Review of Vertex/Silicon detector Technology

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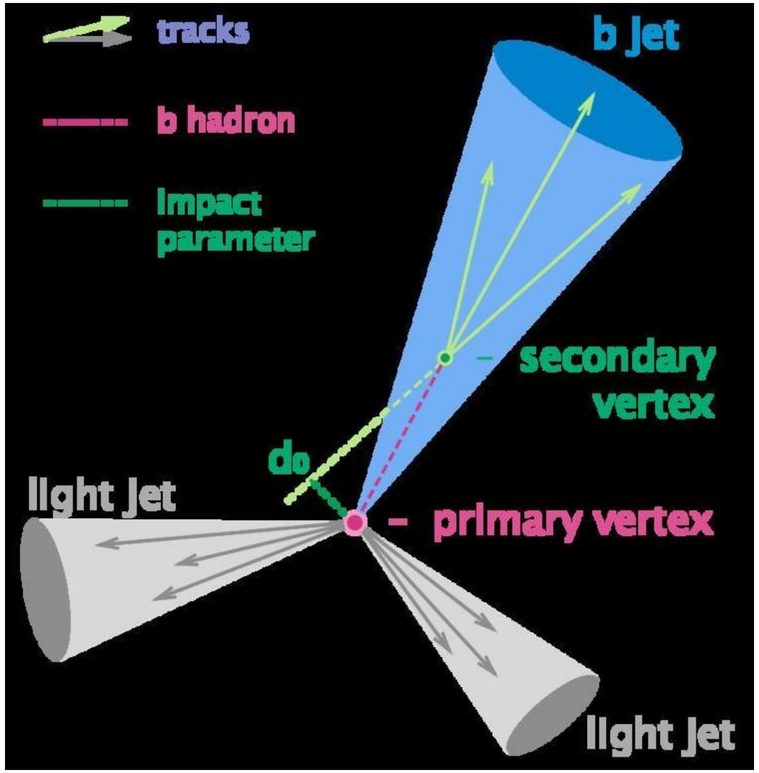
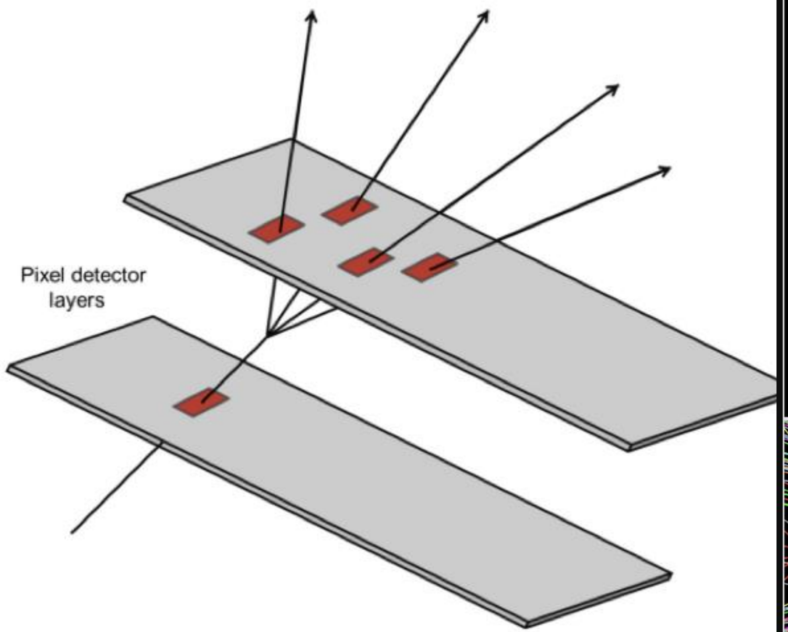
OUTLINE

- Overview of vertex detector
- CEPC vertex detector R & D
- More Future prospect

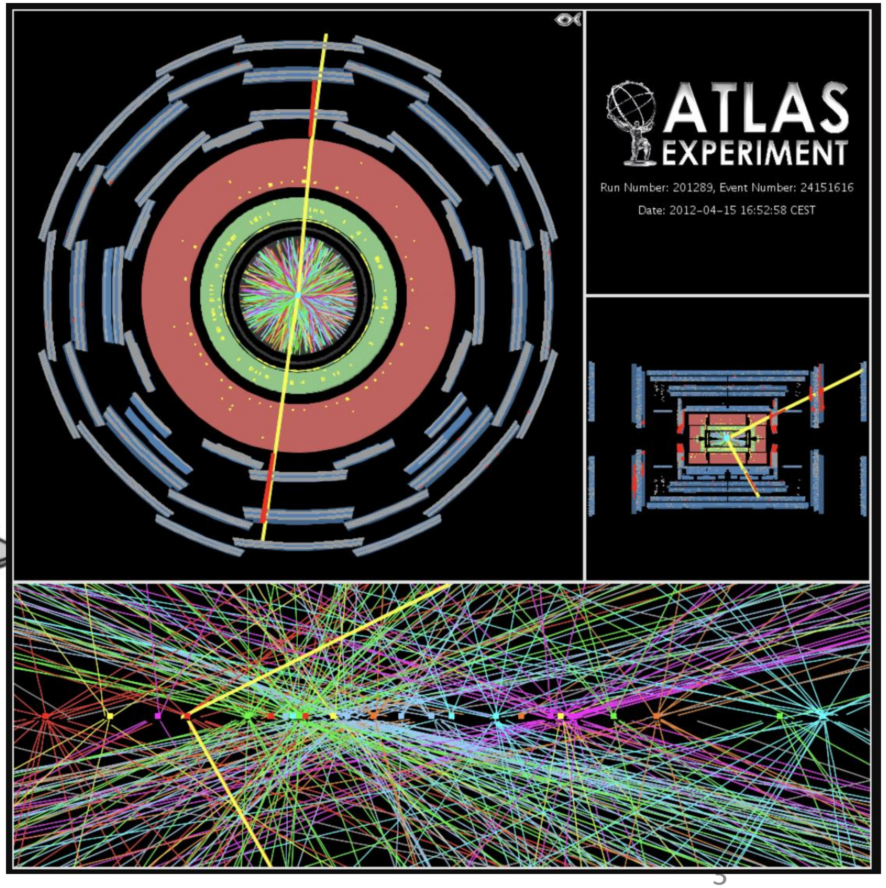
WHY WE NEED VERTEX DETECTOR ?

- High precision vertex detector essential
  - Flavor physics
  - Higgs physics (H→bb/cc/gg and H→ττ)
  - Pileup vertex rejection for hadron collider





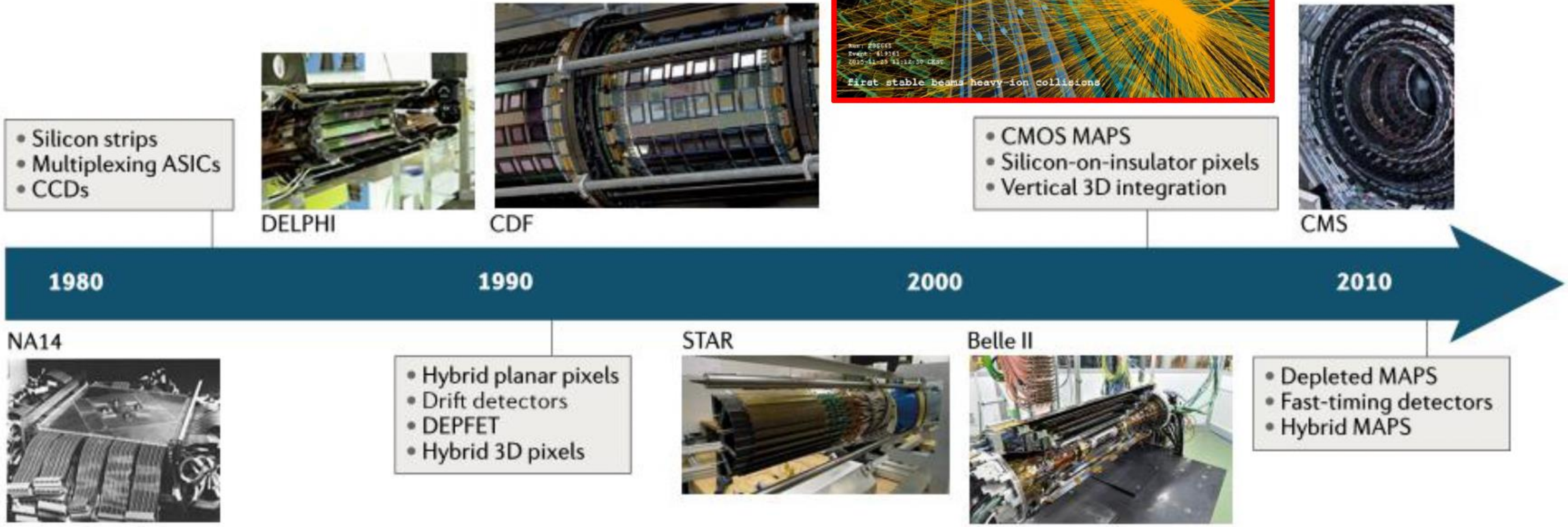
11 Pileup vertex in Z->μμ events at ATLAS



SILICON DETECTOR DEVELOPMENT

P.Allport, CERN detector seminar,
https://indico.cern.ch/event/960851
CERN, Oct.8 2020

Many different silicon detector technologies for particle tracking have been developed over the last four decades.



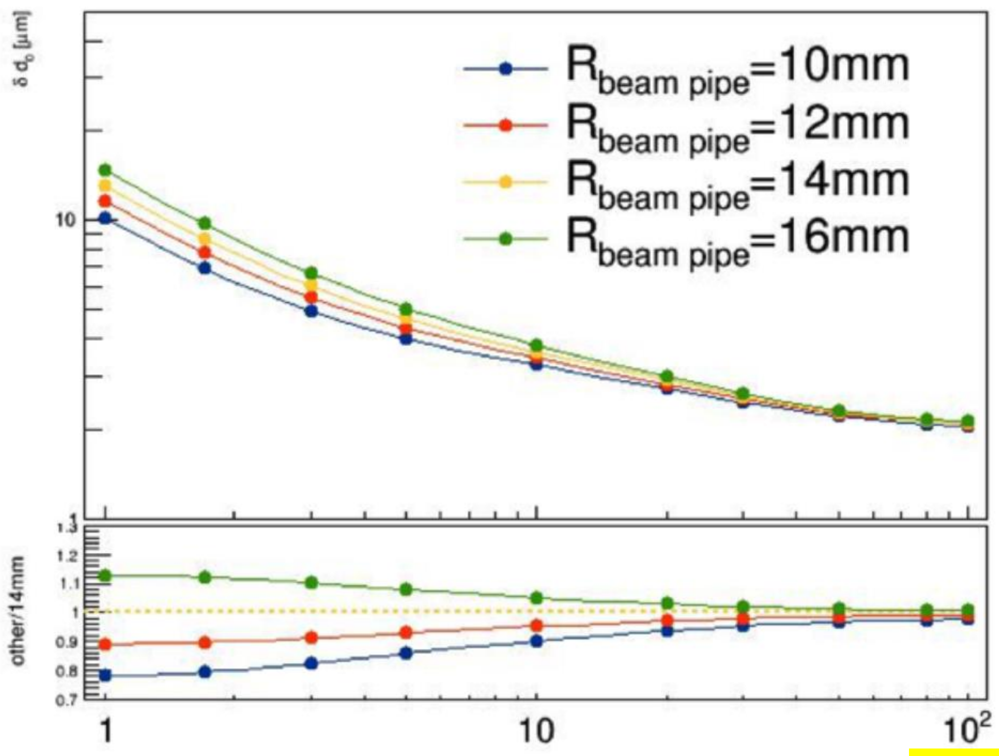
Applications of silicon strip and pixel-based particle tracking detectors - Nature Reviews Physics - https://doi.org/10.1038/s42254-019-0081-z Allport2019ER

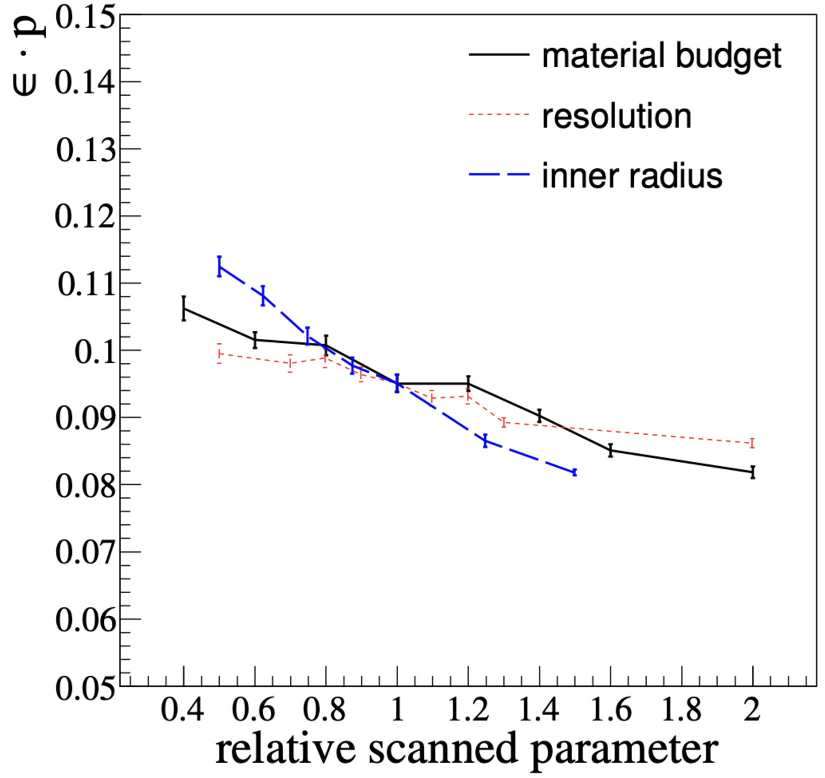
What is remarkable is that <u>every decade</u> the instrumented areas have increased by a factor of 10 while the numbers of channels in the largest arrays have increased by a factor of 100.

VERTEX DETECTOR FOR FUTURE COLLIDER: GENERAL WISHLIST

- Wishlist for vertex detector
  - Closer to beam pipe (most important!)
  - Minimum material
  - High resolution pixel sensor

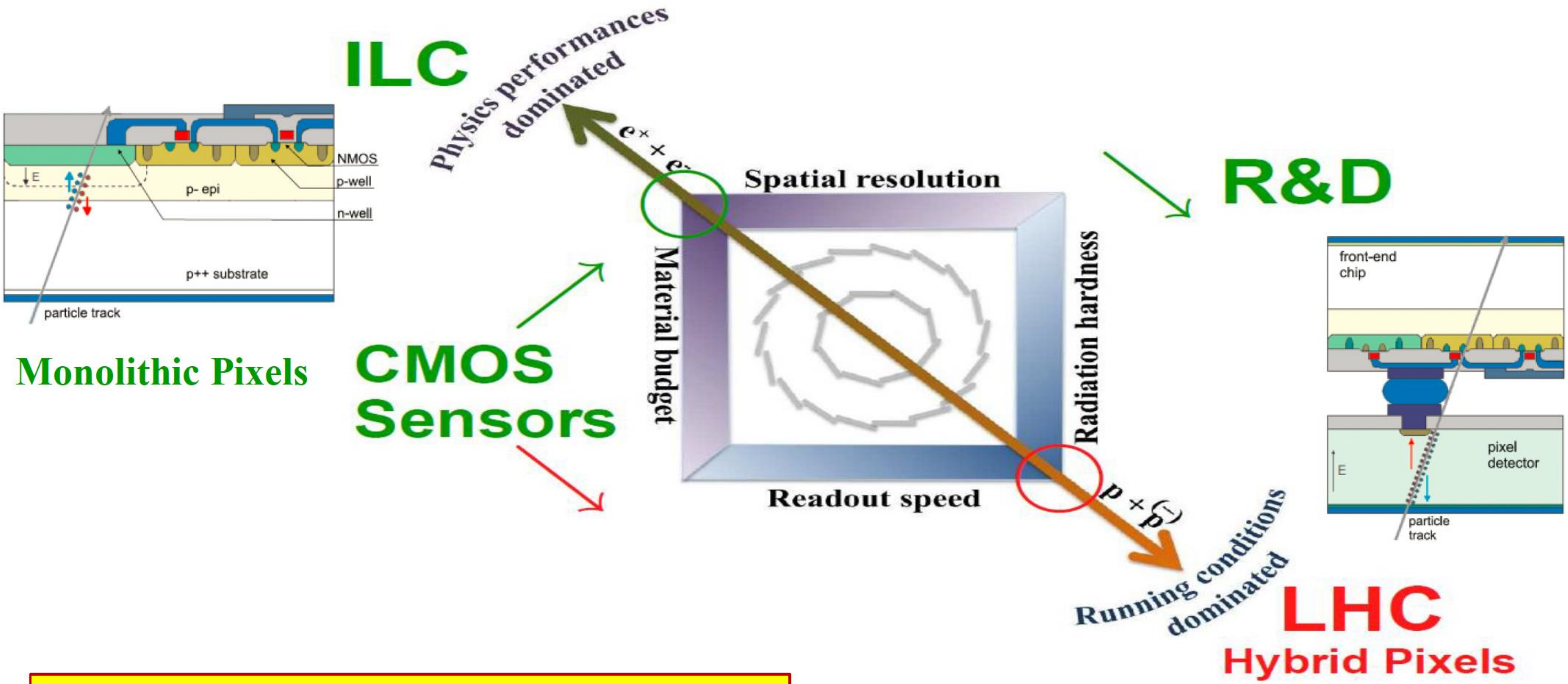
$$\epsilon \cdot p = 0.095(1 - 0.14\frac{\Delta x_{\text{material}}}{x_{\text{material}}})(1 - 0.09\frac{\Delta x_{\text{resolution}}}{x_{\text{resolution}}})(1 - 0.23\frac{\Delta x_{\text{radius}}}{x_{\text{radius}}})$$





ZG Wu, MQ Ruan et al., Study of vertex optimization at the CEPC, 2018 JINST 13 T09002

SILICON DETECTOR DEVELOPMENT

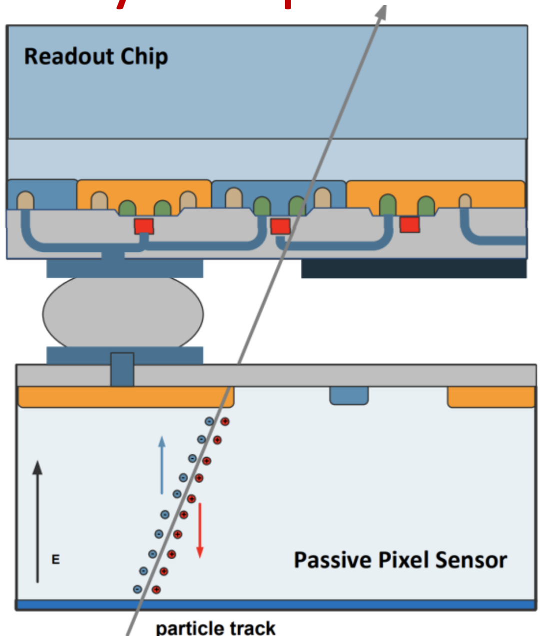


M. Winter, Monolithic Active CMOS Pixel Sensors, iWORID2019

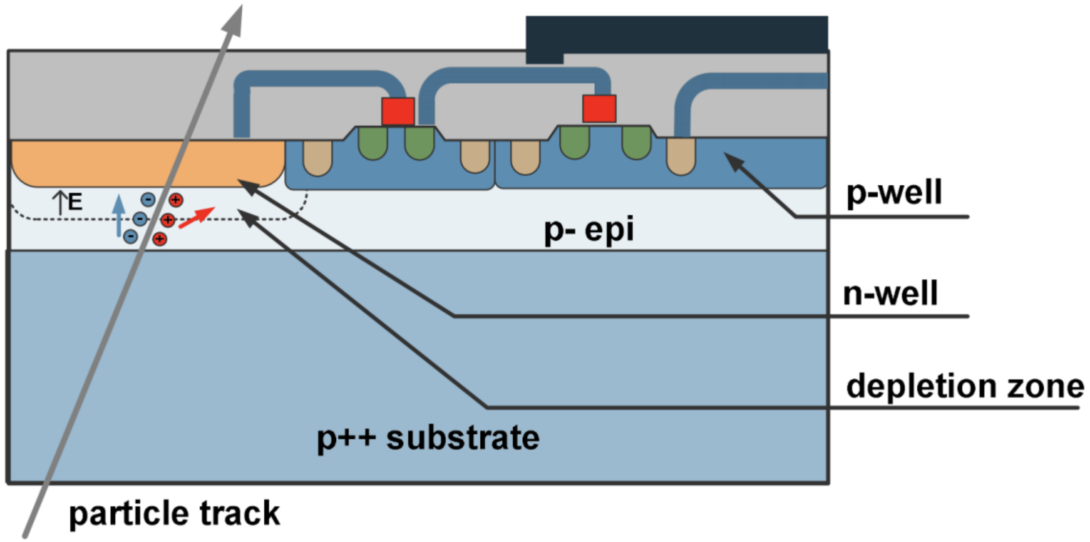
Vertex Sensor Development

- Hybrid pixel technology (example: ATLAS and CMS, LHCb)
  - Sensor and ASIC are designed separately, integrated by bump bonding
  - Advantage: Radiation hard, advanced in spin off application (Timepix, …)
  - Drawback: material budget (sensors and ASIC are both about 300um thick)
- Monolithic pixel (example: Star, BELLE2, ALICE ITS2 , Mu3e….)
  - Advantage: low material budget (can be thin down to 50μm)
  - Drawback: radiation hardness is not as good compared to hybrid pixel sensor

Hybrid pixel

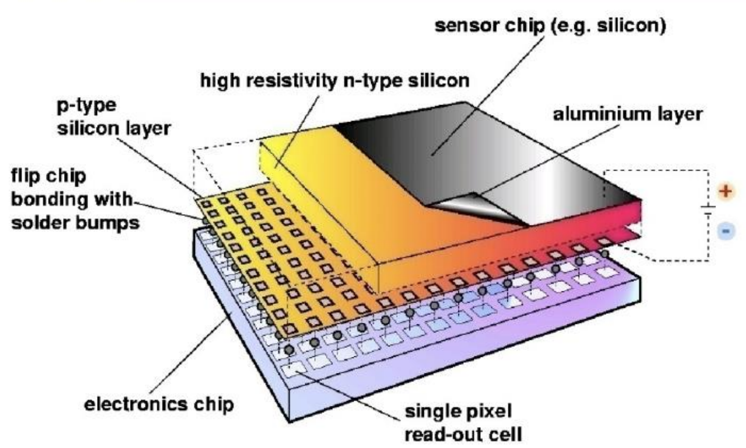


Monolithic Pixels



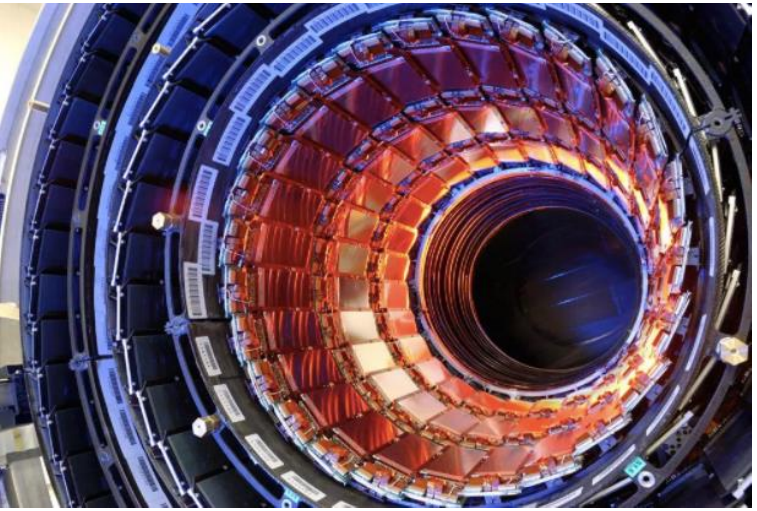
Hybrid pixel technology

- Radiation sensor
  - Current LHC operation showed pixel can work @ 10^{15} Neq/cm2 fluence
  - LHC upgrade (3D pixel sensor) → work up to $2*10^{16}$ N_{eq}/cm^2 fluence
  - Future Fcc-hh or Sppc: how to suffer 10^{17} N_{eq}/cm^2 fluence ?

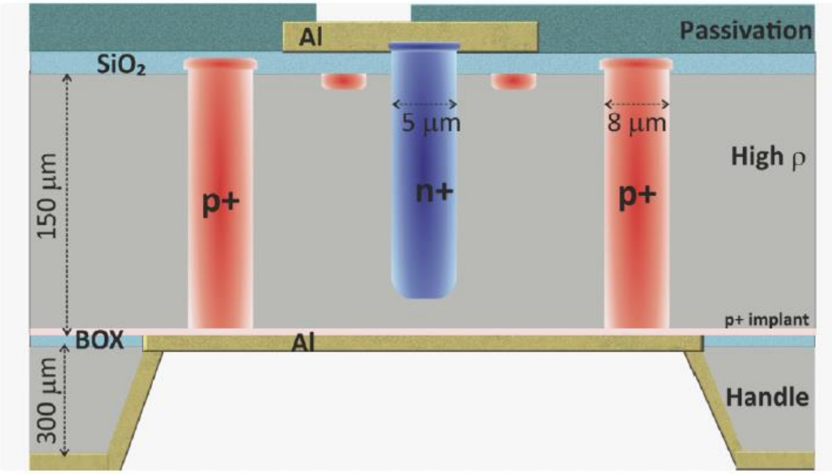


- Fast ASIC
  - RD53 chip: fast readout chip for HL-LHC ATLAS and CMS vertex detectors

Current LHC: CMS silicon tracker

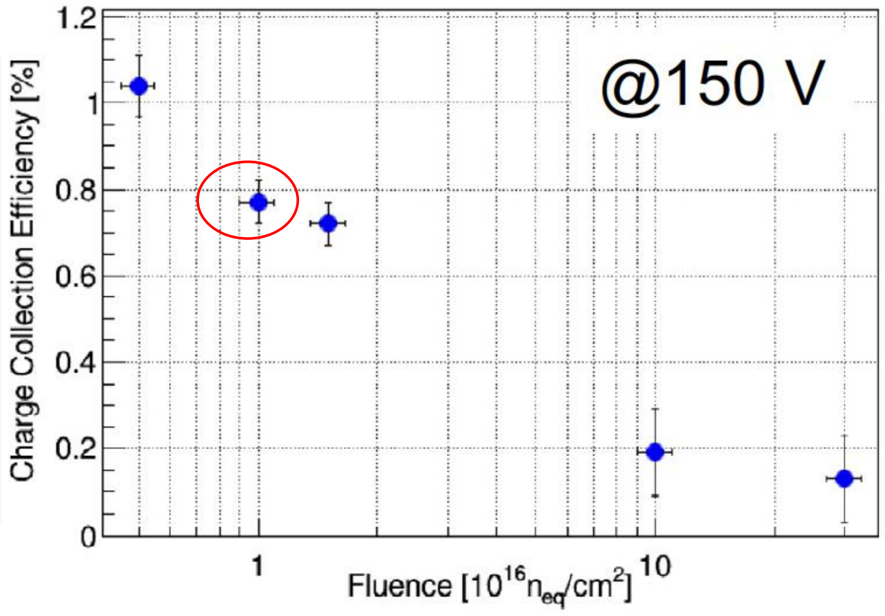


LHC upgrade: 3D pixel sensor

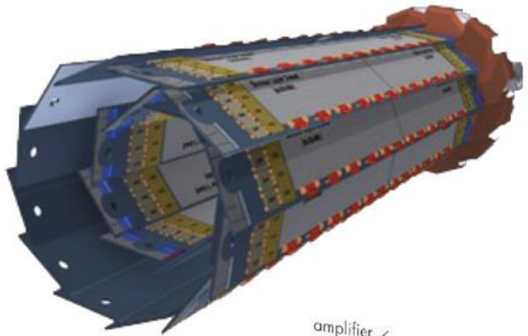


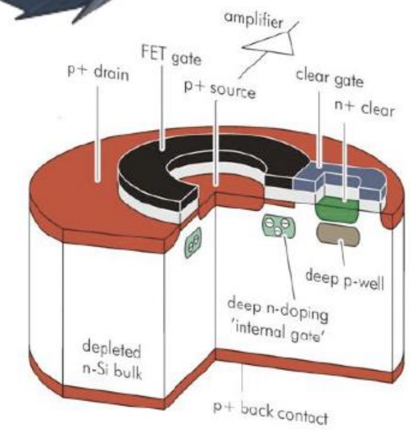
3D pixel sensor performance

M. Manna et al., NIMA 979(2020) 164458

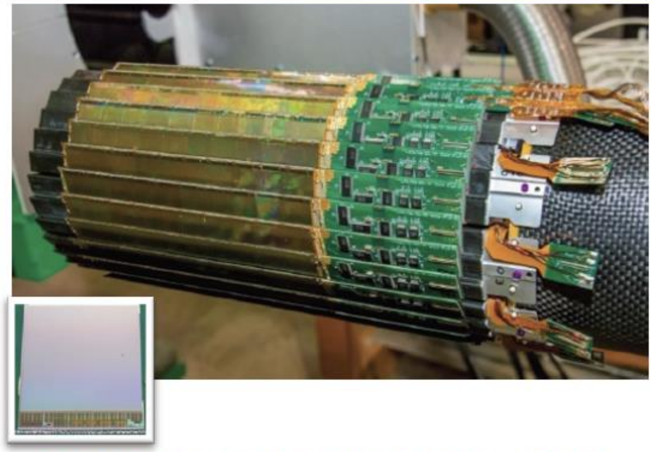


Monolithic sensors in HEP





DEPFET in Belle



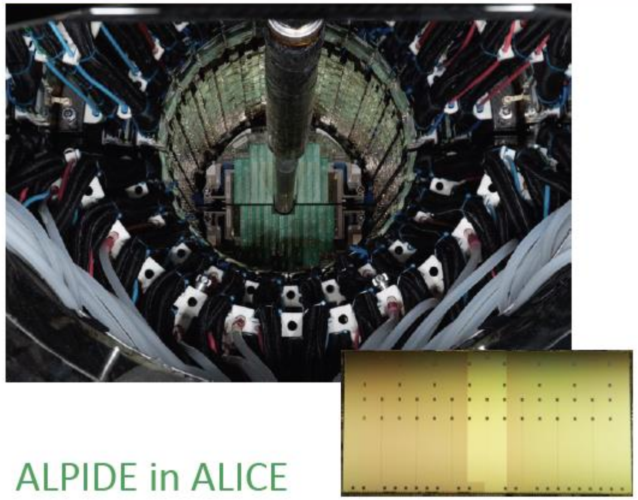
MIMOSA28 (ULTIMATE) in STAR

IPHC Strasbourg

First MAPS system in HEP

Twin well 0.35 µm CMOS

- Integration time 190 µs
- No reverse bias -> NIEL few 10^{12} 1 MeV n_{eq}/cm^2
- Rolling shutter readout



ALPIDE in ALICE

First MAPS in HEP with sparse readout similar to hybrid sensors

Quadruple well 0.18 µm CMOS

- Integration time <10 µs
- Reverse bias but no full depletion -> NIEL ~10^{14} 1 MeV n_{eq}/cm^2

DEPLETED MAPS for better time resolution and radiation tolerance

Large collection electrode

LF Monopix, MuPix,…

Extreme radiation tolerance and timing uniformity, but large capacitance

Small collection electrode

ARCADIA LF, TJ Malta, TJ Monopix, Fastpix, CLICTD, …

- Sub-ns timing
- NIEL >10^{15} 1 MeV n_{eq}/cm^2 and beyond

W. Snoeys, CEPC workshop 2022

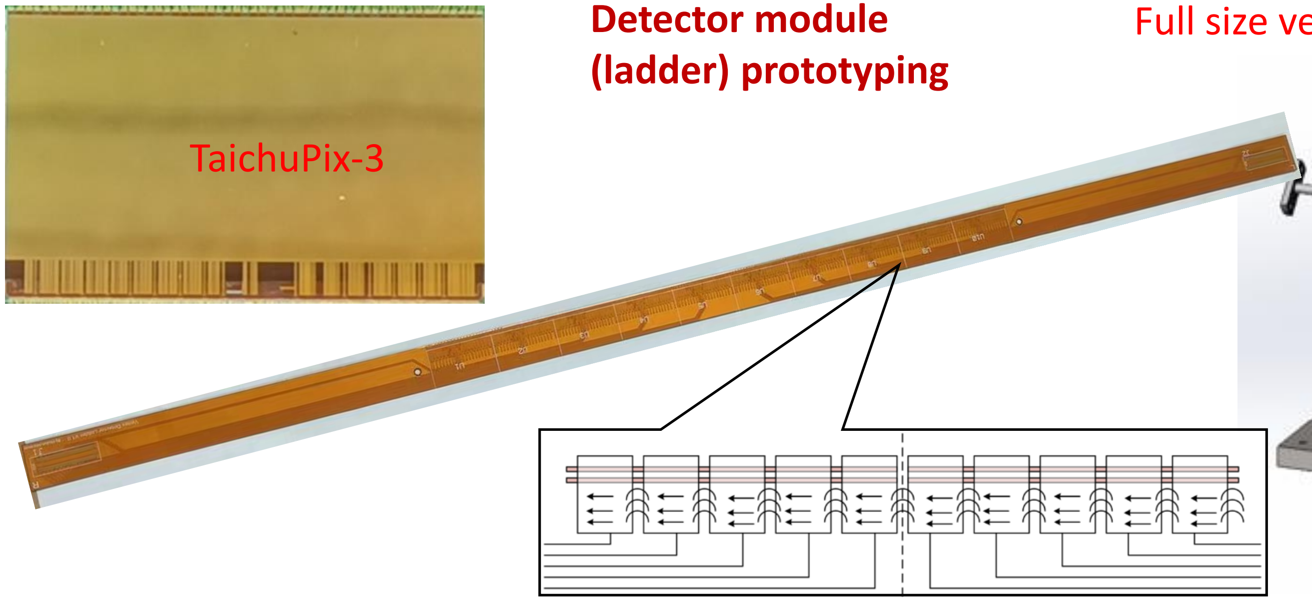
OUTLINE

- Overview of vertex detector
- CEPC vertex detector R & D
- More Future prospect

Overview of CEPC vertex detector prototyping

- **Vertex prototype R & D**
  - CMOS Pixel Sensor chip R&D
  - Detector module prototyping
  - Detector assembly

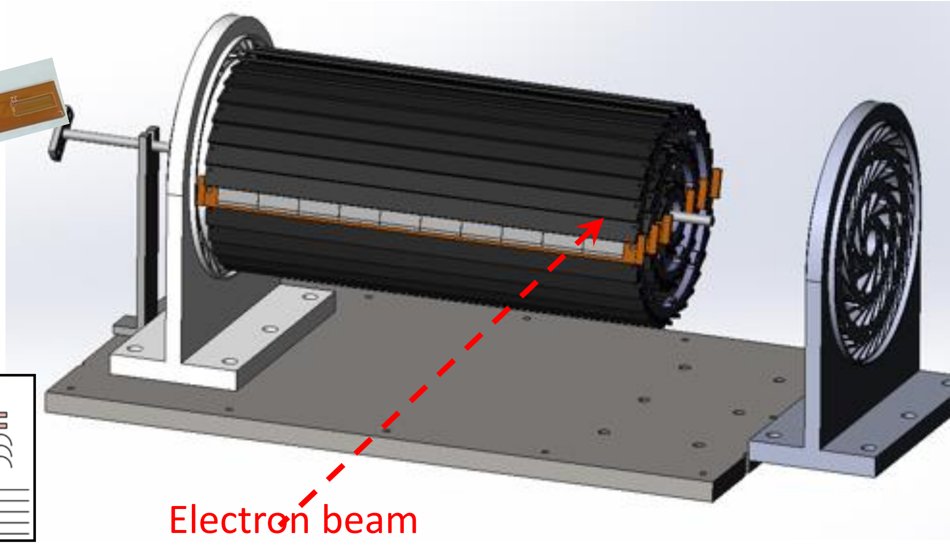
CMOS pixel sensor prototyping



Detector module (ladder) prototyping

Double sided ladder
10 sensors/ladder side, read out from both ends

Full size vertex detector prototype



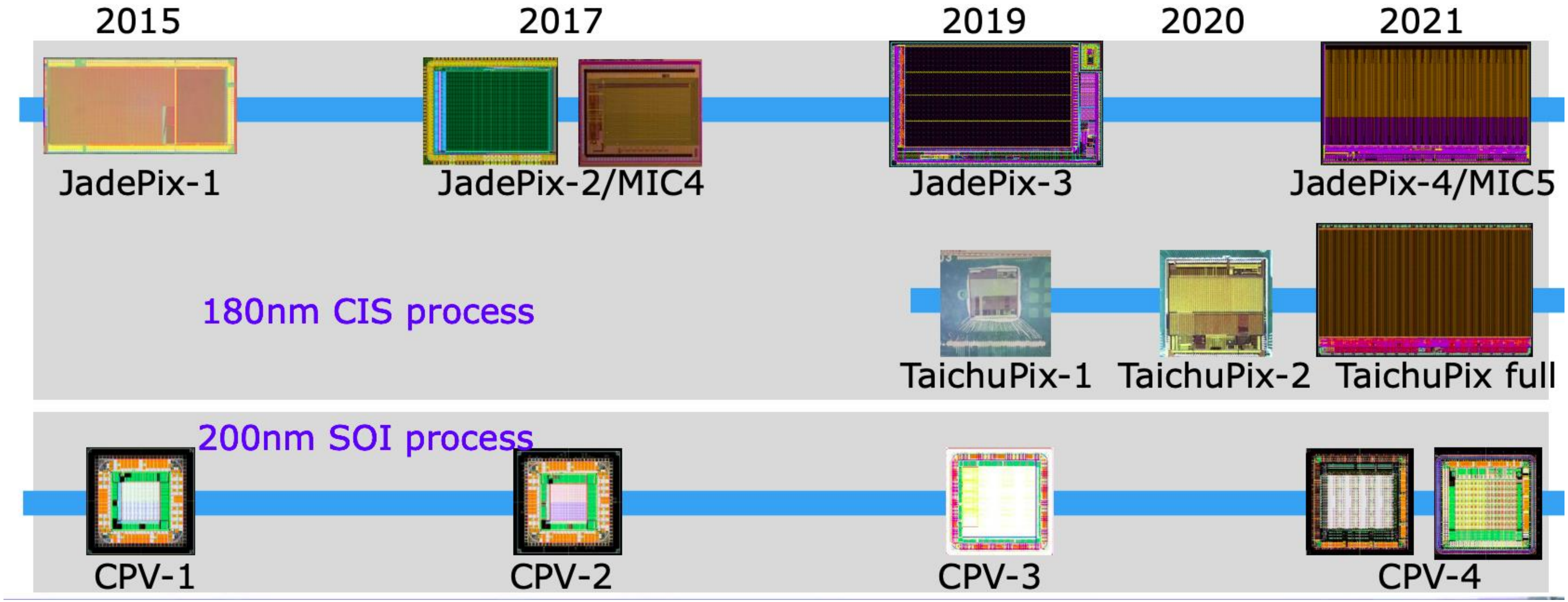
CMOS MONOLITHIC PIXEL SENSOR

- The existing CMOS monolithic pixel sensors can't fully satisfy the requirement
- Major constraints for the CMOS sensor
  - Pixel size: Single point resolution < 3 μm
  - <500ns deadtime @40MHz clock at Z pole
  - Radiation tolerance **(per year):** 1 MRad &2×10^{12} 1 MeV n_{eq}/cm^2

experiment	Chip	Resolution	Readout Speed	TID
ALICE	ALPIDE	✔	X	X (?)
ATLAS	Malta Monopix ATLASpix…	X	✔	✔
Star	MIMOSA	✔	X	X (?)

CEPC VERTEX SENSOR R & D

- CEPC Vertex detector sensor R & D timeline
  - Monolithic Pixel sensor design
    - Based on Tower Jazz CIS 180nm process (Jadepix , TaichuPix)
    - Based SOI 200nm process (CPV chip)

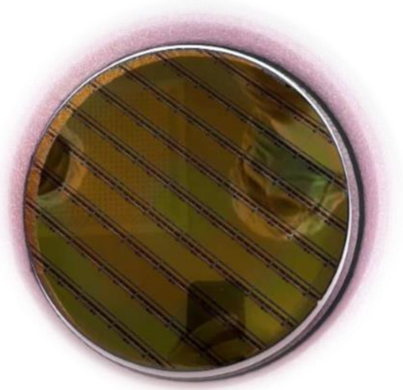


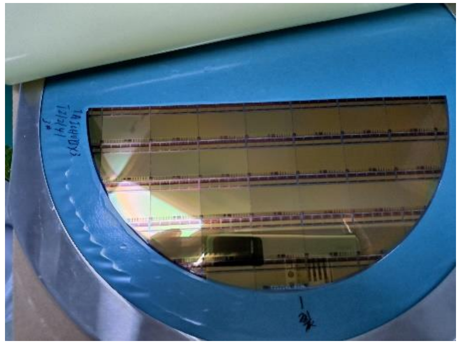
By Yunpeng

Large-scale MAPS sensor for CEPC: TaichuPix-3

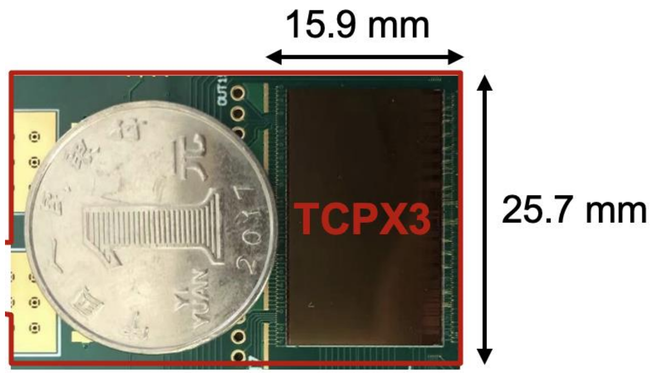
- **6 TaichuPix-3 wafers (thinned down to 150 µm and diced)**

Chip size: 26 ×16 mm
Pixel size: 25µm × 25µm


8-inch wafer

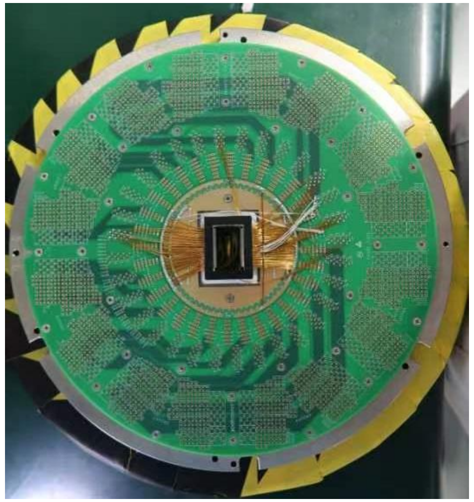

Wafer after thinning and dicing

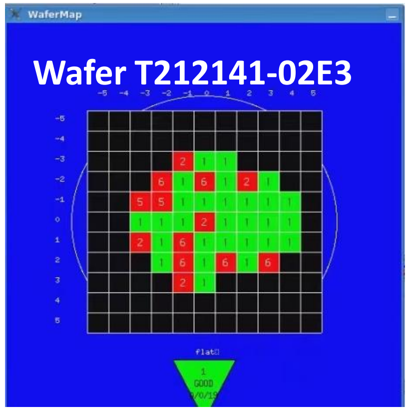

Thickness after thinning



TaichuPix-3 chip vs. coin

wafer test on probe-station → 70-80% yield


Probe card for wafer test

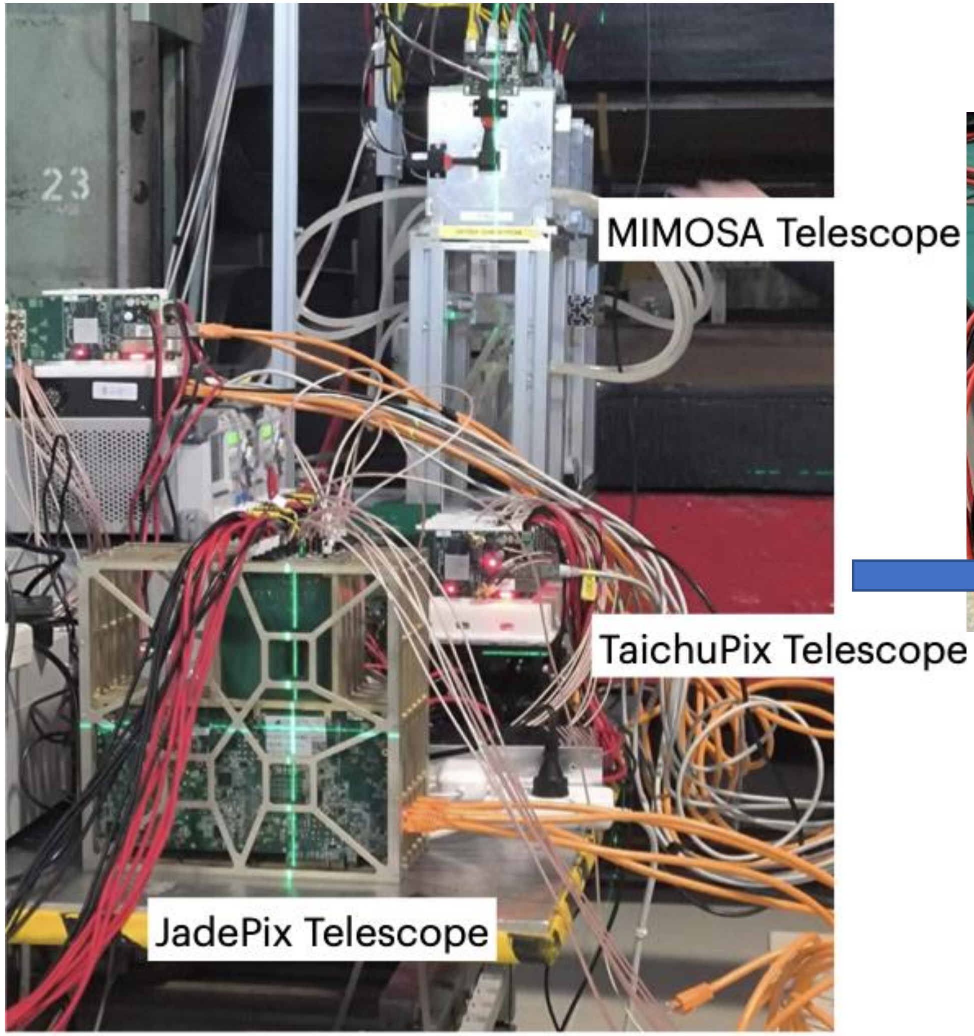


An example of wafer test result

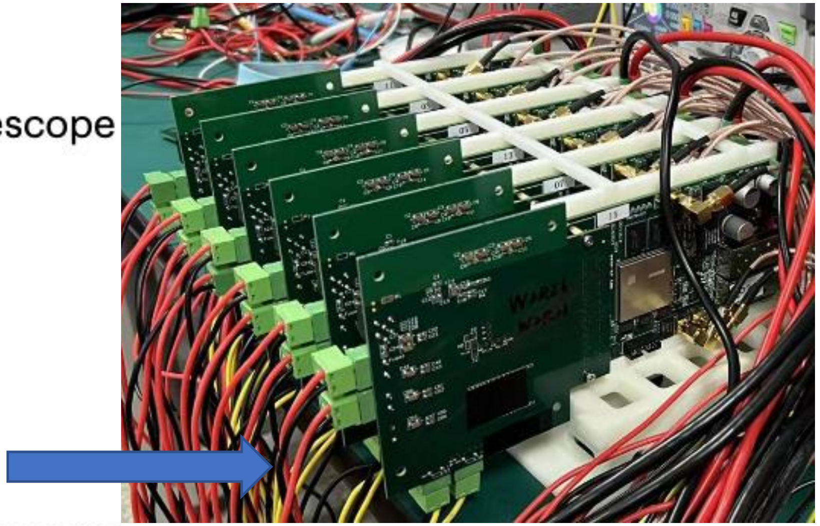
Functional tests of the chip

CEPC vertex detector : DESY Testbeam

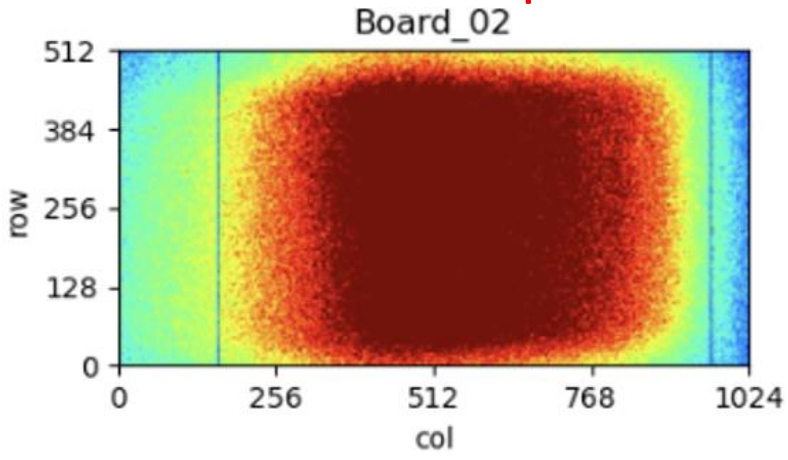
- The 6-layer of TaichuPix3 telescope
- 4-layer JadePix telescope.



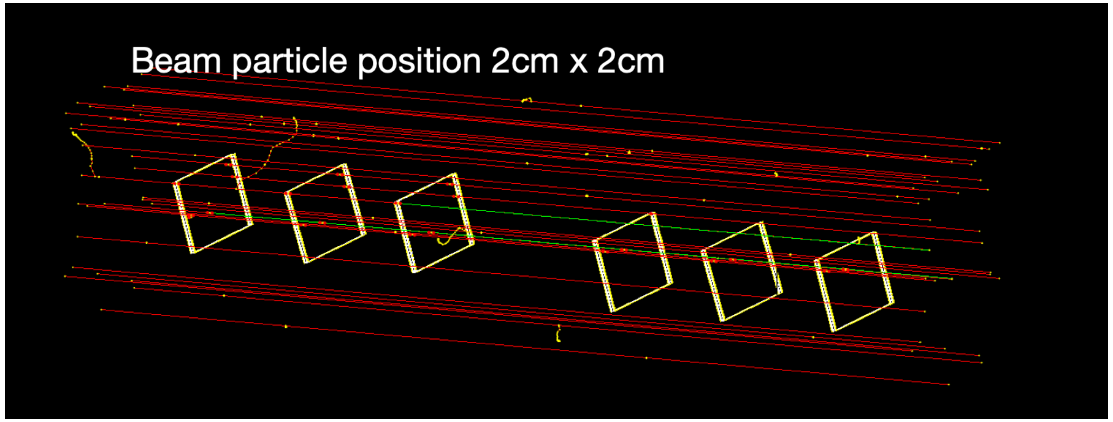
Test Setup @DESY Dec.2022



Hit maps



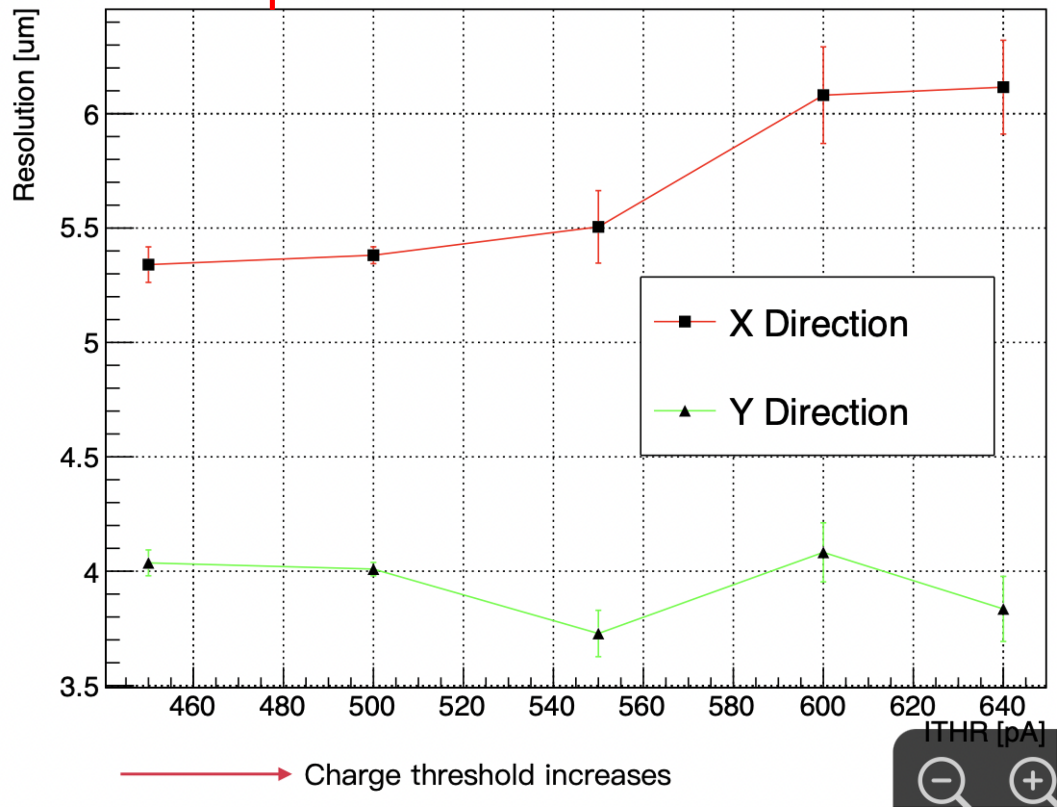
Event display



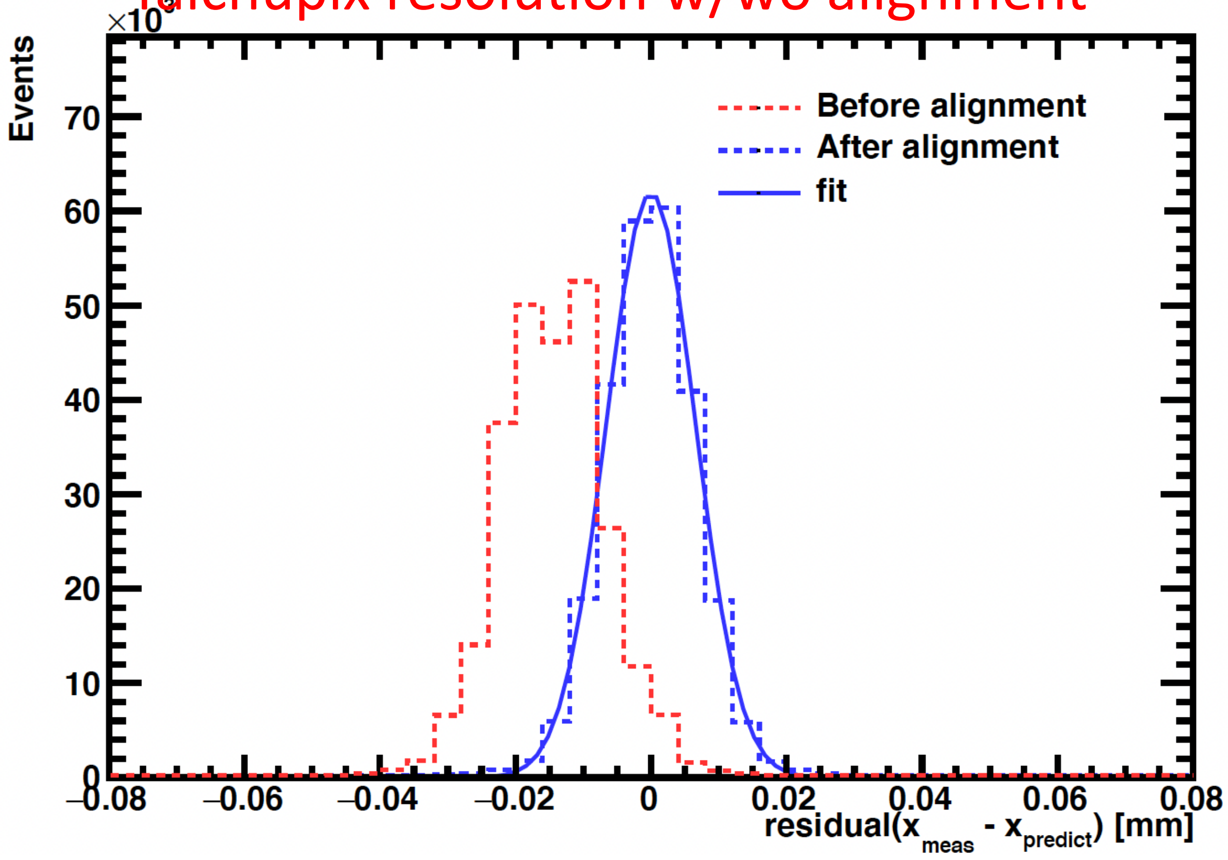
CEPC vertex detector : DESY Testbeam

- **Both CEPC pixel sensor prototype(Taichu and Jadepix) reach 3~5μm resolution**
- **Efficiency can reach ~ 99%**
  - Taichu can work at 20Mhz clock with high efficiency.

Jadepix resolution



Taichupix resolution w/wo alignment



Vertex detector prototype assembly

- **Installation procedure of 3 double layer of vertex detector**

Inner barrel

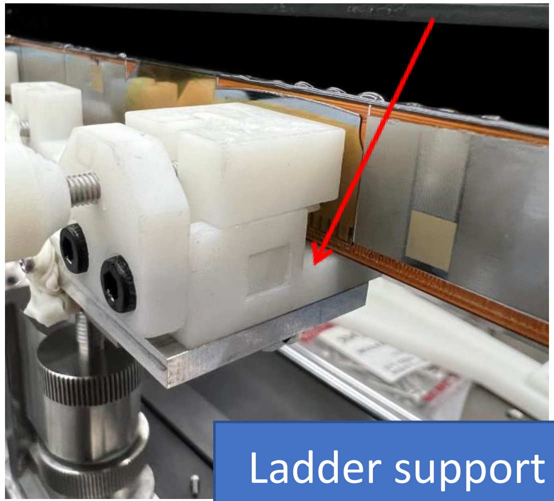
Middle barrel
(half number of ladders)

Outer barrel
(half number of ladders)

CEPC vertex detector: Ladder loading

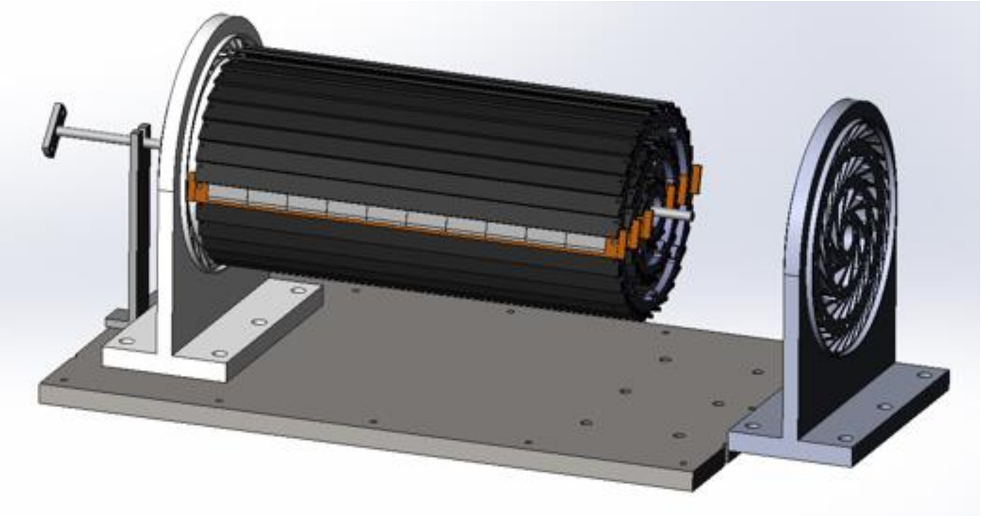
- **Loading procedure of ladder on vertex detector has been tested**
- **Another testbeam with full prototype expected in April 2023.**

Wire-bonding



Ladder support tools

Ladder loaded on vertex detector

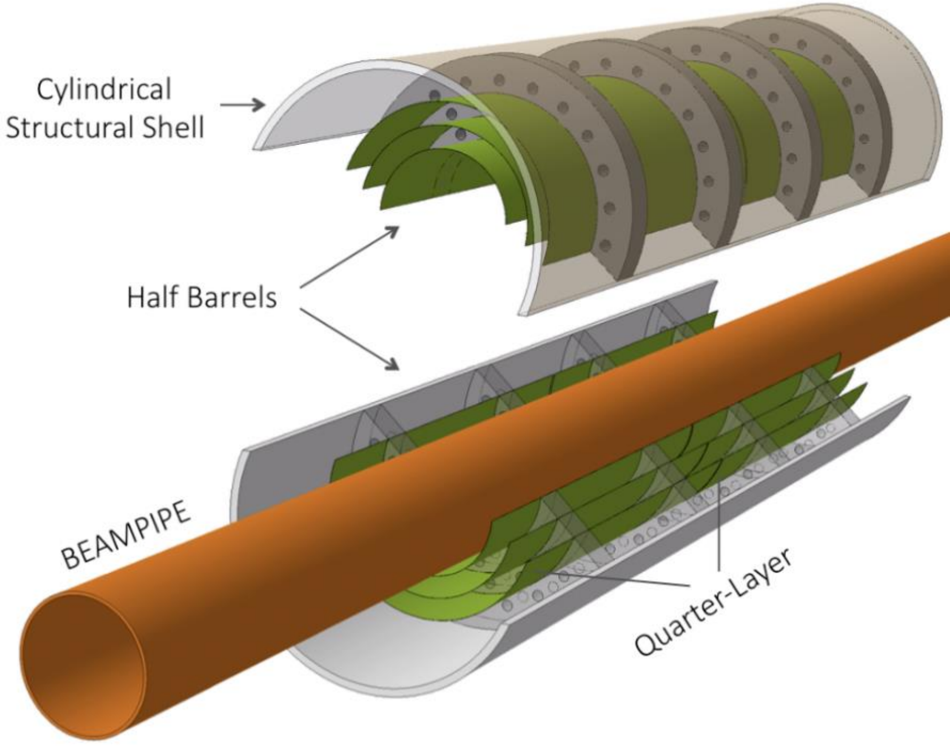


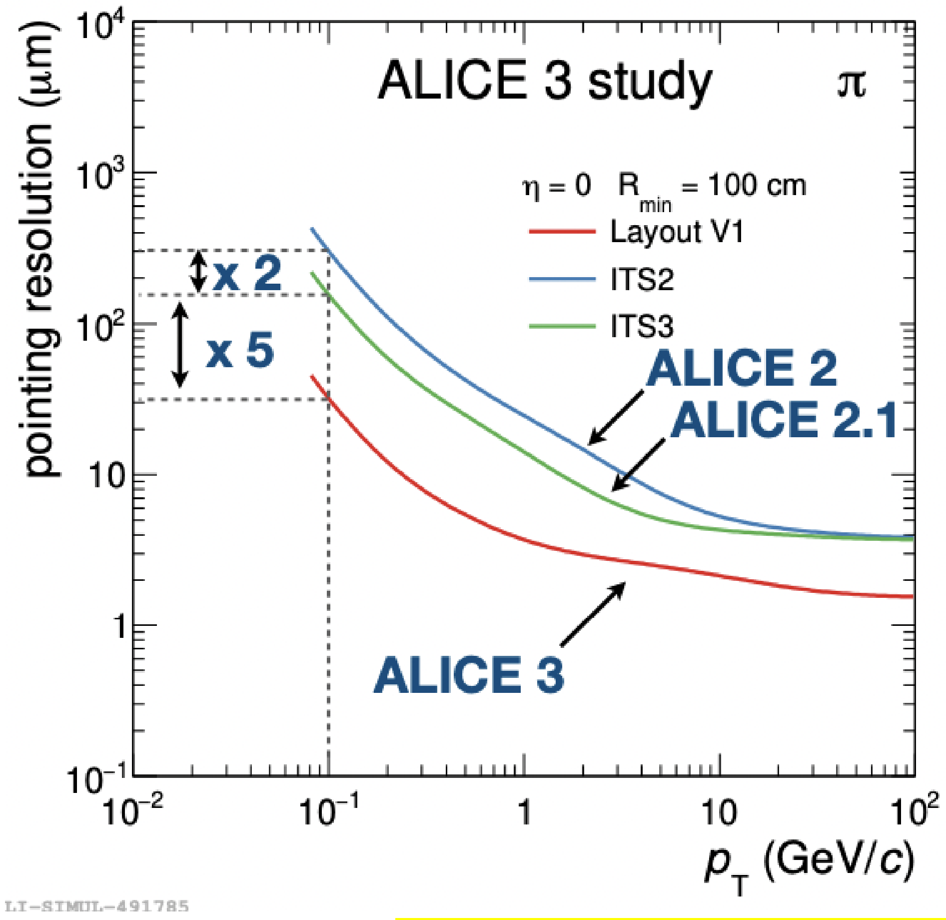
OUTLINE

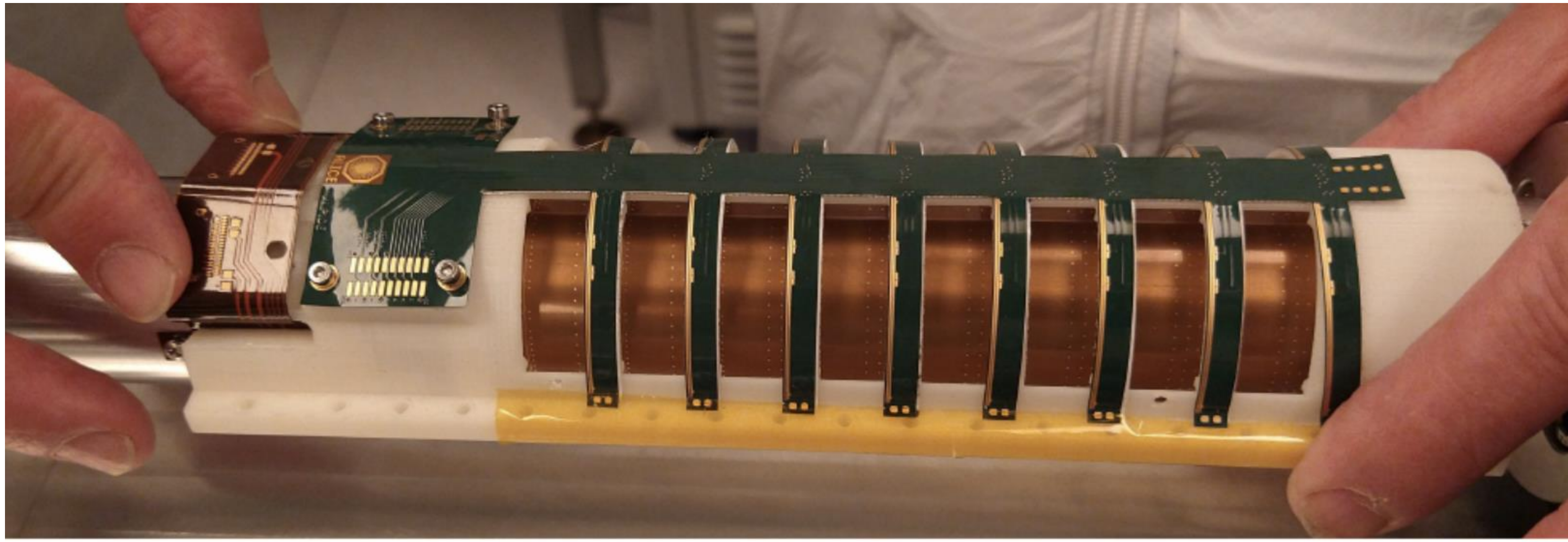
- Overview of vertex detector
- CEPC vertex detector R & D
- More Future prospect
    - Alice upgrade
    - Timing detector

Alice ITS3 upgrade: MAPS

- Cylindrical inner tracker with curved MAPS wafer
  - 5 times better performance expected that ITS2



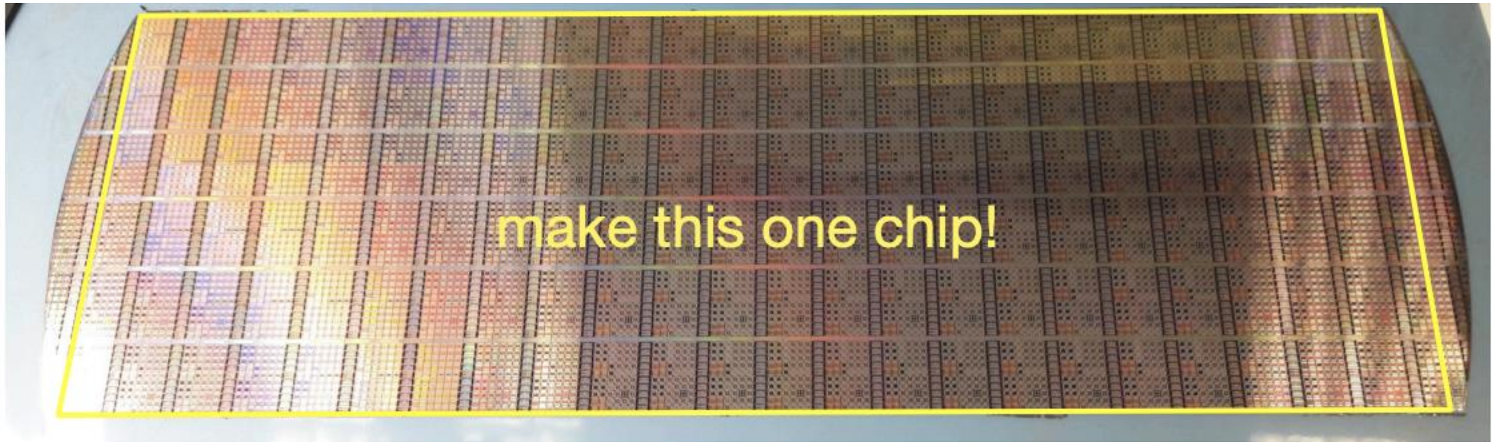


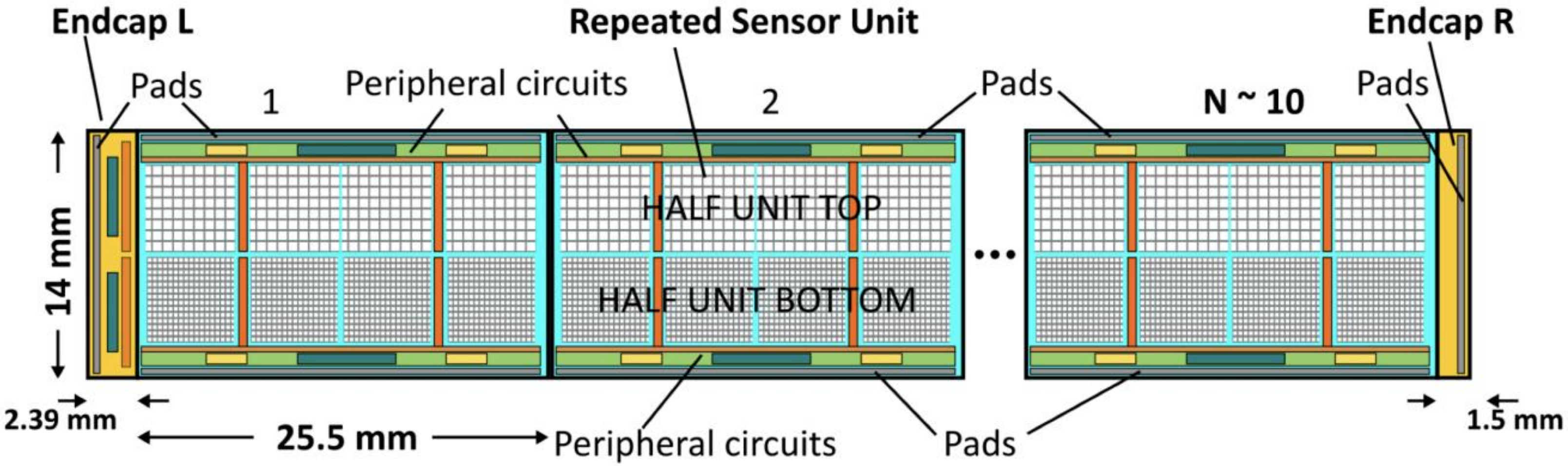


From Magnus Mager & Nicolò Jacazio *(Alice collobration), ICHEP2022*

Alice ITS3 upgrade: 65nm technology & Stitching

- First submission of TPSCo 65 nm CMOS Imaging Technology successful
- next submission by Alice ITS3 community focus on stitching

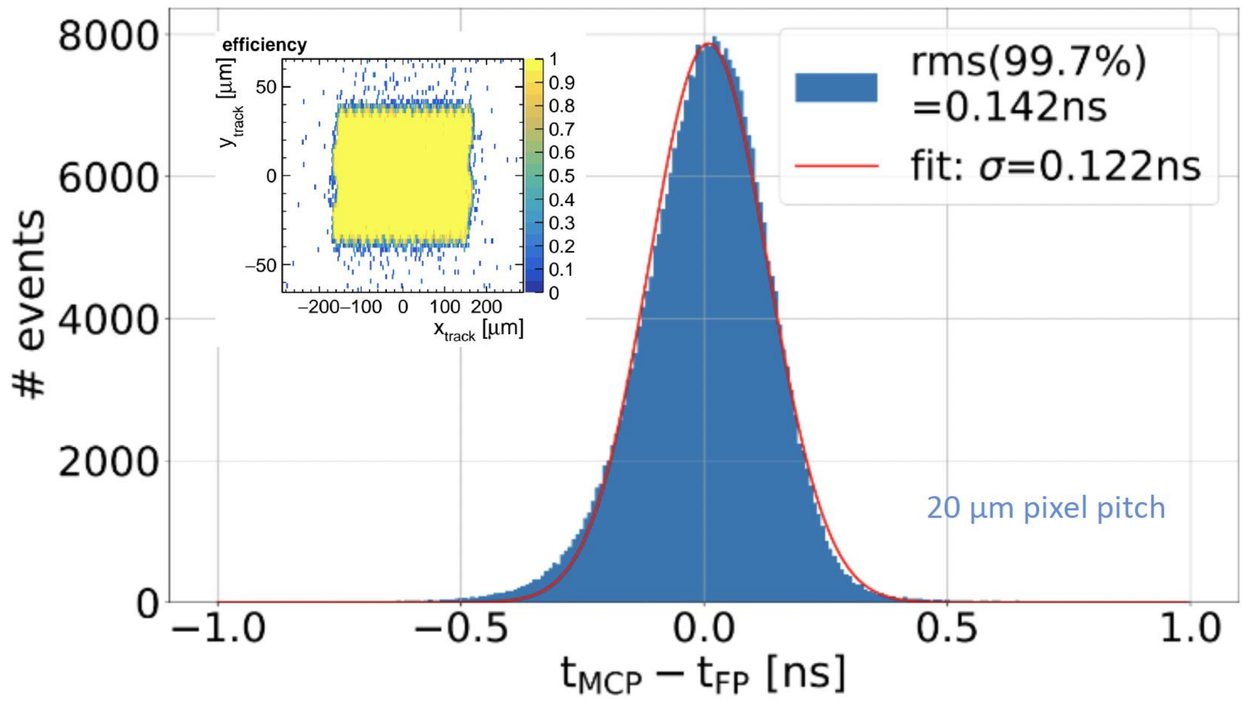


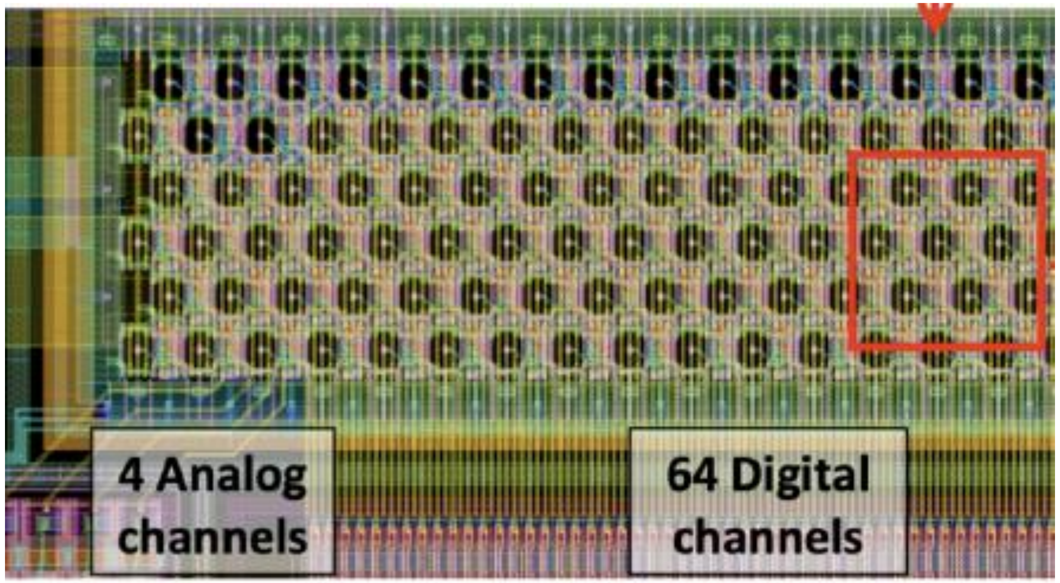


From Magnus Mager (Alice collobration), ICHEP2022

FastPix development

- Future vertex with 4D precision: space resolution + timing
  - 8.6, 10, 15 and 20 μm pixel pitch
  - Time resolution better than 150 ps at full efficiency
  - Si-Ge fast readout

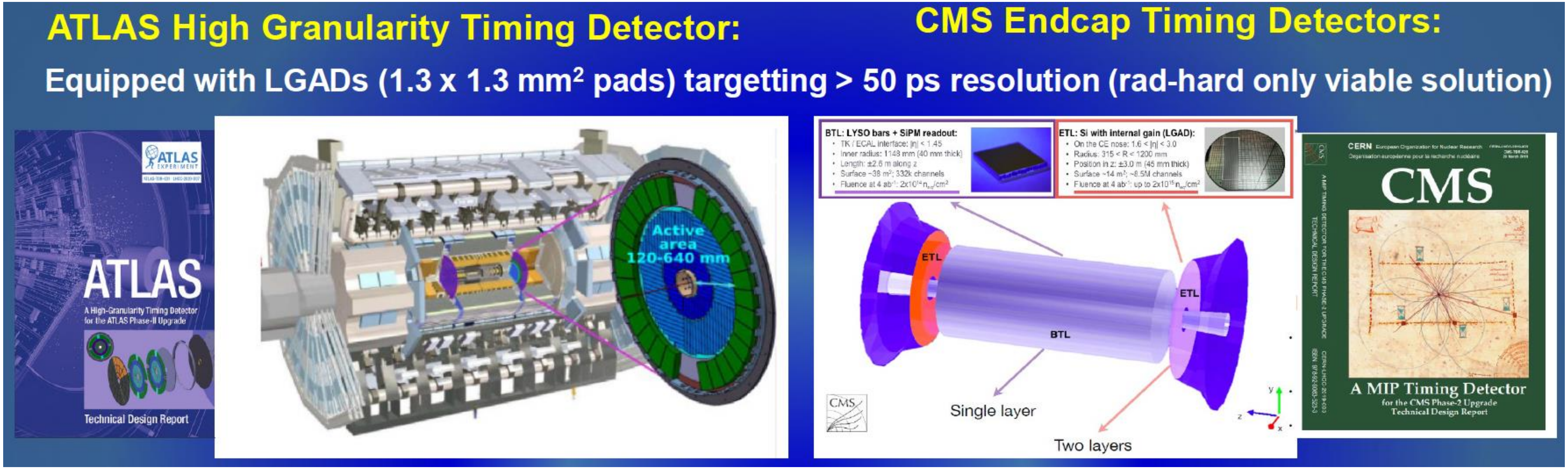




https://www.mdpi.com/2410-390X/6/1/13
J. Braach, E. Buschmann, D. Dannheim, K. Dort, T. Kugathasan, M. Munker, M. Vicente

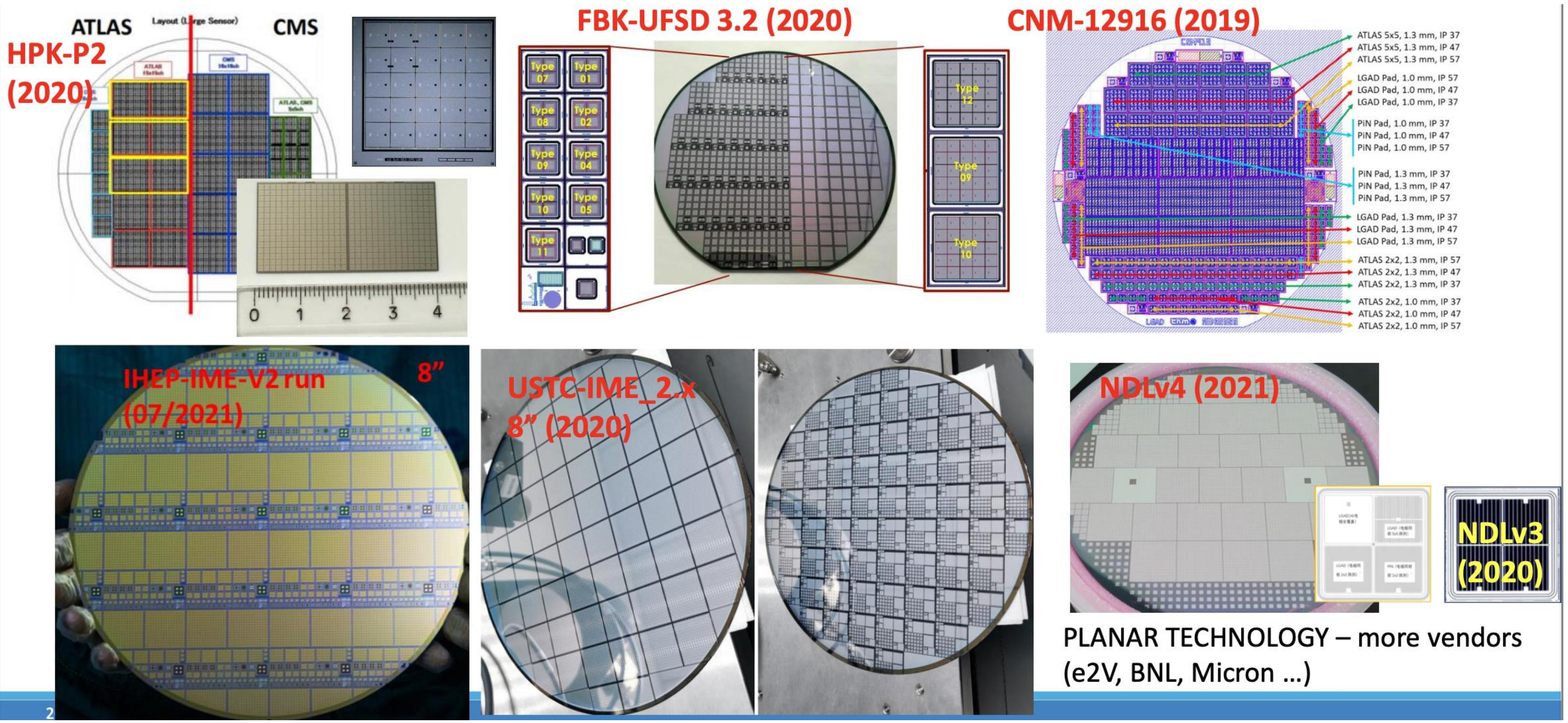
Silicon timing detector development

- Both ATLAS and CMS is aiming for silicon timing detector
  - with Low Gain Avalanche Detectors
  - 1.3mm^2 pad, with 30-50 ps resolution for single charge particle
  - Mainly for pileup vertex rejection
  - Also useful for search long-live particles search

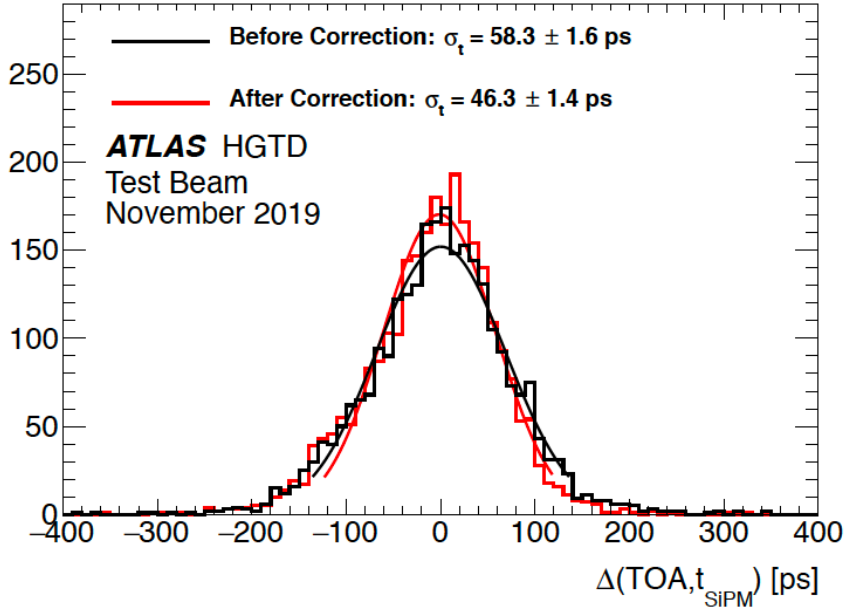


Silicon timing detector development

- Both ATLAS and CMS is aiming for silicon timing detector
  - with Low Gain Avalanche Detectors (LGAD)
  - 30-50 ps resolution for single charge particle
  - Lots of foundries are doing R & D for LGAD around the world
  - LGAD based 4D silicon tracker proposed for future EIC



PLANAR TECHNOLOGY – more vendors
(e2V, BNL, Micron …)



Summary

- CMOS Monolithic pixel is very promising for future lepton collider
  - CPEC MAPS based vertex prototype is in good progress
    - 3 double layer prototype will be built and tested this year
  - ALICE ITS3 Cylindrical tracker has excellent potential in future colliders
- Fast time (<150ps time resolution) 4D pixel detector becoming feasible
  - LGAD based fast sensor
  - MAPS based technology