12th International Conference on
POSITION SENSITIVE DETECTORS

Hosted by
UNIVERSITY OF BIRMINGHAM

Trends in Semiconductor Tracking Detectors

Petra Riedler, CERN

ATLAS ITk pixel module
CERN-EN-MME

Outlook

- Introduction
- Present HEP silicon systems – selection of examples
- Future HEP silicon systems – challenges and developments

Disclaimer:
Major tracking technologies for particle physics experiments include gaseous detectors and fiber based systems.
This presentation will focus on silicon based systems in particle physics experiments.

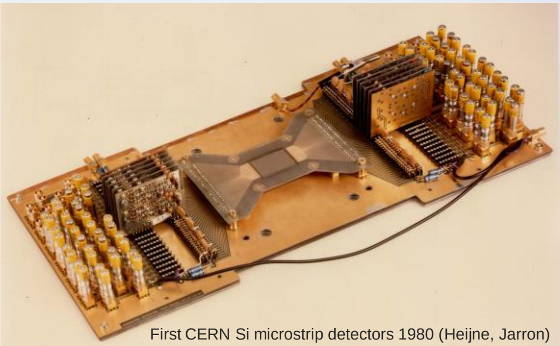
For gaseous systems – see presentation by E. Oliveri

ATLAS SCT
http://cdsweb.cern.ch/search?recid=883309

A Short Historic Excursion …

Intensive R&D in silicon detectors to measure short lived particles (10^{-12} – 10^{-13} s)

1980 first use of **planar technology** (standard IC process) to produce silicon strip sensors

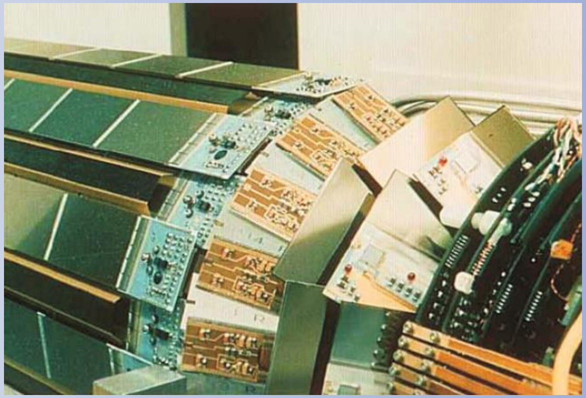


First CERN Si microstrip detectors 1980 (Heijne, Jarron)

From E. Heijne, Silicon detectors 60 years of innovation https://indico.cern.ch/event/537154/

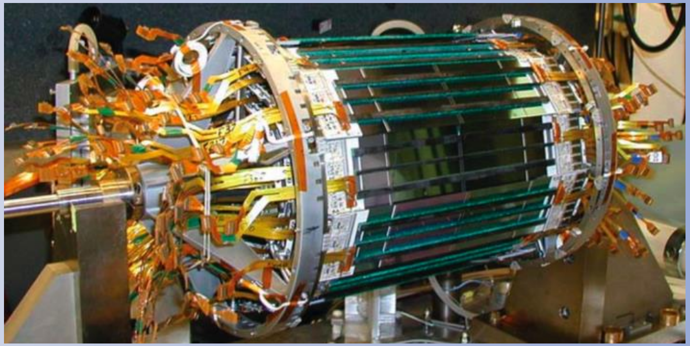
NA14

From P. Allport, Nature Reviews, Vol 1, (575), 2019



DELPHI Vertex Detector (1994 and 1997):

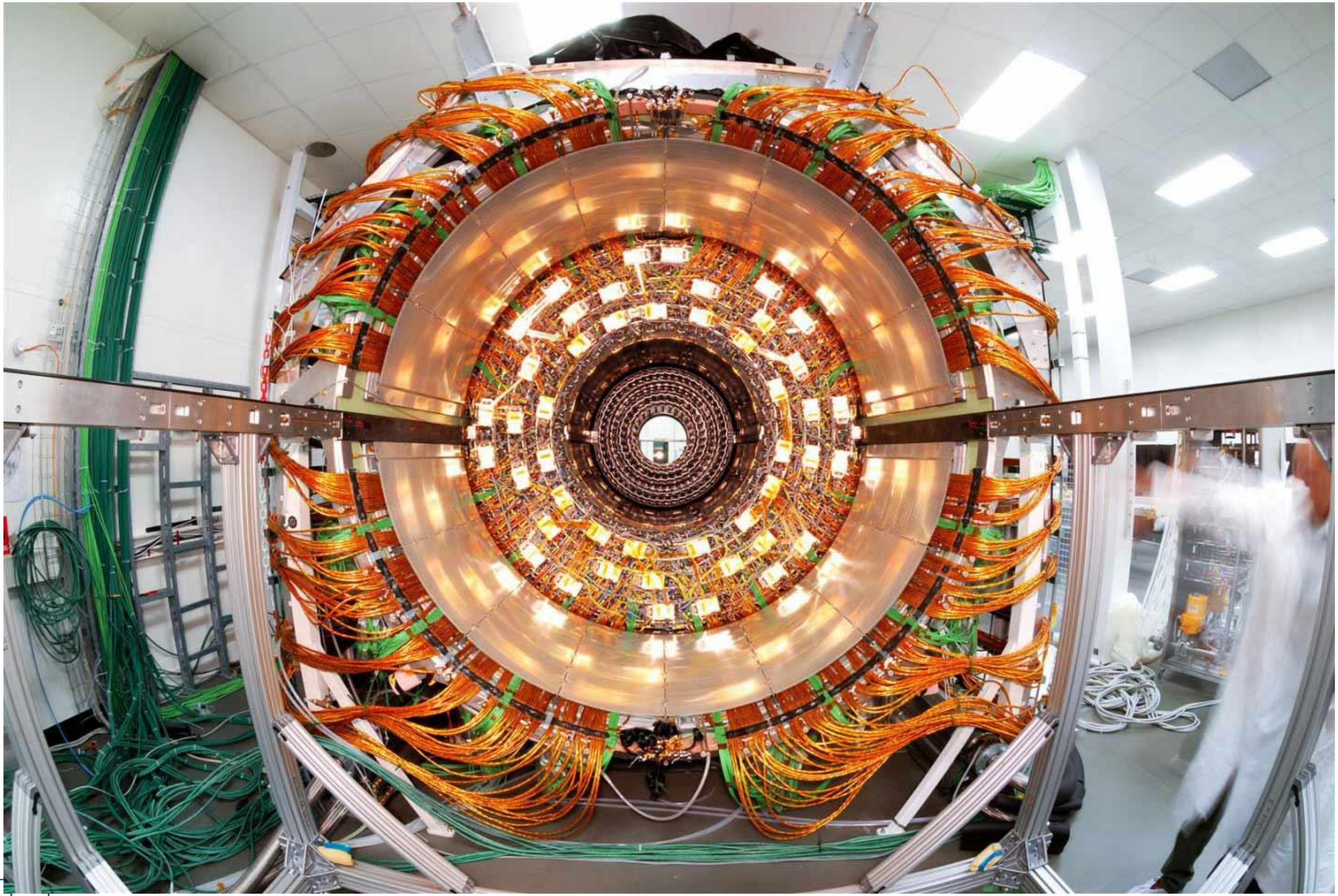
- 3 double sided strip layers, Forward mini strips, extra pixels
- Sensor surface ~1,5 m^2, 888 Silicon sensors



CDF Silicon Tracker

- 7 double sided strip layers, L00 on beampipe, Sensor surface ~10 m^2
- Top quark discovery together with D0 experiment (Phys. Rev. D50 (1994) 2966)

And today….



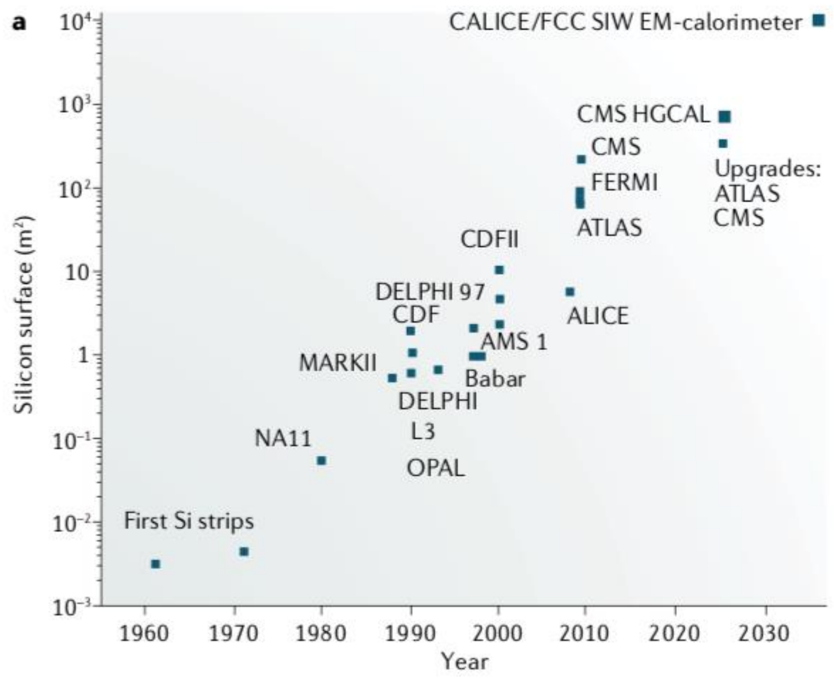
CMS Tracker Outer Barrel (2008),
https://home.cern/fr/node/3942

Silicon trackers get bigger …

For HL-LHC the global surface stays around similar values, but pixel areas increase significantly

ATLAS pixel: 2 m² →12 m²

CMS pixel: 2 m² →6 m²



From P. Allport, Nature Reviews, Vol 1, (575), 2019

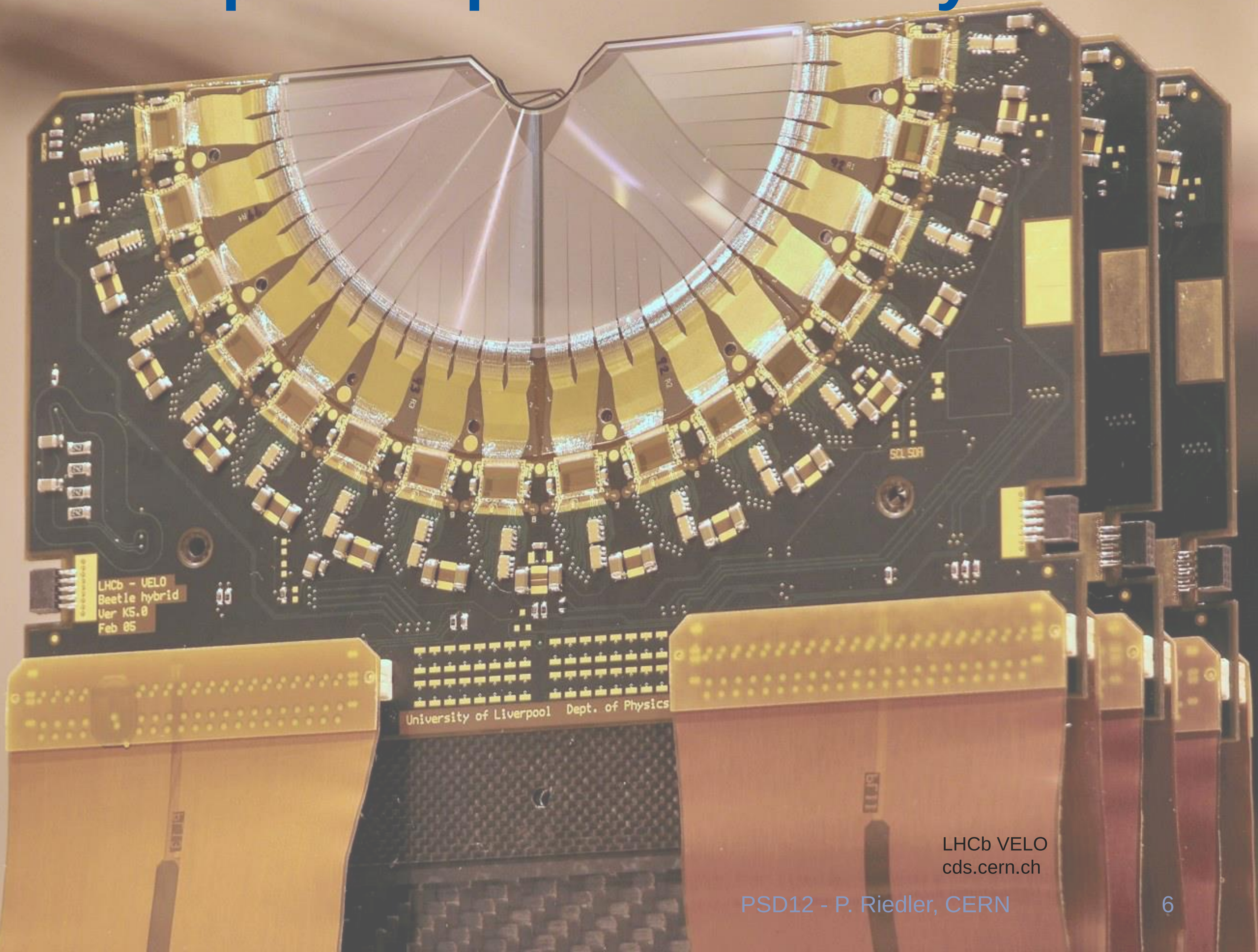
…environments become more challenging

	HL-LHC Outer Pixel	HL-LHC Inner Pixel	FCC pp
NIEL [n_{eq}/cm^2]	**10^{15}**	**10^{16}**	**10^{15}-10^{17}**
TID	**80 Mrad**	**2x500 Mrad**	**>1 Grad**
Hit rate [MHz/cm^2]	**100-200**	**2000**	**200-20000**

…number of components increase (increasing logistics)

…production, testing and assembly are distributed

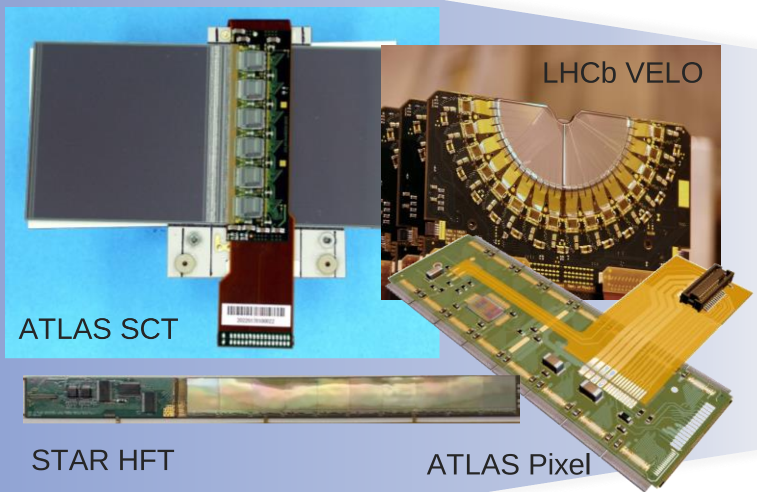
2. Examples of present HEP systems

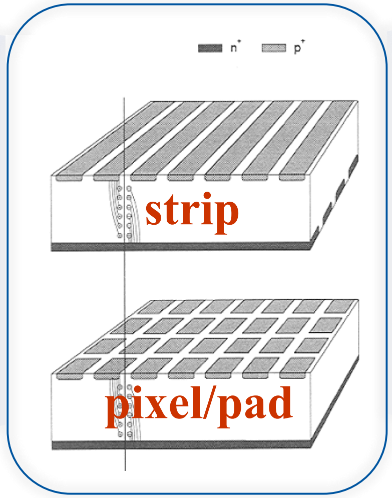


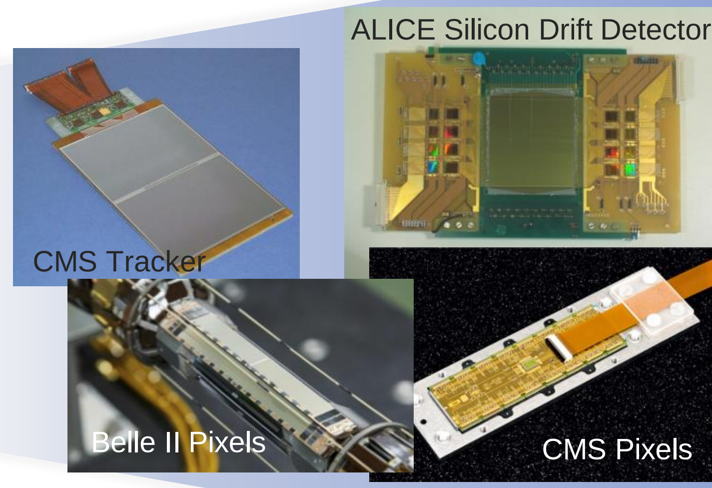
LHCb VELO
cds.cern.ch

Silicon detectors in HEP experiments

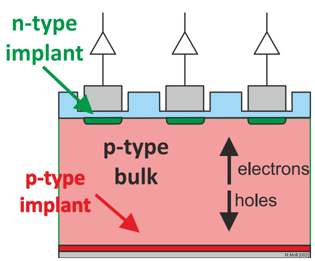
Silicon sensors are present in all HEP experiments - as silicon strip detectors, silicon pixel detectors, silicon drift detectors, monolithic pixel detectors….

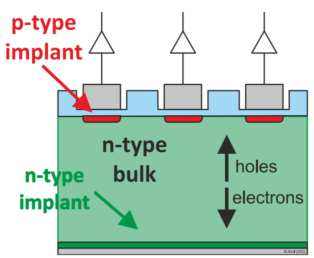


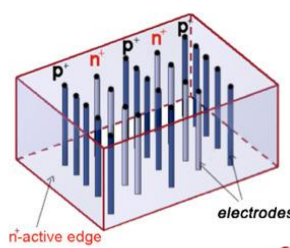


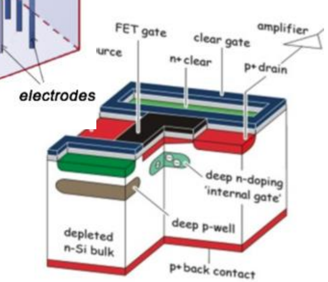


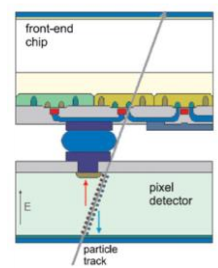
….in different flavors and designs, optimized for the different operating environments:

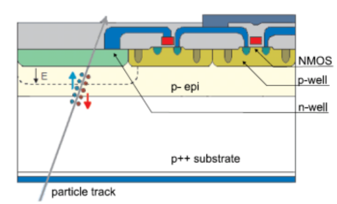










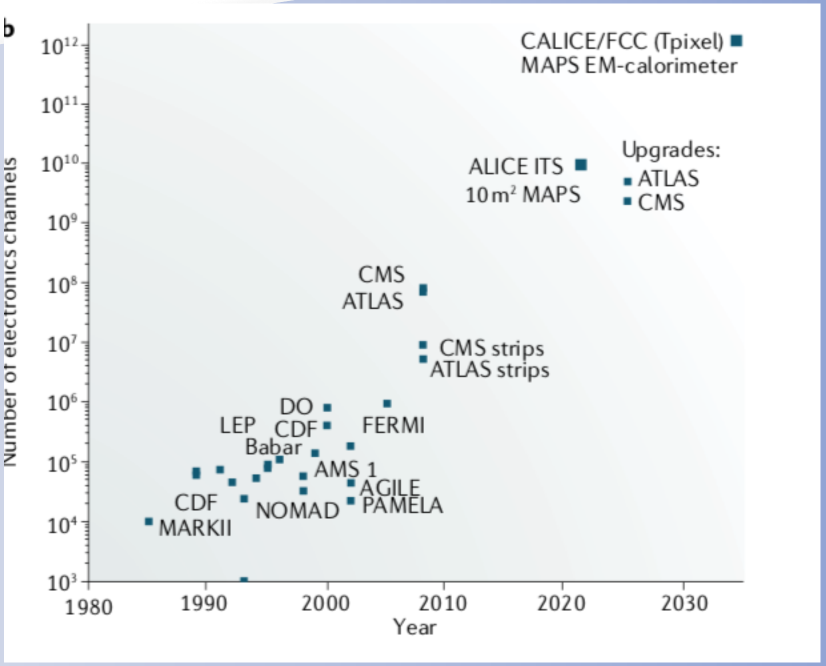


See talks by C. da Via and G. Kramberger

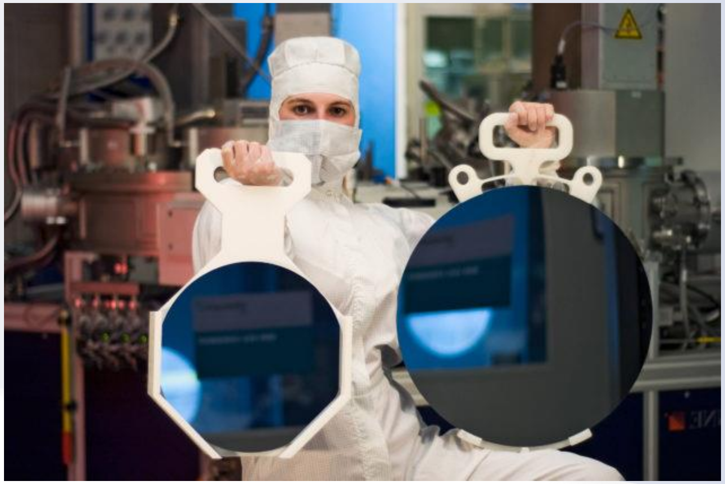
Readout Electronics

The challenges of silicon tracking detectors in terms of **hit rates, track densities and radiation environment** required also substantial developments on the readout electronics side. Together with a substantial increase in **channel numbers.**

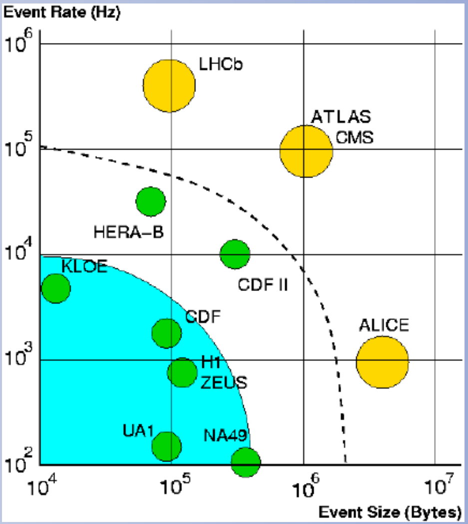
Following the **evolution of CMOS technologies** available on the market, nodes with smaller feature sizes are used to increase the radiation hardness and to add functionality and speed in combination with design and readout architectures.



From P. Allport, Nature Reviews, Vol 1, (575), 2019



https://wccftech.com/foundries-tsmc-companies-shift-300mm-wafers/



Faulkner et al., et Collaboration GridPP. (2021). GridPP: development of the UK computing Grid for particle physics.

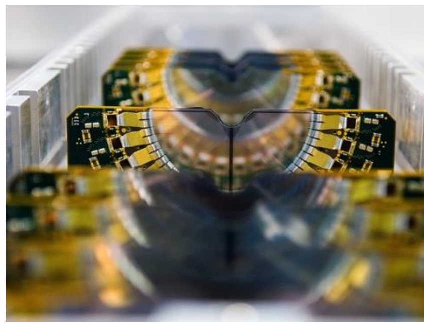
Silicon Trackers at LHC

All LHC experiments use silicon tracker – adapted to the experiments needs.

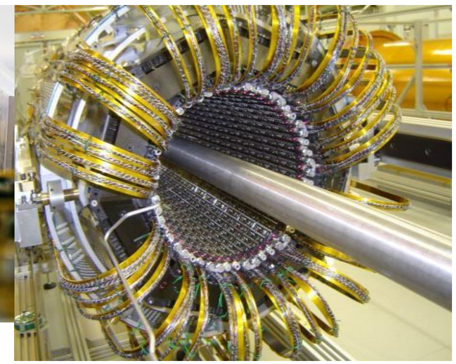
Detector Modules “Basic building block of silicon trackers”

- Silicon Sensors
- Mechanical support and cooling
- Front end electronics and signal routing (connectivity)

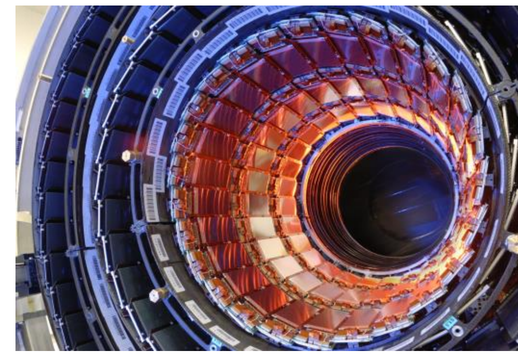
ALICE Pixel Detector



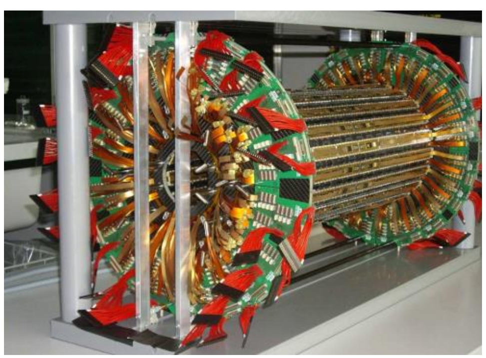
LHCb VELO



ATLAS Pixel Detector



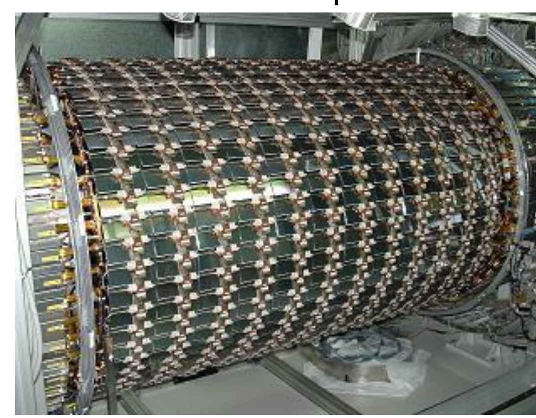
CMS Strip Tracker IB



CMS Pixel Detector

ALICE Drift Detector

ALICE Strip Detector

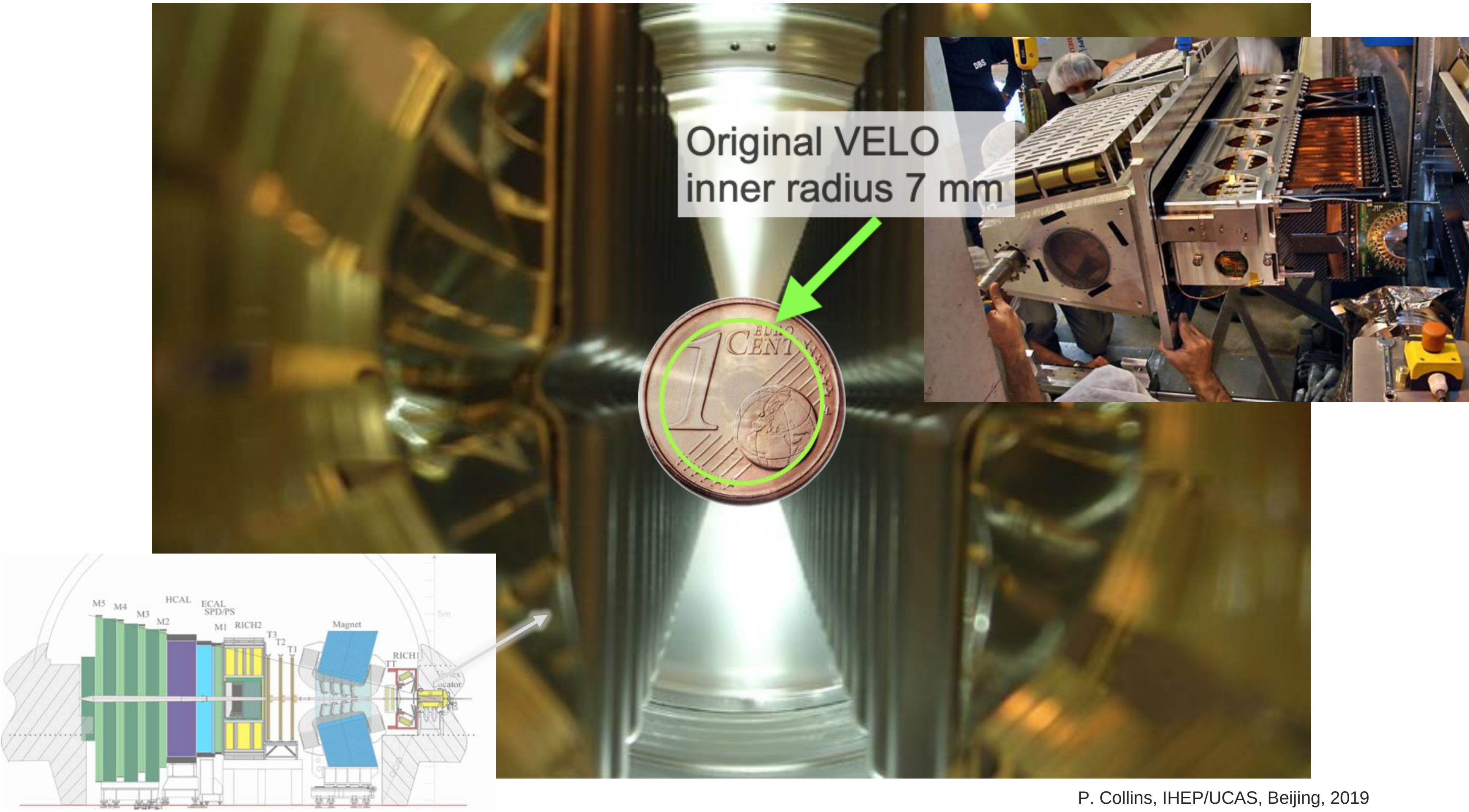


ATLAS SCT Barrel

Example: LHCb VELO

Operating condition can be very challenging:

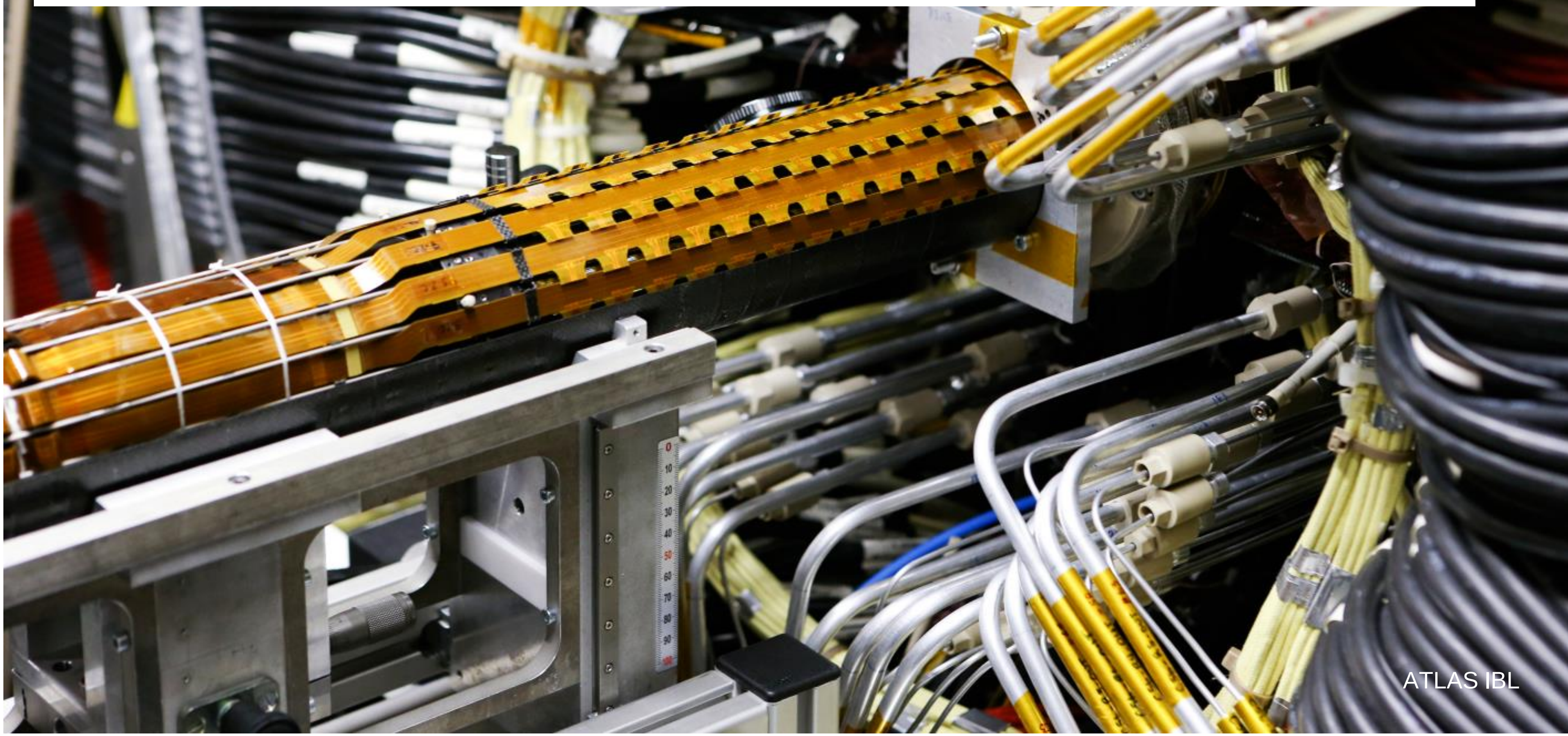
Double sided strip detector planes operated in secondary beam vacuum



P. Collins, IHEP/UCAS, Beijing, 2019

Example: ATLAS IBL phase-I upgrade to increase the performance

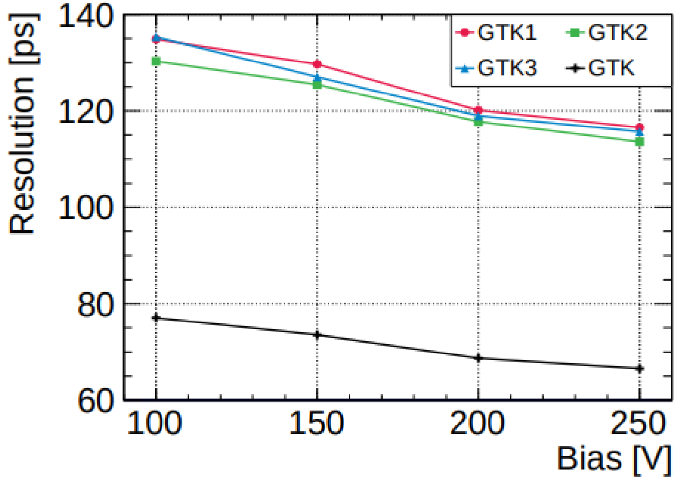
- 4^{th} Pixel layer (instead of b-layer replacement)
- Closer interaction point (5.05 → 3.27 cm)
- Smaller pixels (50 x 250 μm^2)
- Better sensors, better R/O chip
- Significantly reduced X_0/Layer

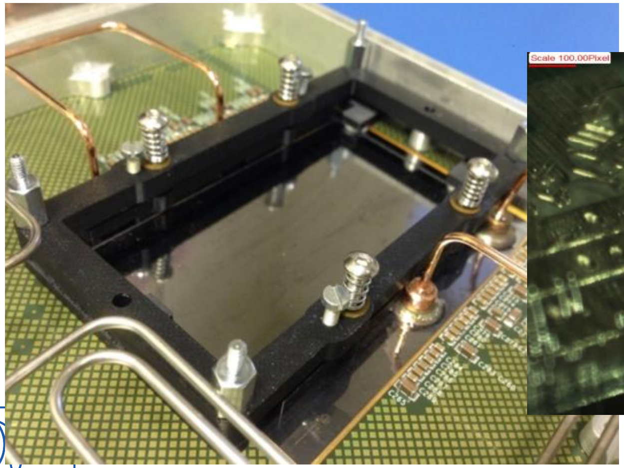


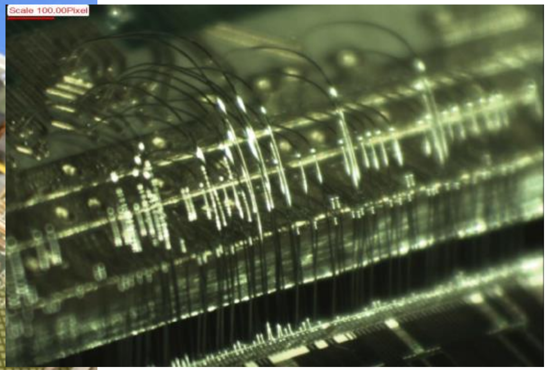
NA62-GigaTracKer

Detector developed in the **2010's** for **NA62**

- Track each particles in a 750 MHz continuous hadron beam
- **Time resolved** pixels with **130 ps** time resolution per hit achieved with n-in-p 200 µm thick planar sensors at 100V bias
- Readout chip (**TDCPix)** is still the best time resolved chip on the market (97ps TDC bin)
- Tight **material budget**: 0.5% X0 per station thanks to micro-channel cooling (0.2mm of Si)
- Smoothly operated since 2015: stable performance up to $2 \cdot 10^{14}$ $1 \cdot$MeV n_{eq}/cm^2
- Plans for upgrade after LS3 with 50ps time resolution and meeting requirements for 4x beam rate







https://iopscience.iop.org/article/10.1088/1748-0221/14/07/P07010

LHC and HL-LHC

https://project-hl-lhc-industry.web.cern.ch/content/project-schedule

Upgrades	Area
ALICE ITS	~10 m^2
ATLAS Pixel	~10 m^2
ATLAS Strips	~190 m^2
CMS Pixel	~5 m^2
CMS Strips	~220 m^2
LHCb VELO	~0.15 m^2
LHCb UT	~5 m^2

- Present accelerator will be upgraded (HL-LHC) to achieve high beam intensity

- Primary motivation of all upgrades is to maximise physics reach (e.g. precision measurements of Higgs couplings, Higgs self-coupling, phenomena beyond the SM)

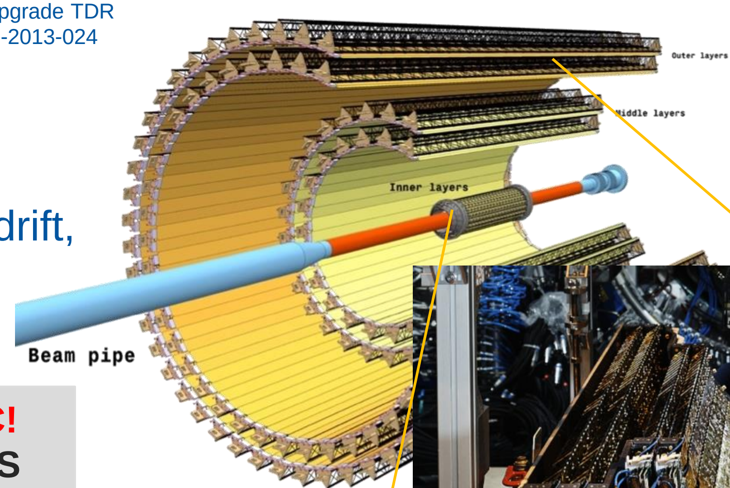
- Design choices for detector upgrades driven by physics goals, but also existing constraints.

- **ALICE and LHCb plan major upgrades for LS2, ATLAS and CMS will build even larger and more complex trackers for LS3.**

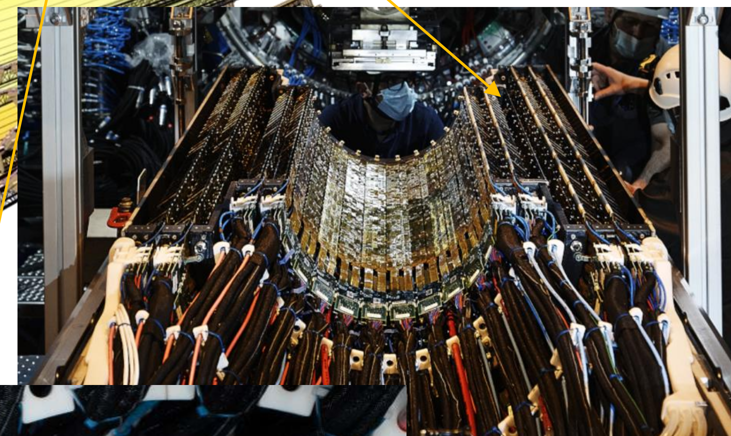
ALICE ITS Upgrade TDR
CERN-LHCC-2013-024

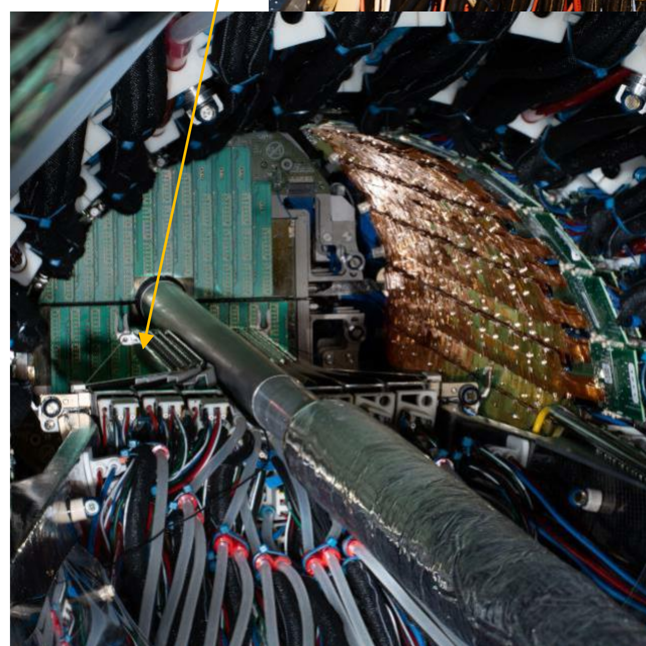
ALICE ITS2

Upgrade of the silicon trackers (pixel, drift, strips) for LS2 - Installation completed



Outer barrel





Inner barrel half and outer barrel layers

First CMOS MAPS based tracker at LHC!
Based on high resistivity epi layer MAPS (ALPIDE)

3 Inner Barrel layers (IB)
4 Outer Barrel layers (OB)

Radial coverage: 21-400 mm

~ 10 m^2, 12.5 Gpixels

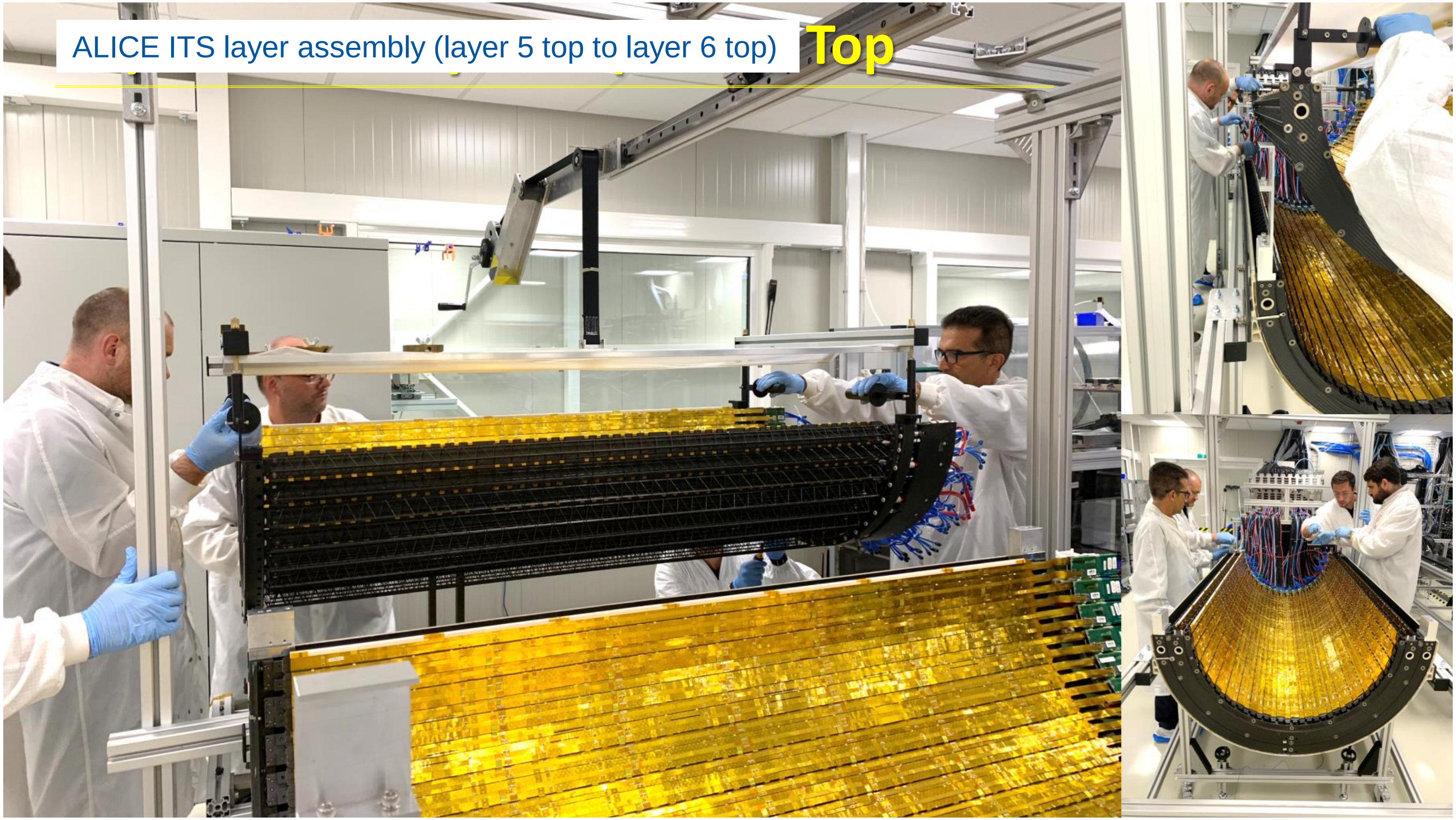
$|\eta|<1.22$ over 90% of the luminous region

0.35% X_0/layer (IB)
1 % X_0/layer (OB)

Radiation level (IB, layer 0): TID: 2.7 Mrad, 1.7×10^{13} 1 MeV n_{eq} cm^{-2}

See posters by J.P. Iddon and M.B. Blidaru

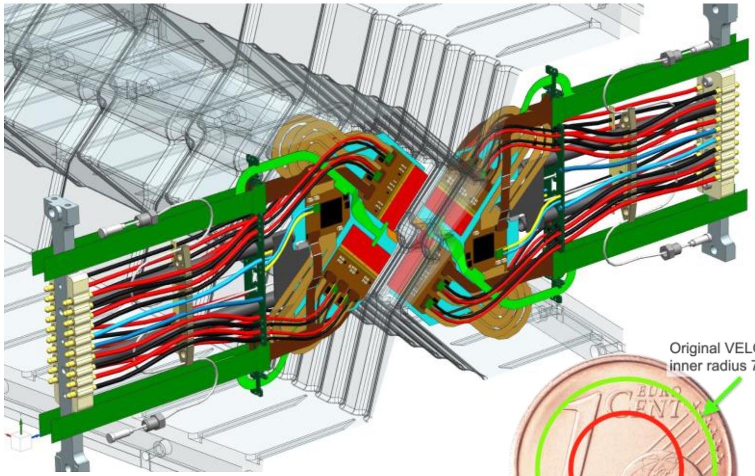
ALICE ITS2 layer assembly

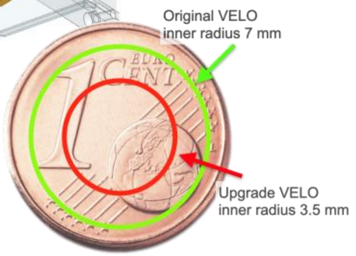


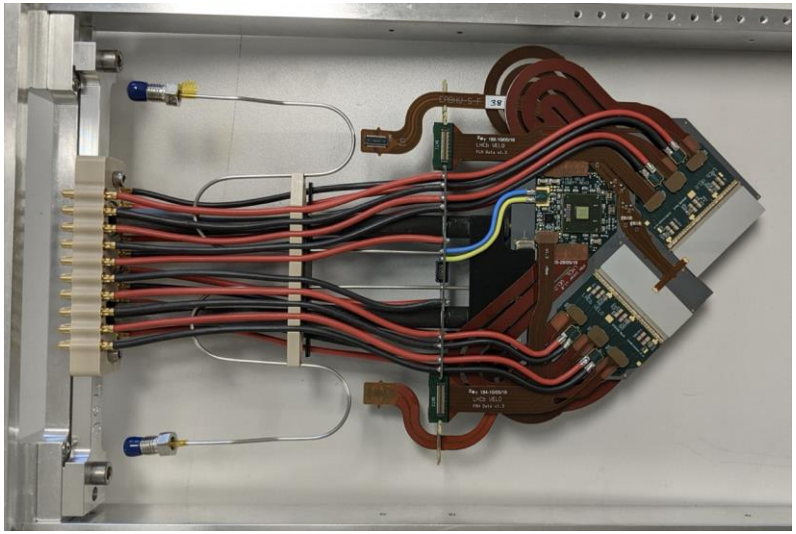
C. Gargiulo, CERN

LHCb Velopix

- New 40 MHz readout pixel detector replaces strip detector and will be installed for Run 3
- Operates at increased luminosity with ultra high speed VeloPix - 800 Mhits/s/ASIC
- Improved performance for high statistics flavour physics programme



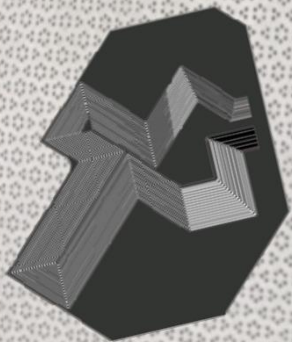




- Each module equipped with 4 hybrid pixel tiles
- 55 µm pitch
- 200 µm thickness
- data driven readout
- highly non uniform irradiation up to 8 x 10^{15} 1 MeV n_{eq} cm^{-2}
- 52 modules total

See talk by K. Carvalho Akiba

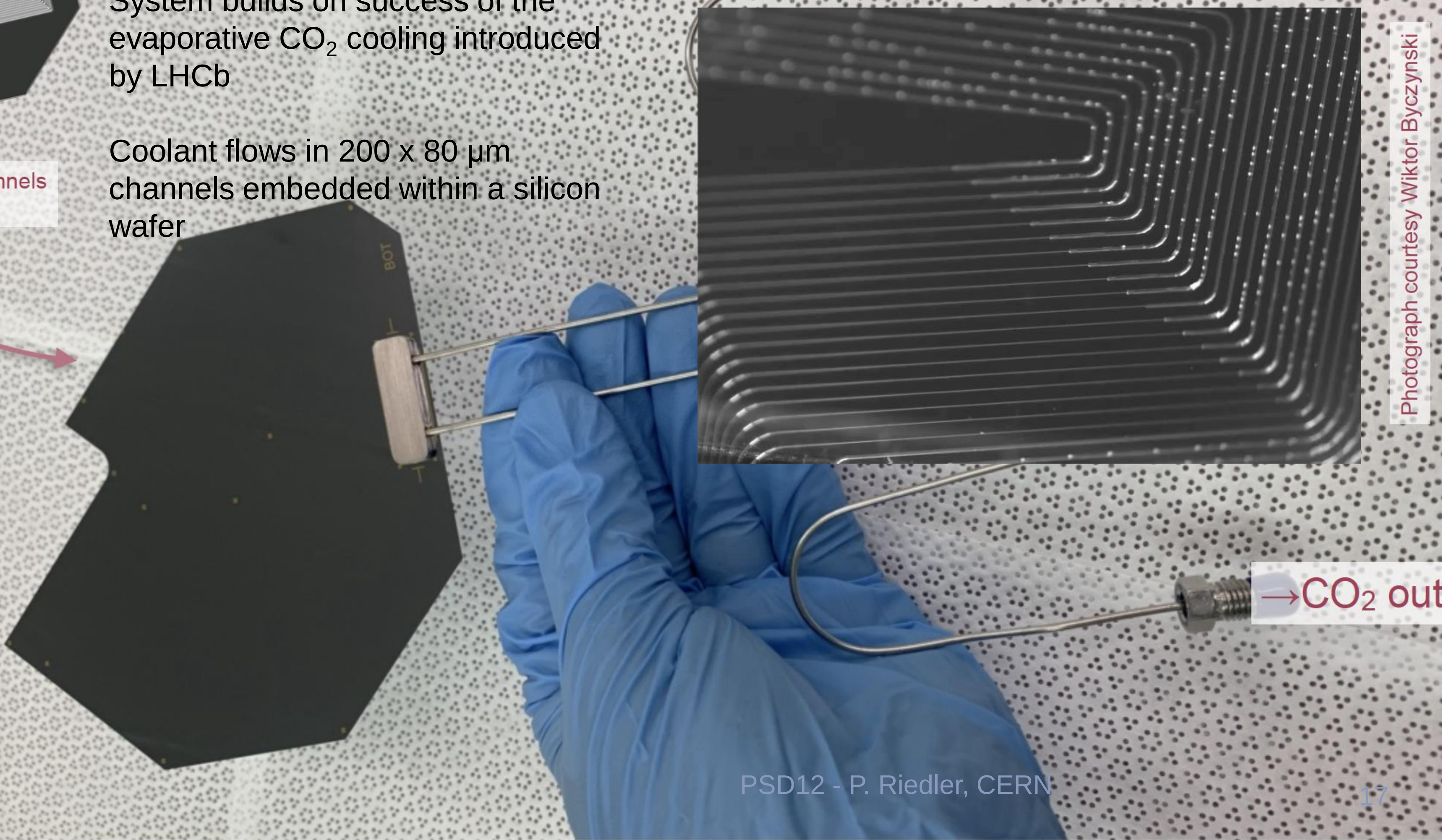
LHCb VELOpix



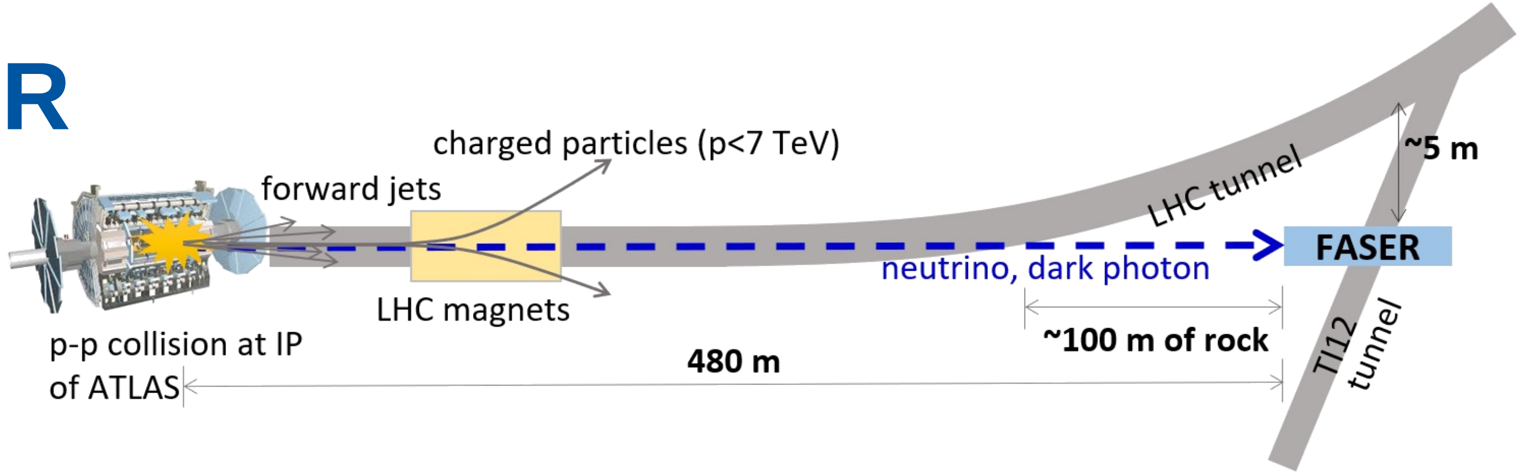
Efficient, light, and powerful cooling needed for pixel detectors operating in vacuum

System builds on success of the evaporative CO_2 cooling introduced by LHCb

Coolant flows in 200 x 80 µm channels embedded within a silicon wafer

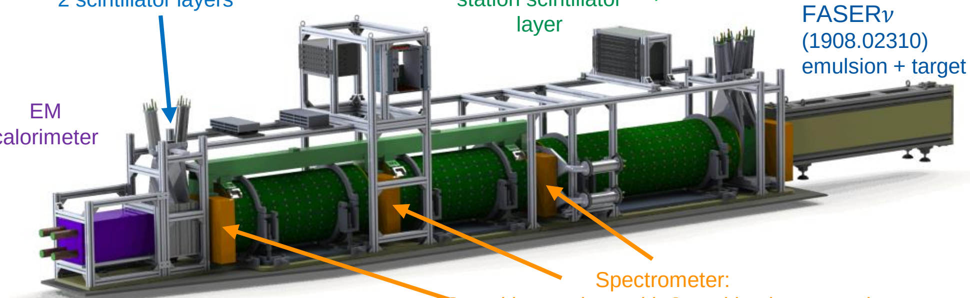


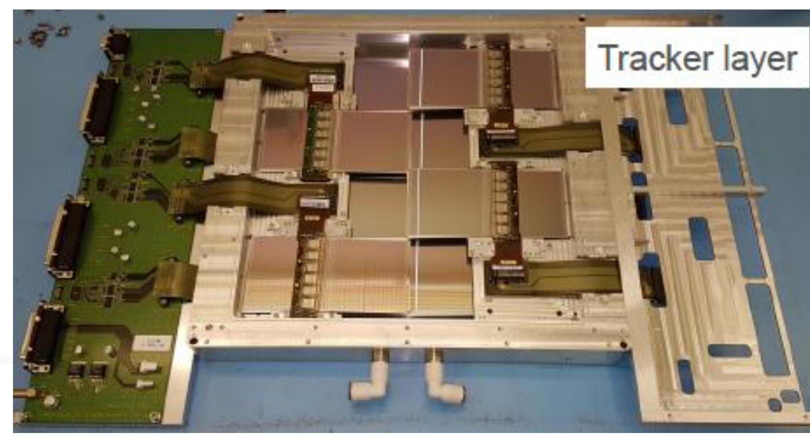
FASER



FASER is **a new small experiment** in an old LEP injector tunnel (TI12), to **start running after LS2**, designed to cover this scenario **at the LHC – detect particles in the forward region, ie dark photon search, Axion-Like-Particles.**

Tracking stations: 80 ATLAS SCT spare modules (single sided p-in-n strip detectors, 80 µm pitch), 10^5 channels in total in three stations





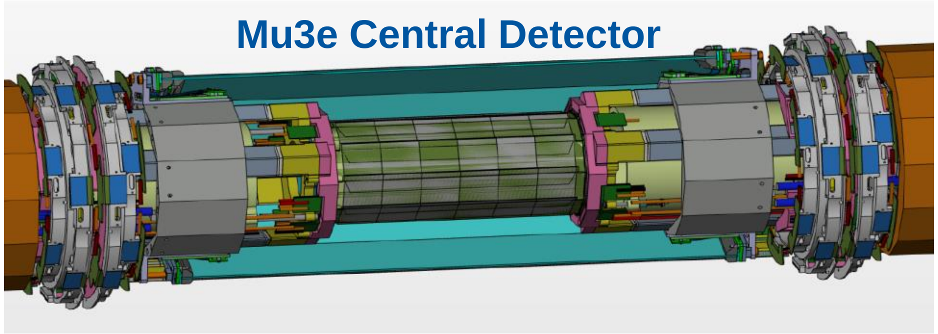
FASER Technical Proposal arXiv:1812.09139

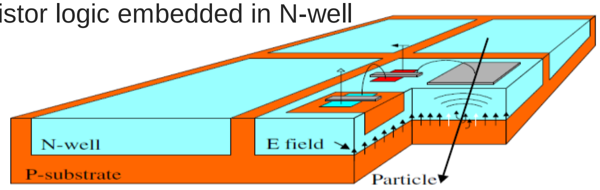
Mu3e

Search for lepton flavor violating decay at PSI – under construction

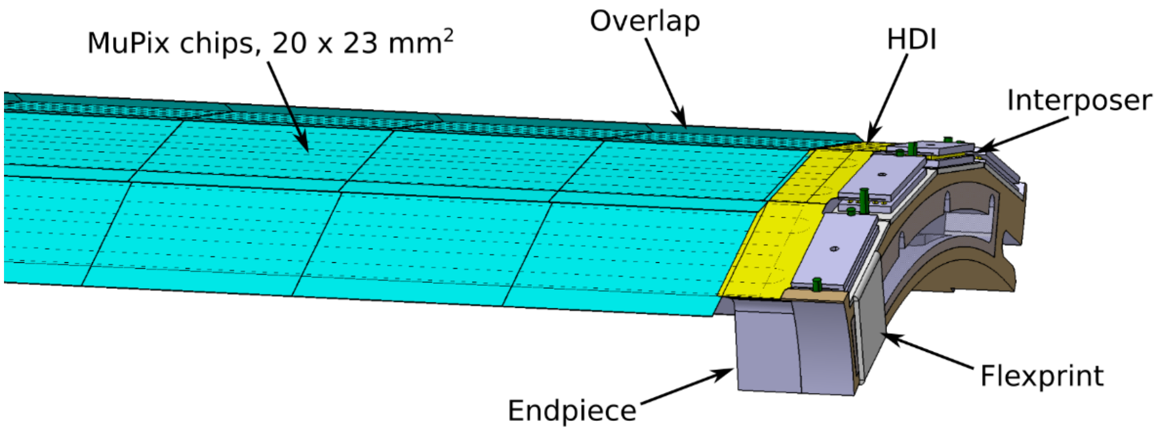
HV CMOS based central detector with **ultra-thin HV CMOS pixel sensor modules** (X/X_0= 1.15 per mille)

Gas-He cooling system

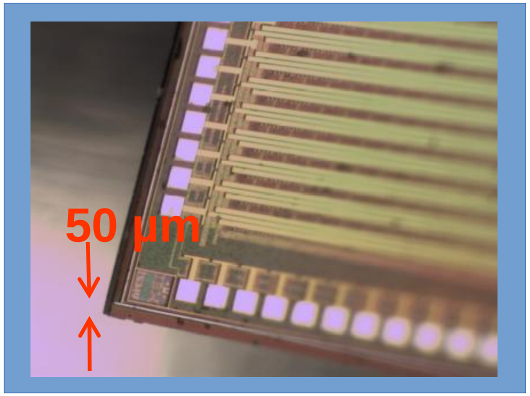




I.Peric et al., NIM A 582 (2007) 876



HDI=High density interconnect cable (Al/Kapton)



Monolithic pixel sensor in 180 nm HV-CMOS

3. Future Developments

LHC experiment upgrades for LS3

https://project-hl-lhc-industry.web.cern.ch/content/project-schedule

Major **tracker upgrades with several hundreds of m^2 of silicon** are foreseen for **ATLAS and CMS** and will be installed during the LS3 shutdown. CMS will also install a silicon based calorimeter (**HGCal**), which will consist of **600 m^2 of silicon.**

ALICE and LHCb will also consider upgrades for parts of their trackers.

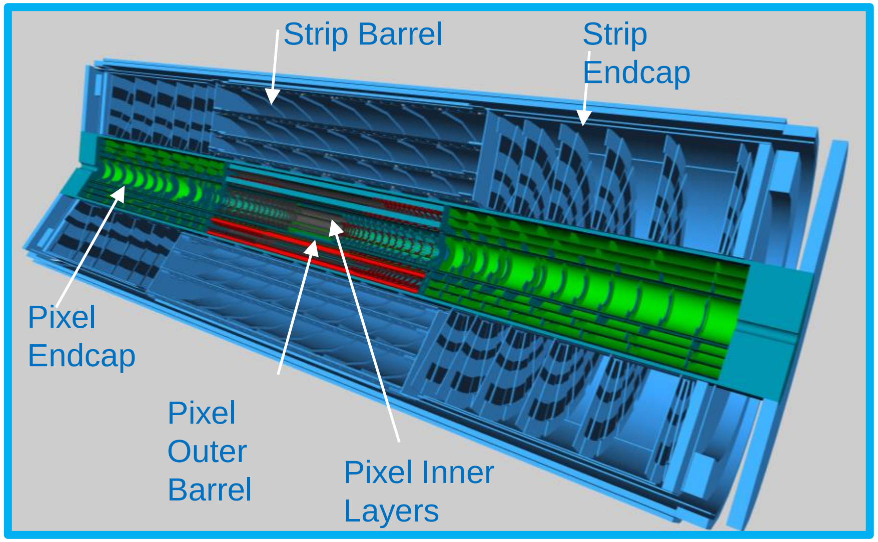
ATLAS ITk phase-2 upgrade

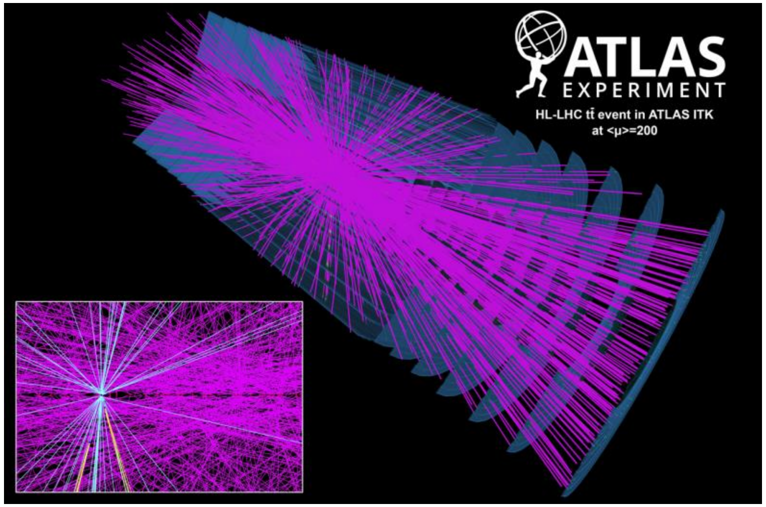
Inner tracker (at present made of TRT, Strips and pixels) will be replaced with a **silicon-only tracker** to meet requirements for p-p up to 14 TeV at higher intensity:

- Instantaneous nominal luminosity x5-7.5 → **Increased particle densities**
- Integrated luminosity x10 → **Increased radiation damage**
- → Increase of **overlapping proton-proton events** (pile-up) from <μ> ~ 50 now to <μ> ~ 200

Plus: low X_0, fast and reliable readout, high vertex and track position resolution, high charge collection efficiency

See talk by J. Weingarten





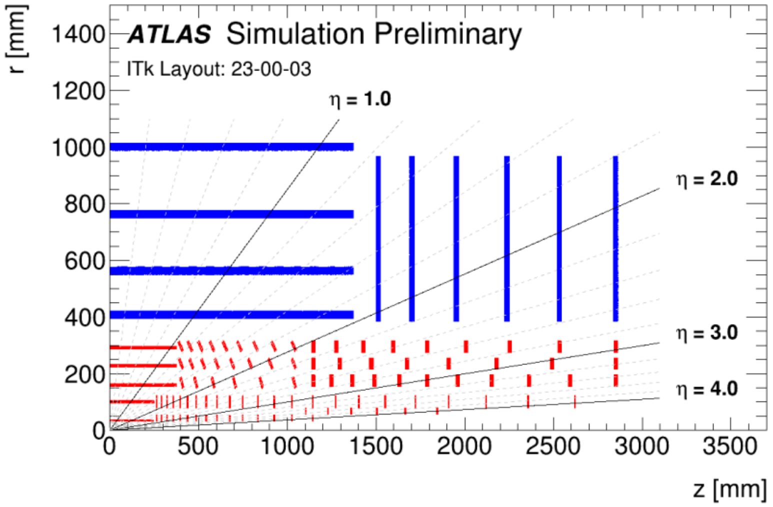
Simulated event with ttbar events and average pile-up of 200 collisions per bunch crossing

ATLAS ITk phase-2 upgrade

Silicon strip and pixel detector in a 2T magnetic field:

4 central strip layers and two endcaps with 6 disks each:

- 18 k modules and ~234 k ASICs
- ~ 60 million channels
- Up to 640 Mbps per module
- Total area about 165 m^2

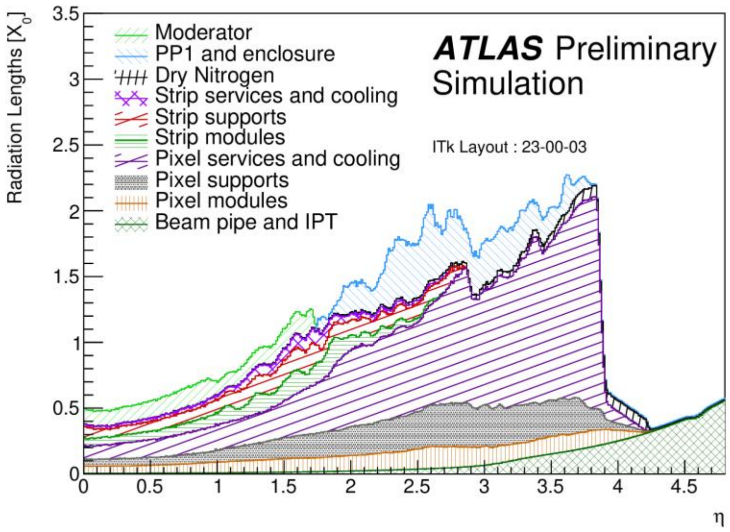


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/

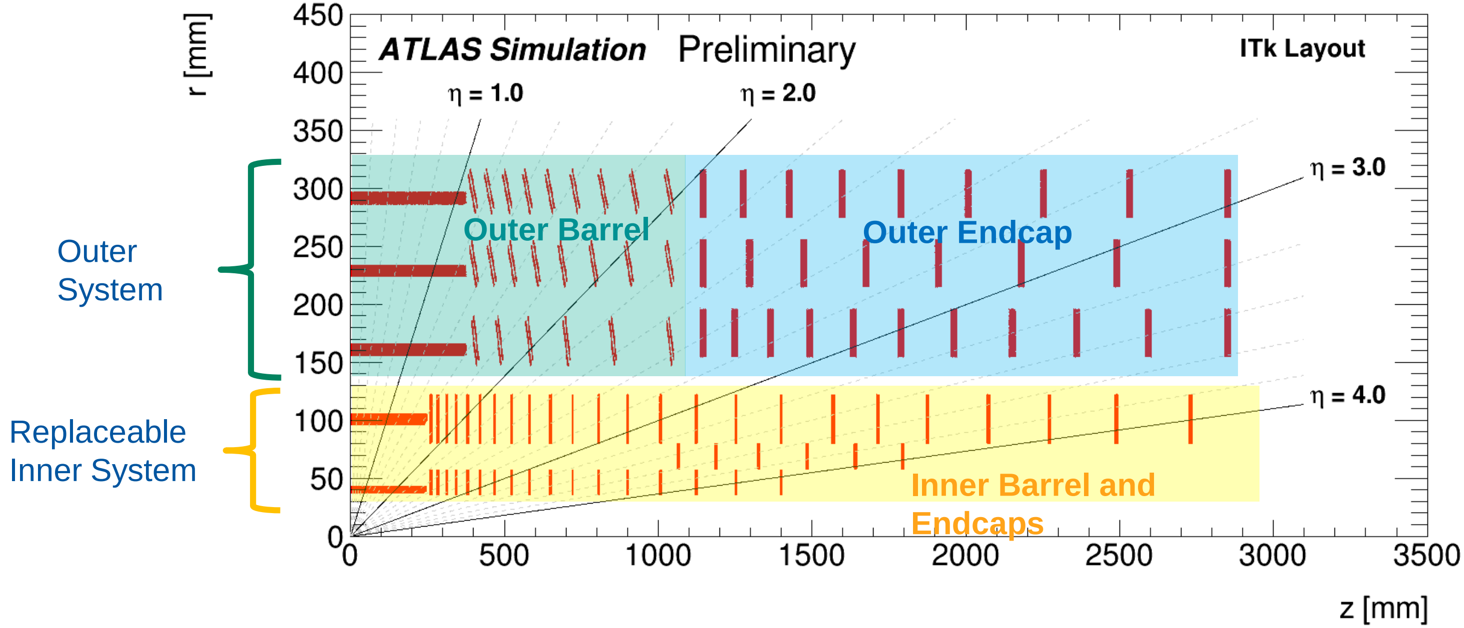
5 pixel layers in the central and forward sections

- ~8.5 k hybrid pixel modules and ~34 k front-end chips
- ~5 billion pixels
- Up to 4x 1.28 Gbps per front-end chip
- Total area about 13 m^2

Reduction of material: thin sensors, CO_2 cooling with Ti pipes, serial powering for pixels, DC-DC convertors for strips, CF structures



ATLAS ITk phase-2 upgrade - Pixels



- About **6x larger than the present pixel detector**, with about 8500 modules and 34 000 FE chips
- **Different sensors types and technologies depending on distance from interaction point**
- 3D-sensors in triplet assemblies (Layer 0), planar with 100 µm (L1), planar sensors with 150 µm (L2, L3, L4) thickness
- Pixel size: 50x50 μm^2 (L1-L4, rings of L0), 25x100 μm^2 (flat part of L0)

ATLAS ITk phase-2 upgrade - Pixels

Thin n-in-p planar sensors

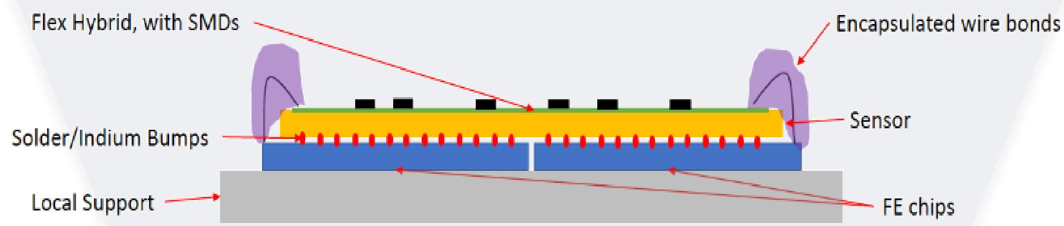
- Dies of 4x4 cm^2, 100/150 μm thick
- Bias voltage up to 600 V (at end of life-time)

3D sensors

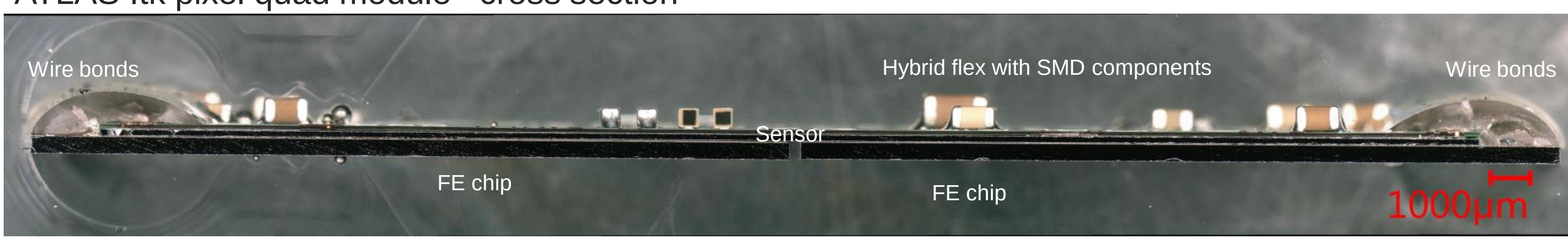
- For innermost layer: 1.3×10^{16} n_{eq}/cm^2 for 2000 fb^{-1}
- Dies of 2x2 cm^2, 150 μm thickness + 100-200 μm support wafer

FE chip:

- RD53 Collaboration: joint R&D of ATLAS and CMS, 65 nm TSMC



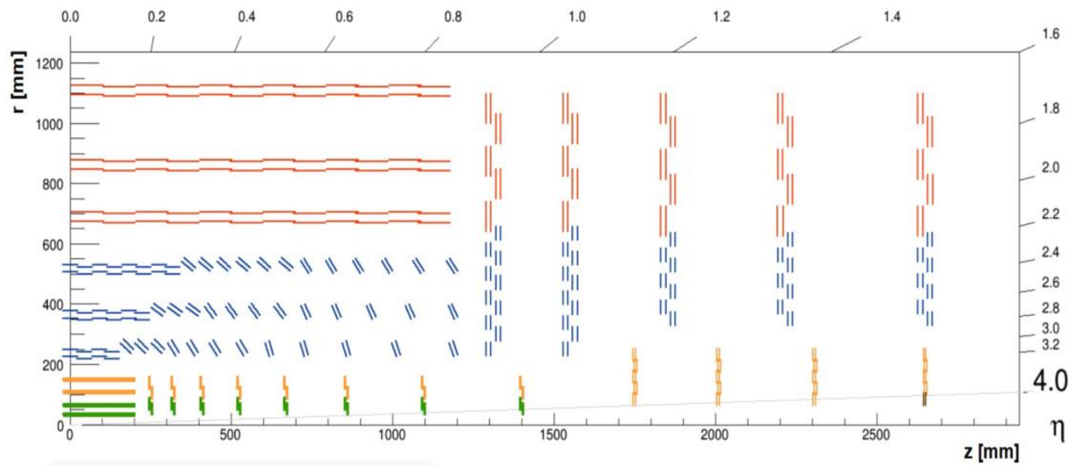
ATLAS Itk pixel quad module –cross section



CMS phase-2 Tracker

Complete replacement of the present tracker:

- **Outer Tracker** (OT) based on silicon strip and macro pixel modules and
- **Inner Tracker** (IT) based on hybrid pixel detectors
- Acceptance up to $|\eta| = 4$
- Low-mass two-phase CO_2 cooling at -35 °C



Outer Tracker (OT)
- 190 m^2
- 213M channels

7608 **strip-strip modules** (2S)
5cm x 90µm strips

Inner Tracker (IT)
- 4.9 m^2
- 1.95G channels

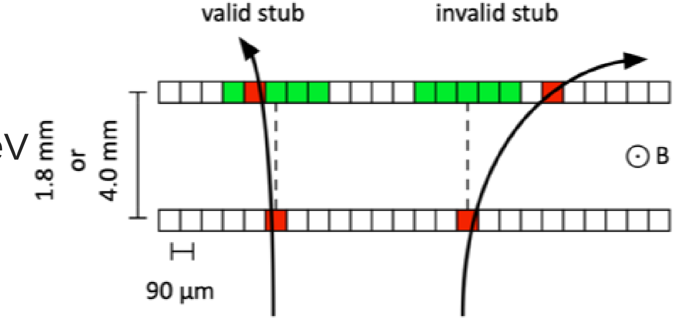
5592 **pixel-strip modules** (PS)
2.4cm x 100µm strips
1.5mm x 100µm macro-pixels

3892 pixel modules
100µm x 25µm pixels
1 x 2 and 2 x 2chips

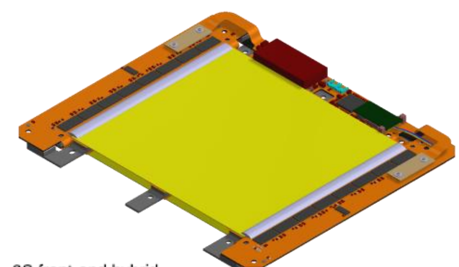
See talk by E. Migliore

CMS phase-2 Tracker OT

- Because of pile up **tracker information is added to L1** by measuring the muon momentum to select only hits with p_T>2 GeV using
- Modules made of two closely spaced sensors read out by a common set of ASICs
  - → **Select pair of hits (“stubs”) from tracks with p_T > 2 GeV (“stubs”)**
- Stubs sent to the backend at 40 MHz → L1 trigger decision
- Whole detector read out in case of L1-Trigger accept (≈ 750 kHz)

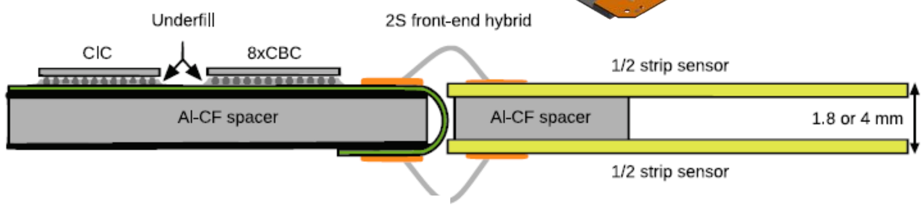


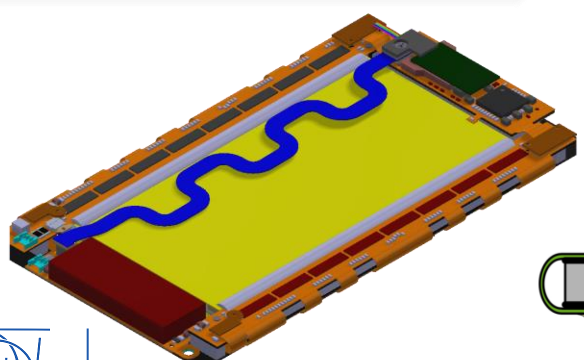
7608 **strip-strip modules** (2S)
5cm x 90µm strips

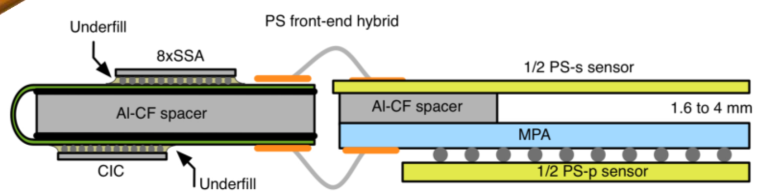


5592 **pixel-strip modules** (PS)
2.4cm x 100µm strips
1.5mm x 100µm macro-pixels

2S-module

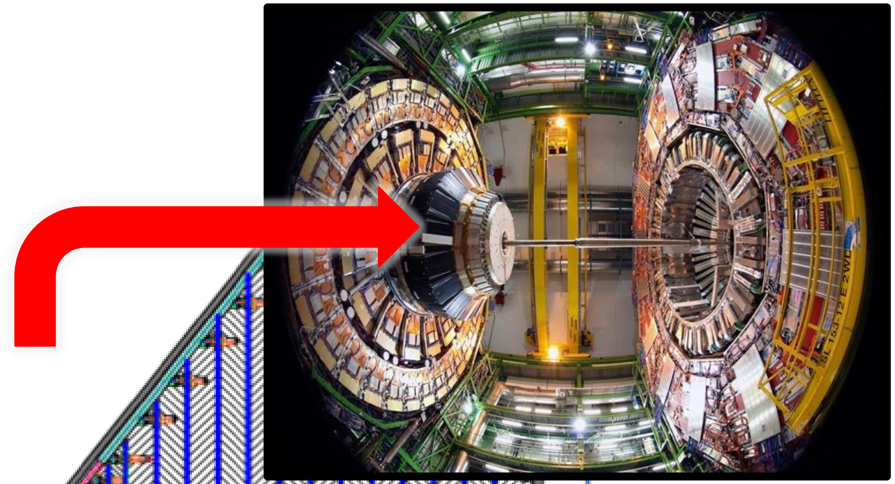


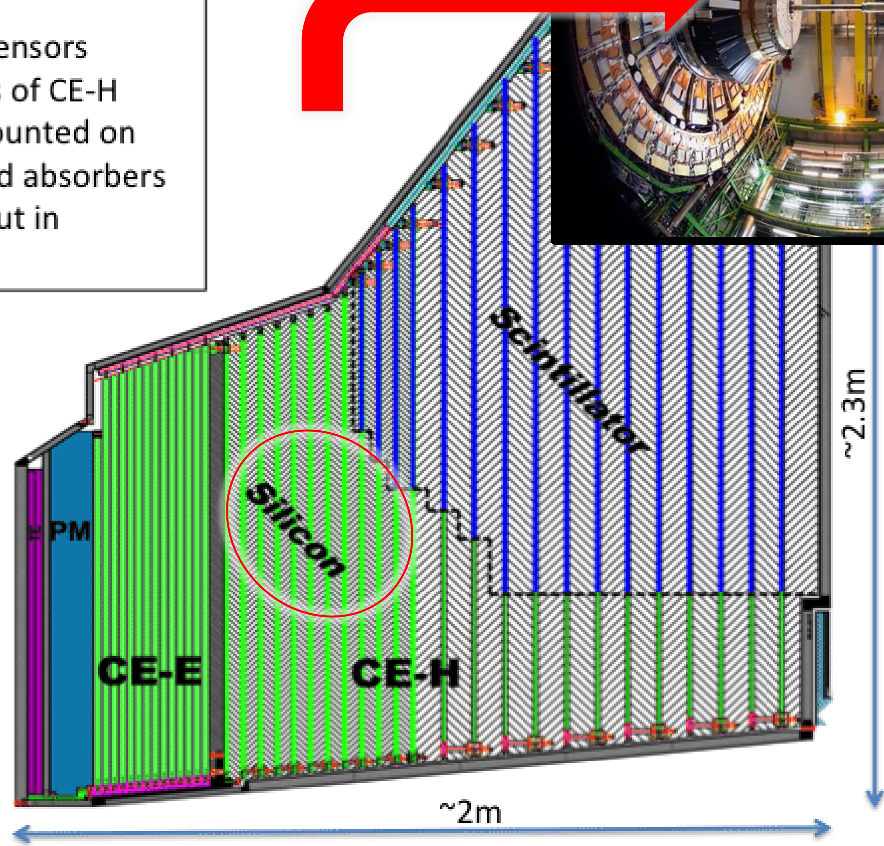




CMS HGCal

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 SiPM readout in low-radiation regions of CE-H





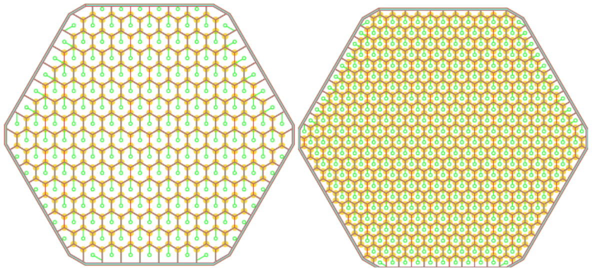
Key Parameters:
- Coverage: $1.5 < |\eta| < 3.0$
- ~215 tonnes per endcap
- Full system maintained at -30°C
- ~600m² of silicon sensors
- ~500m² of scintillators
- 6M Si channels, 0.5 or 1 cm² cell size
- ~27000 Si modules
- Power at end of HL-LHC: ~110 kW per endcap

Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~1.3λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 24 layers, ~8.5λ

See talk by E. Sicking

CMS HGCal

~600m² of silicon sensors (3x CMS tracker) in radiation field peaking at 200 Mrad and ~10^{16}n/cm²



Planar p-type DC-coupled sensor pads

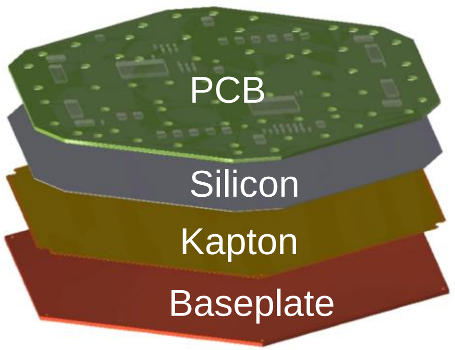
Simplifies production technology, p-type more radiation tolerant than n-type

Hexagonal sensor geometry preferred to square

Makes most efficient use of circular sensor wafer (factor ~ 1.3)

Vertices of the sensors truncated ('mouse-bites')

Provides the clearance for mounting and also further increases the wafer surface used



8" wafers reduces number of sensors and modules (factor ~ 1.8)

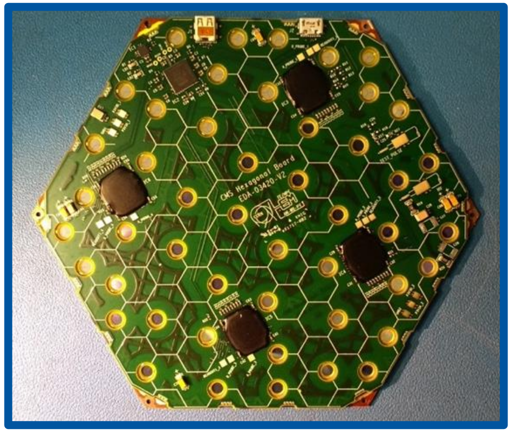
300mm, 200mm and 120mm active sensor thicknesses

Match sensor thickness (and granularity) to radiation field for optimal performance

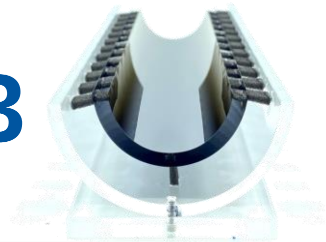
Simple, rugged module design & automated module assembly (~ 30 000 modules)

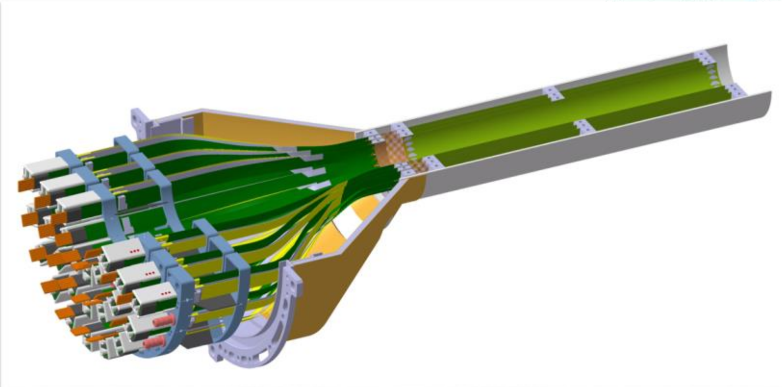
Provide high volume, high rate, reproducible module production & handling

Hexaboard houses the HGCROCs, with bonding through special holes in PCB to connect to sensor readout pads.



ALICE ITS3





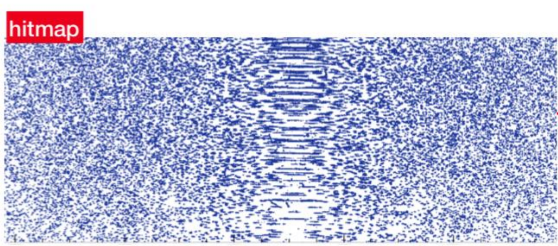
Beam pipe Inner/Outer Radius (mm)	16.0/16.5		
IB Layer Parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	18.0	24.0	30.0
Length (sensitive area) (mm)	300		
Pseudo-rapidity coverage	±2.5	±2.3	±2.0
Active area (cm^2)	610	816	1016
Pixel sensor dimensions (mm^2)	280 x 56.5	280 x 75.5	280 x 94
Number of sensors per layer	2		
Pixel size (μm^2)	O (10 x 10)		

Key ingredients:

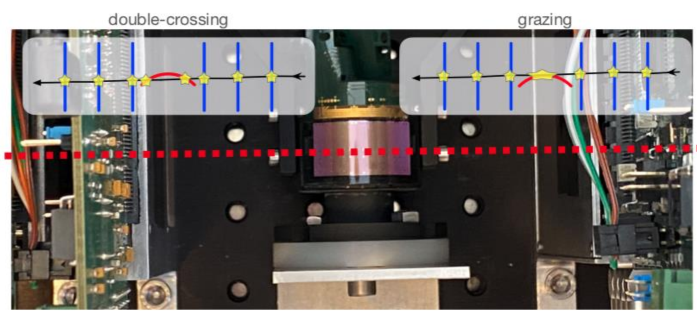
- 300 mm wafer-scale chips, fabricated using stitching
- thinned down to 20-40 µm (0.02-0.04% X0), making them flexible
- bent to the target radii
- mechanically held in place by carbon foam ribs

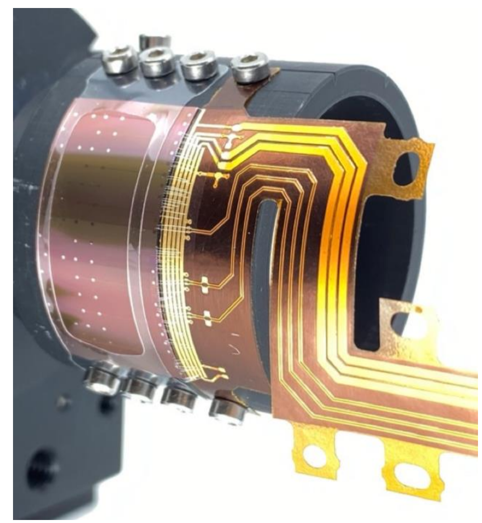
Key benefits:

- extremely low material budget: 0.02-0.04% X0 (beampipe: 500 µm Be: 0.14% X0)
- homogeneous material distribution: negligible systematic error from material distribution



Testbeams at DESY





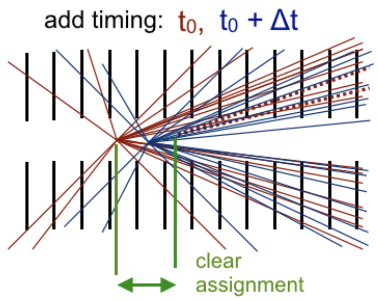
From M. Mager, TIPP2021, https://indico.cern.ch/event/864722/

See talk by D. Colella

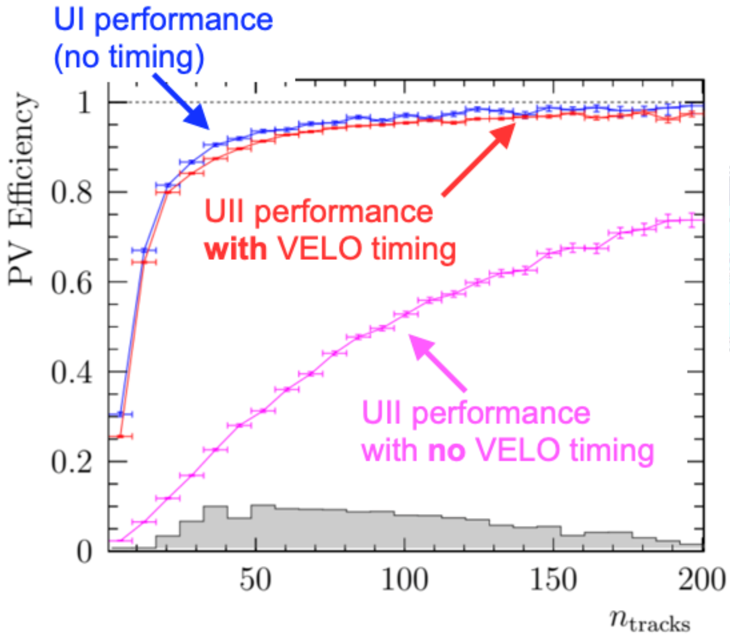
LHCb VELO Upgrade

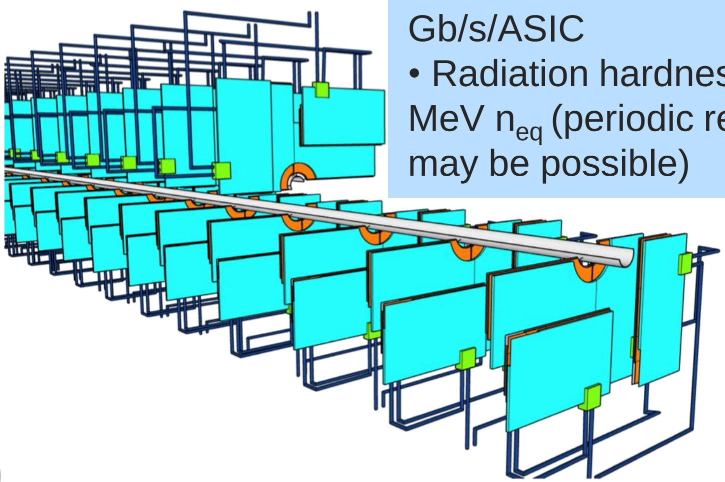
- LHCb Upgrade II Luminosity will increase to 1.5 x 10^{34} cm^{-2} s^{-1} (factor 10)
- Upgrade II VELO will also be based on high granularity pixels operated in vacuum in close proximity to LHC beams
- To cope with increased pile up a timestamp of 20 ps per track will be needed to correctly associate each beauty/charm hadron with the primary vertex from which it originates
- A time stamp per hit of < 50 ps is mandatory to achieve primary vertex reconstruction in the VELO

two primary vertices + time decoding $t_0, t_0 + \Delta t$



Upgrade II VELO challenges
- ultra light foil, cooling and mechanics
- ASIC bandwidth up to 250 Gb/s/ASIC
- Radiation hardness up to 10^{17} 1 MeV n_{eq} (periodic replacements may be possible)



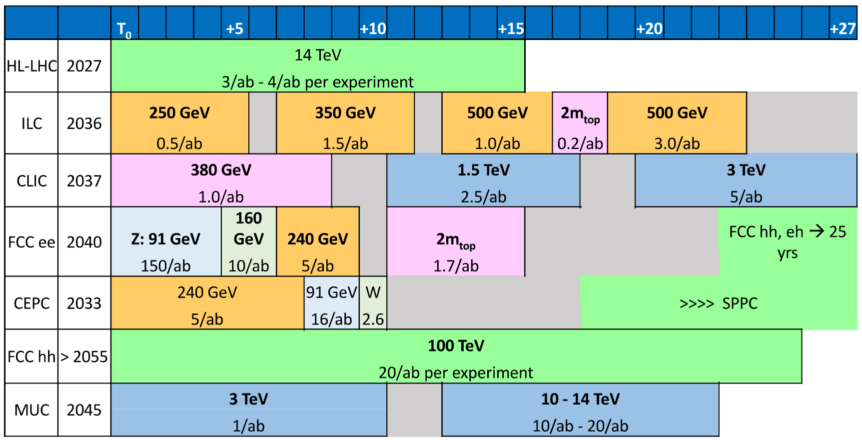


See poster by J. Haimberger and talk by K.C. Akiba

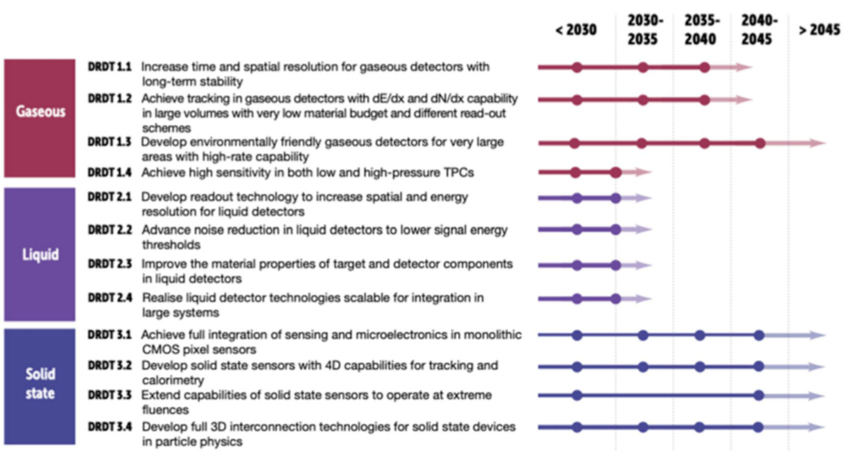
See talk by N. Cartiglia for position sensitive fast timing detectors

Future projects

Future colliders with earliest feasible start date

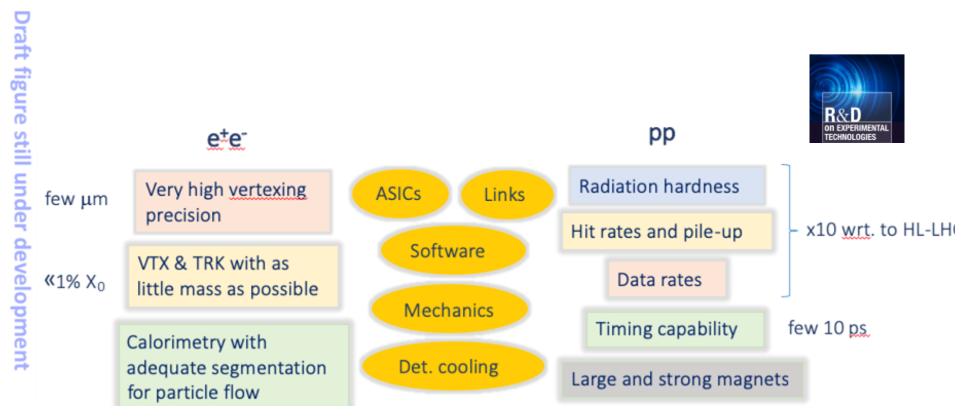


From L. Rivkin, EPS conference 2021



From P. Allport, EPS conference 2021

- **R&D activities** are pursued for future facilities and projects to provide **novel silicon tracking detectors with enhanced performance and capabilities.**
- The **ECFA detector R&D roadmap** has identified several key areas for for future silicon detectors, including 4D capabilities for silicon in tracking and calorimetry.
- **CERN EP R&D** started in 2020 is addressing a range of key detector developments for future detectors (https://ep-rnd.web.cern.ch/node/263)



From C. Joram, CERN-EP

Summary

- Particle physics experiments depend on silicon based tracking systems, with needs for larger and more performant systems.

- The phase-2 upgrades will represent the largest tracking systems built so far. Applications such as the CMS HGCal require even larger silicon surfaces.

- A very strong and diverse R&D effort is exploring different paths, including novel concepts for trackers and other applications and aiming to include new features such as 4D tracking.

I would like to thank my colleagues who kindly provided material and information for this presentation:

Duccio Abbanea, Stefania Beole, Phil Allport, Paula Collins, Hans Danielsson, Anotnello Di Mauro, Corrado Gargiulo, Karl Gill, Christian Joram, Susanne Kuehn, Magnus Mager, Mathieu Perrin-Terrin, Heinz Pernegger, Andre Schöning

Thank you!