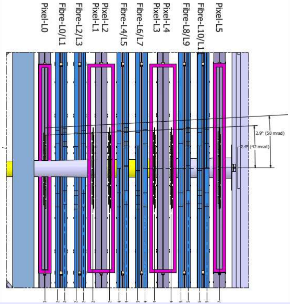
[LHCC Open session]

Higher coverage: LHCb Mighty Tracker

Mighty Tracker at LHCb

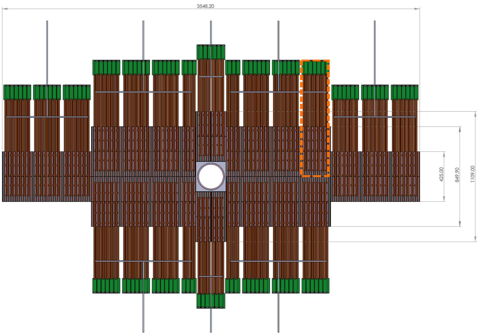


[LHCB-TDR-023] [LHCB-TDR-026]



Run 5

- Inner region based on silicon detector technology (Mighty-Pixel)
- Scintillating fibres (Mighty-SciFi) cover most of the surface



- MT-Pixel: Based on HV-CMOS design based on the experience of ATLASPix and MuPix (MightyPix) and alternative HV-CMOS (RadPix) → 6 layers, 2.4 m^2 each, for a total of $14\,m^2$
- MT-SciFi: over 10000 km of scintillating fibres, coupled with SiPMs at cryogenic temperatures

Stronger: Radiation hardness

Trends in silicon sensors presented here (not a review)

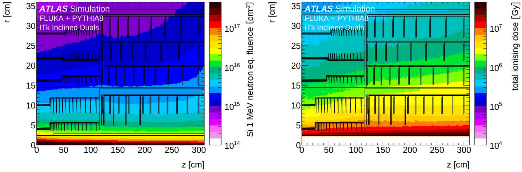
Detector	Fluence [1 MeV n_{eq} cm^{-2}]
Alice ITS3	4×10^{12}
MT-Pixel	1×10^{14}
ATLAS ITK	1.4×10^{16}
CMS HGCAL	1.5×10^{16}
CMS IT	1.9×10^{16}
Velo LHCb	2.5×10^{16}

↓

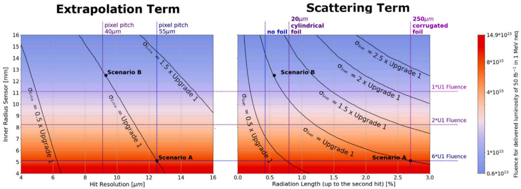
	Dose	Fluence
	MGy	[10^{16}MeV n_{eq}cm^{-2}]
Alice ITS	0.01	10^{-3}
LHC	1	0.1-0.3
HL-LHC	5	1.5
FCC-hh	10-350	3-100

Monolithic sensors are an increasing trend, key development for long term plans in HEP

[see Walter Snoeys' seminar]



[ATLAS-TDR-030]

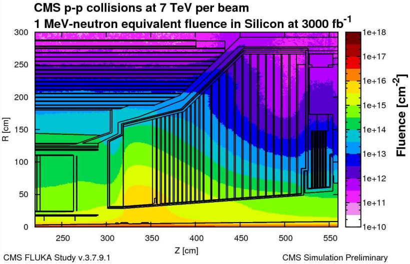


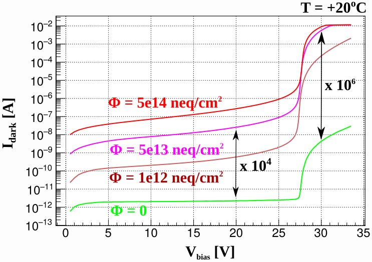
[Velo readout studies]

Balance in IP, distance between first sensor at interaction point, η coverage together with radiation levels expected

Stronger: Radiation hardness

Trends in SiPMs (not a review)
SiPMs employed in calorimetry, tracking and now increasing trend in PID (both ALICE3 and LHCb Upgrade II)





https://doi.org/10.1016/j.nima.2017.11.003

From E. Garutti's summary of radiation effects in SiPMs at PD2025

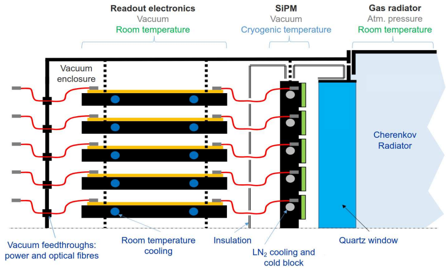
Some requirements examples:

- Imaging calorimeters for collider experiments: Hadronic calorimeter for lepton collider (CALICE) $\rightarrow \phi_{\mathrm{eq}} \sim 10^{10}\,\mathrm{cm}^{-2}$ after $500\,\mathrm{fb}^{-1}$
- Upgrade of CMS hadronic calorimeter (HGCAL) $\rightarrow \phi_{\mathrm{eq}} \sim 5 \times 10^{13}\,\mathrm{cm}^{-2}$ after $3000\,\mathrm{fb}^{-1}$
- New CMS MIP timing detector $\rightarrow \phi_{\mathrm{eq}} \sim 2 \times 10^{14}\,\mathrm{cm}^{-2}$ after $3000\,\mathrm{fb}^{-1}$
- RICH detectors at EIC: Single photon detection up to $\rightarrow \phi_{\mathrm{eq}} \sim 2 \times 10^{10}\,\mathrm{cm}^{-2}$
- Space experiments: High radiation expected for detectors in space $\rightarrow \phi_{\mathrm{eq}} \sim 5 \times 10^{10}\,\mathrm{cm}^{-2}$, AGILE gamma ray detector

$\Rightarrow$ Operating temperature is a key ingredient to cope with increased DCR

Increased complexity

SiPMs @HGCAL operated at -35° with CO_2 cooling



Readout electronics
Vacuum
Room temperature

SiPM
Vacuum
Cryogenic temperature

Gas radiator
Atm. pressure
Room temperature

Vacuum enclosure

Cherenkov Radiator

Vacuum feedthroughs: power and optical fibres

Room temperature cooling

Insulation

LN_2 cooling and cold block

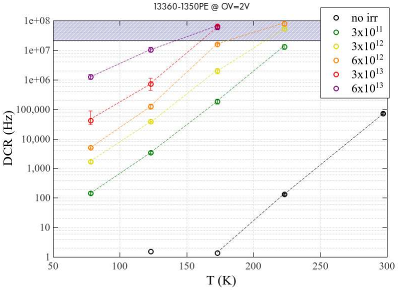
Quartz window

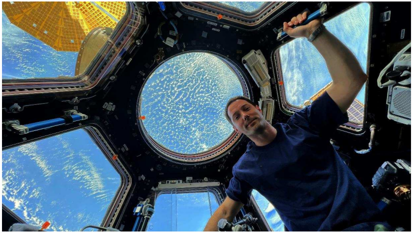
Incresead complexity in mechanics and services

See Cryo demonstrator studies at RICH2025

SiPMs @LHCb RICH at cryogenic temperatures to operate in single photon mode ($\phi_{eq} \sim 3 \times 10^{13}\,\mathrm{cm}^{-2}$ after $300\,\mathrm{fb}^{-1}$)

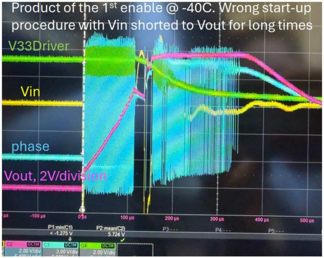
See SiPMs studies at RICH2025





Stronger: The curious case of the bPOL

Issue with bPOL12V discovered in Summer 2025 by ATLAS Inner-Tracker: strip modules irradiated to 70 Mrad (during a study dedicated to gluing process).



Courtesy of ATLAS-ITK, Freiburg

Some pictures of the test campaign

Courtesy of K. Wyllie and S. Baron

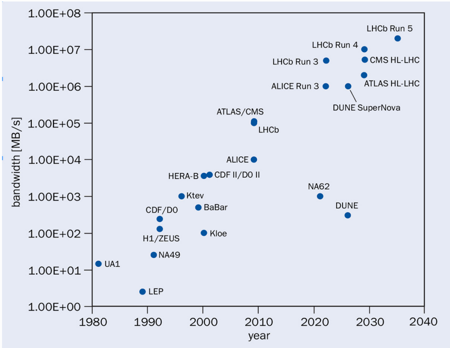
- Reproduce the behaviour → testing in collaboration with institutes to isolate the source (December)
- Understand the problem → Irradiation testing campaign (X-rays, 4 Co60 sources worldwide), Irradiation programme in low-T environment scanning 5, 10, 20, 70 Mrad (10 Mrad covers many users)
- Advise on mitigations (for v6): connect Enable and Vin pins together to limit the stress time and/or use the bPOL12V in low radiation environment and high temperature
- Corrective solutions → Modifications to circuit around bPOL12V; new version pin-compatible with old version.
- Latest news → Two new issues observed in recent large irradiation campaign to 80Mrad, impact on use of existing bPOL12V (v6) under study; New chip version (FIX1) is under production using new technology (OnSemi I3T80). Test on irradiated devices ongoing before validating the new solution

Consequence: unexpected delays due to stalled assembly while issue was being debugged: assembly progressing where solutions with bPOL12V v6 could be found, further delays where FIX1 is required

Stronger: The bandwidth issue

New Trigger strategies are key to empower physics reach of experiments. That will especially the case for HL-LHC

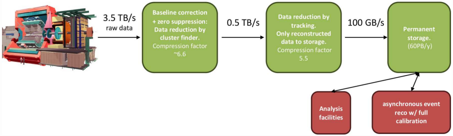
- Profit from the event reconstruction / data reduction done by the trigger system
- "Real Time Analysis" both online (producing aggregated results) and offline
- Remove hardware trigger (ALICE and LHCb)
- ALICE: Continuous read-out of all detector data, with reduced data volume to disk
- LHCb: HLT1 partial event reconstruction on GPUs hosted in the event-building servers, HLT2 provided with real-time computed calibration constants, performs full event reconstruction on CPU



[credit to A. Cerri, University of Sussex]

ALICE O^2 system

(common online-offline system)


3.5 TB/s raw data

Baseline correction + zero suppression: Data reduction by cluster finder. Compression factor ~6.6

0.5 TB/s

Data reduction by tracking. Only reconstructed data to storage. Compression factor 5.5

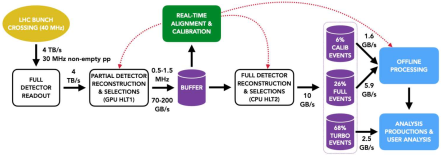
100 GB/s

Permanent storage. (60PB/y)

Analysis facilities

asynchronous event reco w/ full calibration

LHCb RTA system


LHC BUNCH CROSSING (40 MHz)

4 TB/s 30 MHz non-empty pp

FULL DETECTOR READOUT

4 TB/s

PARTIAL DETECTOR RECONSTRUCTION & SELECTIONS (GPU HLT1)

0.5-1.5 MHz

70-200 GB/s

BUFFER

REAL-TIME ALIGNMENT & CALIBRATION

FULL DETECTOR RECONSTRUCTION & SELECTIONS (CPU HLT2)

10 GB/s

6% CALIB EVENTS

26% FULL EVENTS

68% TURBO EVENTS

1.6 GB/s

5.9 GB/s

2.5 GB/s

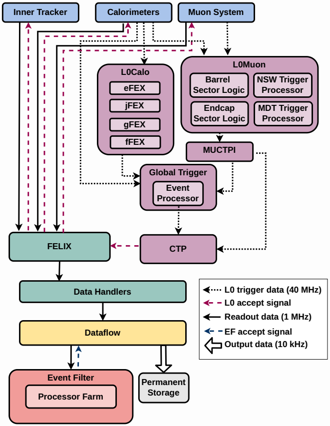
OFFLINE PROCESSING

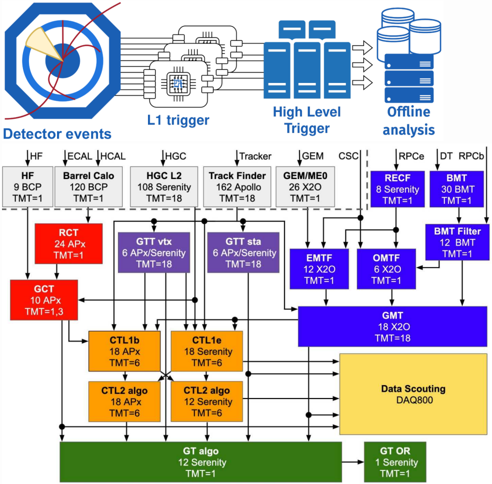
ANALYSIS PRODUCTIONS & USER ANALYSIS

Stronger: Trigger strategies

← ATLAS TDAQ Ugrade

CMS DAQ and L1 trigger Upgrade ↓

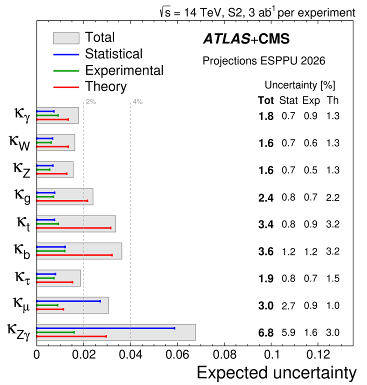




ATLAS L0: Full granularity data from Calorimeters, data from all muon detectors; global Trigger: offline-like algorithms to combine/refine regional candidates running on farm of common HW

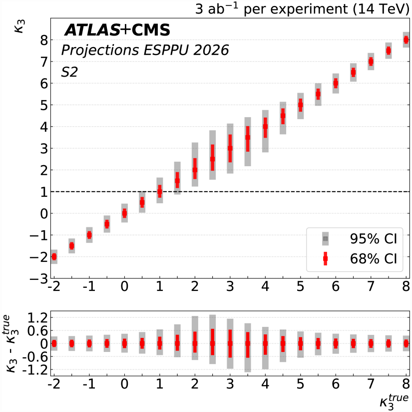
CMS L1: All detectors (but silicon-pixel detector) participating in providing primitives; information from sub-systems combine in a offline-like fashion by the Trigger-correlator

LHC Upgrades: Why?

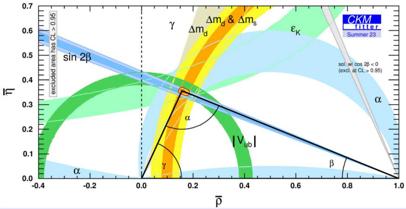


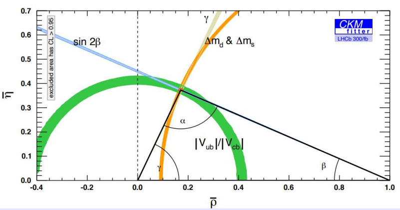
Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.7	0.9	1.3
κ_W	**1.6**	0.7	0.6	1.3
κ_Z	**1.6**	0.7	0.5	1.3
κ_g	**2.4**	0.8	0.7	2.2
κ_t	**3.4**	0.8	0.9	3.2
κ_b	**3.6**	1.2	1.2	3.2
κ_τ	**1.9**	0.8	0.7	1.5
κ_μ	**3.0**	2.7	0.9	1.0
$\kappa_{Z\gamma}$	**6.8**	5.9	1.6	3.0



[ATL-PHYS-PUB-2025-018], [CMS-HIG-25-002], [LHCb-PUB-2025-001], [ALICE-PUBLIC-2025-005]

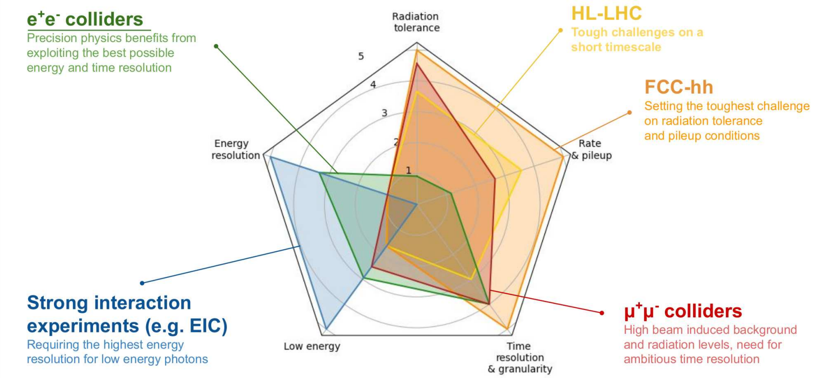




LHC Upgrades: Conclusions

Qualitative representation of requirements for calorimeters at future colliders

M. Lucchini's seminar on calorimeters for Future e^+e^- colliders



e^+e^- colliders

Precision physics benefits from exploiting the best possible energy and time resolution

HL-LHC

Tough challenges on a short timescale

FCC-hh

Setting the toughest challenge on radiation tolerance and pileup conditions

Strong interaction experiments (e.g. EIC)

Requiring the highest energy resolution for low energy photons

$\mu^+\mu^-$ colliders

High beam induced background and radiation levels, need for ambitious time resolution

Much more can be found on the Input session of Future Facilities I

Technological advancements during HL-LHC era are mission critical for today's High Energy Physics programme but also for the Future Facilities

"The unique ecosystem of particle physics research centres and universities in Europe should be further strengthened in order to address the objectives set out in this Strategy." [CERN-ESU-2025-002]