Current and future detector technologies with focus on silicon detectors

30.6.2022

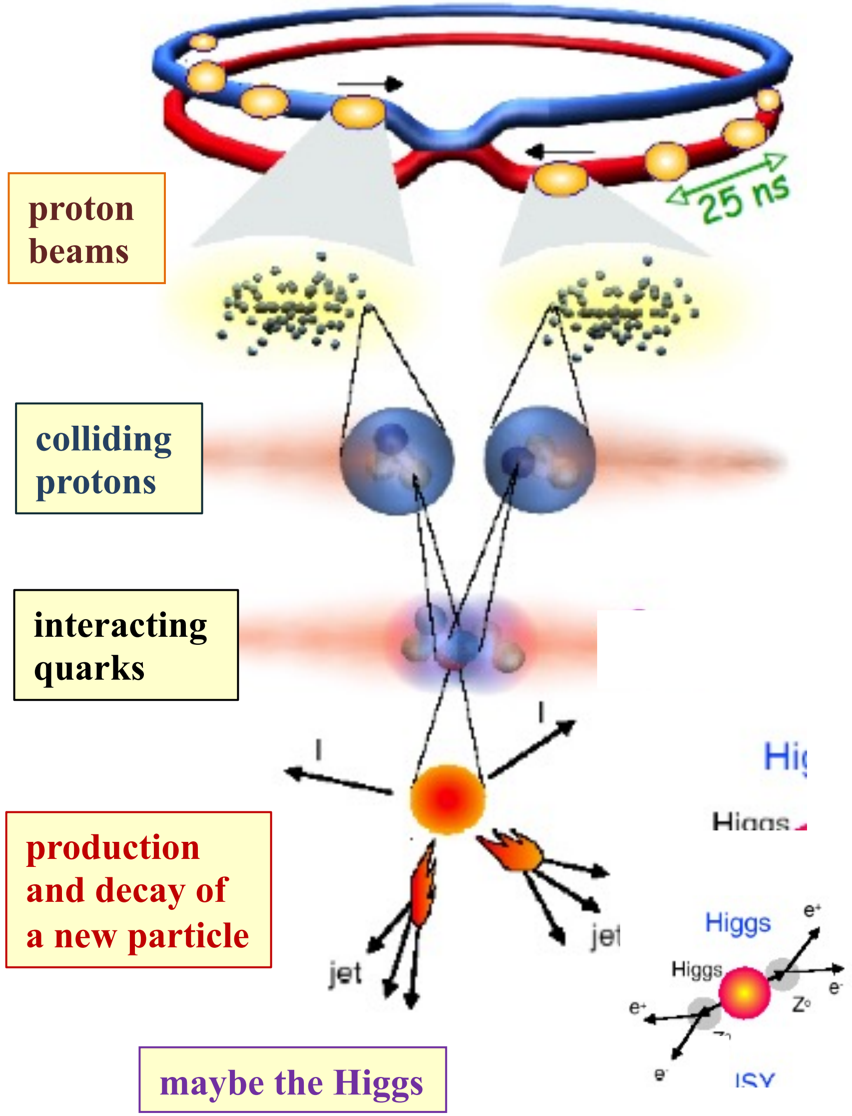
Susanne Kuehn, CERN

Overview

- Introduction to particle detectors
- Examples of current detectors in LHC experiments: tracking detector and calorimeter
- Future facilities and example for R&D for future detectors

Disclaimer: selection of a few detector concepts and examples from experiments

Collisions at the LHC



proton beams

colliding protons

interacting quarks

production and decay of a new particle

maybe the Higgs

- Two independent proton beams are brought to collision (at specific interaction points)
- Protons are arranged in bunches (~10^{11}). Several pp-collisions per bunch crossing.
- the colliding protons “break” into their fundamental constituents (i.e. quarks) → only a fraction of the proton energy is available for the creation of new particles.
- → lots of non-interesting background
- The new particles are generally unstable and decay promptly into lighter (known) particles: electrons, photons, etc.

Detectors must be ultra-selective

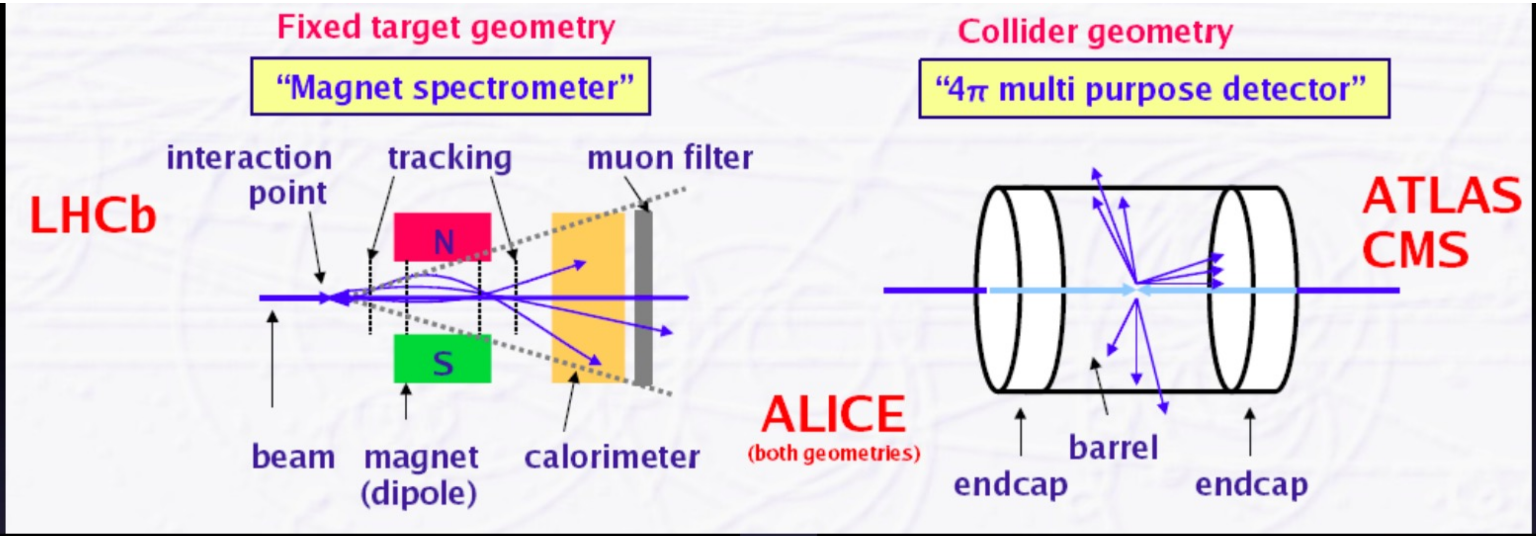
Distinguish (new) rare particle decays from (known) abundant particle decays
→ very performant detectors with excellent particle identification

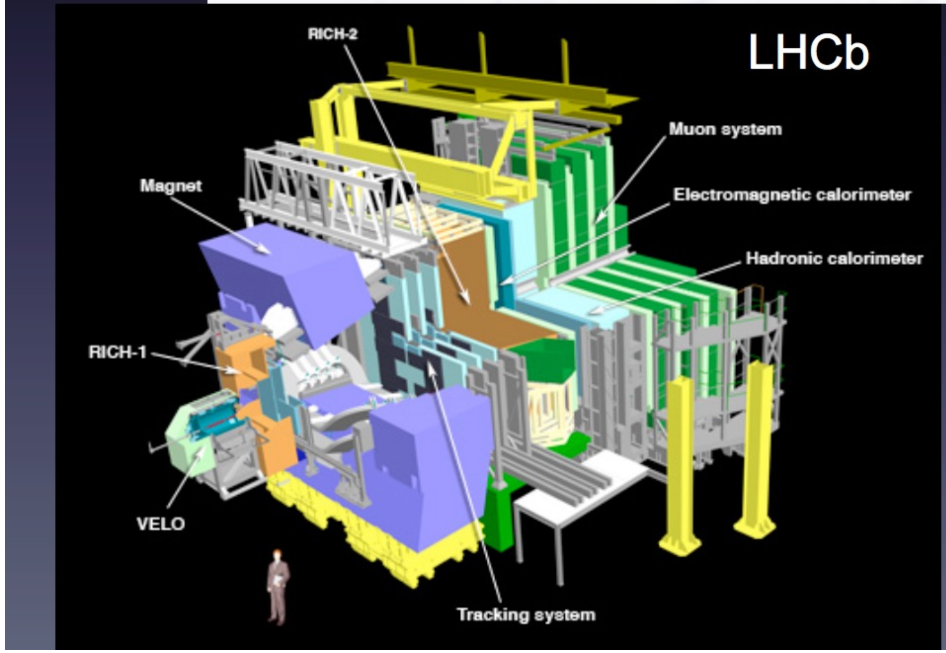
You are looking for this particular particle physicist!

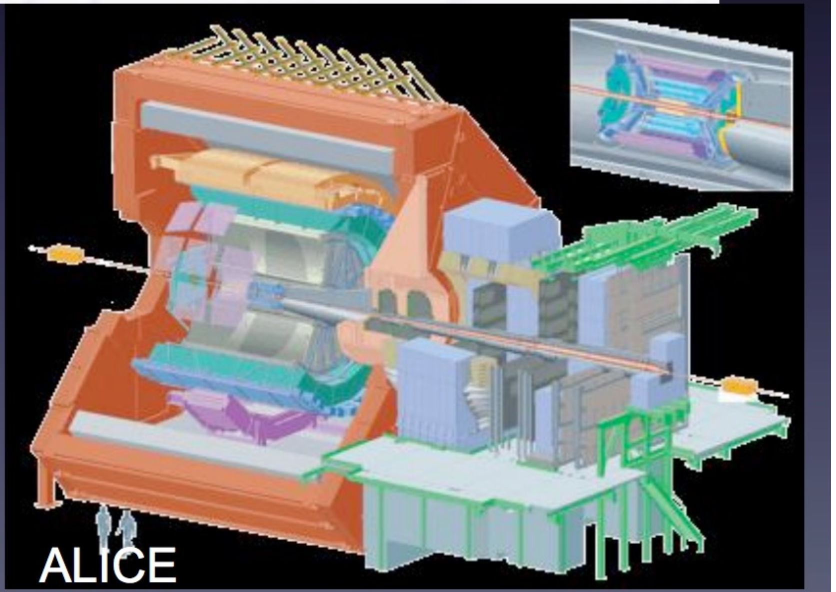
Needs VERY high
- ✓ precision
- ✓ statistics
- ✓ selectivity
- ✓ background suppression

Note:
- ➢ the world population is ~$7.5 \cdot 10^9$
- ➢ typical very rare decay $B(B_s \rightarrow \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$

Configuration of HEP detectors

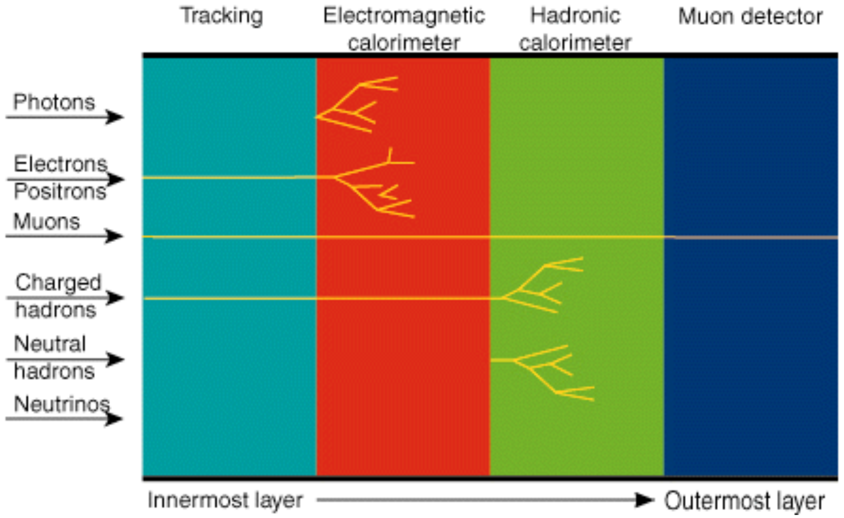






Particle Detectors

- **There is no type of detector which provides all measurements we need**
  → "Onion" concept → different systems taking care of certain measurement
- **Detection of particles (collision products) within the detector volume**
  resulting in signals (mostly) due to electro-magnetic interactions

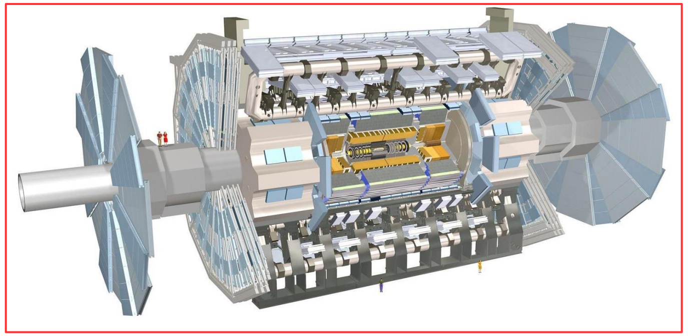


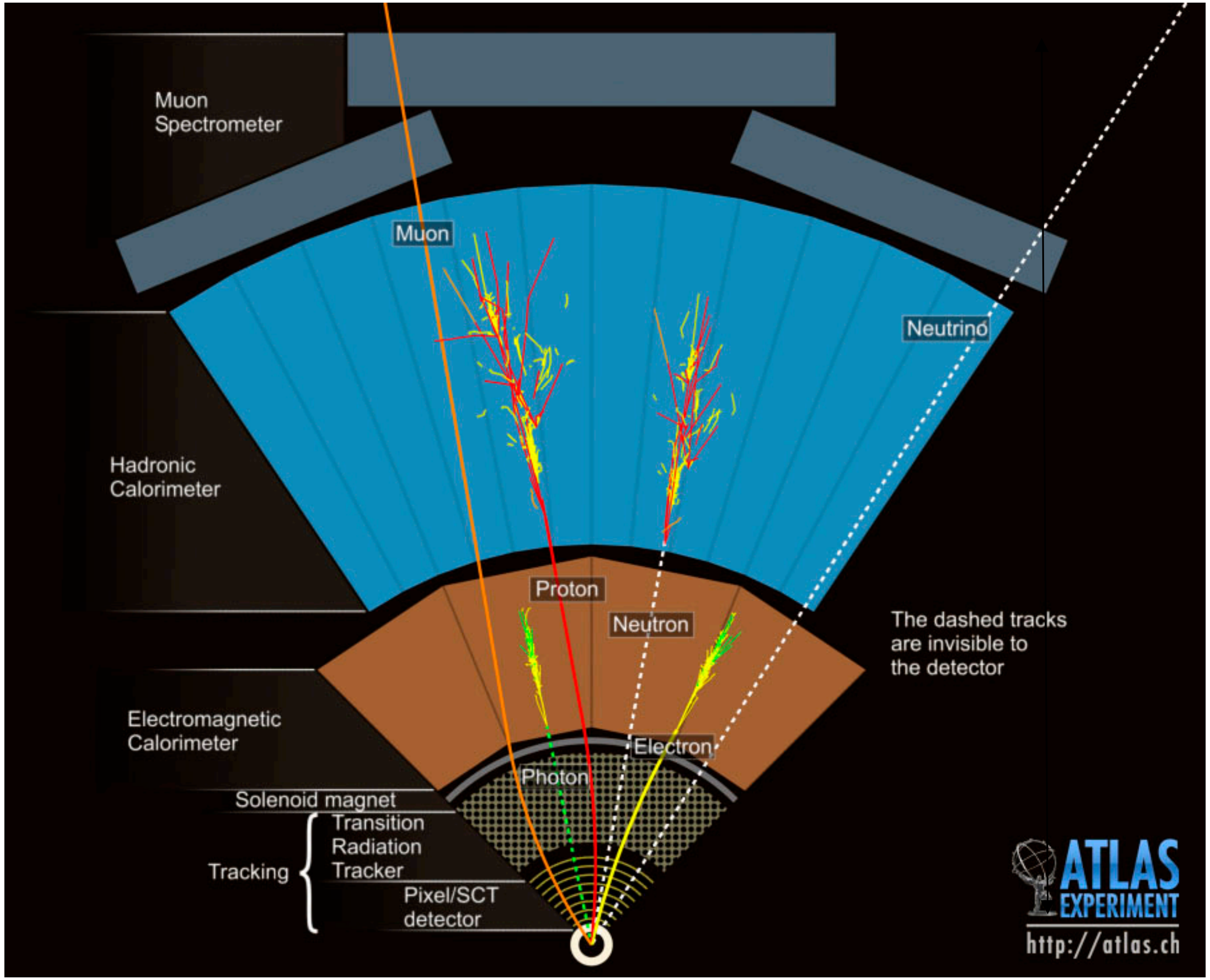
Low density → High density
High precision → Low precision
High granularity → Low granularity

Configurations of multi-purpose detectors

Layers of the ATLAS experiment at the LHC

- Different types of detectors to identify particles and measure their energy and momentum





Timeline of LHC and High-Luminosity LHC

From LHC to HL-LHC

Instantaneous luminosity x5 (for ATLAS, CMS, LHCb) → Particle densities x5-10

Integrated luminosity x10 (for ATLAS, CMS, LHCb) → Radiation damage x10

Increase of overlap of pp events (pile up x3-5)

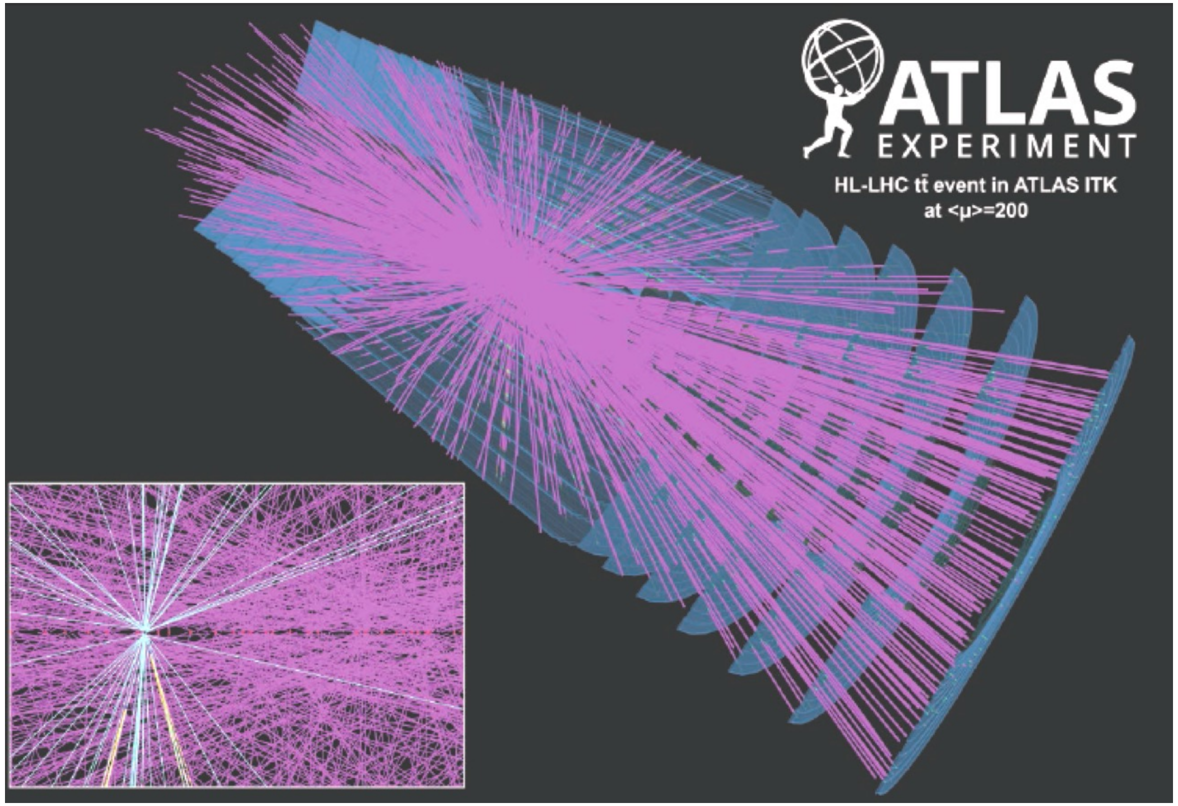
Detectors for HL-LHC

- 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 major upgrades in LS2, ATLAS and CMS will build even larger and more complex trackers and further upgrades for LS3.**

Investigate events like this one:



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

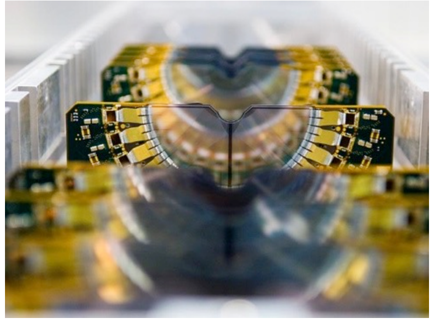
Let’s look at Silicon detectors

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

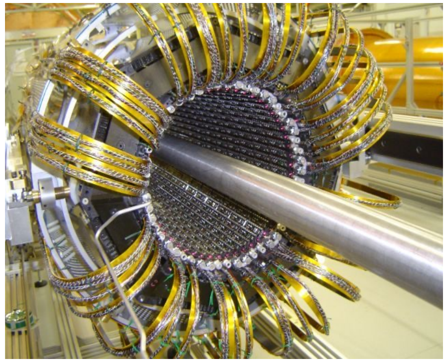
Detector Modules “Basic building block of silicon trackers”

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

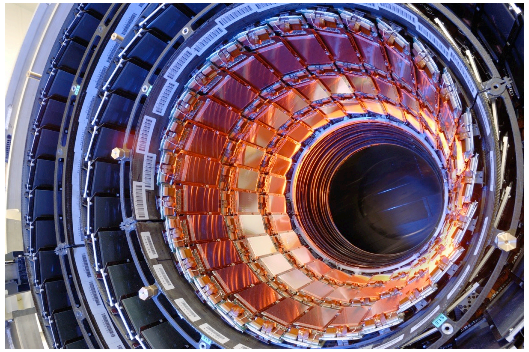
ALICE Pixel Detector



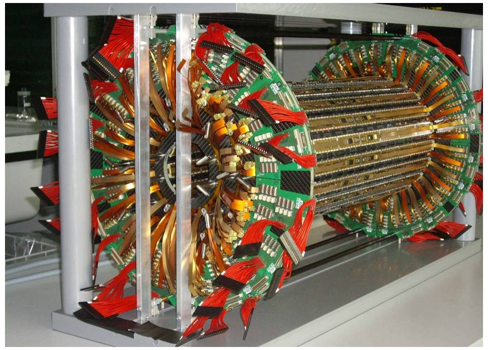
LHCb VELO



ATLAS Pixel Detector

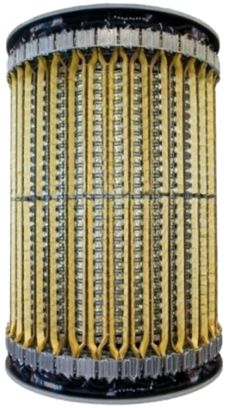


CMS Strip Tracker IB

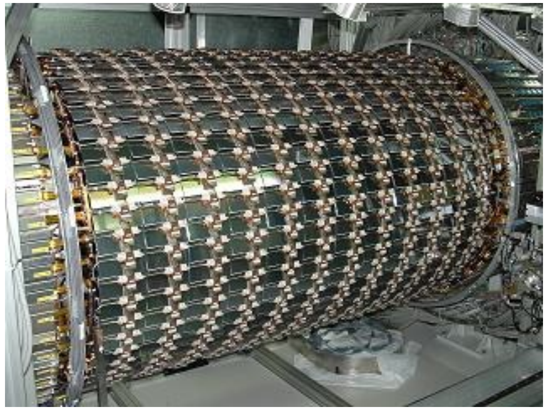


CMS Pixel Detector

ALICE Drift Detector



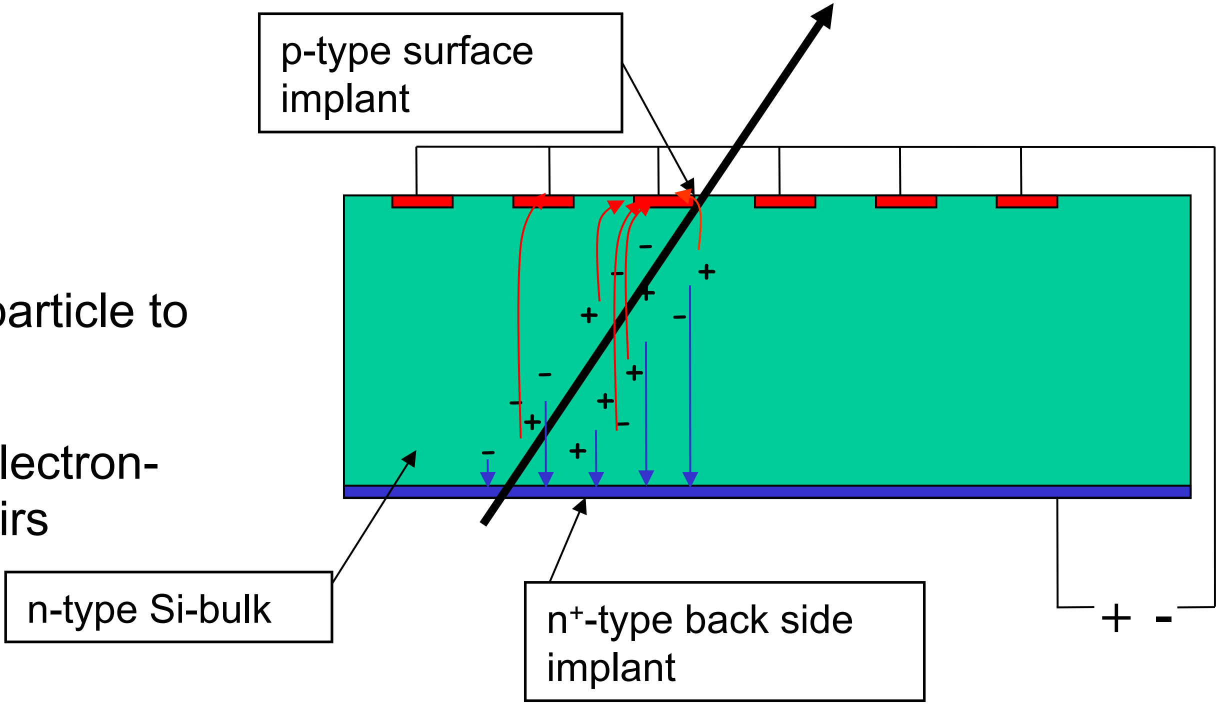
ALICE Strip Detector



ATLAS SCT Barrel

Recap: Principle of a silicon detector: reverse biased depleted pn-diode

- Take a pn-diode
- Segment it
- Apply a bias voltage
- Wait for an ionising particle to deposit charge
  - Ionisation → Electron-hole (e^-, h^+) pairs

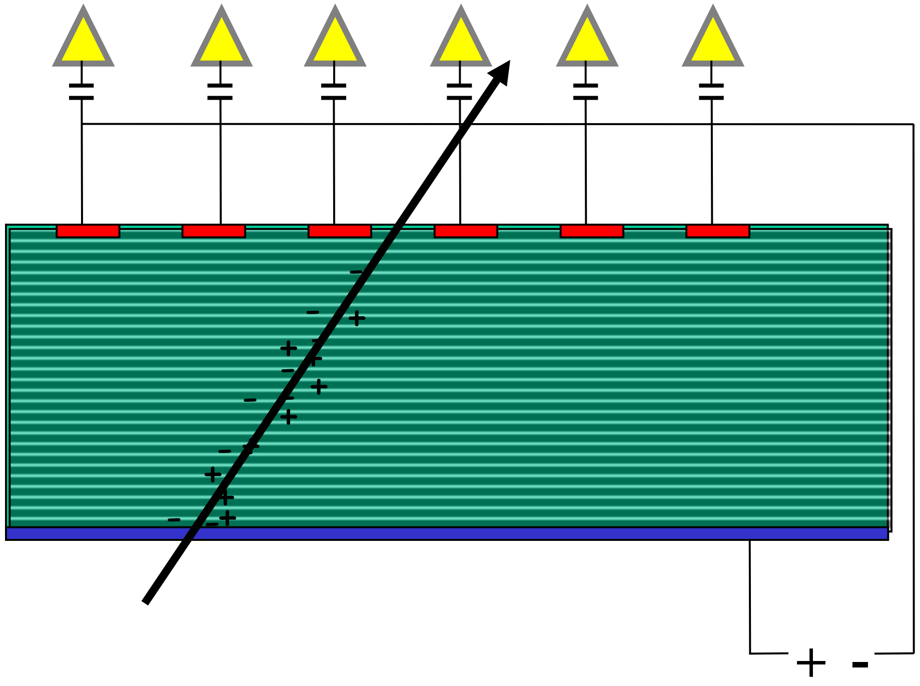


- Charges separate and drift in the electric field

Recap: Principle of a silicon detector: Signal

→ Segmented and depleted piece of silicon and an ionising particle generates electron-hole pairs

- e^-h^+-pairs separate in E-field, and drift to electrodes
- Moving charges → electric current pulse
- Small current signal is amplified, shaped and processed in integrated circuits (“chips”) on readout electronics

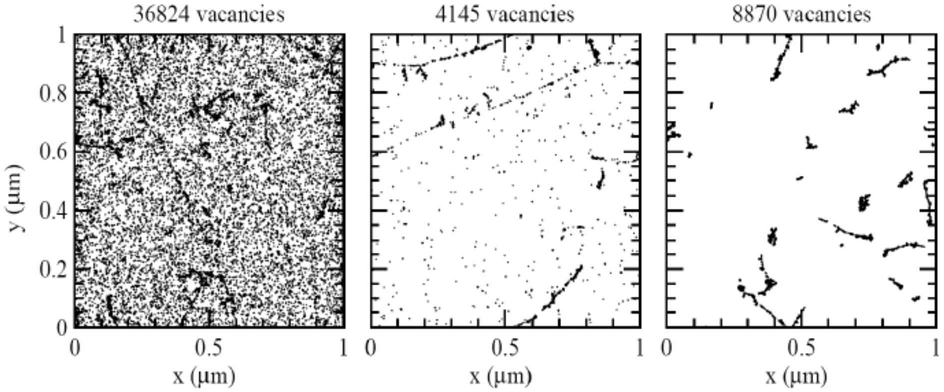


Typical drift velocity 50 µm/ns (drift time ~ 6 ns, in 300 µm)
With fast read-out electronics: signal collected in few ns

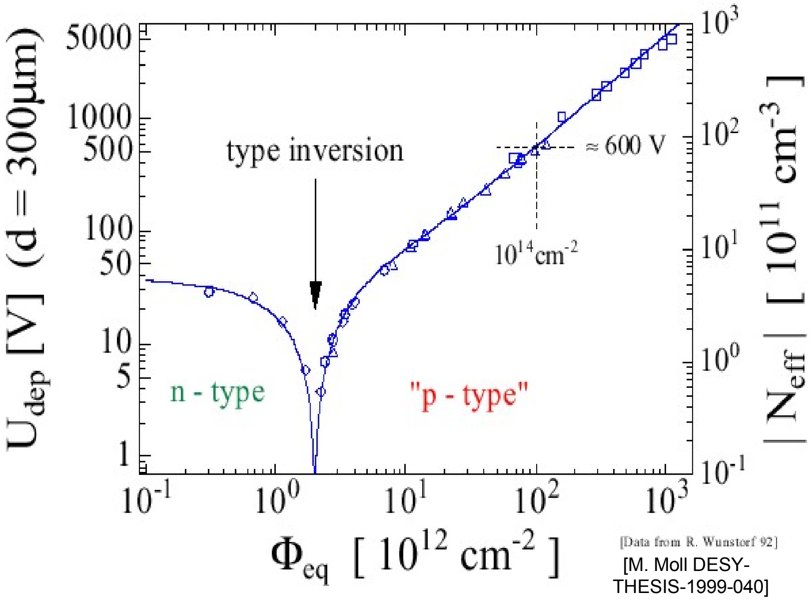
Recap: Principle of a silicon detector: Radiation damage

Radiation damage: non-ionising energy loss of charged and neutral particles → damage in silicon bulk (defects: recombination/generation centers)

- Increase of leakage current
- Generation of charged centers, which change effective doping concentration
  → Type inversion (n-doped material becomes p-doped, eventual loss of resolution)
- Increase of depletion voltage
- Centers act as trapping centers affecting the charge collection efficiency



Simulated defects in silicon after 10 MeV protons, 24 GeV protons and 1 MeV neutrons at $1*10^{14}$ N_{eq}/cm^2

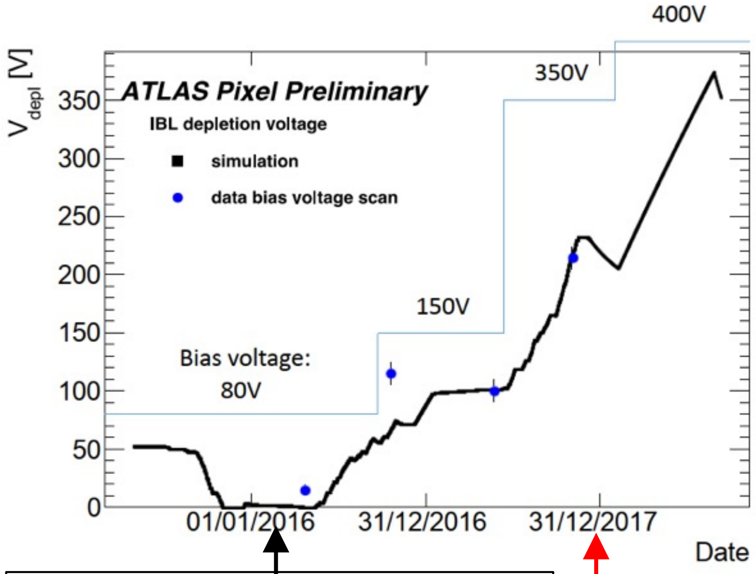


[M. Moll DESY-THESIS-1999-040]

- ➢ Radiation damage degrades detector performance and limits life time

Operation of the ATLAS Pixel Detector

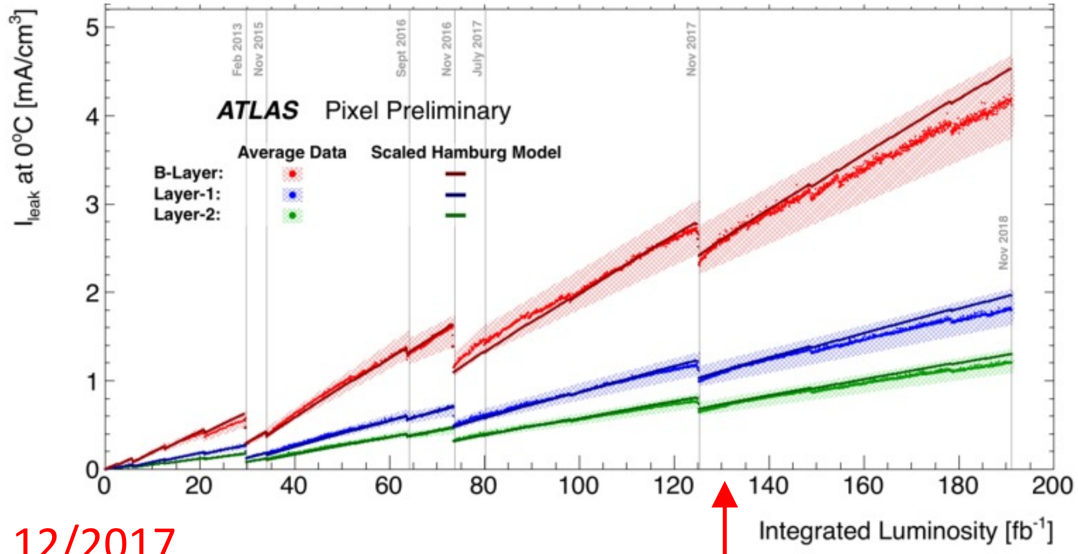
Change of Depletion Voltage



inversion of space charge sign

Increase of Leakage Current

$5.3 \cdot 10^{14}$ n_{eq}/cm^2



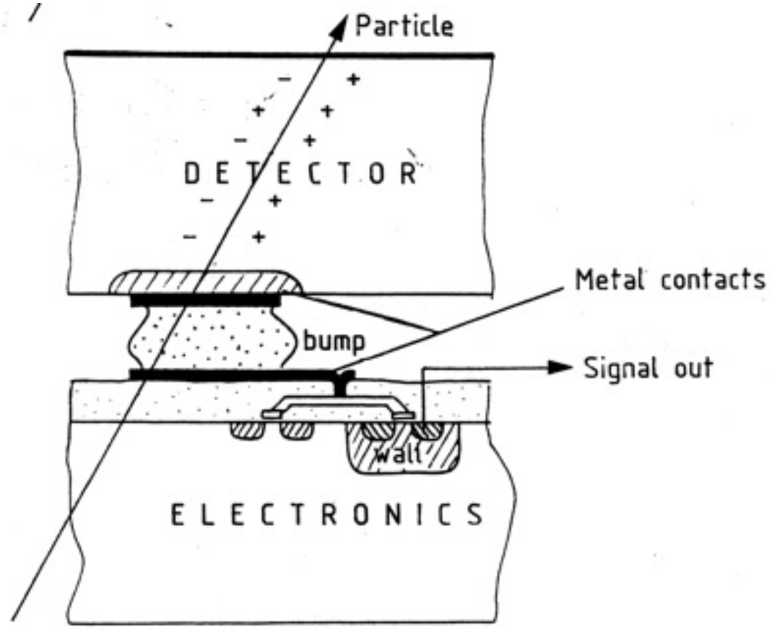
12/2017

from EIROforum School 2018, M.Moll and P.Riedler

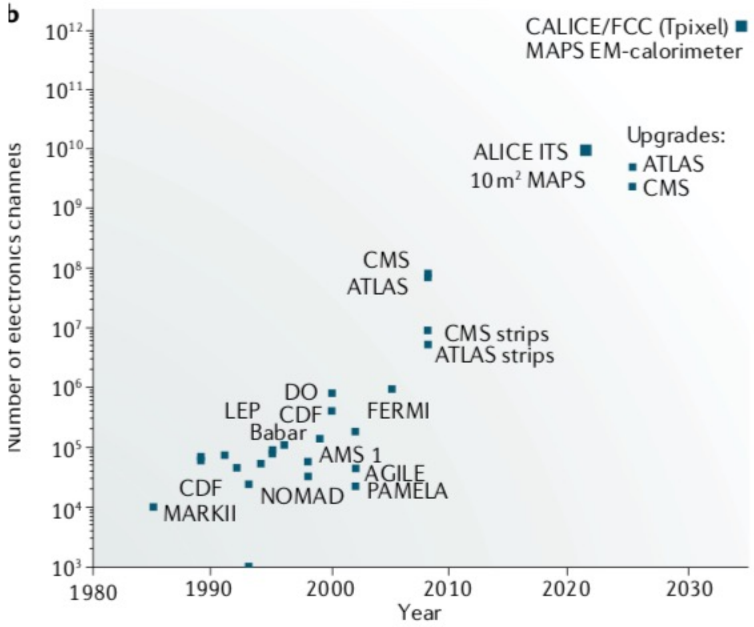
Radiation Damage: Mitigation?

- **Operation**: Cold operation & storage: Reduces leakage current and stops "reverse annealing" *i.e. avoids that charged defects can re-configure to form even more detrimental effects.*
- **LHC upgrade:** Device and material engineering approaches are followed; Example: ATLAS and CMS tracker upgrades will use **p-type** silicon instead of **n-type** silicon.
- **FE electronics:** dedicated (rad hard) design and using smaller technology nodes

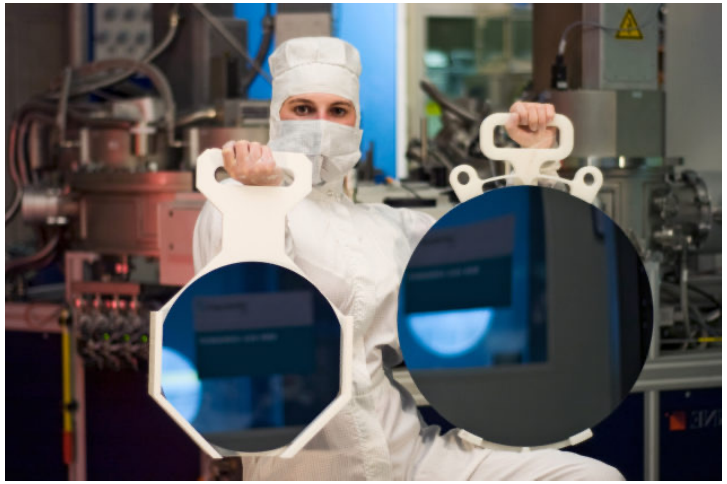
Readout electronics and channel numbers



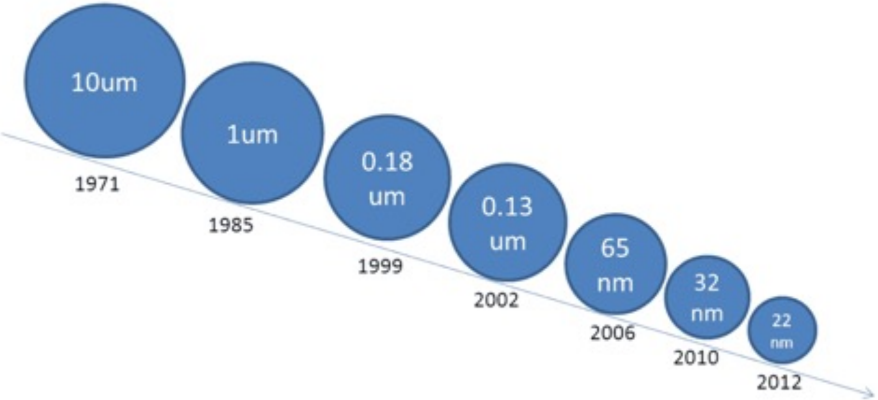
From E. Heijne, Silicon detectors 60 years of innovation
https://indico.cern.ch/event/537154/



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

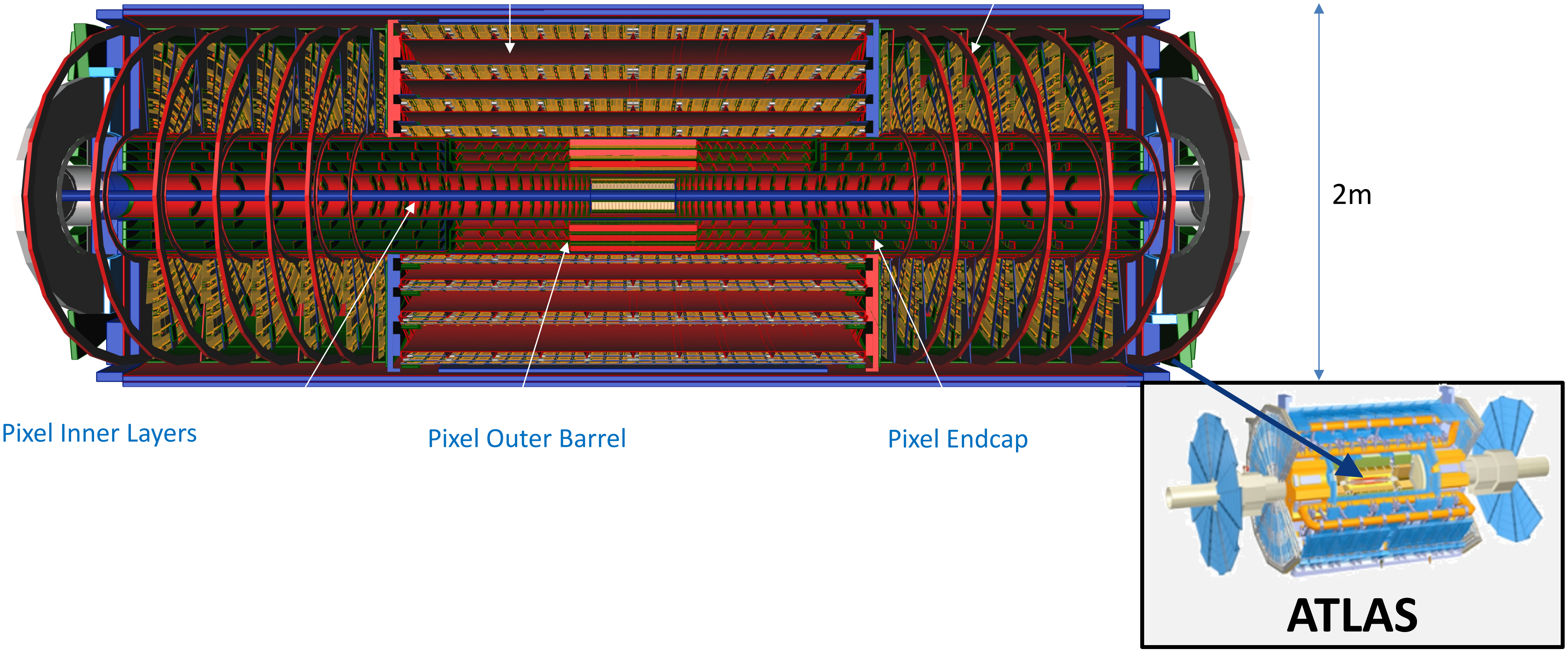


https://wccftech.com/foundries-tsmc-companies-shift-300mm-wafers/



https://anysilic`on.com/semiconductor-technology-nodes/

Upgrade of the tracker of the ATLAS experiment for HL-LHC



Strip Barrel

Strip Endcap

2m

Pixel Inner Layers

Pixel Outer Barrel

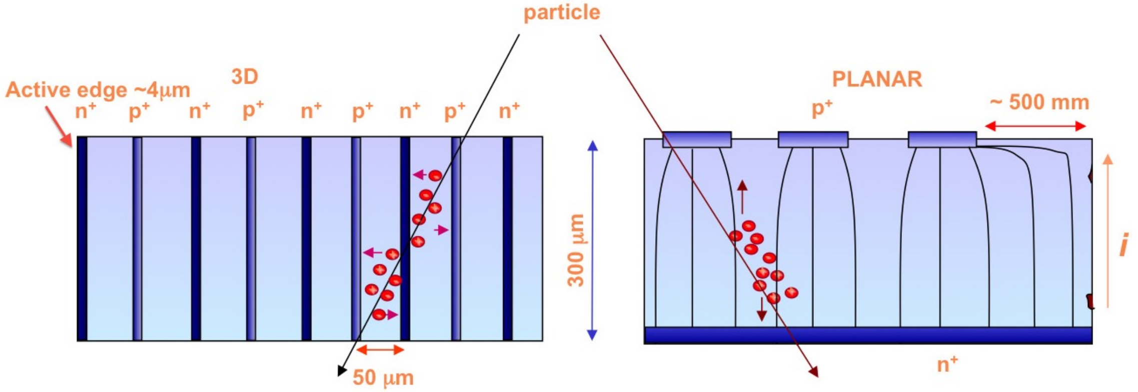
Pixel Endcap

ATLAS

Upgrade of ATLAS trackers for HL-LHC: New Pixel detector

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

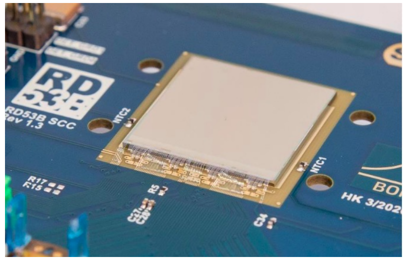


Thin n-in-p planar sensors

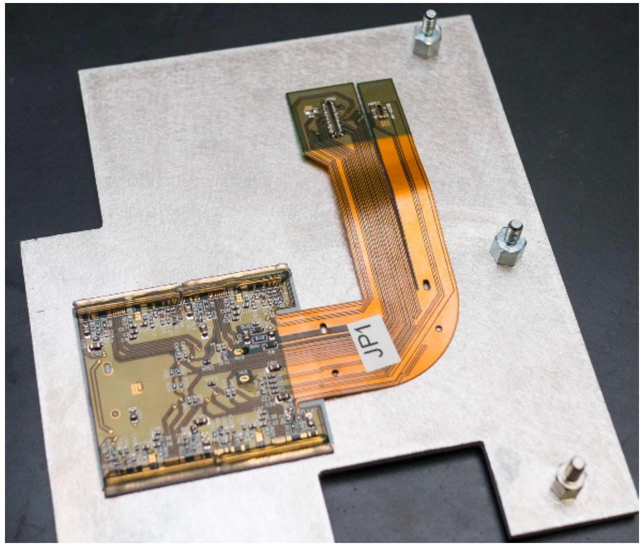
- Dies of 4x4 cm^2, 100/150 µm thick
- Bias voltage up to 600 V (at end of life-time)

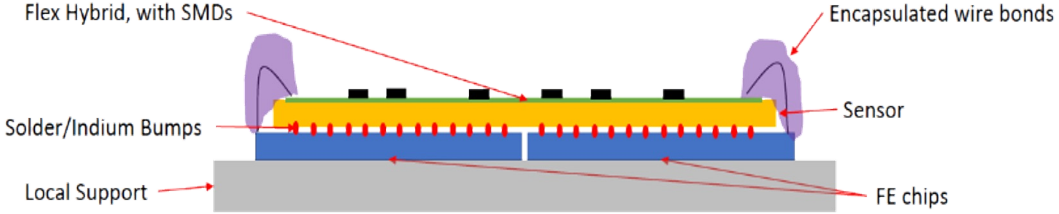
FE chip:

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

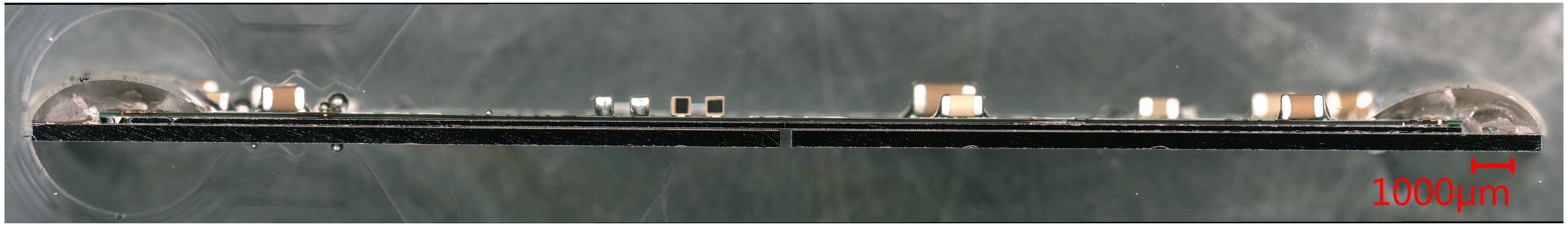


www.rd53.cern.ch
CERN-RD<53-PUB-17-001

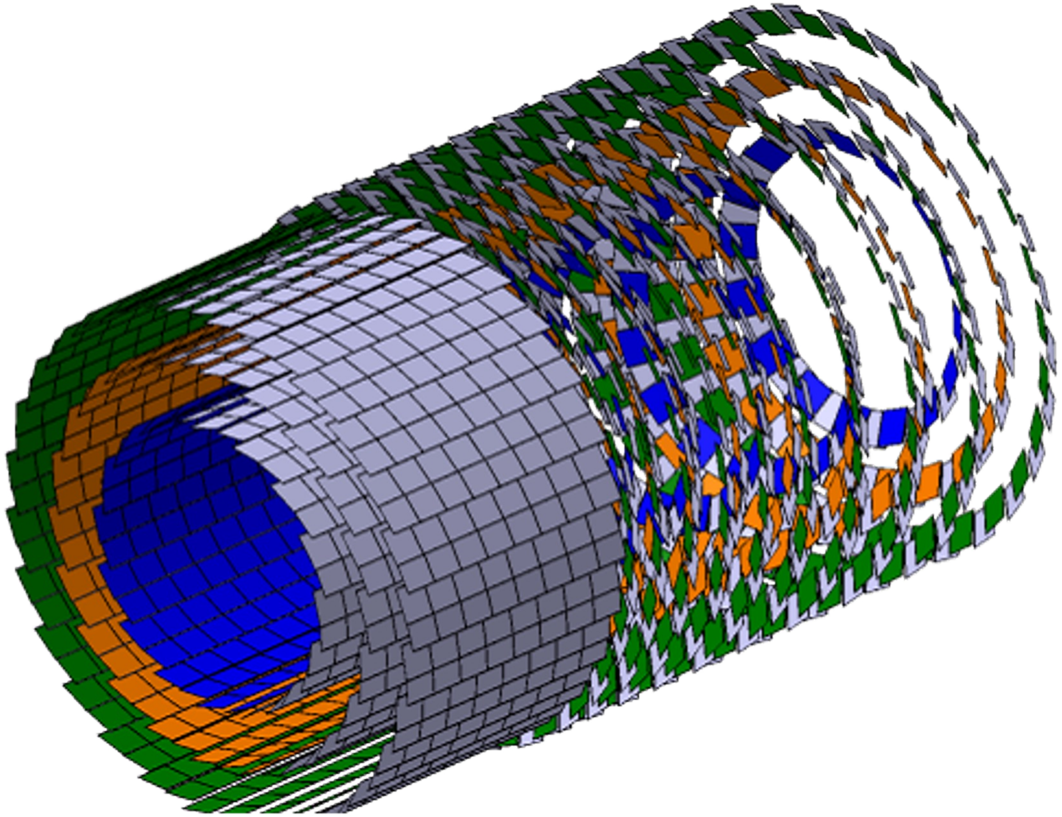




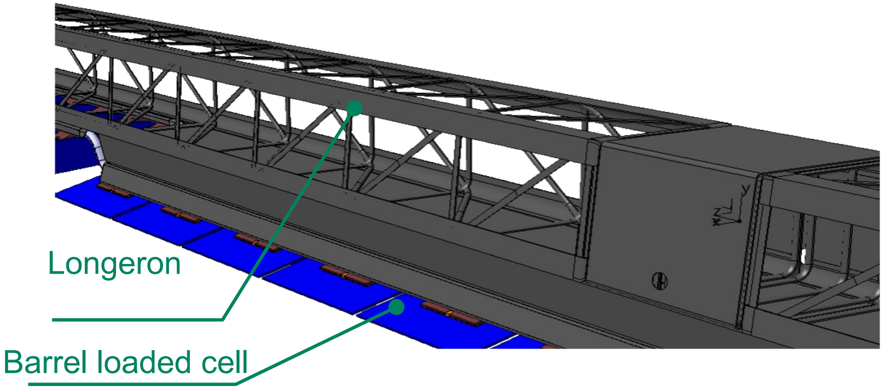
ATLAS Itk pixel quad module –cross section



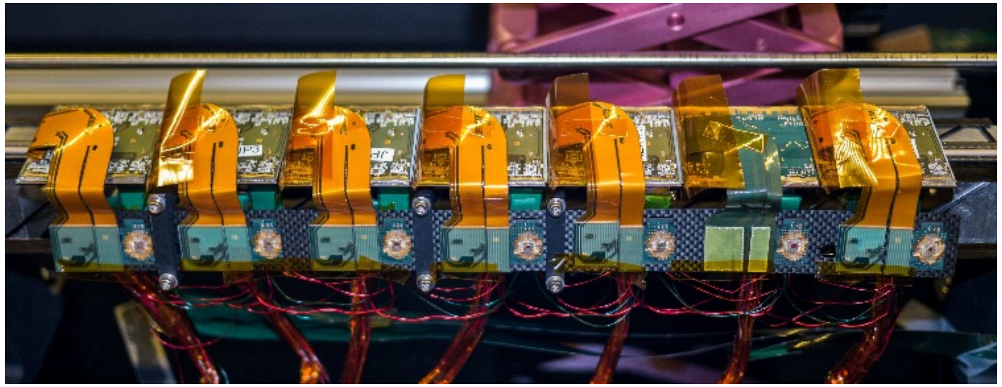
Upgrade of ATLAS trackers for HL-LHC: New Pixel detector



- Structure from carbon-fibre composites
  - Example for outer central region: longerons



Electrical prototype with FE-i4 based modules



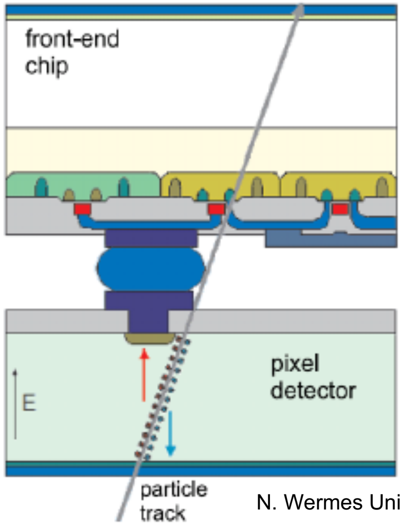
Combining silicon sensor and readout electronics

Alternative for light detector: CMOS technology

Hybrid Pixel Detector

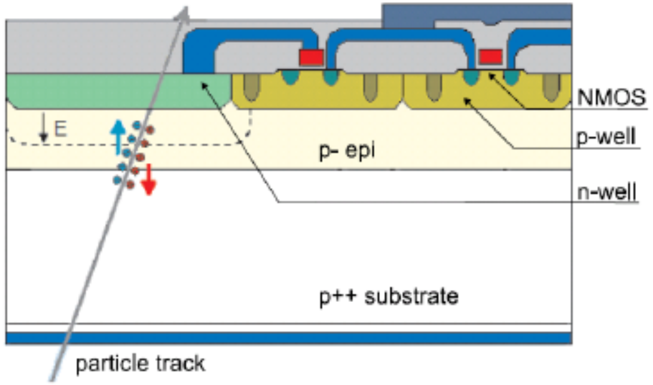
Readout chip

Sensor



N. Wermes Univ. Bonn

Monolithic Pixel Detector (example)



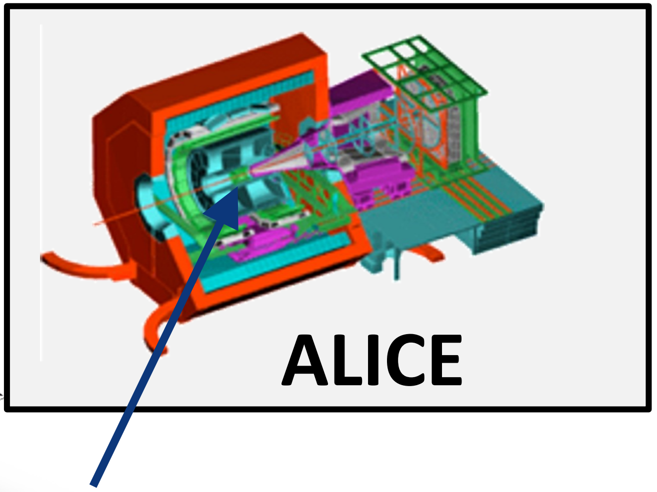
Readout chip + Sensor

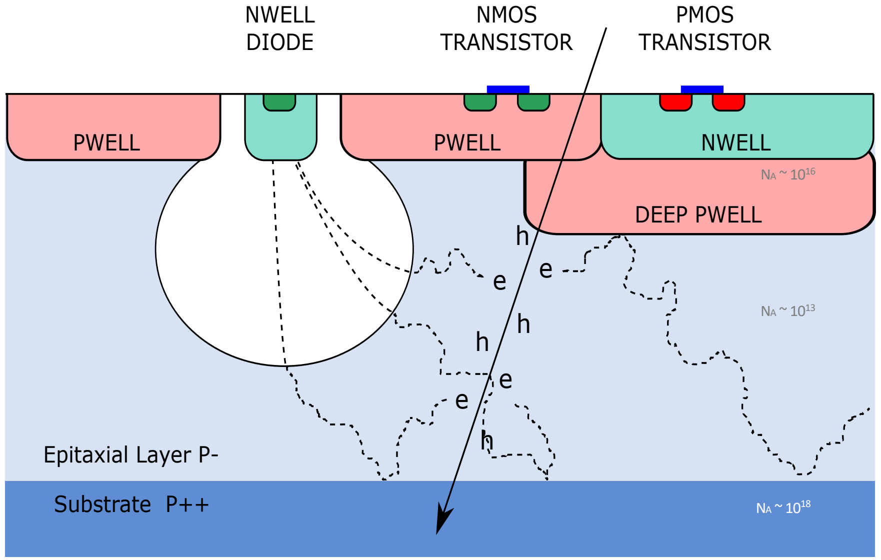
- Sensor element is n-type material (deep n-well) in low resistivity p-type substrate, size > 15 x 15 μm², thickness O(100 μm)
- Pre-amplifier integrated in sensor
- Depletion with low bias voltage, signal around 1000-2000 electrons
- Commercial process → cost reduction
- Tests after irradiation show good performance

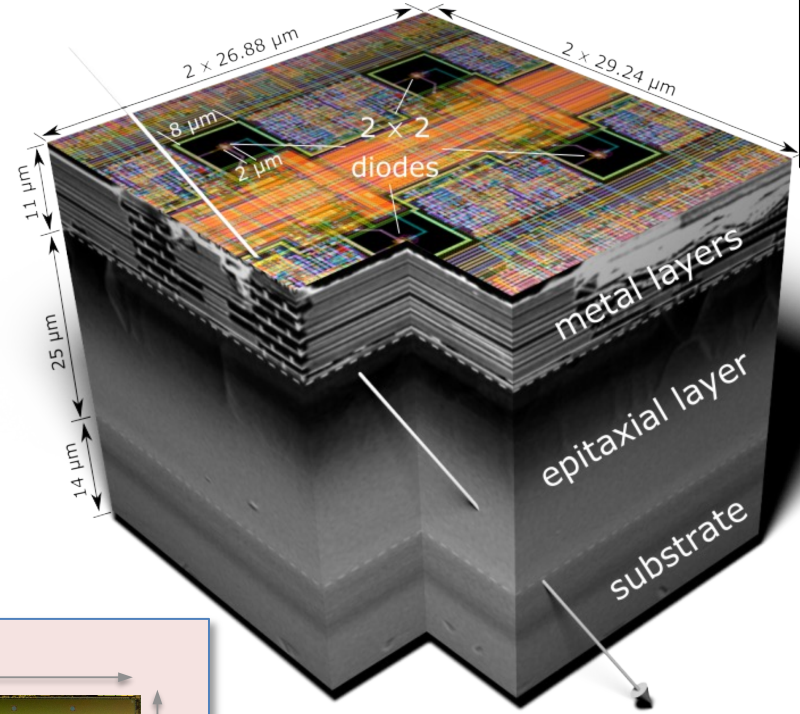
Upgrade of the ALICE Inner Tracking System ITS

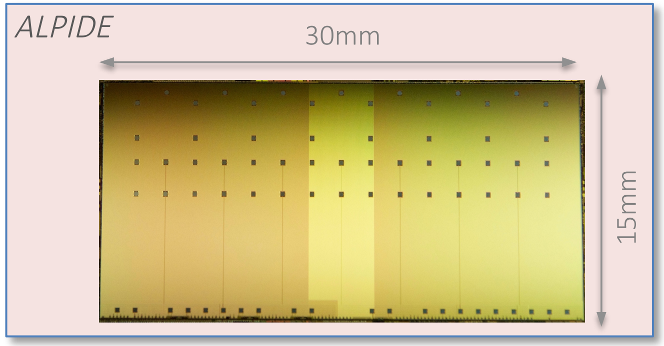
CMOS Pixel Sensor using TowerJazz 0.18 µm CMOS Imaging Process

- Small n-well diodes → low capacitance and reverse bias voltage ~6 V
- Deep p-well shields on n-well of PMOS transistor
- Pixel size 28 µm x 28 µm









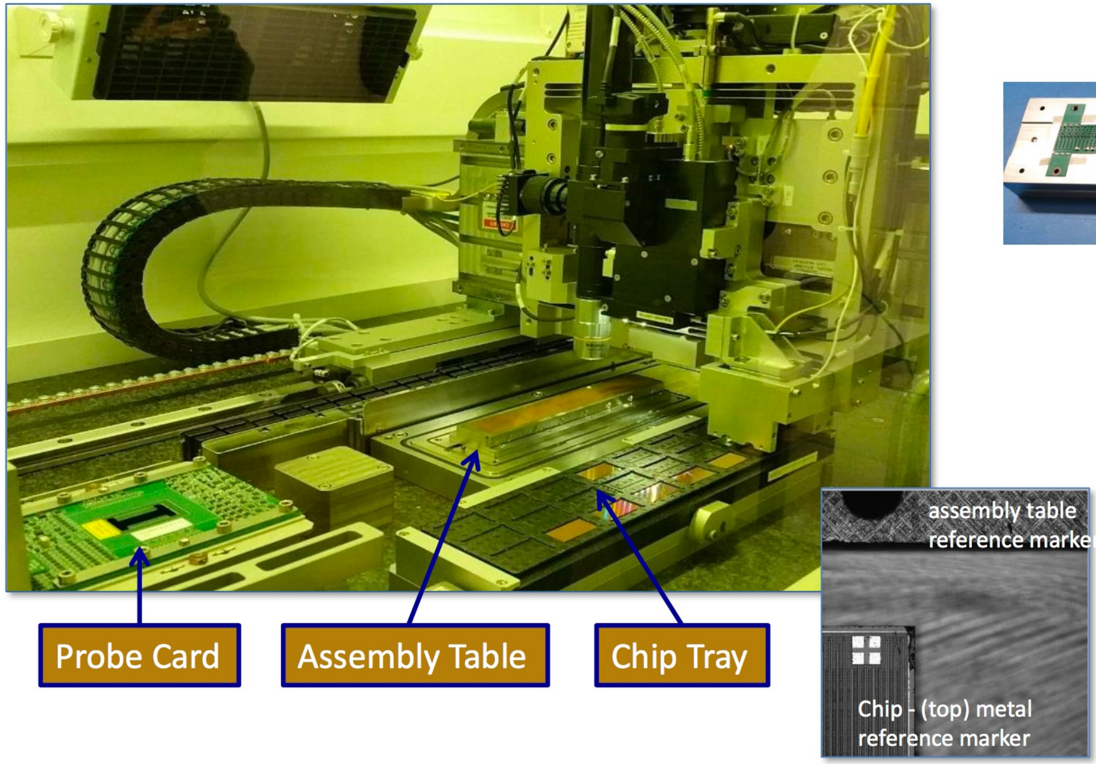
Large CMOS detector

First CMOS MAPS based tracker at LHC!

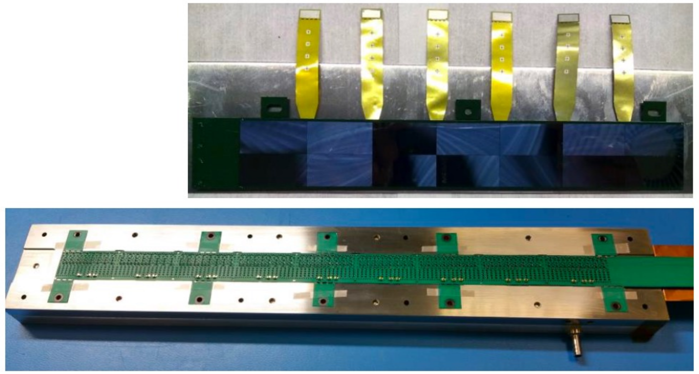
Upgrade of the ALICE Inner Tracking System ITS

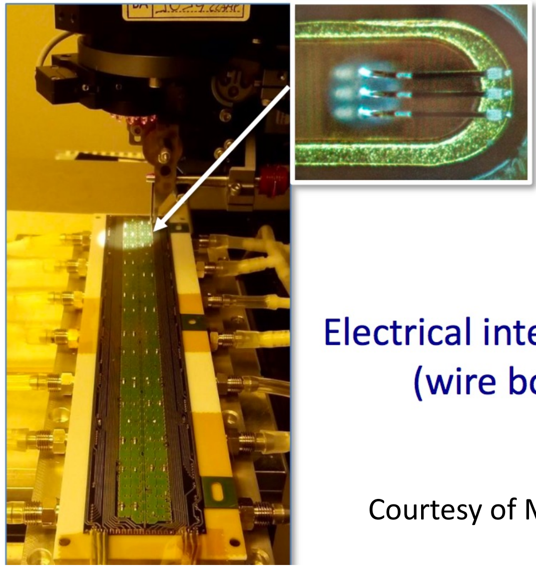
Automated module assembly (custom-made machine)

- Placement accuracy < 5um



6 machines distributed to different construction sites

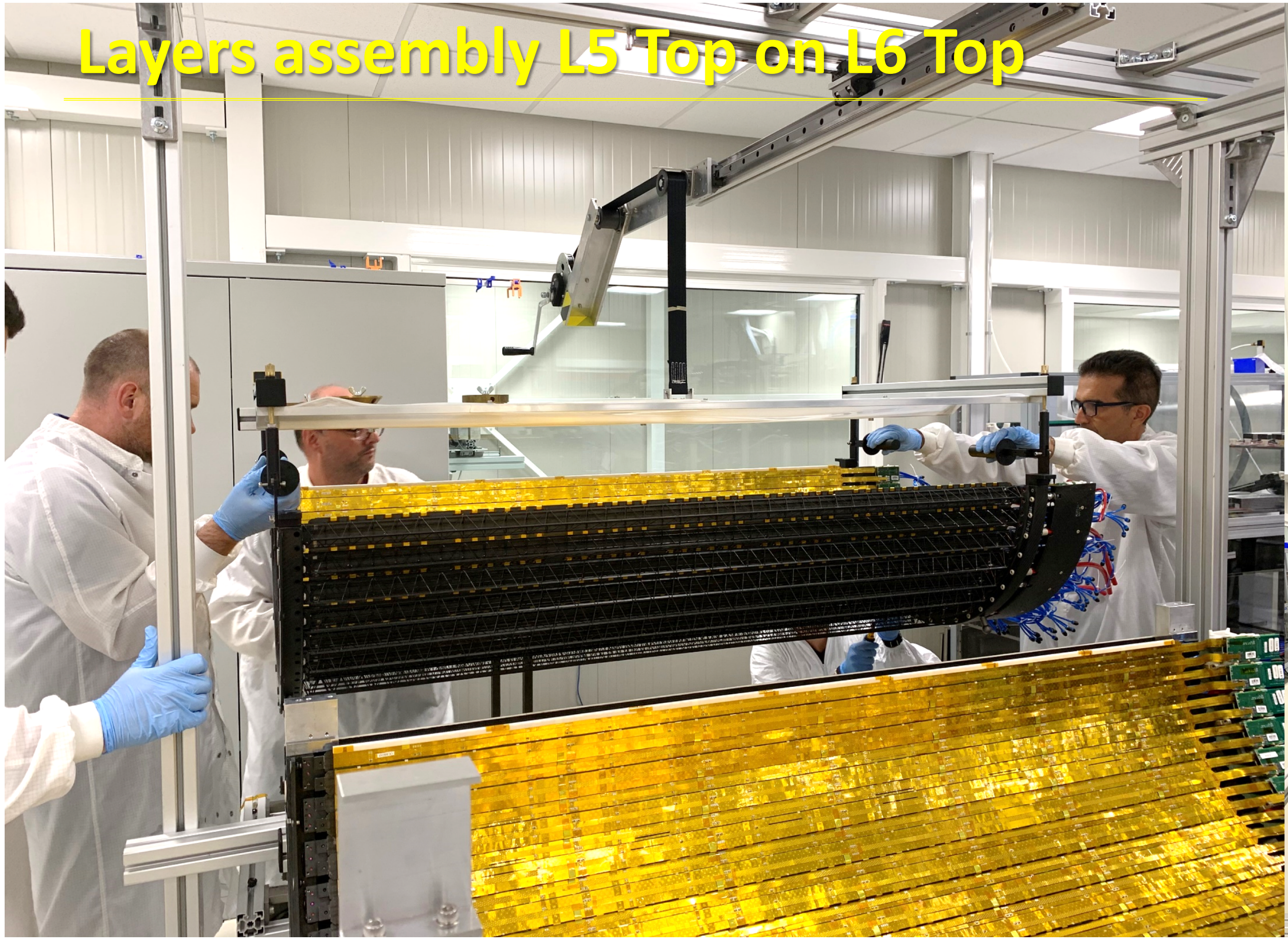


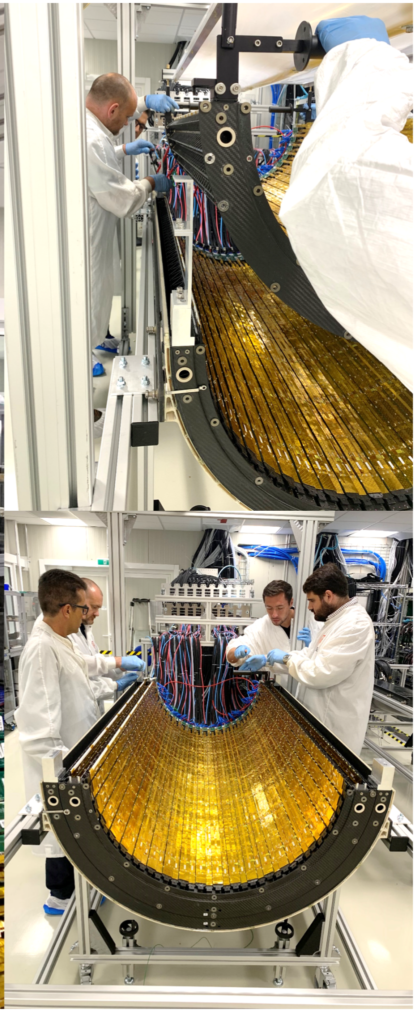


Electrical interconnection (wire bonding)

Courtesy of Marielle Chartier

Upgrade of the ALICE Inner Tracking System ITS





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

~ 10 m^2, 12.5 Gpixels

C. Gargiulo, CERN

Recap: Electromagnetic Calorimeters

- Dominant processes at high energies (E > few MeV) :

- Photons: Pair production

$$\sigma_{pair} \approx \frac{7}{9}\left(4\alpha r_e^2 Z^2 \ln\frac{183}{Z^{1/3}}\right) = \frac{7}{9}\frac{A}{N_A X_0}$$

$$I(x) = I_0 e^{-\mu x} \qquad \mu = \frac{7}{9}\frac{\rho}{X_0}$$

μ= attenuation coefficient
X_0 = radiation length in [cm] or [g/cm²]

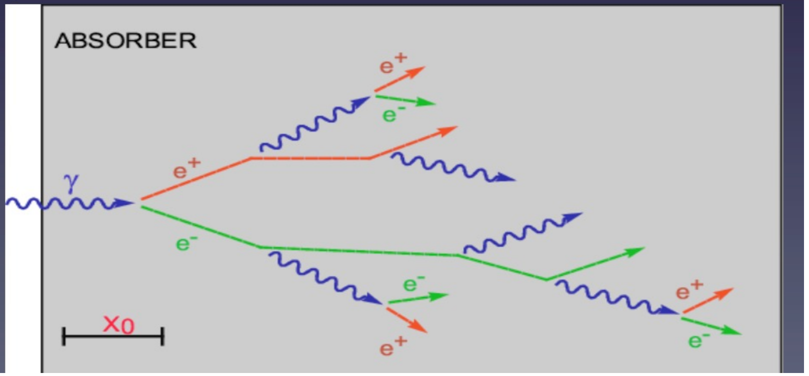
$$X_0 = \frac{A}{4\pi N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

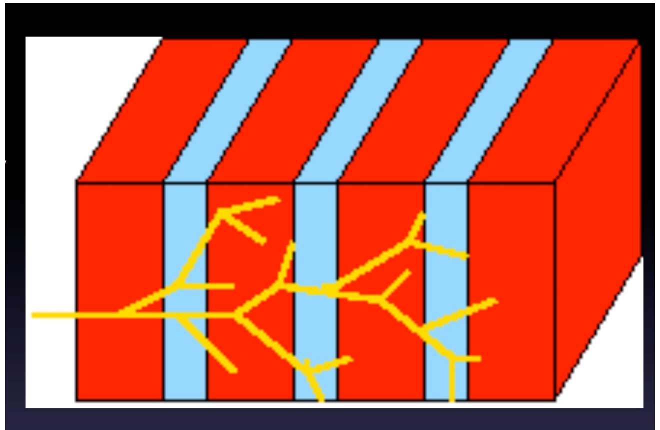
- Electrons: Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}} = \frac{E}{X_0}$$

$$E = E_0 e^{-x/X_0}$$

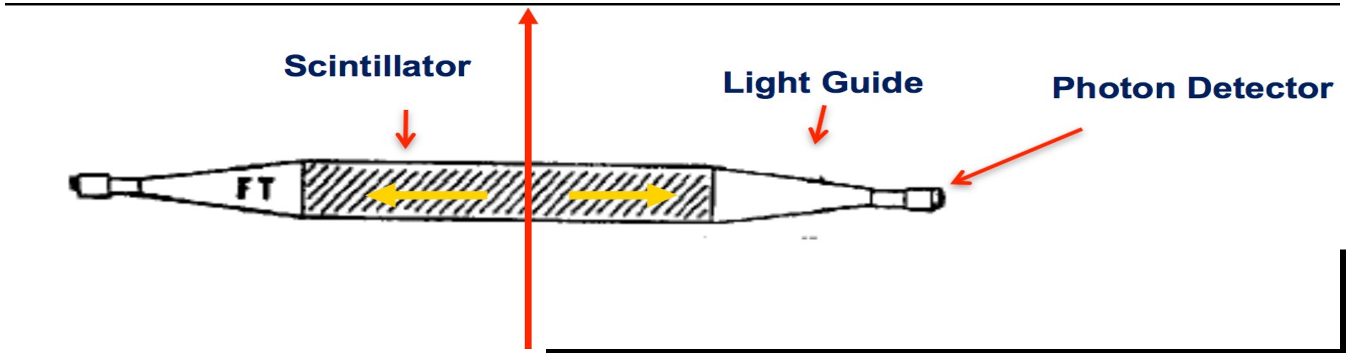
After traversing x=X_0 the electron has only 1/e=37% of its initial energy





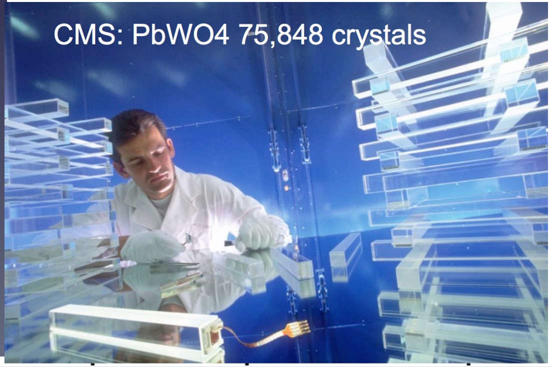
- Sampling fraction

Recap: Scintillators



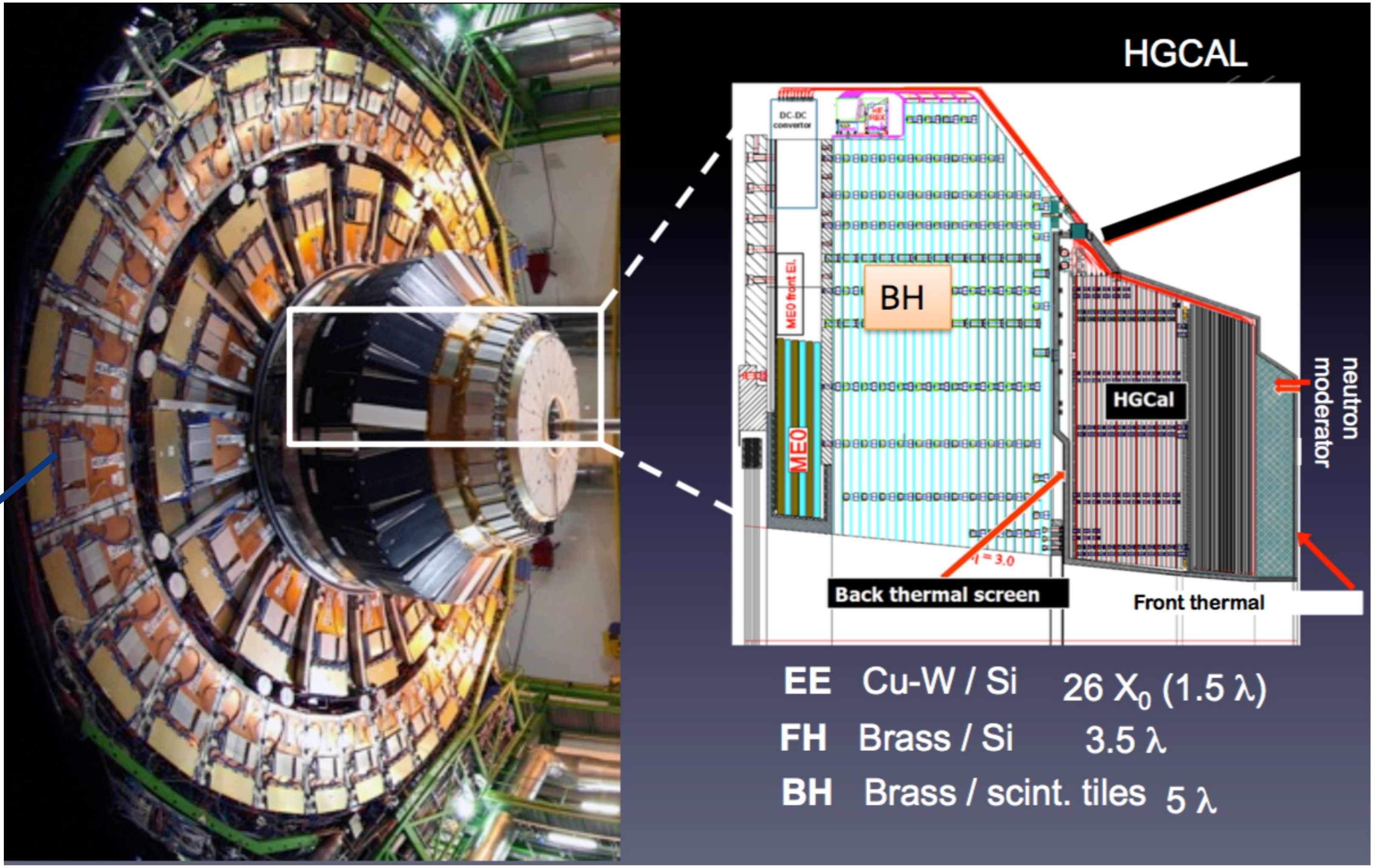
- dE/dx converted into light and then it is detected via photo-sensor (photomultipliers, SiPM,….)
- Main features
  - Sensitivity to energy
  - Fast time response
  - Pulse shape discrimination
- Requirements:
  - High efficiency for conversion of exciting energy to fluorescent radiation
  - Transparency to its fluorescent radiation to allow transmission of light
  - Emission of light in a spectral range detectable for photo-sensors
  - Short decay time to allow fast response


Plastic Scintillator BC412

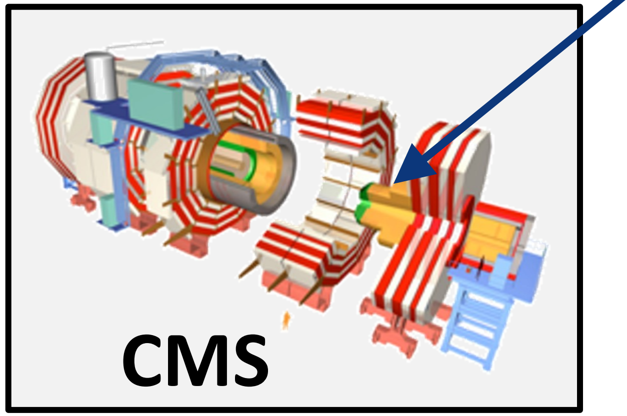

CMS: PbWO4 75,848 crystals

New Endcap calorimeter for CMS for HL-LHC

- Complement tracker upgrade with extended coverage of calorimeter to $|\eta| < 4$ and high granularity (high energy resolution): HighGranularityCalorimeter HGCal
- Sampling calorimeter with silicon sensors and scintillators, share depending on radiation damage



EE	Cu-W / Si	$26\ X_0$ (1.5 λ)
FH	Brass / Si	3.5 λ
BH	Brass / scint. tiles	5 λ



New Endcap calorimeter for CMS for HL-LHC

~600m^2 of silicon sensors (3x CMS tracker) in radiation field peaking at 200 Mrad and ~10^{16}n/cm^2

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)

300um, 200um and 120um active sensor thicknesses

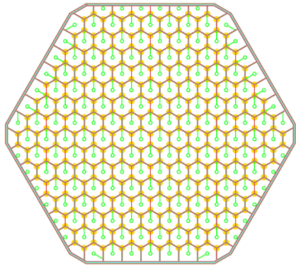
Match sensor thickness (and granularity) to radiation field for optimal performance

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

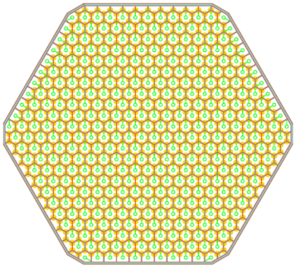
Provide high volume, high rate, reproducible module production & handling

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

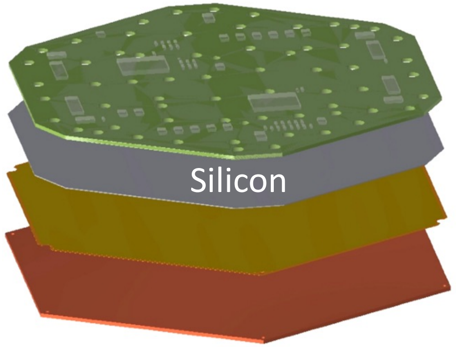
~215 tons per endcap

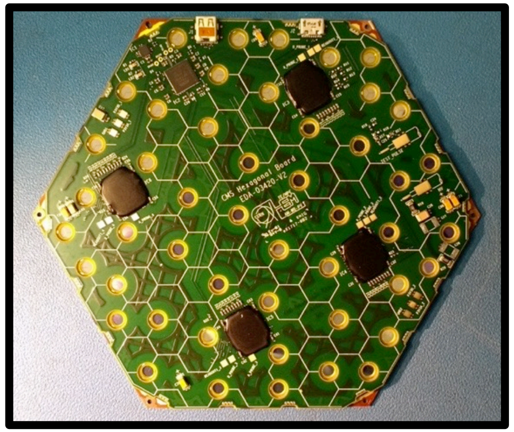


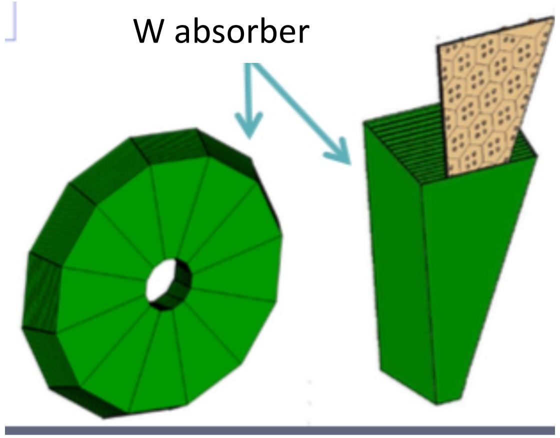
192 cells
“low density”



432 cells
“high density”



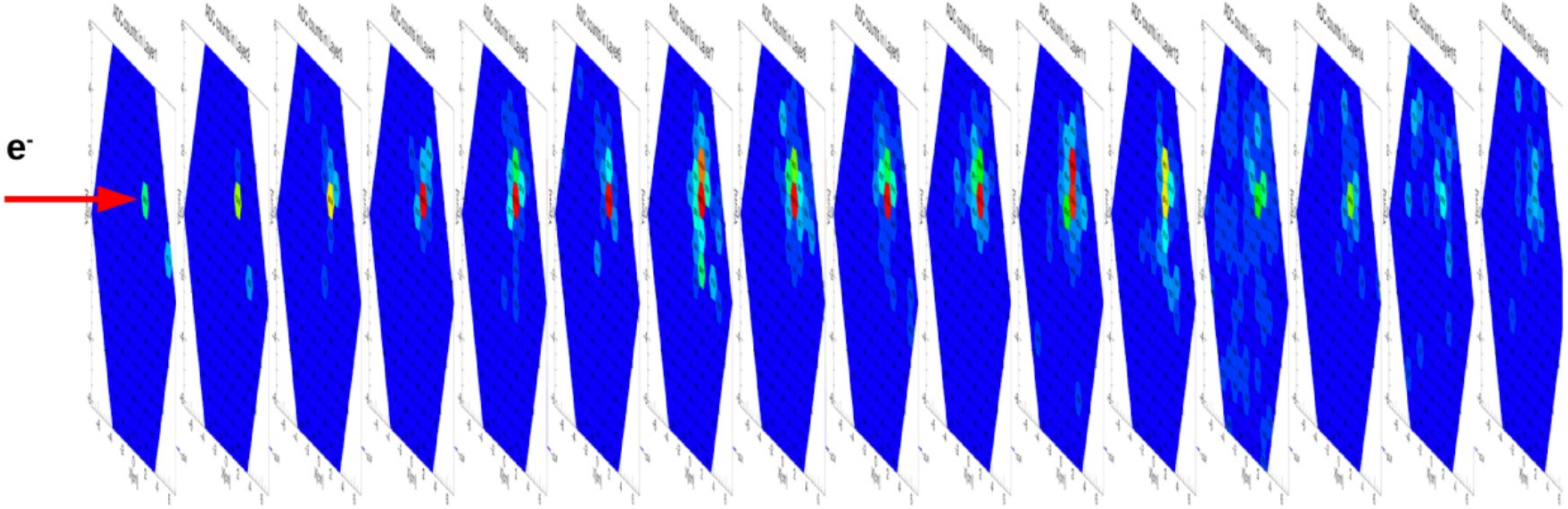




New Endcap calorimeter for CMS for HL-LHC

Imaging Calorimeter: Test beam measurement

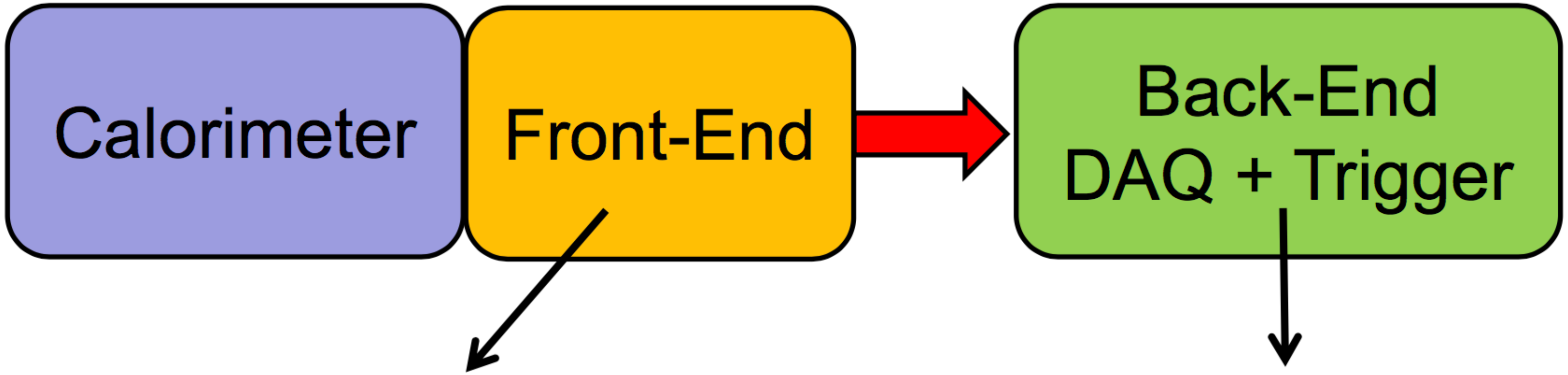
Allows measurement of the 4D (space+time) topology of energy deposits in particle shower, to enhance particle ID, energy resolution and pile-up rejection



A 32 GeV electron event at Fermilab Test Beam Facility

Shower development clearly seen

Further Calorimeter and Muon detector upgrades



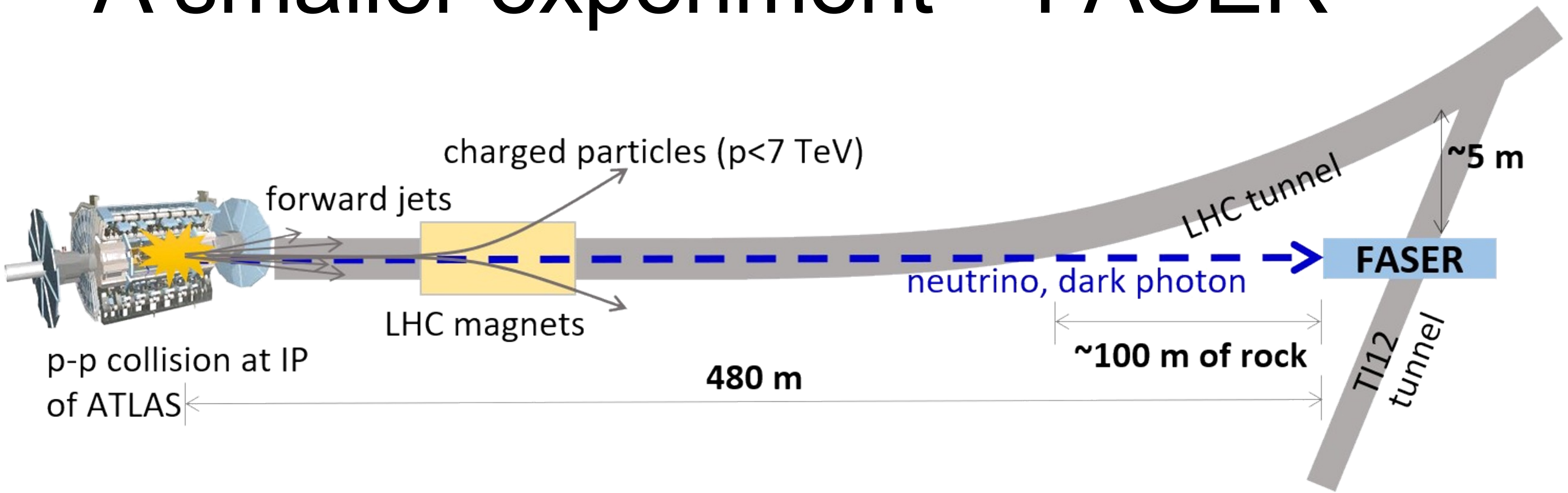
- Radiation tolerant ASICs and Commercial-Off-The-Shelf (COTS) components:
  - signal amplification and shaping
  - ADCs, TDCs
  - optical links with 5-10 Gbps
- Trigger, Timing and Control (TTC) distribution
- Power distribution for HV and LV

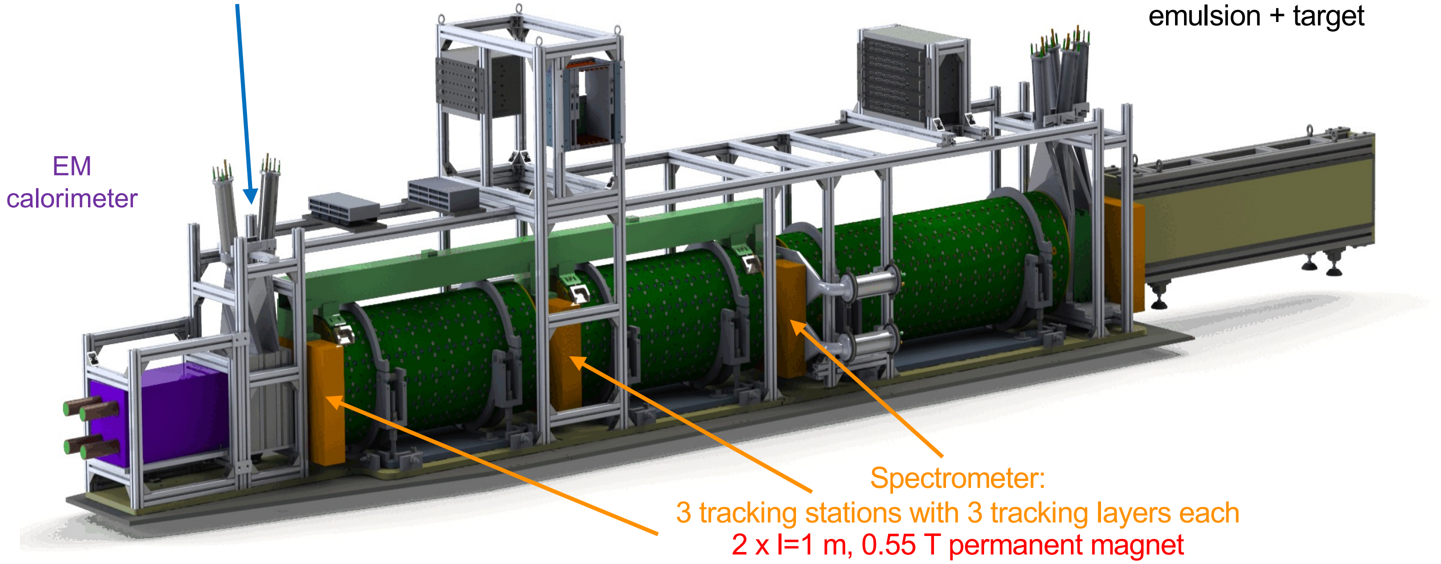
- High-bandwidth, low-latency signal processing with FPGAs
- Data buffering in FPGAs or on-board memory
- High-bandwidth interfaces to hardware trigger and to network based trigger/DAQ systems

Forw***A***rd ***S***earch ***E***xpe***R***iment at the LHC

A smaller experiment – FASER

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


charged particles (p<7 TeV)
forward jets
LHC magnets
p-p collision at IP of ATLAS
neutrino, dark photon
FASER
LHC tunnel
~5 m
~100 m of rock
480 m
TI12 tunnel


Preshower / trigger station
2 scintillator layers

Tigger / timing station
scintillator layer

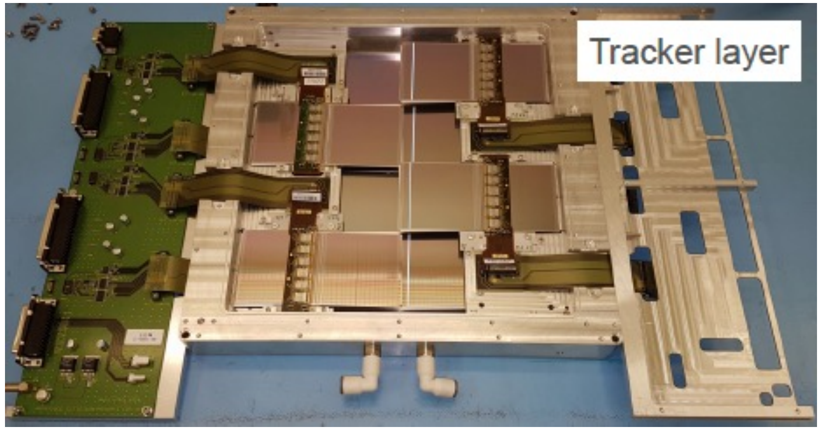
Veto station 2x2
scintillators
photon shield

FASERν (1908.02310)
emulsion + target

EM
calorimeter

Spectrometer:
3 tracking stations with 3 tracking layers each
2 x l=1 m, 0.55 T permanent magnet

Using spare detector parts from large experiments e.g. from ATLAS tracker

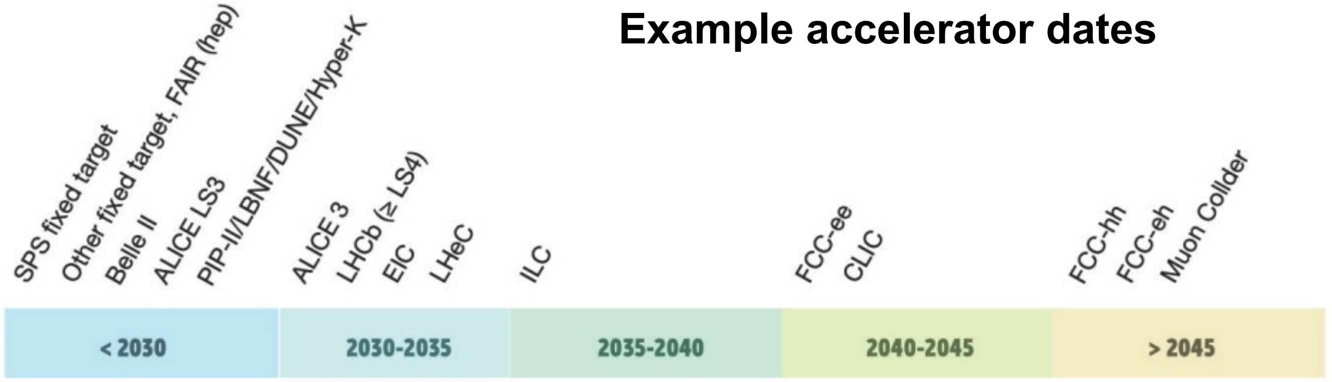


FASER Technical Proposal arXiv:1812.09139

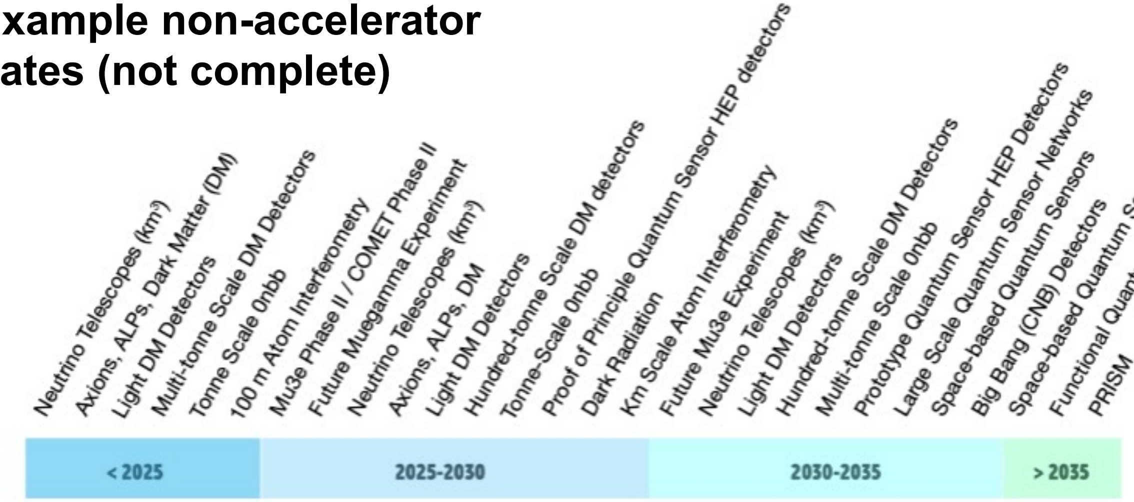
Future facilities

- Many different future facilities proposed/foreseen based on accelerators and non-accelerators
- Overview from ECFA Detector R&D Roadmap Document (CERN-ESU-017, 10.17181/CERN.XDPL.W2EX)

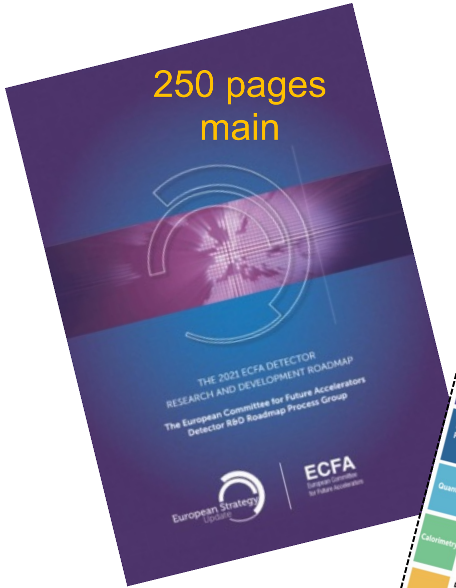
Example accelerator dates

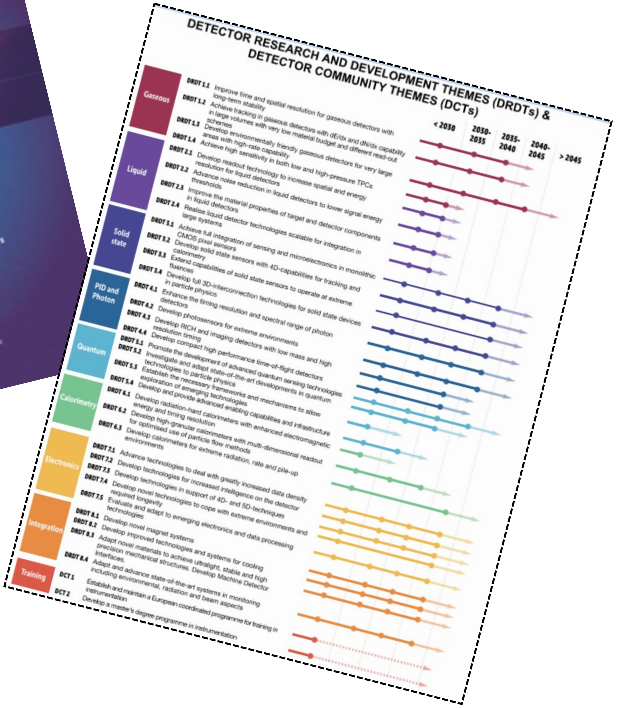


Example non-accelerator dates (not complete)



"Technical" Start Date of Facility
(This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)





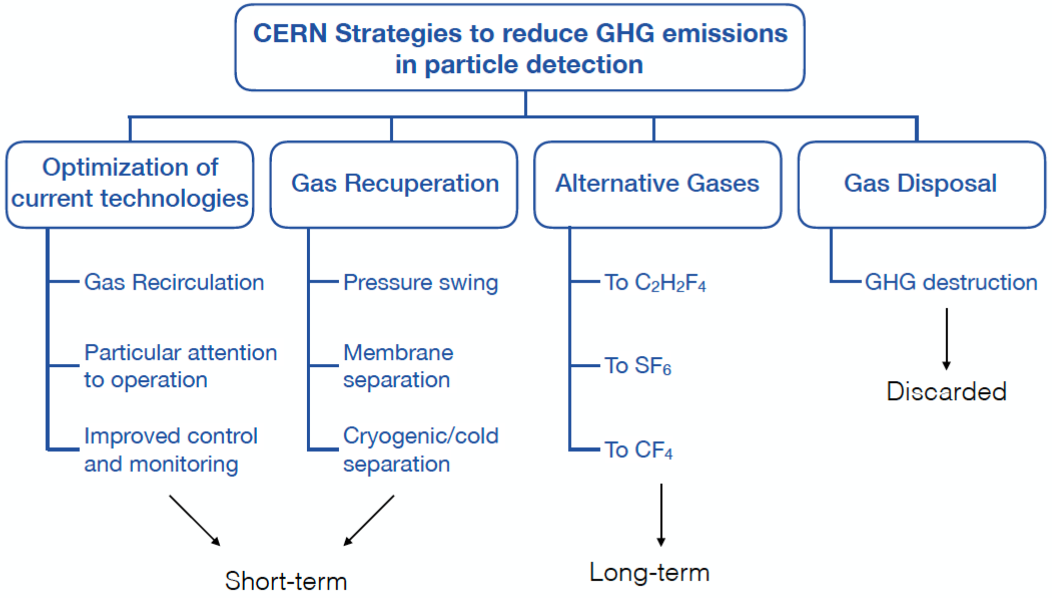
→ Many detector concepts at different future facilities

* 2020 European Particle Physics Strategy Update
https://europeanstrategyupdate.web.cern.ch/

Gaseous Detectors: eco-friendly gases

- 92% of emission at CERN related to large LHC experiments
- Thanks to gas recirculation GHG emission already reduced by > 90% wrt. to open mode systems!
- Many LHC gas systems with gas recuperation

CERN strategies for GHG reduction



CERN Strategies to reduce GHG emissions in particle detection

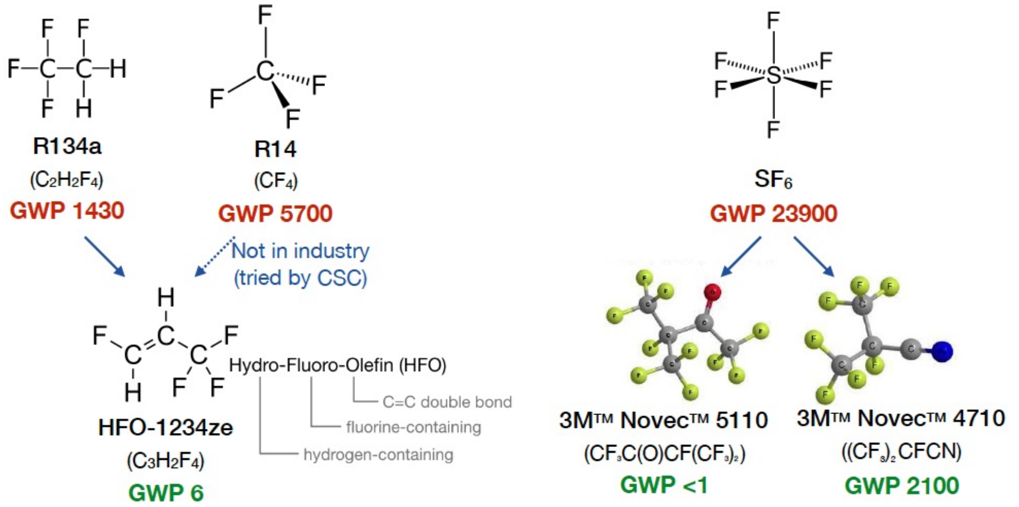
- Optimization of current technologies
  - Gas Recirculation
  - Particular attention to operation
  - Improved control and monitoring
- Gas Recuperation
  - Pressure swing
  - Membrane separation
  - Cryogenic/cold separation
- Alternative Gases
  - To $C_2H_2F_4$
  - To SF_6
  - To CF_4
- Gas Disposal
  - GHG destruction → Discarded

Short-term

Long-term

Possible alternatives to GHG gases

New eco-friendly liquids/gases have been developed for industry as refrigerants and HV insulating medium...
ionisation properties in particle detection not well known



R134a ($C_2H_2F_4$) **GWP 1430**

R14 (CF_4) **GWP 5700**

SF$_6$ **GWP 23900**

Not in industry (tried by CSC)

HFO-1234ze ($C_3H_2F_4$) **GWP 6**

3M™ Novec™ 5110 ($CF_3C(O)CF(CF_3)_2$) **GWP <1**

3M™ Novec™ 4710 ($(CF_3)_2CFCN$) **GWP 2100**

- Alternative gases:
  - A lot of work especially in RPC community to search for alternative to $C_2H_2F_4$
  - Not an easy task to find new eco-friendly gas mixture for current detectors

B. Mandelli

Summary

- The progress in experimental particle physics was driven by the advances and breakthrough in instrumentation, leading to the development of new, cutting-edge technologies.
- Few examples presented of the many different technologies and detectors
- There are many technological challenges for future experiments at future colliders
- Exciting and fun to design, prototype, build, commission and run a detector which can reveal nature

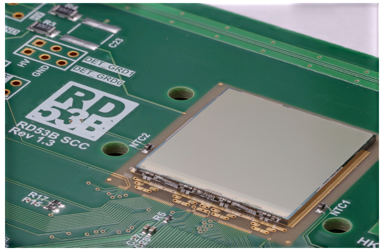
Thank you!

Acknowledgment
Phil Allport, Petra Riedler, Kerstin Borras, Maxim Titov, Roman Pöschl, Christian Joram, Laura Baudis, Corrado Gargiulo, Thomas Peitzmann, Frank Simon, Sunil Gowala
the ECFA Roadmap Panel

SPARE

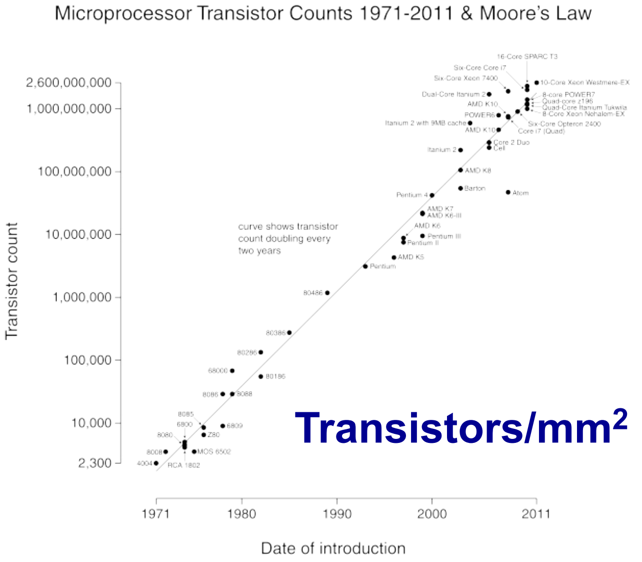
Electronics

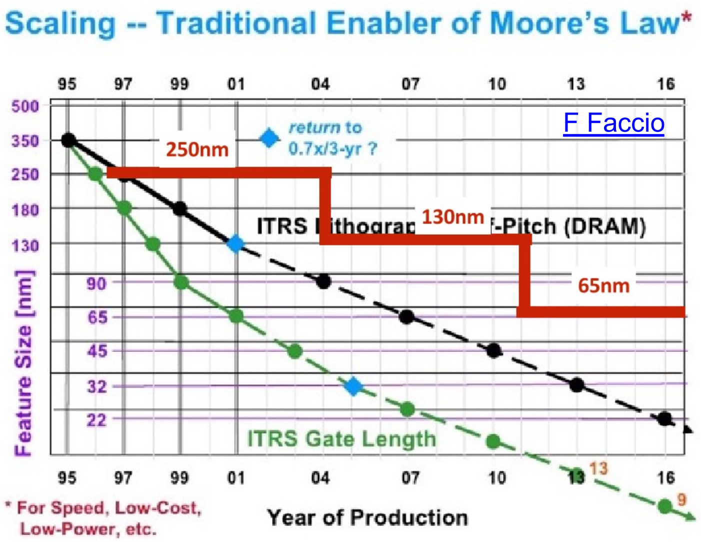
- **Precision timing** (ToF; 4D tracking), **ultra-high granularity** and improved signal **resolution** all **come at a cost in terms of data handling, processing, complexity and power.**
- These inevitably **require exploiting the latest advances in commercial <u>microelectronics</u> and <u>high-speed links</u>**.
- The need for bespoke solutions for even modest **radiation or magnetic fields is a further problem** as these are not commercial drivers, with HEP at best a niche low volume market.
- For example: Long time to develop radiation tolerance in 65 nm O(GRad) and large cost → technology is not straightforward;

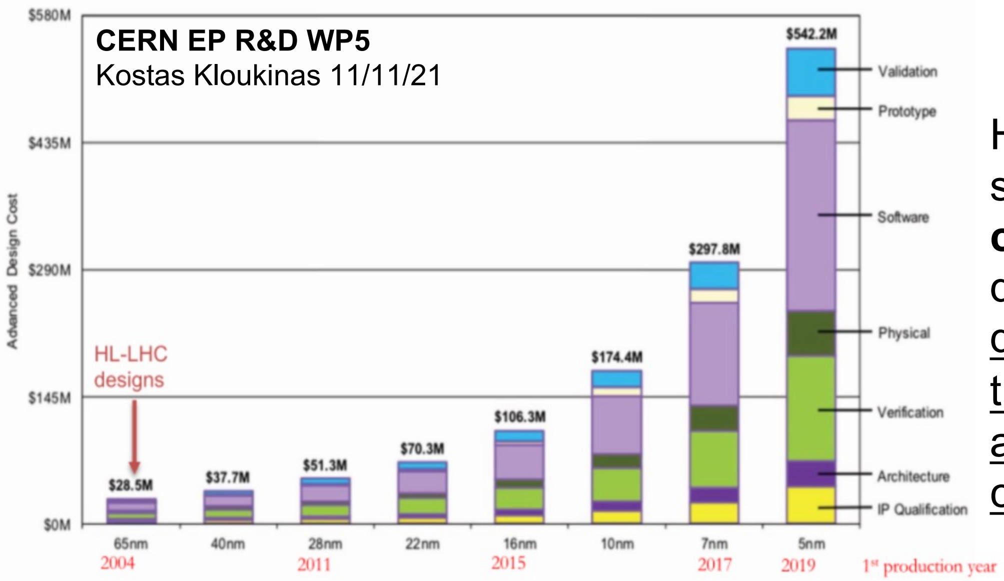


RD53 Collaboration (65 nm ASIC for HL-LHC)

- HEP Community now looks into 28 nm for the future and dedicated 130/65 nm technologies for monolithic pixels







CERN EP R&D WP5
Kostas Kloukinas 11/11/21

Chip Design and Manufacturing Cost under Different Process Nodes: Data Source from IBS*

However, increasing sophistication, entry **cost and complexity** demand <u>radically different approaches to those historically adopted by the HEP community</u>

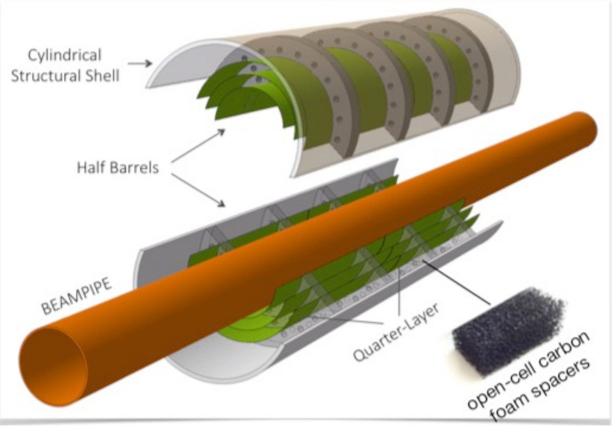
CMOS MAPS

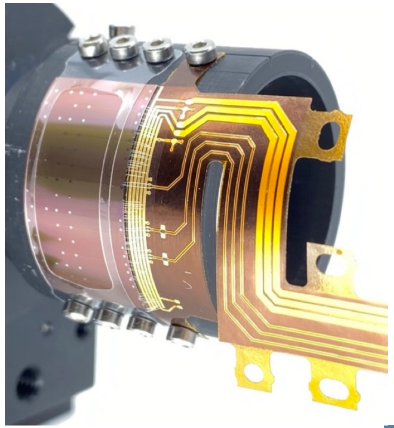
- Monolithic sensors combining sensing and readout elements
- Example: For FCC-ee vertex detector targeting spatial resolution per layer of ≤ 3µm and $X/X_0 \leq 0.05\%$, essential to have low power. Plus radiation-hardness up to $8\times10^{17} n_{eq}/cm^2$ for pp-collider.

CMOS MAPS for ALICE ITS3 (Run 4):

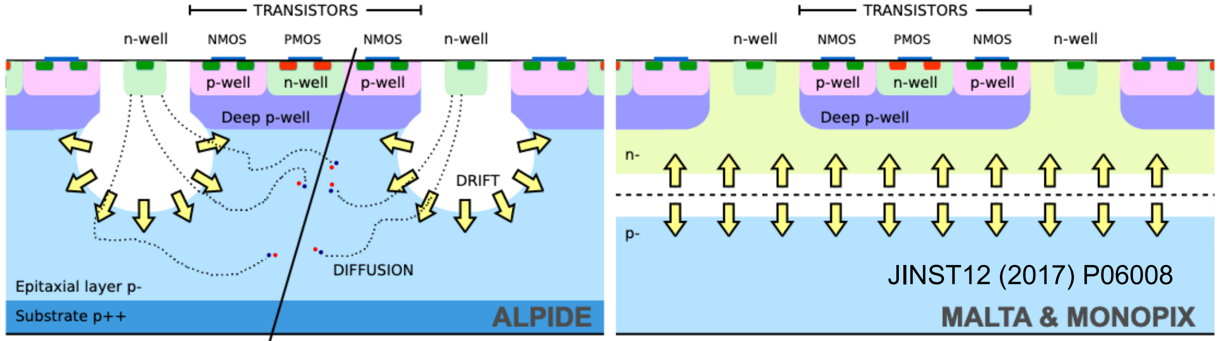
(LOI: CERN-LHCC-2019-018, M. Mager)

- Three fully cylindrical, wafer-sized layers based on curved ultra-thin sensors (20-40 µm), air flow cooling
- Very low mass (IB), < 0.02-0.04% per layer





Radiation hardness of MAPS: From ALPIDE to MALTA/Monopix with modified Tower Jazz 180 nm process

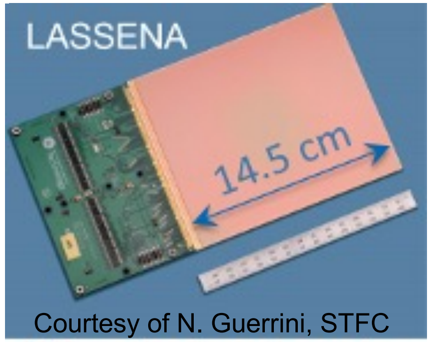


TJ180nm Standard Process TJ180nm Modified Process

→ Up to 97% efficiency after fluence of $1\times10^{15} n_{eq}/cm^2$ H. Pernegger

MIMOSA @ EUDET BeamTest
Telescope → 3 µm track resolution achieved

Large area: stitching
INMAPS process



Courtesy of N. Guerrini, STFC

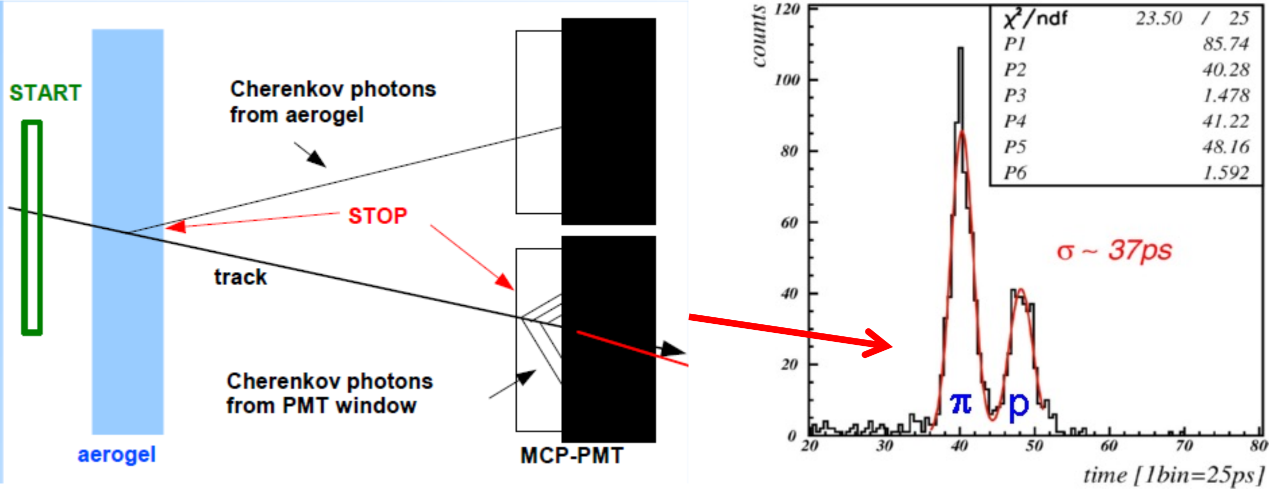
50µm pixel, waferscale

To achieve higher radiation hardness:
Hybrid technologies with thin, 3D-structures (columns/trenches) silicon and/or high bandgap materials (e.g. diamond) are mostly considered for really high radiation environments.

PID and Photon Detectors: RICHes

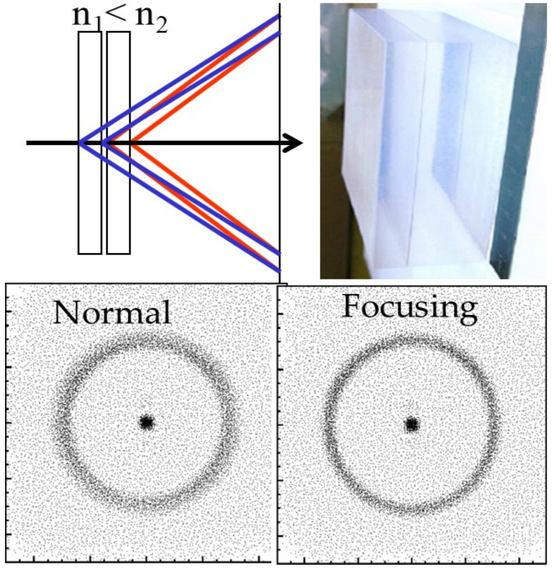
Examples of trends in proximity focusing aerogel radiator RICHes:

- **Combination of proximity focusing RICH + TOF with fast new photon-sensors** → MCP-PMT or SiPM using Cherenkov photons from PMT window
- Use of focusing configuration, e.g. ARICH (Belle), Forward RICH (Panda)



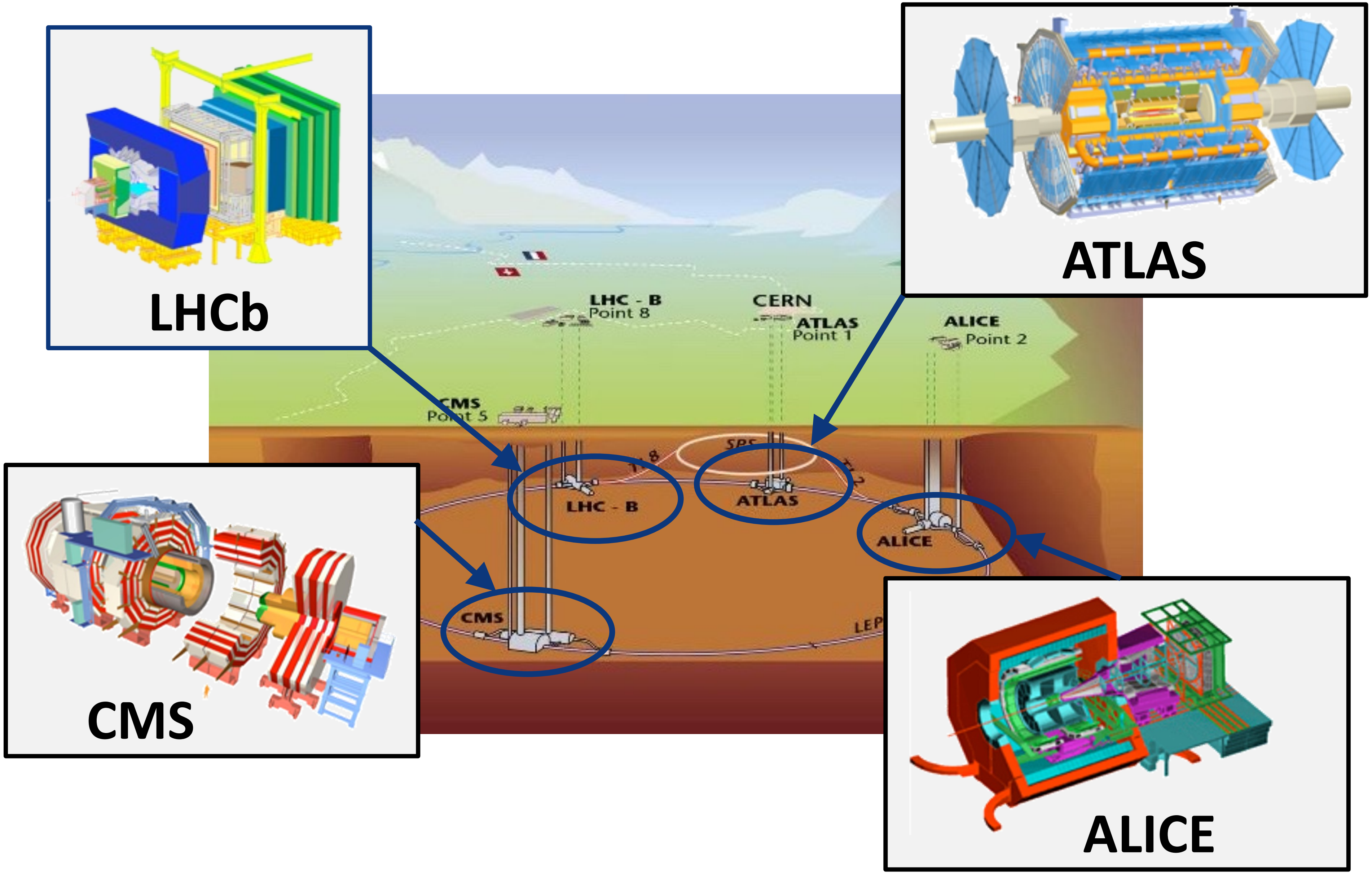
Cherenkov photons from PMT window can be used to positively identify particles below threshold in aerogel

P. Krizan @INSTR2020
T. Credo, 2004 IEEE NSS/MIC Conference Record



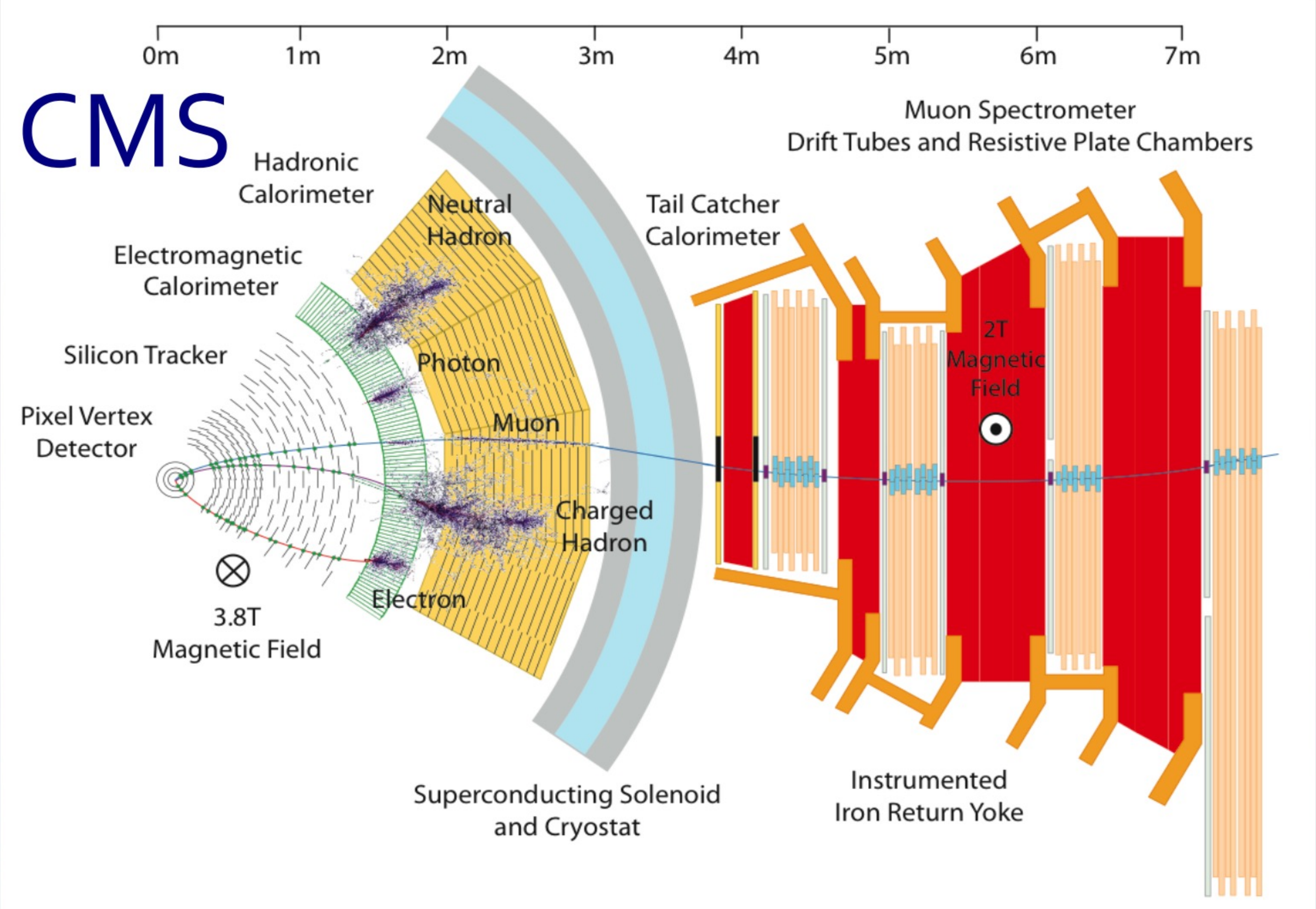
- RICHes with proximity focusing: thin radiator (liquid, solid, aerogel) and low momenta
- Time-Of-Flight (TOF) detectors: use prompt Cherenkov light, fast gas detector
- RICHes with focalisation: extended radiator (gas), mandatory for high momenta

The LHC experiments



Configurations of multi-purpose detectors

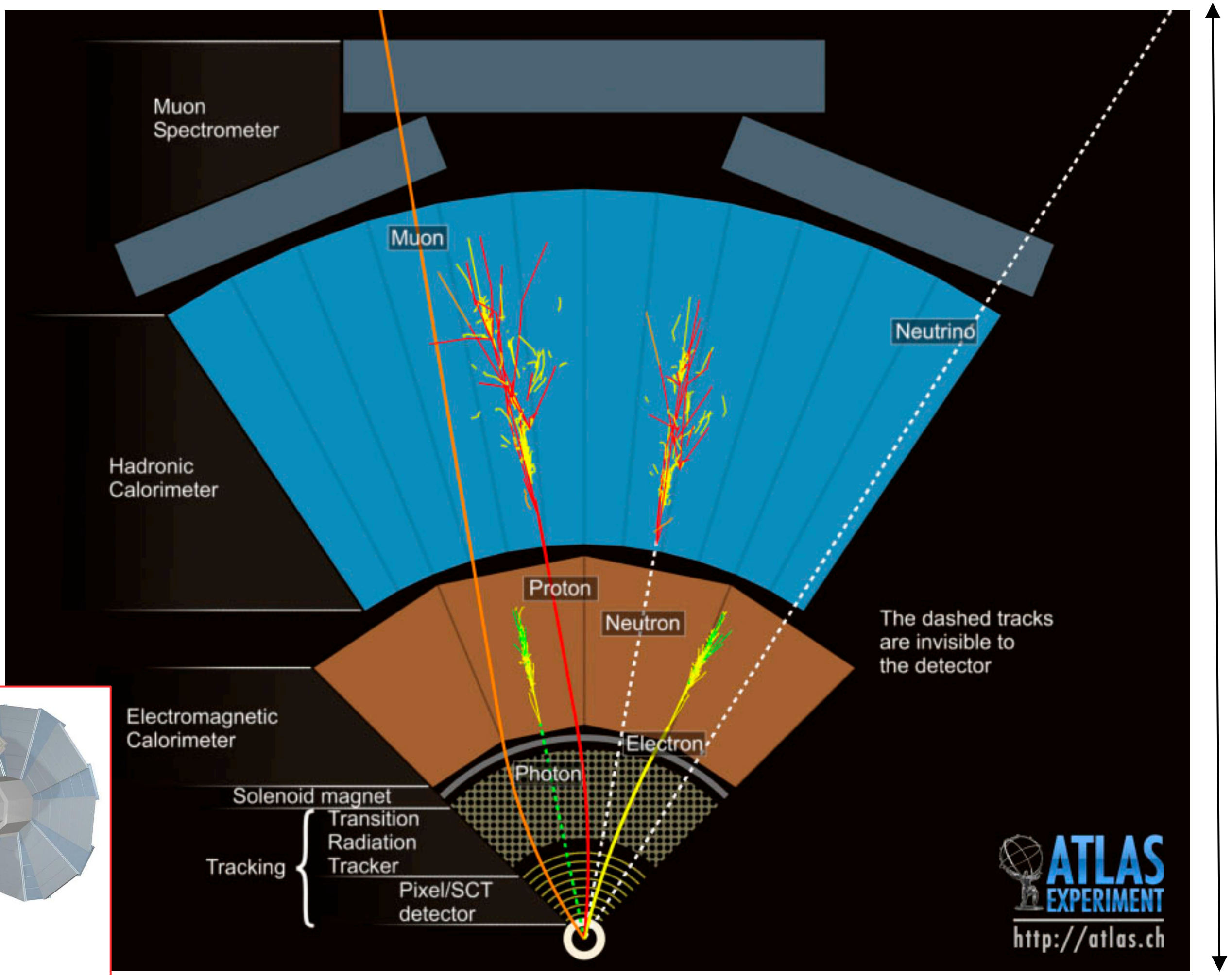
Particle flow reconstruction

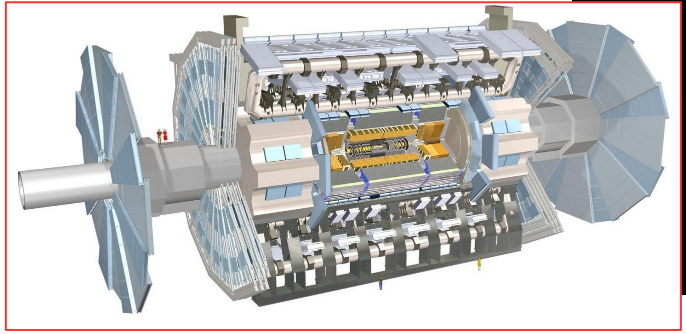


Configurations of multi-purpose detectors

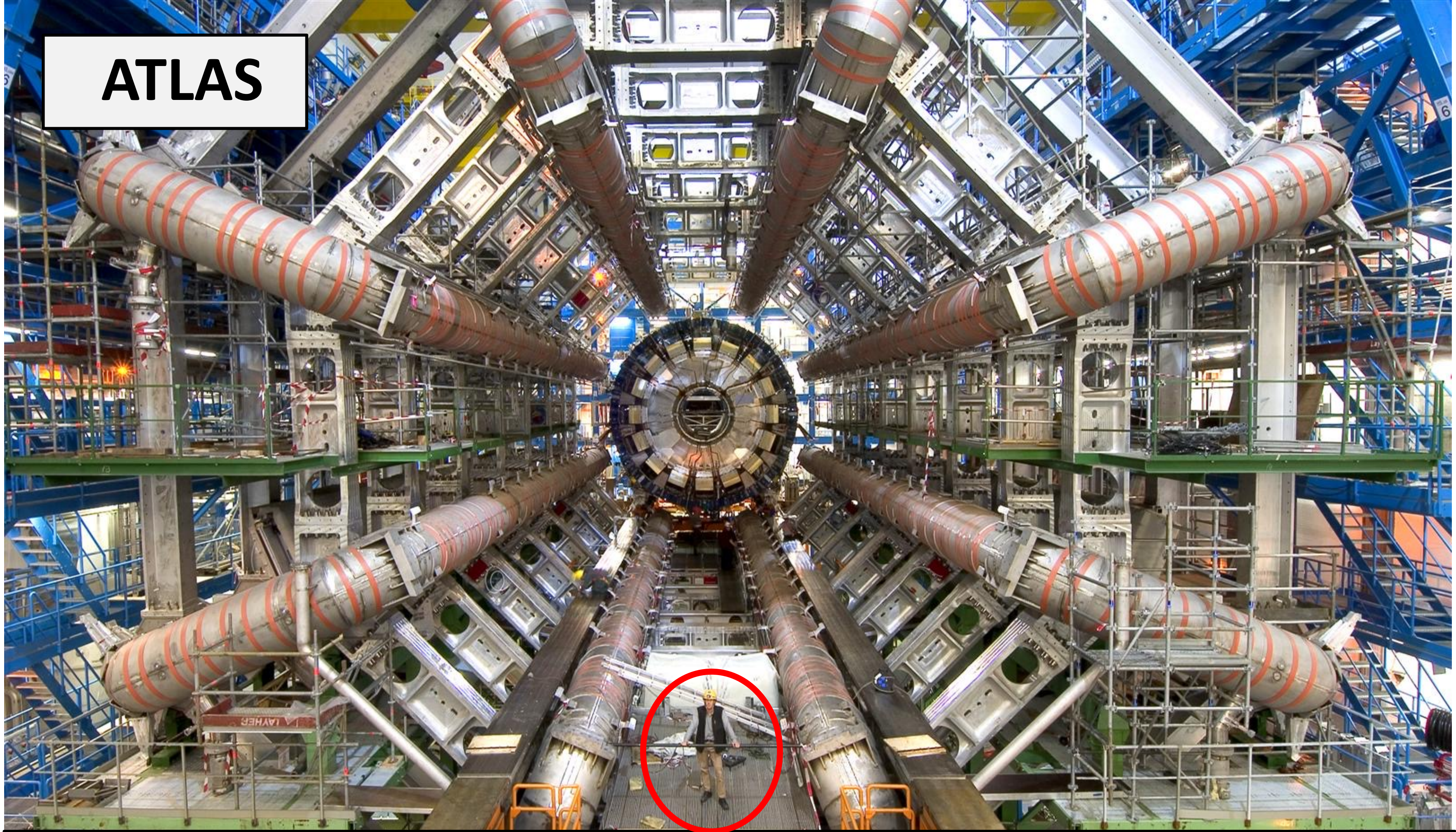
Layers of the ATLAS experiment at the LHC

- Different types of detectors to identify particles and measure their energy and momentum





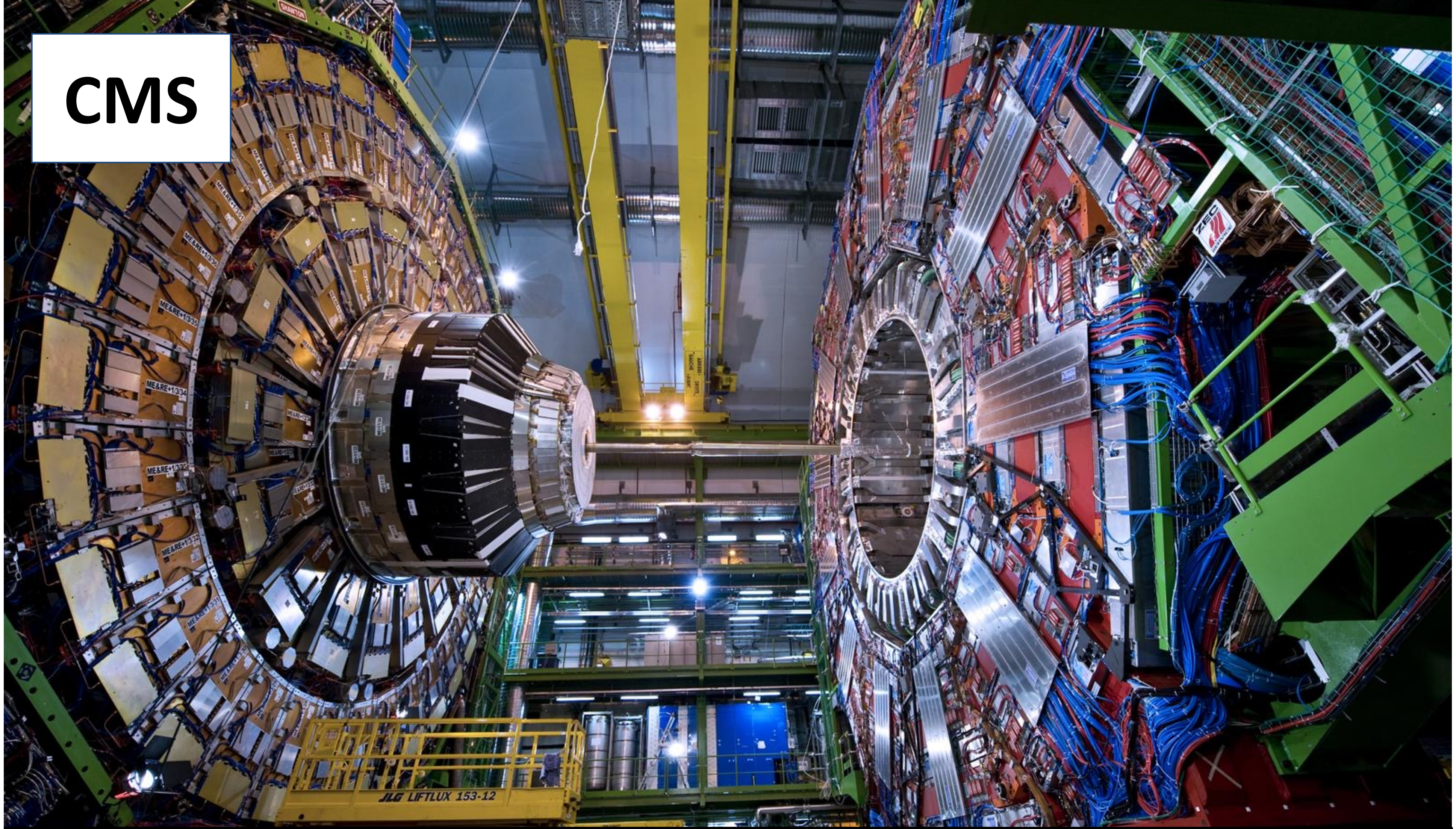
ATLAS



The ATLAS detector:

- Largest general purpose detector: ~ half Notre Dame cathedral
- number of detector sensitive elements: 160 millions
- cables needed to bring signals from detector to control room: 3000 km
- data in 1 year per experiment: ~10 PB (2 million DVD)

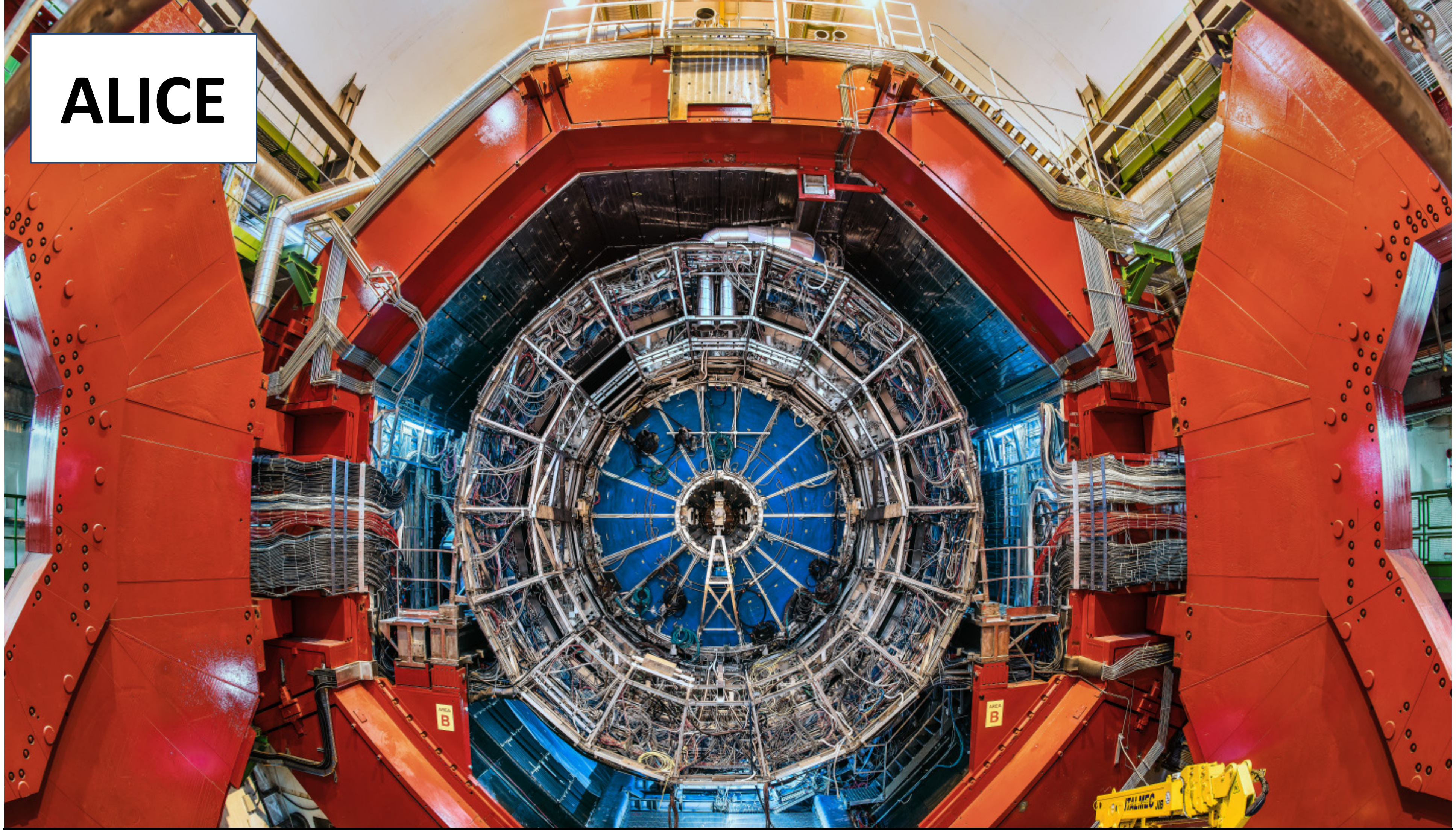
CMS



The CMS detector:

- Very compact general purpose detector
- Heavier than the Eiffel tower: 14 000 tons
- 4T superconducting magnet, about 100 000 times the magnetic field of the Earth
- It was built in 15 sections on the ground before lowering it into the cavern

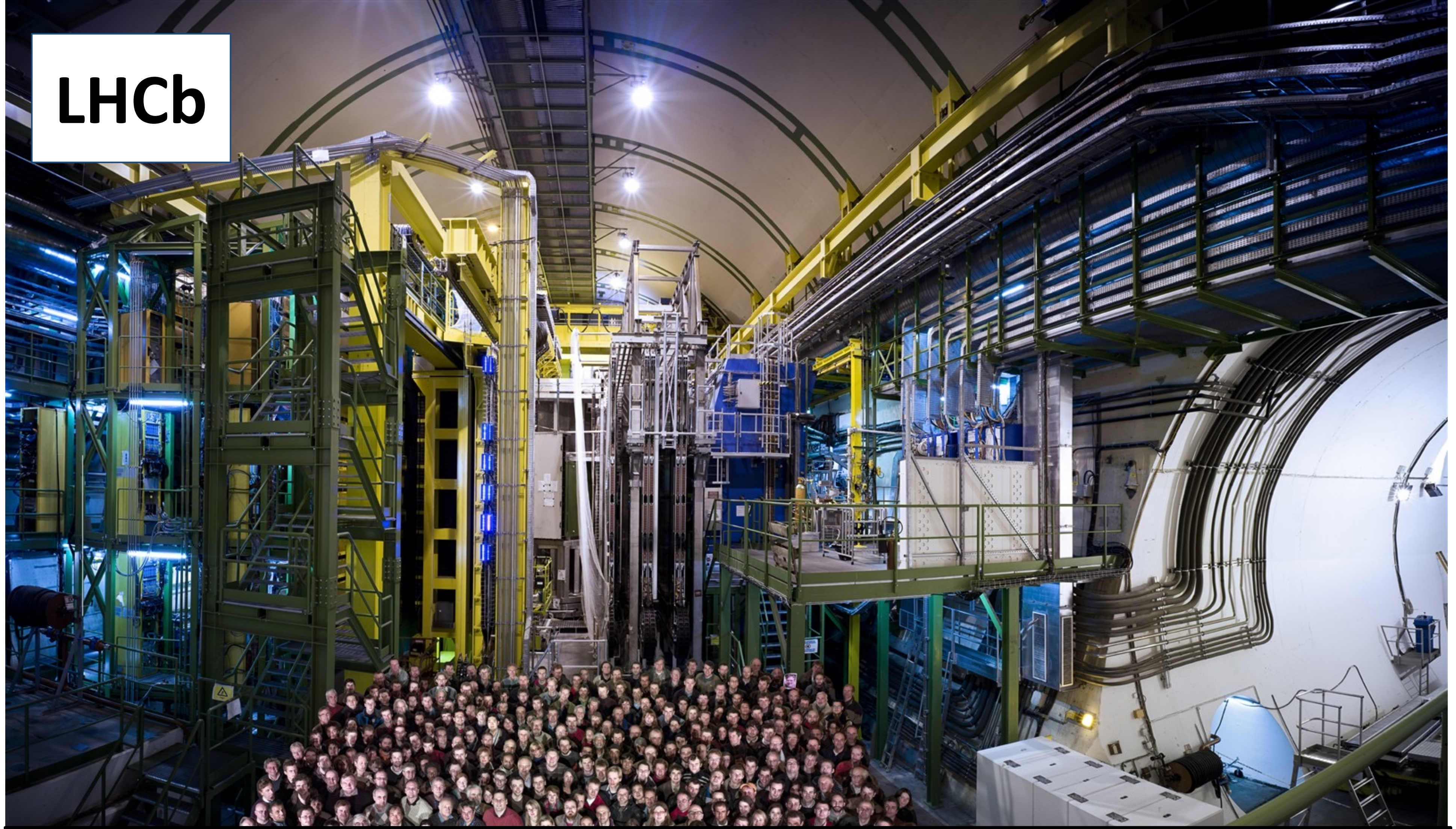
ALICE



The ALICE detector:

- Built for collisions of nuclei at ultra-relativistic energies
- To study quark-gluon plasma as a few millionth seconds after the Big Bang.
- 90 m^3 large gas detector as central tracking device
- Installation of the largest monolithic silicon pixel detector in HEP just completed

LHCb

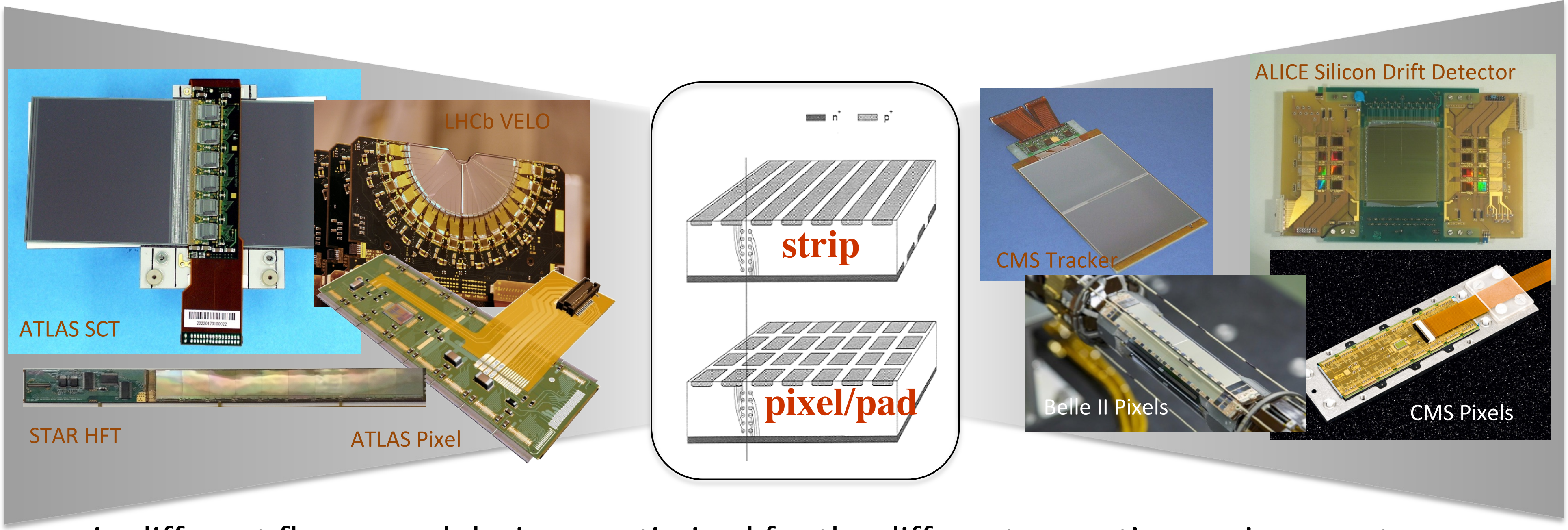


The LHCb detector:

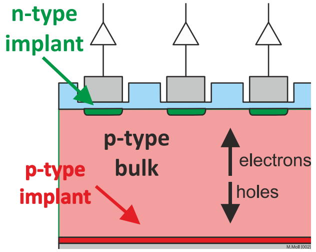
- Specializes in investigating the differences between matter and antimatter
- Sub-detectors are arranged in a row, different from the other experiments
- Allows to study particles that emerge mainly in the forward direction from the collision
- The “b” in LHCb stands for “beauty” as it is the key particle of study

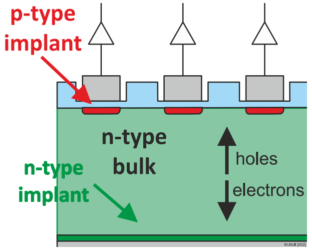
Silicon detectors in HEP experiments

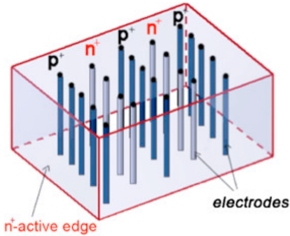
Silicon sensors are present in all HEP experiments - as silicon strip detectors, silicon pixel detectors, silicon drift detectors, monolithic pixel detectors….

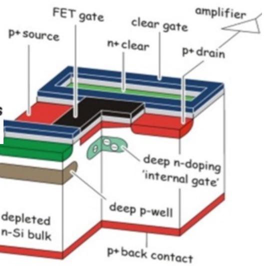


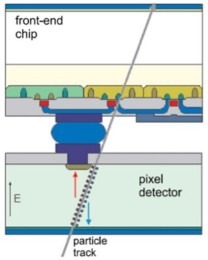
….in different flavors and designs, optimized for the different operating environments:

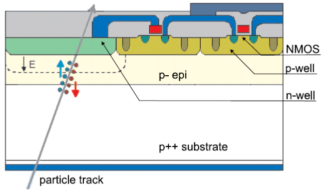










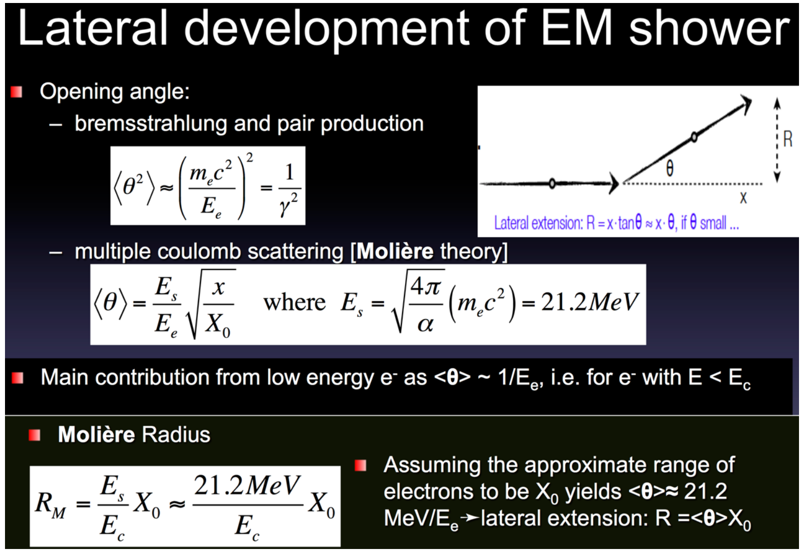


Example: ATLAS IBL phase-I upgrade to increase the performance

- 4th 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

Recap: Electromagnetic Calorimeters

Shower development



Lateral development of EM shower

- Opening angle:
  - bremsstrahlung and pair production

$$\langle\theta^2\rangle \approx \left(\frac{m_e c^2}{E_e}\right)^2 = \frac{1}{\gamma^2}$$

Lateral extension: $R = x \cdot \tan\theta \approx x \cdot \theta$, if θ small ...

  - multiple coulomb scattering [**Molière** theory]

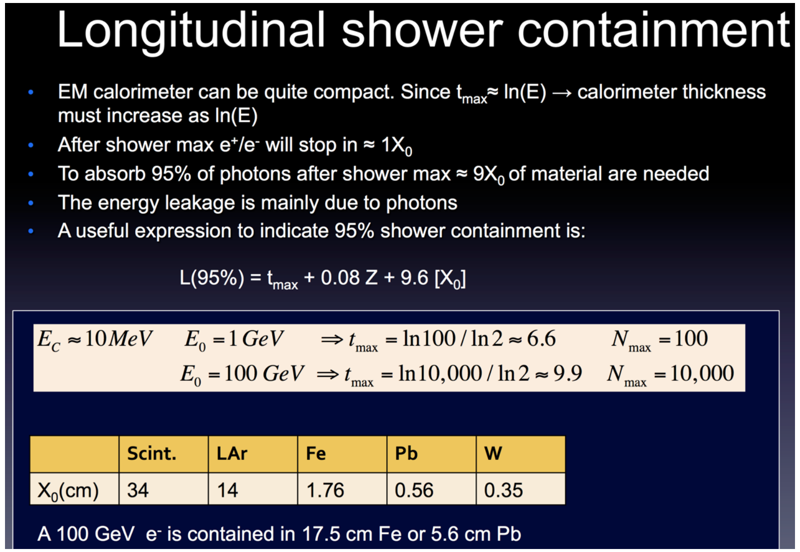
$$\langle\theta\rangle = \frac{E_s}{E_e}\sqrt{\frac{x}{X_0}} \quad \text{where} \quad E_s = \sqrt{\frac{4\pi}{\alpha}}\left(m_e c^2\right) = 21.2 MeV$$

- Main contribution from low energy e^- as <**θ**> ~ $1/E_e$, i.e. for e^- with $E < E_c$

- **Molière** Radius

$$R_M = \frac{E_s}{E_c} X_0 \approx \frac{21.2 MeV}{E_c} X_0$$

- Assuming the approximate range of electrons to be X_0 yields <**θ**>≈ 21.2 MeV/E_e ➛ lateral extension: R =<**θ**>X_0



Longitudinal shower containment

- EM calorimeter can be quite compact. Since $t_{max} \approx \ln(E)$ → calorimeter thickness must increase as ln(E)
- After shower max e^+/e^- will stop in ≈ $1X_0$
- To absorb 95% of photons after shower max ≈ $9X_0$ of material are needed
- The energy leakage is mainly due to photons
- A useful expression to indicate 95% shower containment is:

$$L(95\%) = t_{max} + 0.08\,Z + 9.6\,[X_0]$$

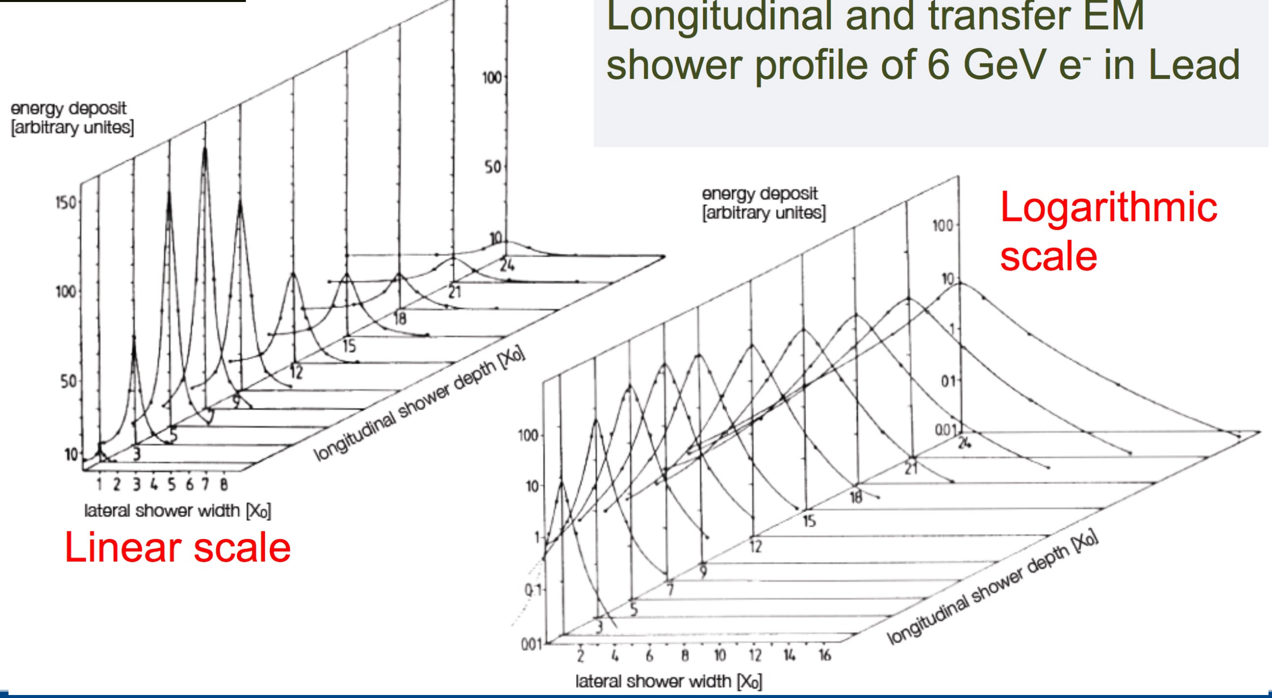
$$E_C \approx 10 MeV \quad E_0 = 1\,GeV \quad \Rightarrow t_{max} = \ln 100 / \ln 2 \approx 6.6 \quad N_{max} = 100$$

$$E_0 = 100\,GeV \Rightarrow t_{max} = \ln 10{,}000 / \ln 2 \approx 9.9 \quad N_{max} = 10{,}000$$

	Scint.	LAr	Fe	Pb	W
X_0(cm)	34	14	1.76	0.56	0.35

A 100 GeV e^- is contained in 17.5 cm Fe or 5.6 cm Pb

Longitudinal and transfer EM shower profile of 6 GeV e^- in Lead

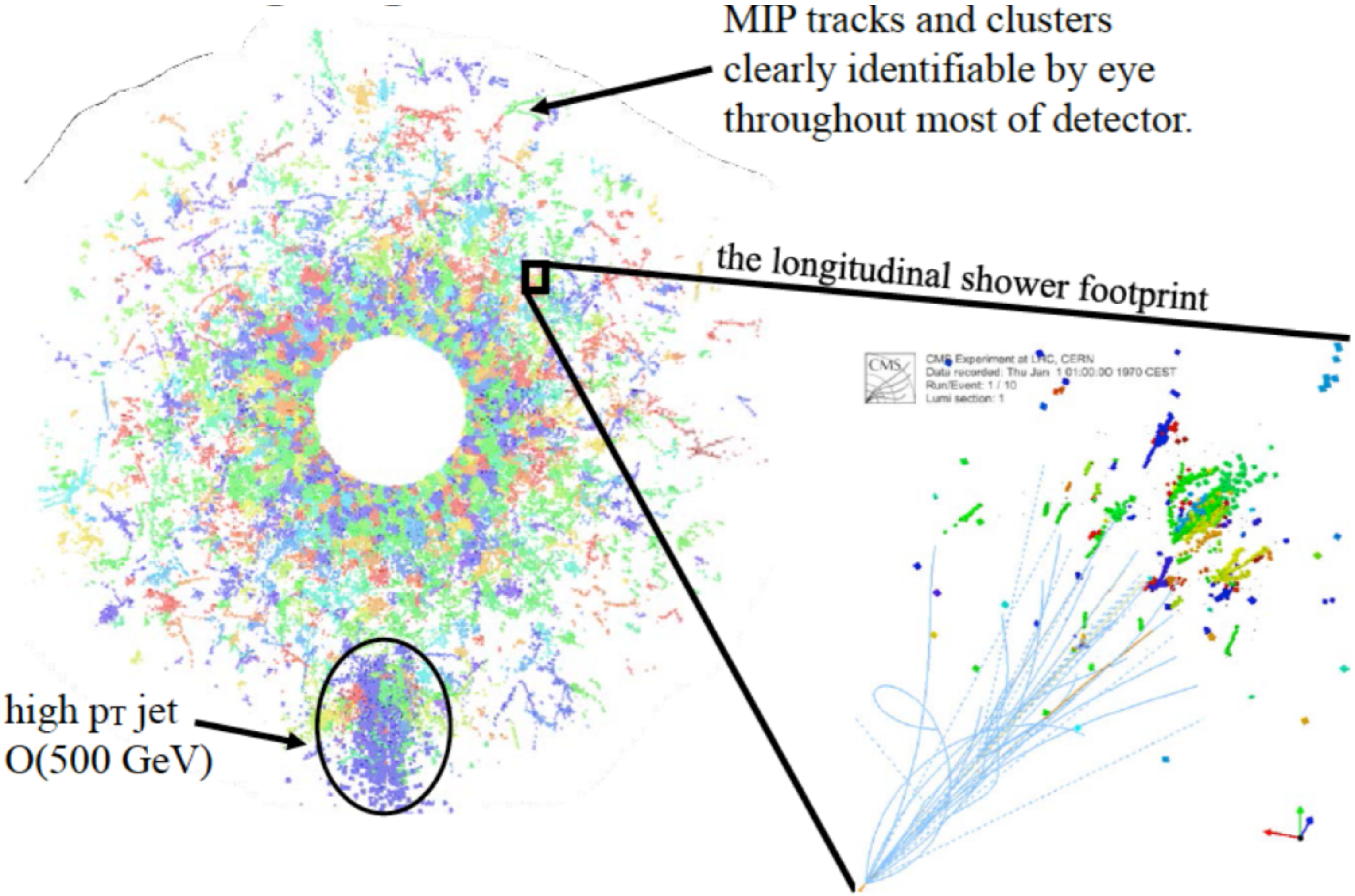


Linear scale

Logarithmic scale

New Endcap calorimeter for CMS for HL-LHC

Imaging Calorimeter: Simulation



MIP tracks and clusters clearly identifiable by eye throughout most of detector.

the longitudinal shower footprint

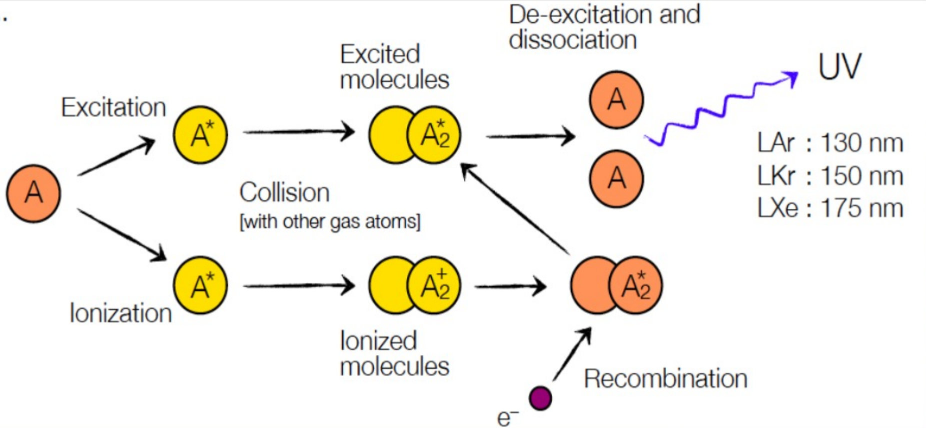
high p_T jet O(500 GeV)

Recap: Scintillators

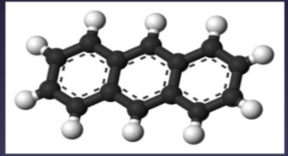
Scintillators

- Inorganic (Sodium iodide (NaI), Cesium iodide (CsI),…)

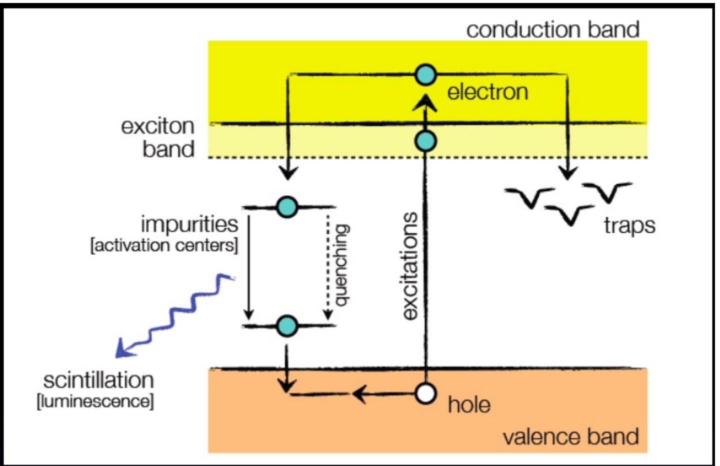
…



- Organic crystals
  - Aromatic hydrocarbon compounds with benzene rings such as Anthracene (C14H10), etc

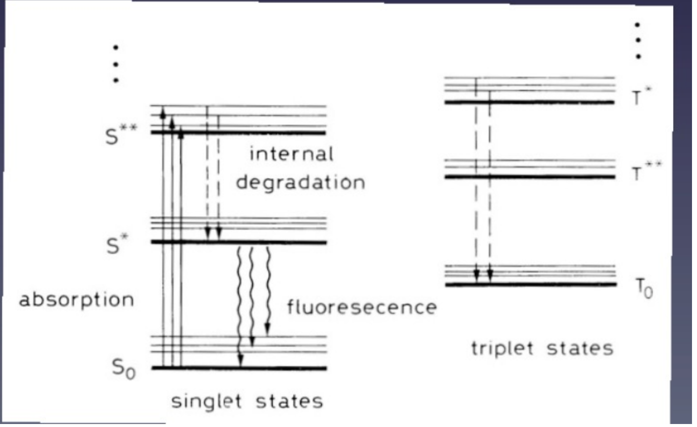


- Plastic scintillators
  - Organic scintillators suspended in the aromatic polymer (easy to mold and machine)
- Liquid scintillators

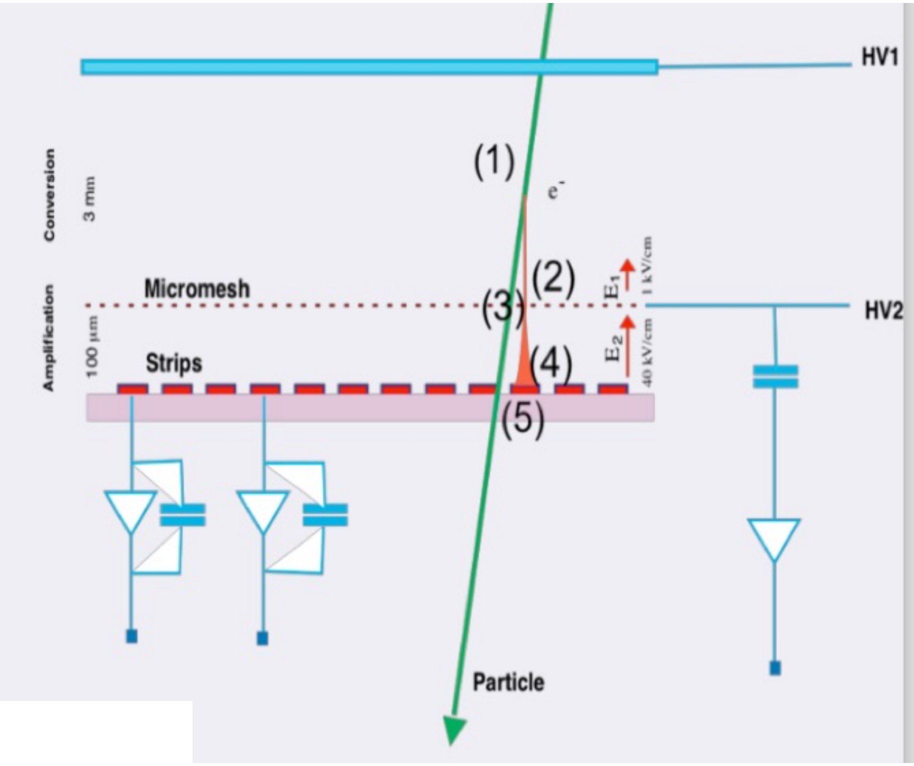


- Noble gasses (Liquid Argon, Liquid Xenon…)

- Molecule structure generates energy levels with transition λ=360-500 nm

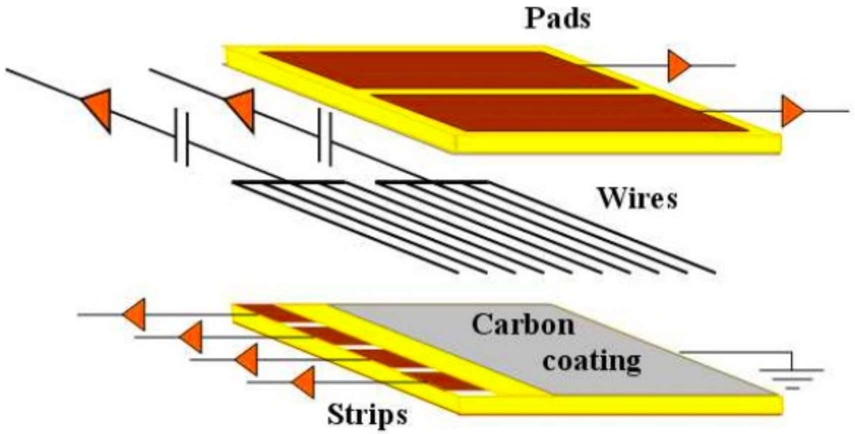


Recap: Micromegas and TGCs



Micromegas
- Gas volume divided in two by metallic mesh
- Gain = 10^2, fast signal of 100 ns

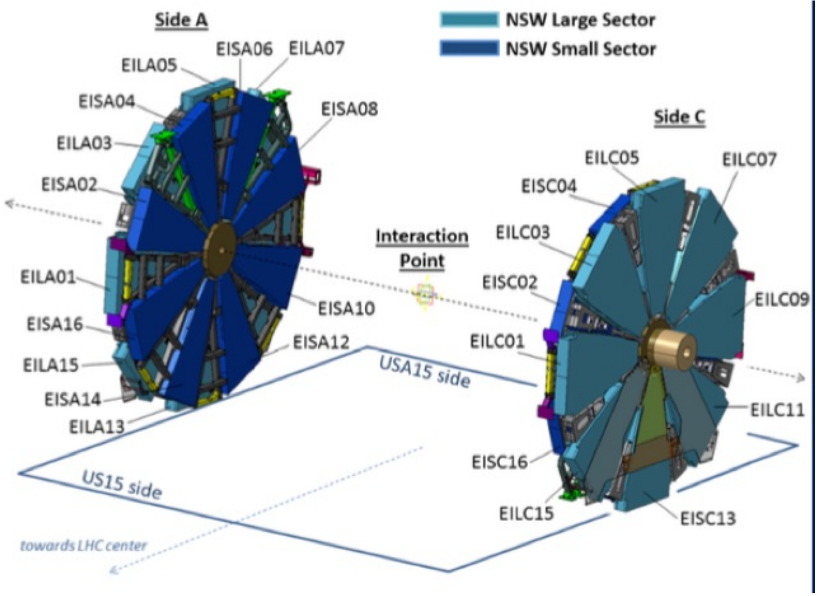
TGC – Thin Gap Chambers

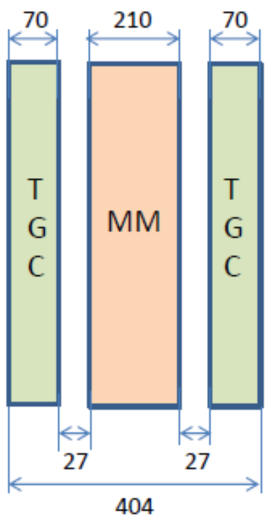


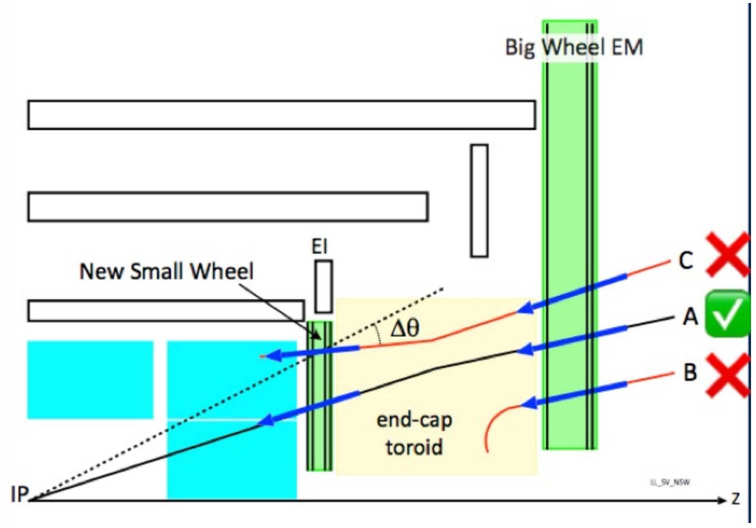
ATLAS Phase-1 Upgrade: Muon System

- Improved muon tracking for |η| > 1.3
- Reduce fake rates and keep precision at high rates for triggering

→ New Small Wheels

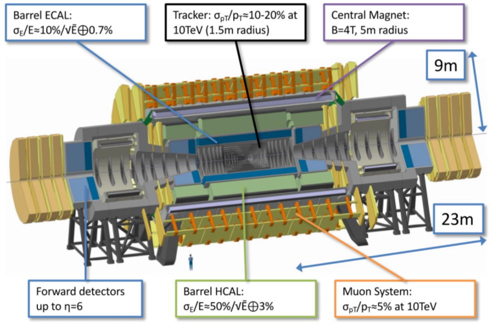






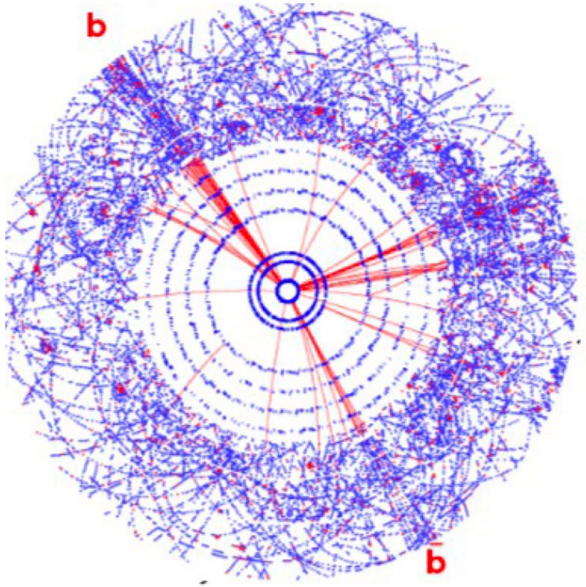
- Micromegas: ~1200 m² for precision tracking, high rate capable
- Small-strip thin gap chambers: ~1200 m² for triggering, bunch ID will give good timing, proven technology
- Space resolution < 100 μm

Example of future detectors at accelerators



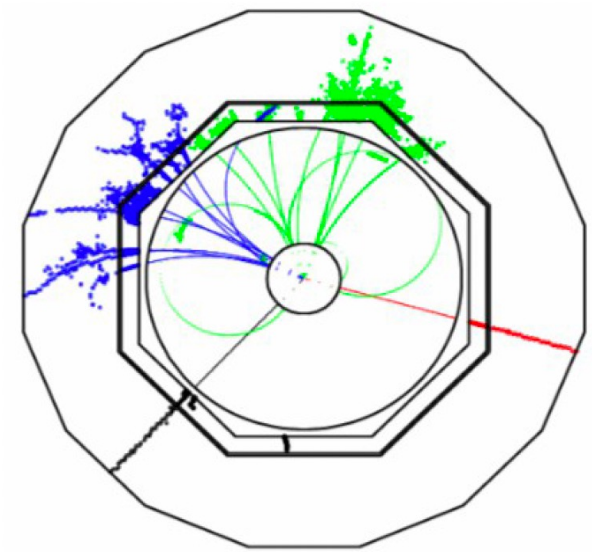
FCC-hh CDR

Hadron-hadron collisions e.g. LHC

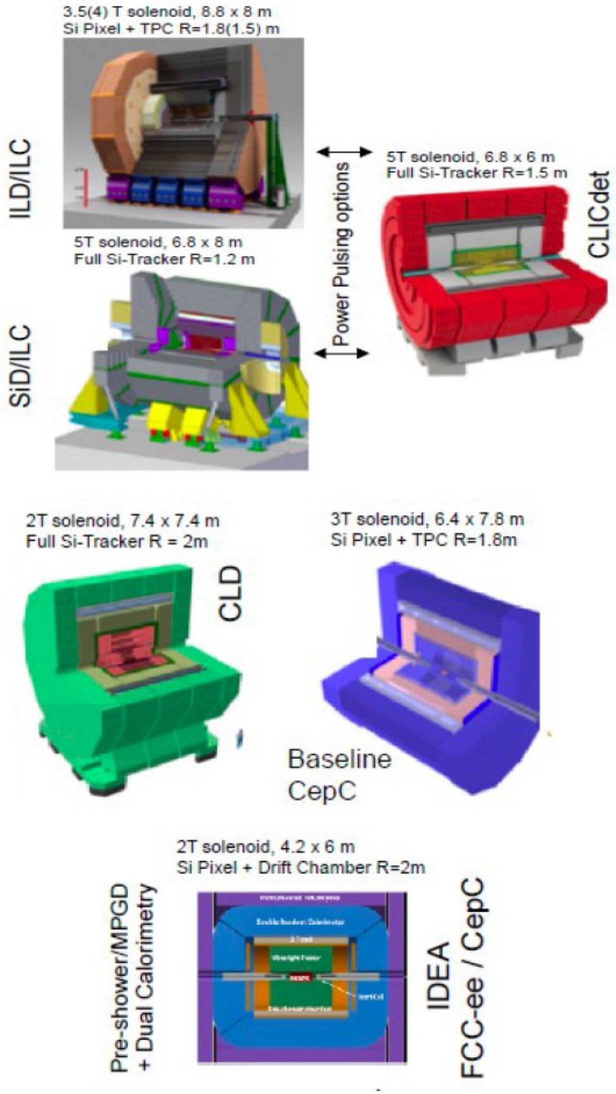


- Busy events
- Require hardware and software triggers
- High radiation levels

e^+e^--collisions



- Clean events
- No trigger
- Full event reconstruction



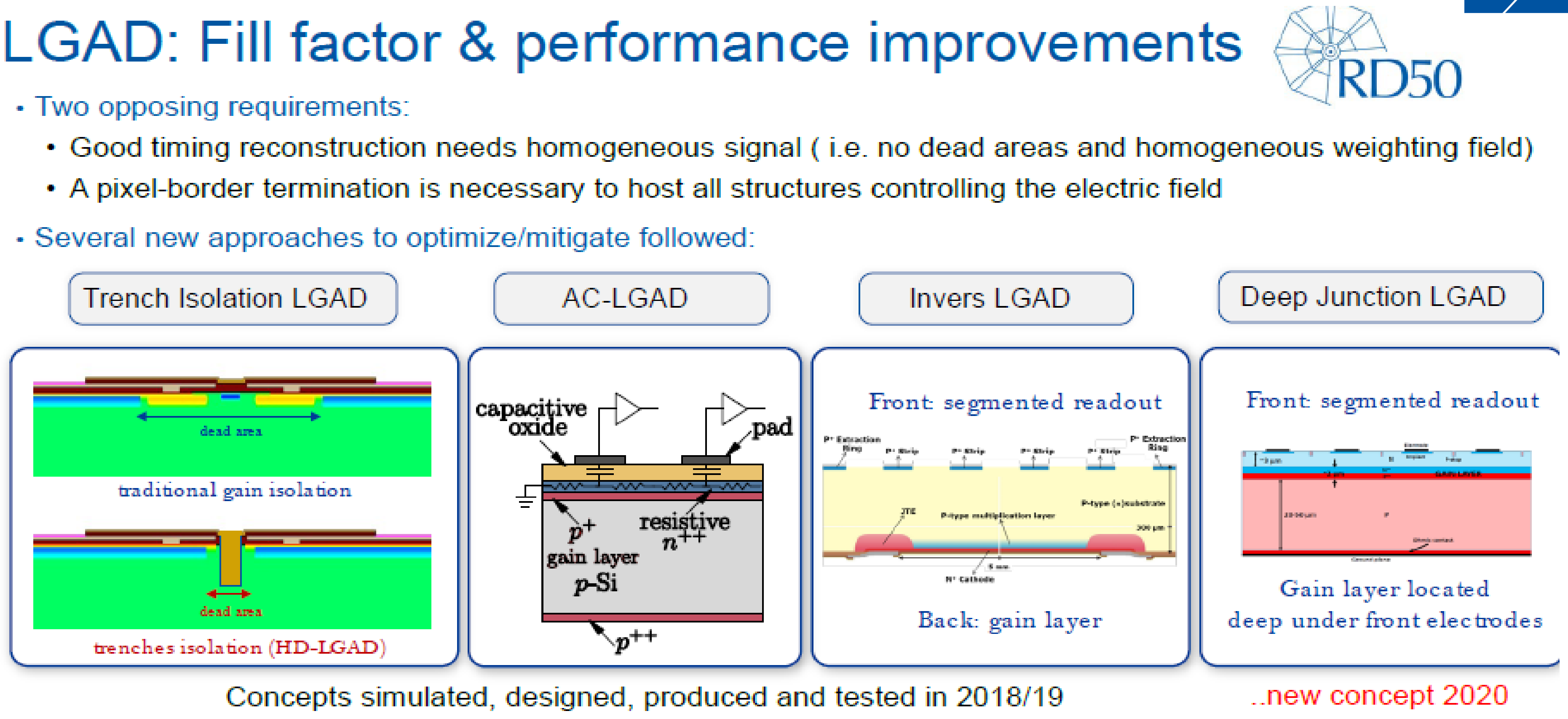
- One of the many challenges: radiation hardness. Radiation levels of e.g. 300 MGy/5-6 10^{17} n_{eq}/cm^2 in first tracker layers go well beyond what any currently available microelectronics can survive ($\lesssim$ MGy) and few sensor technologies can cope beyond ~10^{16} n_{eq}/cm^2

→ Detector R&D essential

Silicon timing detectors

Sensors for 4D-Tracking: position and time resolution → Development of Radiation Hard Timing Detectors (Low Gain Avalanche Detectors)

- For LGADs, three main foundries (CNM, FBK, HPK), more producers interested
- Time information hugely beneficial to supress pile-up in pp-collisions



LGAD: Fill factor & performance improvements

- Two opposing requirements:
  - Good timing reconstruction needs homogeneous signal (i.e. no dead areas and homogeneous weighting field)
  - A pixel-border termination is necessary to host all structures controlling the electric field
- Several new approaches to optimize/mitigate followed:

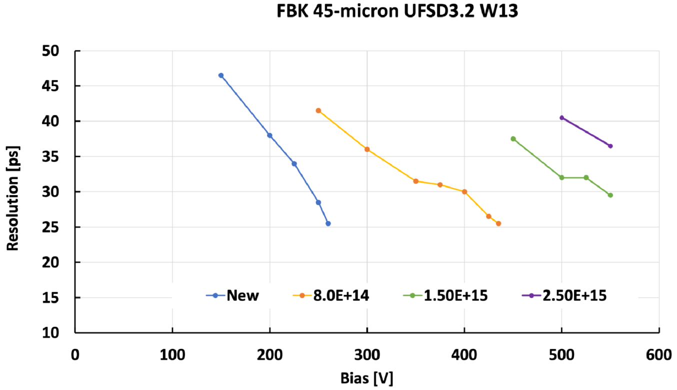
Trench Isolation LGAD | AC-LGAD | Invers LGAD | Deep Junction LGAD

Concepts simulated, designed, produced and tested in 2018/19

..new concept 2020

Areas of LGAD developments within RD50 Collaboration:

- Timing performance (~ 25 ps for 50 µm sensors)
- Fill factor and signal homogeneity
- Position resolution is about 5% of the distance between electrodes O(5-15 µm) (AC-LGAD)
- Radiation Hardness (~$2x10^{15}$ n_{eq}/cm^2)
- Performance Parameterisation Model



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