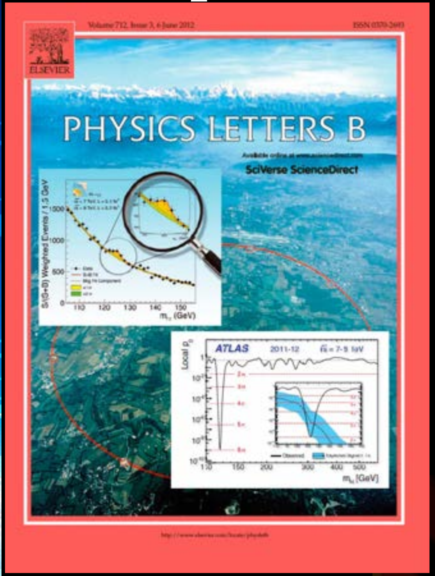
Innovative silicon detectors for HL-LHC

Daniela Bortoletto

Large Hadron Collider (LHC)

A 27km discovery machine colliding pp at 13 TeV

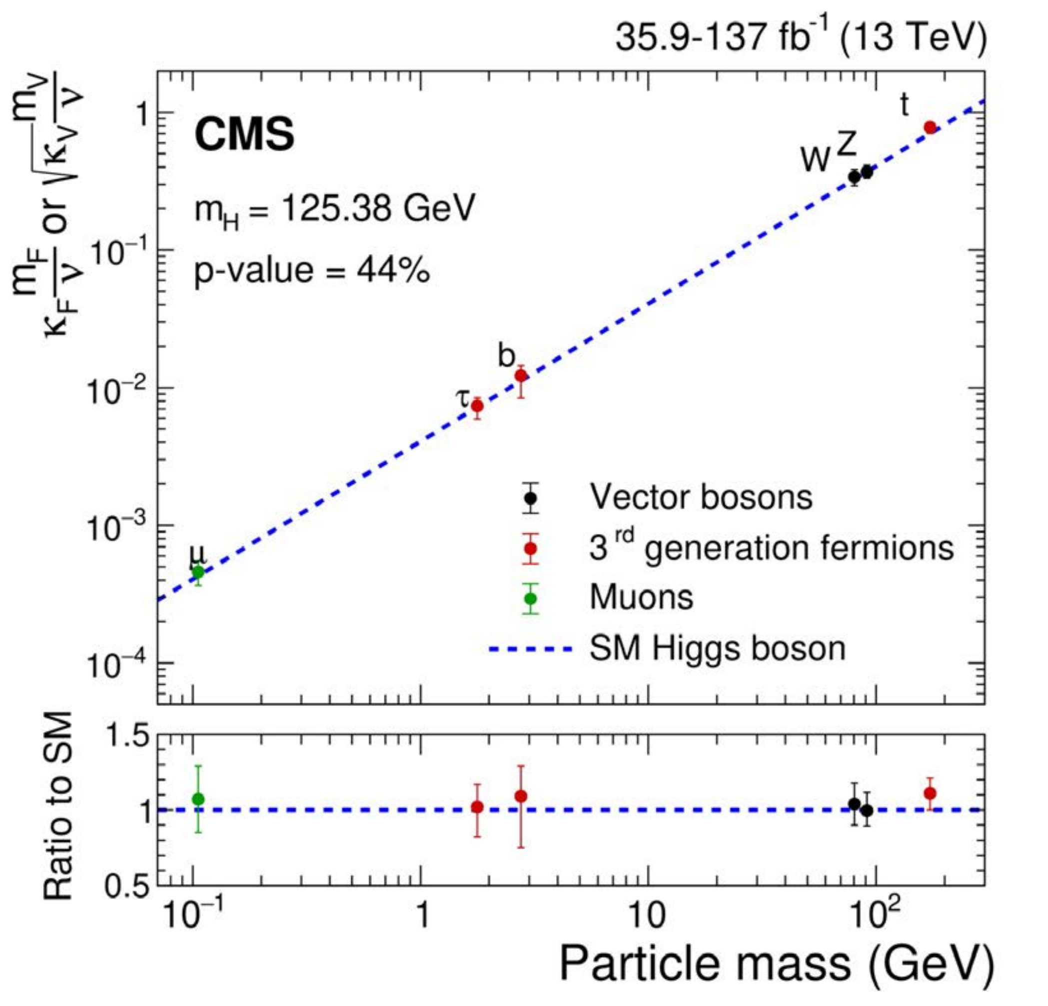
Unprecedented discoveries: Higgs



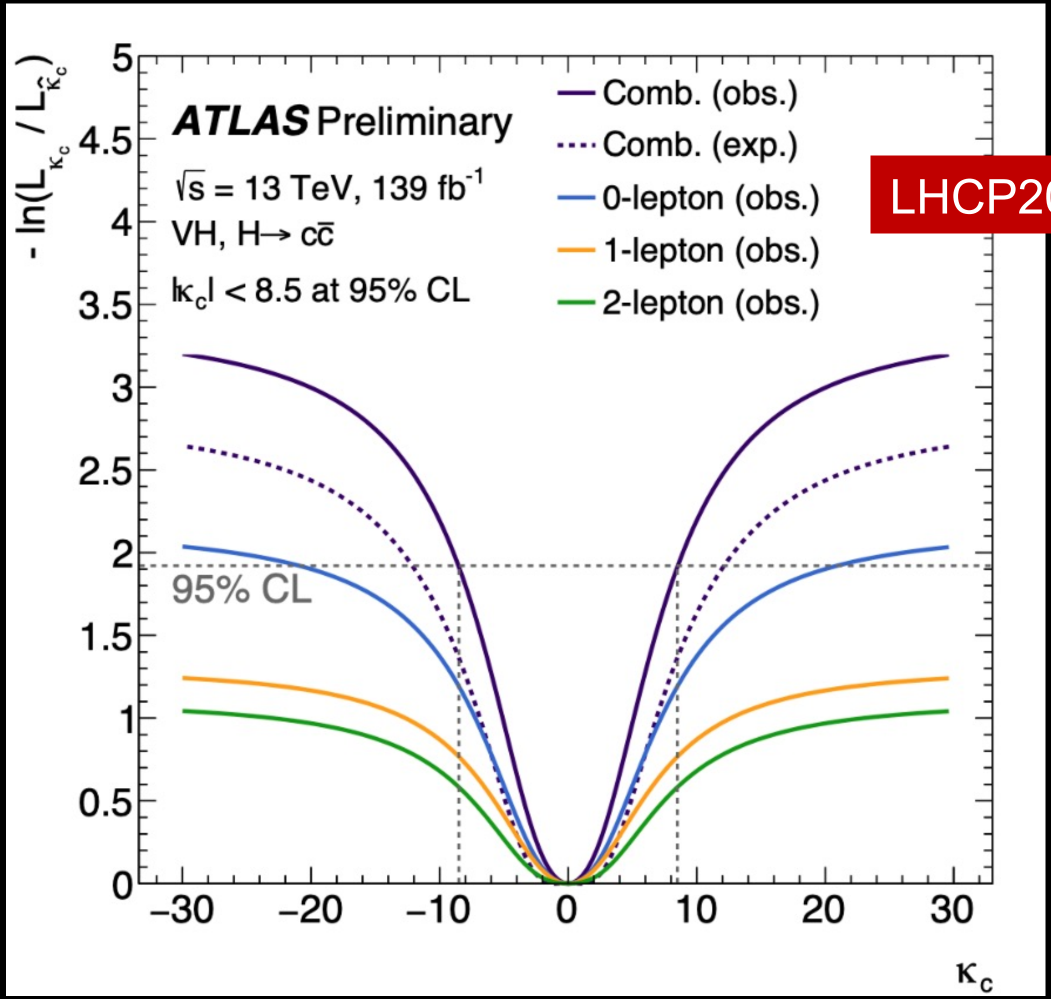
To François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider "

Unprecedented discoveries: Higgs

Probing the predictions of SM



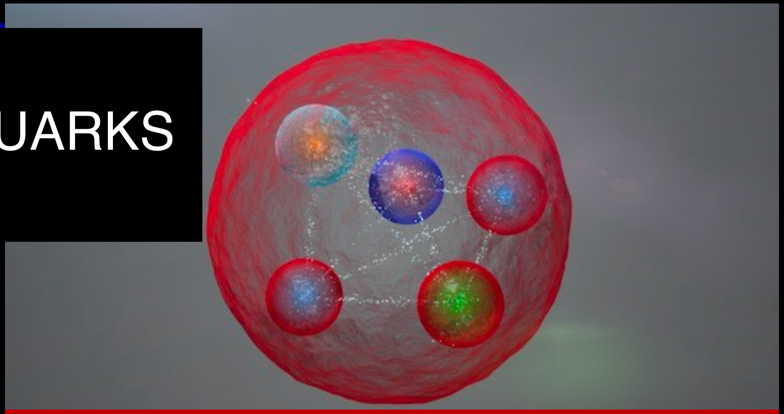
Yukawa coupling modifier $|\kappa_c|<8.5$ at 95% CL



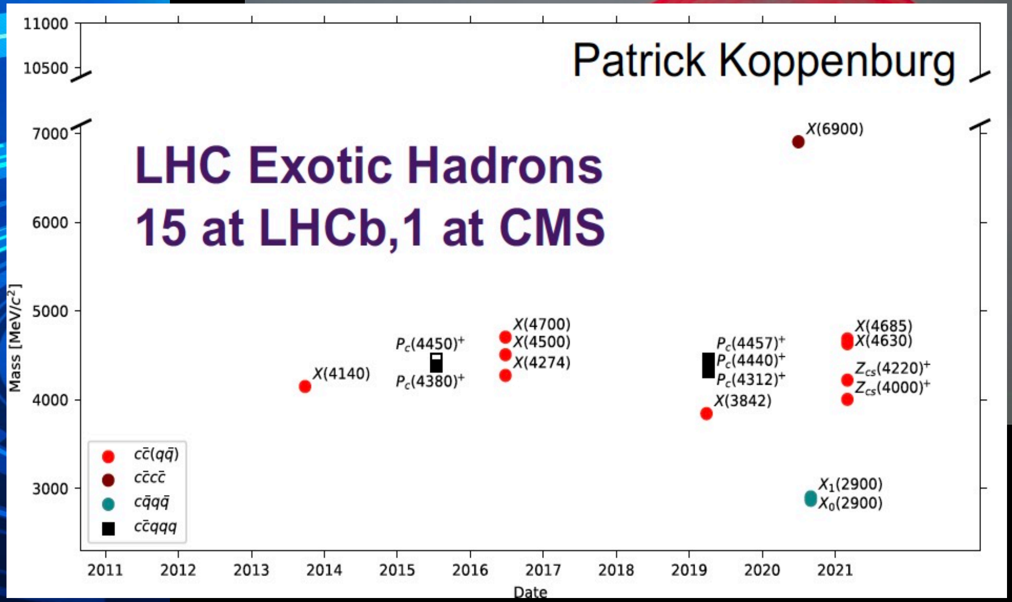
LHCP2021

But also others

LHCb:
PENTAQUARKS
2015



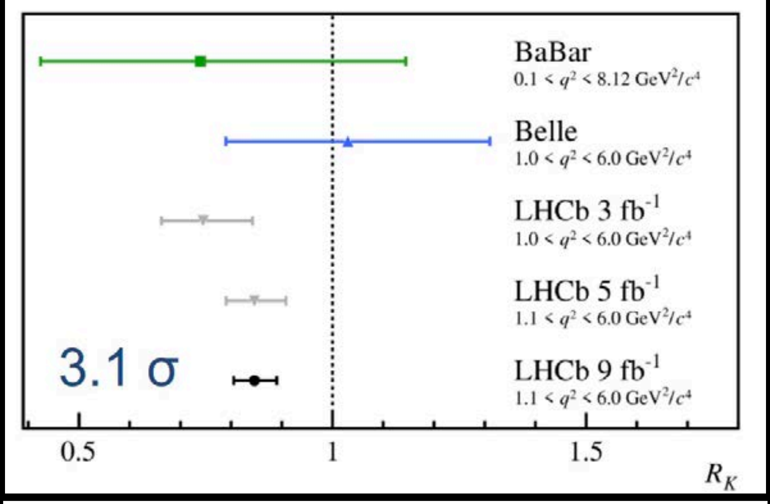
Spherical: five tightly bound quarks contained in symmetric volume?

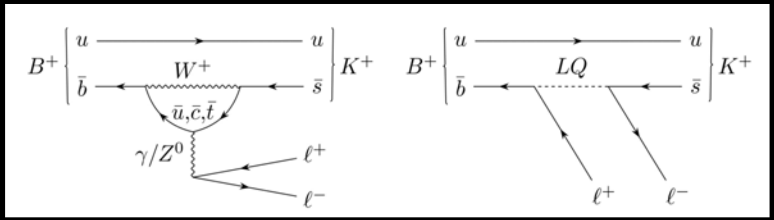


LHCb: R_K
Perhaps showing some cracks in the SM

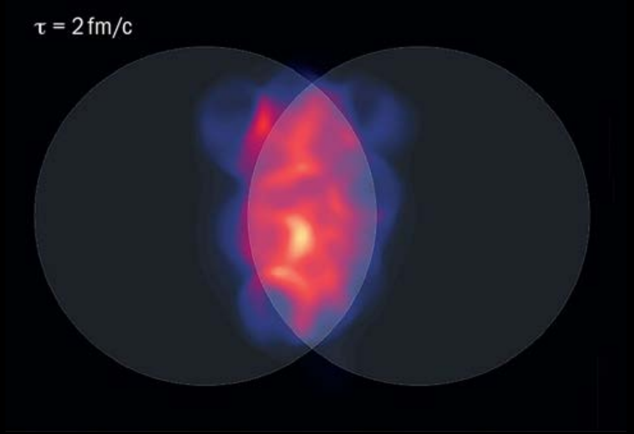
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

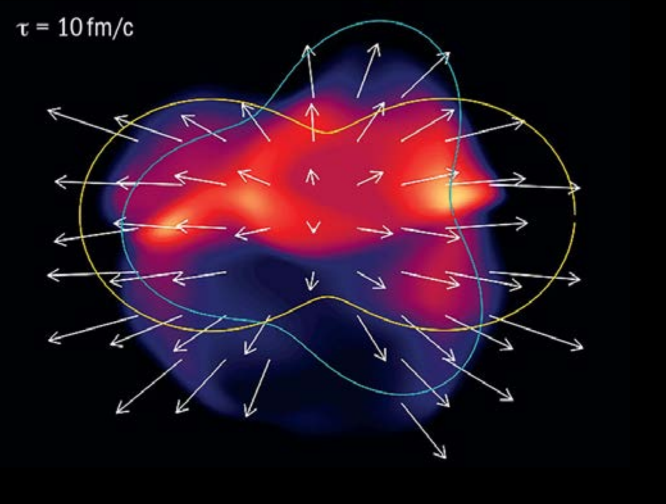
$$R_K = 0.846\,^{+0.044}_{-0.041}$$





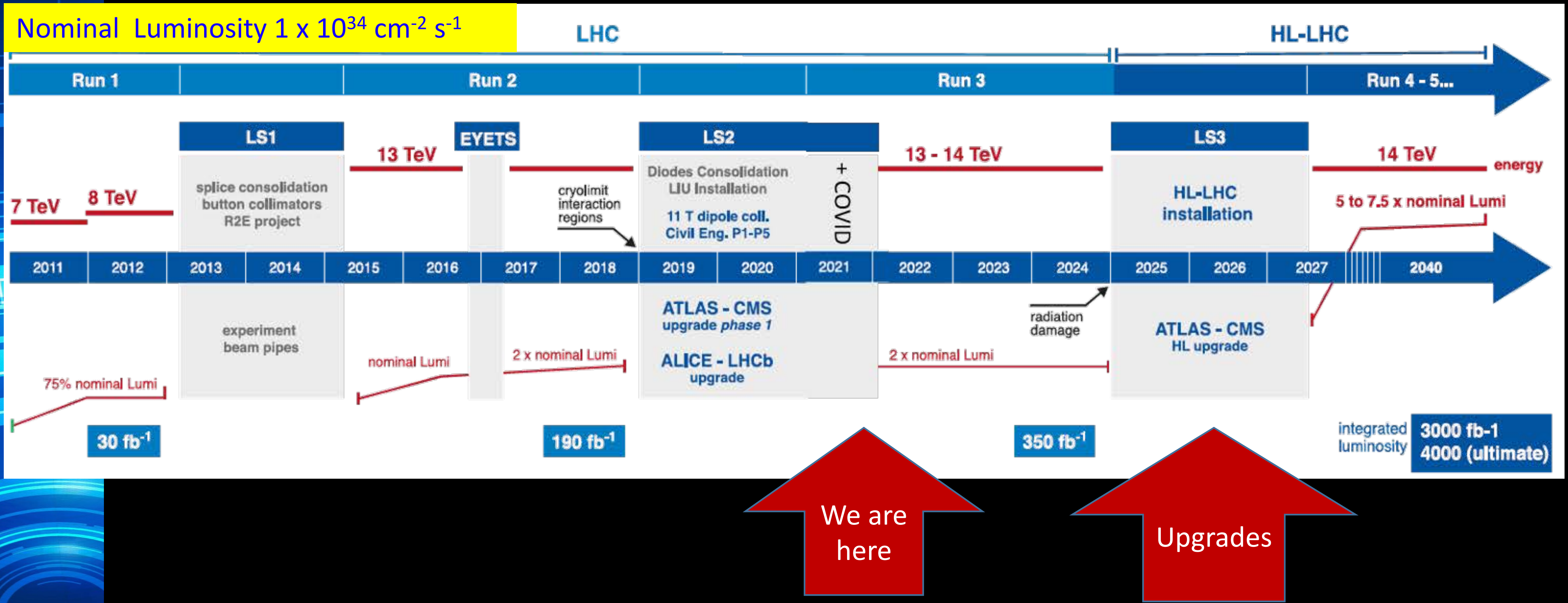
ALICE: QGP





Elliptical flow

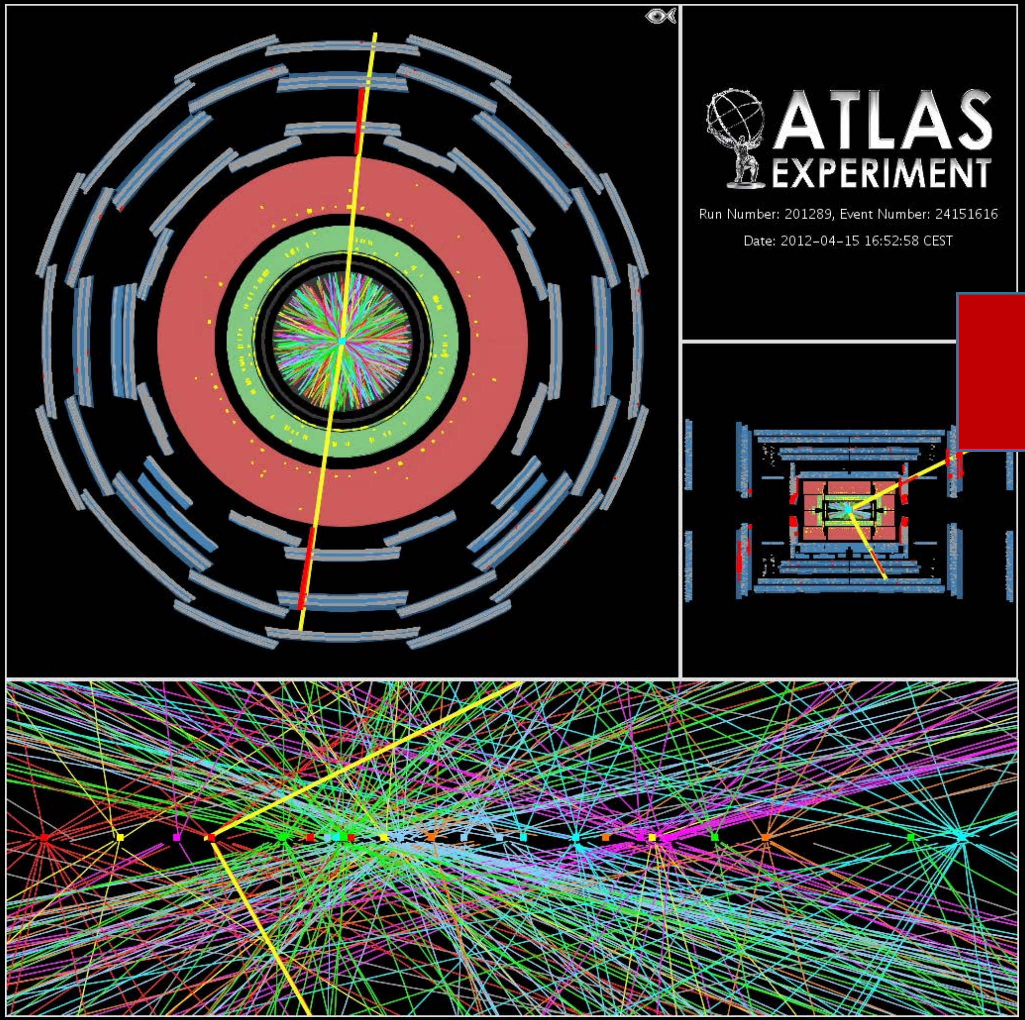
High-Luminosity LHC



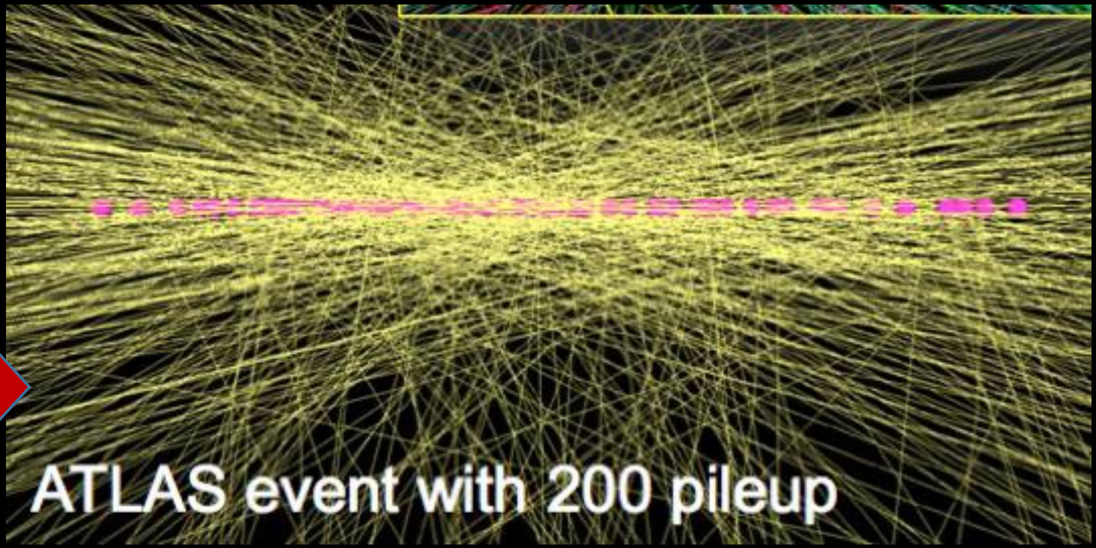
- 190 fb^{-1} only about 5% of the entire programme
- LHC + HL-LHC is the largest pp dataset for the next few decades

The incredible challenge of HL-LHC

Run 2 LHC pileup $<\mu> =$ 37

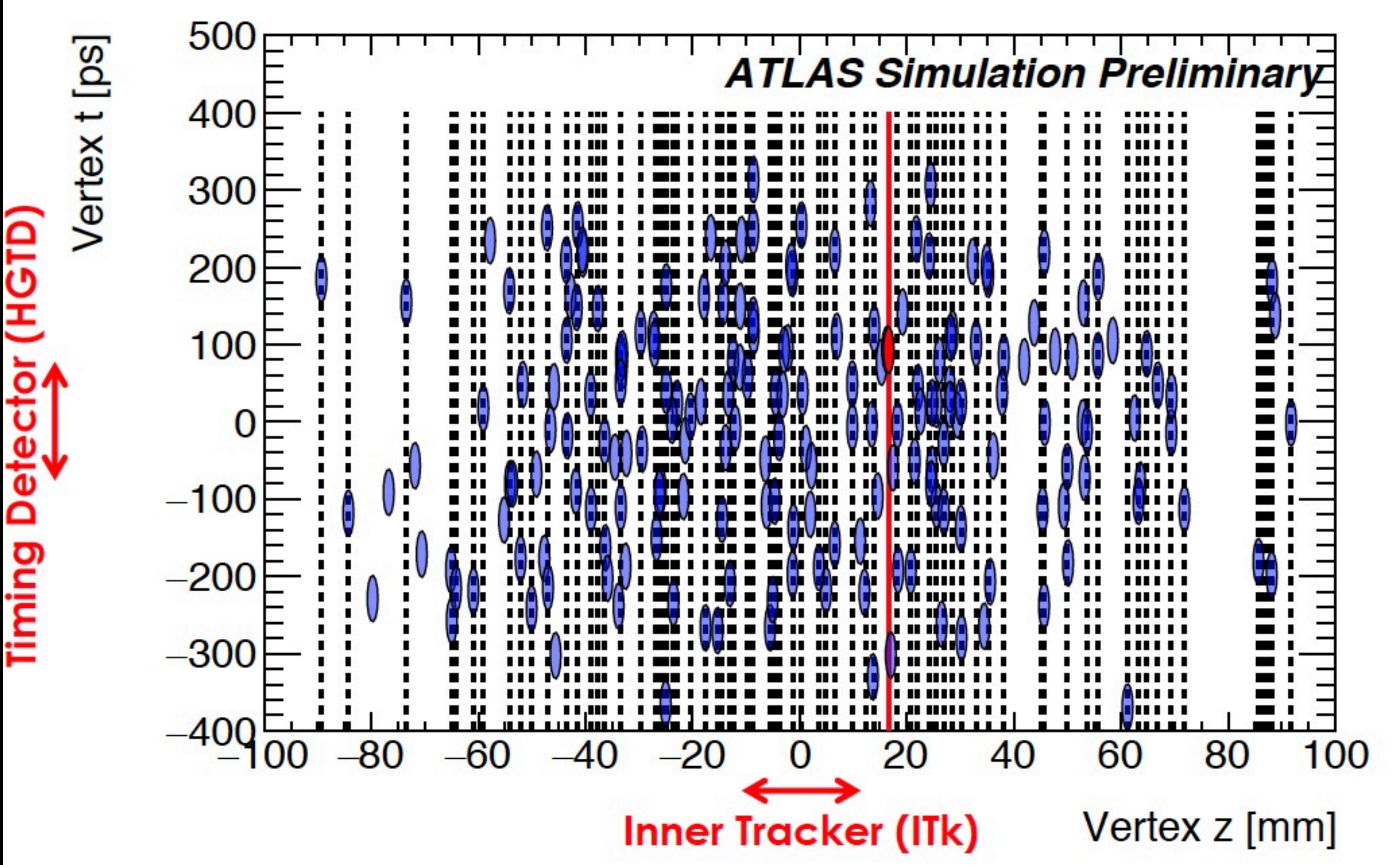


HL-LHC pileup $<\mu> =$ 200



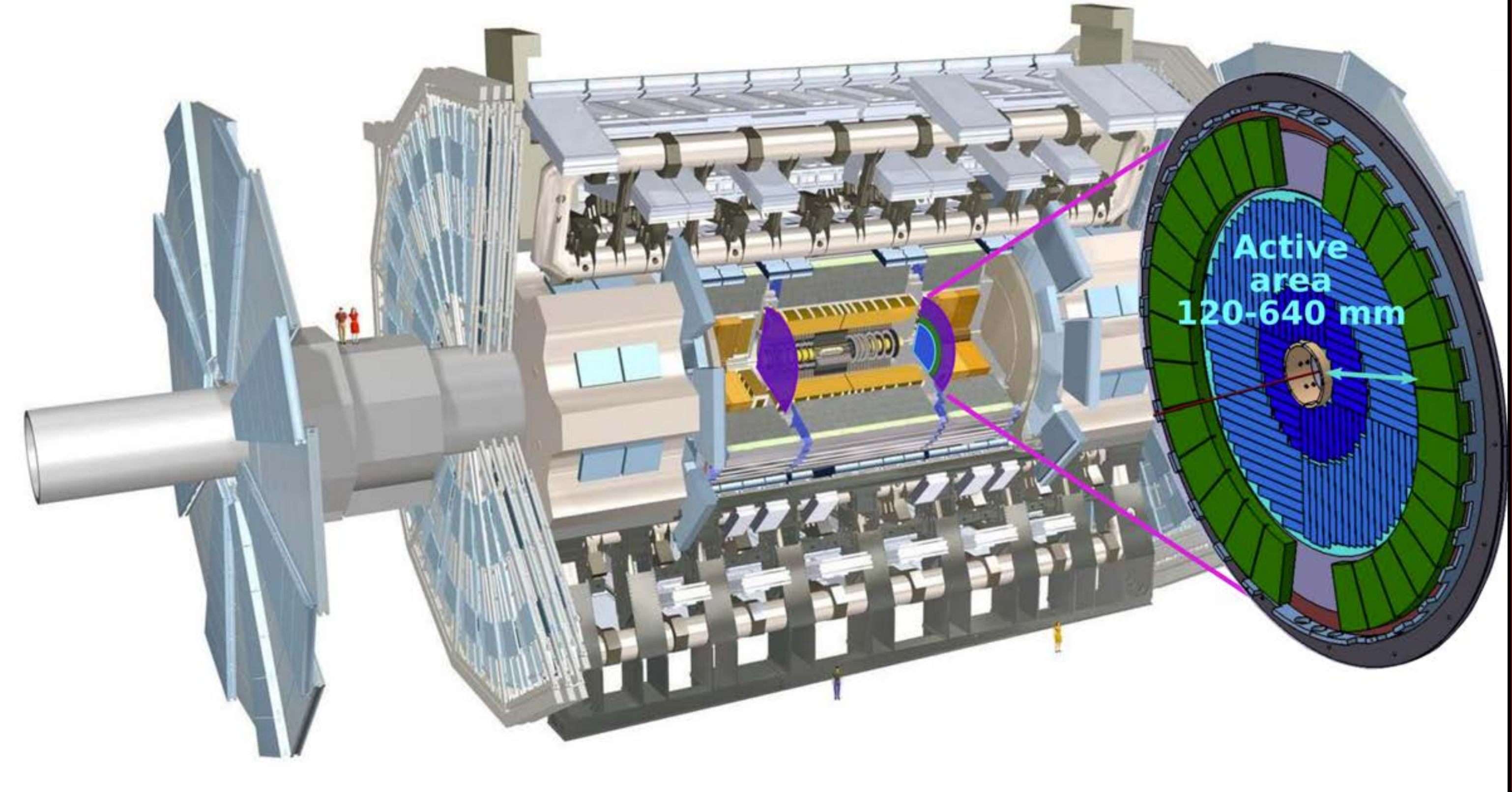
- Radiation levels in the inner most layers of the detectors up to:
  - fluence of 2×10^{16} 1 MeV n_{eq}/cm^2
  - Total Ionizing Dose (TID) ~ 1 Grad

Timing



Exploit the time spread of collisions to reduce pileup contamination

ATLAS High Granularity Timing Detector

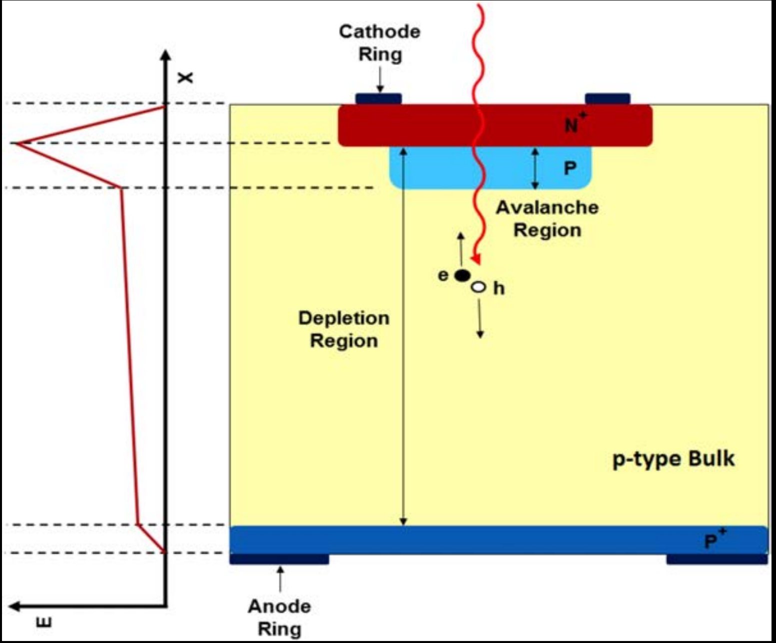


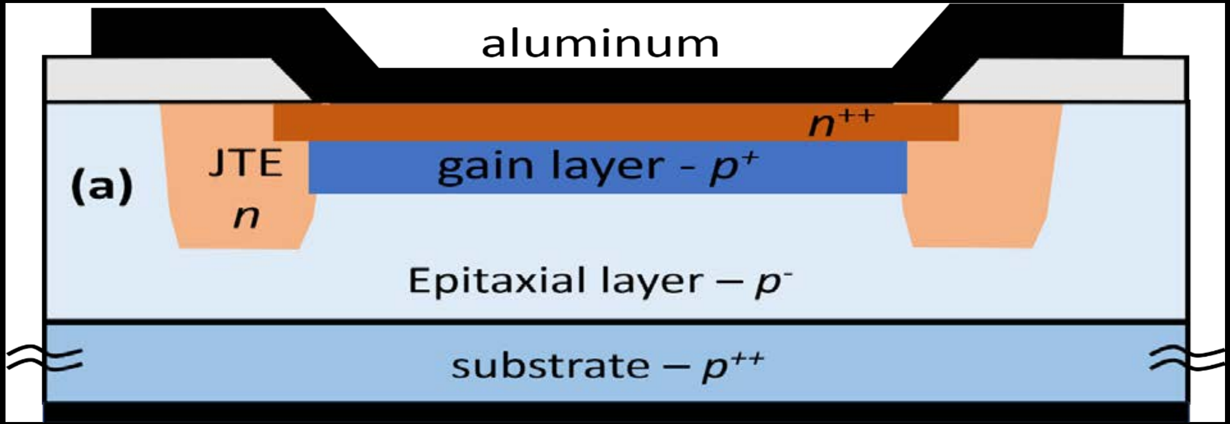
- Low Gain Avalanche Detectors (LGADs) pixel size: 1.3x1.3 mm^2
- Excellent time resolution (30-50 ps/track)
- Radiation-hard (up to 2.5×10^{15} n_{eq}/cm^2 and 1.5 MGy)
- Occupancy< 10%

- 2 double planar layers per endcap providing an average number of hits per track of 2-3
- Pseudorapidity coverage: $2.4<|\eta|<4.0$
- Radial extension: 12 cm < R < 64 cm
- z position: 3.5 m; Thickness in z: 7.5 cm
- Operated at -30 ^{0}C

Timing detectors will also be implemented in CMS

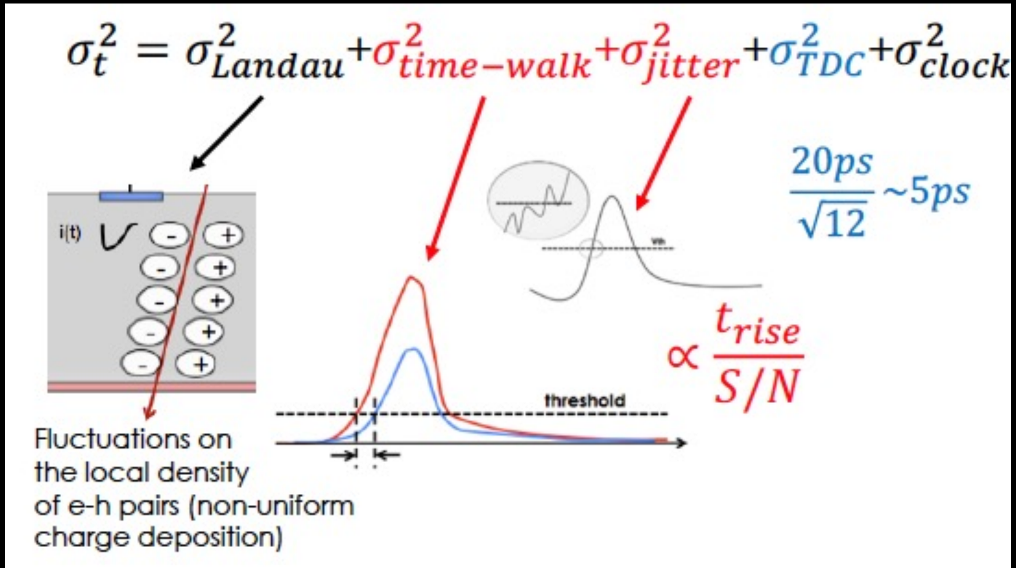
Low Gain Avalanche Diodes



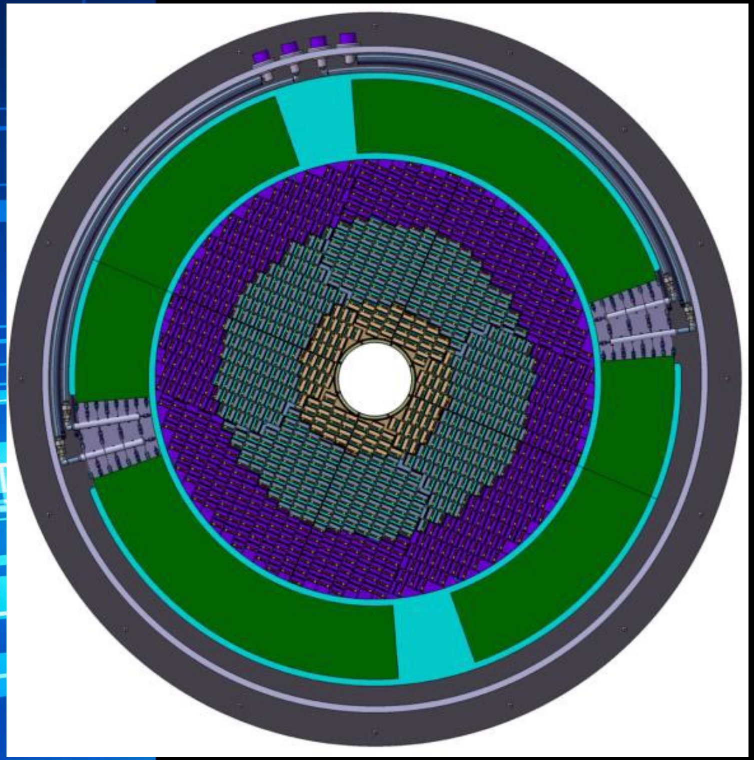


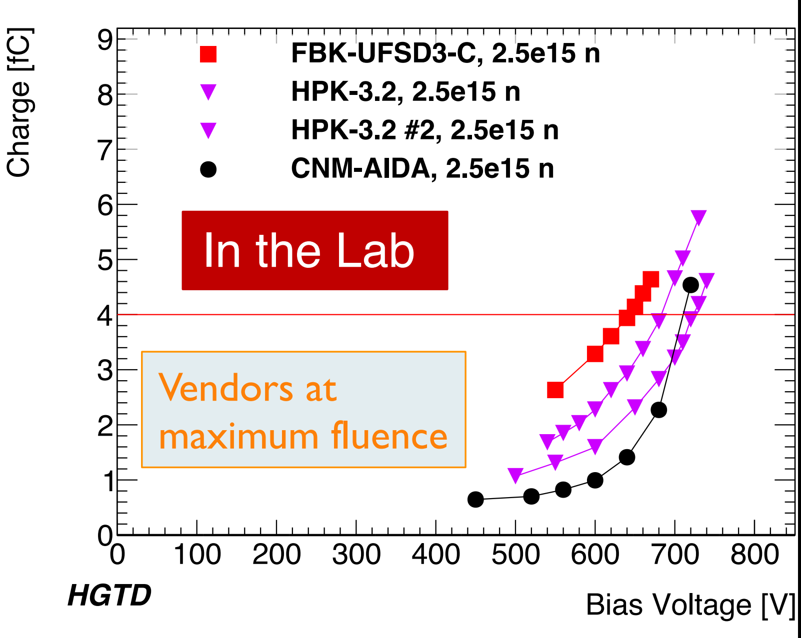
- The Junction Terminating Extension (**JTE**) allows high depletion but limits position resulution

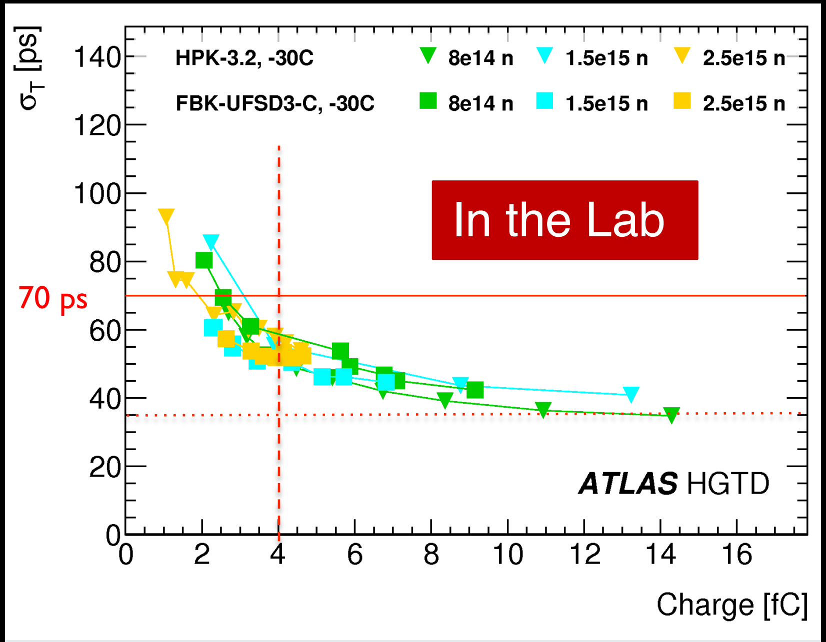
- Timing resolution: 35 - 70 ps/hit
- Gain> 20 decreases to > 8 at the end of lifetime (V_{bias}<800 V)
- Collected charge >4 fC /MIP/hit after 2.5x10[15] n_{eq}/ cm^2
- Prototypes from CNM (Spain), HPK (Japan), BNL (USA), FBK (Italy), IME & NDL (China), T-e2v & Micron (UK)



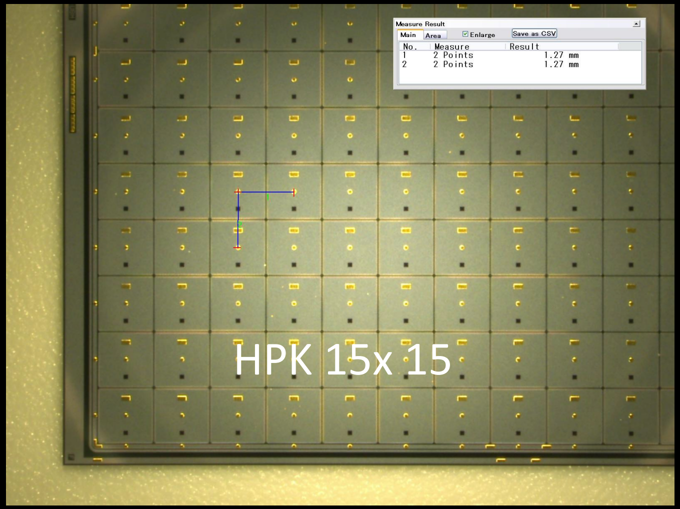
Ultra Fast Silicon Detectors

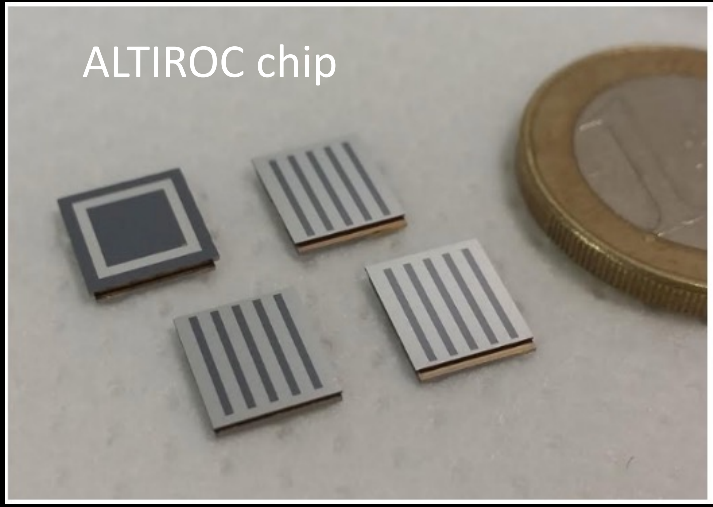




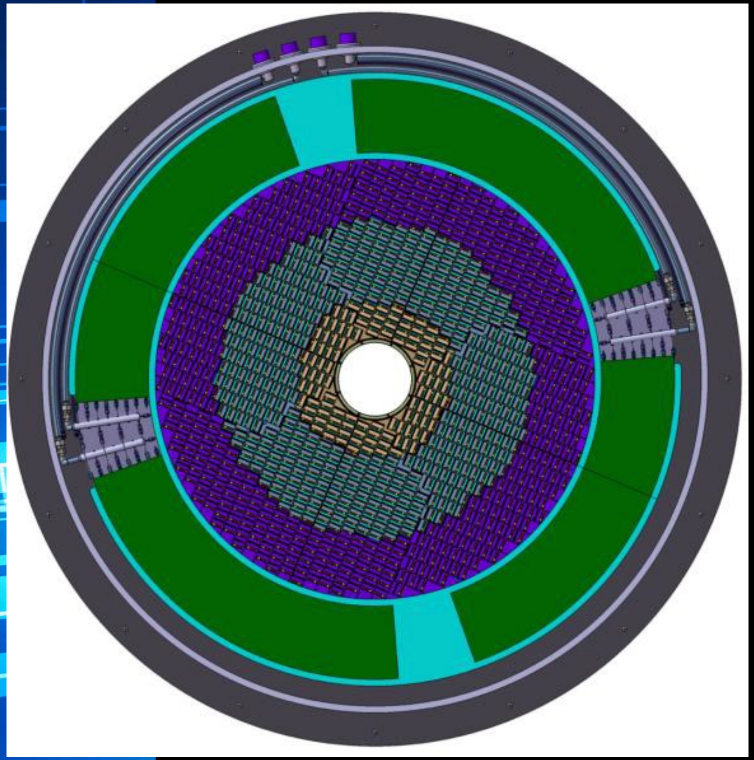


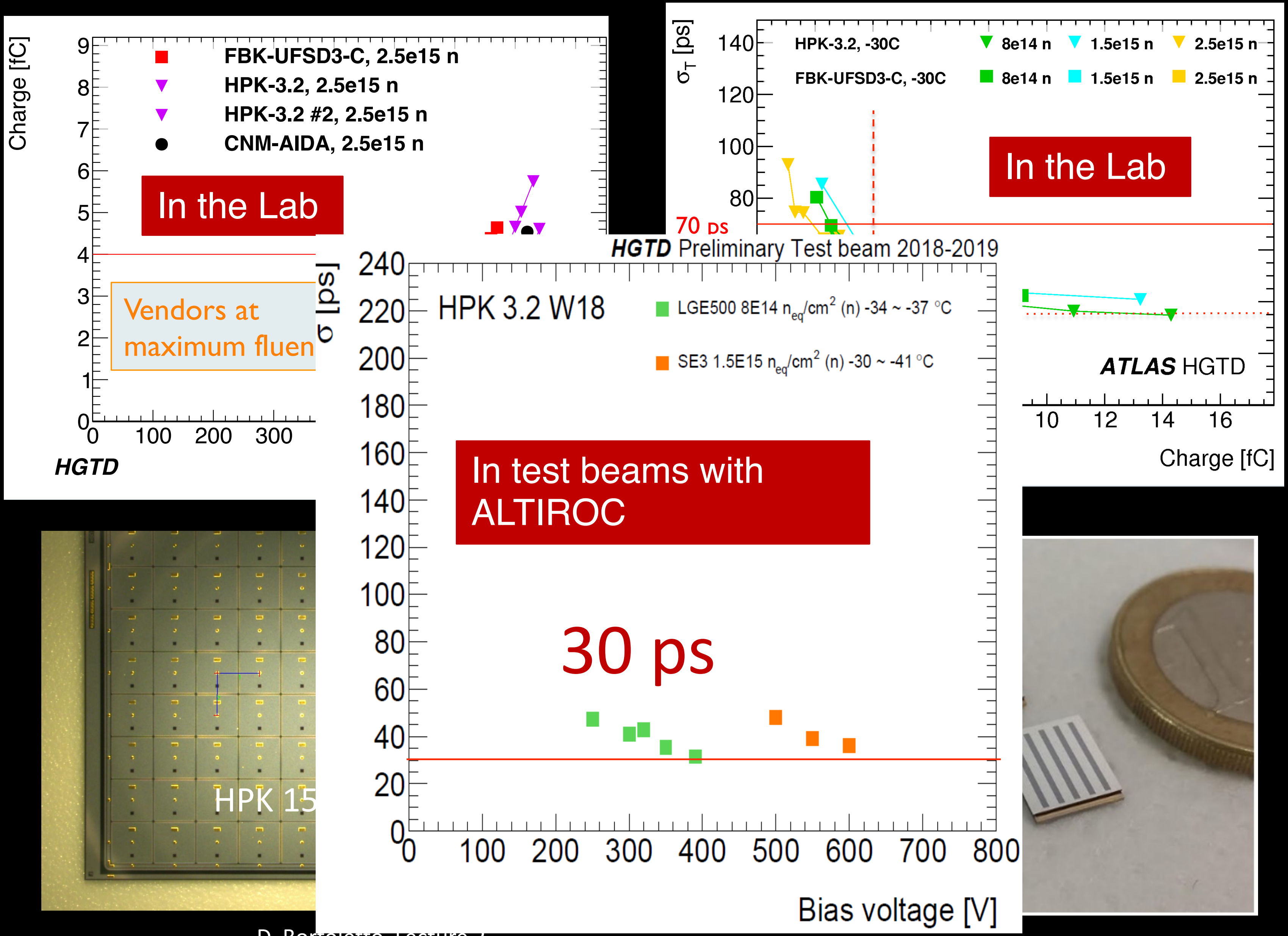
- Inner (12-23 cm) every 1000 fb^{-1}
- Middle (23-47 cm) every 2000 fb^{-1}
- Outer (47-64 cm) never replaced





Ultra Fast Silicon Detectors

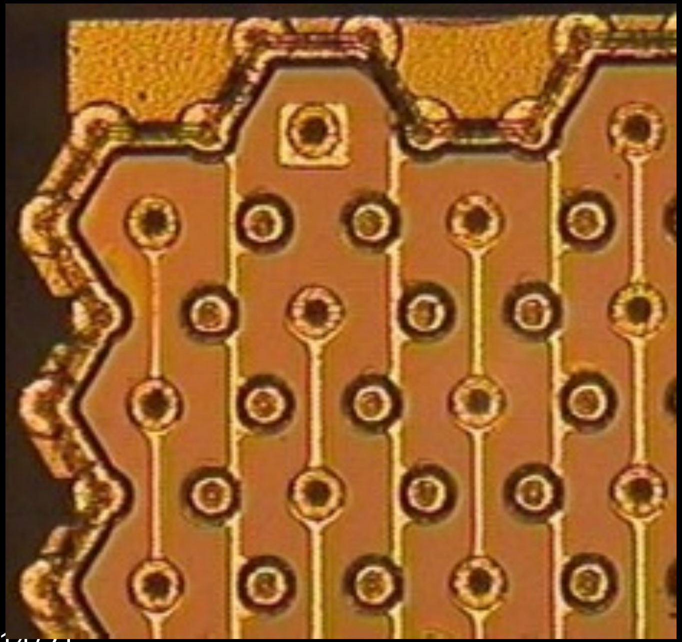


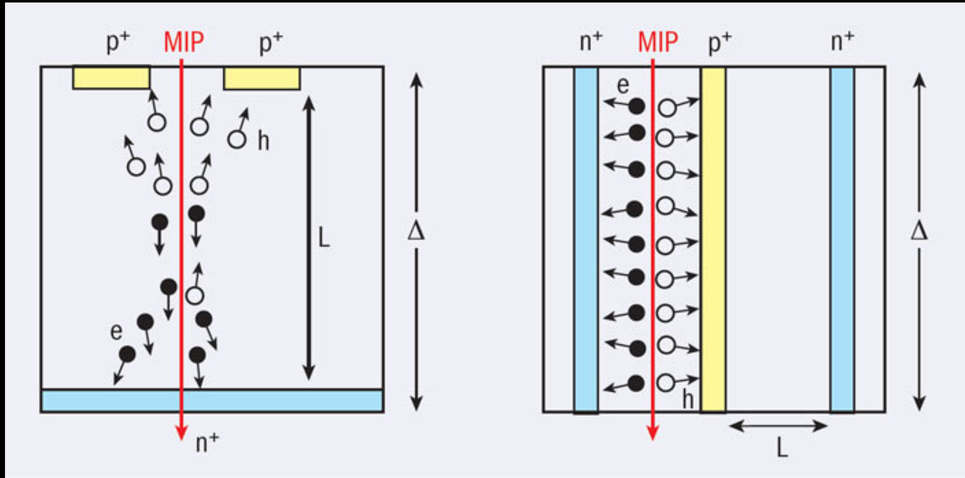


- Inner (12-23 cm) every 1000 fb^{-1}
- Middle (23-47 cm) every 2000 fb^{-1}
- Outer (47-64 cm) never replaced

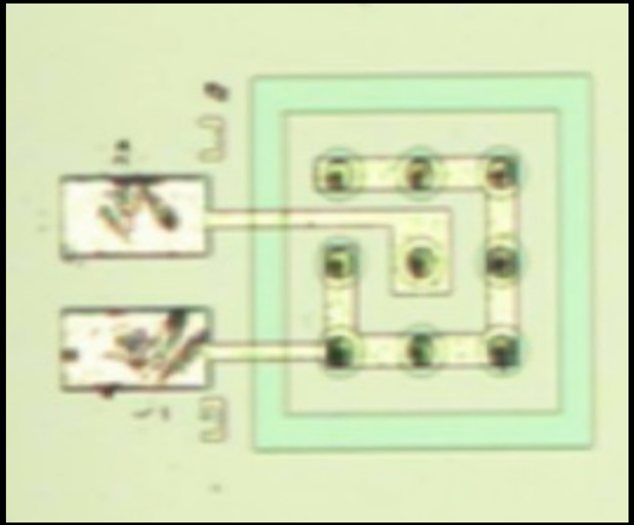
Timing with 3D sensors

- Parker et al. IEEE TNS 58(2) (2011) 404
- Hexagonal geometry L=50 μm, 20 V bias
- Tested under 90Sr β source at RT
- σ_t = 31- 177 ps (according to signal amplitude)
- Limited by RO electronics noise

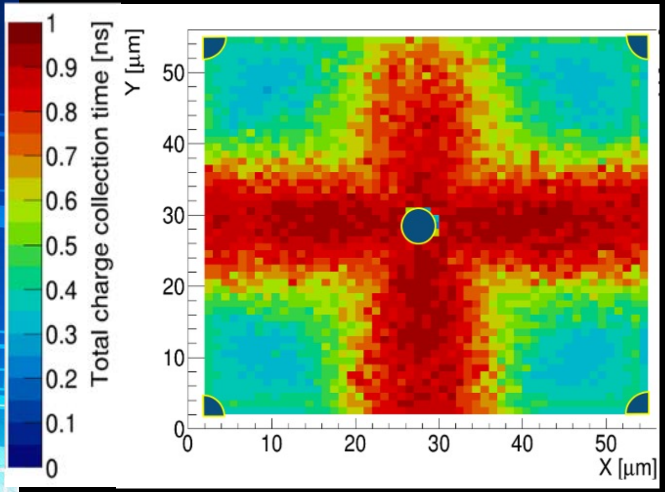




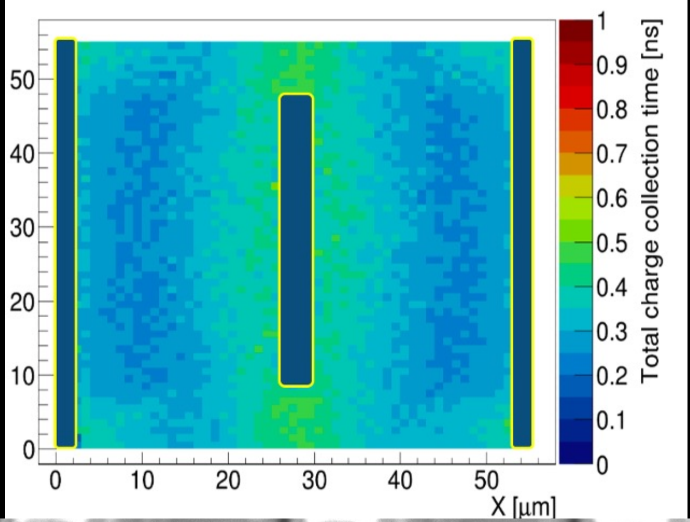
- G. Kramberger et al., NIMA 934 (2019) 26-32
- Squared geometry L=50 μm. Depth = 300 μm. 50 V bias
- Tested under 90Sr β source. Room temperature.
- σ_t = 75 ps



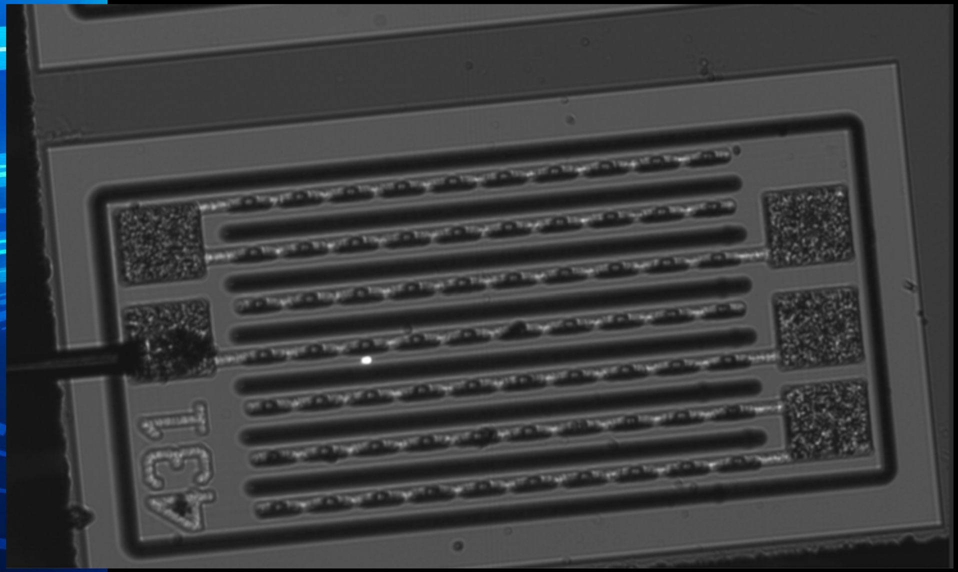
Timing with 3D sensors

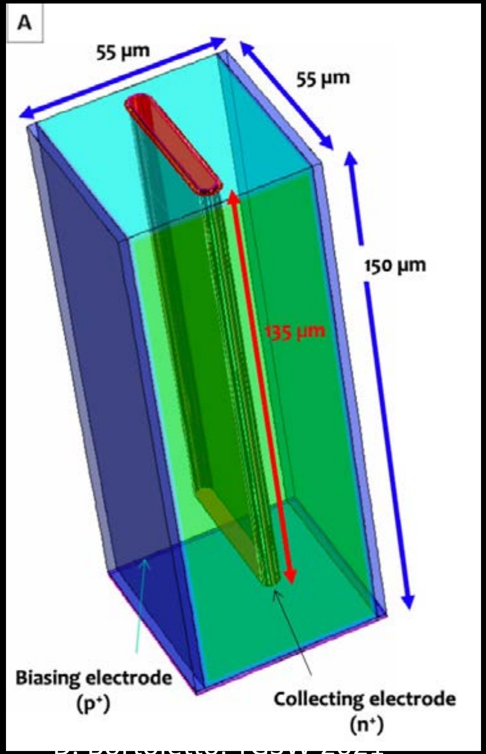


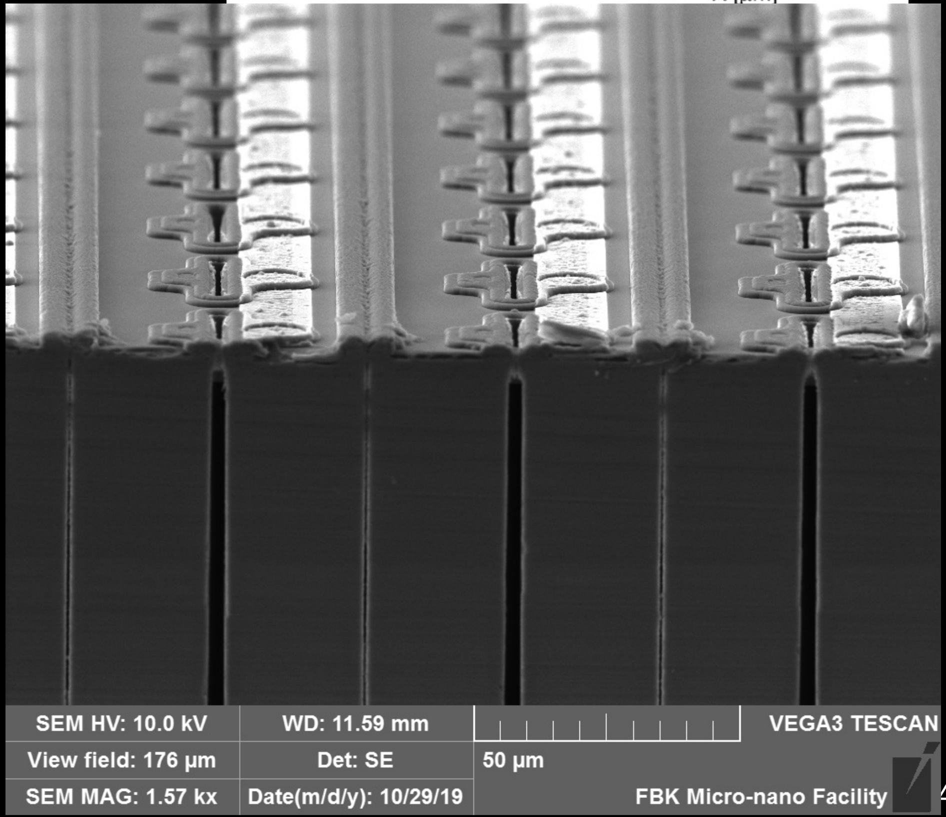
Column geometry (e.g. ATLAS IBL)



TimeSPOT
TIME and SPace real-time Operating Tracker

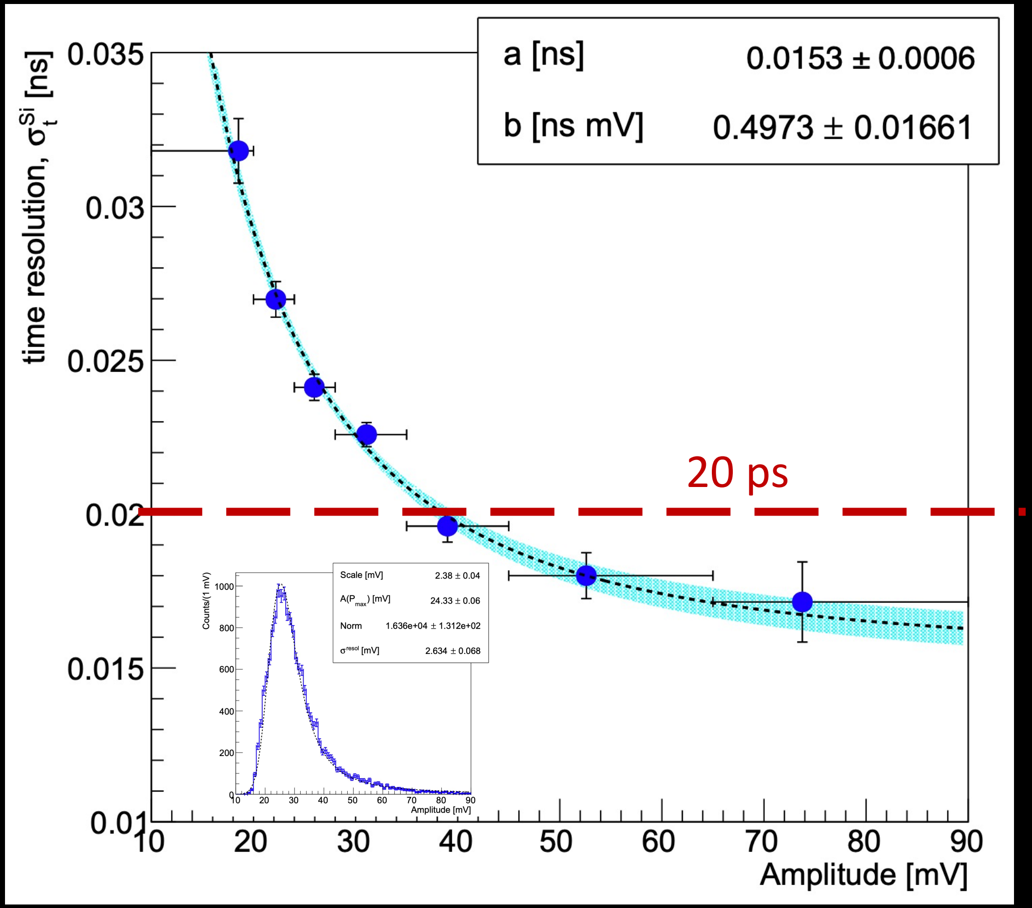


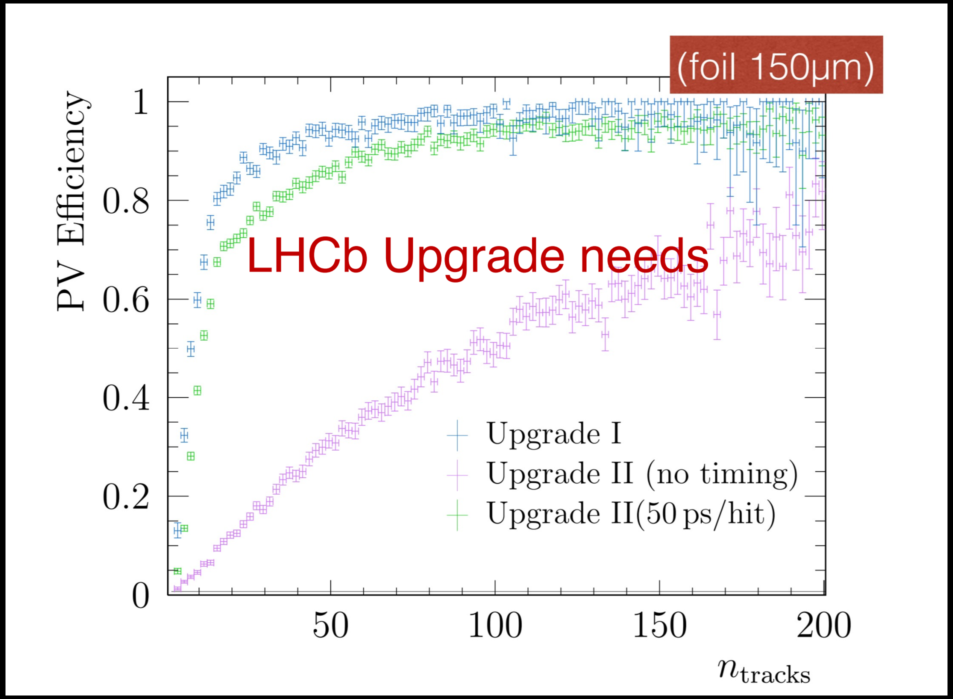




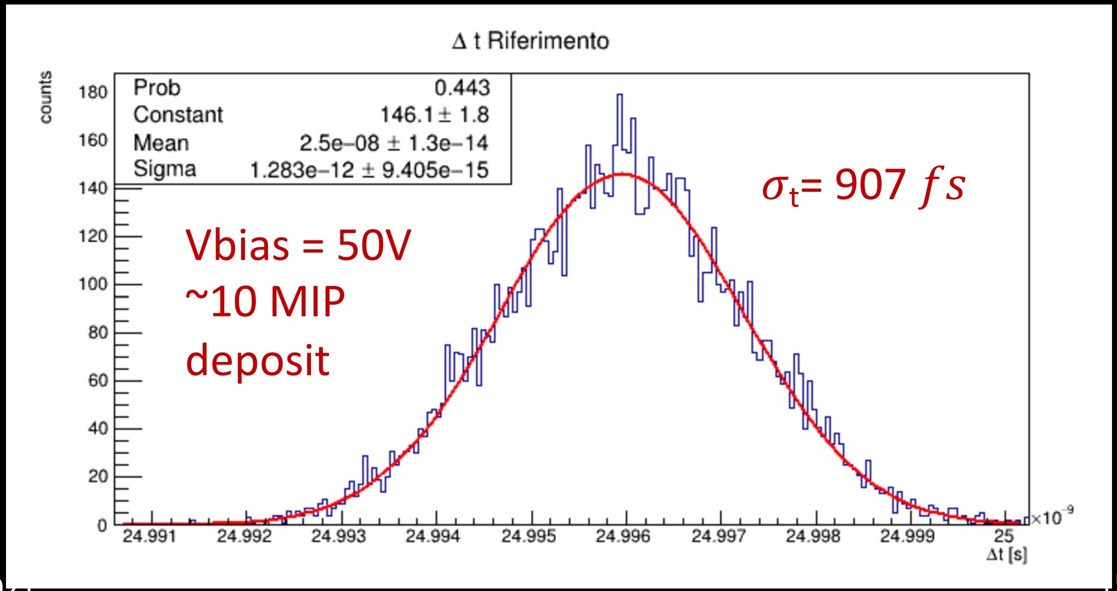
TimeSpot

- Beam test results (270 MeV/c π+ at PSI)
- Fast Front End Electronics (SiGe BJT)



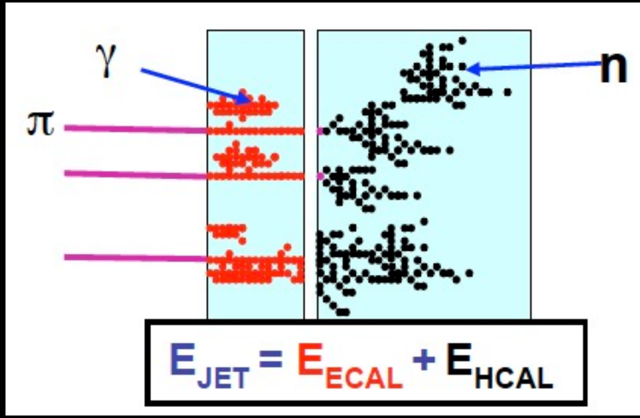


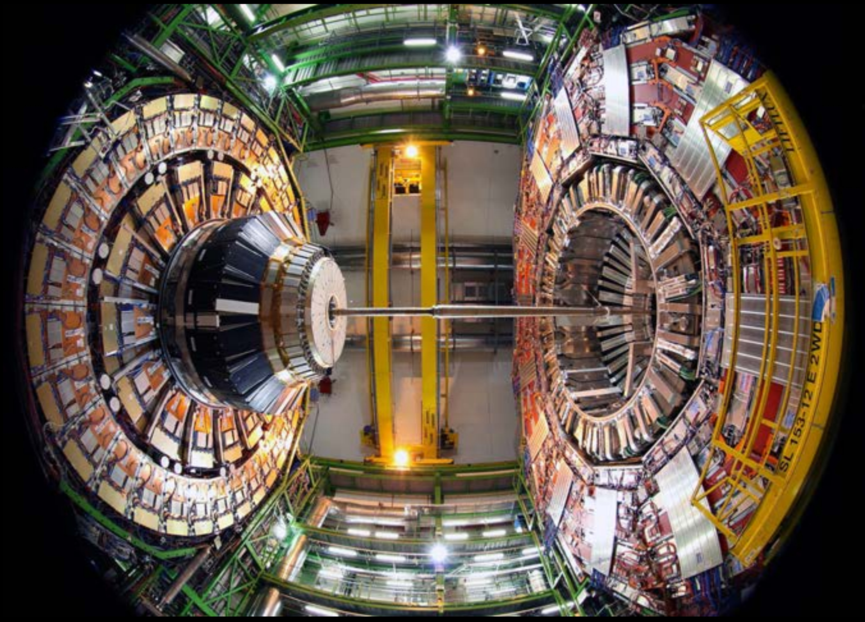
In the lab with infrared laser



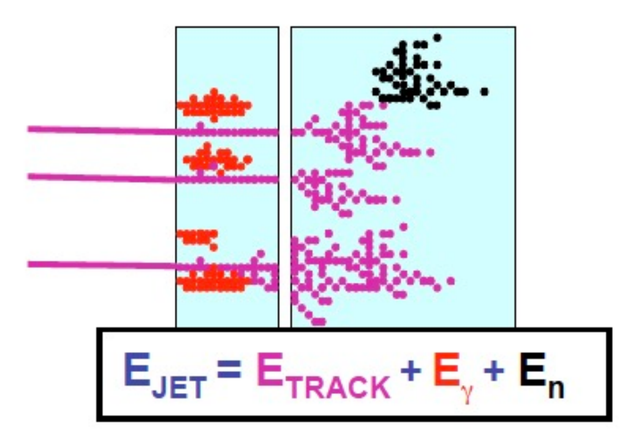
Imaging 5-D Calorimetry

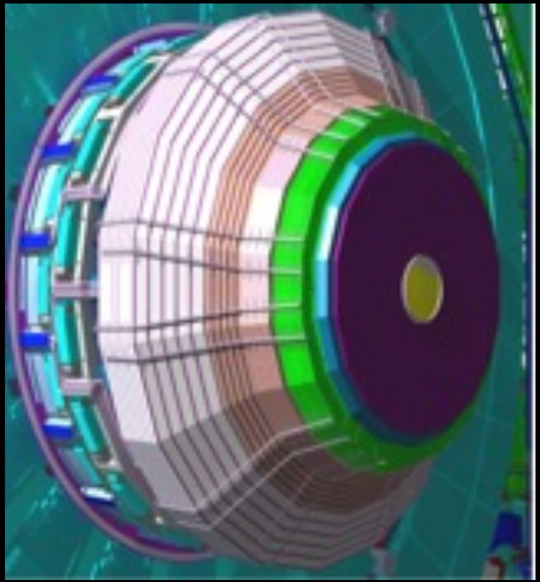
- Standard calorimetry





- Particle Flow calorimetry



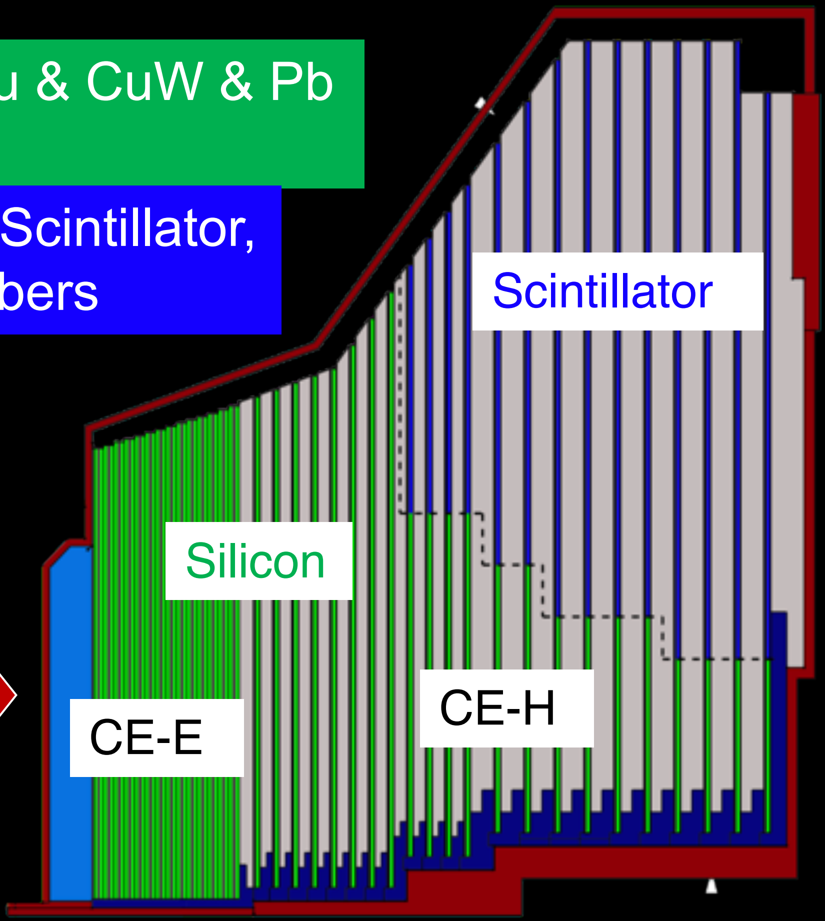


- High Granularity Calorimeter Replacing existing CMS endcap pre-shower, electromagnetic and hadronic calorimeter at HL-LHC
- Extremely challenging:
  - Fluence up to 10^{16} n/cm^2 Dose up to 200 Mrad
  - -30^{o}C

CMS High Granularity CALorimeter

CE-E: Si, Cu & CuW & Pb absorbers

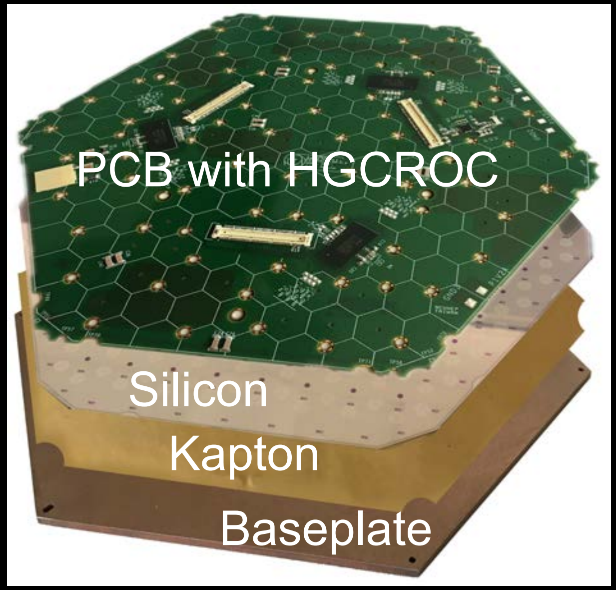
CE-H: Si & Scintillator, Steel absorbers

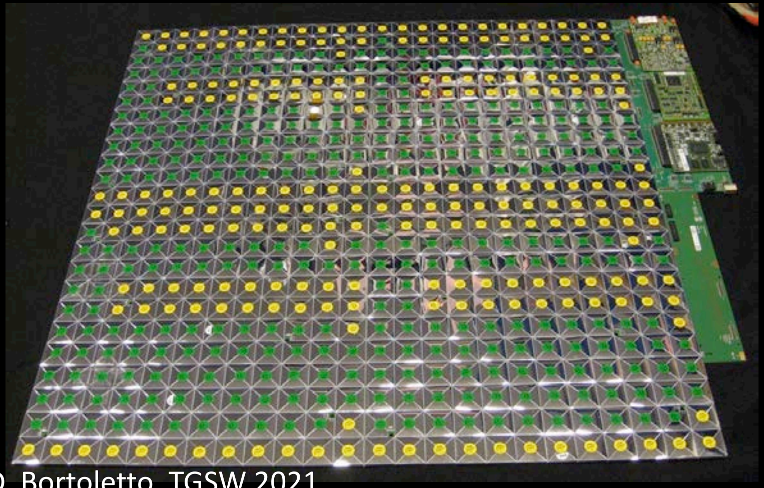


R&D
ILC

- Silicon: 620 m^2, 30K modules, 6M channels, 0.5/1 cm^2 cell size
- Scintillator: 400 m^2 , 4K boards, 240k channels, 4-30 cm^2 size

Silicon sampling calorimeter





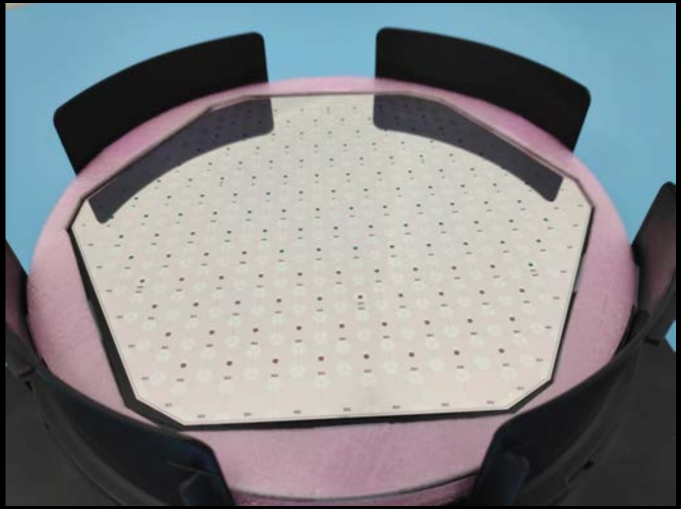
Scintillator tiles with on-tile SiPM readout

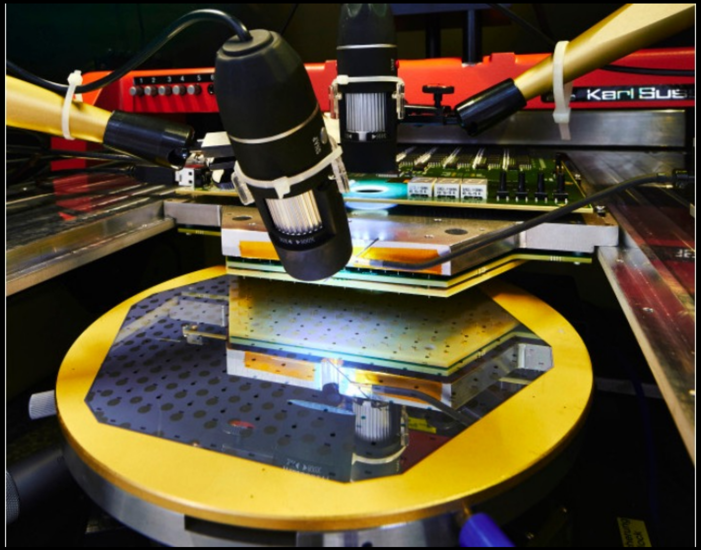
- HGCROC electronics both for SiPM and silicon (OMEGA)
  - Measures charge and and time (TOA)
- Trigger data from ASICs fed through concentrators to the back-end system

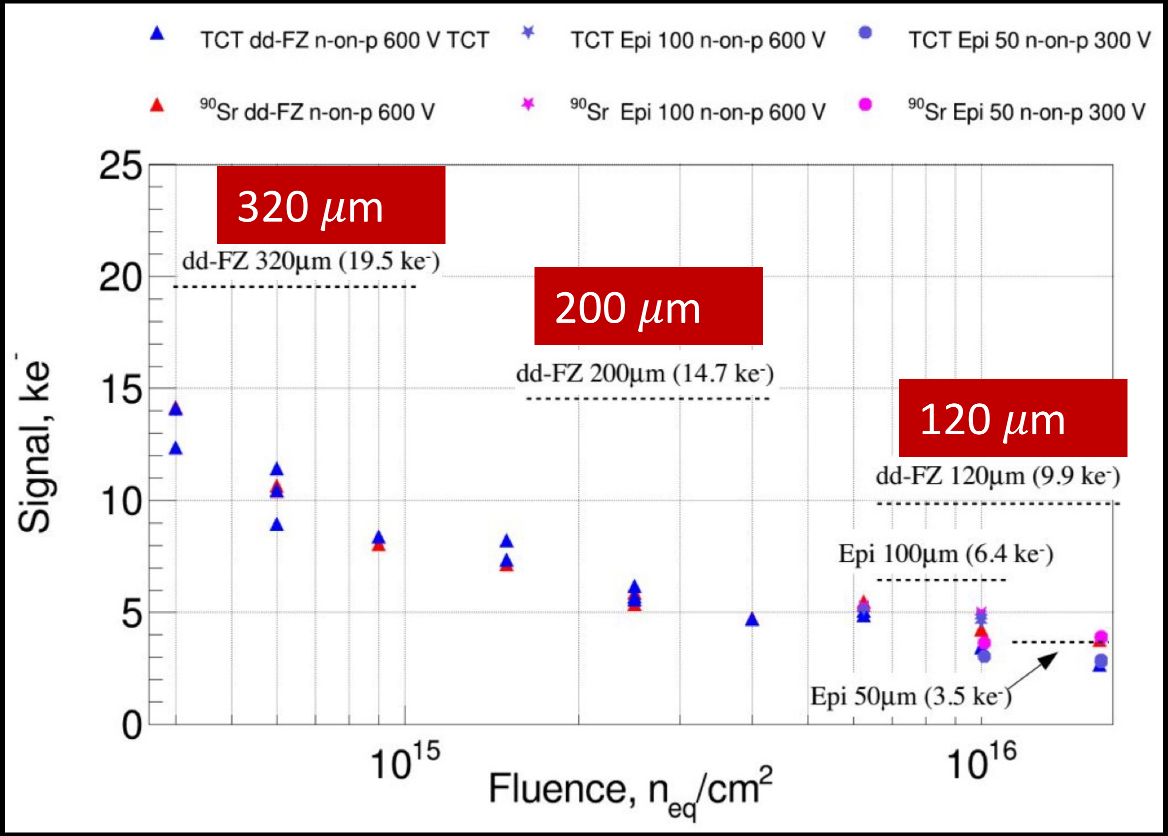
ILC
CLIC, CepC
FCC

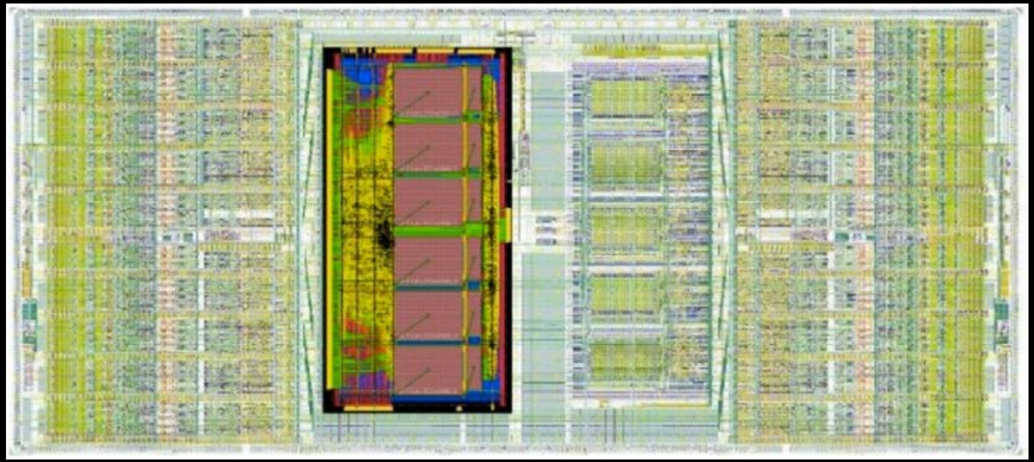
CMS HGCAL

- 8" prototype sensor (HPK) p-type silicon





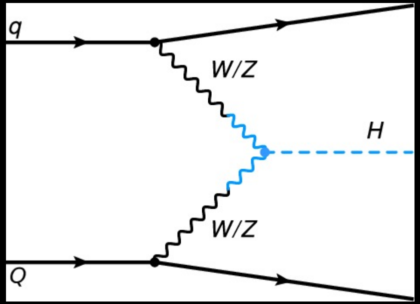




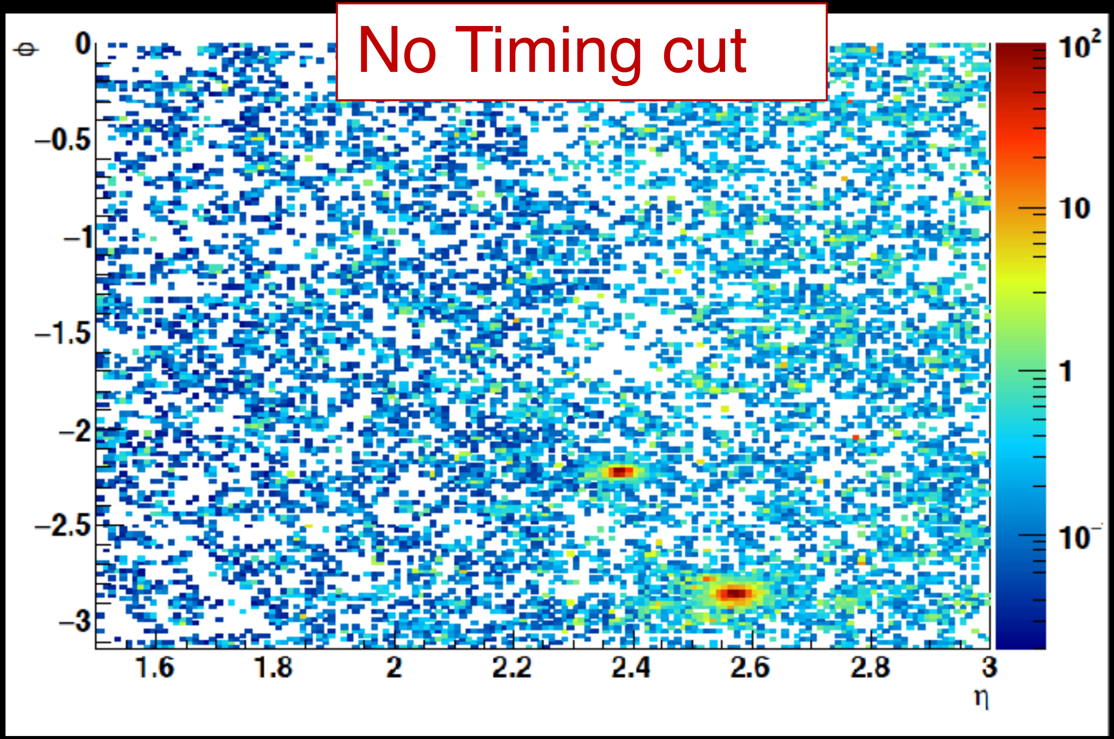
HGCAL FE electronics requirements:

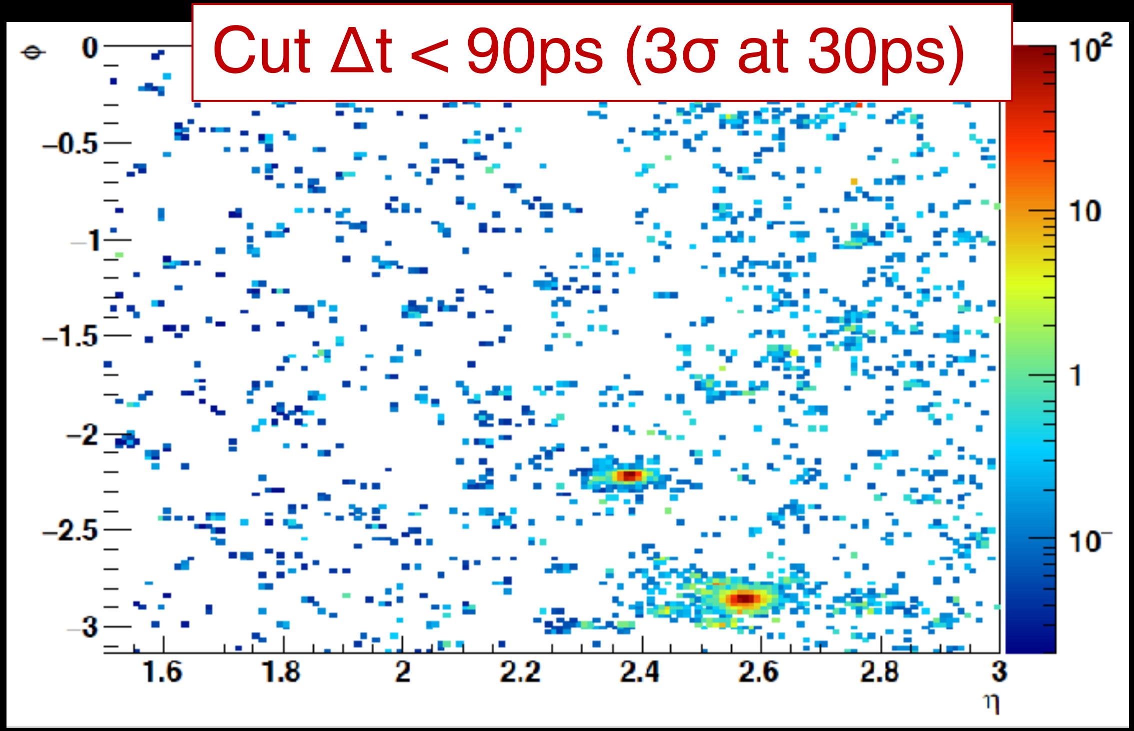
- ***Low noise*** (<2500e)
- ***high dynamic range*** (0.2fC -10pC)
- ***Timing to tens of picoseconds***.
- ***Radiation tolerant***
- ***<20mW*** per channel

HGCAL 5D Power



Vector Boson Fusion (H→γγ) event with one photon and one VBF jet in the same quadrant

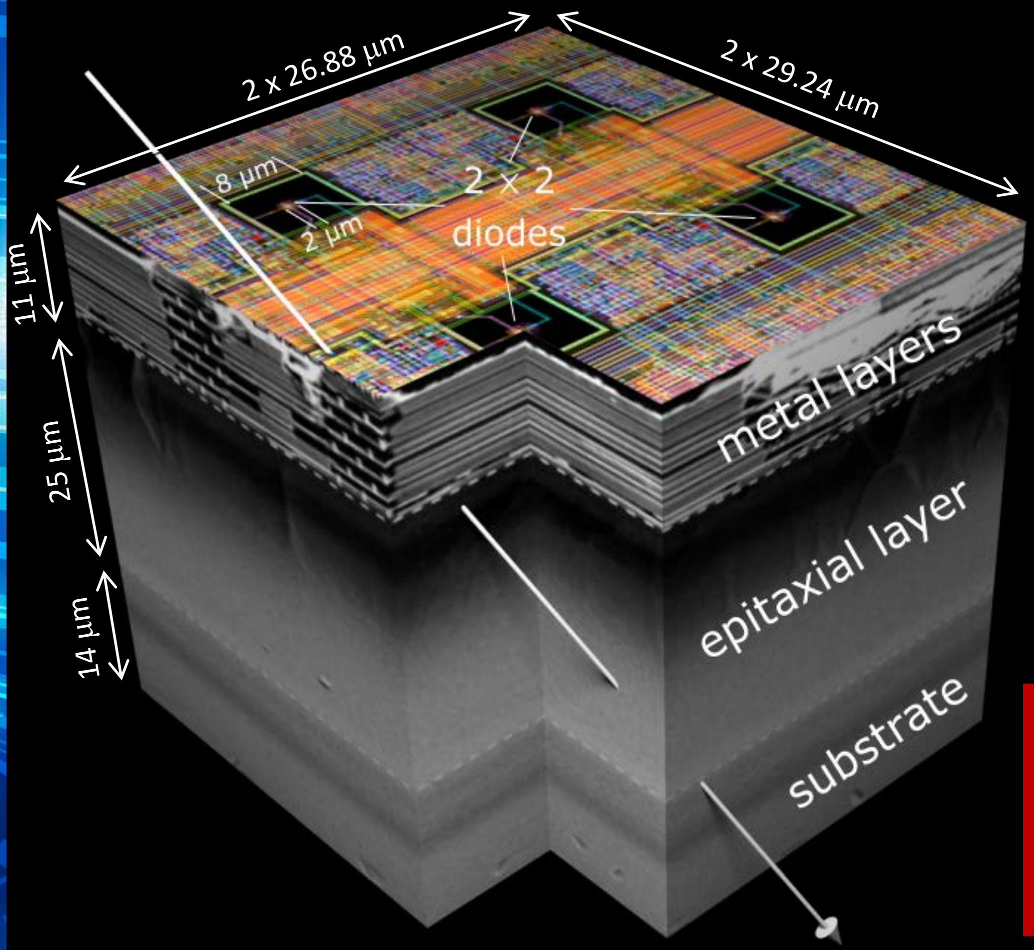




- Cells with Q > 12 fC projected to the front face of the endcap calorimeter.
- Identify high-energy clusters, then make timing cut to retain hits of interest

ALICE ITS

- Based on the Alpide chip in TJ 180 nm

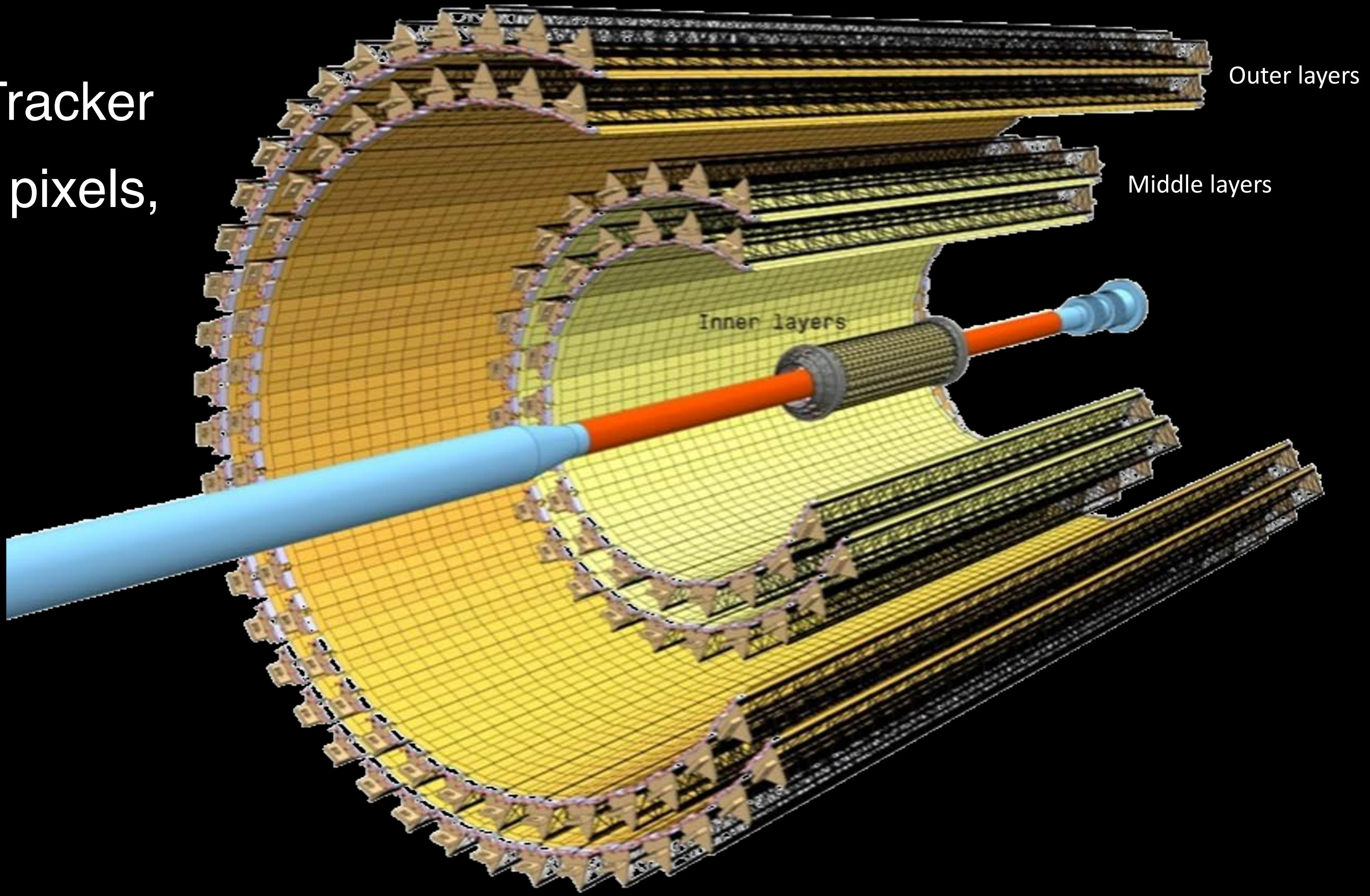


- Tremendous progress in CMOS pixel designs
  - Pixel pitch: 29 μm x 27 μm
  - Power < 40 mW/cm^2
  - Integration time <10 μs

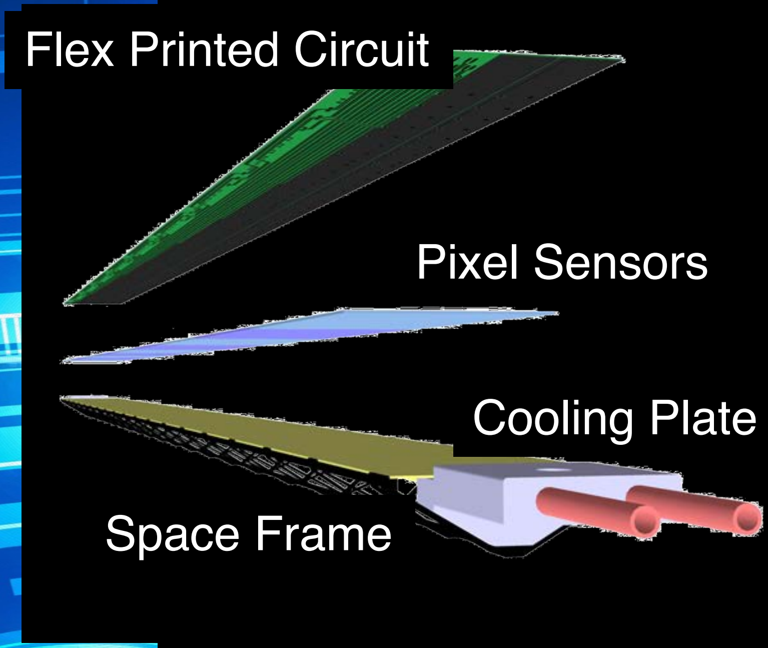
All monolithic silicon pixel tracking becoming possible

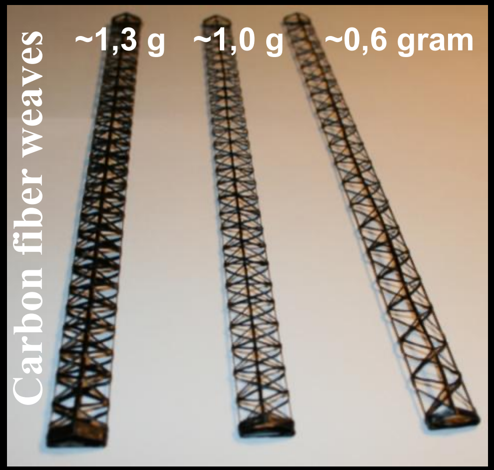
Material reduction

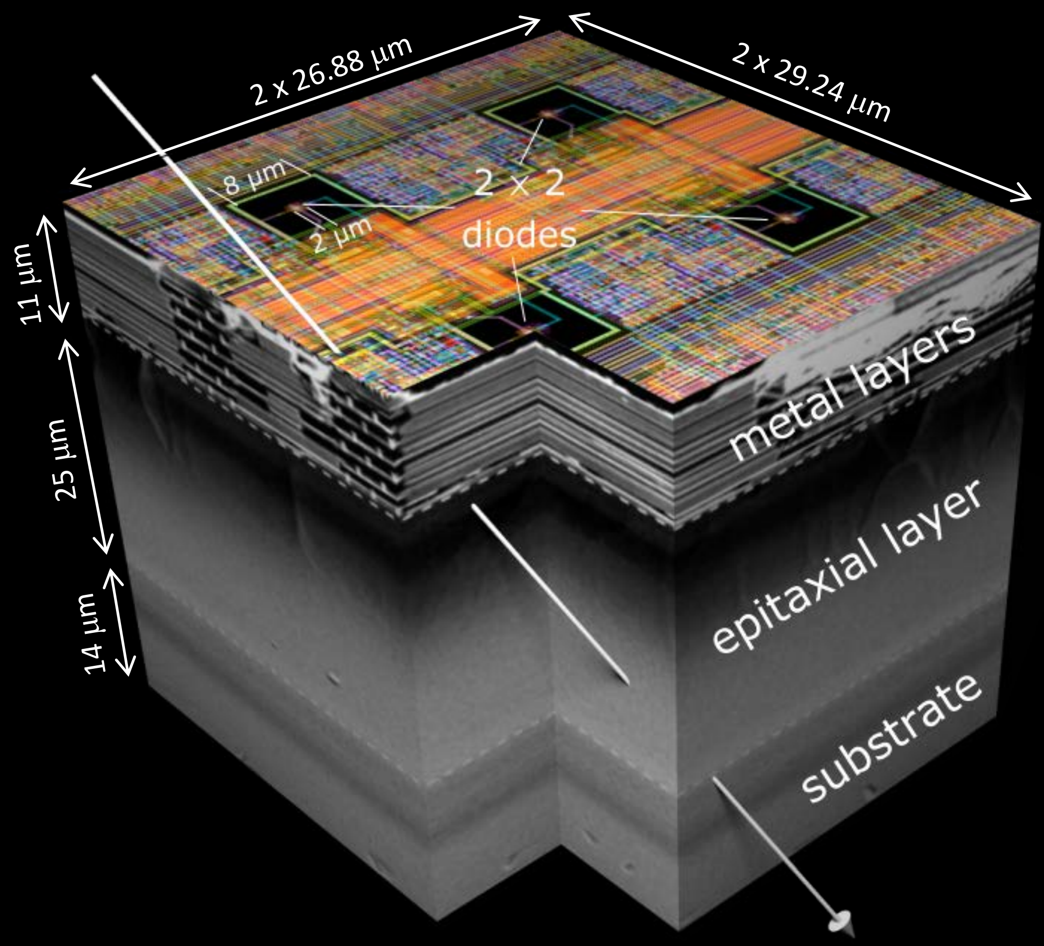
- ALICE MAPS-CMOS Tracker
  - –7-layers, 12.5 Giga pixels, 10m²
  - –R coverage: 23 – 400 mm
- Material/layer:
  - –0.3% X_0 (IB)
  - –1.0% X_0 (OB)



CMOS Pixel Chips & Material



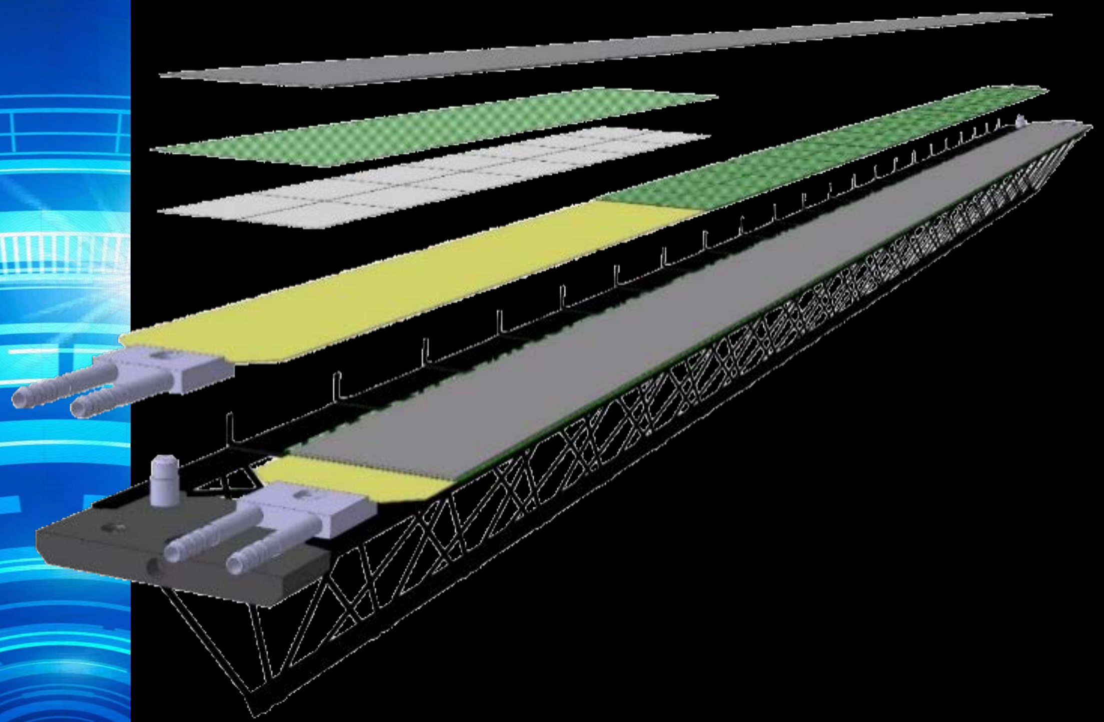




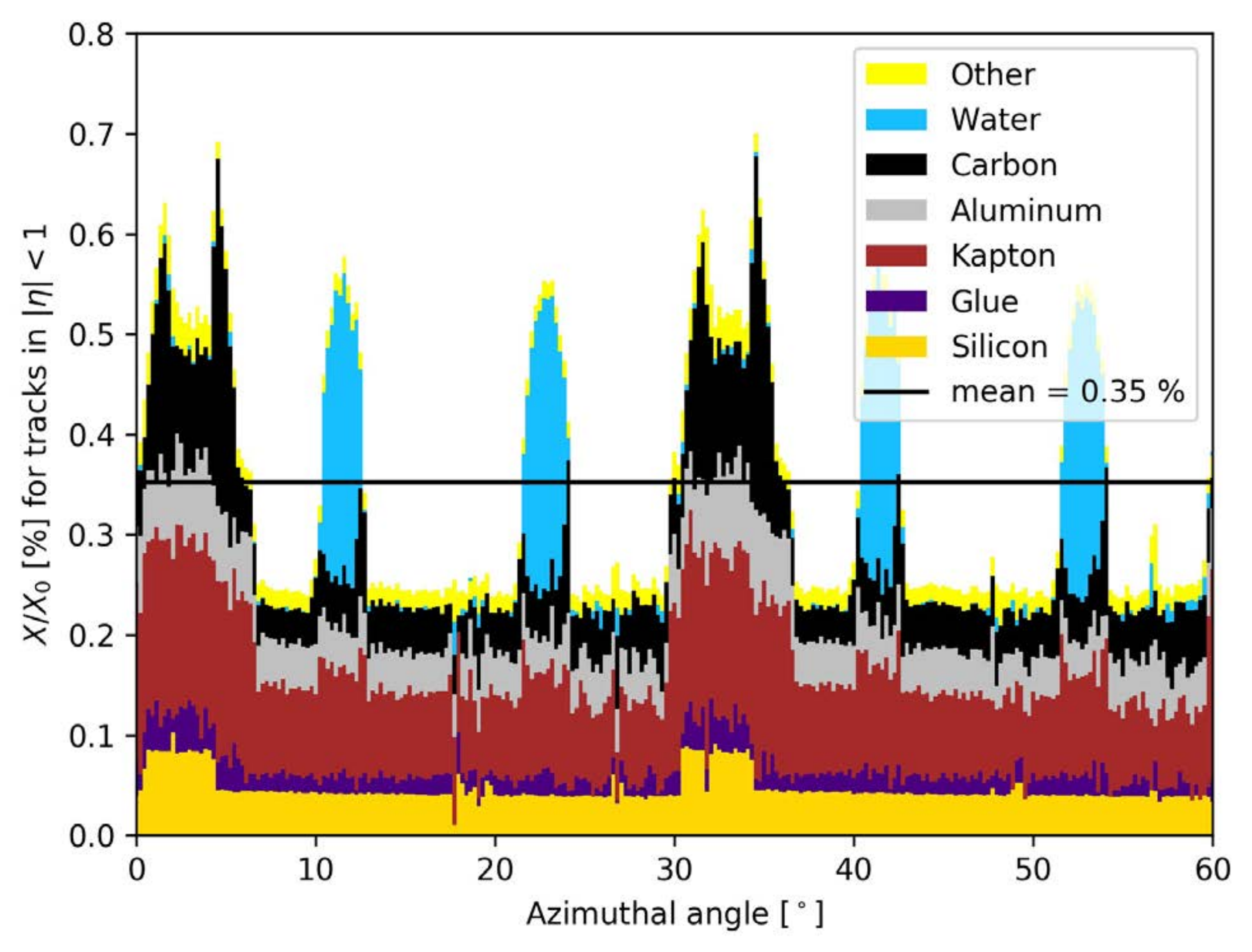
ALPIDE (ALICE)

Depleted CMOS Sensors

Minimize the material budget



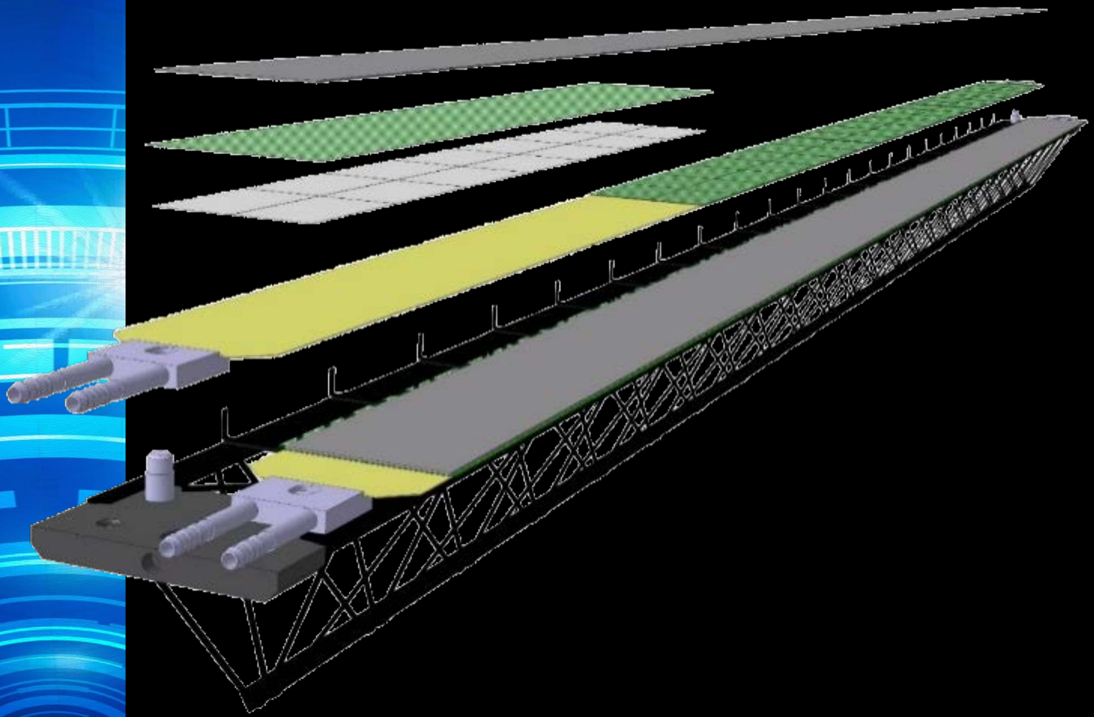
Overall Material Budget



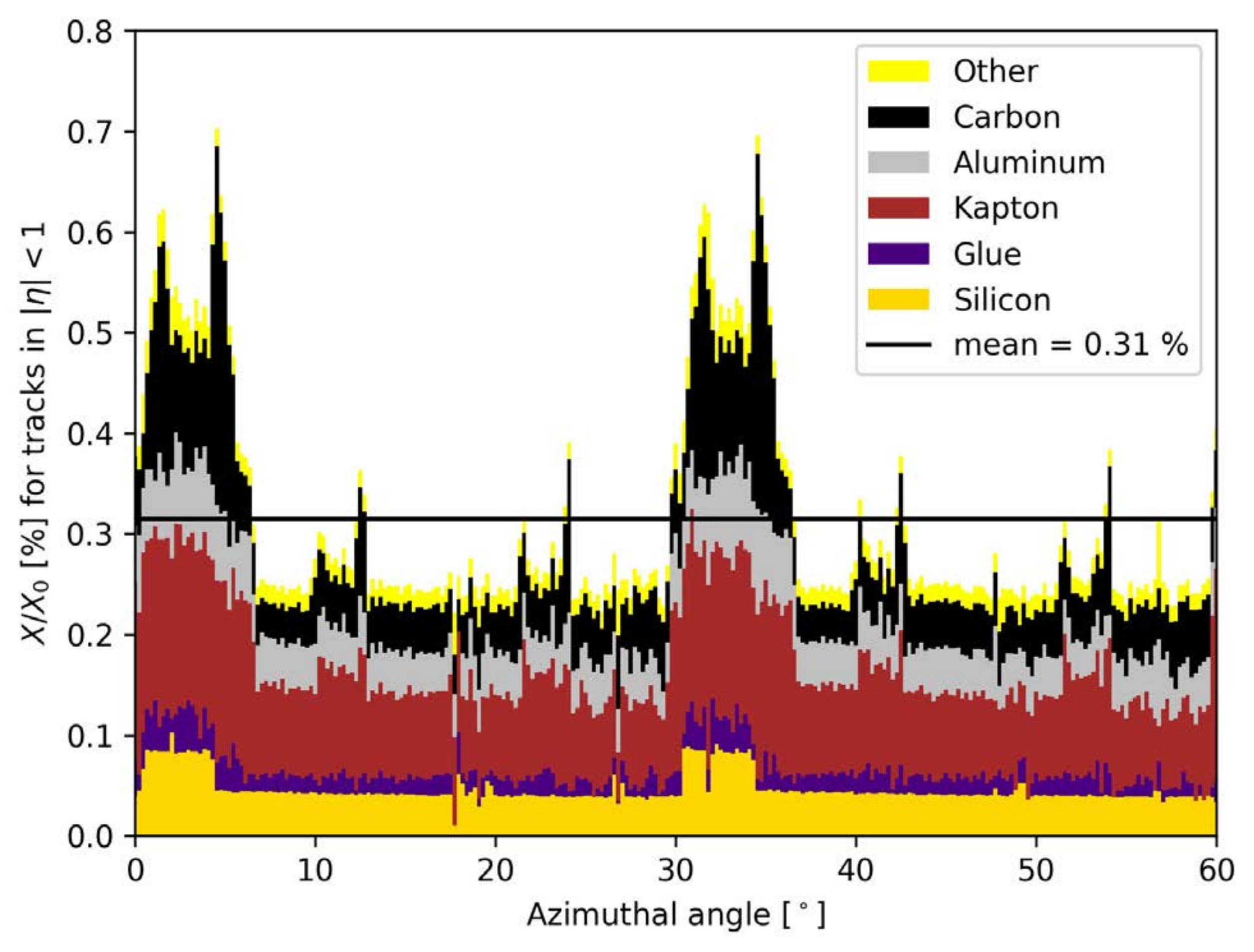
Luciano Musa, Bergen, August 2019: https://indico.cern.ch/event/836343/

Depleted CMOS Sensors

Minimize the material budget

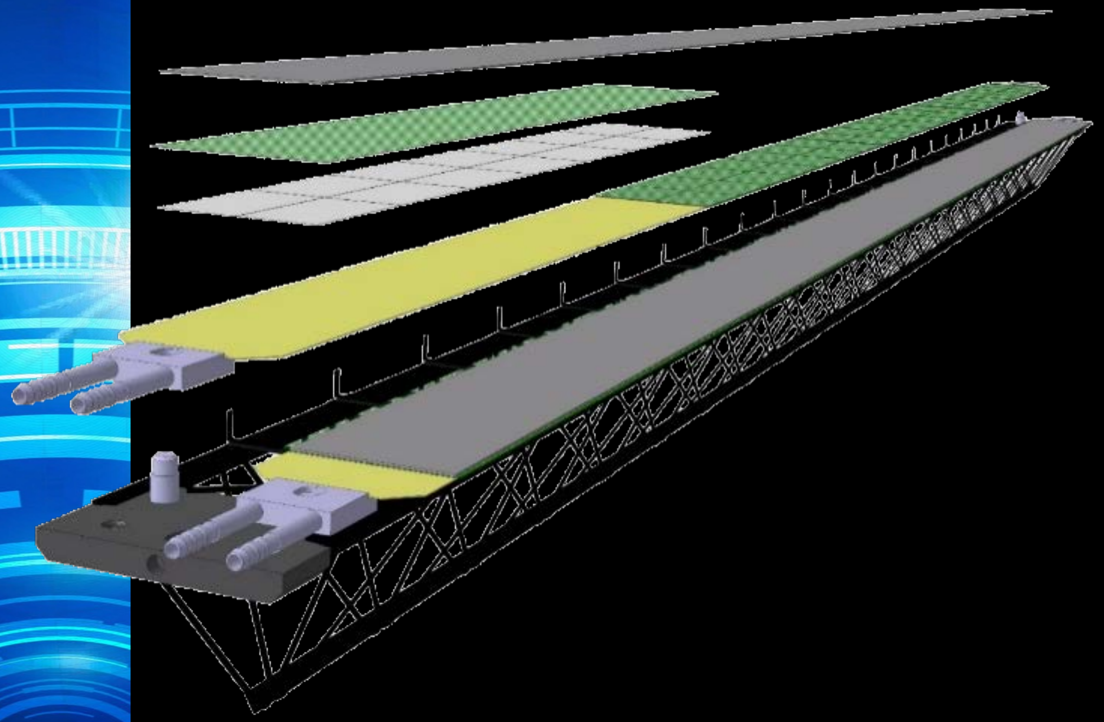


Reduce Power (< 20 mW/cm^2) and Remove Cooling

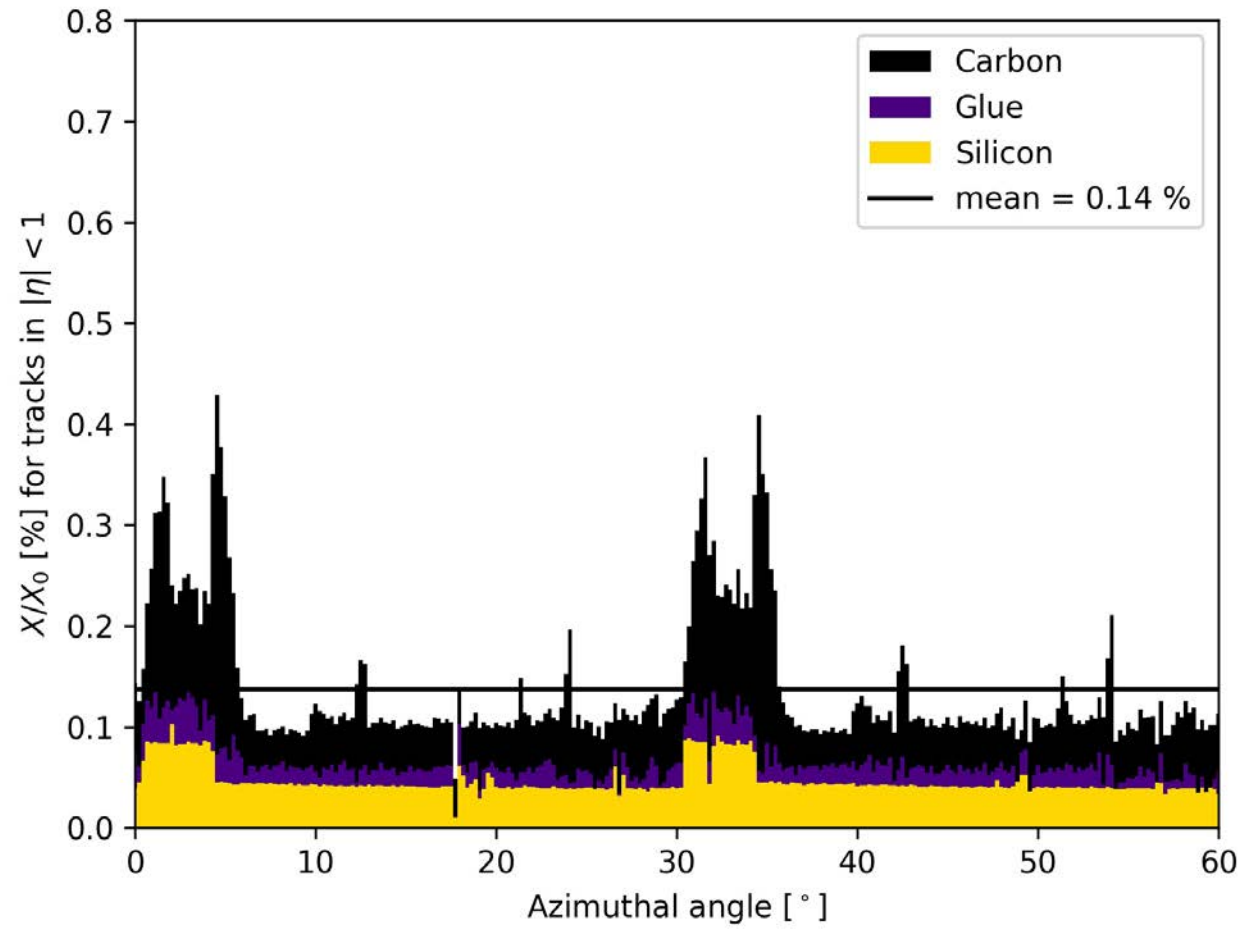


Depleted CMOS Sensors

Minimize the material budget

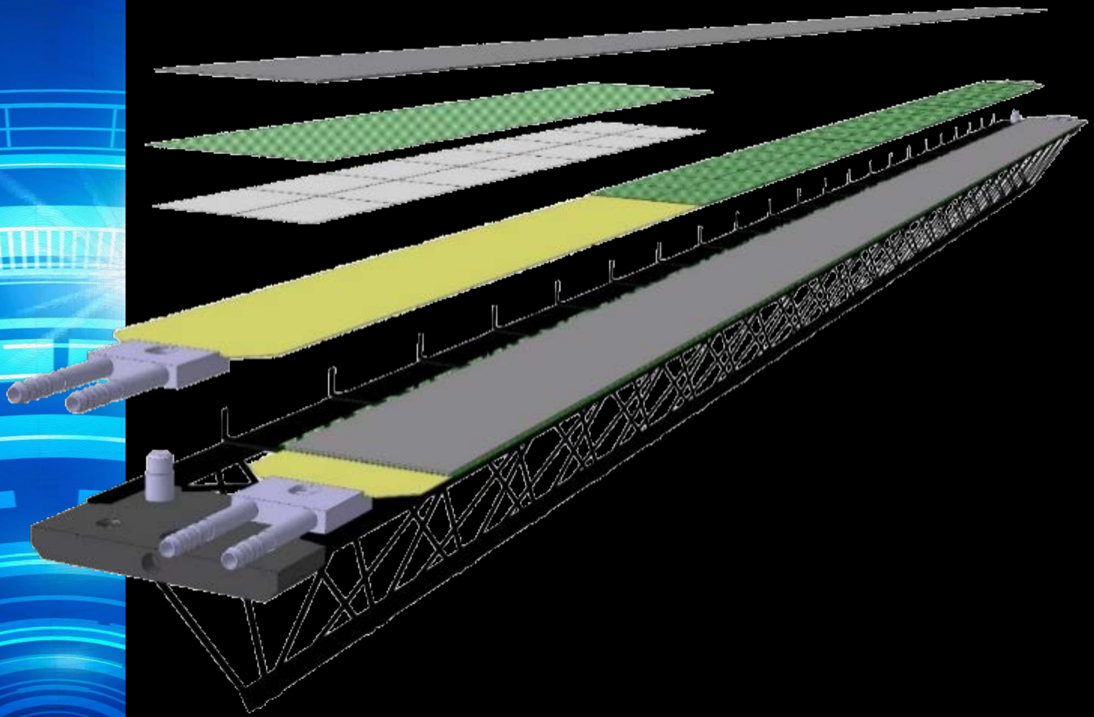


Remove PCB and integrate components on chip

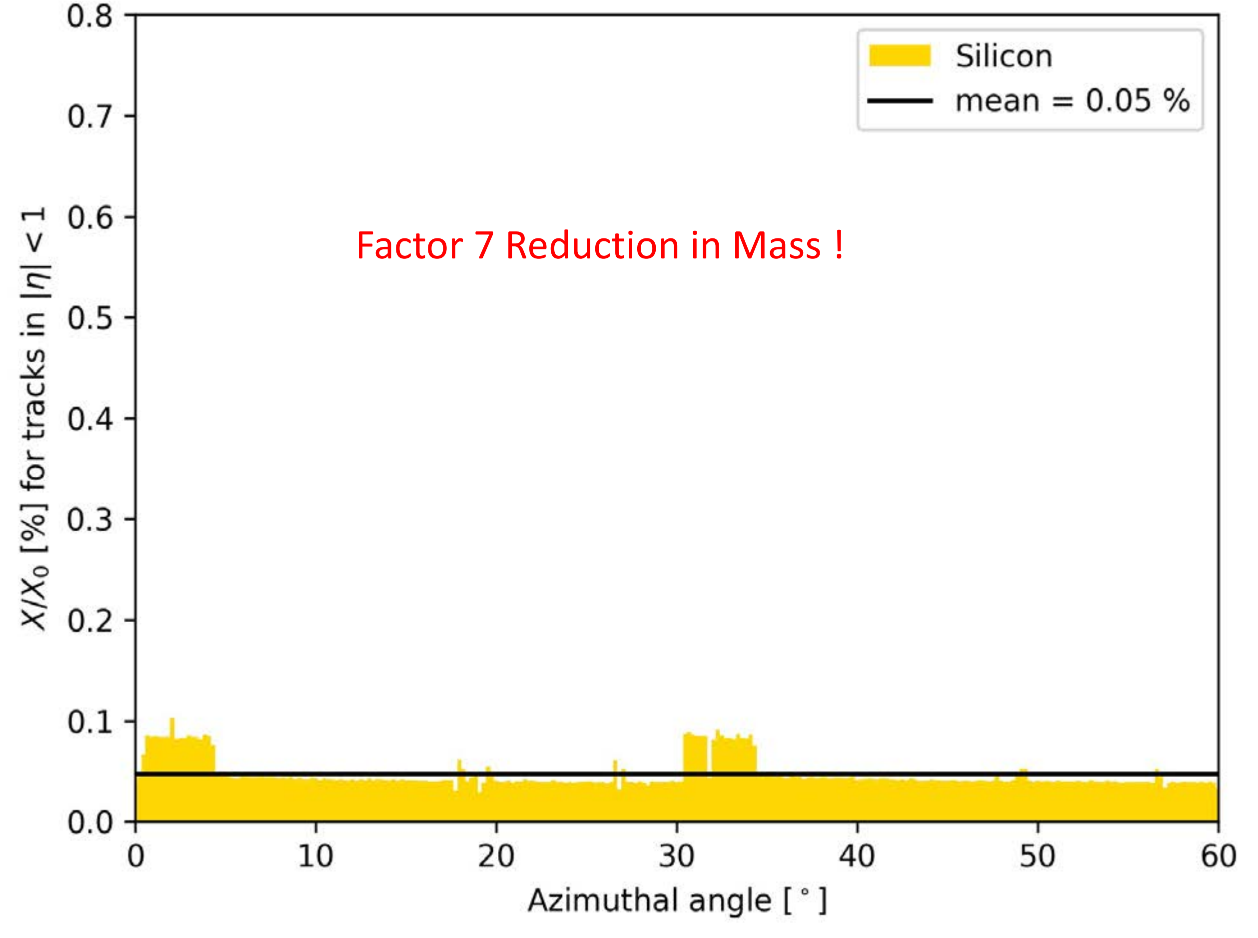


Depleted CMOS Sensors

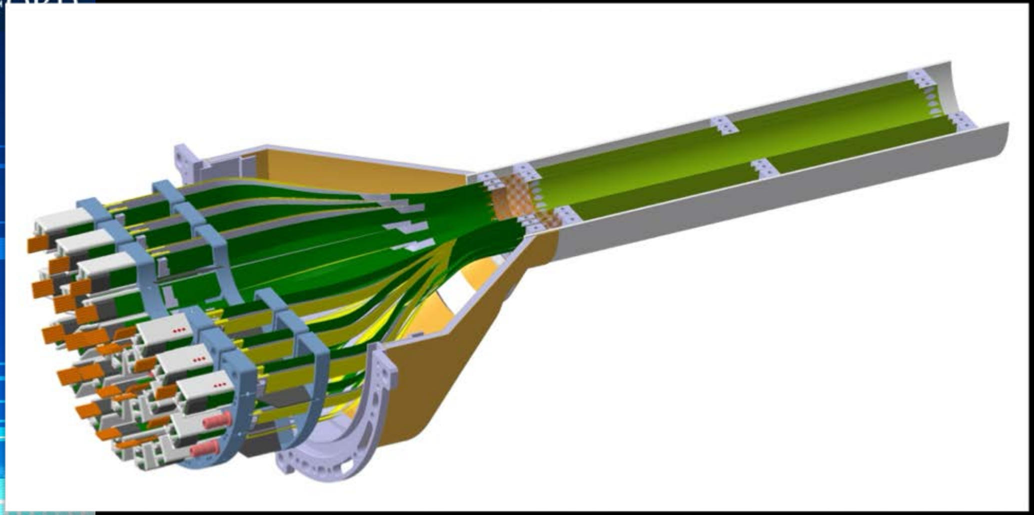
Minimize the material budget



Remove mechanical support and use stiffness provided by rolling Si wafers



IT3 Concept

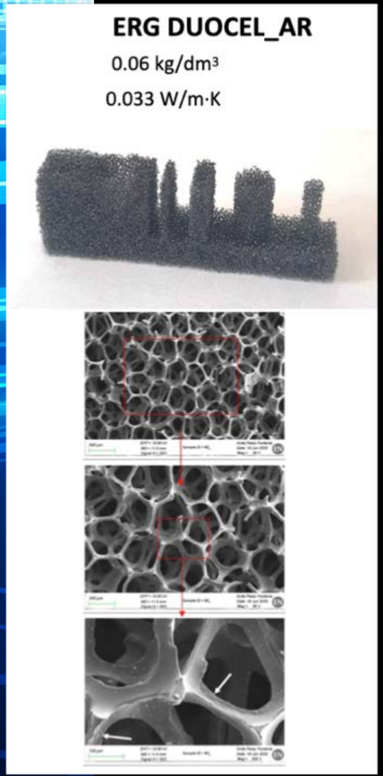


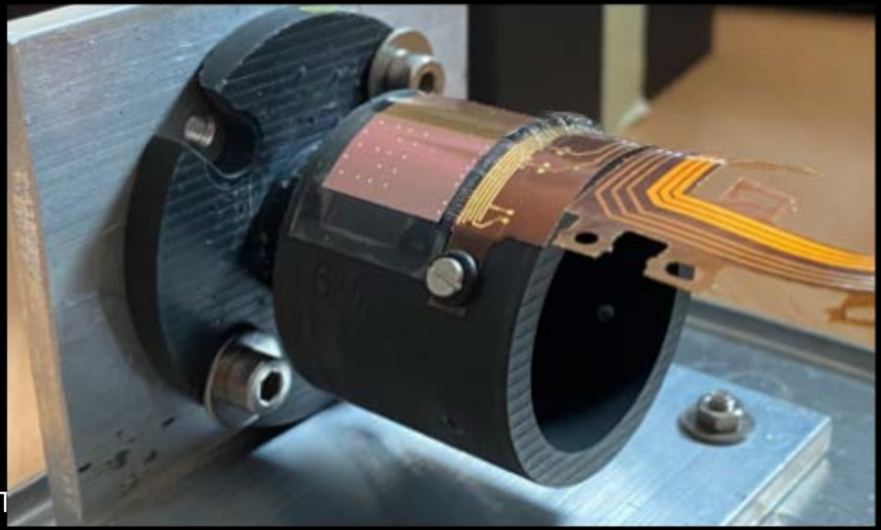
Technology advances:

- 300 mm wafer-scale chips fabricated with stitching
- thinned down to 20-40 μm bent to the target radii
- held in place by carbon foam ribs

Key benefits:

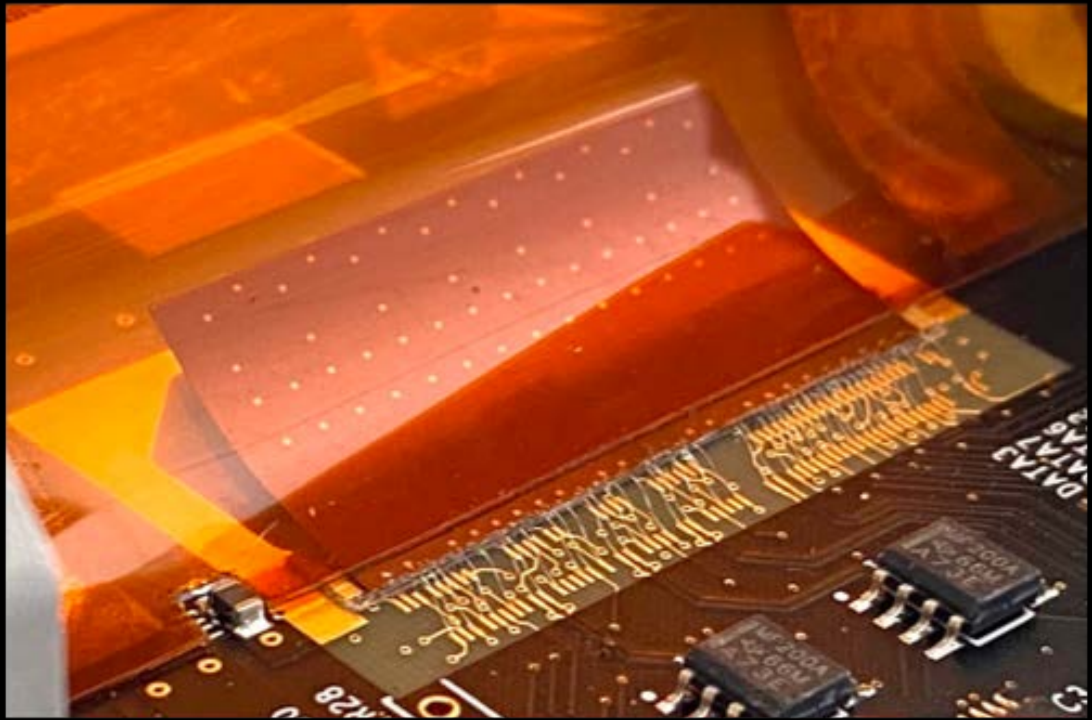
- extremely low material budget: 0.02-0.04% X_0 (beampipe: 500 μm Be: 0.14% X_0)
- homogeneous material distribution leading to smaller systematic error

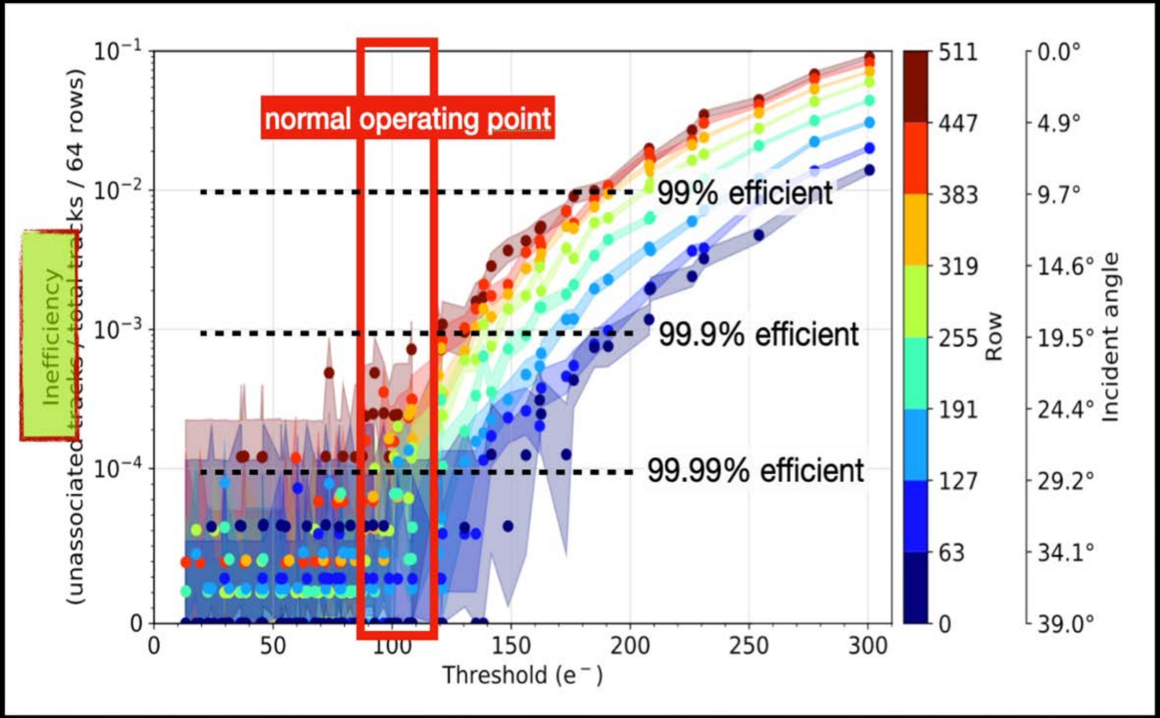




Test beams

June 2020 test beam data shows that bent MAPS work perfectly





Collaboration investigating TowerJazz 65 nm

Magnus Mager (CERN) | ALICE ITS3 | TIPP 2021 | 26.05.2021 |

Test beams

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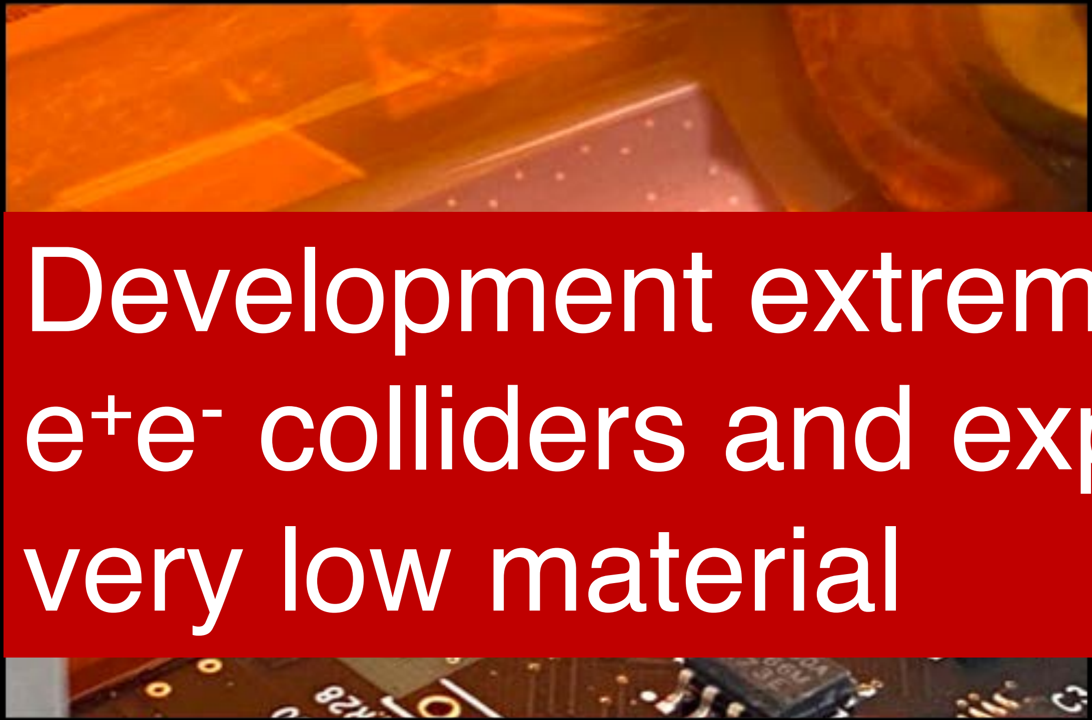

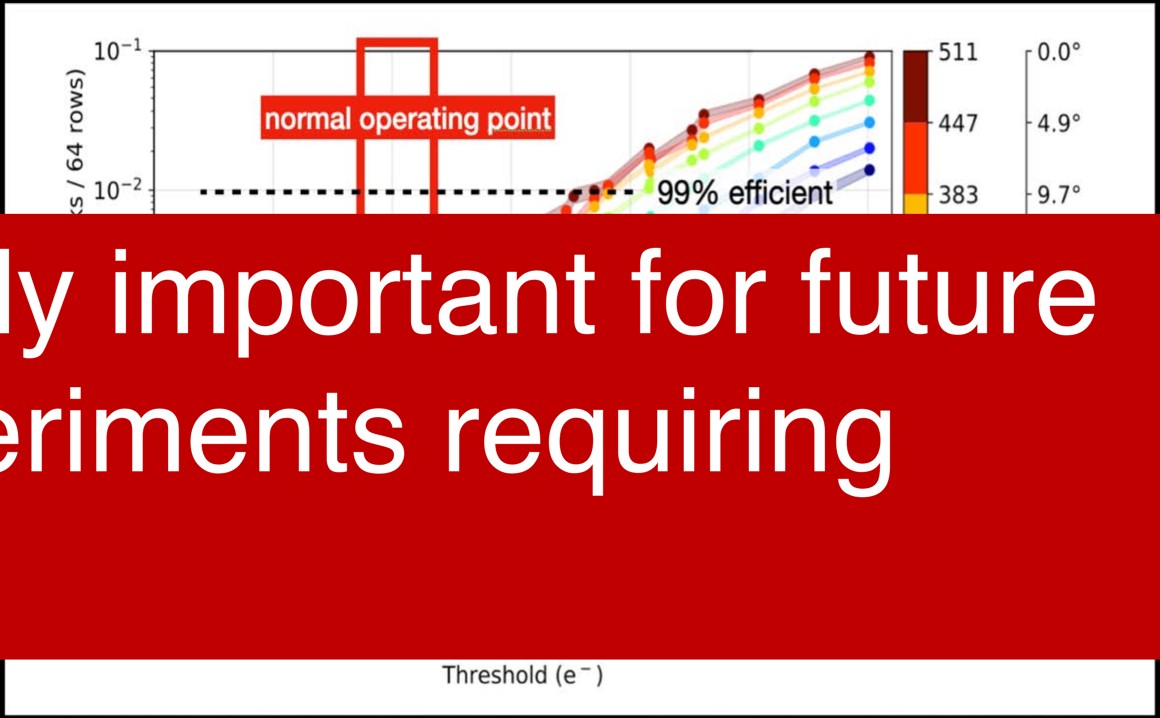

Development extremely important for future e^+e^- colliders and experiments requiring very low material

Collaboration investigating TowerJazz 65 nm

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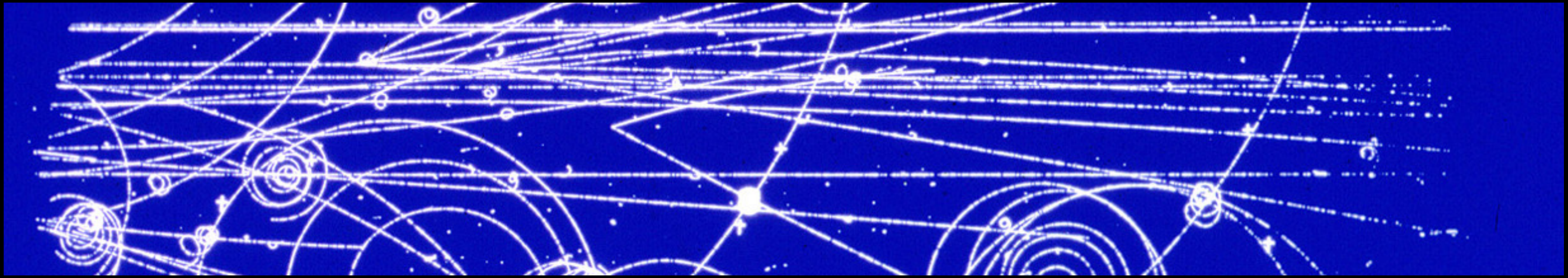
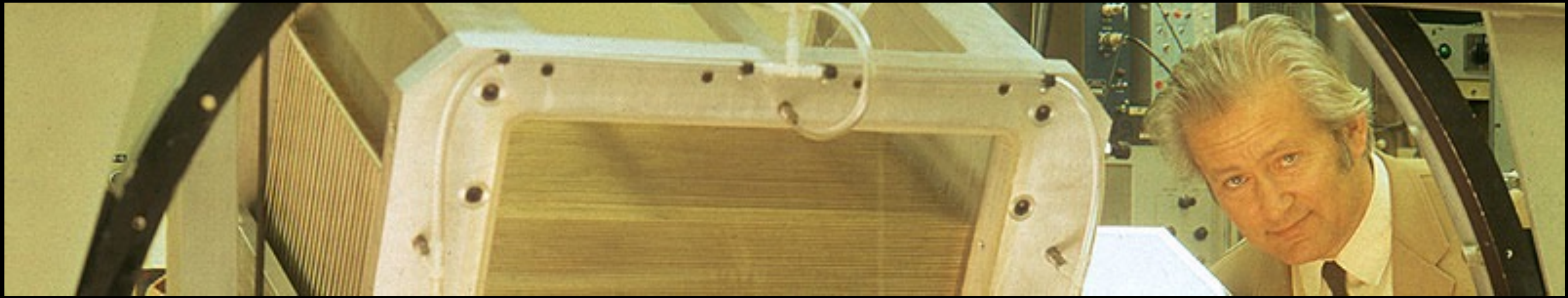
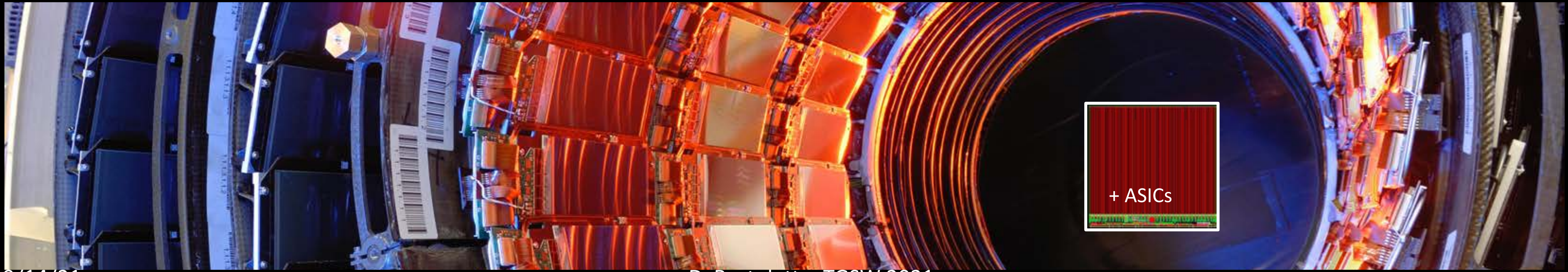
Perspective





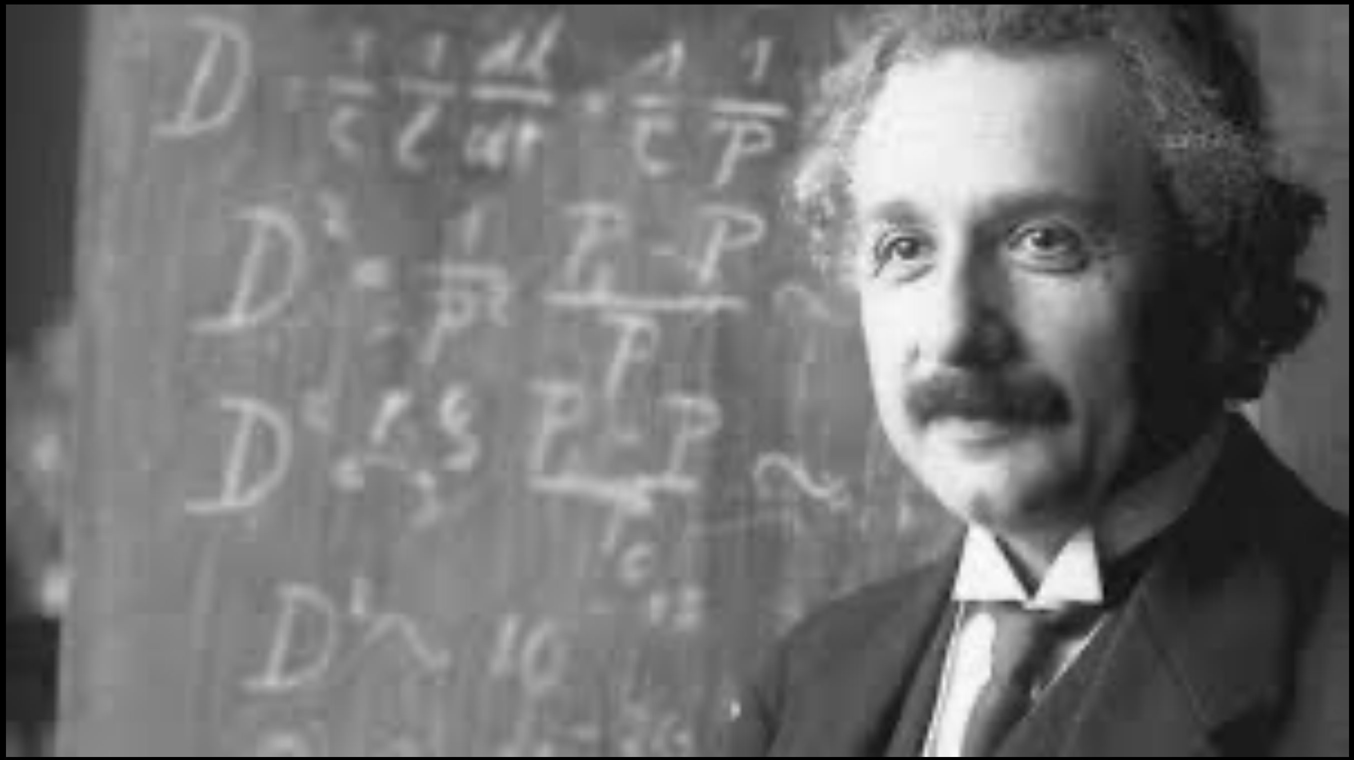


Conclusions

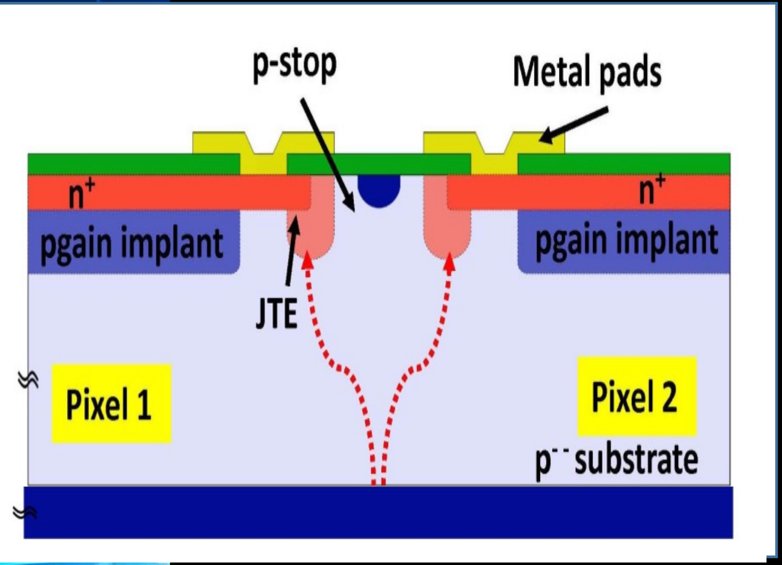
Imagination is more important than knowledge.

For knowledge is limited, whereas imagination embraces the entire world, stimulating progress, giving birth to evolution.

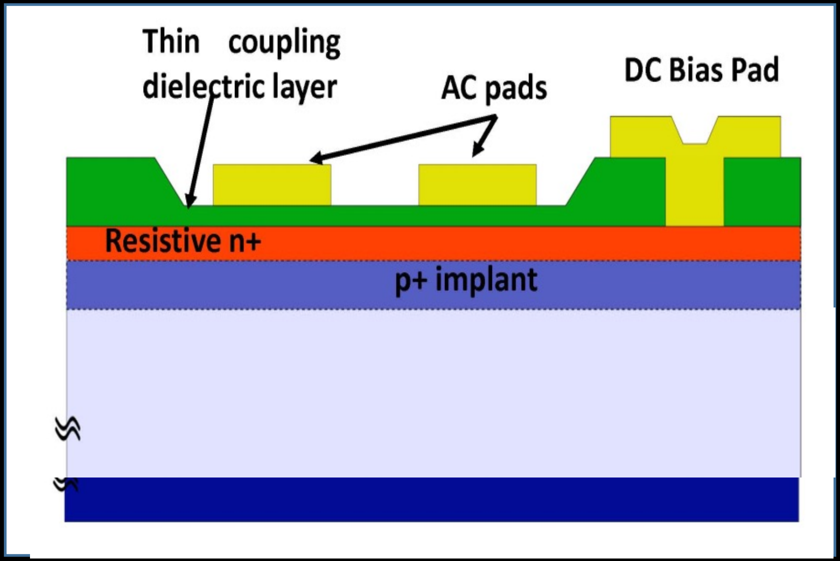
Albert Einstein, What Life Means to Einstein (1924)



4 D tracking

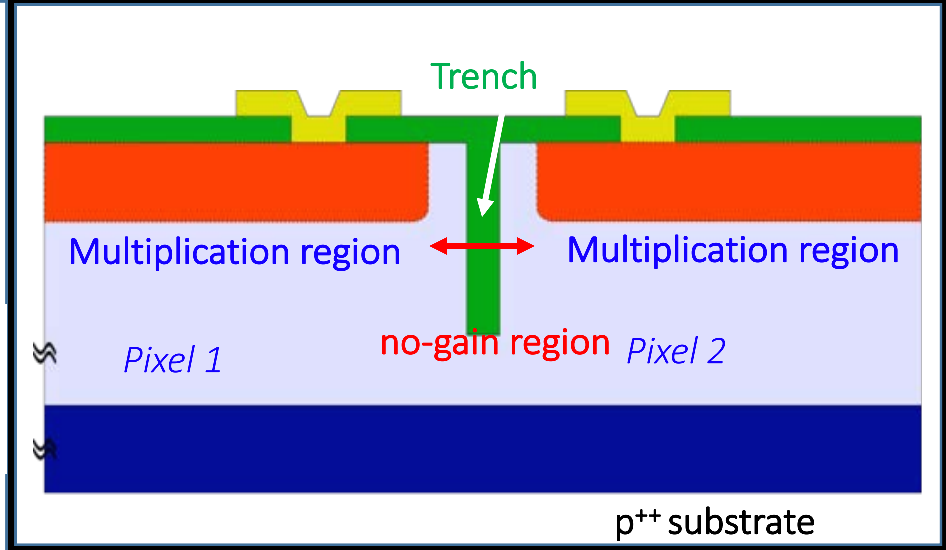


LGADS



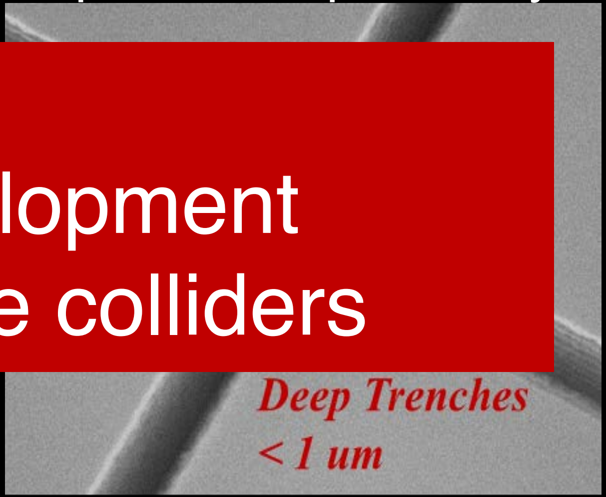
AC LGADS

- n++-implant more resistive



Trench Isolated

- p-stop & JTE replaced by a trench



- These are just examples
- Many other ideas under development
- Timing info essential for future colliders

HGCAL as an Imaging calorimeter