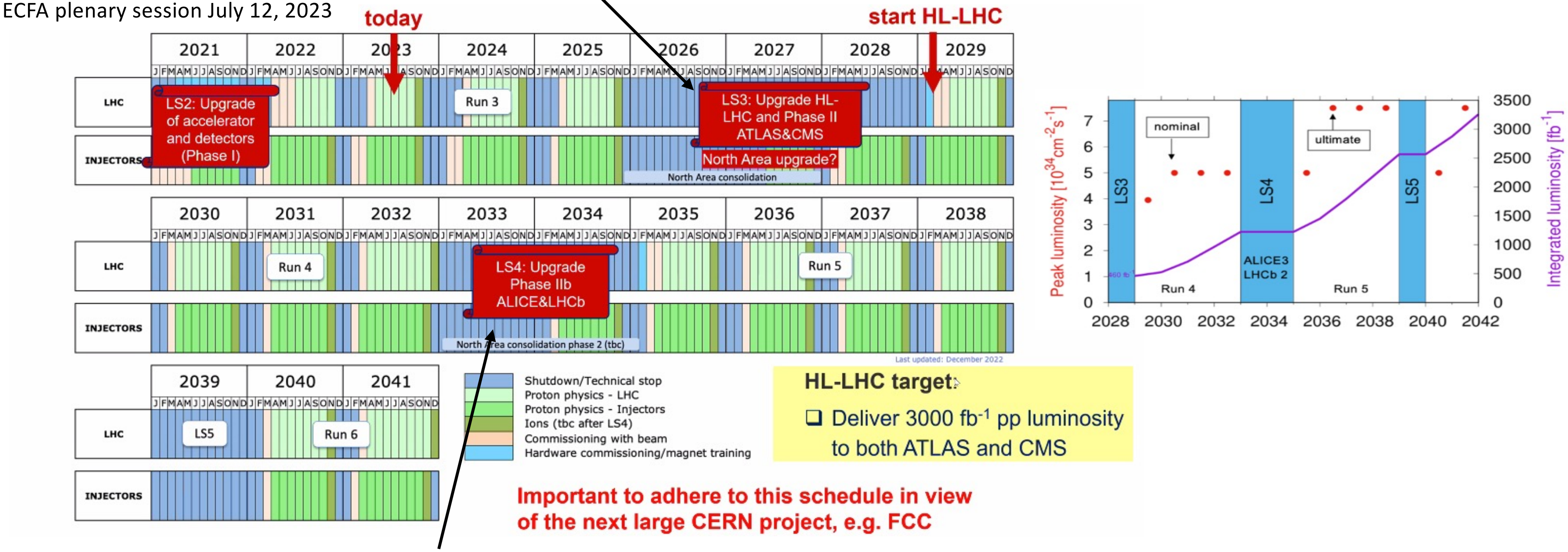
Upgrades of the experiments for the High Luminosity LHC

D. Contardo, IP2I CNRS/IN2P3 – on behalf of ALICE, ATLAS, CMS and LHCb

HL-LHC planning for p-p luminosity and experiment upgrades

ATLAS and CMS Phase-2 installed in LS3 (2026-2028) - now entering production

J. Mnich ECFA plenary session July 12, 2023



ALICE-3 and LHCb-II installed in LS4 (2023-2034) - in R&D phase, preprаring for approval

Outline

ATLAS - CMS – LHCb-II and ALICE-3

highlights of major upgrades and new experimental paradigms
recent progress and stepping stone R&Ds

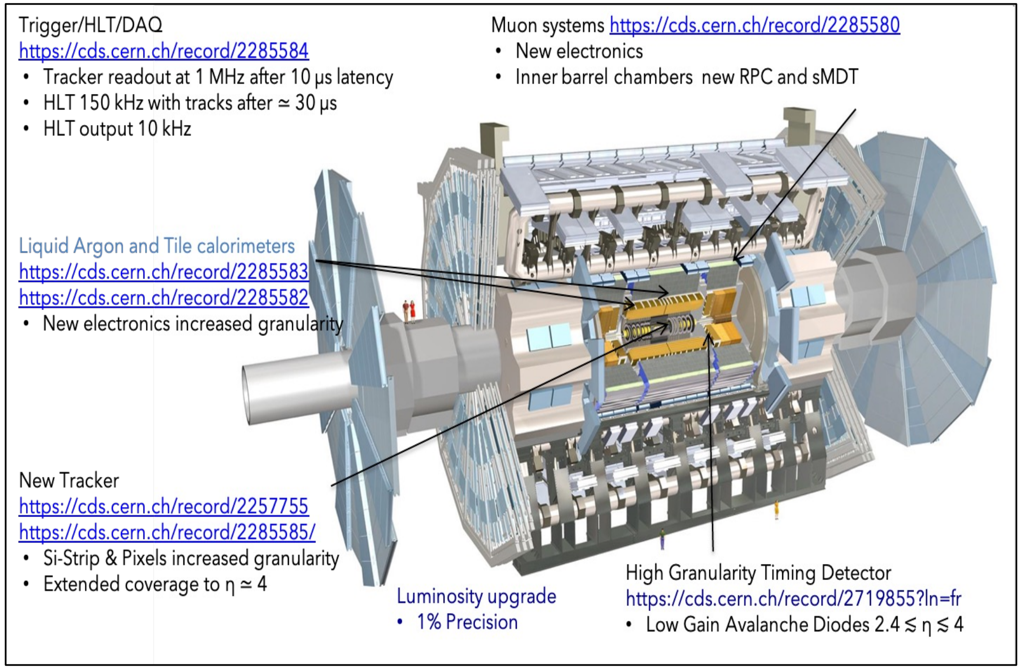
thanks to A. Di Mauro, M. Palutan, B. Gorini, F. Hartmann

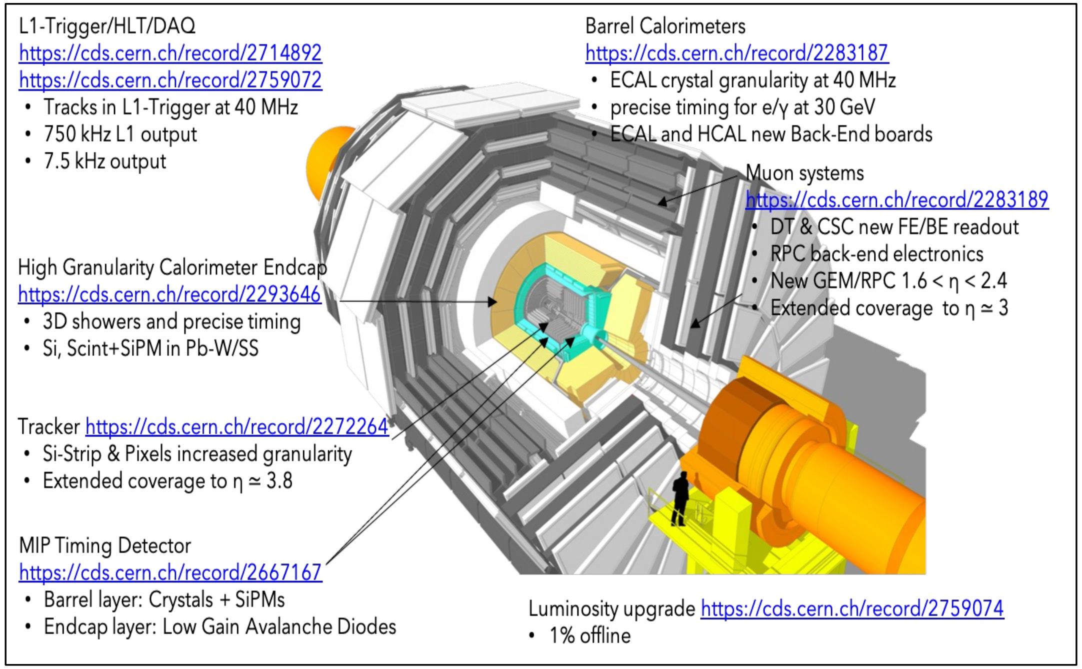
ATLAS and CMS Phase-2 upgrade overview

exploit HL-LHC at $L_{inst.} \simeq 7.5\times10^{34}$ cm^{-2} s^{-1}, $L_{integ.} \simeq 3000$ fb^{-1} ($\simeq$ x 10 end of Run-3)

challenge to maintain current performance at <200> collisions/event* - sustain rates and irradiation

new electronics, new tracker - timing layers - tracking in trigger - new endcap calorimeter in CMS





* compared to <60> today, experiment ability to sustain collision pile-up is the limitation to instantaneous luminosity

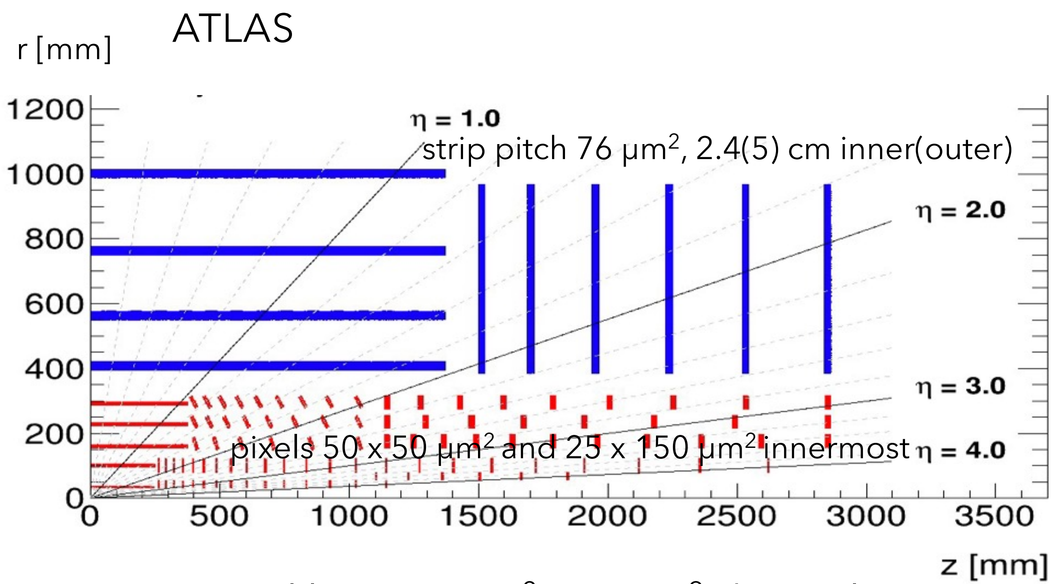
ATLAS and CMS Phase-2 Tracker upgrade

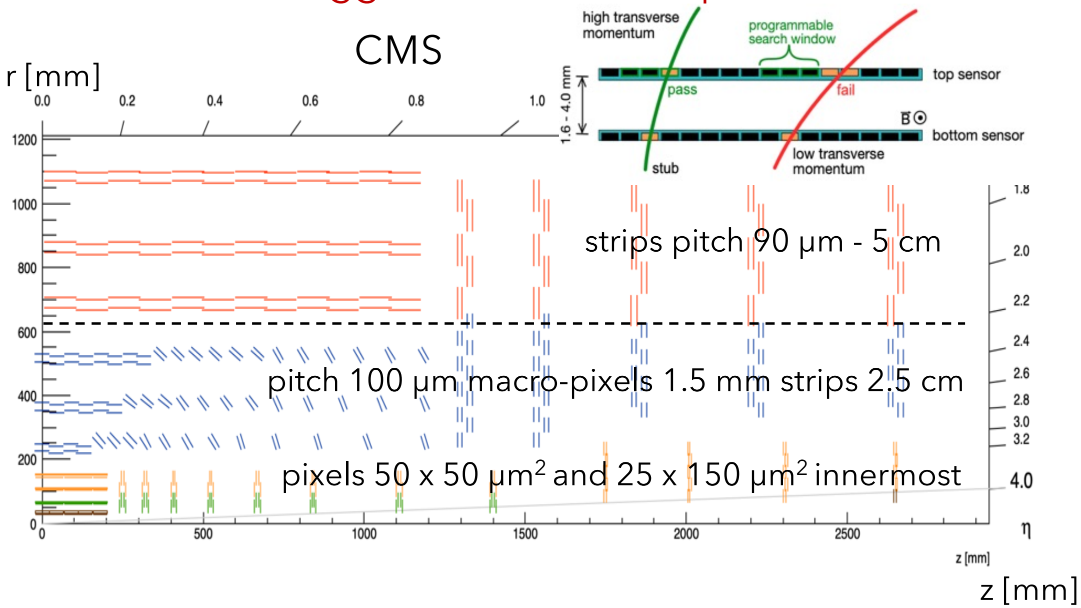
$\simeq$ x 4(6) channels OT(IT), $|\eta|$ up to 4, tilted design, CO_2 cooling, serial powering ($\simeq$ ½ weight)

Outer strip-Tracker

$\simeq$ 170 m^2 - stereo modules – 60 x 10^6 channels

$\simeq$ 200 m^2 - trigger module concept - 10^6 channels





5 pixel layers 13 m^2 - 5 x 10^9 channels

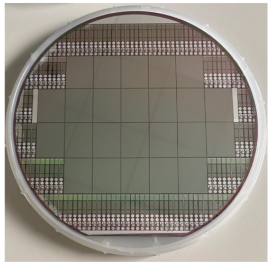
4 pixel layers 5 m^2 - 2 x 10^9 channels

Inner pixel-Tracker - innermost layers replaceable

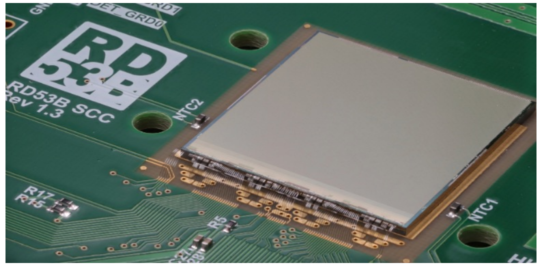
ATLAS and CMS Phase-2 Inner pixel-Tracker progress

new technology 65 nm TSMC ASIC enabling 50(25) x 50(100) μm^2 pitch at $\simeq$ 3 GHz/cm^2

- Silicon sensors - planar and 3D - production started
- Front–end common ASIC development (RD53)
  - final ATLAS submitted, CMS imminent
- Hybridization of sensor proceeding at vendors
- Several modules of different types available (1^{st} FE versions)



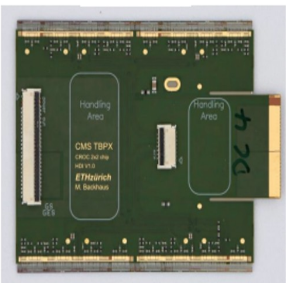
3D wafer



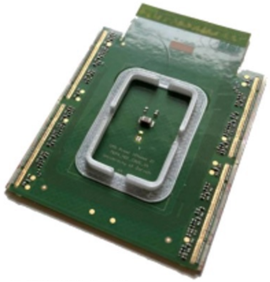
ITkPixV1 ASIC

Modules: 2 CMS types (left) and assembly and test in ATLAS (rigth)

2 x 2

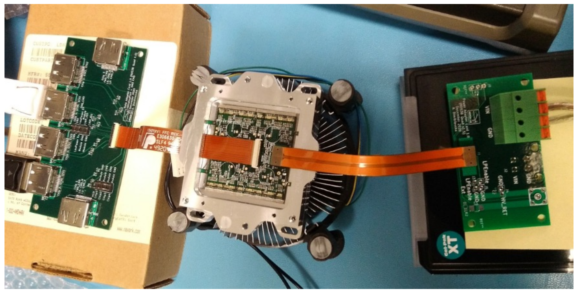


1 x 2



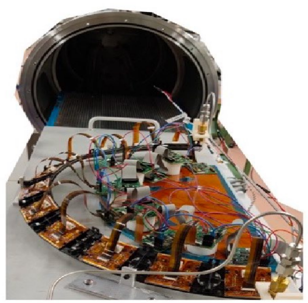
$\simeq$ 4 kmodules

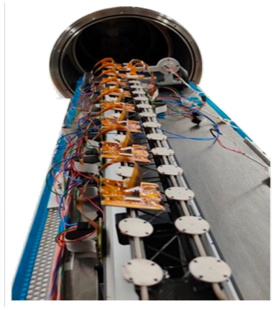
2 x 2 here (and 1 x 3)



$\simeq$ 7 kmodules

Thermal tests in ATLAS mechanics

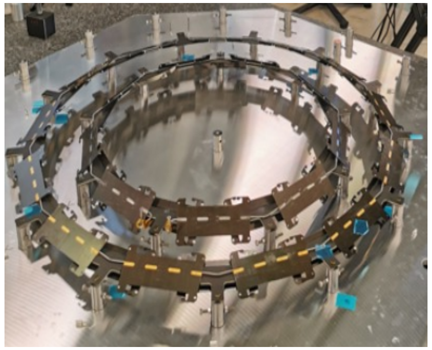




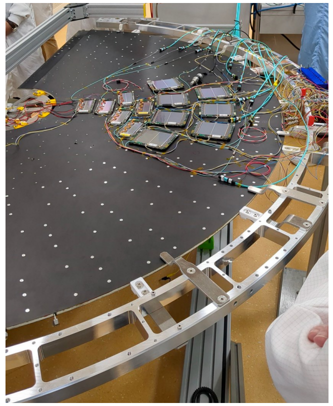
ATLAS and CMS Phase-2 Outer strip-Tracker progress

- Substantial fractions of sensors delivered
- ASICs in production
- Hybrid pre-production started
- First assembly in rods, petals, disks performed
- Main mechanics components being ordered

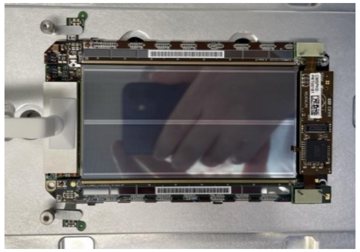
CMS tilted rings

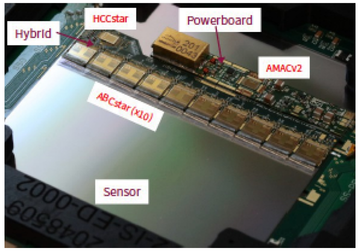


CMS endcap dee

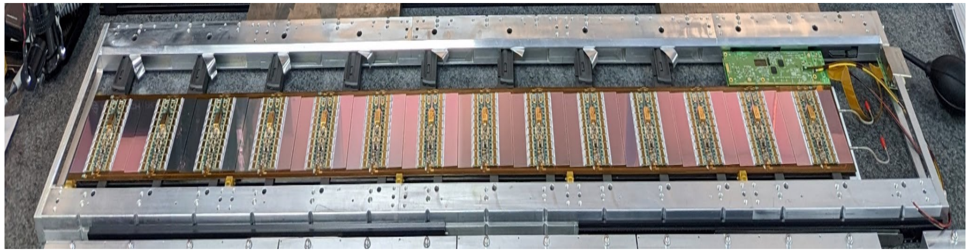


modules CMS (left) ≃ 13000, ATLAS (right) ≃ 18000

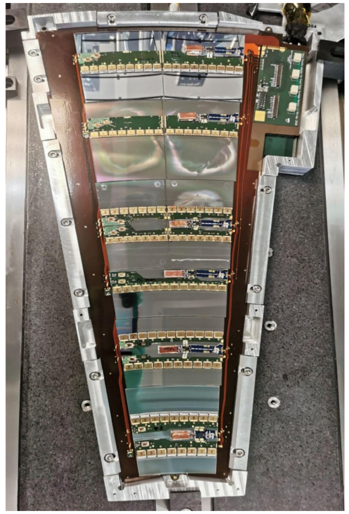




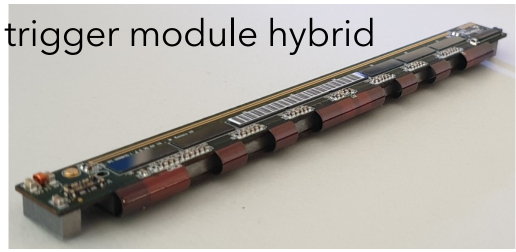
1st barrel rods ATLAS (top) – CMS (bottom)



ATLAS endcap petal



CMS trigger module hybrid

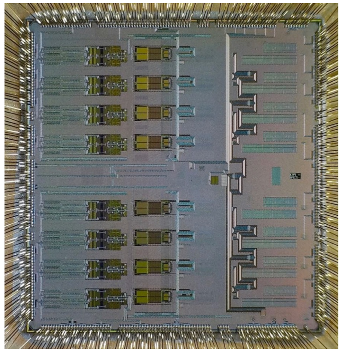


ATLAS and CMS Phase-2 Calorimeter electronics upgrade

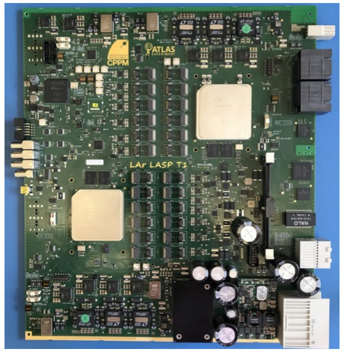
full granularity at 40 MHz - improved precision - increased bandwidth

ATLAS

Liquid Argon Calorimeter
continuous readout at 40 MHz



65 nm ADC ASIC
16 bit dynamics
in production



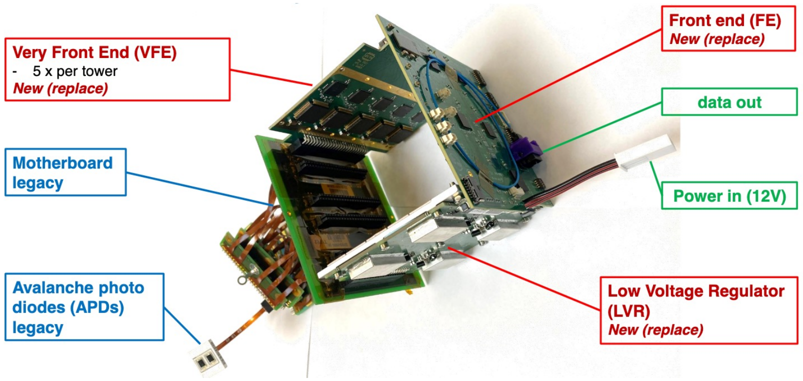
ATC board 10 Gb/s
waveform sampling
final prototype

HCAL-tile PMT & readout

FE & main boards
in production
mechanics production
completed

CMS

ECAL $PbWO_4$ crystals readout



160 MHz sampling - 30 ps resolution (40 Gev/c)
ASICs and component procurements on going
operation at 8° for radiation tolerance

CMS Phase-2 High Granularity Calorimeter upgrade

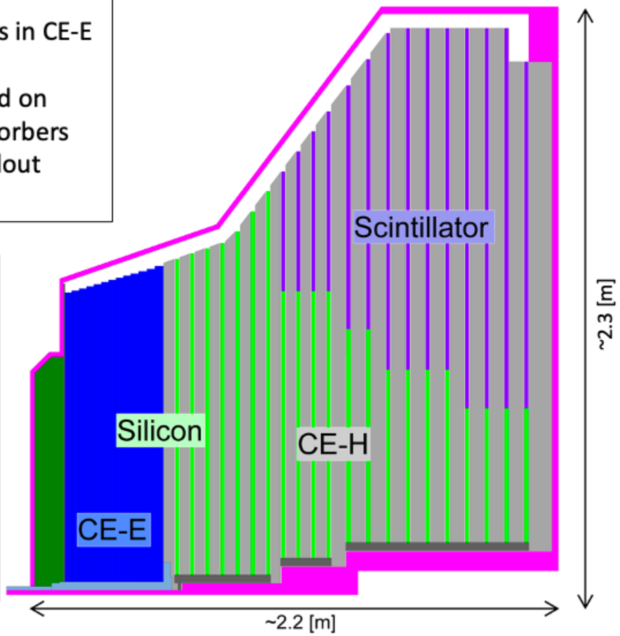
first experiment implementation of CALICE concept developed for ILC

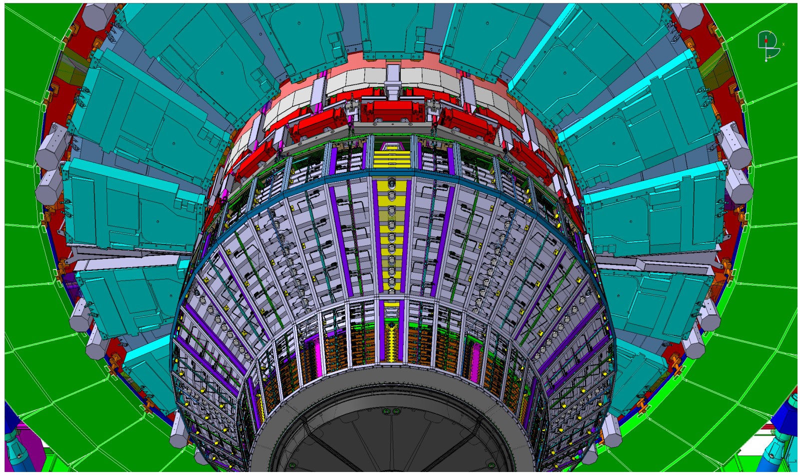
26 Si layers in CE-E, with Pb/Cu/CuW absorbers; 8 Si layers & 13 mixed Si/Scint layers in CE-H, with Cu/SS absorber

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- “Cassettes”: multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

Key Parameters:

Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -35°C
~620m^2 Si sensors in ~30000 modules
~6M Si channels, 0.5 or 1cm^2 cell size
~400m^2 of scintillators in ~4000 boards
~240k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap

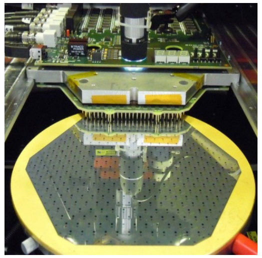




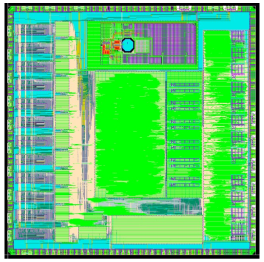
3D topology and $\sigma_t \simeq 20$ ps for 25 GeV/c electrons

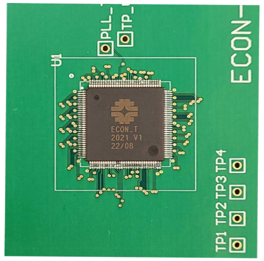
CMS upgrade Phase-2: High Granularity Calorimeter progress

8″ hexagonal sensor
production started (≃ 22000)

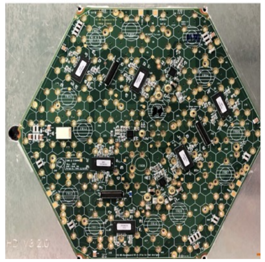


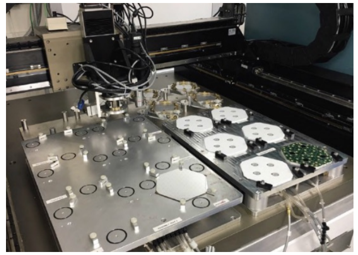
Final FE ASIC submitted (in BGA left)
trigger & data transfer ASICs in test (right)



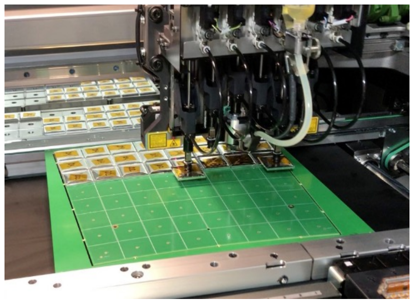


Hexaboards pre-series on going (left)
module robot assembly (right)





Scintillating tile - production started
SiPM in procurement process

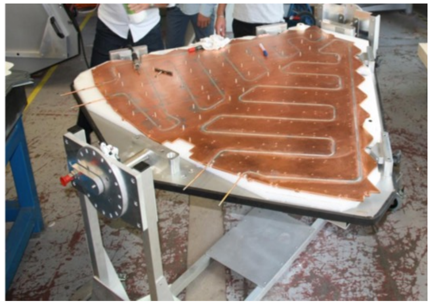


Tileboard robot assembly
PCB in procurement process

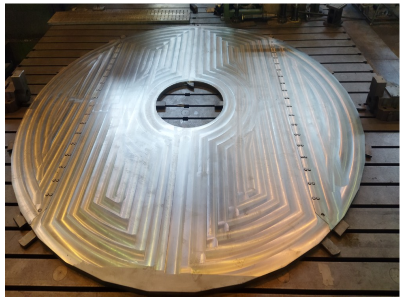
CE-H cassette test

Data transfer board being characterized

1st CE-E Cu cassette



1st SS absorber disk



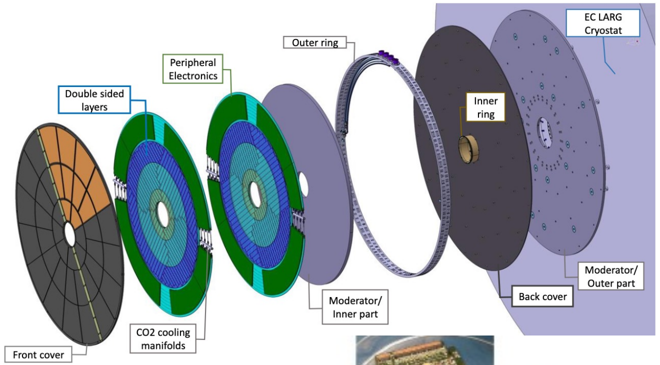
ATLAS and CMS Phase-2 Timing Layers

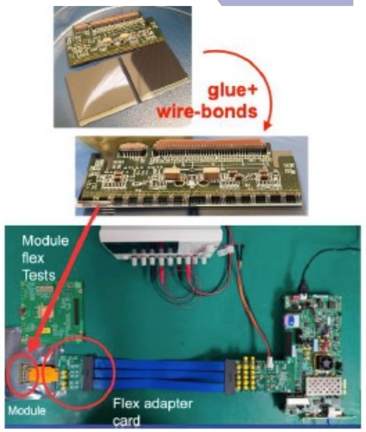
reduce number of collision vertices according to their time in the bunch crossing

endcap timing layers first use of Low Gain Avalanche photoDiodes

2 double sided thin layers providing $\sigma_t \simeq$ 30/50 ps (/track)* before/after irradiation with 1.3 x 1.3 mm^2 pads

ATLAS 75 mm x 6.4 m^2 - 2.4 < $|\eta|$ < 4 - 3.6 Mch.



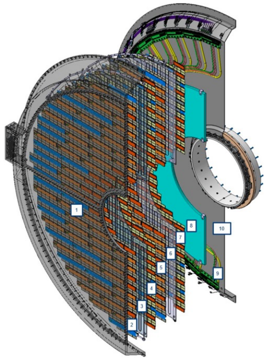


- LGAD pre-prod. started
- final ASIC being tested
- modules assembly demonstrated

sensors ≃ 2 x 4 cm^2 - 8 kmodules (1 sensors)

CMS 45 mm x 14 m^2 - 1.6 < $|\eta|$ < 3 - 8.5 Mch.

- LGAD market survey completed
- last but final ASIC being qualified
- module assembly demonstrated



FE ASIC test - readout board and module assembly

sensors ≃ 2 x 4 cm^2 - 9 kmodules (1 or 2 sensors)

* σ_t should remain ≲ 35 ps with sensors being at $|\eta|$ < 3

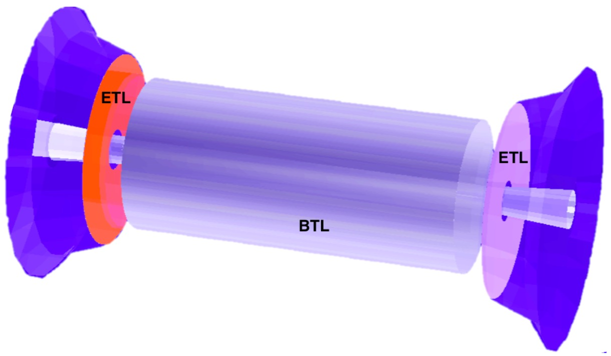
CMS Phase-2 Barrel Timing Layer

first HEP experiment “PET-like” system

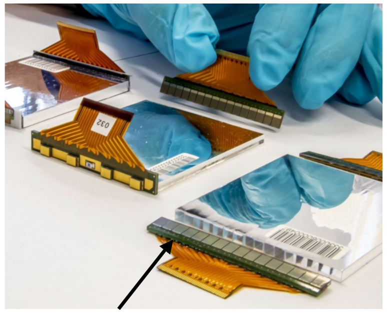
thin layer of LYSO crystals + SiPM in front of ECAL providing $\sigma_t \simeq$ 30/60 ps before/after irradiation

40 mm thick - 38 m^2 - 332 kcrystals

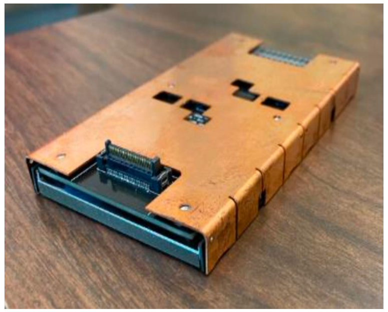
early installation within the tracker tube, starting procurements

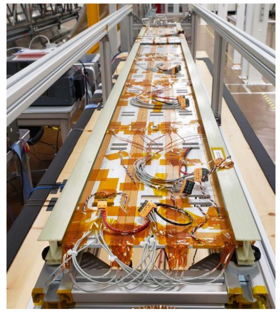


16 LYSO bars (56 x 3 x 3 mm^3) per module ($\simeq$ 21000)



SiPM on both sides



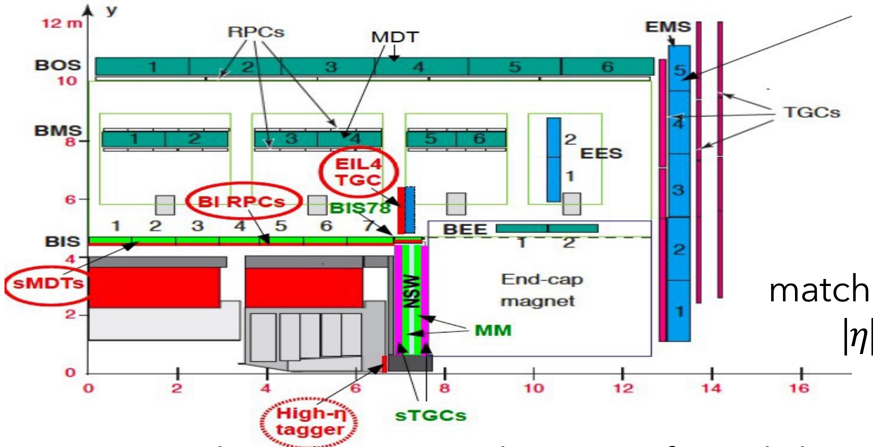


24 modules readout unit grouped in trays (right)

ATLAS and CMS Phase-2 Muon upgrades

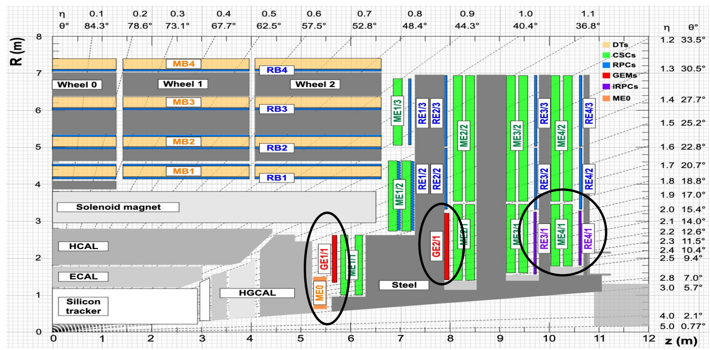
new electronics, improved coverage & p_T resolution for trigger, sustain high rates

New layers, sMDT, TGC and RPC



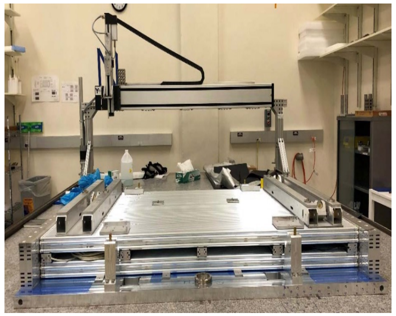
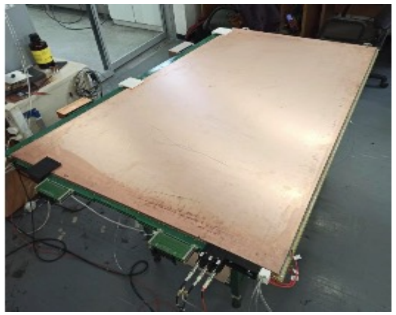
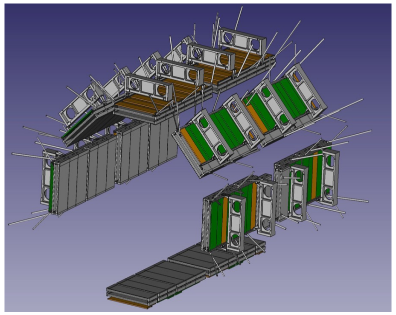
match tracking
$|\eta| \simeq 4$

Electronics in Barrel DT and RPCs
GEM/iRPC in $1.6 < \eta < 2.4$ - GEM to $\eta = 3$



ATLAS TGC: ASIC produced, pre-production of modules

Slice tests DT, GEM & iRPC at P5

ATLAS sMDT chamber production almost completed
RPC moving to production - ASIC final protype in test

CMS GEM (left) & iRPC (right) in production

ATLAS and CMS Phase-2 Trigger and DAQ boards

ATLAS trigger: 1 MHz L0 in 10 μs - tracks with FPGA/GPU in 30 μs - 10 kHz output

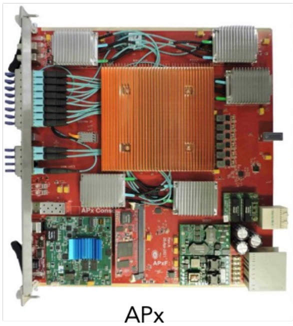
CMS trigger: (OT) tracks in FPGA at 40 MHz, 750 kHz full readout in 12.5 μs, 7.5 kHz output

high processing power FPGAs, 25 Gb/s links, AI PFlow algorithms in firmware

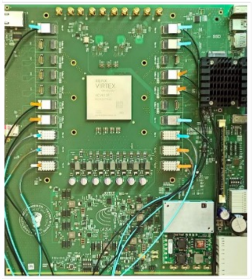
CMS

4 trigger boards tuned to detectors needs (cost) + 1 DAQ board

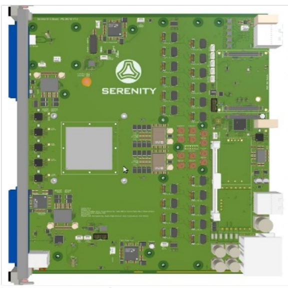
pre-production completed for slice test and yield



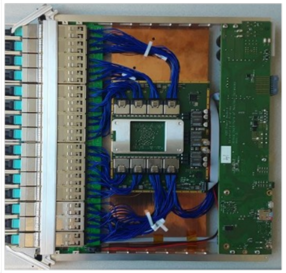
APx
Barrel ECAL and HCAL



BMT
Barrel Muons



Serenity
HGCAL and Tracking

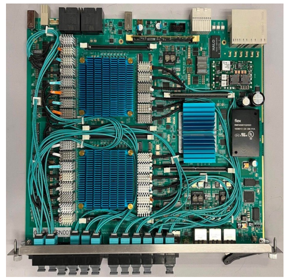


X2O
Endcap Muons

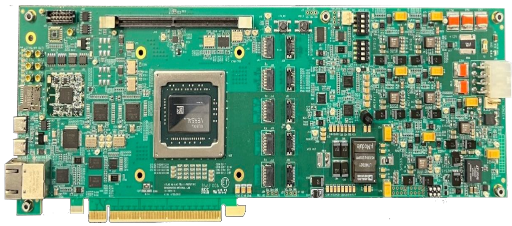
DTH
DAQ interface

ATLAS

Global Trigger Board



single DAQ back-end board FELIX



LHCb upgrade II

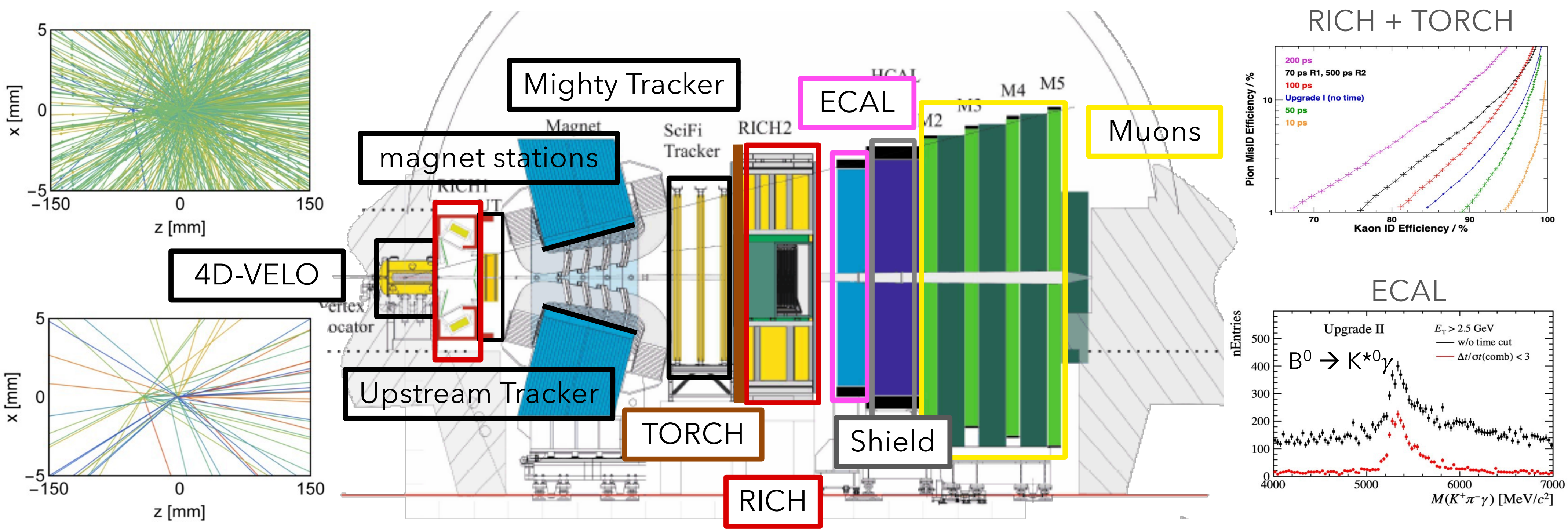
exploit HL-LHC at $L_{inst.} = 1.5 \times 10^{34}$ cm^{-2} s^{-1}, $L_{integ.} \geq 300$ fb^{-1}

challenge to maintain current performance at <40> collisions/event - sustain rates and irradiation

high granularity, timing precision ≃ 10's ps, 200 Tb/s data bandwidth

EoI 2017 - Physics Case 2018 - [Framework TDR]() 2022 - Scoping Document 2024 - TDRs 2025-26

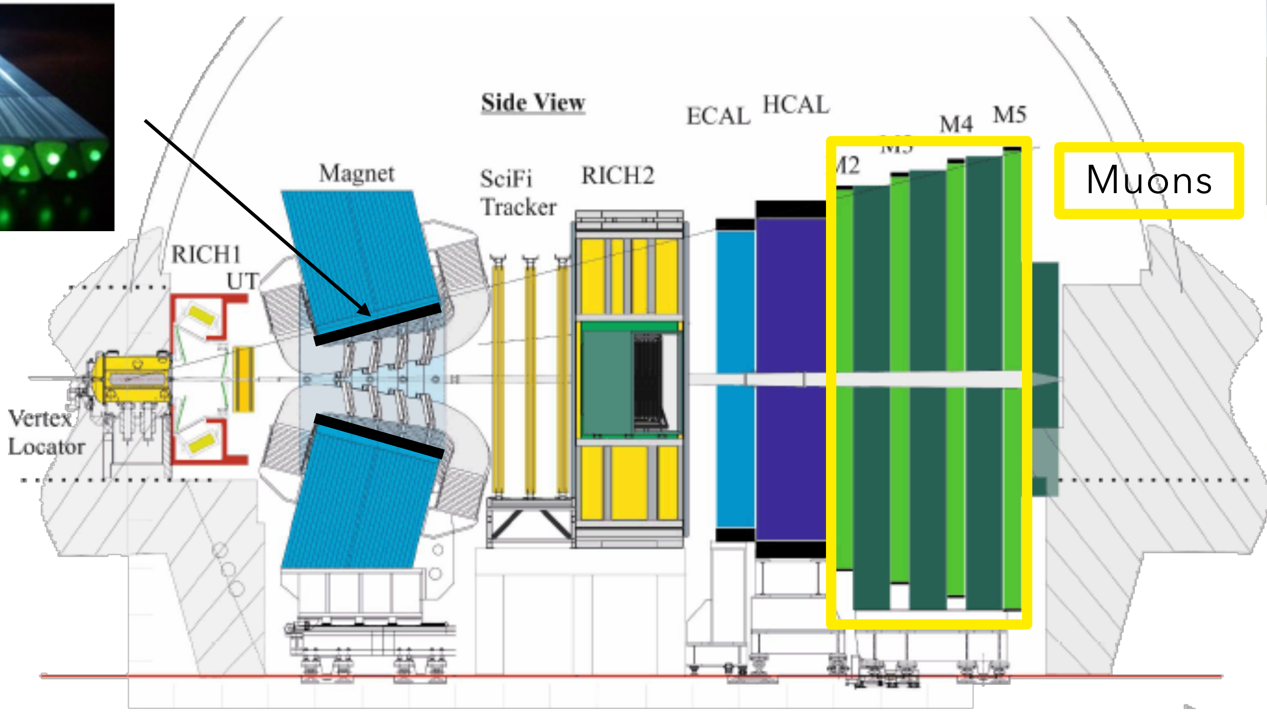
infrastructure LS3 2026-28 – construction 2027-33 - installation LS4 2033-2034



LHCb upgrade II

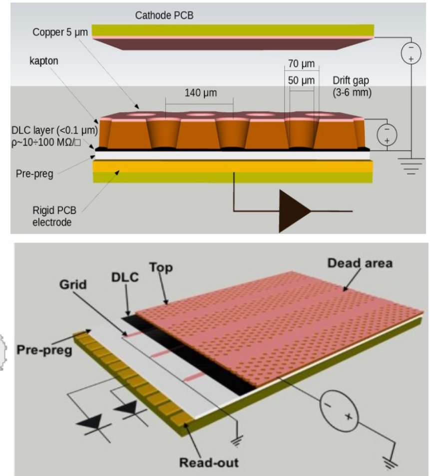
magnet and muon stations

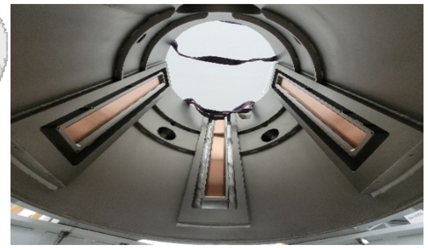
Scint . bars + WLS



inner region

new generation of MPGD: μ-RWELL 1st application





DLC coating
machine at CERN

LHCb VELO upgrade II

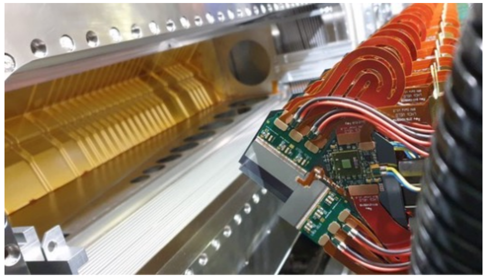
First 4D-tracking system; and at high channel density, highest rates and radiation tolerance

r_{in} = 7 mm option driven by TID 1.2 GRad - NIEL 2.5 x10^{16} N_{eq}/cm^2 – 6 GHZ/cm^2

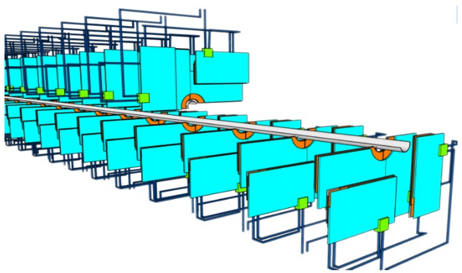
σ_{hit} = 11 µm (40 µm pitch) (σ_{IP} = 26 µm at 1 GeV/c), σ_t = 50 ps (20 ps/track), 1.5 % X/X_0 /layer

Detector within beam pipe

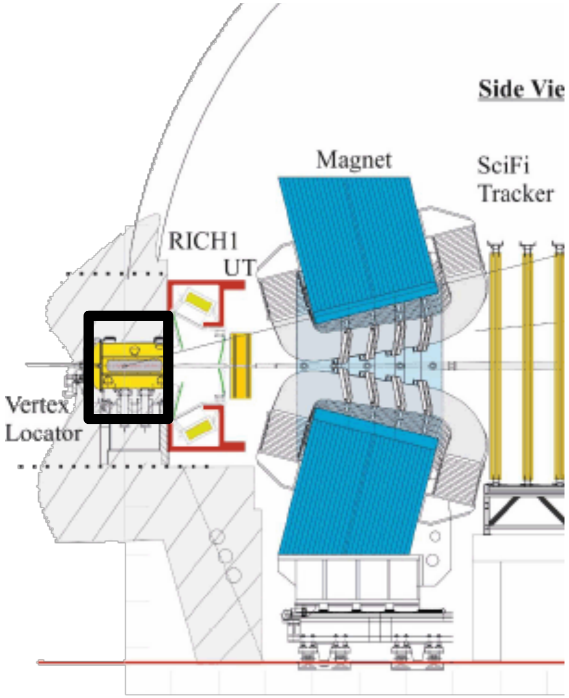
VELO - 2022



new design ↓

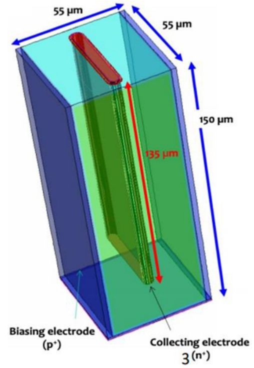


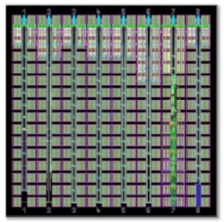
cylindrical RF Al foil 20-50 µm



3D design for timing

3D trench sensors





PicoPix ASIC
TSMC 28 nm

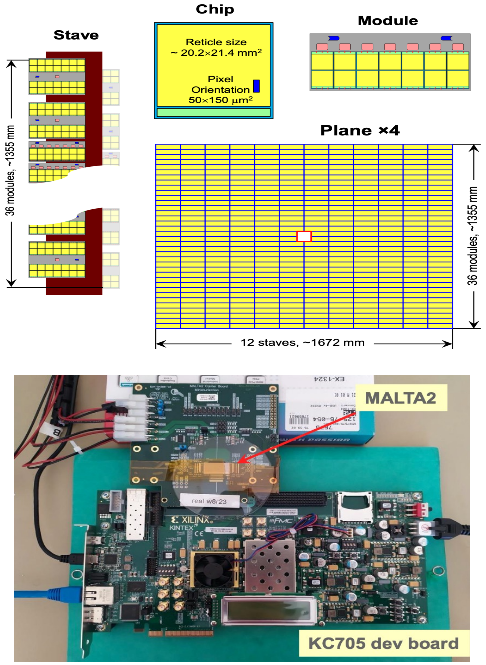
Potentially of interest for ATLAS - CMS inner pixel layer(s) replacement

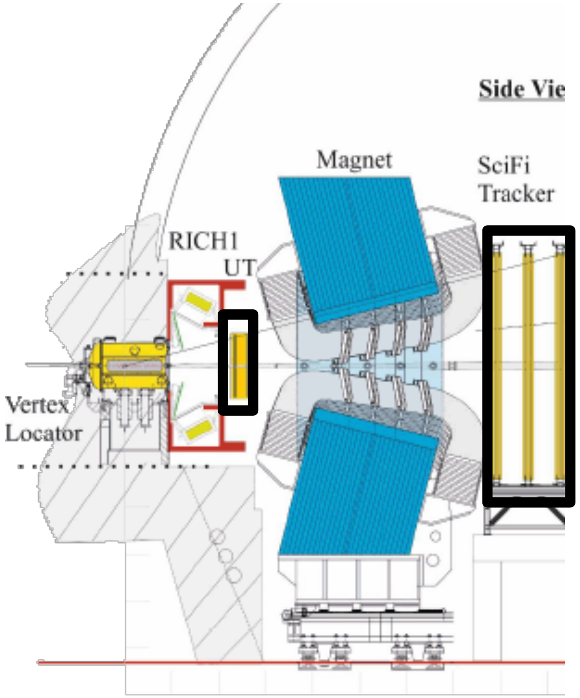
LHCb Tracker upgrade II

1st large tracking area with Monolithic CMOS sensors $\simeq 30\ m^2$, 1% X/X_0 / layer

Upstream Tracker

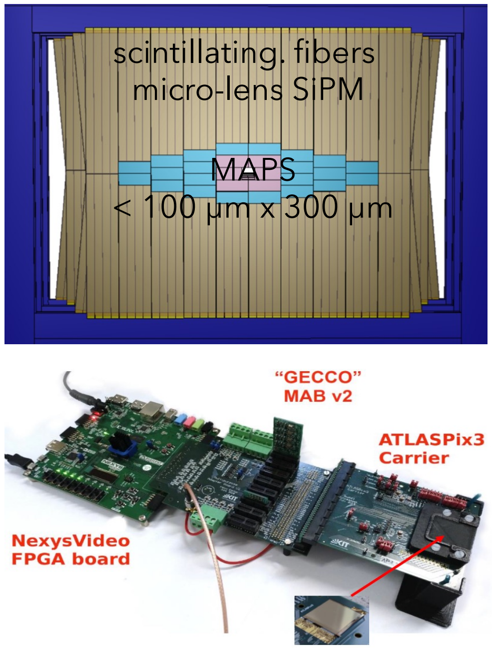
4 layers - 9 m^2





Mighty Tracker

2 layers x 3 stations = 18 m^2



study small electrode (TJ-MALTA) versus large electrode (TSI ATLASPIX)

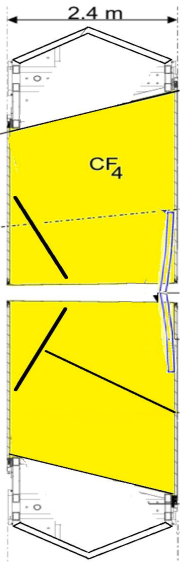
alternative technology/foundries possible

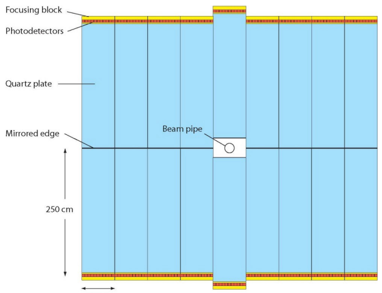
LHCb PID upgrade II

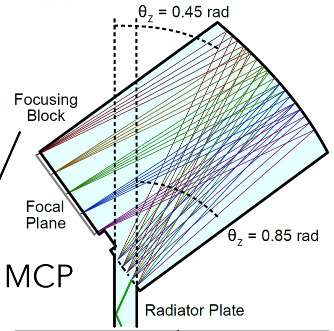
Cerenkov: RICH and TORCH concept, with resp. $\sigma_t \simeq$ 25 & 15 ps (70 ps SPTR)

ECAL: SpaCal(inner)/Shashlik (outer), 2-sides readout, $\sigma_t \simeq$ 20 ps (at 5 GeV), $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$

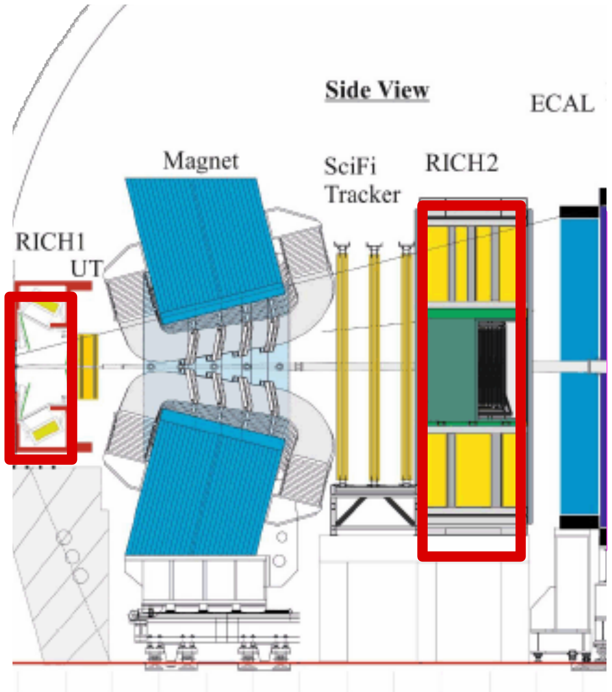
CF mirrors in acceptance + SiPM micro-lens or MCP-PMT





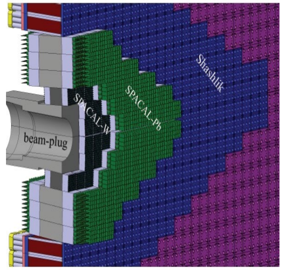


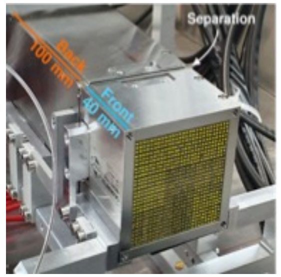
Silica fused radiator

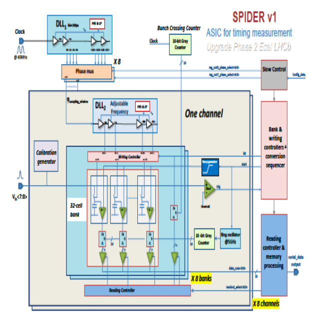


W/GAGG crystals - square fibers 1 x 1 mm^2

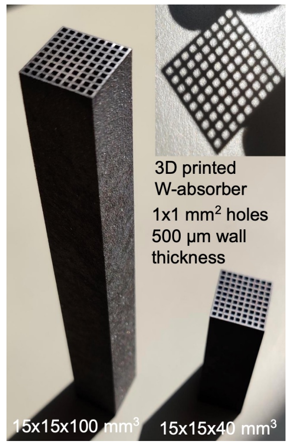
Pb/polystyrene - round fibers 1 x 1 mm^2







Spider ASIC TSMC 65 nm waveform digitizer



W absorber 3D printing

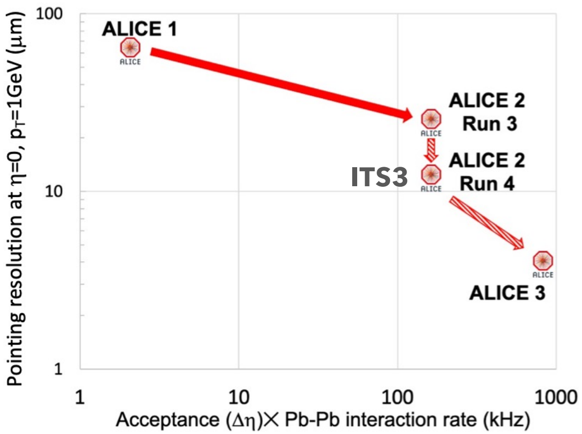
ALICE-3 is a new detector

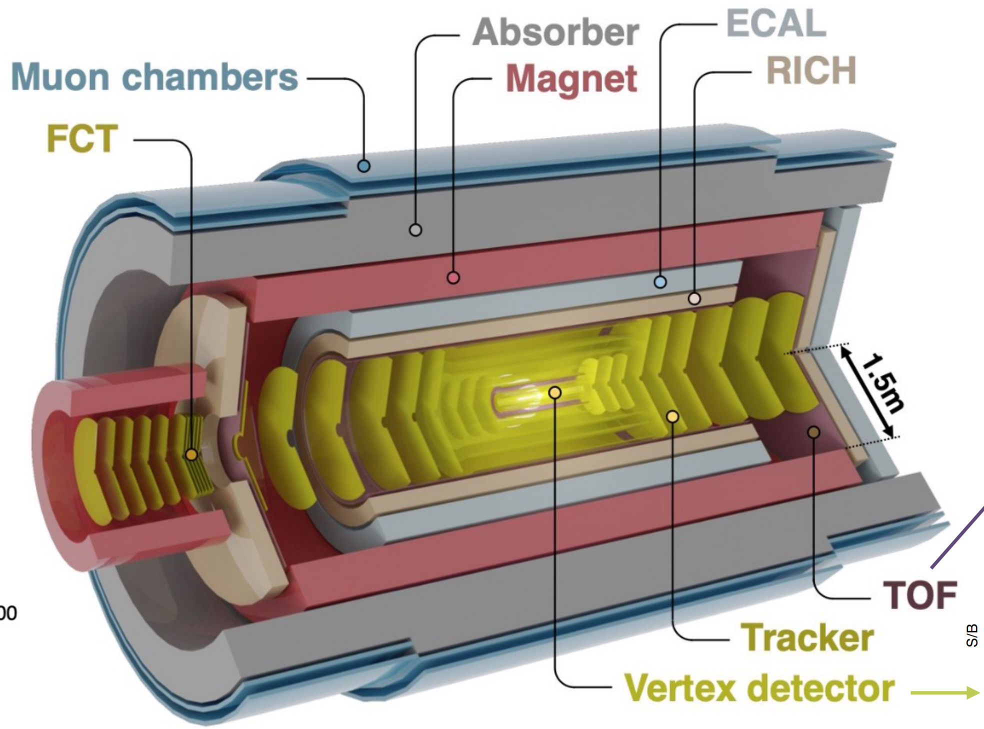
exploit HL-LHC with 10 x RUN 3 statistics, $L_{integ.}$ = 35 nb^{-1} HI &18 fb^{-1} pp

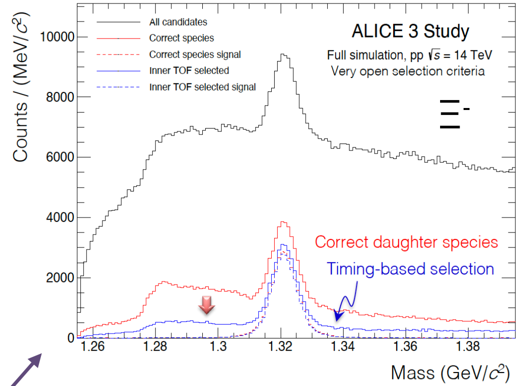
challenge of pointing precision and PID at low p up to $|\eta|$ = 4, rate capability x 5(25) in HI(pp)

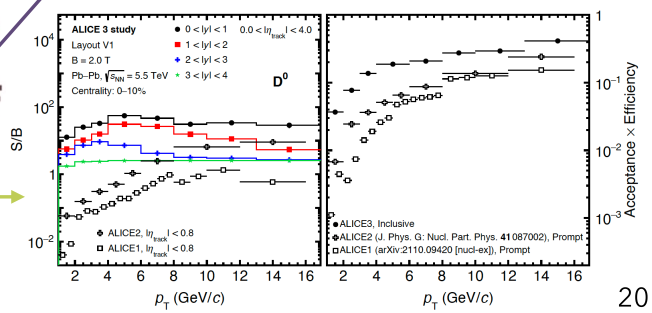
FoCal and ITS3 installation in LS3 2026-2028

ALICE-3 LoI 2022 - TDRs 2026-2027 construction 2028-32 - installation LS4 2033-2034





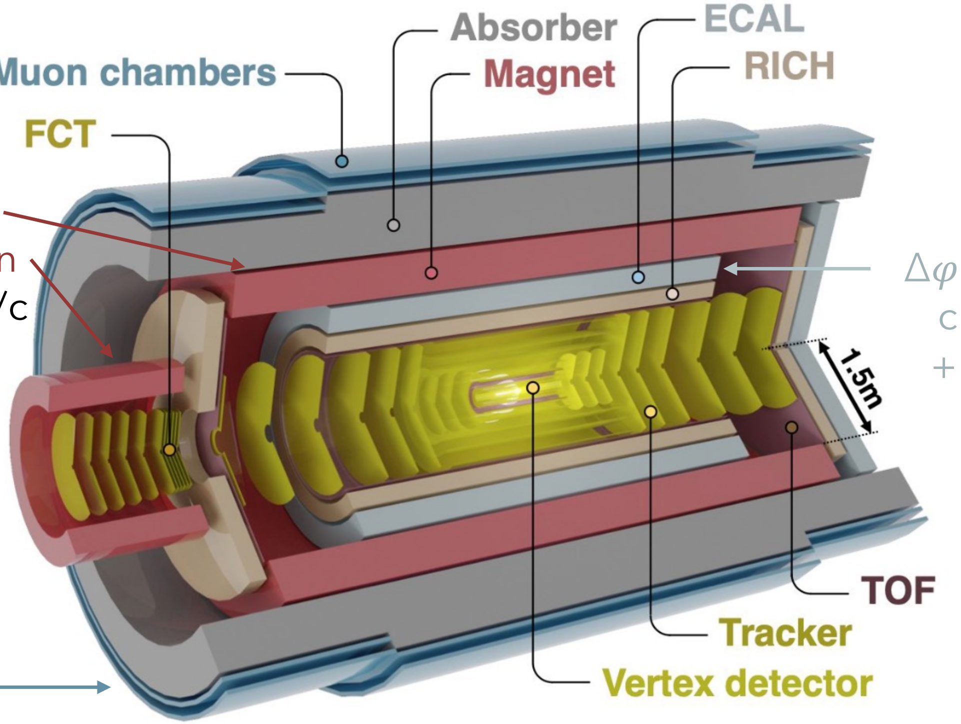




x 2 HI luminosity and 4 x 10^{34} $s^{-1}cm^{-2}$ pp

ALICE-3 upgrade
Solenoid, muon and ECAL

2T field
superconducting solenoid
and dipole in forward region
4% p_T resolution at 100 MeV/c



$\Delta\varphi = 2\pi$, η coverage -1.6 to 4
current $PbWO_4$, $|\eta| < 0.33$
+ Pb/scintillator sampling
with SiPM readout

μ-tagging
scint. bars + WLS + SiPM

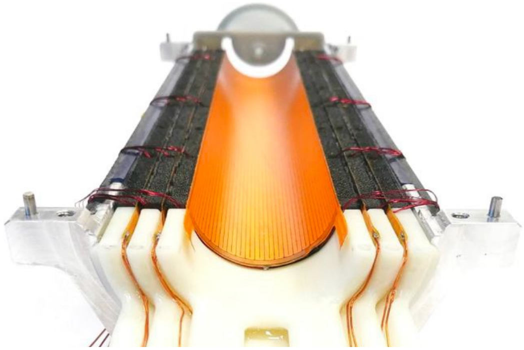
ALICE Inner Tracker upgrades

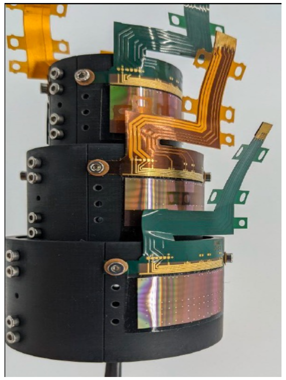
highest precision and lightest tracking system; and closest to the beam

Monotlithic CMOS new technology node TPSCo 65 nm with reticle stitching

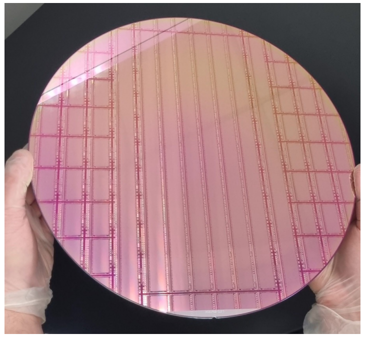
28 cm bent sensors in ITS3, IRIS design in beam pipe in ALICE-3, pitch to ≲ 10 μm (25 μm DCA at 100 MeV/c)

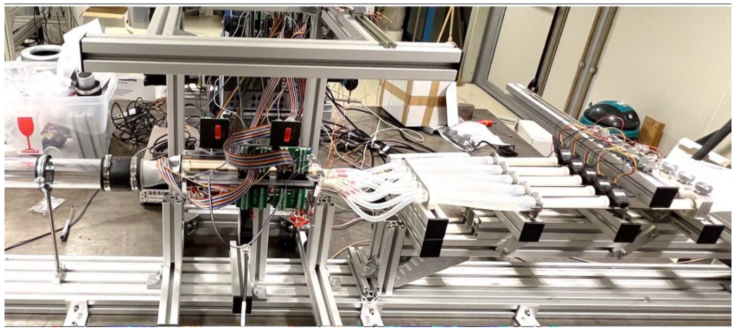
ITS3 planned for LS3
3 layers at 18-24-30 mm – functional bent sensors



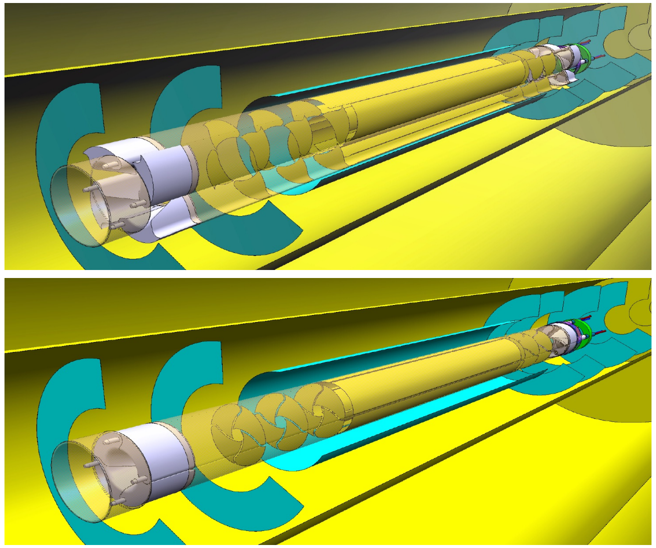


1st 28 cm sensors thinned to 50 μm, airflow cooling test set-up





ALICE-3 3 layers at 5 -12 - 25 mm

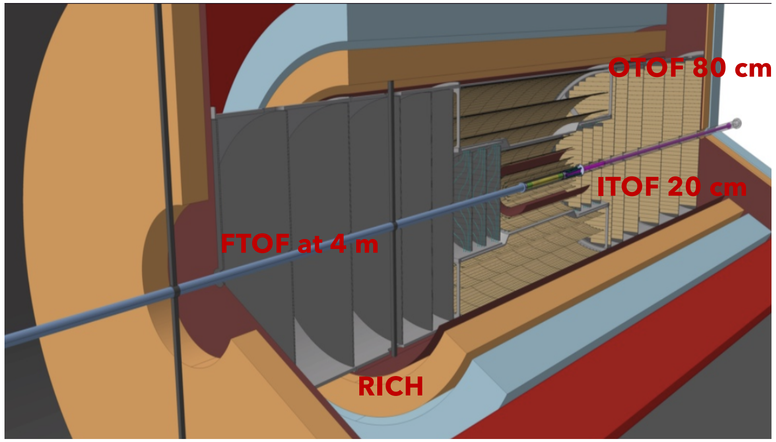


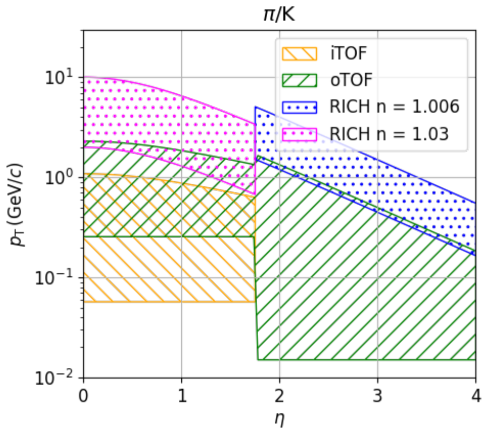
2.5 μm resolution, 0.1% X/X0 /layer
NIEL 10^{16} neq/cm^2 - TID 300 MRad
hit rate 100 MHz/cm^2
CO_2 colling -35° micro-channel plate
attached to Berylium case (250 μm)

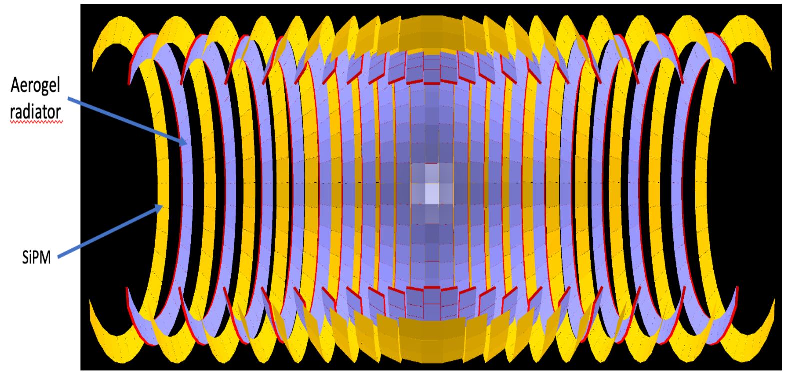
ALICE-3 Outer Tracker and PID

1st large area tracker 60 m^2 - $\sigma(p_T)/p_T$ = 2% at 1 GeV/c
Monolithic CMOS sensors (TPSCo 65 nm)

45 m^2 ToF with Monolothic CMOS with gain (or LGADs)
pitch 1 to 5 mm^2 - 20 ps resolution - 50 mW/cm^2

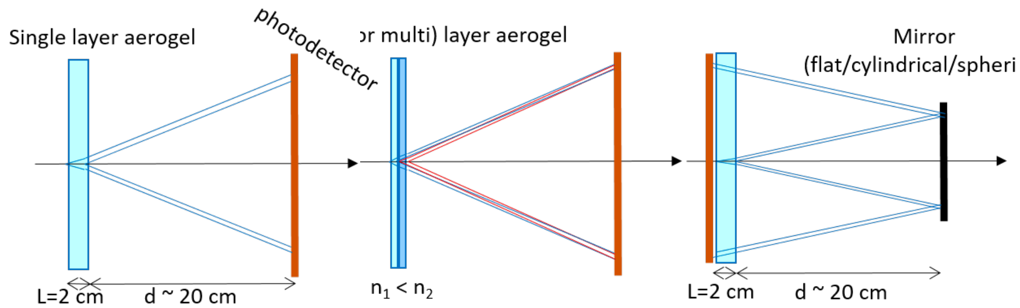






- 8(9) barrel(endcap) layer(disks)
  - 10 µm resolution
  - $\lesssim$ 10% X/X_0 (total)
  - low power 20 mW/cm^2
- Modules 10 x 10 cm^2
  - industry standard for assembly and testing
  - water cooling at room temperature

Aerogel RICH + SiPM 34 m^2 with projective geometry



Outlook

ATLAS and CMS

enormous effort and impressive progress toward production
final qualification of systems/assembly (modules, rods/stave…) on going with pre-series
production and QA/QC at assembly centers is well advanced
schedule remains challenging

ALICE-3 and LHCb-II

proceeding with R&D and toward approvals
several innovation studies paving the path toward detectors for future colliders
(see process to form new international DRD collaborations as ECFA detector R&D roadmap implementation)
schedule is as well challenging