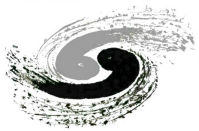
Pixel Detectors for HEP

Xin Shi



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2022.01.18

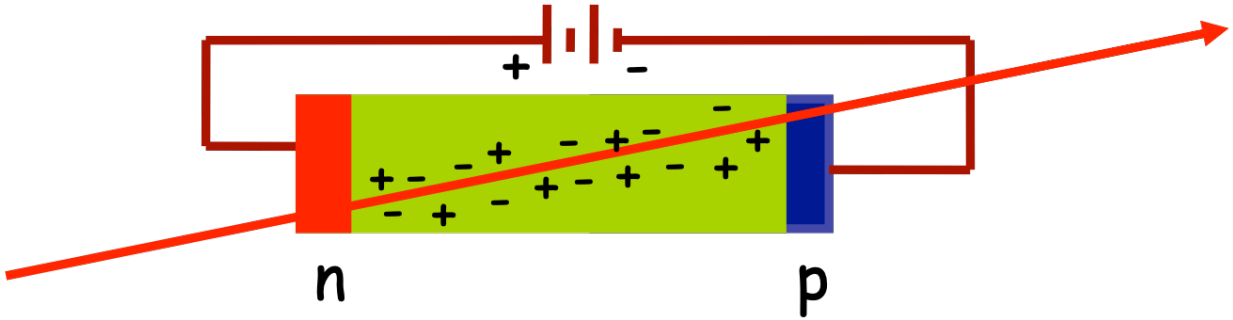
SiC Detector Monthly Meeting

Outline

- Introduction of silicon sensors in HEP
- ATLAS ITk Pixel

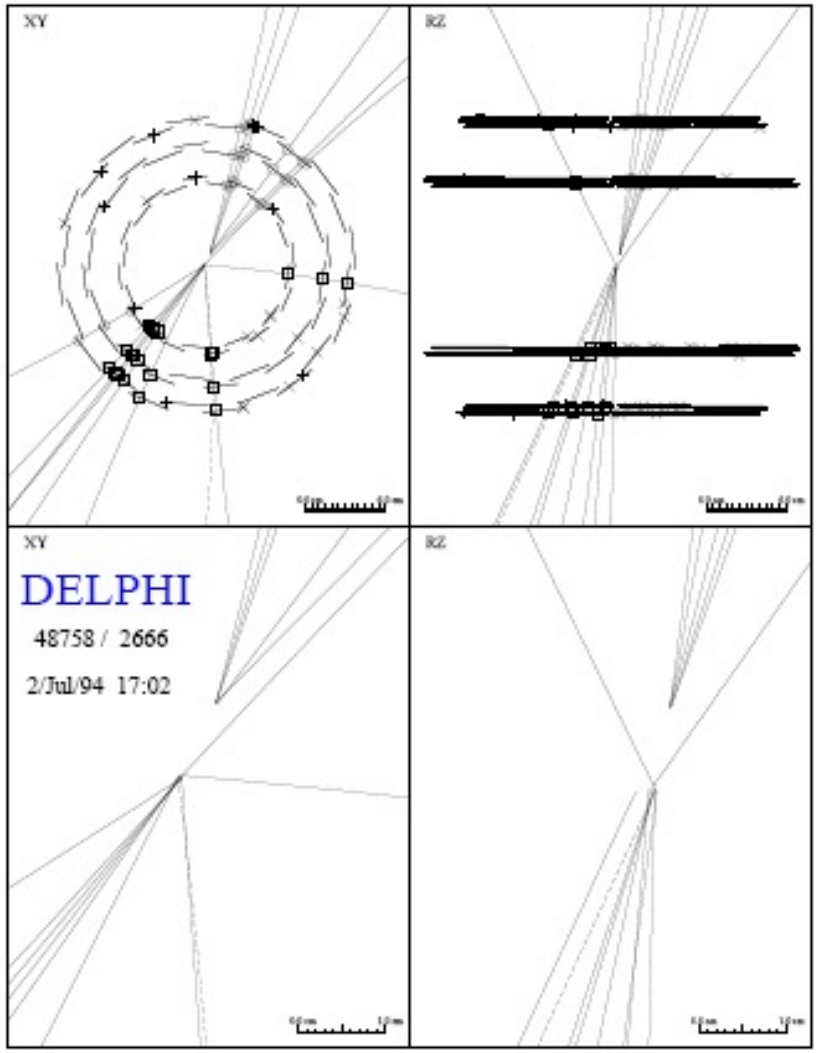
Silicon Detectors for HEP

- Basic principle: detect electron hole pairs created in reverse biased segmented silicon diode
- Originally were not considered for HEP detectors
  - Costly, bulky, small signal, challenges of miniaturization



- However with the increasing interest in very precise measurements of the vertex position, and the advent of silicon planar processing technology, silicon detectors took off

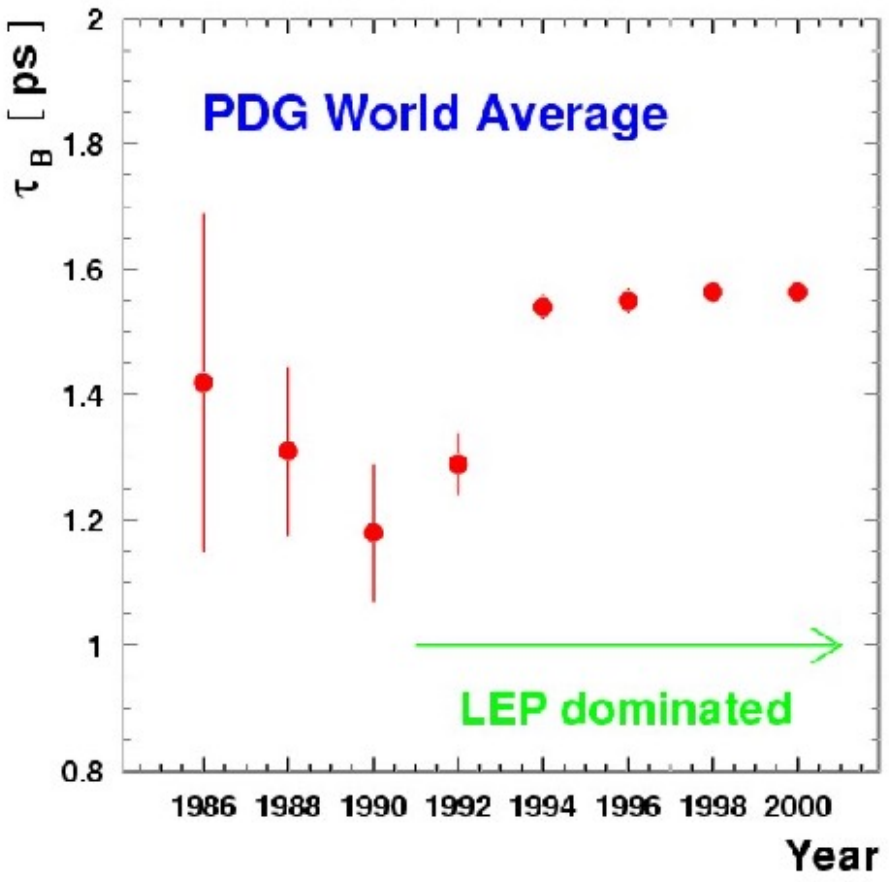
Silicon Detectors for HEP

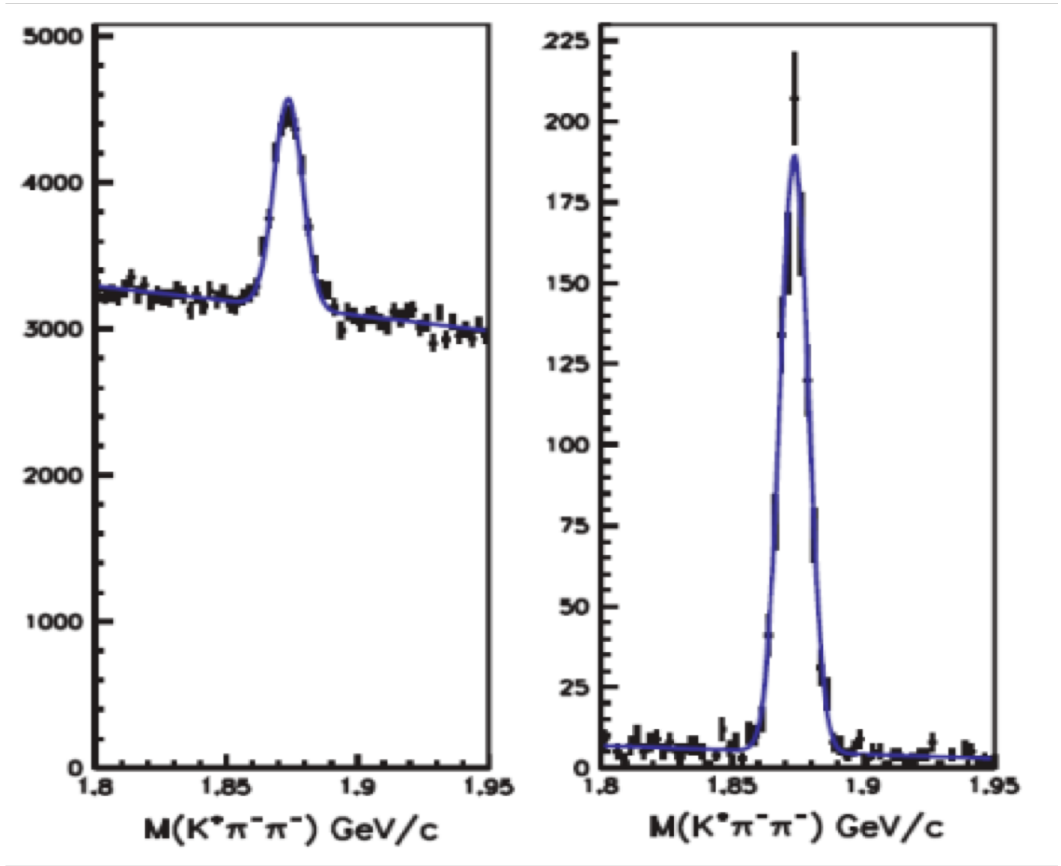


- Late 80's MARK II (SLC) and early 90's all LEP experiments had silicon, with continuous upgrades
- Pixel detector at SLC in early 90s
- The new detectors exploited access to micro-lithography technology, low noise amplifiers to cope with the small silicon signals, and readout with electronics miniaturization

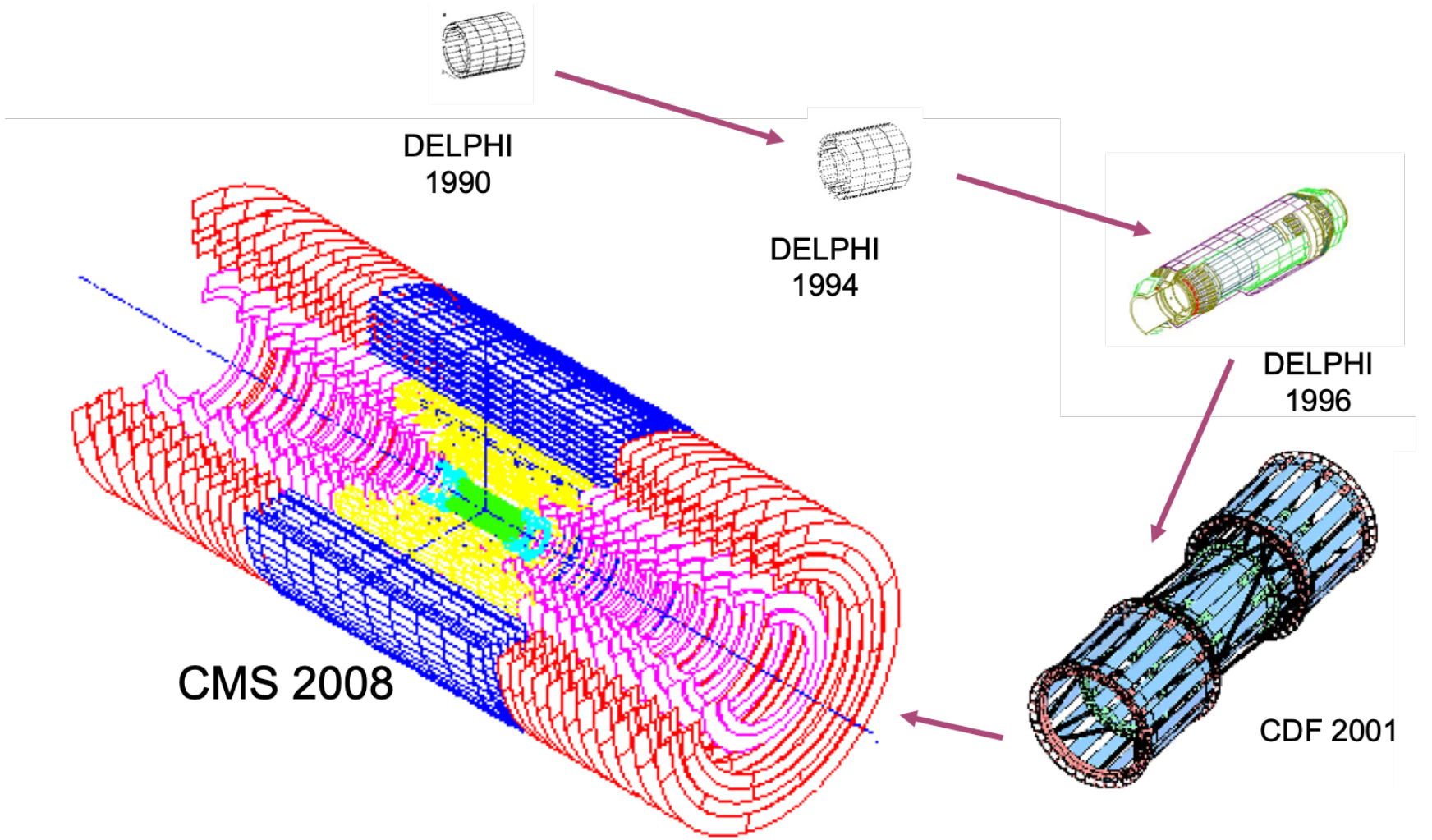
Silicon Detectors for HEP

- Dramatic effect on measurement precision!

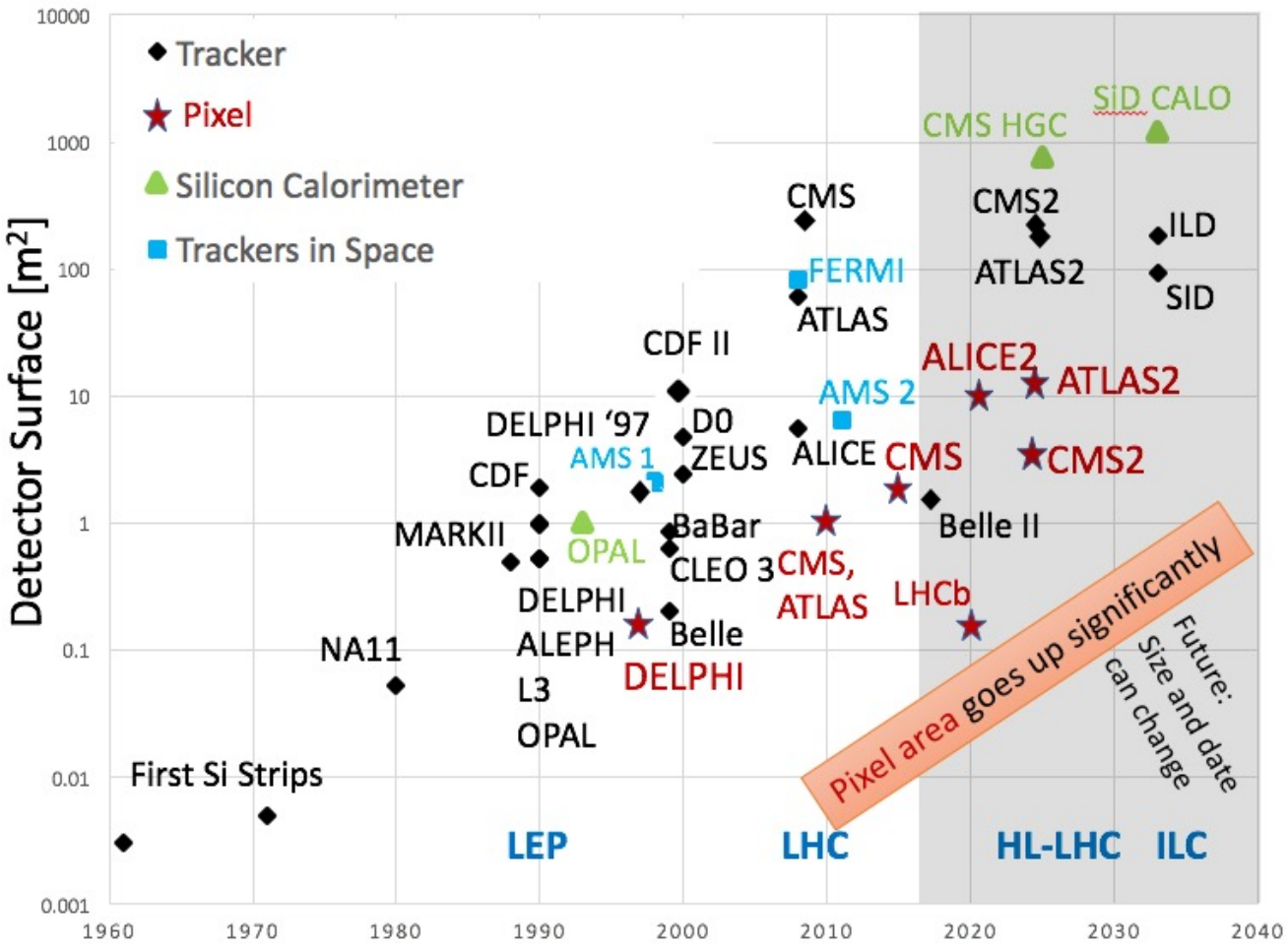




Systems quickly increased in size



And became more and more segmented



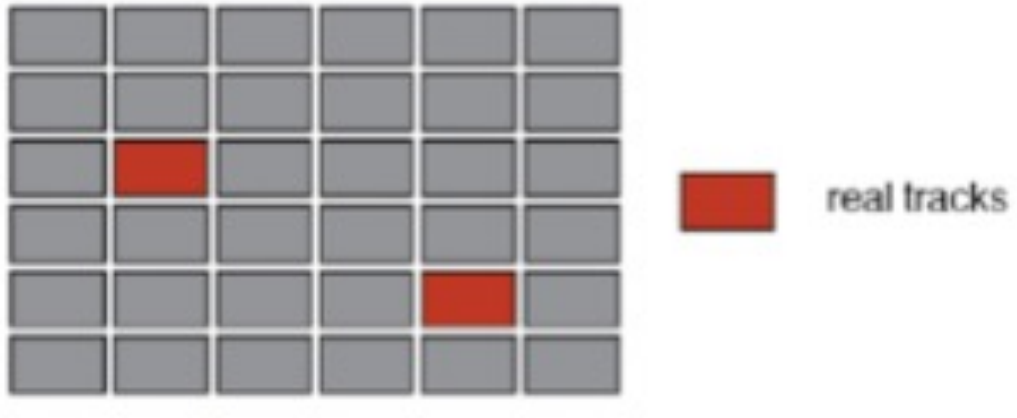
- In general global tracker sizes are saturating
- However cell sizes and data rates are evolving significantly

Detector	Current	Upgrade
CMS strips	9.8M	42M + **172M**
CMS Pixels	127M	2GP
ATLAS strips	6.3M	60M
ATLAS pixels	92M	**5GP**
VELO	171k	41M
ALICE	12.5M	**12.5G**

Cell granularity, the weapon against high-PU keeping occupancy at a reasonable level

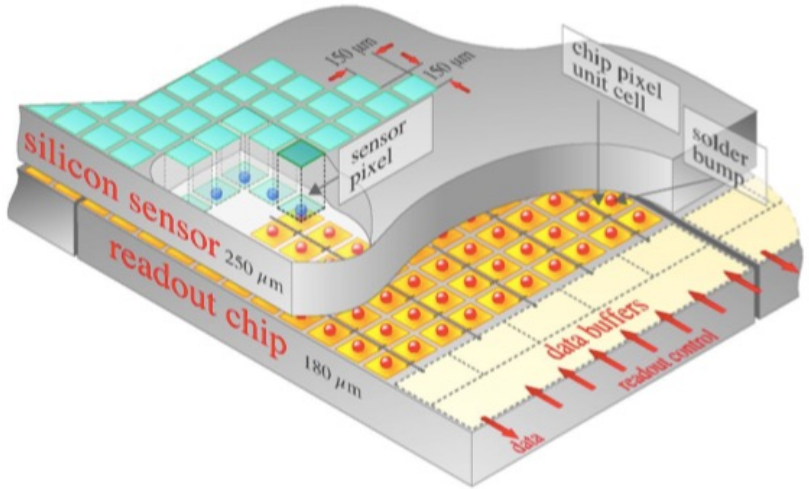
With the rise of pixel detectors





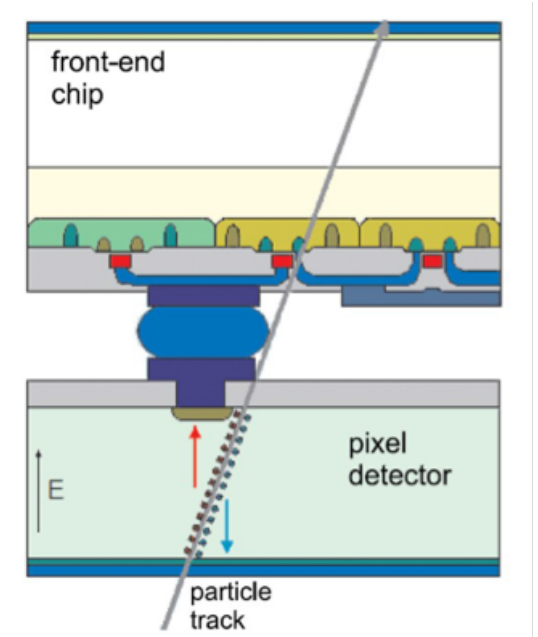
Strip detector measures 1 coordinate only.
Two orthogonal detectors give a 2 dimensional position of a particle.
However with more than one particle hits the strip detectors the measurement is no longer unambiguous. "Ghost" hits appear!

Pixel detectors produce unambiguous hits



Exploit technology to new level, taking advantage of industry miniaturization and silicon processing advances

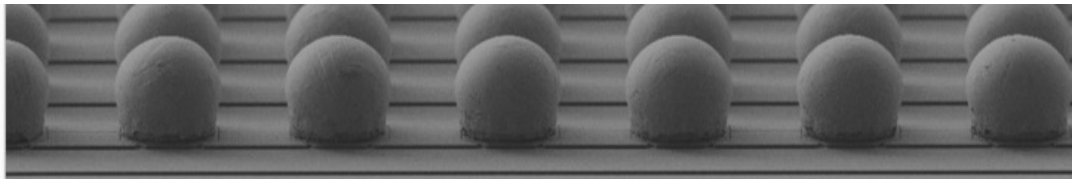
The Hybrid Pixel Detector



Fine pitch bump bonding to connect sensor and readout chip

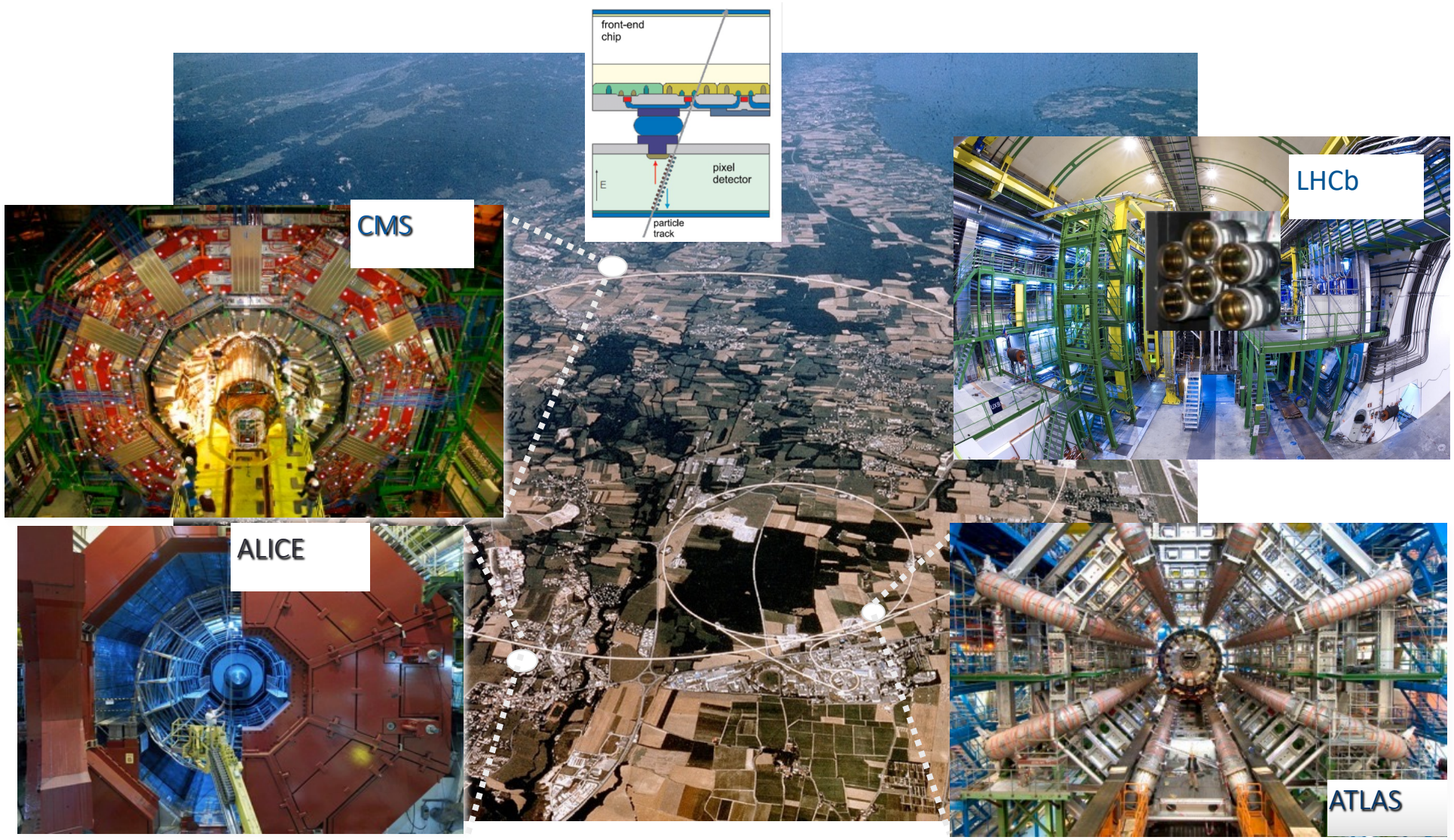
Offer a number of pros due to the split functionality of sensor and readout:

- Complex signal processing in readout chip
- free choice of sensor material (Si, GaAs, CdTe..)
- Separate optimisation of sensor and FE-chip for very high radiation environment
- zero suppression and hit storage during L1 latency
- radiation hard chips and sensors to > 10^{15} n_{eq}/cm^2
- high rate capability (~MHz/mm^2)
- spatial resolution ~ 10 - 15 µm
- Potential for C2W and W2W bonding to connect sensor and readout chips



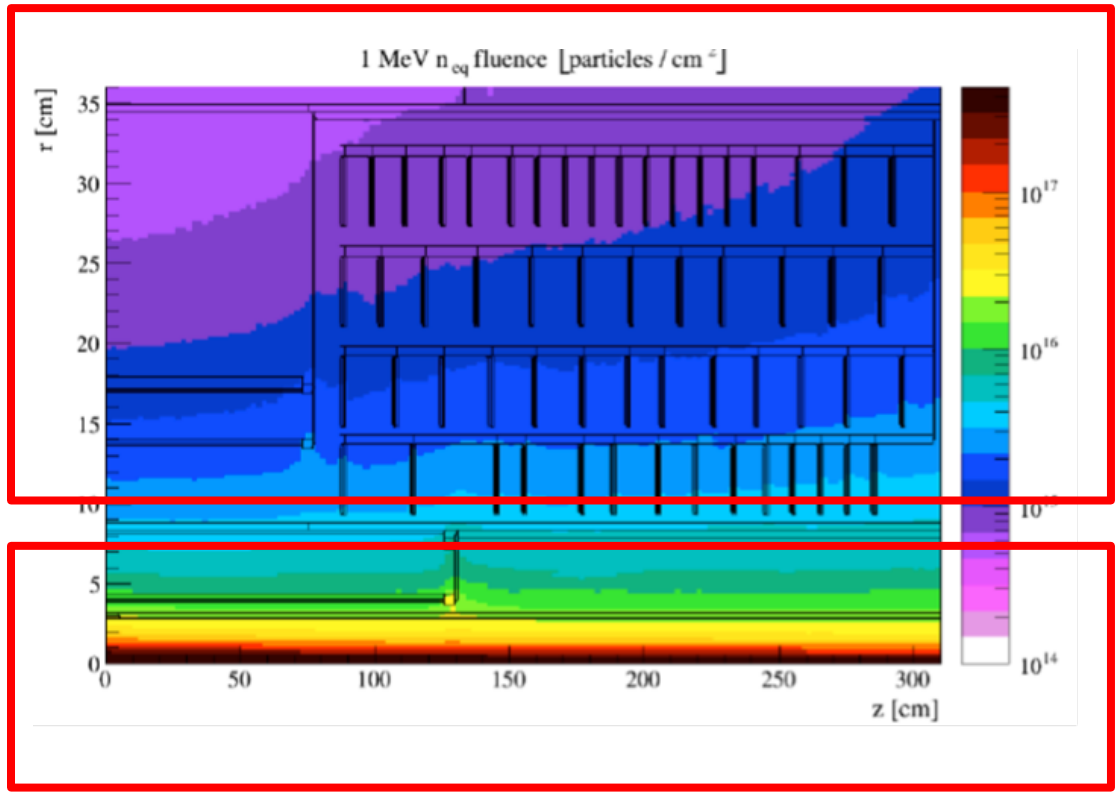
SEM image of 55 µm pitch SgAn bumps courtesy Sami Vähänen, ADVACAM Oy

Hybrid Pixels at the LHC



And at HL-LHC

- Designs governed by LHC radiation levels, hit rates and bunch structure
- *Example: ATLAS*



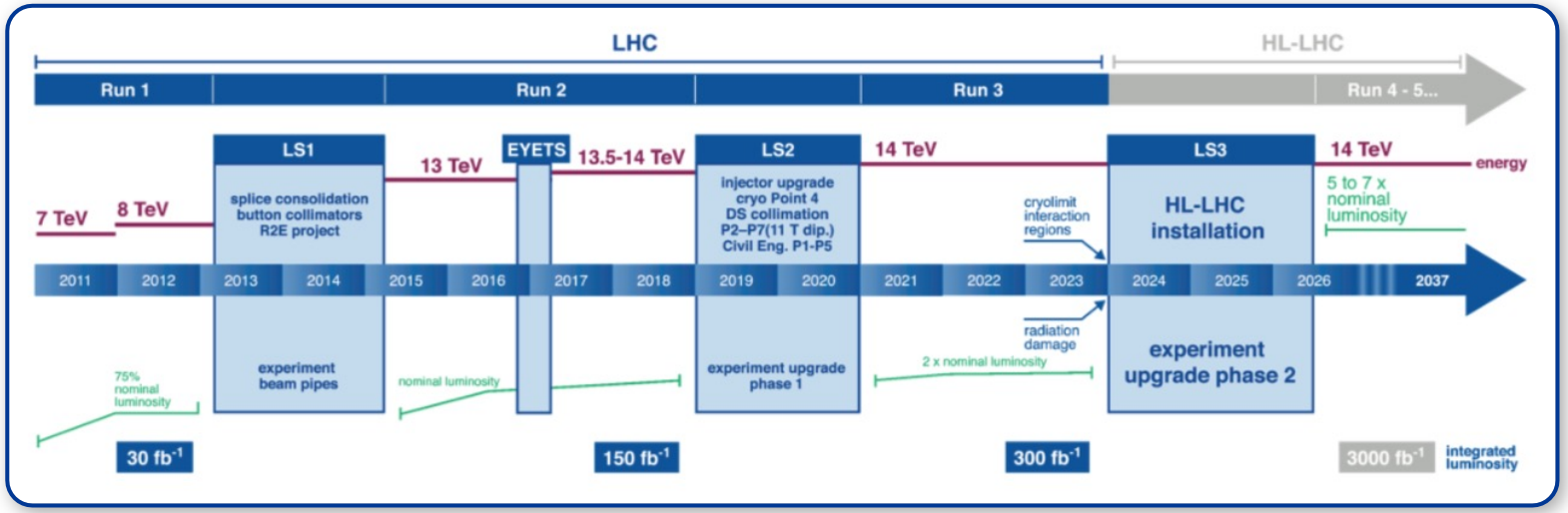
Outer Pixel layers

- Occupancy 1MHz/mm^2
- NIEL ~ 10^{15} n_{eq}/cm^2
- TID ~ 50 Mrad
- Larger area O(10m^2)

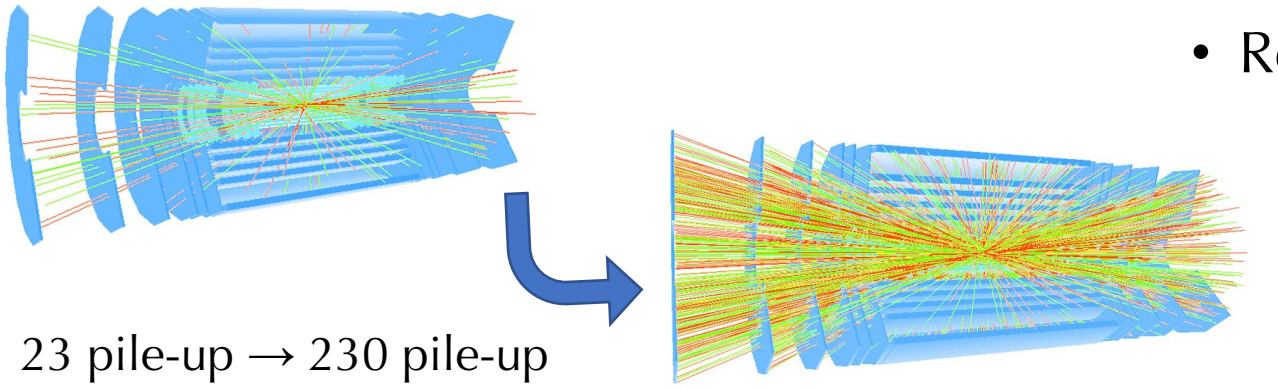
Inner Pixel layers

- Occupancy 10 MHz/mm^2
- NIEL ~ 10^{16} n_{eq}/cm^2
- TID ~ 1Grad
- Smaller area O(1m^2)

High Luminosity Upgrade of the Large Hadron Collider



- Average collisions/BC:
  30 → ~200
- Peak luminosity:
  $1 \cdot 10^{34} \rightarrow 5 - 7 \cdot 10^{34}$ cm^{-2}s^{-1}
- Integrated luminosity:
  350 → 4000 fb^{-1}

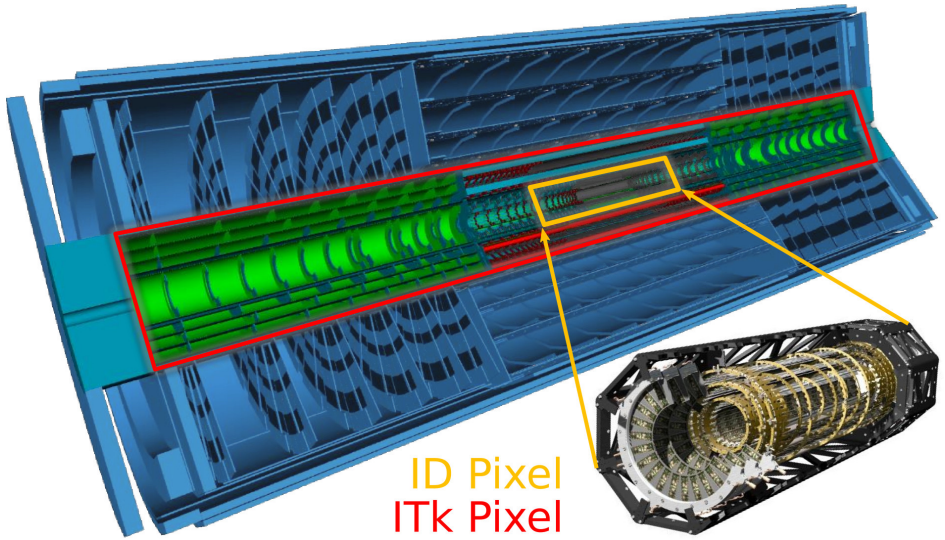


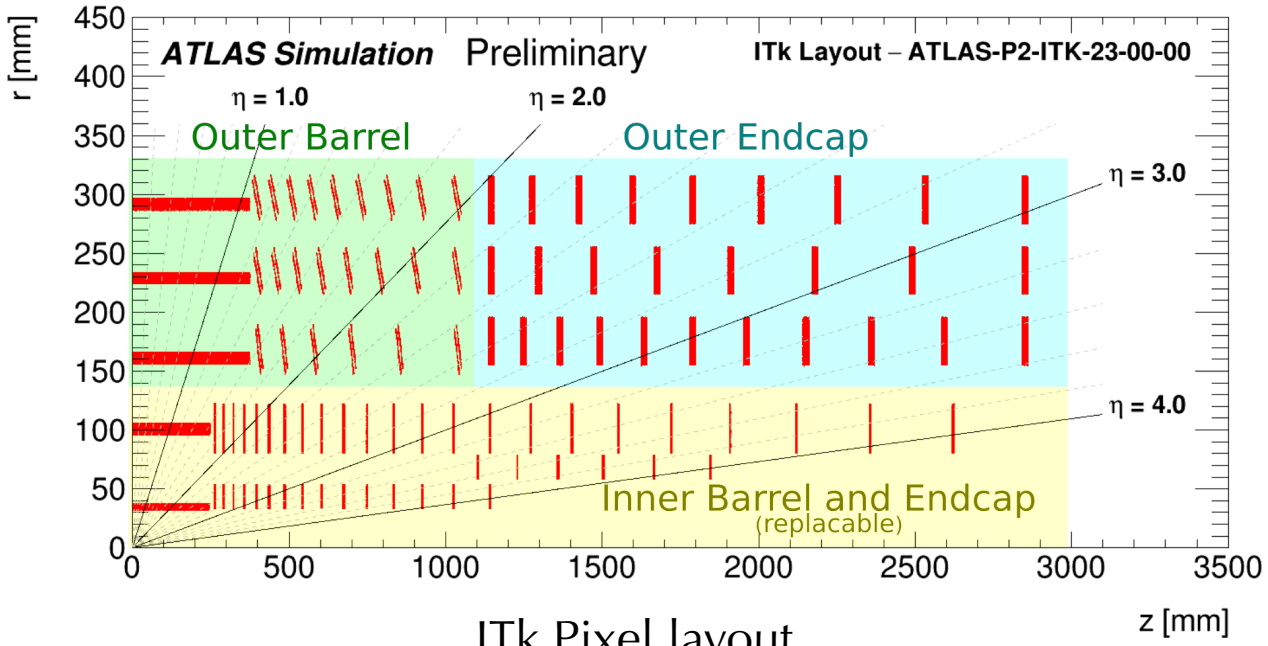
23 pile-up → 230 pile-up

- Requirements for pixel detector & readout:
  - High trigger rate: 1 MHz
  - High granularity: occupancy at 1 %
  - Radiation tolerant: up to $2 \cdot 10^{16}$ n_{eq}/cm^2

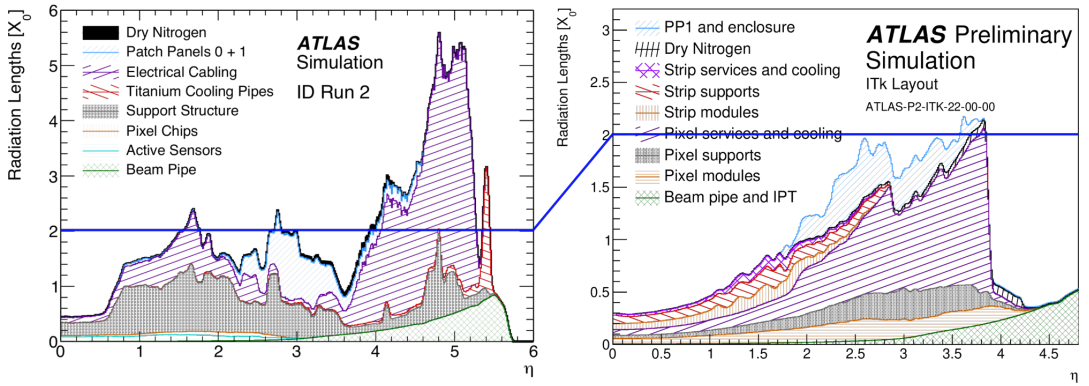
ATLAS Inner Tracker (ITk) Upgrade

- Detectors close to the interaction point are most affected
- Replace current Inner Detector with all-silicon ITk
- Pixel: 1.7 m^2 → 13 m^2 (5 · 109 channels)
- Strip: 60 m^2 → 160 m^2 (50 · 106 channels)
- η : 2.5 → 4.0





ITk Pixel layout

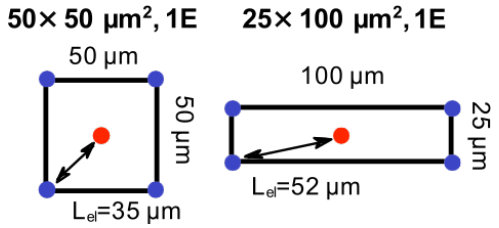


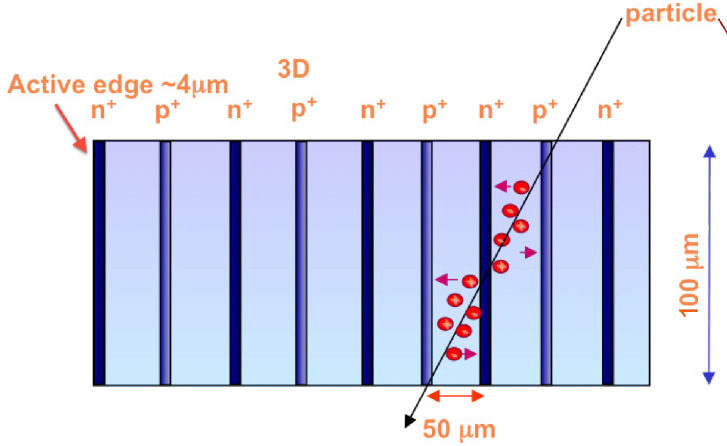
Material budget ID vs ITk

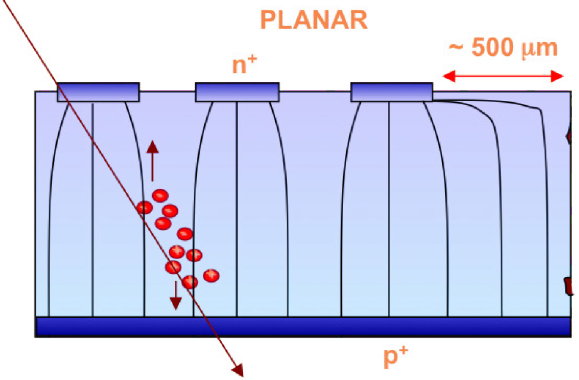
ITk Pixel Sensors

- Requirement: hit efficiency at orthogonal incidence: > 98.5 % before & > 97 % after irradiation

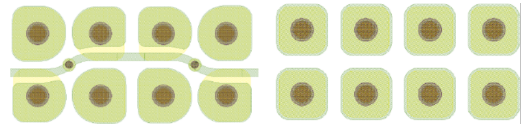
3D sensors in L0
(triplet module)

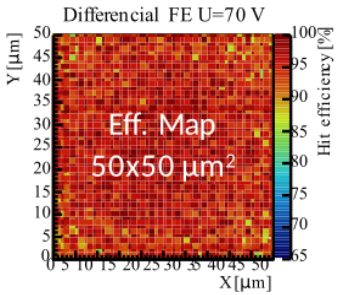


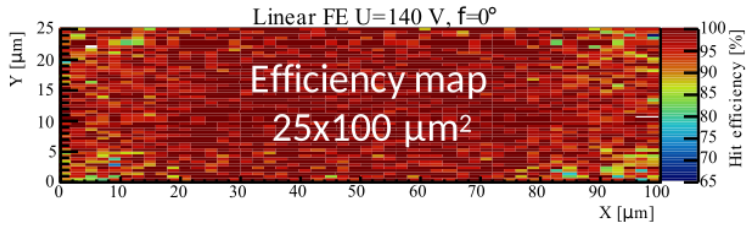




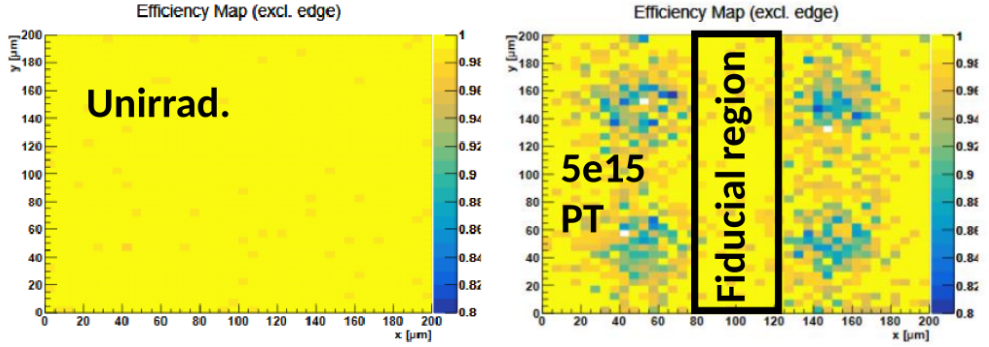
Planar sensors in L1-L4
(quad module)







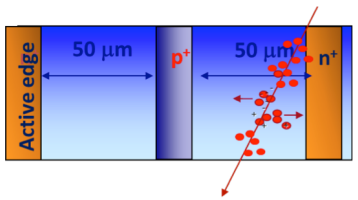
- Pixel size: 50 × 50 μm² (endcap) and 25 × 100 μm² (barrel)
- 150 μm active thickness + 100 μm support wafer
- Maximum fluence in the innermost layer (34 mm from beam): $1.3 \cdot 10^{16}$ n_{eq} /cm² for 2000 fb^{-1}

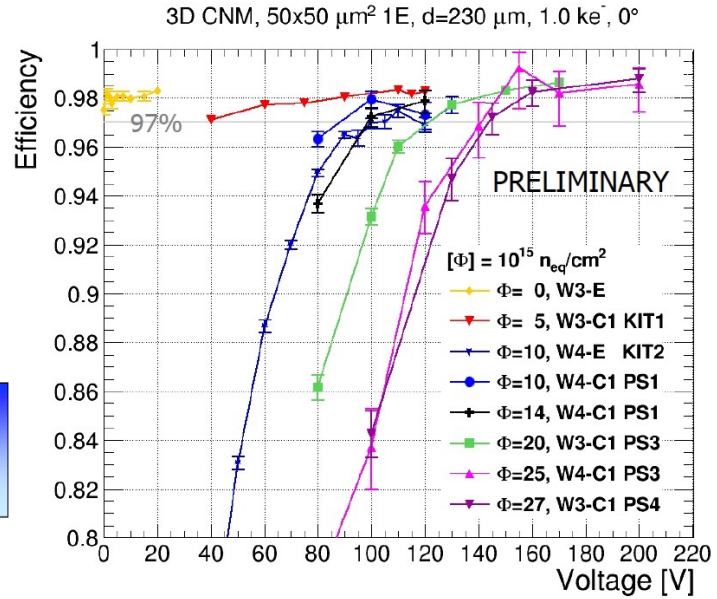


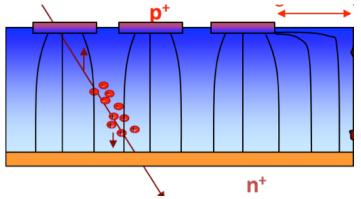
- Pixel size: 50 × 50 μm² with n-in-p technology
- 100 μm thickness in L1, 150 μm thickness in outer layers

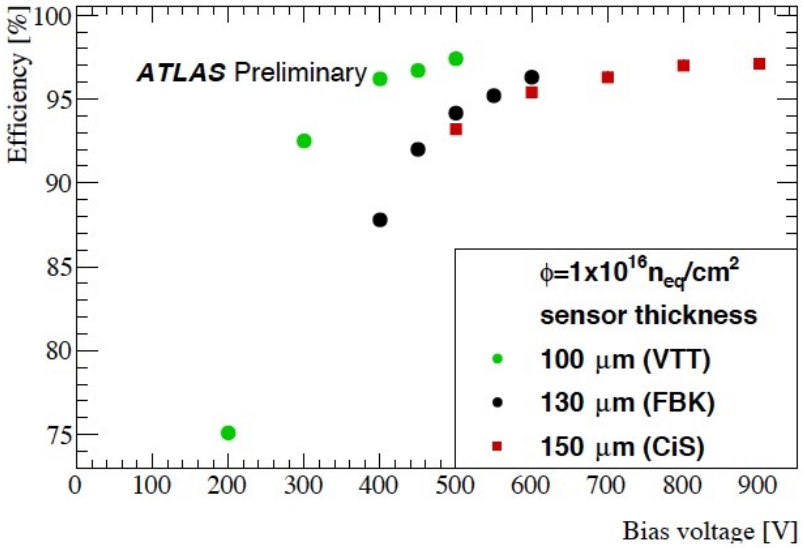
- Thinner sensors: charge and hit efficiency saturation at lower bias voltages → reduction of power dissipation

Radiation Hardness - 3D sensors



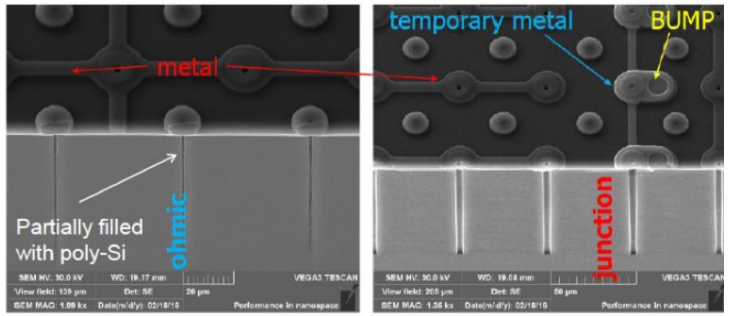




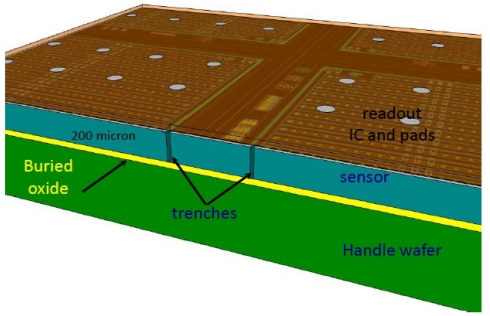


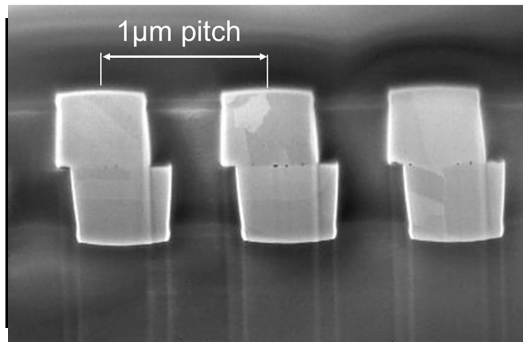
3D sensors are still a very promising technology for the innermost layers
ATLAS measurements show radiation hardness up to 3 x 10^{16}/1 x 10^{16} n_{eq} cm^{-2} for 3D/thin sensors

Many process refinements are under investigation

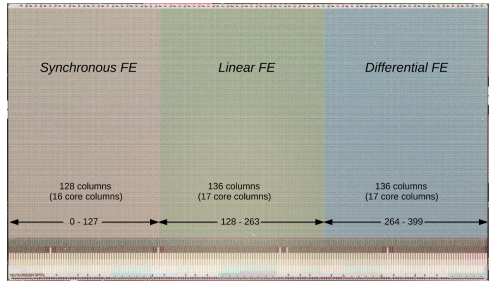


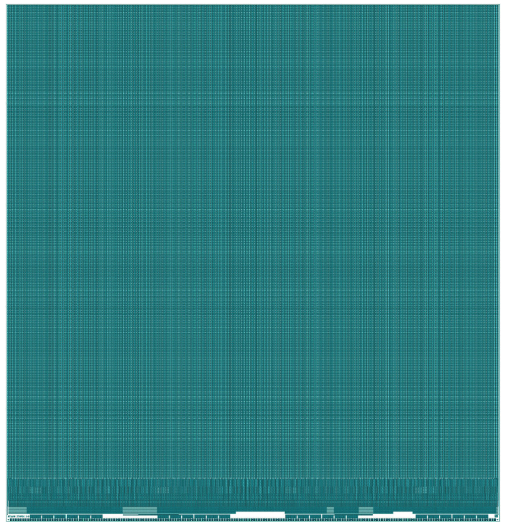
Holy grail remains chip to wafer
or wafer to wafer direct bonding



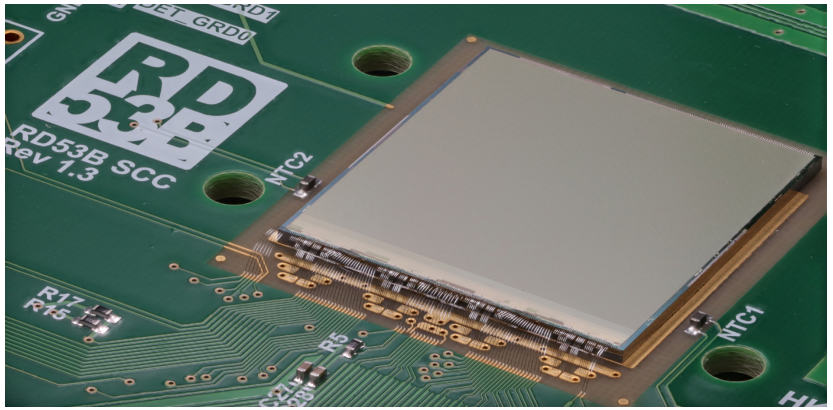


RD53 Readout Chip





RD53A → ITkPixV1



ITkPixV1 chip on Single Chip Card (SCC)



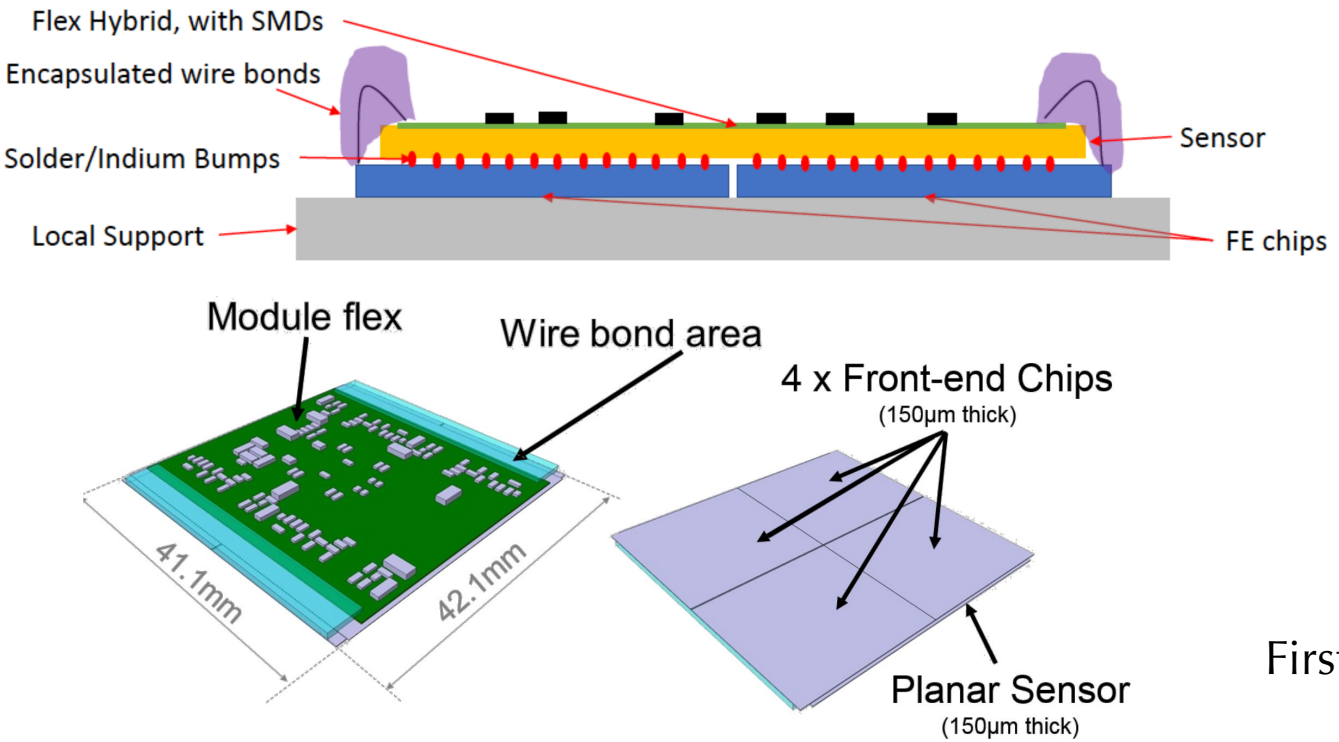
RD53 Collaboration: 24 institutes from Europe & US

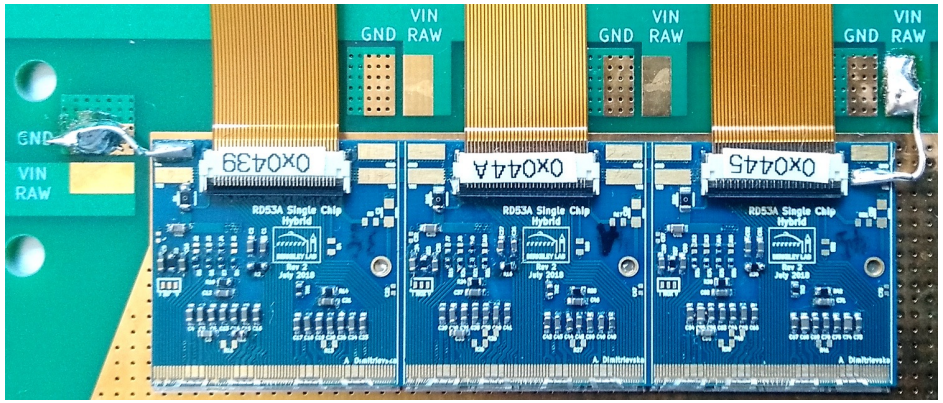
- Common readout chip
  - ATLAS (ITkPix): 400×384 pixels, differential FE
  - CMS (CROC): 432×336 pixels, linear FE
- ITkPixV1 submission March 2020, being verified
- ITkPixV2 (production) submitted end of 2021

Chip size (ATLAS)	20 × 21 mm2
Pixel size	50 × 50 µm2
High hit rate	3GHz/cm2 (vs. FEI4: 400MHz/cm2)
High trigger rate	1 MHz with 12.8 µs latency
High data rate	up to 5.12 Gbit/s per chip
Low threshold	~ 600 e
Radiation tolerance	500 Mrad
Low power	~ 4 µA/pixel (analog/digital)

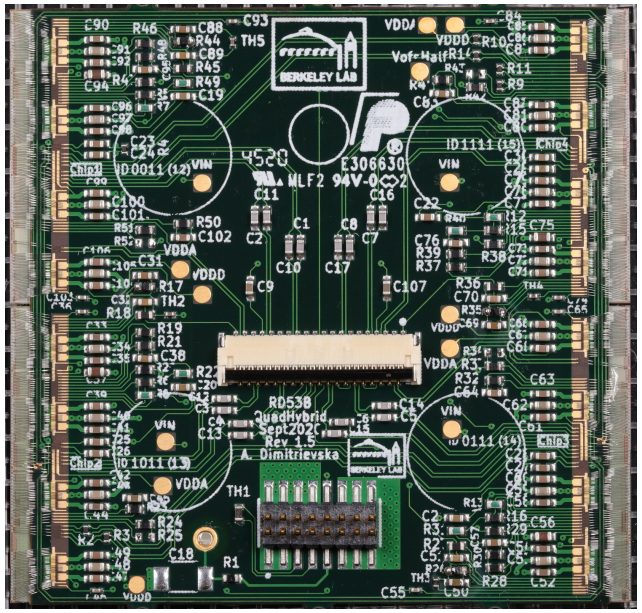
Pixel Module

- ~ 10000 modules needed for ITk
- L0: triplets for barrel (linear) and ring (round)
- L1-4: common quad modules everywhere
- Module flex PCB designs being finalised
  - Quad PCB: 3 copper layers at ~250 µm thickness



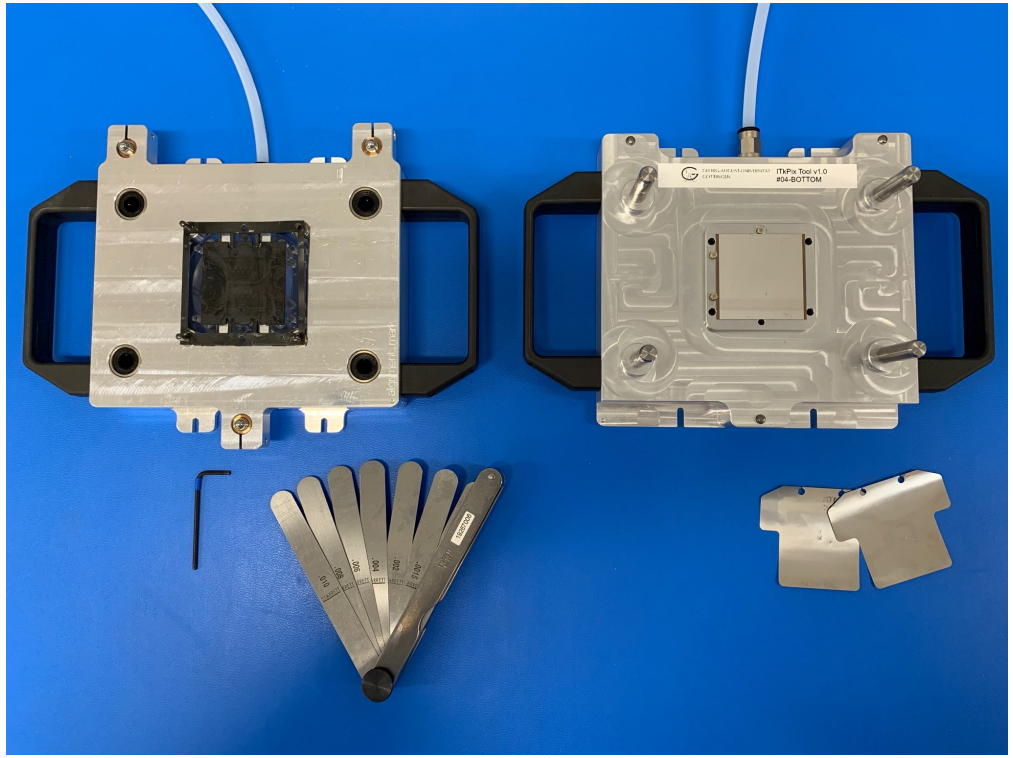


Linear RD53A triplet module



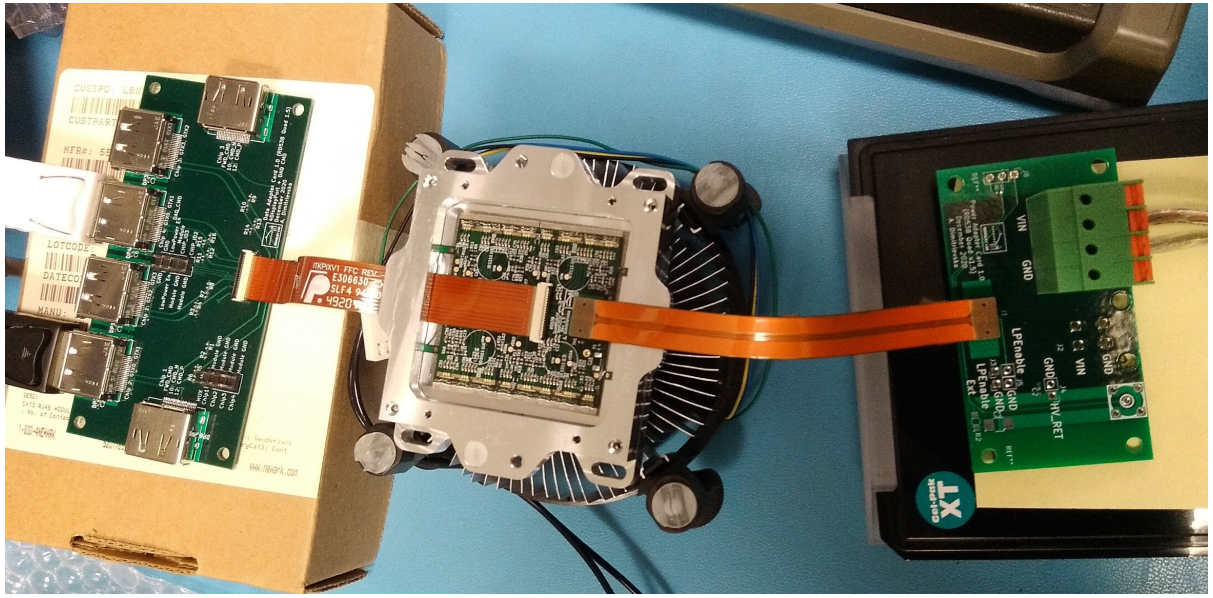
First ITkPixV1 digital quad module on prototype PCB

Module Assembly and Testing



- Modules being produced during the next 4 years
- Glueing of sensor-FE ensembles and module PCBs
- Custom module assembly tooling
- Glue dispensation via stencil
- HV protection via Parylene coating

- Every module has to go through quality control
- RD53A module testing site qualification ongoing
- First ITkPixV1 digital quad module being tested
- Custom readout/power adapter boards and flexes



Summary

- Pixel Detectors for HEP have been evolved in the past several decades
- ATLAS ITk Pix module is being build and test

- The next big challenge: Introducing timing to give a defector with the proven reliability, flexibility, speed, processing power and data throughput of the hybrid pixel but with a 4^{th} dimension added.

- Can this be done in the next 8 years?
  (ATLAS ITk Pix / LHCb Upgrade II ~ 2030)