Karlsruhe Institute of Technology

Novel Detectors for Tracking and Timing

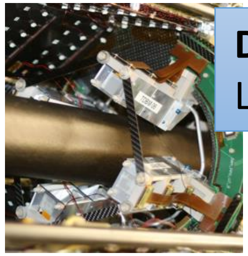
"satellite view"

Pixel 2022

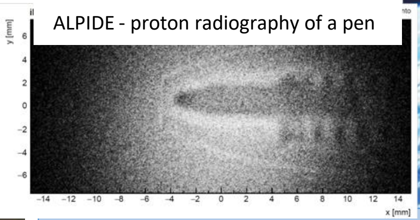
Frank Hartmann

I prepared an introduction talk – a bit of everything
- **Full credits** go to the **people doing the real work**, i.e. not me
- I am personally very curious to get the real news in the next days

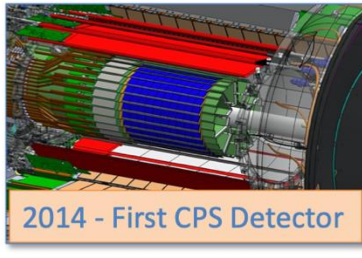
We are all using Silicon in various configurations
Some of us are also using Germanium, Tellurium, Diamonds



Diamonds – NuPECC; ECFA
LHC, GSI, KEK – *BCM, Lumi, Spectroscopy, timing (ToF)*

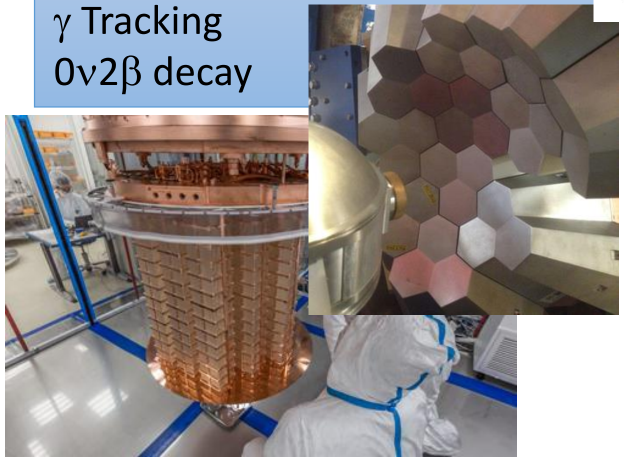


CSES – HEPD2

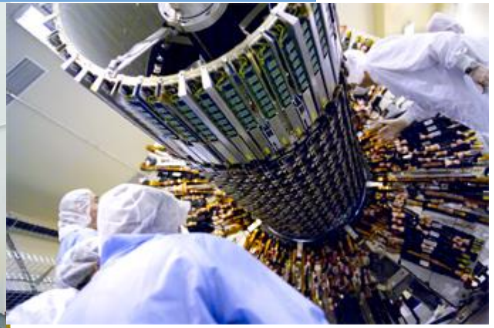


STAR HFT
0.16 m^2 – 356 M pixels

Germanium – NuPECC, ApPEC
γ Tracking
$0\nu2\beta$ decay

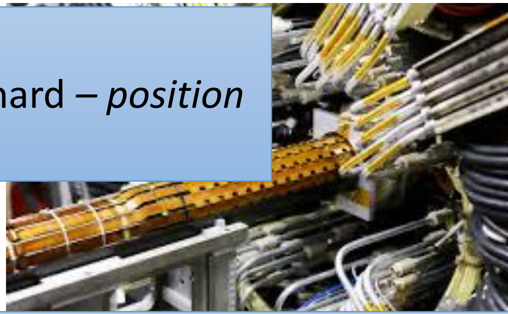


Si-Strips – NuPECC; ECFA, ApPEC
LHC, KEK, GSI, ISS, Satellite – *position*



MAPS/CMOS – NuPECC; ECFA, ApPEC
LHC, STAR, PSI satellite, CBM, medical – *position, imaging*

3D silicon – ECFA
Innermost layers - Radiation hard – *position*
ATLAS, CMS, timing

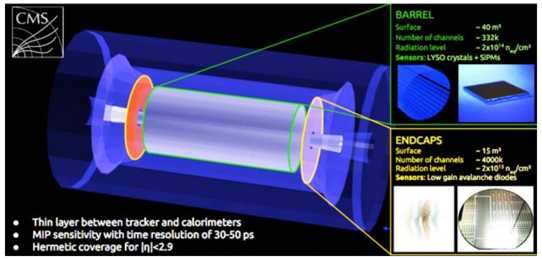


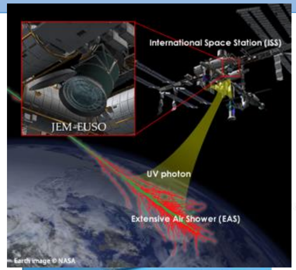
SiPM – NuPECC, ECFA, ApPEC
LHC, GSI, ISS, Satellite, medical (PET, X-ray) – *photons, energy, timing*

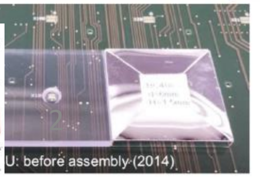
Si-Hybrid Pixel – NuPECC; ECFA, ApPEC
LHC, GSI, ISS, Satellite – *position*

+ synchrotron photon counting (HCPDs)

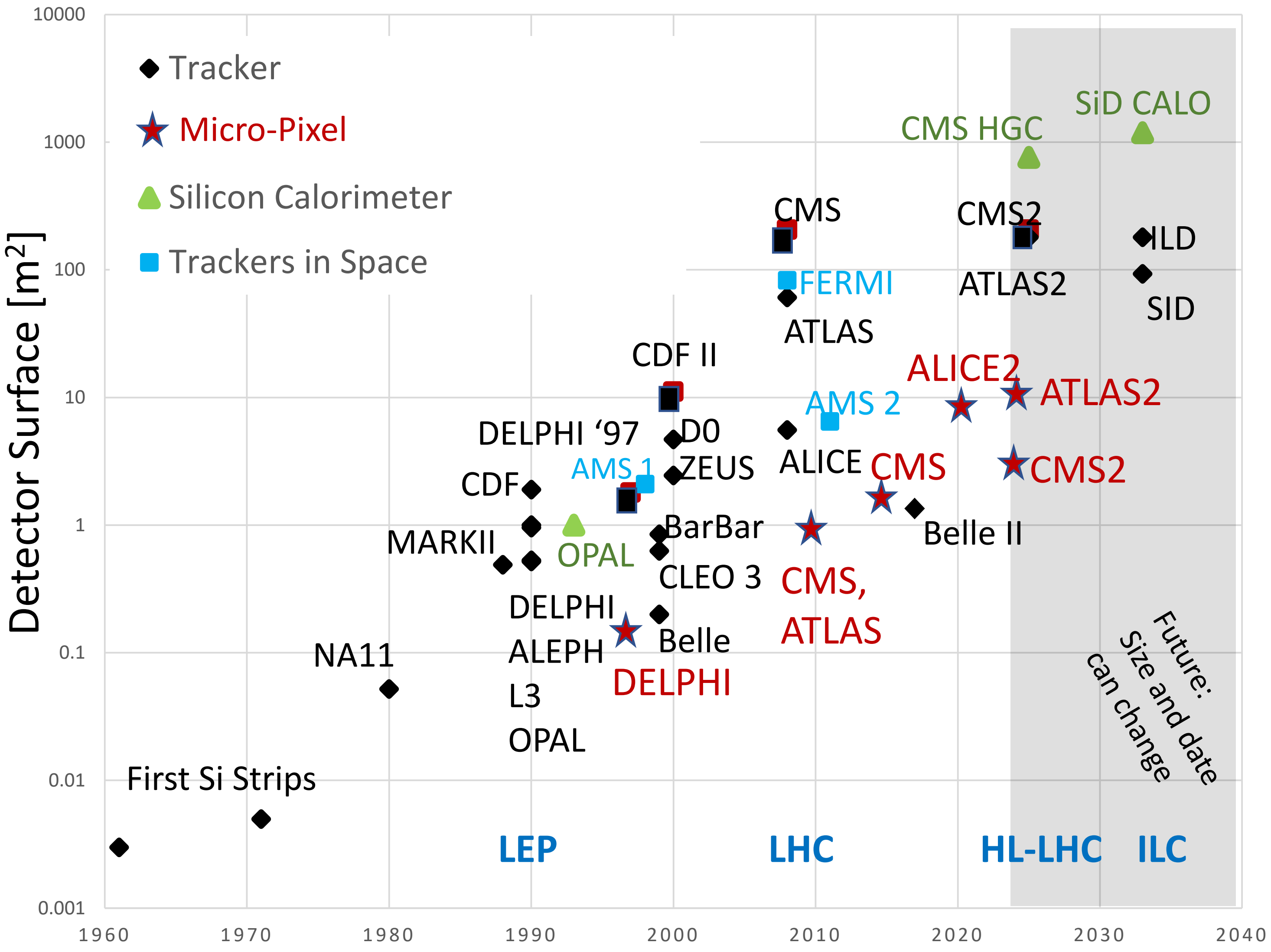
LGADs – ECFA
ATLAS & CMS – *timing, position*







Size matter! Does it?

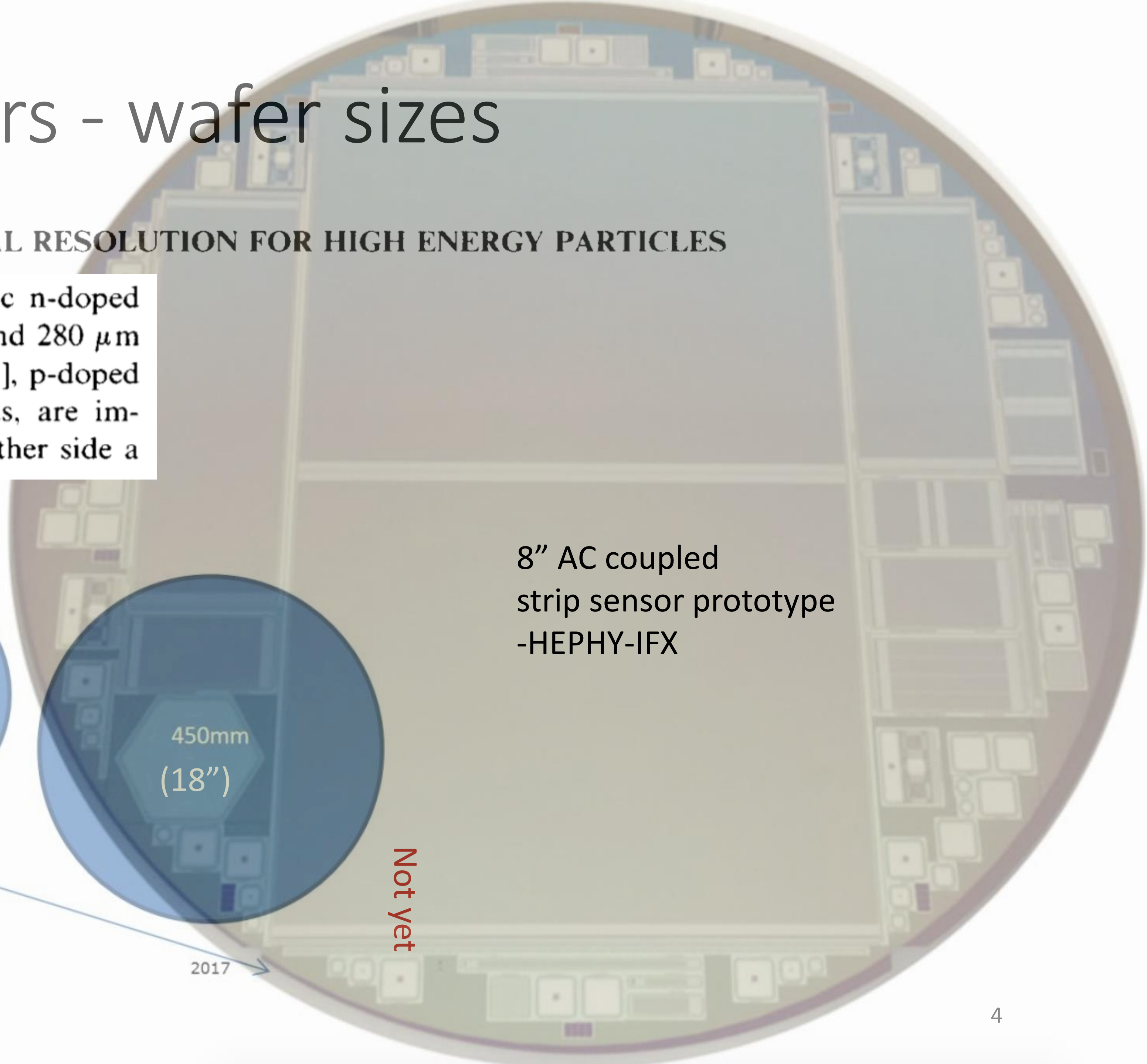


FCC-h
(no number)

Cell size **goes down significantly**
Cell count **goes up significantly**

We are counting in GIGA these days

Planar Silicon Sensors - wafer sizes

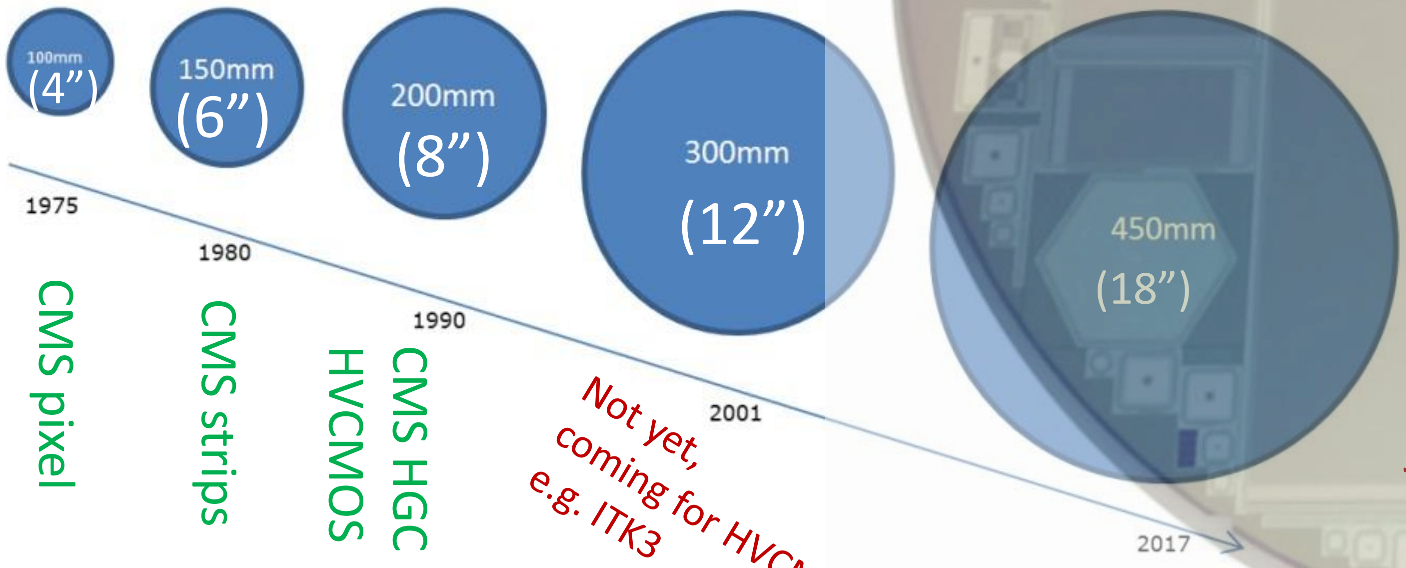


SILICON DETECTORS WITH 5 μm SPATIAL RESOLUTION FOR HIGH ENERGY PARTICLES

1983!

The detectors [2] are made of high-ohmic n-doped silicon single crystal wafers of 2″ diameter and 280 μm thickness (fig. 1). Using the planar process [1], p-doped strip diodes, covered by aluminium contacts, are implanted into one side of the wafer. On the other side a

Wafer Areas in Chip industries:



CMS pixel

CMS strips

HVCMOS

CMS HGC

Not yet,
coming for HVCMOS
e.g. ITK3

Not yet

8” AC coupled
strip sensor prototype
-HEPHY-IFX

We are stuck in the 90’

I discuss some items, that I consider novel but do not fully fit into the "Pixel" theme and/or are not discussed in later talks this week

Starters

- First 8" sensors for HEP *(for tracking inside a calorimeter and proof of concept for tracker)*
- Passive CMOS – is this a path?
- Level-1 Track and Vertex Trigger – a concept not a sensor, but needs *macro-pixel!*

Main

- Timing detectors and their evolution
  - Planar and 3D – with and without gain
- 3D pixels and their evolution
- HV-CMOS/DMAPS – is this the future?

Dessert

- Coffee Break

Appetizers

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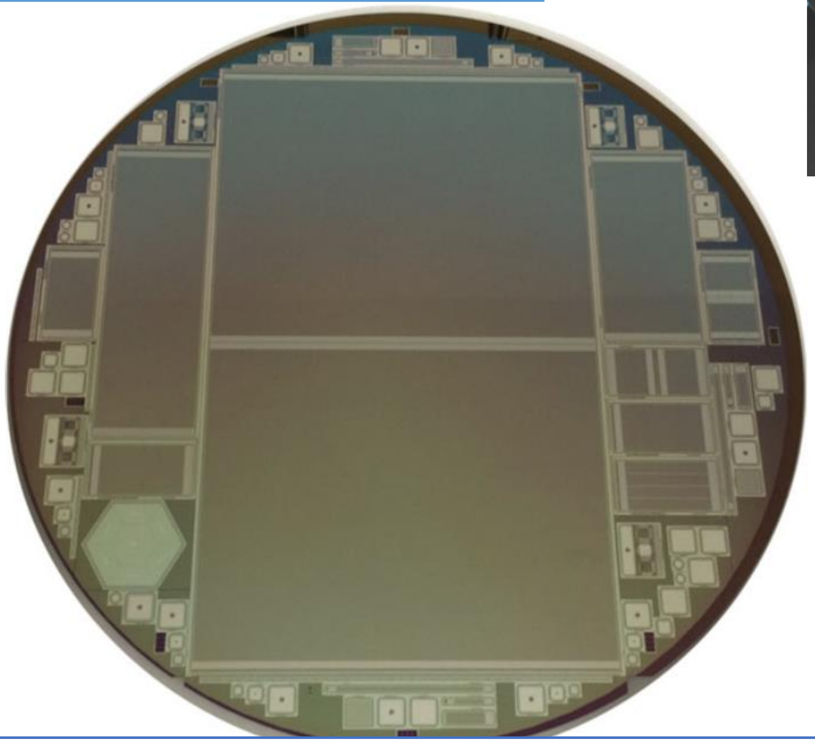
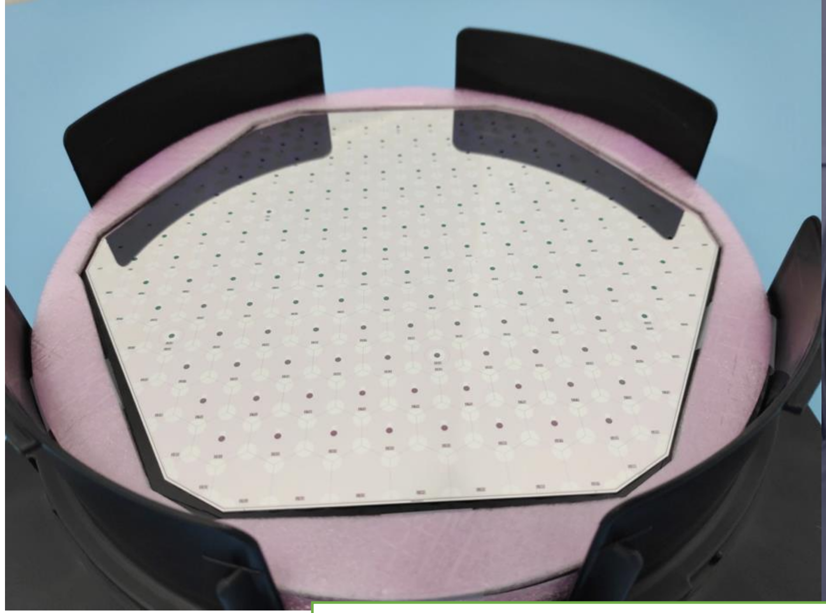
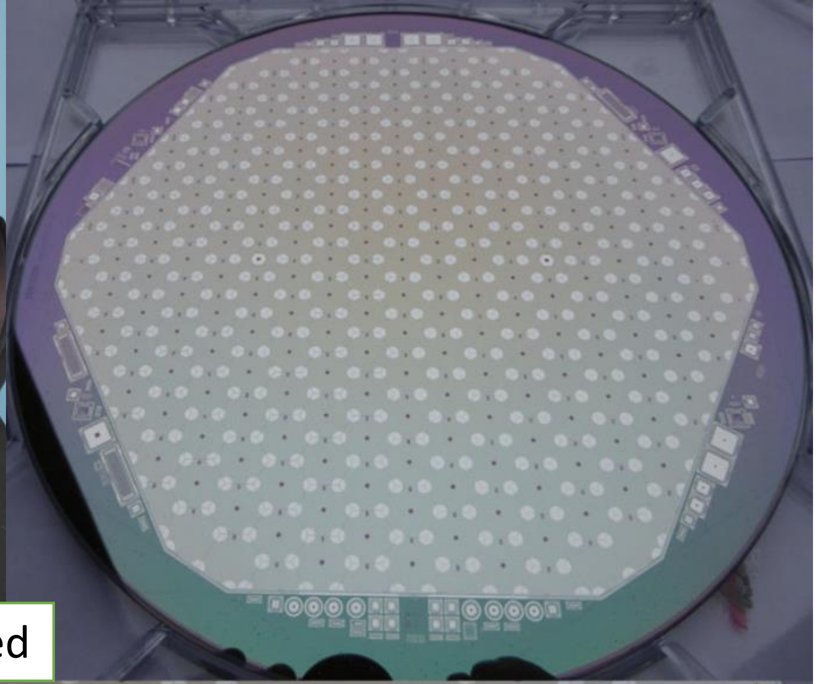
8” wafers – a big and novel step, but not for all!?!?!

8” n-in-p **strips AC**-coupled

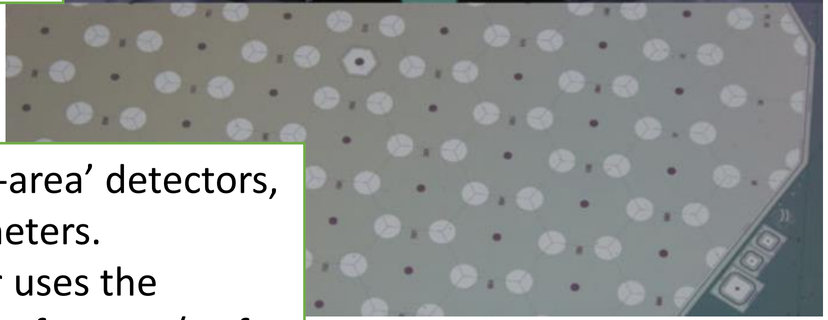
Picture – Courtesy of HEPHY







8” n-in-p **pads DC**-coupled



8” is a **game changer** for ‘really-large-area’ detectors, like the CMS forward imaging calorimeters.
And, the hexagonal shape pad sensor uses the circular area in an optimal way - ratio of sensor/wafer

8” **not** for **strip** tracker as ratio of sensor/wafer not ideal; and 6” still more mature. *Both ATLAS and CMS are using 6”!*

Hybrid pixels would strongly benefit on real estate, and especially on flip-chipping effort/cost.

I am also aware of 8” wafers for active*
& passive CMOS sensors and LGADs!
At coffee you tell me where else!

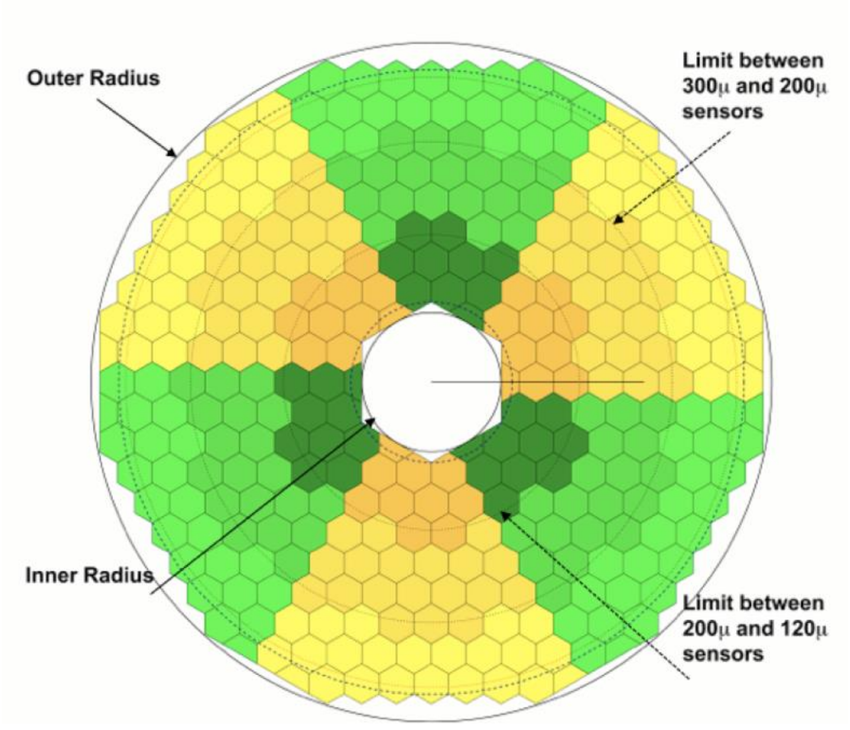
* e.g. ALPIDE 8” and ITS targets 12”

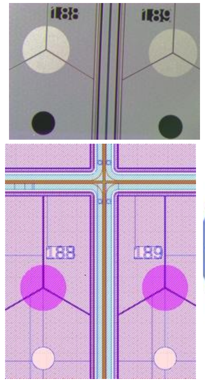
CMS HGCAL Collaboration, Neutron Irradiation and Electrical Characterisation of the First 8" Silicon Pad Sensor Prototypes for the CMS Calorimeter Endcap Upgrade, submitted to JINST, https://doi.org/10.48550/arXiv.2209.10159

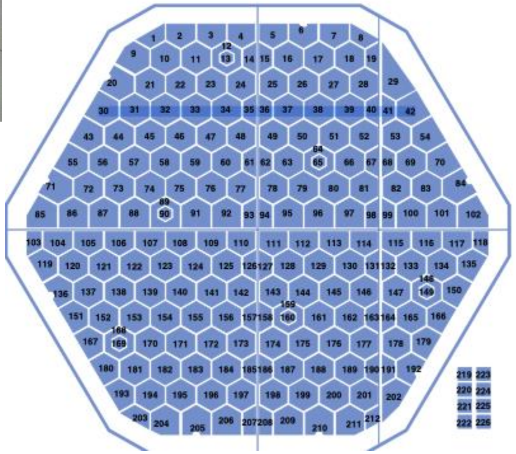
Another cost saving, novel idea – Multi-Geometry Wafer

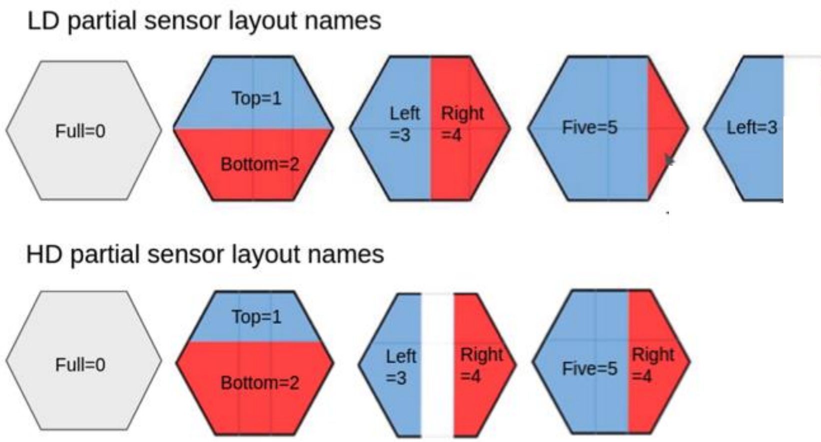
Use one mask and cut to different geometries

CMS needs many so-called ‘partials’



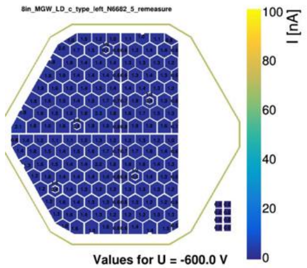


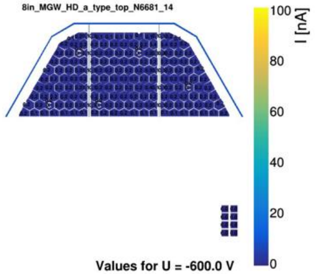




Pay attention to the cutlines, guard and bias lines.

Et Voila it works!

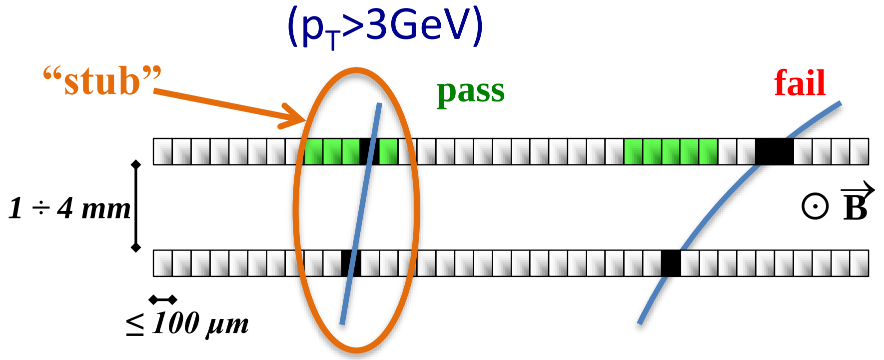


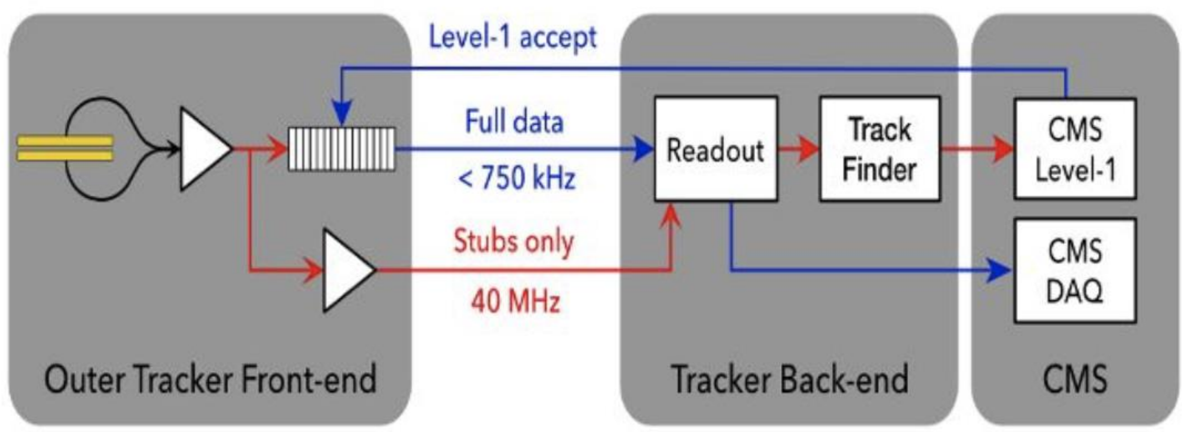


Courtesy of the CMS HGCAL team

Triggering on tracks at 40 MHz – CMS Phase-2

- Traditionally, Trackers cannot be be read out at full speed
  - too complex, too much data, not enough bandwidth
  - ‘a track' as a trigger object needs information of several layers *but* they are *not* connected
- Can we connect internally? Yes we can – a bit, very local, on parts of the track!



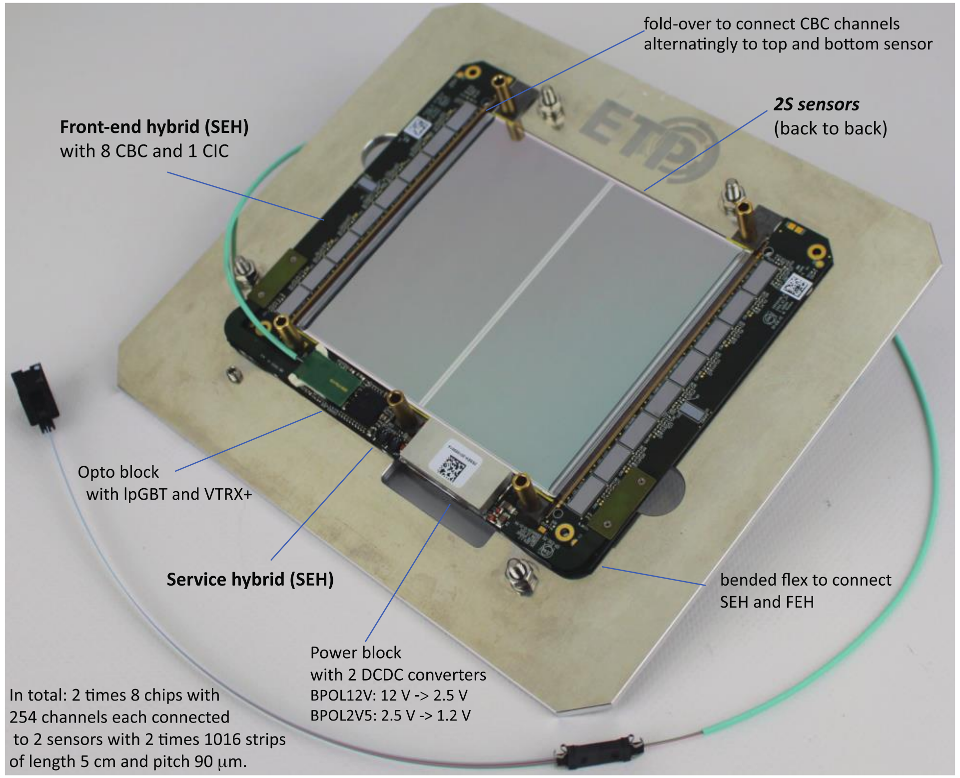


- But what about the z coordinate?

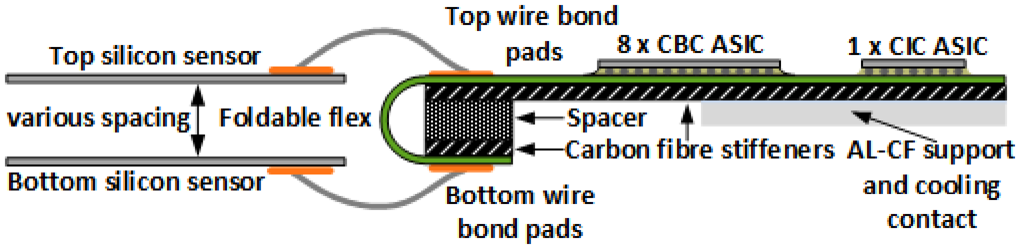
Stub data being sent out at 40 MHz
(data reduction factor 10, still ~ 80% of bandwidth)
Full track reconstruction in backend FPGA (~4µs) as trigger objects

CERN-LHCC-2017-009 CMS-TDR-17-001

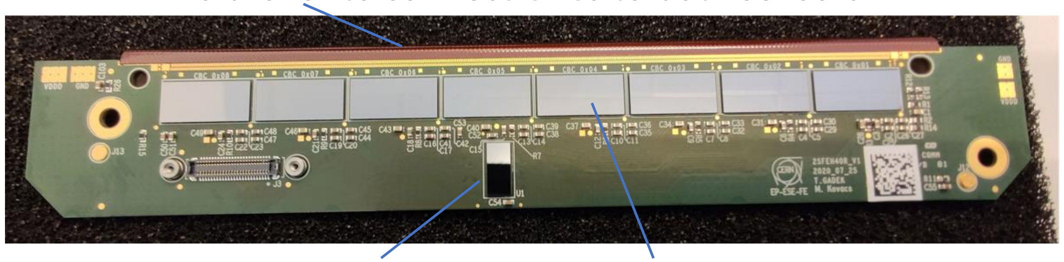
How does it work locally? Is there a drawback? Stereo angle? Z-resolution?

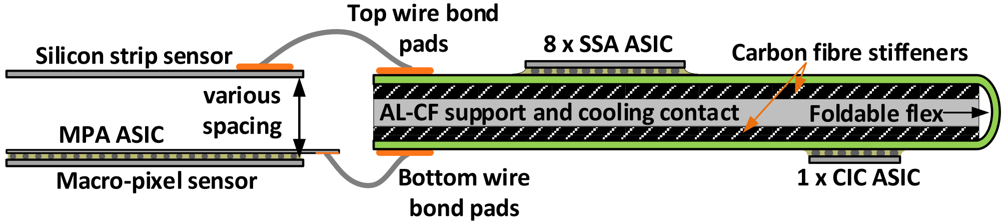


- Bottom **and** top strips connected to **same** ASIC via flex **fold-over**, doing the correlation
  - Strips **parallel** - stereo angle not possible – no z-resolution only p_T
- 2nd module version with 1.5 mm macro-pixels (and 2.5 cm strips)
  - **Strip ASICs** provide info to **pixel ASIC** doing the correlation
  - Unambiguous z-resolution at trigger level (~1mm vertexing possible) - @trigger
  - Results in a 25 m^2 macro-pixel detector (bump bonded)

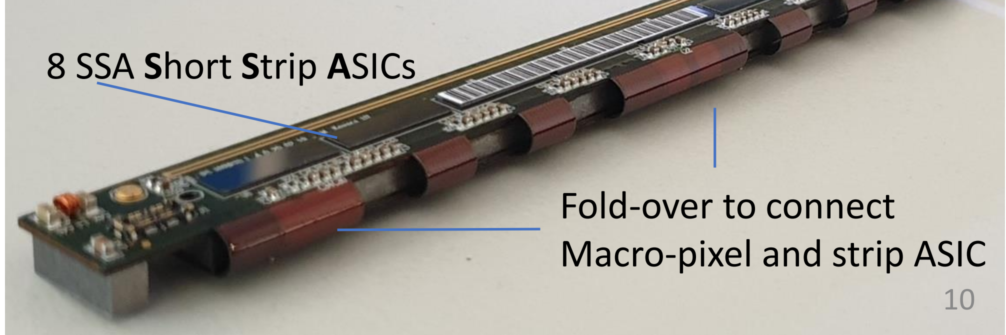


Front-end hybrid (FEH) - *2S module*





Front-end hybrid (FEH) – *PS module*
(left version)



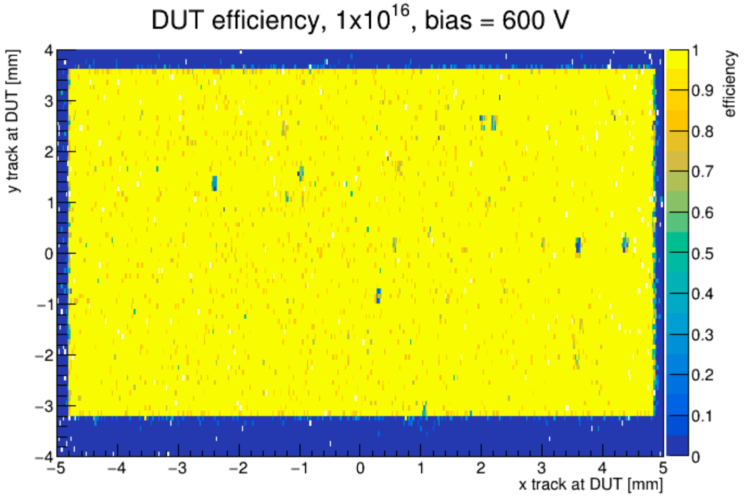
Passive CMOS sensors – a cost effective alternative?

- In search of more sensor producers, several groups are evaluating strip and pixel sensors from CMOS companies!
  - Use n-well/p-well/metal/polysilicon layers for sensor implantations, biasing, field shaping
- The process is distinctively different to 'our' standard, mature planar process!

  Different = new **complications** and new **opportunities.**

  Mask sizes are limited to so-called reticles – same limits as for ASICs
    - Large sensors can only be realised by stitching
  - **Multiple metal layers** allow interesting redistributing schemes, e.g. disentangle electrode implant from readout connection
  - **MIM** (Metal-Insulator-Metal Capacitance) allows AC coupling for small structures (pixels) with decent coupling
  - HIGH and LOW resistivity **polysilicon layers** allow for bias resistors on small real estate or field shaping structures

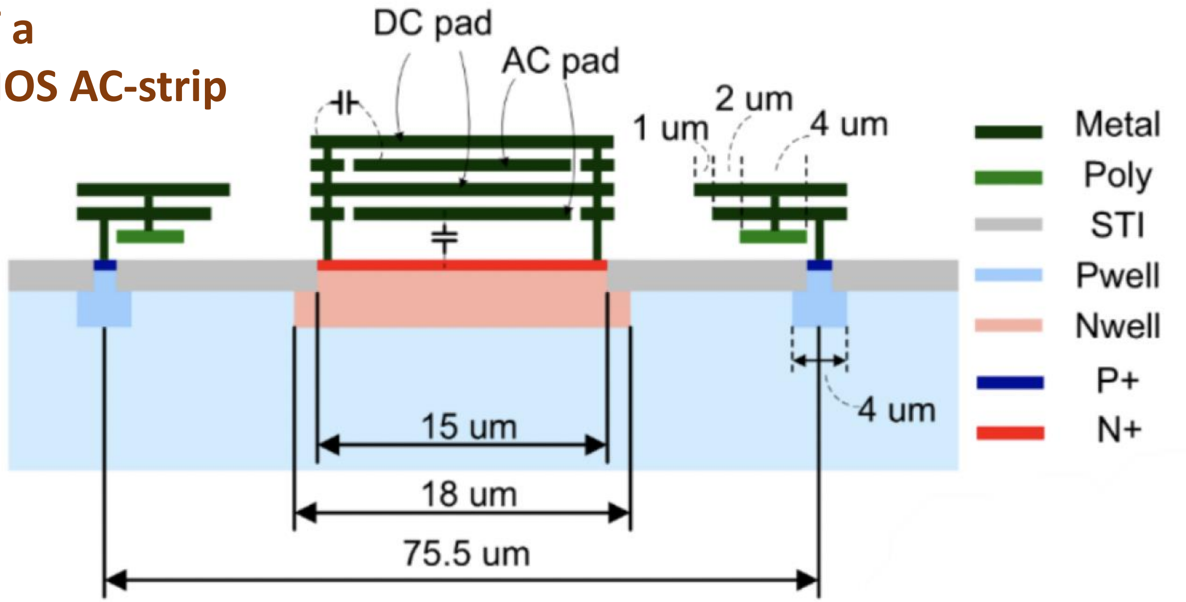
- In a nut-shell it works!



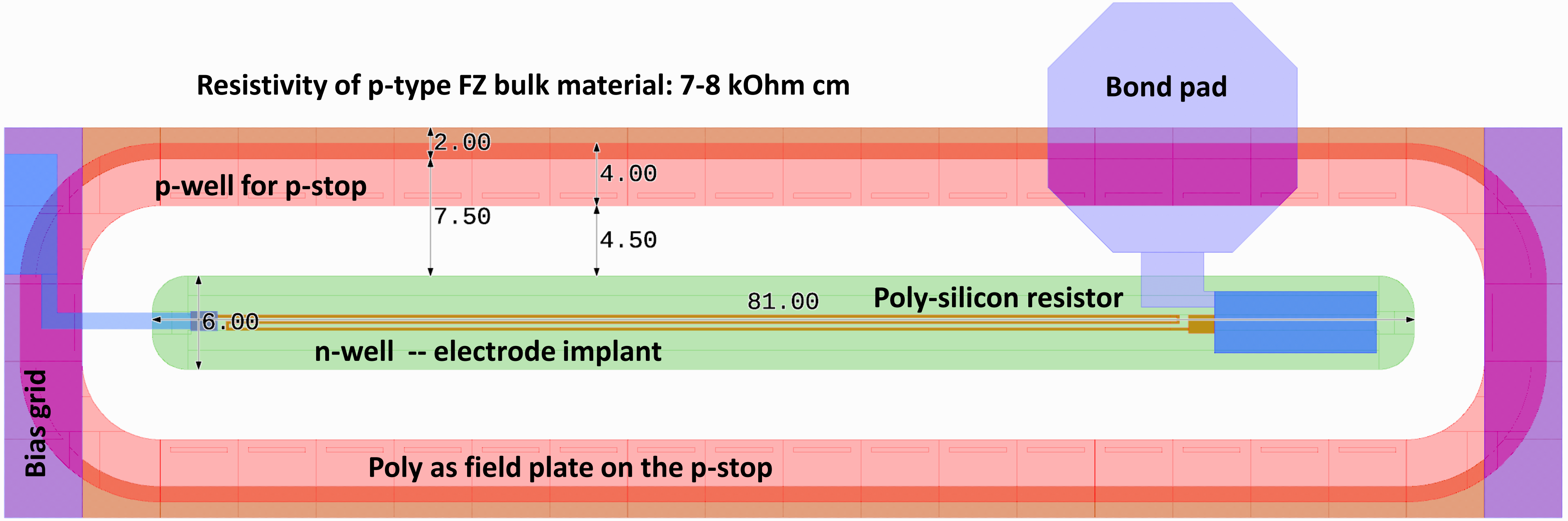
Obviously many features are common to ***active*** CMOS sensors.

Not our usual Planar Process

Example of a passive CMOS AC-strip



Example of a passive CMOS DC-pixel



Courtesy CMS Pixel

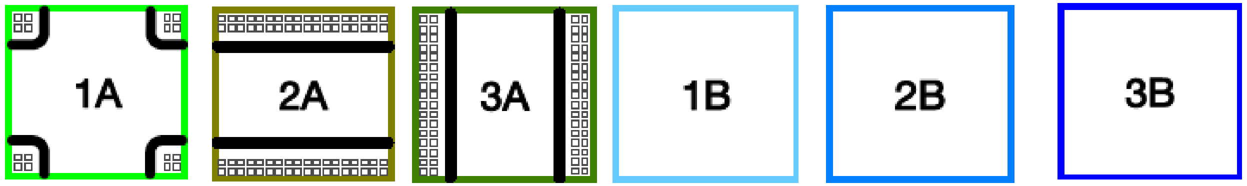
NIMA 1033 (2022) 166671

https://arxiv.org/abs/2203.11376; https://arxiv.org/abs/2111.07797; https://arxiv.org/abs/1702.04953

Reticle stitching

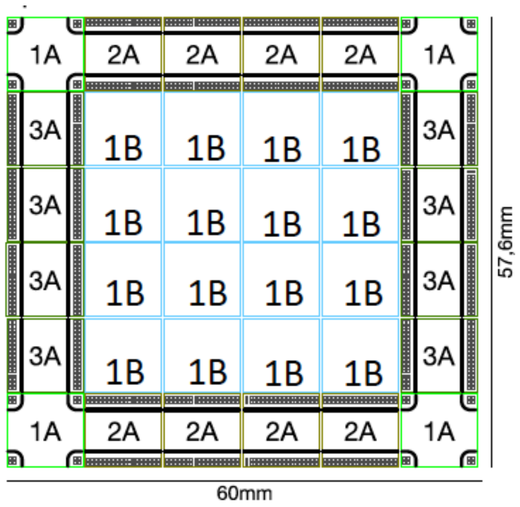
Sensor size > reticle size 26 mm x 32 mm→ reticle stitching needed

- Different sub-reticles (~ 1 cm x 1 cm) for edge and active areas:

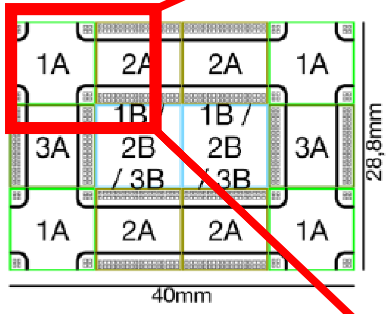


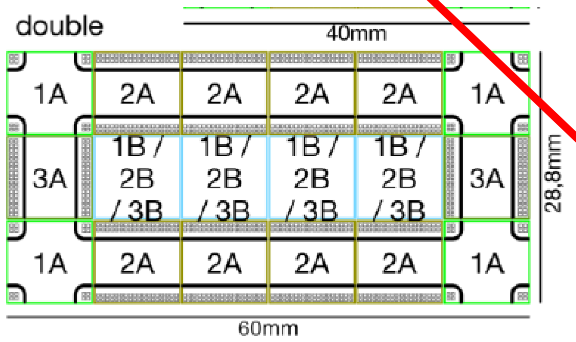
- Repeat them for different designs:

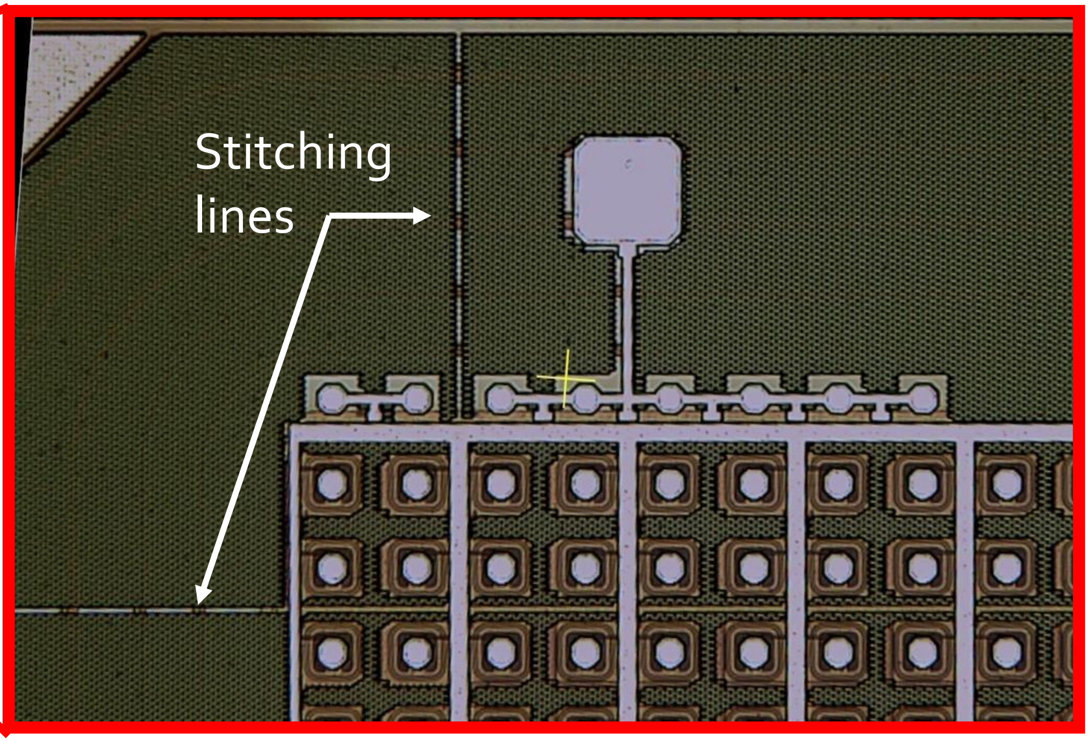
quad



single







Slide from A. Macchiolo (CMS)

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Onto the three main courses

Timing

… 3D

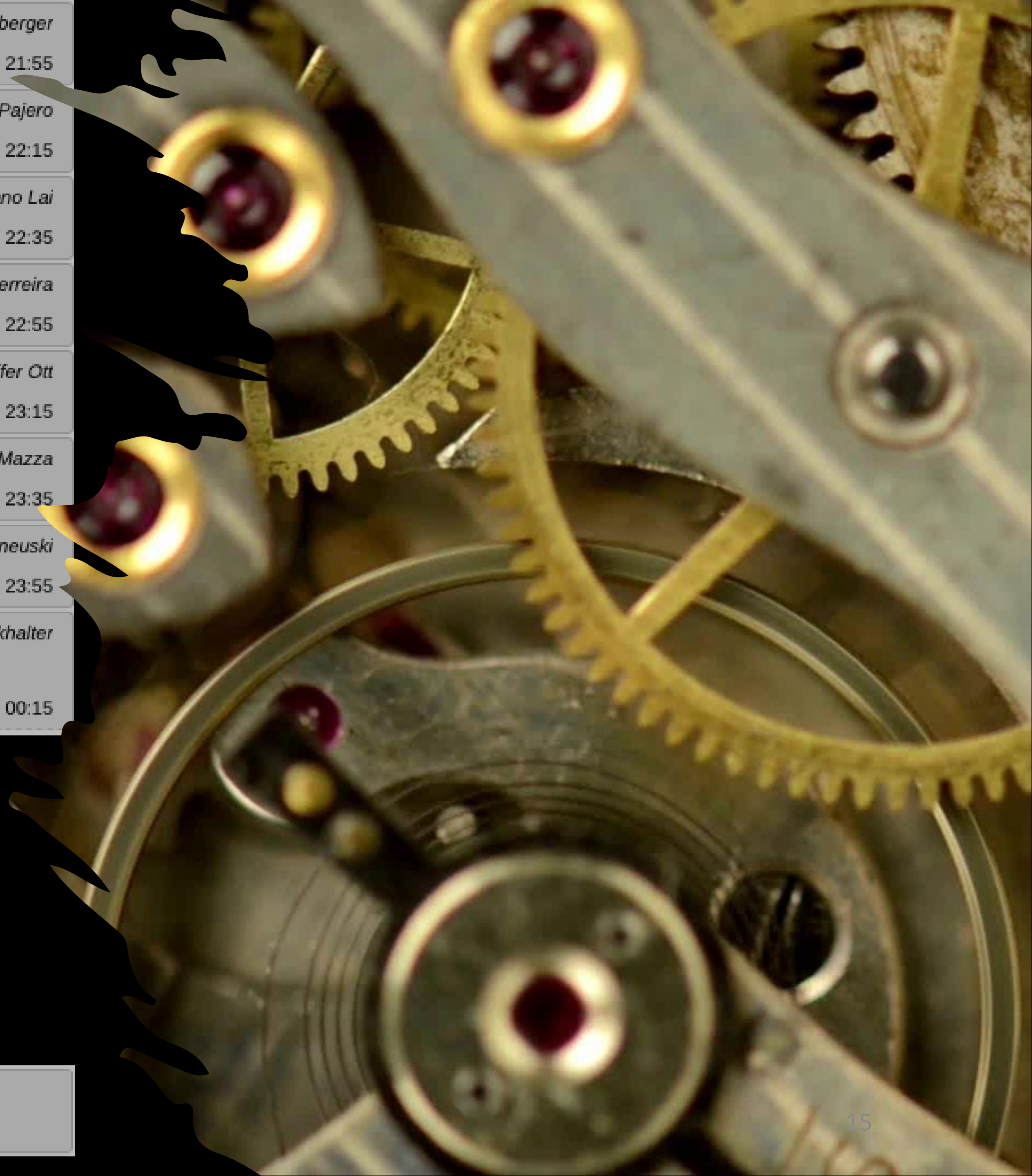
… HV-CMOS

Precision timing with silicon detectors	*Gregor Kramberger*	
North Ballroom, La Fonda Hotel		21:35 - 21:55
VELO Upgrade II- the LHCb 4D Pixel Detector	*Tommaso Pajero*	
North Ballroom, La Fonda Hotel		21:55 - 22:15
10-ps timing with 3D-trench silicon sensors at extreme rates	*Adriano Lai*	
North Ballroom, La Fonda Hotel		22:15 - 22:35
A High Granularity Timing Detector for the ATLAS Phase-II Upgrade	*Afonso Soares Canas Ferreira*	
North Ballroom, La Fonda Hotel		22:35 - 22:55
AC-coupled Low Gain Avalanche Diodes for 4D tracking: impact of electrode geometry on charge sharing	*Dr Jennifer Ott*	
North Ballroom, La Fonda Hotel		22:55 - 23:15
An LGAD-based full active target for the PIONEER experiment	*Dr Simone Michele Mazza*	
North Ballroom, La Fonda Hotel		23:15 - 23:35
Performance studies of Inverse Low Gain Avalanche Detectors (i-LGAD) coupled to the Timepix3 ASIC	*Dr Dima Maneuski*	
North Ballroom, La Fonda Hotel		23:35 - 23:55
MoTiC: Prototype of a Monolithic Particle Tracking Detector with Timing	*Stephan Tobias Burkhalter*	
North Ballroom, La Fonda Hotel		23:55 - 00:15

Precision timing

Goal: σ_T= 0,000 000 000 005 s

MONOLITH - picosecond time stamping capabilities in fully monolithic highly granular silicon pixel detectors
Lorenzo Paolozzi



Precision timing

– WHY, do we need it and *WHAT* and *WHERE*?

Why? Probably by consensus as we all like it :-) *It is new!*

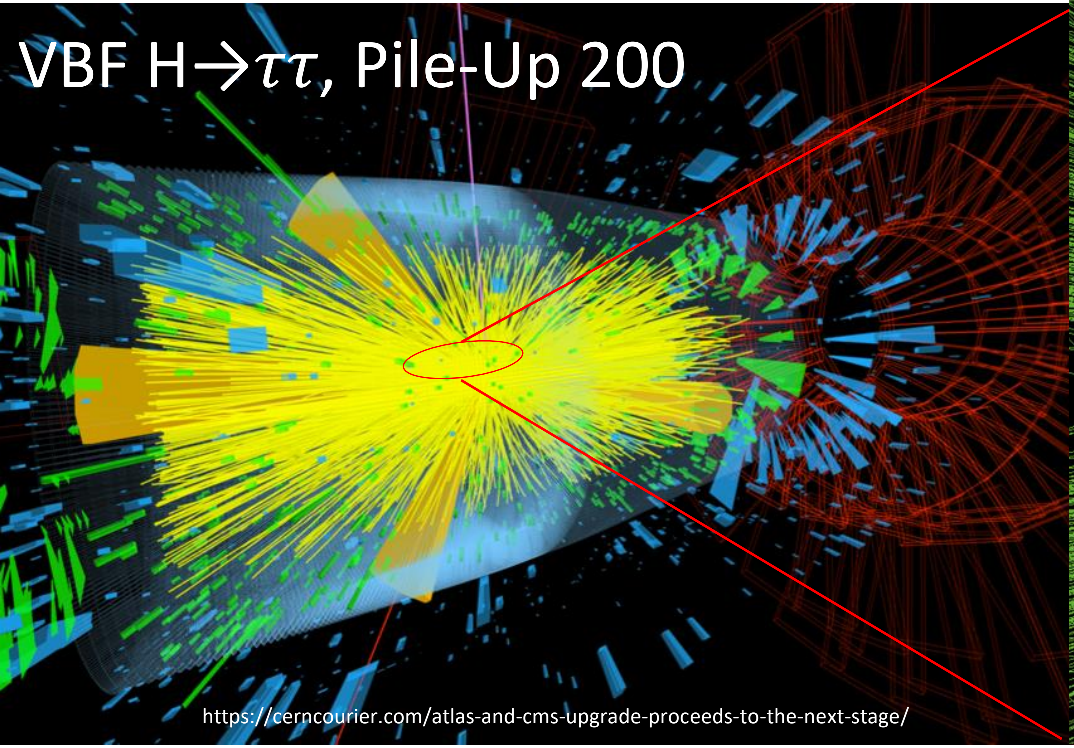
1. Precise timing information of 'a track'
   – mitigate pile-up, PID in Heavy Ion, increase reach to measure LLP
   - Here **modest spatial information** is OK, good fill factor is a plus – **LGADs and scintillator can do the job**
2. Precise timing information of 'track points', or of 'each track point'
   – all the above plus reduce combinatorics for track finding
   - **Superb spatial information** & **100% fill factor** is mandatory – standard LGADs are probably NOT good enough!

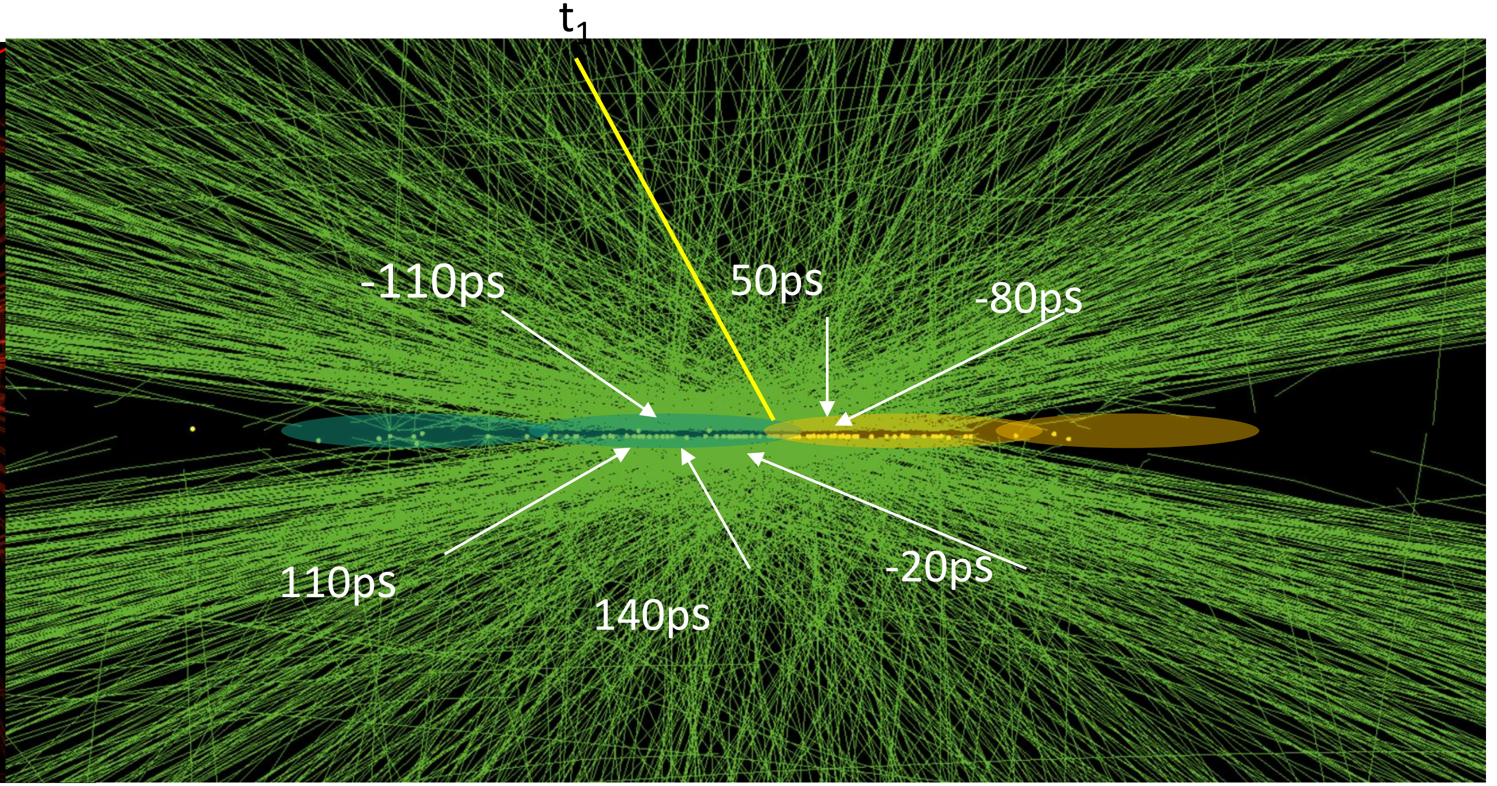
LHCb 4D Pixel Detector – by Tommaso

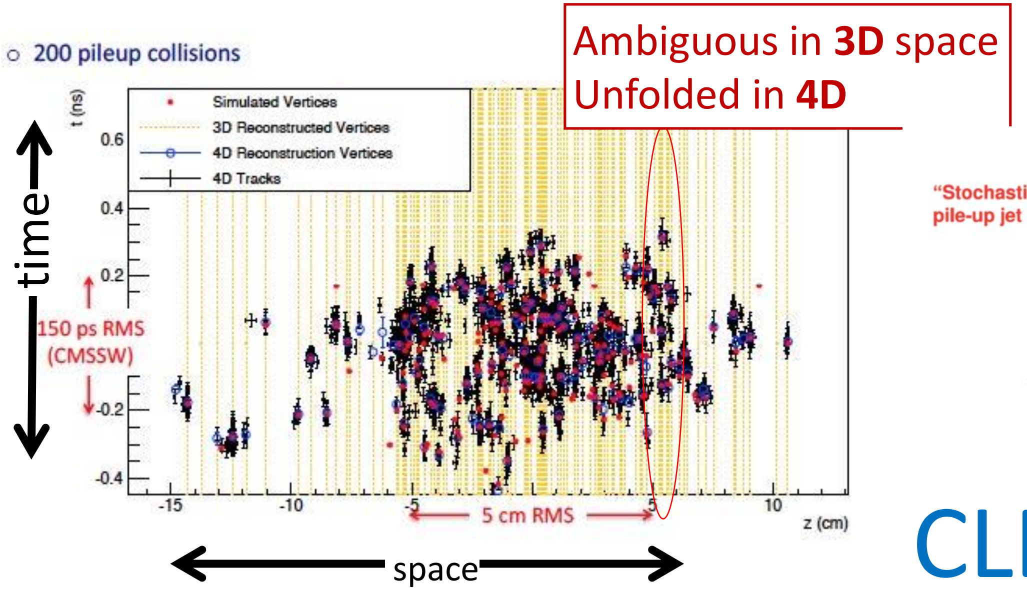
➔ **Ok, we want superb timing and spatial precision with 100% fill factor, (all in power budget)**
in general it must be radiation tolerant and best full-monolithic and with volume suppliers

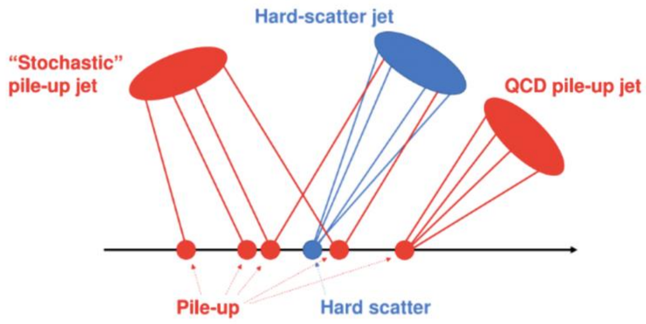
I am looking forward to "Precision timing with silicon detectors" – **by Gregor**

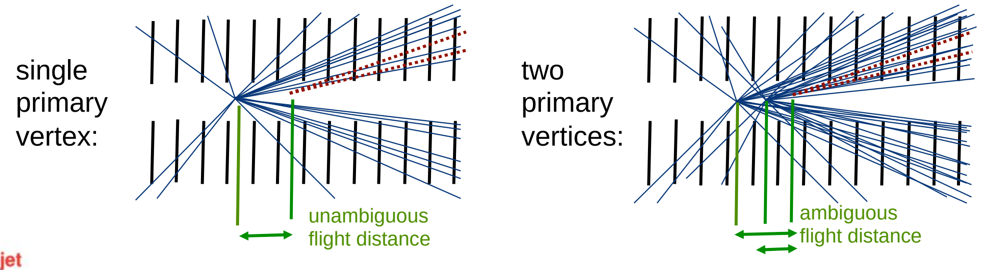
LLP: Long lived Stable Particle

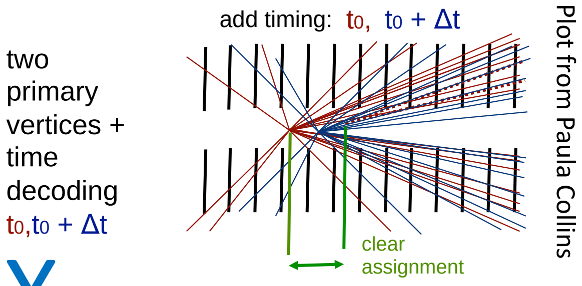










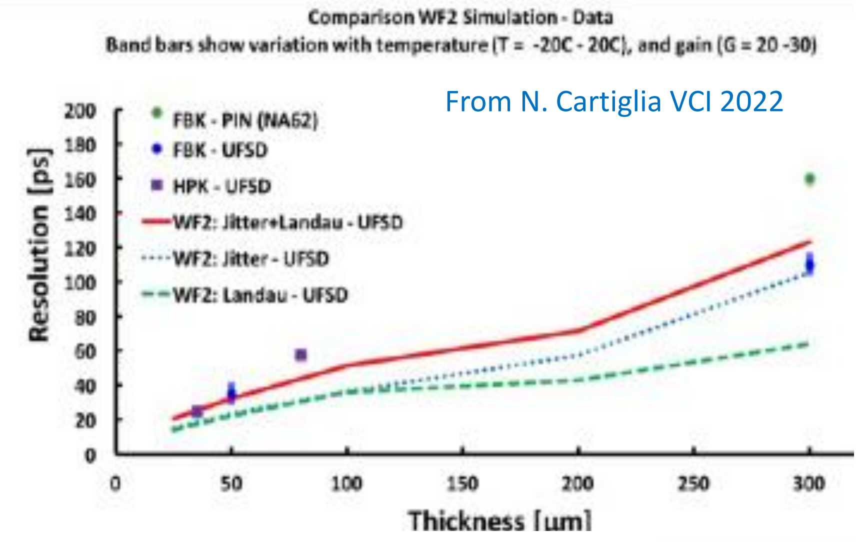


CLEAN YOUR VERTEX

A bit of random wisdom (no no, not from me)

- Intrinsic timing capability of sensors is basically infinite* (sub ps) **– W. Riegler**
- Landau noise (non-uniform ionization - *spatial*) and electronic noise is the issue **– everybody says this**
  - Decreasing electronic noise 'costs' power', which is 'limited' **– I say this but I heard it from somewhere**
  - Decreasing sensor thickness decreases drift length and Landau noise **– from the experts**

Landau noise = physical limit of timing precision



From N. Cartiglia VCI 2022

- Using signal **gain** beats electronic noise and decreases 'jitter',
  - wait for the electrons to arrive at the gain layer
  (similar for concentrated weighting fields)
- In "timing circuits", things can go wrong very rapidly (quote stolen from a chip designer) **– N. Cartiglia**

$$\sigma_t = \frac{noise}{\boldsymbol{dV/dt}}$$

Compensate in electronics

$$\sigma_t^2 = \sigma^2_{Time\ walk} + \sigma^2_{Landau\ noise} + \sigma^2_{jitter} + \sigma^2_{Distortion} + \sigma^2_{TDC}$$

electronics

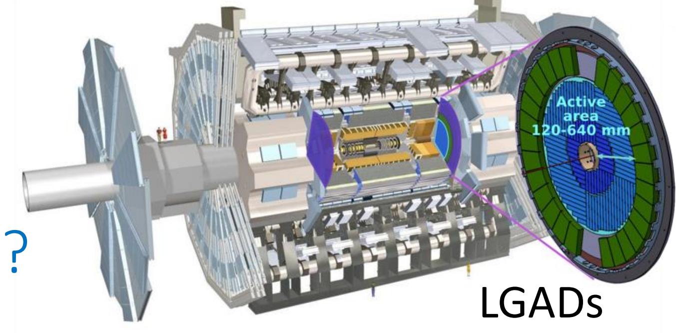
Go thin

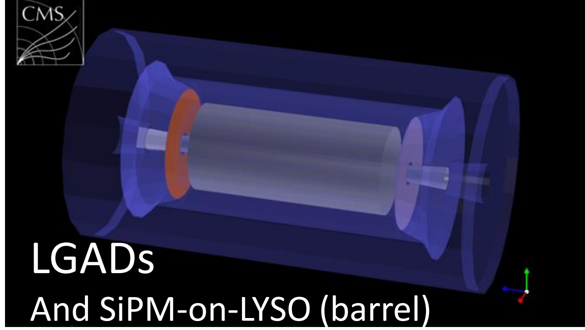
Weighting field

* acceleration of electrons to 10^7cm/s in vacuum is 0.14ps & passage of the particle through a 50um sensor takes 0.16ps

Low Gain Avalanche Detector - LGAD

aka the **working horse for HL-LHC**
aka the mature but already obsolete technology??



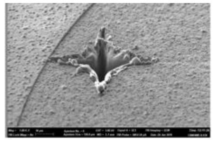


- Timing precision σ_t = <30 ps 
- Fill factor mediocre (~80%)
  as inter-pad region = no gain
- Spatial precision ~mm

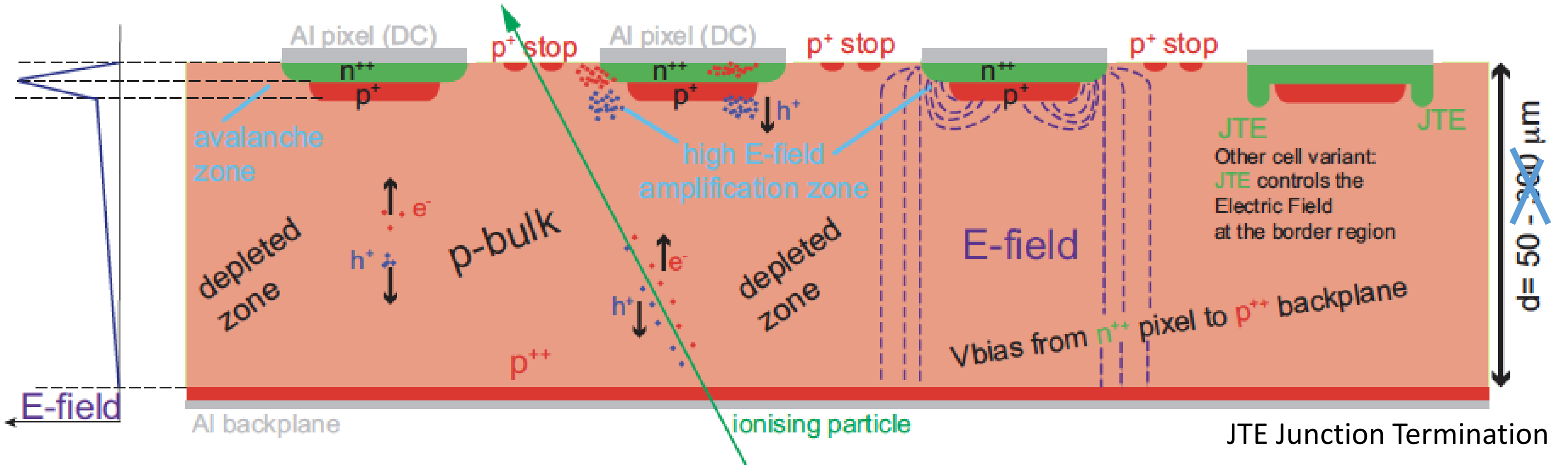
Numerous iterations, testbeams, market survey – several vendors, radiation studies

➔ **Mature technology** ~ $2{*}10^{15}{}_{MeV\_n}/cm^2$

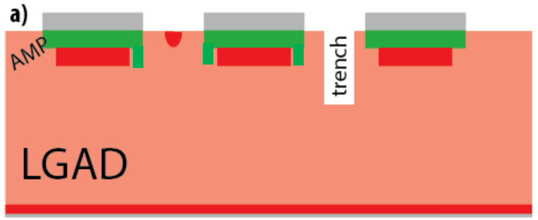
- E.g. adding of C in gain layer
- Understood single event burnout!
- Lots of effort to increase fill factor, e.g. TI-LGADs Trench Isolation LGADs
  - ~50 → 5 μm dead zone

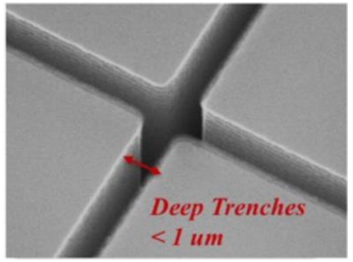


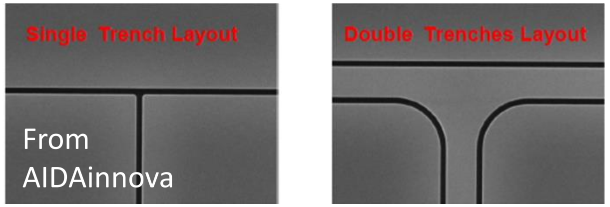
From CMS ETL



JTE Junction Termination







From AIDAinnova

Function: Signal from electron avalanche – arrival time starts avalanche – gain beats noise/jitter **– limit is Landau noise**

Thinner sensor decreases Landau Noise - shorter drift time (shorter path and higher field) (& no weighting field effect as pads >> thickness)

And, the LGAD concept is not brand new

IEEE TRANSACTIONS ON ELECTRON DEVICES, JUNE 1972

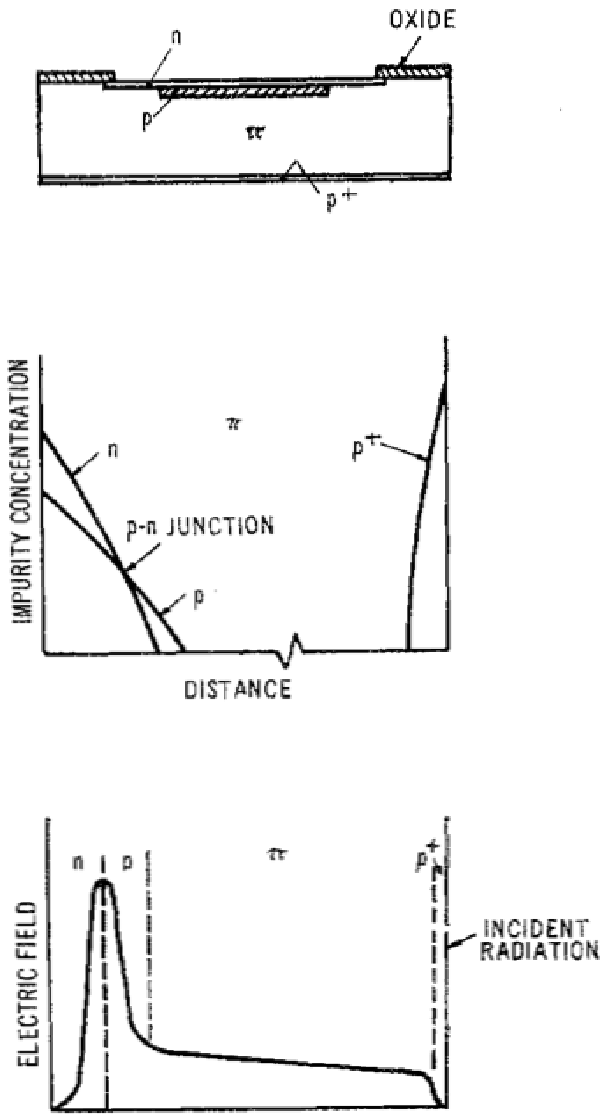


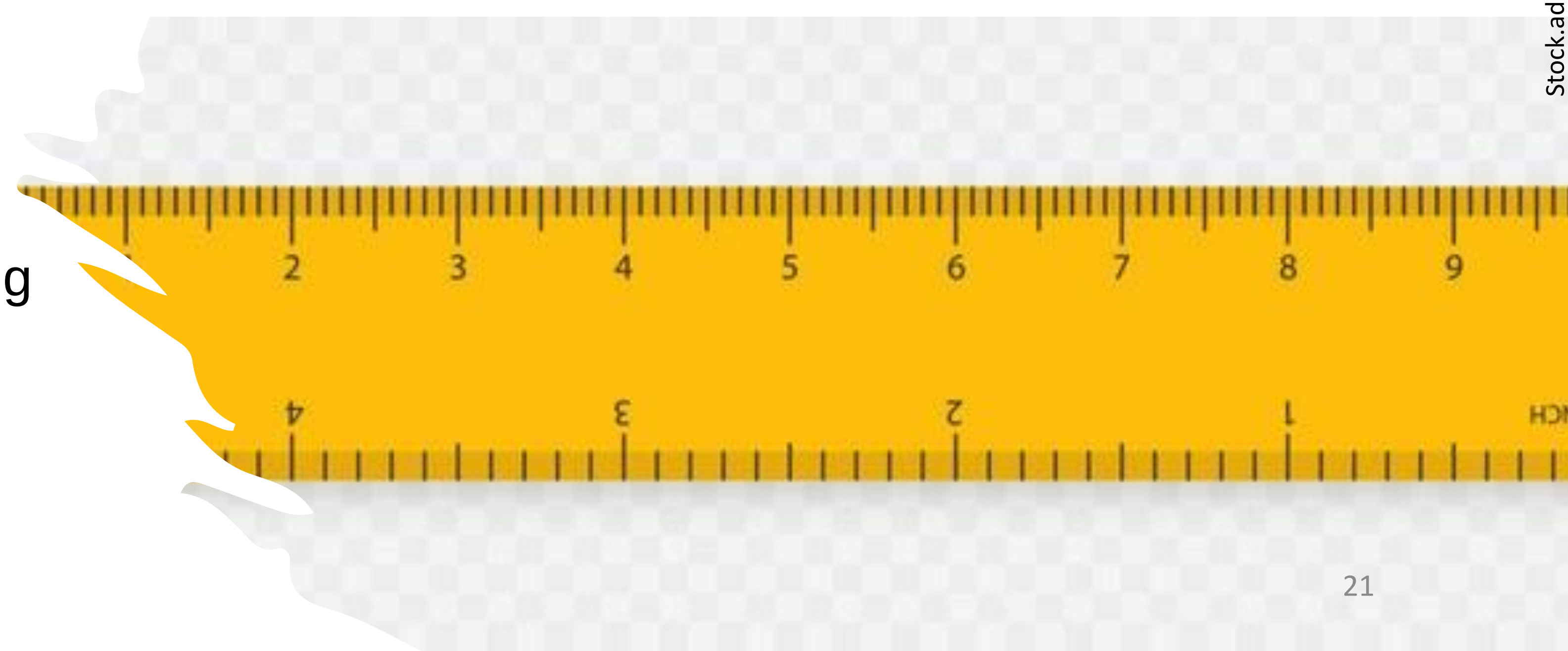
Fig. 1. Sketeches of reach-through avalanche-diode structure, impurity-concentration profile, and electric-field distribution.

From Abe Seiden, Hartmut Sadrozinski and Nicolo Cartiglia pioneers on LGADs:

I'm wondering if we can do both measurements (space and time) in one object, a silicon detector with very good timing resolution.

We thought it was a dumb question...but over lunch, we jotted down some numbers.

... The main question is understanding the gain in silicon sensors

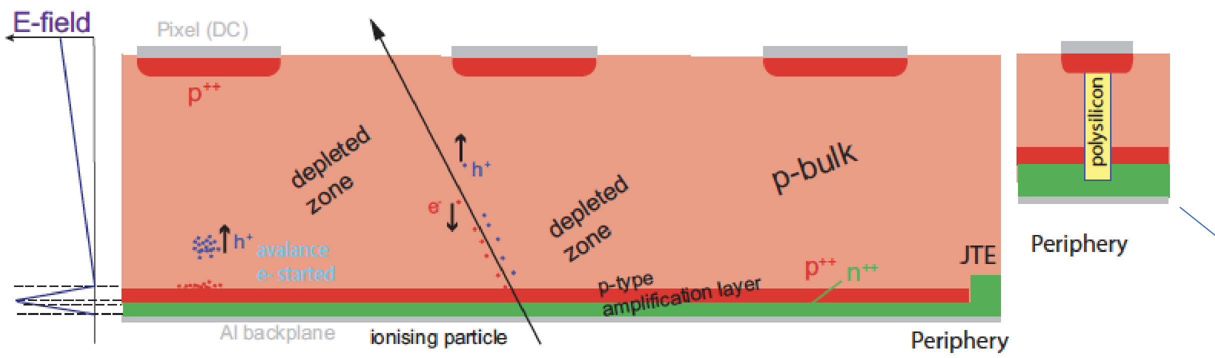


Ok, we achieved precision timing

Now let’s think about fill factor and spatial resolution!

MOVE the amplification layer - Disentangle amplification and readout electrodes

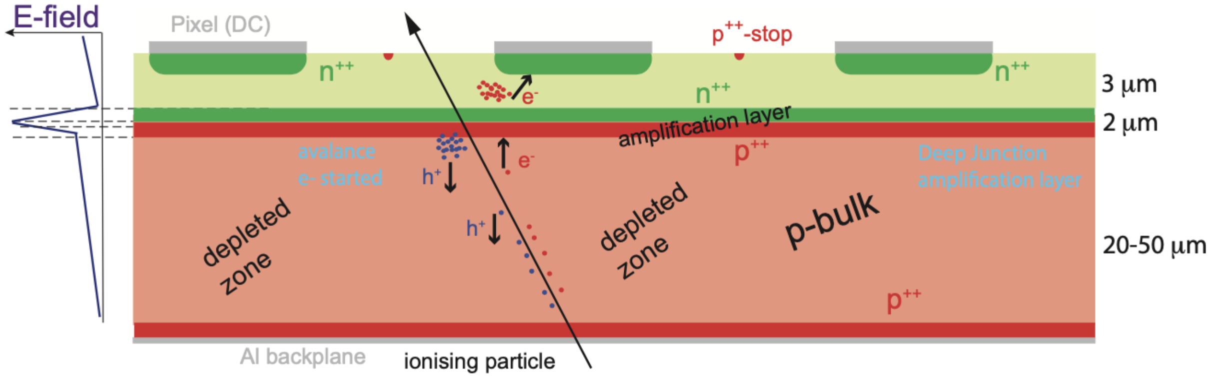
- Inverse LGADs



- Fill factor 100%
- Spatial resolution – good
- Timing limited to ~100 ps
  - Thickness ~ 300 μm
    - JTE at back ask for **double** sided process
  - hole collection
- New version using 3D technology
  - Thin and slim edge & **single** sided process

Performance studies of Inverse Low Gain Avalanche Detectors (i-LGAD) coupled to the Timepix3 ASIC – by Dima

- Deep Junction LGADs – DJ-LGADs



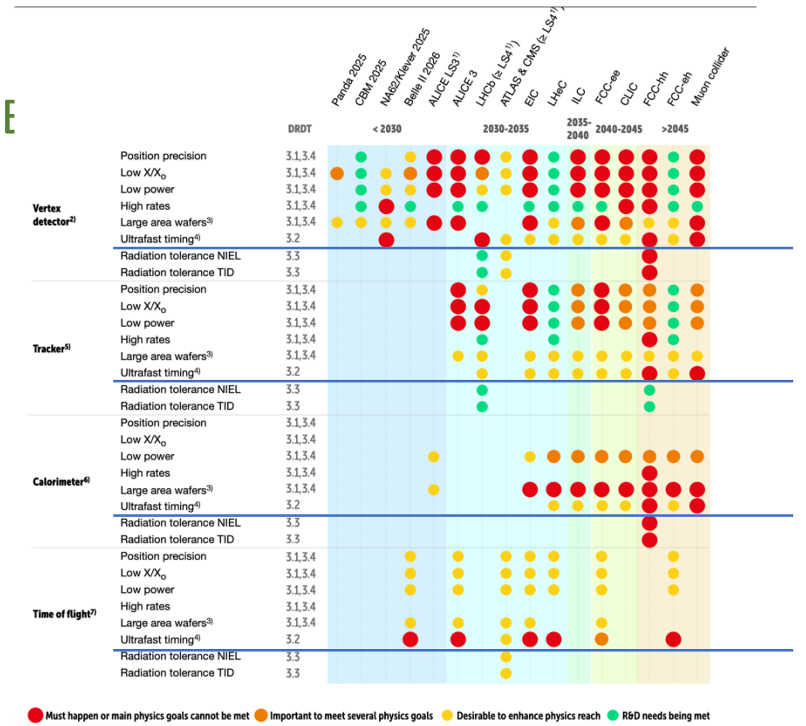
- Fill factor 100%
- Spatial resolution – good
- Timing good < 30 ps
- How easy to build?? Finetuning??

Same function, advantages and limitation of standard LGADs on timing (signal starts at arrival) **– limit is Landau noise**

Timing, *same* reason for everybody??

(see DOE Basic Research Needs for High Energy Physics Detector Research and Development Report, ECFA roadmap, Snowmass)

- HL-LHC (**mitigate pile-up, PID in Heavy Ion, increase reach to measure LLP**) - 30 ps – DONE
- Future e+e- colliders (Higgs Factories):
  - Spatial Resolution **~3 μm**
  - Time resolution - would enhance **particle identification** and reconstruction
- Future Hadron collider **Pileup** (~1000; 4THz of tracks) and radiation levels up to 8 x 10^{17} n/cm^2
  - Track resolution **< 10 μm** per layer
  - Time resolution 5 – 10 ps
- Muon Collider - for **BIB background** rejection
  - Track and time resolution 20 – 30 ps
- Electron-Ion Collider (EIC) Time of Flight (ToF):
  fine time and space resolution needed for **PID** π/K/p separation at low/medium momentum
  - 20 – 30 ps timing per hit
- Very Forward Physics *PPS* at the (HL-)LHC and future hadron colliders:
  fine time and space resolution needed for precise proton momentum reconstruction and **association to correct vertex**
  - 5 ps timing to suppress pileup (needs many timing layers), 5 μm tracker resolution
    - Greatly reduced to 20 ps in case 4π timing detector in the central region



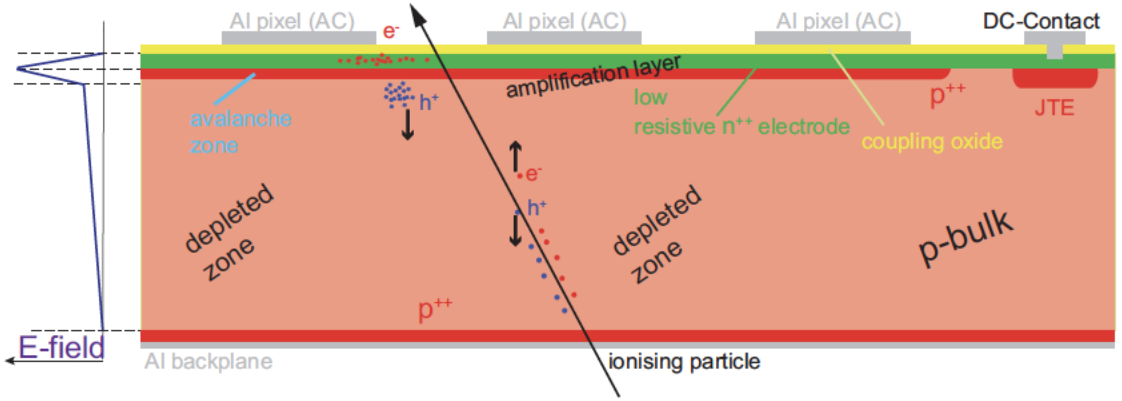
➔ 20 – 30 ps seem OK **but** for FCC-hh

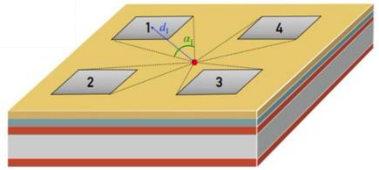
LLP: Long Lived Stable Particle

Evolving further

– and apologies for all developments I overlooked

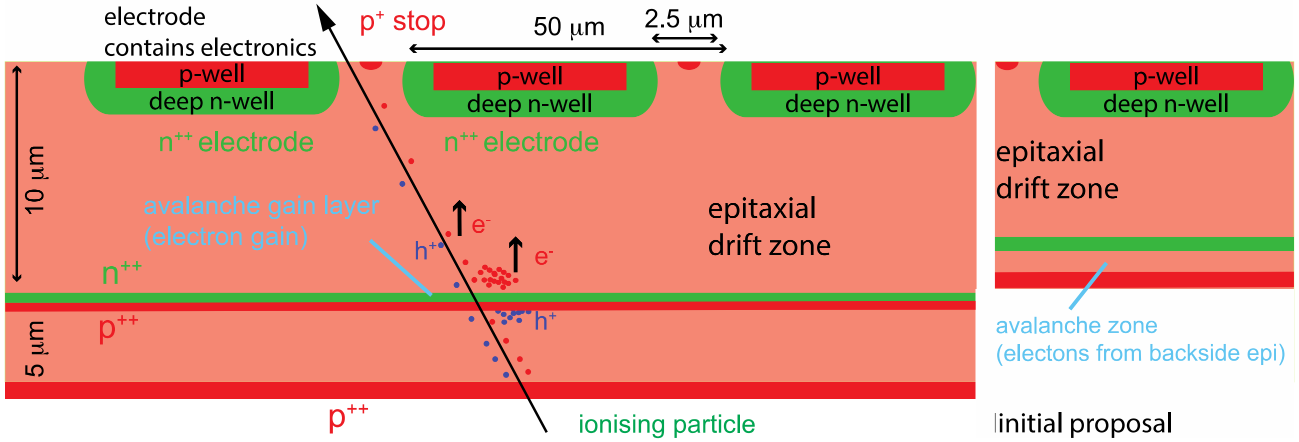
- AC-LGADs or Resisitive Silicon Sensors RSD





M. Tornago et al.,
RD50 Workshop (2020)

- Monolith



*Btw. with this THIN thickness, one could also think about 3D connections**??***

- Timing ~30 ps  
- 100% fill factor
- ~5 μm spatial resolution with *150 μm pitch*
  
  - *Excellent ratio*
  - Due to charge distribution and sharing in intrinsic low resistivity n++ layer with ~4 AC pads as smallest impedance to ground

→11m² TOF for EiC?

- Fresh idea; do DC-RSD

AC-coupled Low Gain Avalanche Diodes for 4D tracking: impact of electrode geometry on charge sharing – by Jennifer

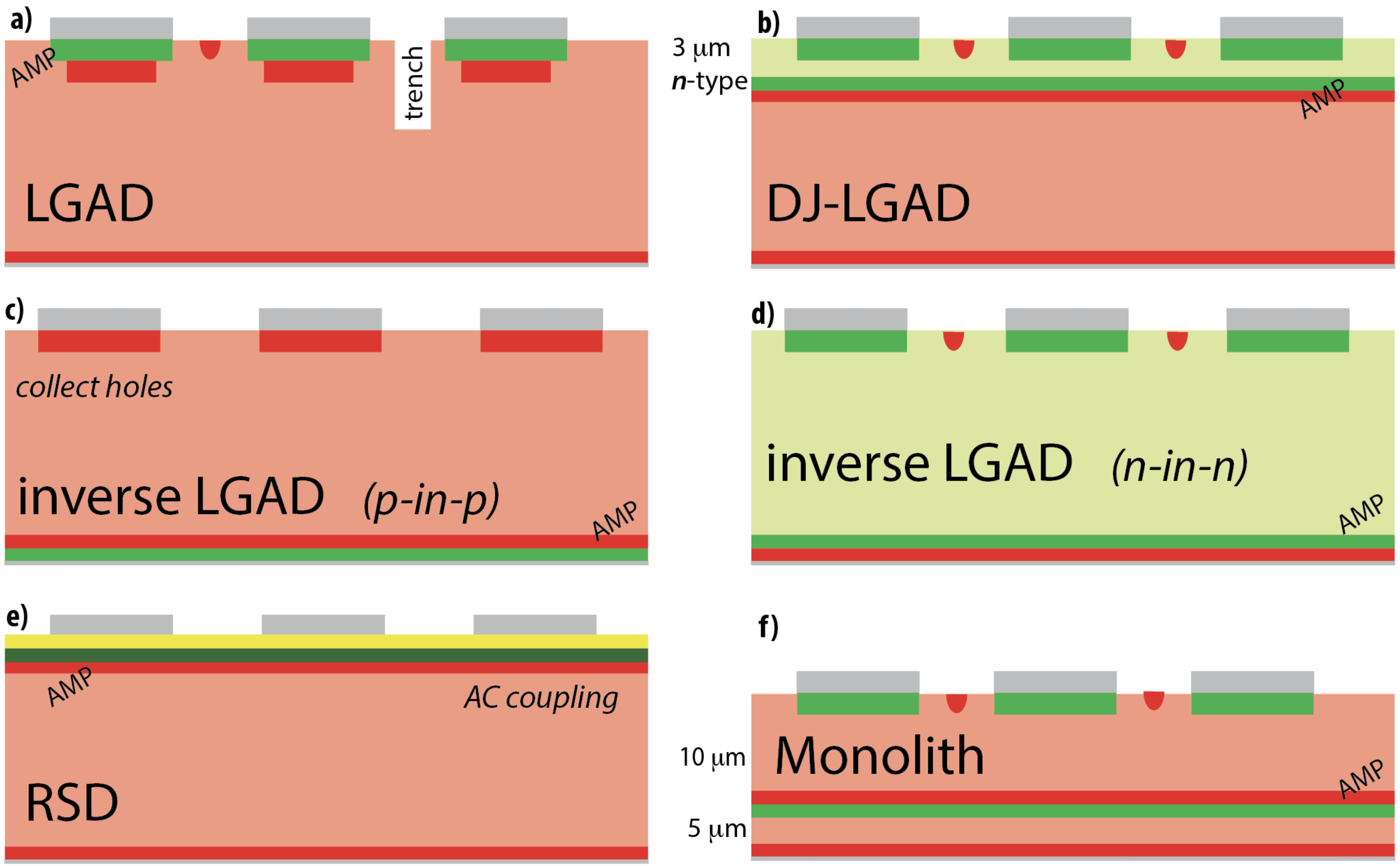
- Timing goal <10ps
  - Beats Landau Noise due to ultra-thin amplification zone  
- 100% fill factor,
- ~ 10 μm spatial resolution (small pixel)
- **Fully monolithic** device 
- Radiation tolerance?

MONOLITH - picosecond time stamping capabilities in fully monolithic highly granular silicon pixel detectors – by Lorenzo

First results very encouraging (**IMHO great**)

In summary, I present THE ZOO

Anybody up for a bet?



And, not to forget HV-CMOS achieving σ_T = 100 - 200 ps

or the new DC-RSD

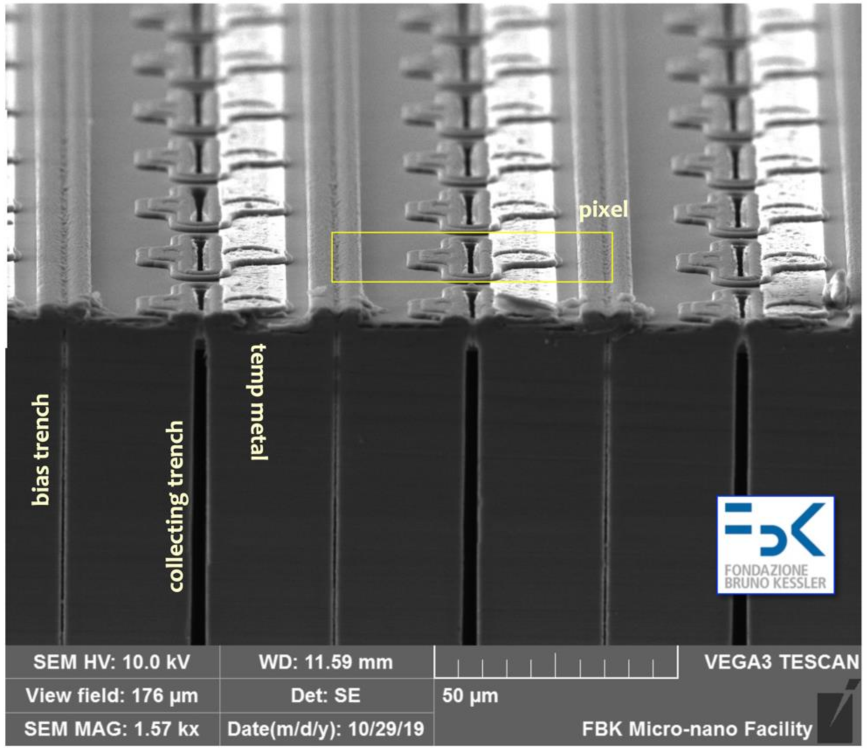
Or the other 'working' philosophy – precision timing without gain layer – 3D trenches

- **Simply great concept** - 'box' signals (perpendicular track) from electrons and holes (induction) – good amount of charge ('thick') – no weightfield distortion – 'no' landau noise
- For sure radiation tolerant

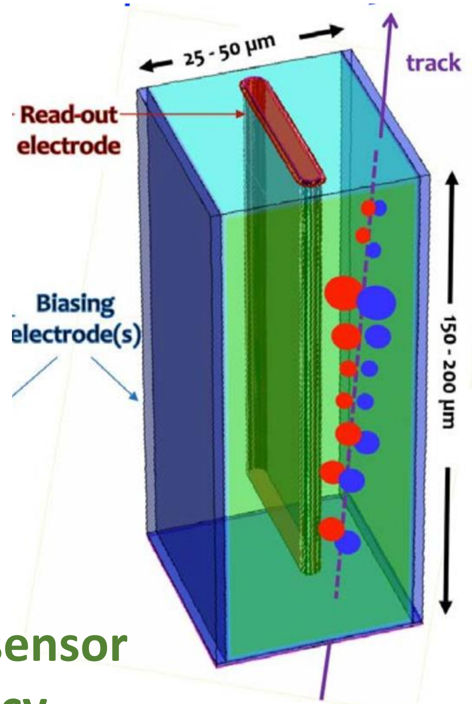
$$\sigma_t^2 = \sigma_{Time\ walk}^2 + \sigma_{Landau\ noise}^2 + \sigma_{jitter}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2$$

Compensate in electronics

electronics



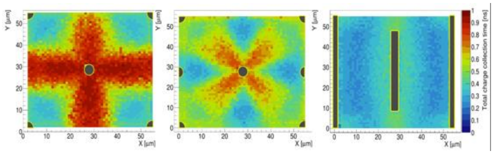
- 3D-trench
- 5x40x135μm3 trench
- 150 μm pixel depth



≈ 10 ps & 10 μm at sensor level at 99% efficiency >> 10^{16} n_{eq}/cm^2

Adrinao will probably tell us more on

- how tilting helps
- other 3D geometries



- 3D diamond
- 28nm TIMESPOT ASIC
- power and cooling challenges

TimeSPOT results – A. Lai – Vertex 2022
TIME and **SP**ace real-time **O**perating **T**racker

Math from Werner R. here: https://indico.cern.ch/event/1083146/

Last words on timing detectors

- Many thought, the development of silicon sensors will not see many surprises anymore
- Well, it is so good to see all these innovatitive ideas and their incrediby fast implementations into real devices

- Homework:
  - < 5 μm spatial
  - < 20 ps (eventually 5ps) timing
  - Monolithic
  - **Low power** ⟸
    - Even more for gas cooled systems
  - Radiation tolerant
  - (low cost)

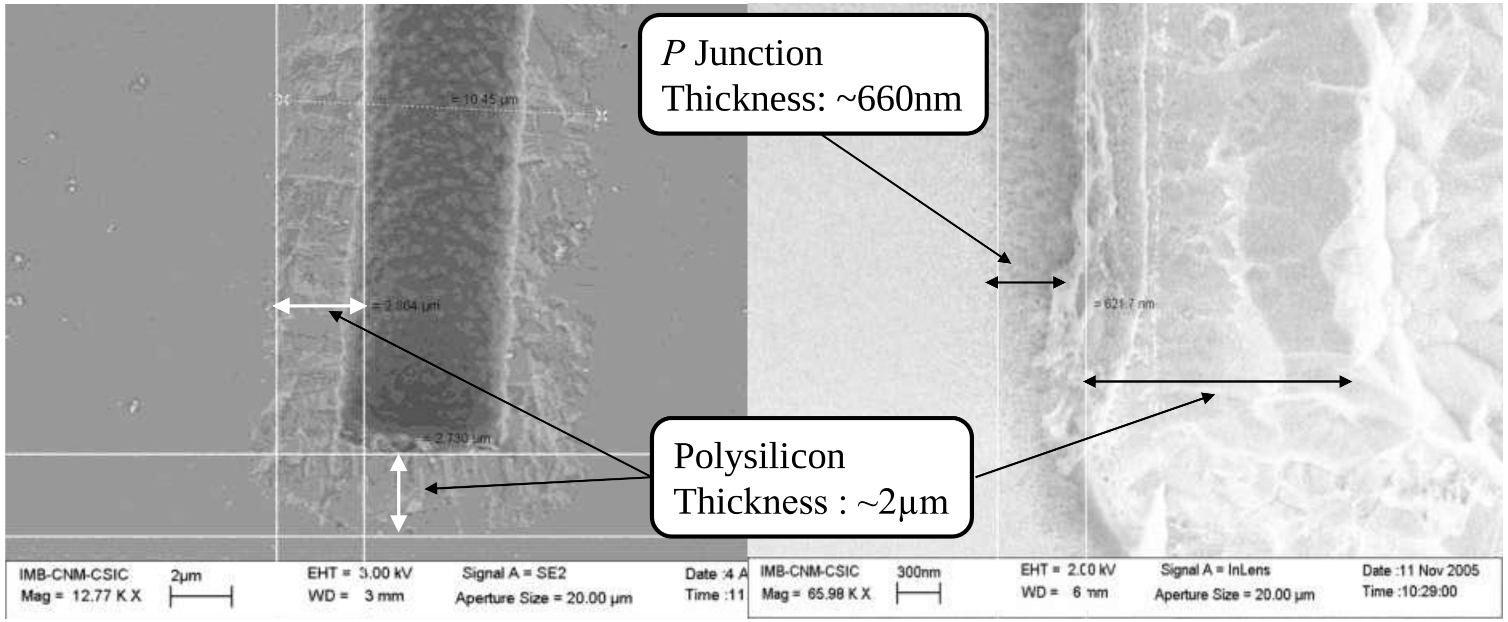
3D

Only small number of dedicated talks in this conference!

Is it a done deal?

Qualification of the first preproduction 3D FBK sensors with ITkPixV1 — *Martina Ressegotti*
North Ballroom, La Fonda Hotel — 09:10 - 09:30

Results on 3D pixel sensors for the CMS upgrade at the HL-LHC — *Rudy Ceccarelli*
North Ballroom, La Fonda Hotel — 17:50 - 18:10



Courtesy CNM

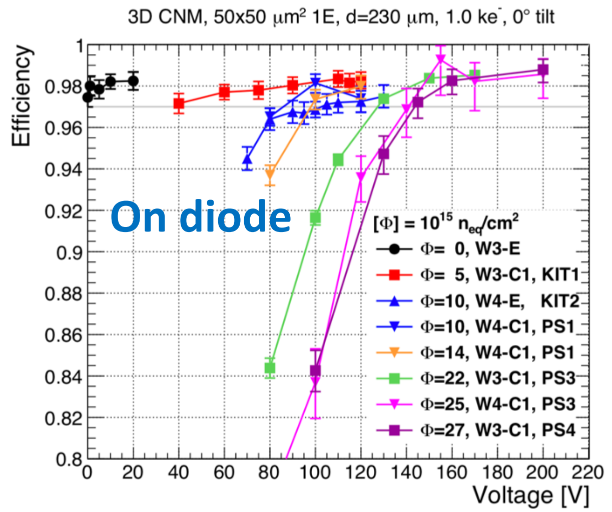
Preaching to the Choir

preach to the choir
to speak for or against something to people who already agree with one's opinions
www.merriam-webster.com/

3D – facts we all know

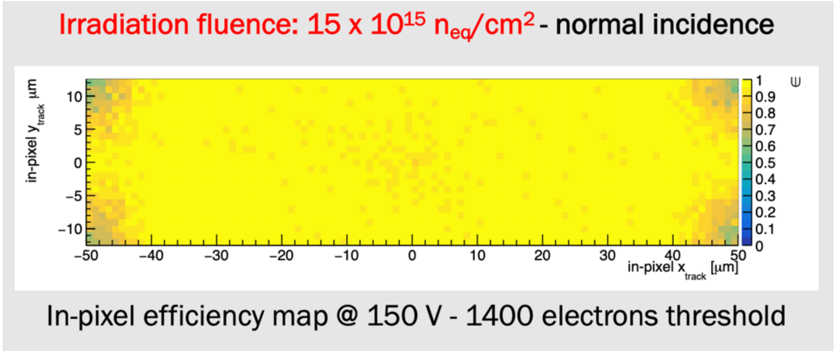
- 3D sensors are radiation tolerant!
  - **Short drift path** – less trapping
    Full thickness for signal
  - Lower depletion voltage – lower power
  - Can do slim (active) edge

  - Higher Capacity
  - Lower yield

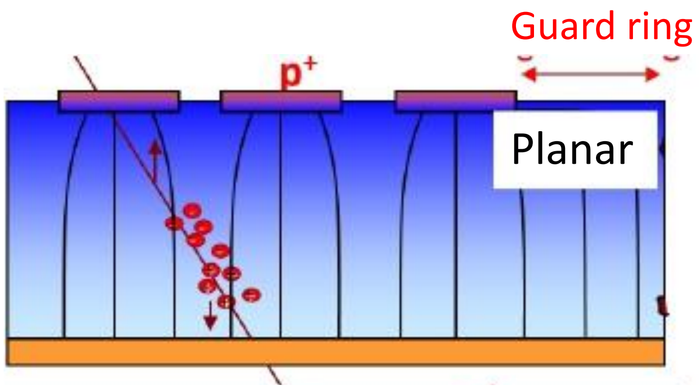


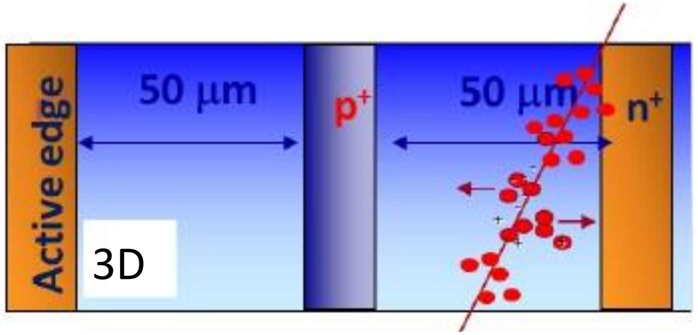
J. Lange *et al* 2018 JINST **13** P09009

Technology works after $3*10^{16}\ n_{eq}/cm^2$



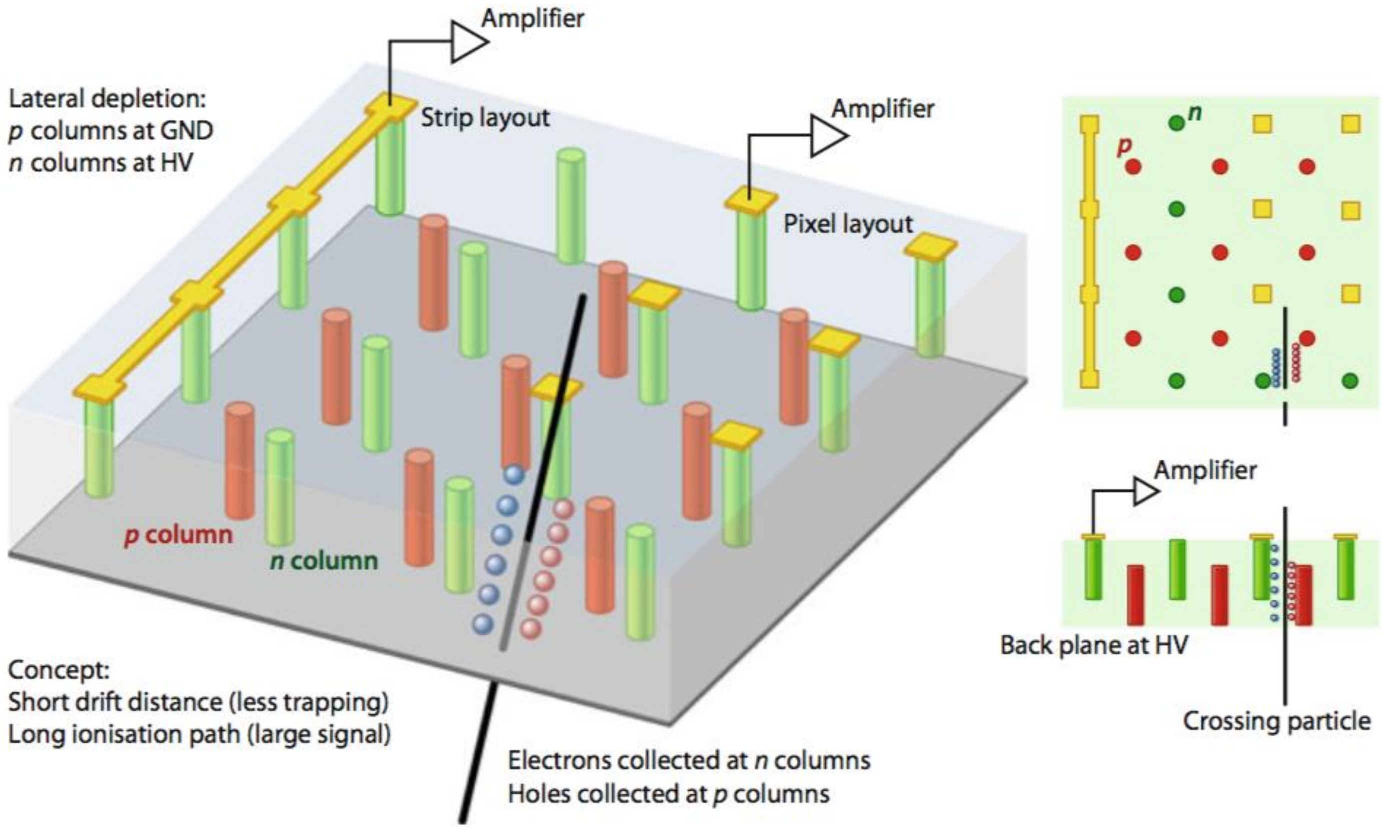
Davide Zuolo - VCI2022





- and are efficient,
and have good resolution

The evolution of 3D sensors

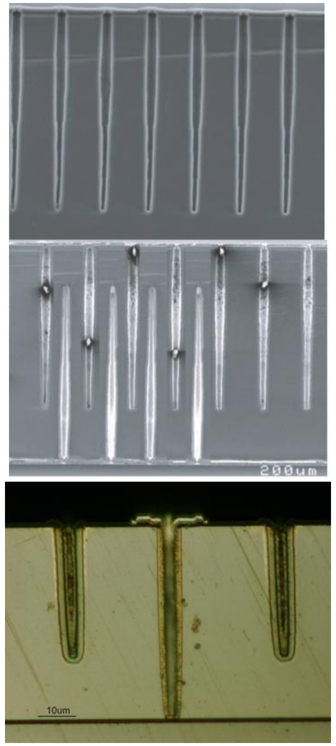


Example double sided, double type

- Double or single type?
- Double or single sided?
- Full 3D-pass-through?
- Thin or thick?

- For HL-LHC we need small pixel cells - 25x100 μm^2
  - We need narrow columns, thus good column depth/width
  - & **medium** thickness

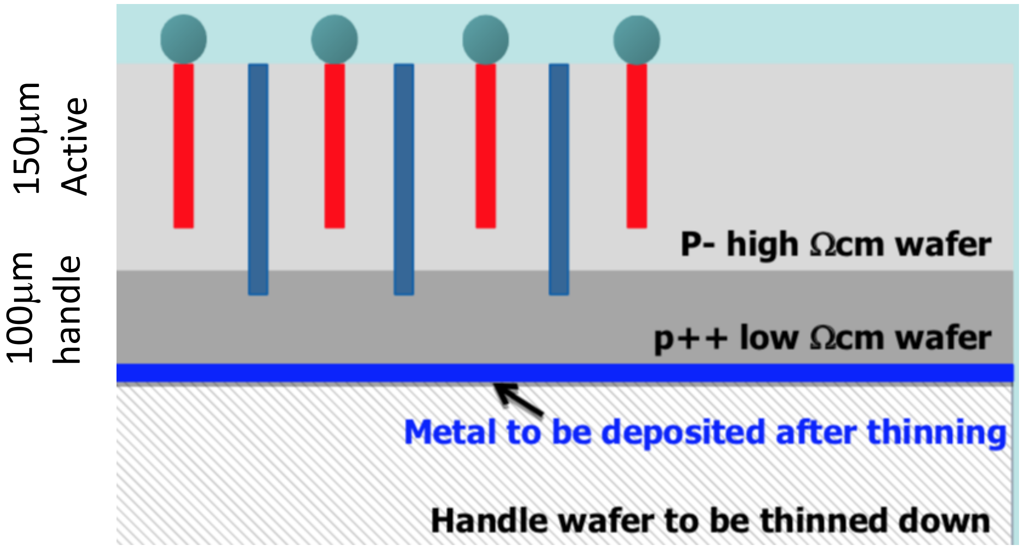
- What do we want later??



Courtesy CNM

Tell me, but I assume nobody considers 3D for strips ...
... it was useful for early testing.

3D Silicon Sensors for HL-LHC – **yes, we chose**



Made possible by Direct Wafer Bonding (Si-Si-DWB)

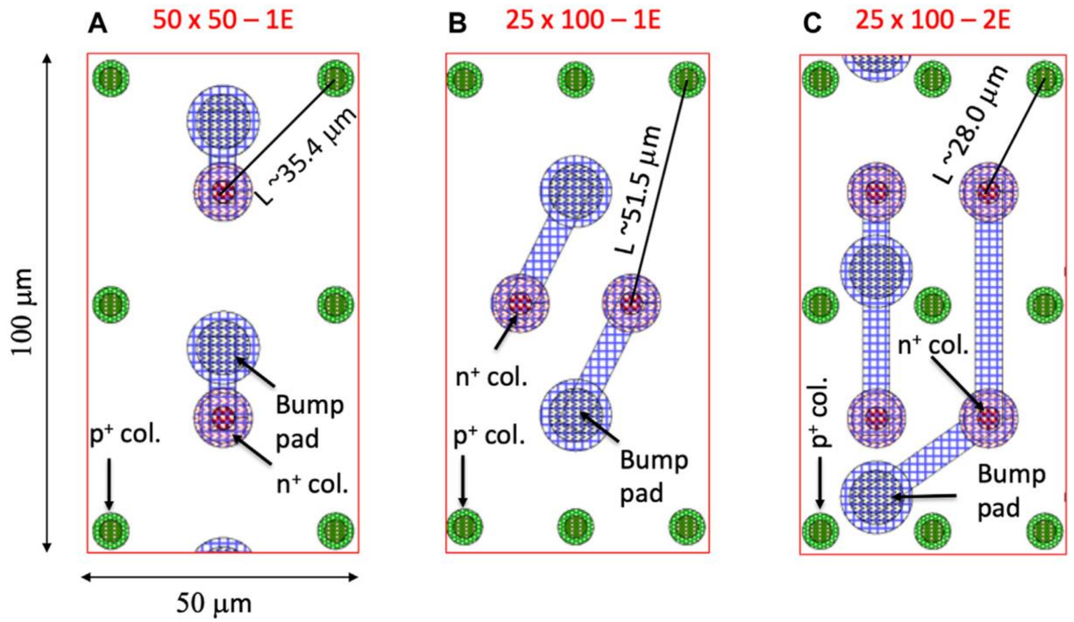
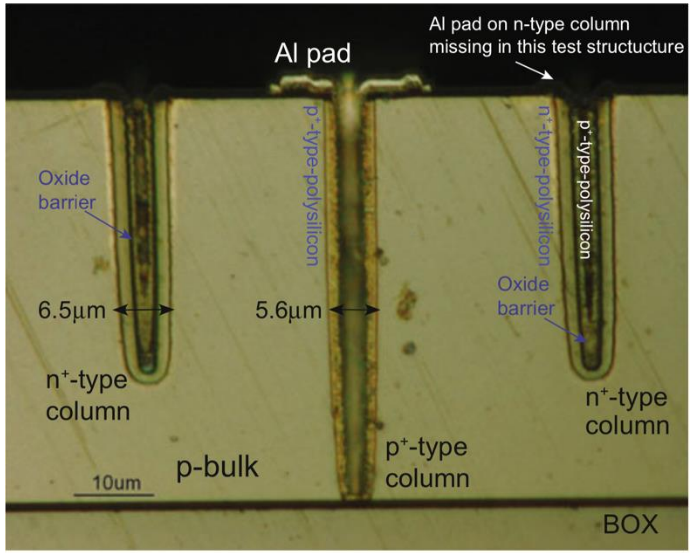


FIGURE 2 | Layouts of two adjacent small-pitch 3D pixels of different geometry for the ATLAS and CMS upgrades at HL-LHC: 50 *µ*m × 50 *µ*m-1E **(A)**, 25 *µ*m × 100 *µ*m-1E **(B)** and 25 *µ*m × 100 *µ*m-2E **(C)**.

Dalla Betta G-F and Povoli M (2022) Progress in 3D Silicon Radiation Detectors. Front. Phys. 10:927690. doi: 10.3389/fphy.2022.927690



Courtesy CNM

Close to this one…

Technology, thickness and cells chosen!

We are quarrelling a bit with noise these days at Φ>E16 and higher voltages

For the future we might like smaller cell sizes (e.g. 25x25 mm^2):

- Even shorter drift pathes – even more radiation tolerant?
- Higher occupancy
- Tune charge multiplication, already at lower voltages?

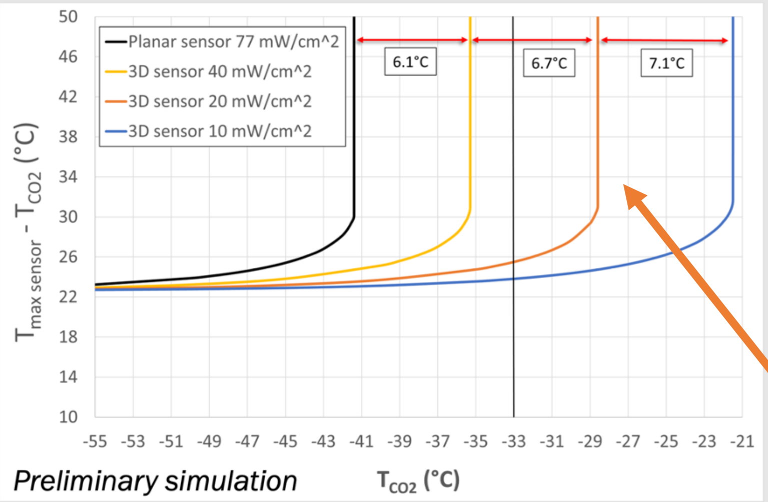
3D, in the end, do we do it for the radiation tolerance?

(used in ATLAS IBL, AFP, CMS PPS; to be used Phase-2 ATLAS & CMS inner layer)

- The goal of radiation tolerance is around $1\text{-}2 * 10^{16}{}_{1MeV\_eq}/cm^2$
- In principle planar pixels can do this …
  - Resolutions ~5 μm and efficiencies (98-99%) are very similar *(probably equal)*
- I guess, we do it due to power and to prevent corresponding thermal runaway (at minimal cooling contact)
  - Depletes at much lower voltage

Davide Zuolo - VCI2022 (CMS example)

Power dissipation simulation



- Barrel Layer 1
- planar sensors: T_{CO2} required to prevent thermal runaway is much lower than -33 ºC achievable
- 3D sensors: at least 4 ºC margin if the power dissipated in the active volume of the sensor is less than 20 mW/cm² after $2 \times 10^{16}\ n_{eq}/cm^2$
- power dissipation <20 mW/cm² confirmed by lab measurements

More in

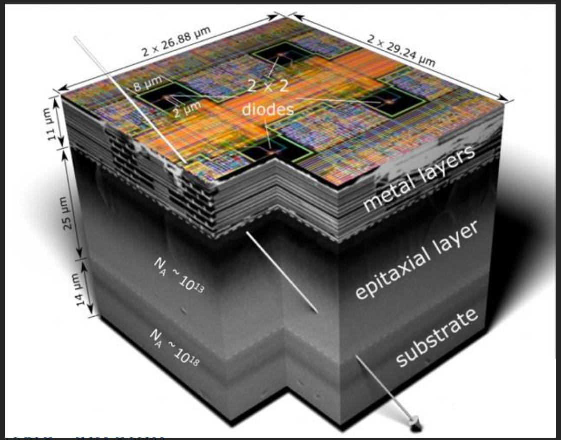
Qualification of the first preproduction 3D FBK sensors with ITkPixV1 – by Martina

Results on 3D pixel sensors for the CMS upgrade at the HL-LHC – by Rudy

Monolithic CMOS

CMOS Sensors for the Subaru Telescope	*Satoshi Miyazaki*	
North Ballroom, La Fonda Hotel	17:15 - 17:35	
X-ray polarization measurements with CMOS for satellites	*Hirokazu Odaka*	
North Ballroom, La Fonda Hotel	17:35 - 17:55	
CMOS pixel sensors for ULTRASAT	*Steven Worm*	
North Ballroom, La Fonda Hotel	17:55 - 18:15	
AstropPix: Status and Outlook of Monolithic Active Pixel Sensors for Future Gamma-ray Telescopes	*Dr Regina Caputo*	
North Ballroom, La Fonda Hotel	18:15 - 18:35	
Extremely high density and position resolution digital pixel sensors	*Gianluigi Casse*	
North Ballroom, La Fonda Hotel	15:50 - 16:10	
Pixel detector developments for future lepton colliders	*Dominik Dannheim*	
North Ballroom, La Fonda Hotel	16:10 - 16:30	
ATLASPIX3 modules for experiments at electron-positron colliders	*Prof. Attilio Andreazza*	
North Ballroom, La Fonda Hotel	16:30 - 16:50	
TJ-MALTA	*Valerio Dao*	
North Ballroom, La Fonda Hotel	16:50 - 17:10	
LF-Monopix2	*Patrick Breugnon*	
North Ballroom, La Fonda Hotel	17:10 - 17:30	
Depleted monolithic active pixels sensor in 180nm TowerJazz CMOS technology with column drain readout architecture		
Christian Bespin		
A derivation of the electric field inside MAPS detectors from beam-test data and limited TCAD simulations	*Arka Santra*	
North Ballroom, La Fonda Hotel	14:10 - 14:30	
From vertex detectors to applications in ion detection and spectrometry: a glimpse of MAPS R&D in Strasbourg		
Jerome Baudot		
Optimization of a 65 nm CMOS imaging technology for monolithic sensors for high energy physics	*Walter Snoeys*	
North Ballroom, La Fonda Hotel	14:50 - 15:10	

some call it
HV-CMOS or HR-CMOS
some call it DMAPS
I call it exciting!



And in my very **personal** humble opinion it must be fully **monolithic***

And getting all logic in and cope with high rates will be a challenge -- experiencing the struggle to get all ATLAS and CMS needs into the 65nm pure pixel ASIC (RD53)

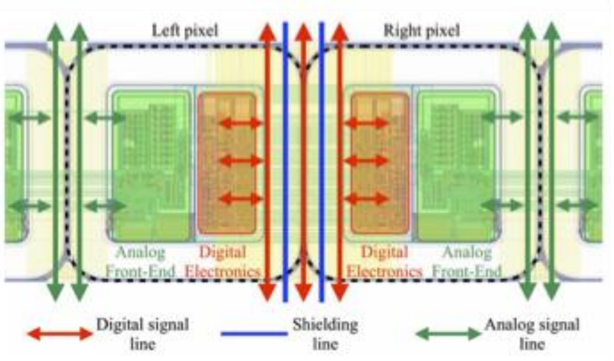
* I believe we all know why

Stating the Obvious

What we all know – **Advantages** of HV-CMOS

Stock.adobe.com

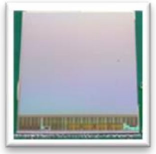
- Thin
  - Low material budget: X/X0 ~ 0.05%
  - Radiation tolerant (also 'collects' electrons): $\Phi > 10^{15}{}_{MeV\_eq}/cm^2$
- Low power
- No bump bonding – cost saving, easier logistics
- In-cell processing – monolithic
- Small cells ($10x10\mu m^2$) – high resolution ~$3\mu m$



From RD50 talk

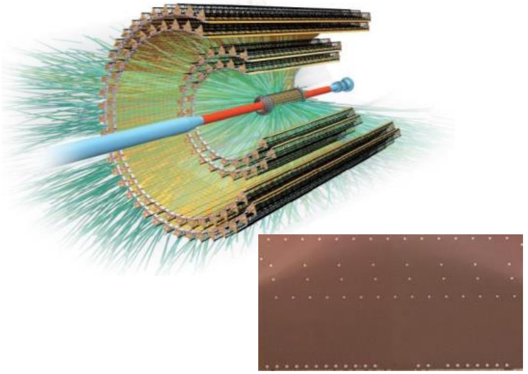
- Challenges:
  - Stitching
  - How much digital parts features fit in a pixel (and how much in chip periphery)?
    - timing, buffering, L1, data handling - state machine

MAPS Monolithic Active Pixel Sensors



ULTIMATE in **STAR**

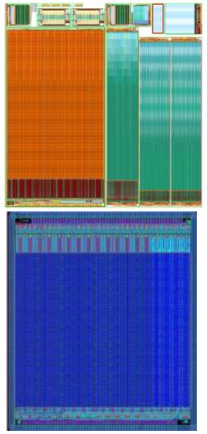
First HEP MAPS system



ALPIDE in **ALICE**

First MAPS with sparse readout similar to hybrid sensors

Chip-to-chip communication for data aggregation



Recent developments (ATLAS, ALICE, MU3e, etc.)

Depleted radiation hard MAPS with:

'high' voltage

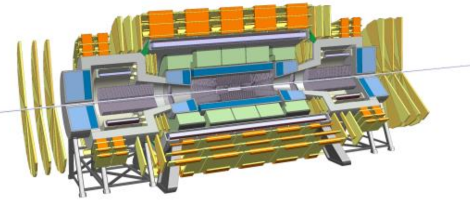
Sparse readout

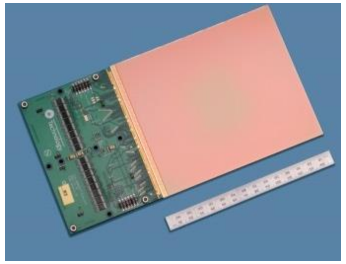
Chip-to-chip communication

Serial power

…

Many more in betwen, some to be discussed this week





FCC, e^+e^- collider, …

Large stitched fast radiation hard MAPS with:

Sparse readout

Chip-to-chip communication

Serial power, timing

… many more

12”, <65nm?,

new read-out schemes?

…

Important steps in every iteration

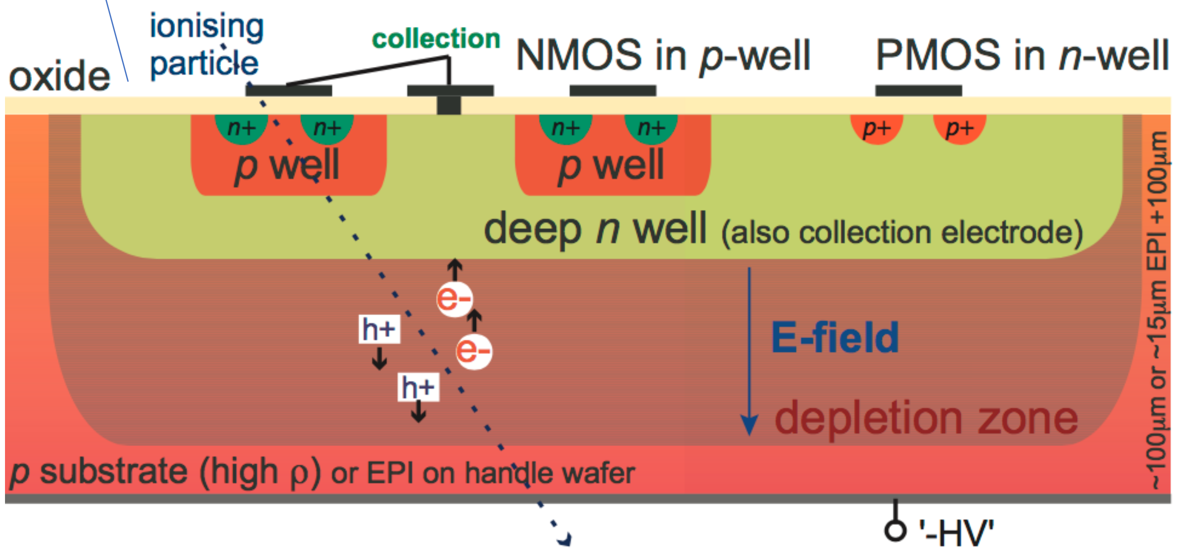
Many uses: STAR, ALICE, CBM, NICA MPD, sPHENIX, Mu3e, CSES – HEPD2, Medical, …

candidates for LHCb, PANDA, BELLE-2, EiC, ILC … **~ well everybody**

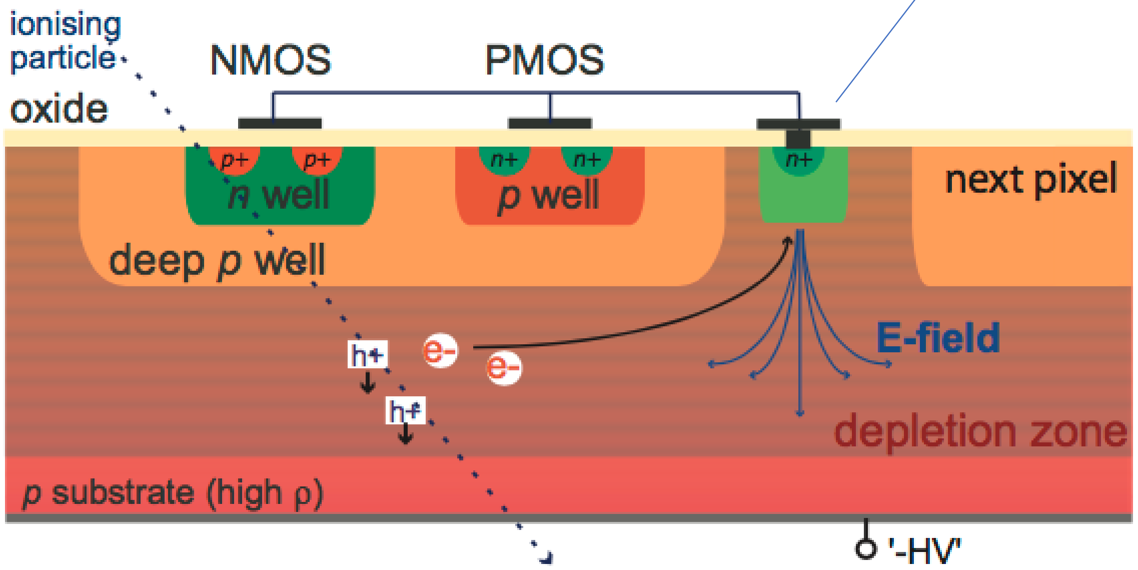
Nodes being used: 180, 150 and *65 nm technology* and 130 nm SiGe BiCMOS

LARGE or SMALL electrode??

e.g. 50-60 μm (for RD50)



e.g. 3 μm (for Malta)



- Short drift path (faster ‘*collection*’)
- High C - higher noise O(100 e$^-$)
- Homogeneous weighting field
- High homogeneous electrical field
- *E.g. MUPIX, RD50, MONOLITH, LF-MONOPIX, ATLASPIX*

- Long drift path
- Very low C - reduced noise (~10 e$^-$ & low power)
- δ weighting field – arrival
- *Some adaptions help further*
- *E.g. ALPIDE, MALTA, TJ-MONOPIX. CLICTD, FASTPIX*

LF-Monopix2 – by Patrick

Where can we have more real estate for CMOS circuitry?
Radiation tolerance – we are around > $10^{15}{}_{MeV\_eq}/cm^2$ — is *LARGE* better?

TJ-MALTA - by Valerio

SMALL CELL HV-CMOS EVOLUTION

To overcome:

- Lateral depletion
- Direct drift to to small electrode
    - Mind δ weigthing field

Achievements

- Thresholds ~100 e^-
- Noise ~ 10 e^-

TJ-MALTA - by Valerio

E.g. ALPIDE, MALTA, MONOPIX, CLICTD, FASTPIX

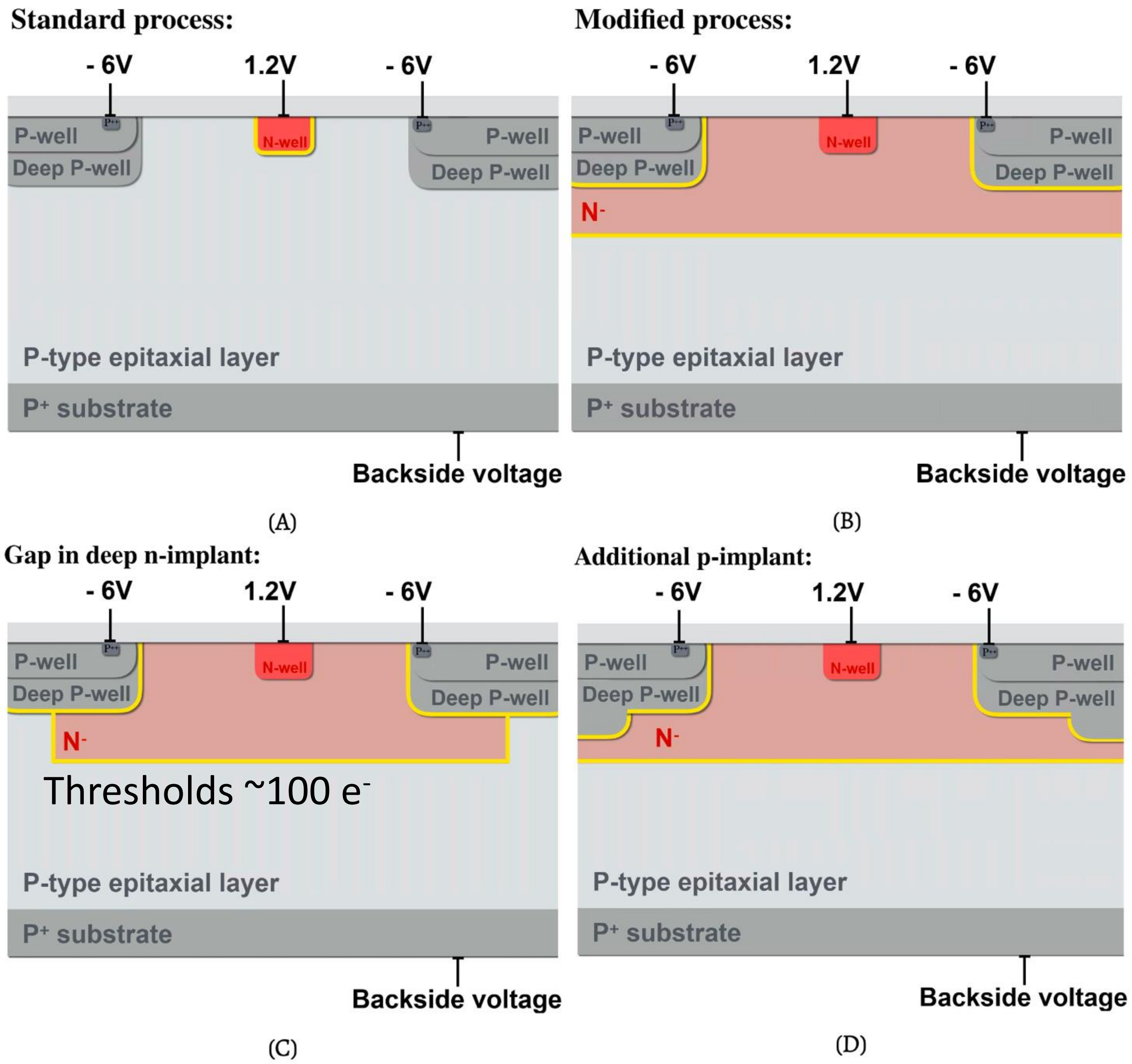


FIGURE 9.1: Four different pixel flavours are shown [119]. (A) shows the standard flavour which was used in ALPIDE. (B) shows the modified flavour which features a blanket deep n-implant. (C) shows the gap flavour which leaves a gap in the deep n-implant. (D) shows the extra-p flavour which features an extra deep p-implant. The junction is represented in yellow. The voltages are the ones used in this chapter. All the drawings are not to scale.

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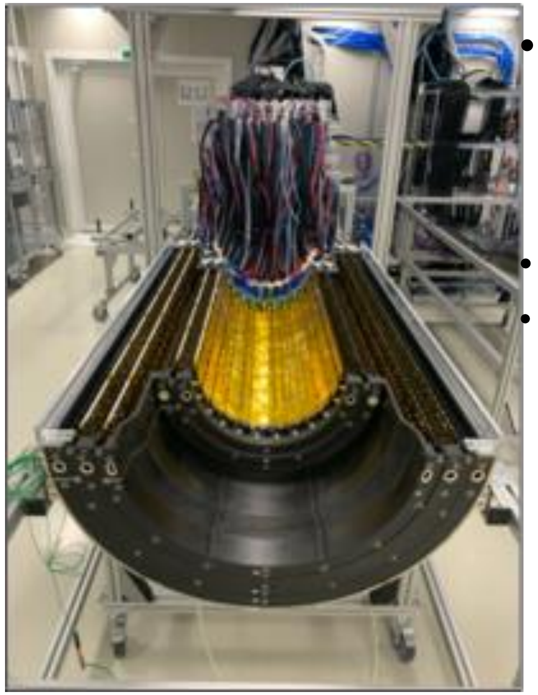
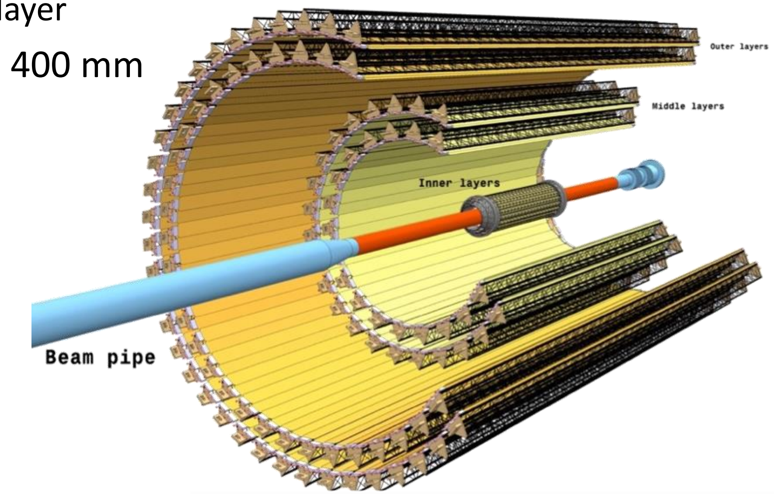
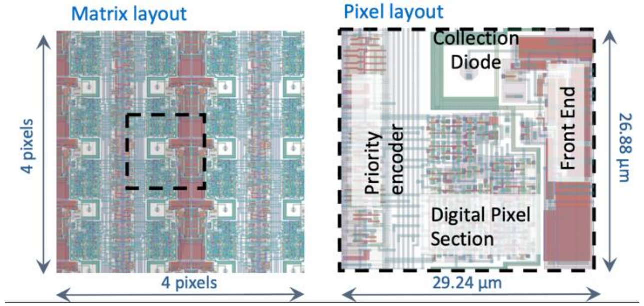
The ‘big’ *Small Cell* example of MAPS - ALICE

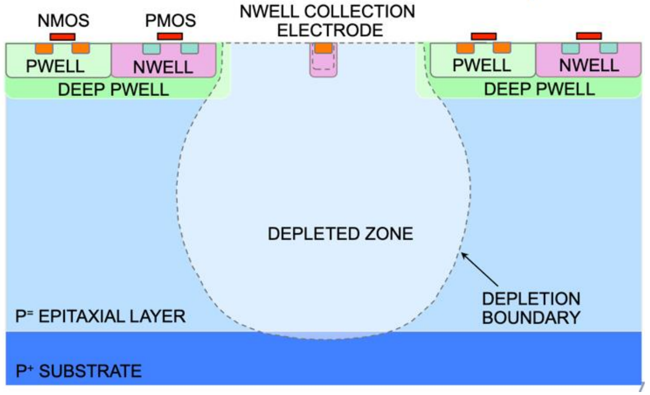


- **LS2:** 3+4 layers of **MAPS (CMOS) ~10m²**
  - 27x29 μm² pixels - **12.5 G-pixels**
  - MAPS thinned to 50 μm
    - ~0.3 % X_0 per layer
- Radial coverage R= ***21*** **-** 400 mm
- Limited voltage ~3V



ALICE ITS Upgrade TDR CERN-LHCC-2013-024

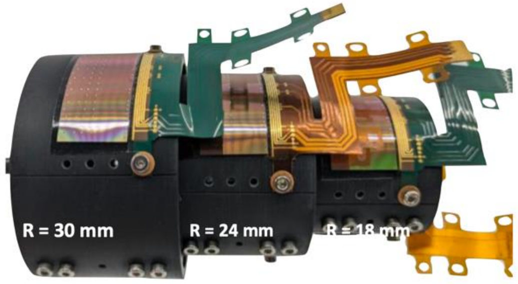




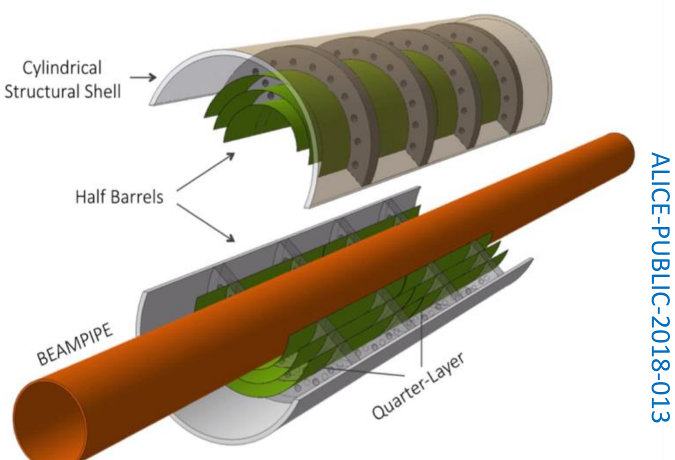
MAPS

- **Future:** ALICE upgrade (ITS3) – **HR/HV CMOS**
  - Push technology further: **thinner,** large sensors through stitching
  - Faster signal, more radiation hard
  - Pixel sizes 10x10μm² → 3μm position resolution
  - X/X0 per layer 0.05%
  - **CURVED**

In test beam
Bent ALPIDE



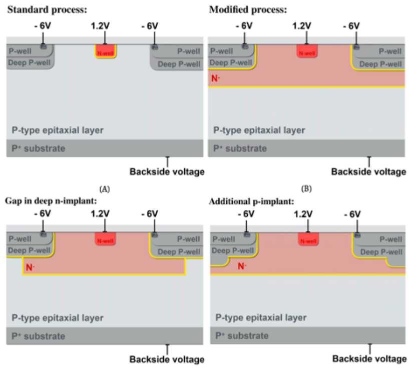
Vertex 2022 Lukas Lautner



Truly cylindrical vertex detector

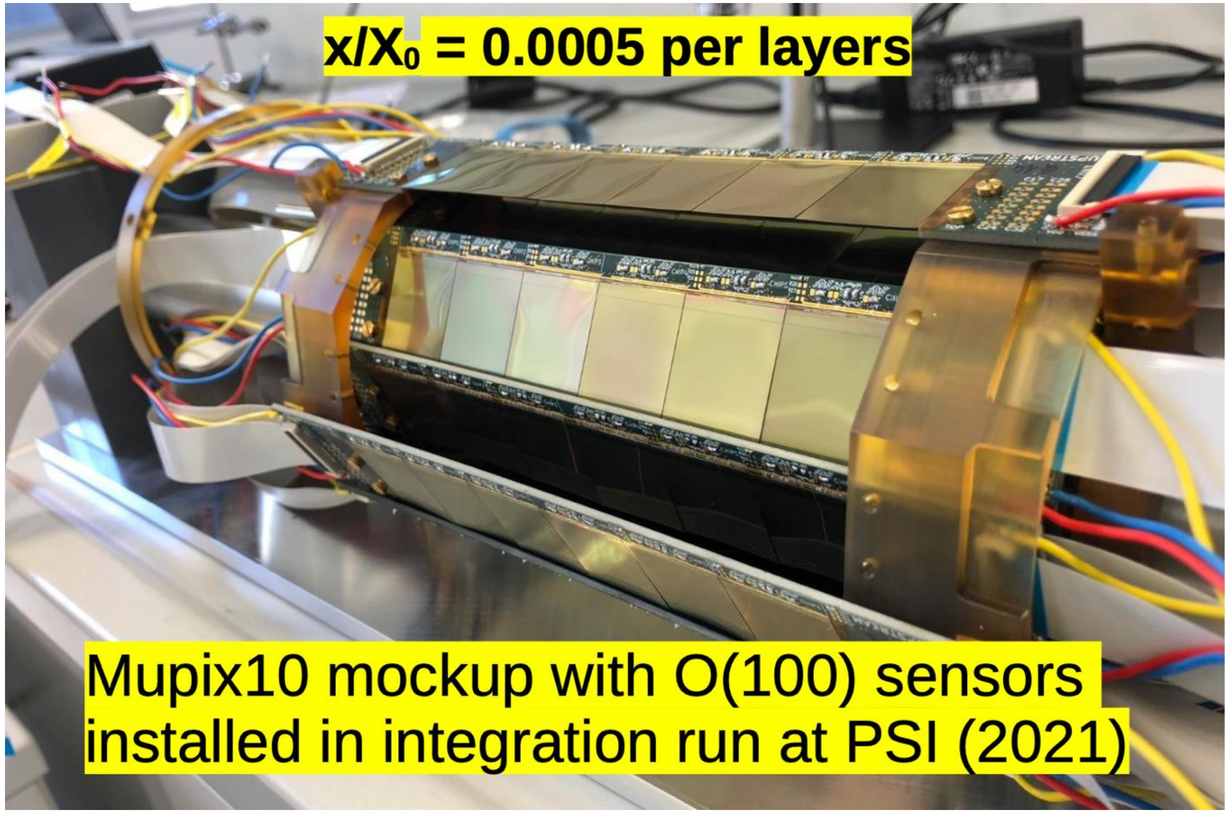
ALICE-PUBLIC-2018-013

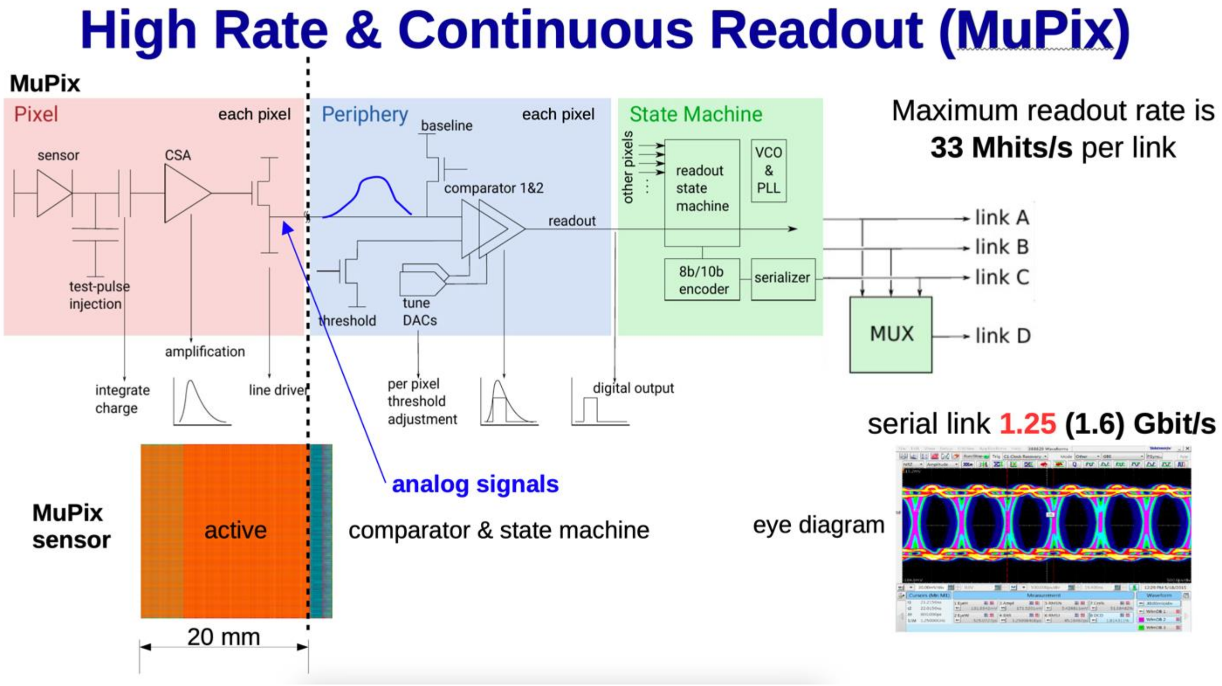
Let’s see, which option they will chose?



DMAPS

Mu3e – Another wonderful example on HV-CMOS
Big Cell approach - MUPIX





Full monolithic – great example!

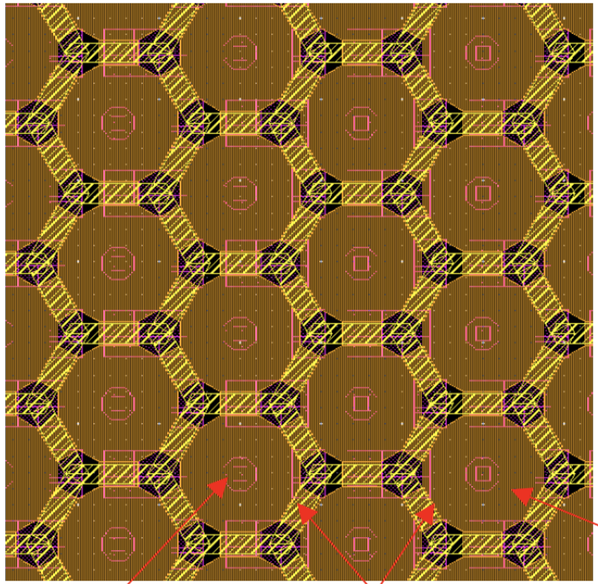
- Phase-1: 6 layers (50mm thin and cooled by **gaseous helium** (up to 400 mW/cm2)

Material from Andre Schoening - Monolith Workshop, Sep. 2022

HEP starts to like hexagonal structures – approximate circle!

- Collection electrodes on hexagonal grid
- Charge sharing in the corners between 3 pixels instead of 4
  - Smaller cluster sizes, increase of seed signal -> more margin
- Electrode distance to edges similar boarder improves time resolution - Homogeneous drift field
- Reduce breakdown (minimise edge effects)

FASTPIX (small cell)

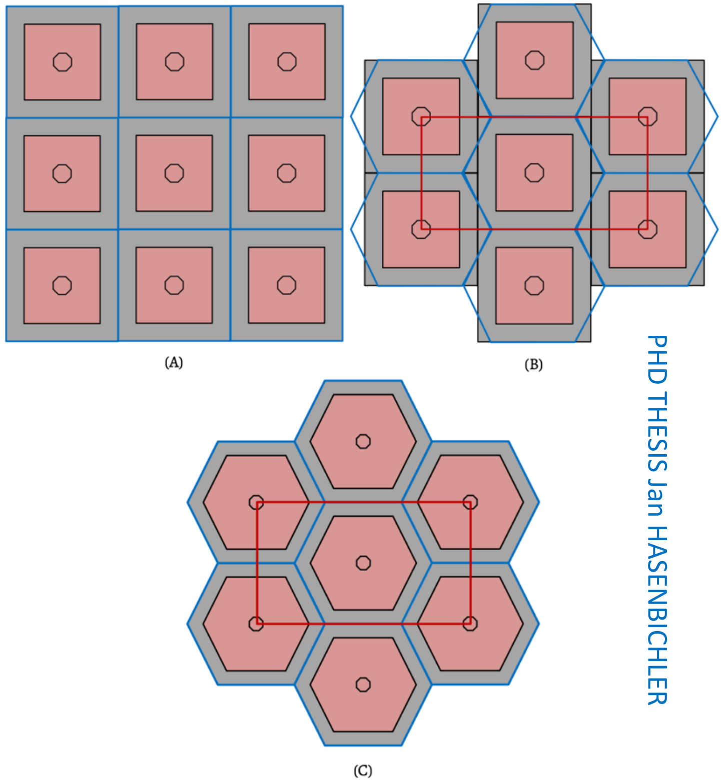


n-well electrode

extra p-type implant

low-dose n-type implant

https://www.mdpi.com/2410-390X/6/1/13



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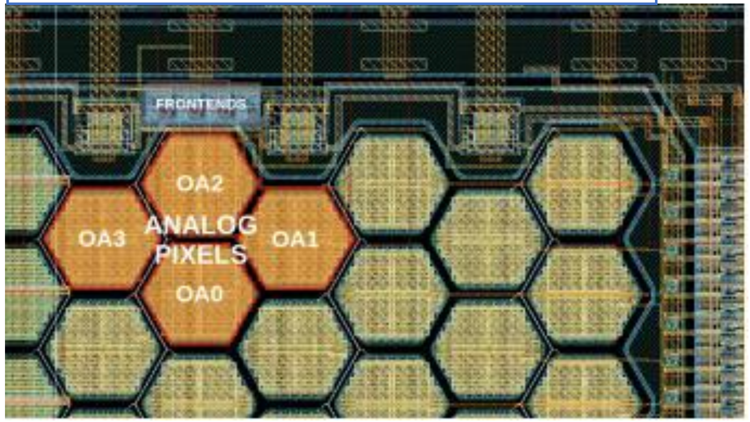
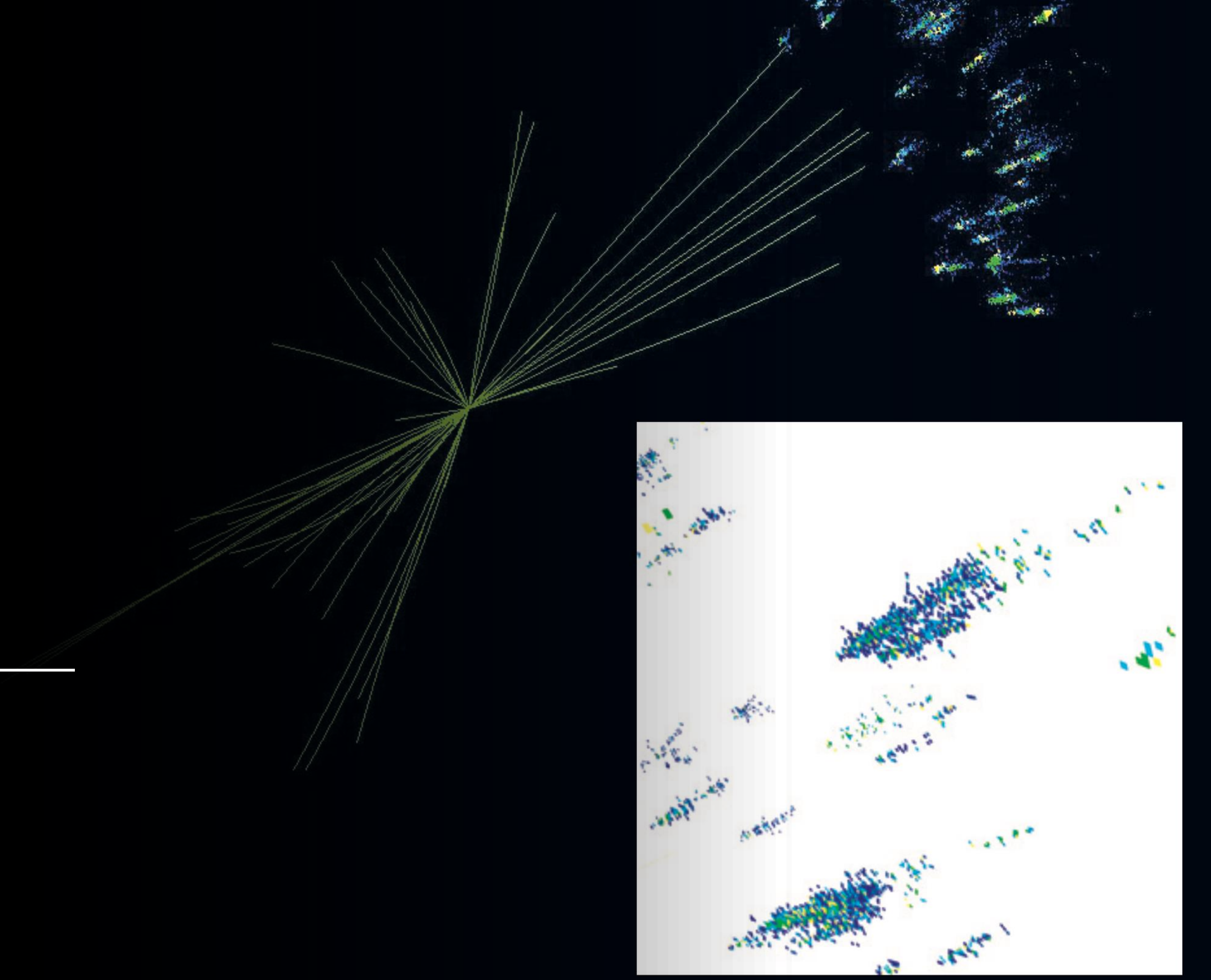
PICOAD/MONOLITH (large cell)



MONOLITH

That’s it

Soon, we also ‘track’ inside calorimeters



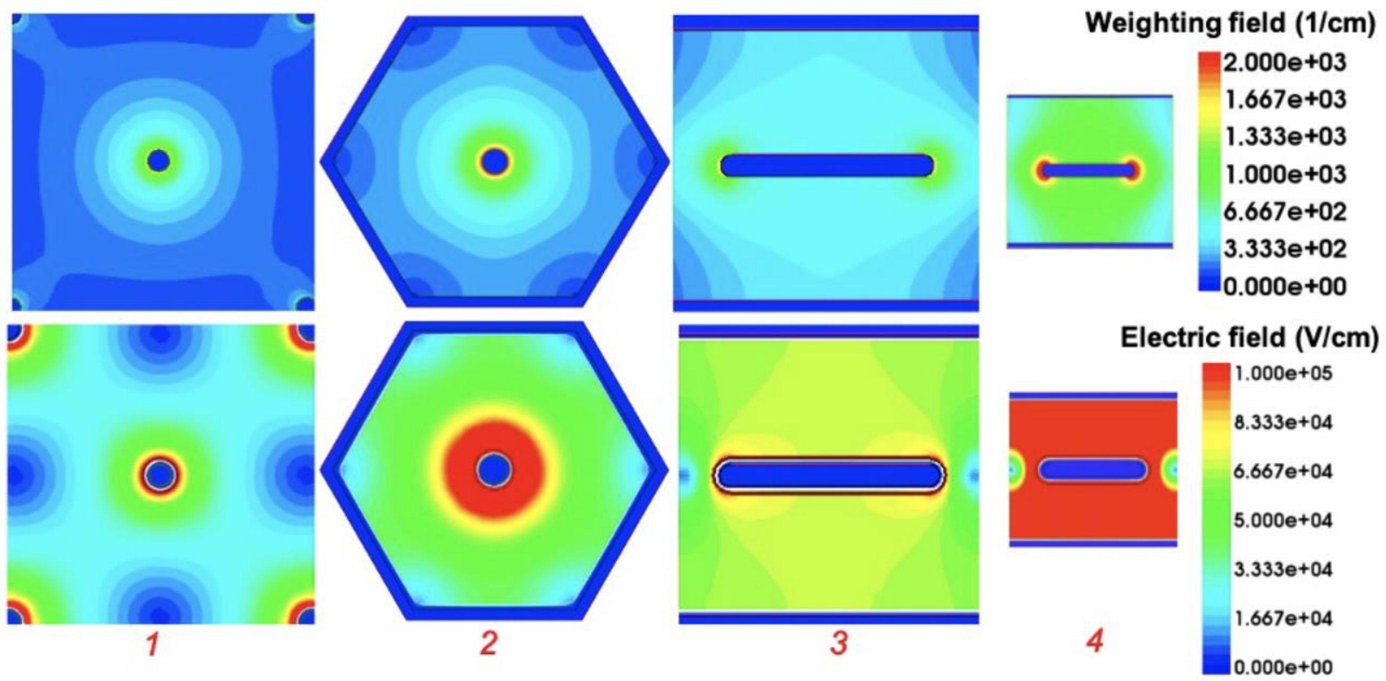
→ ALICE FOCAL & CMS HGCAL

I love this incredibly lively field of sensor and detector system development.

And, it will be a great pleasure to talk to you later

Only problem, such meetings animate me to stop doing managerial work and to go back having fun in the lab.

BACKUP


Weighting field (1/cm)
2.000e+03
1.667e+03
1.333e+03
1.000e+03
6.667e+02
3.333e+02
0.000e+00
Electric field (V/cm)
1.000e+05
8.333e+04
6.667e+04
5.000e+04
3.333e+04
1.667e+04
0.000e+00
1
2
3
4

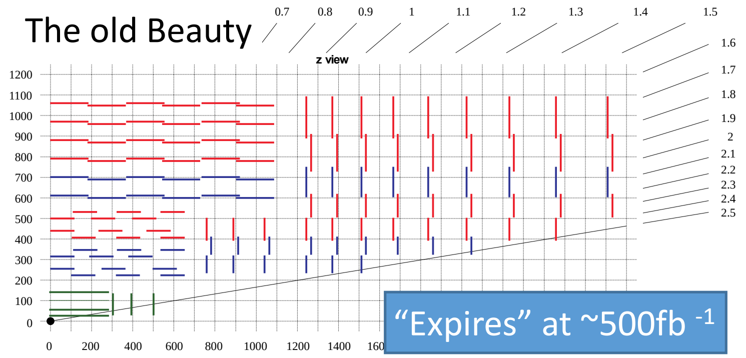
The new Beauty

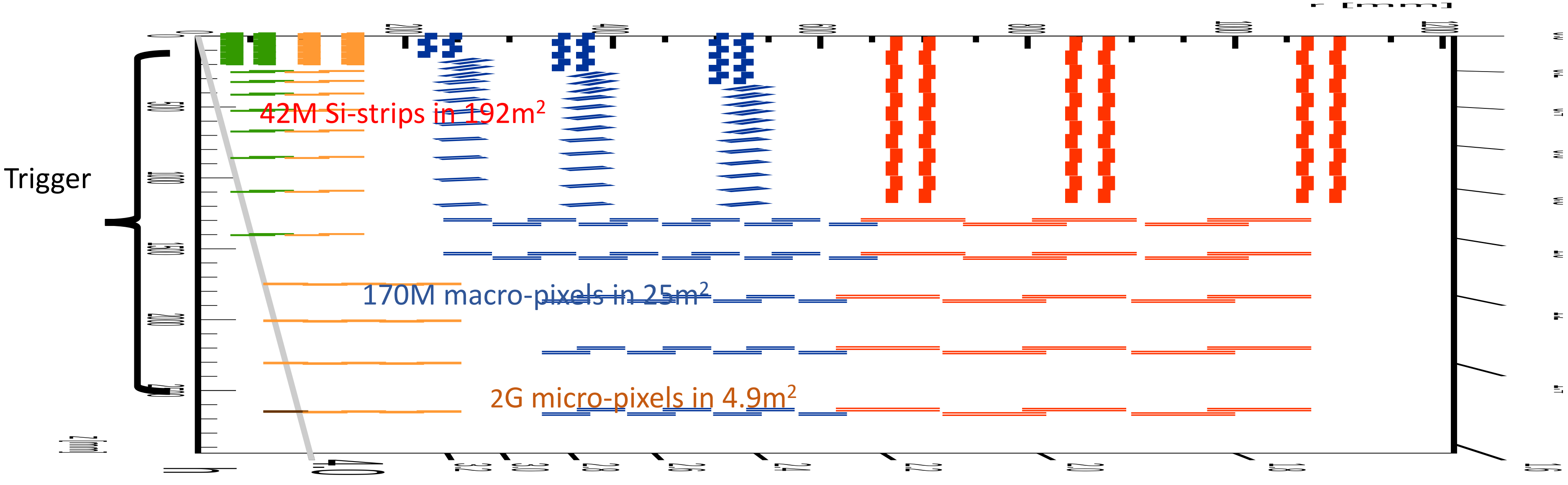
- Outer Tracker design driven by ability to provide **tracks at 40 MHz to L1-trigger** (p_T>3GeV)
  - **World's first**

- Tilted modules in three OT layers

- Inner Tracker (pixel) extend coverage to η ≃ 3.8

The old Beauty





CERN-LHCC-2017-009 CMS-TDR-17-001

p_T transverse momentum