Towards picosecond timing with ultrathin silicon pixel detectors

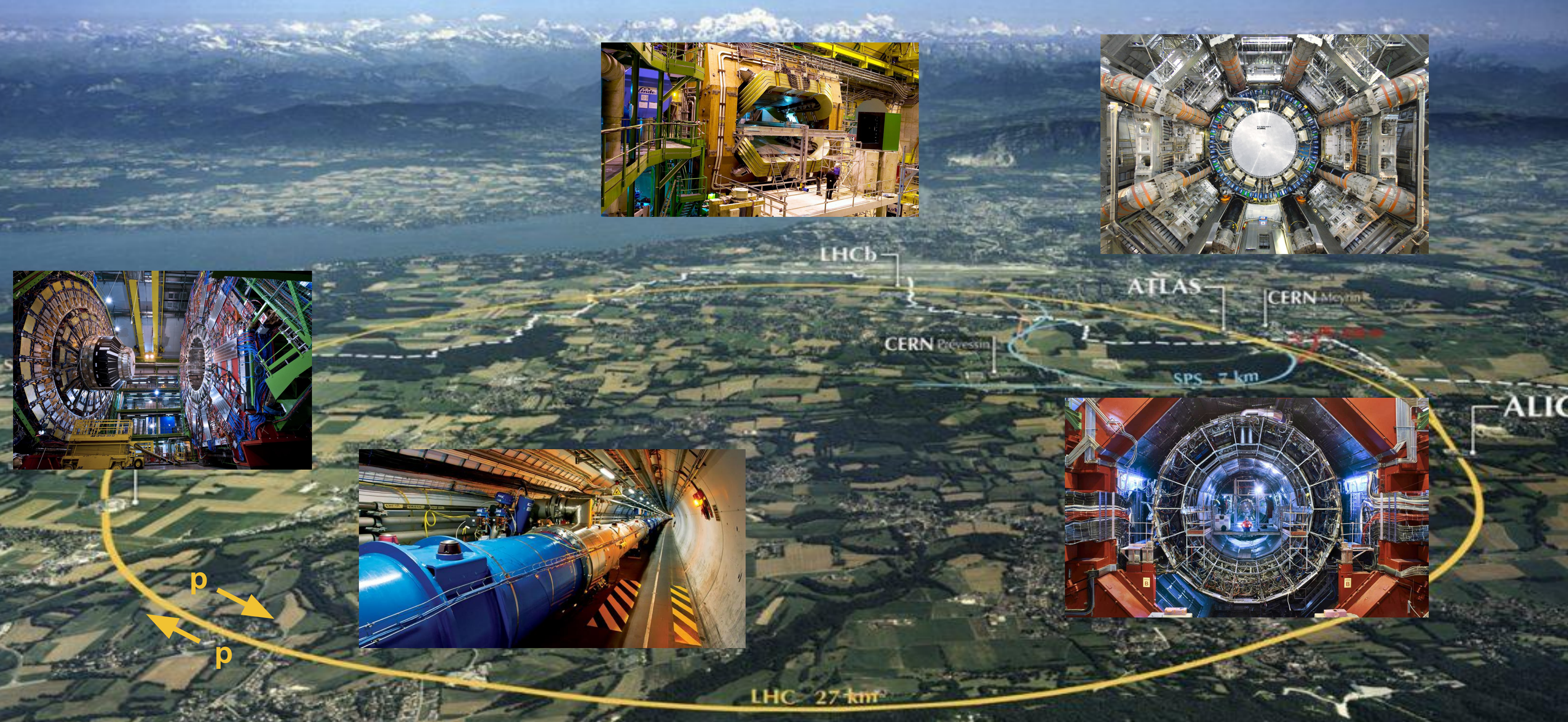
Jory Sonneveld

Nikhef

University of Amsterdam

Nikhef colloquium 2021-10-01

Large Hadron Collider: very fast detectors needed



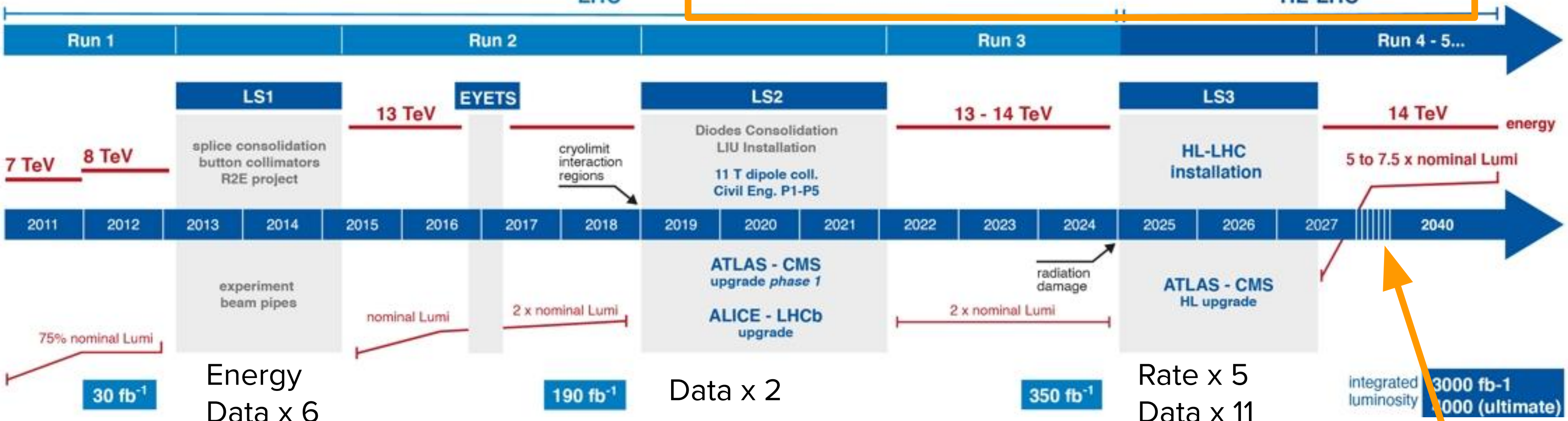
jory.sonneveld@nikhef.nl

https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg
H t tp://s ites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg
https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG
https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg
https://www.youtube.com/watch?v=NhXMXiXQWAA

LHC timeline: collect more and more data

From the high lumi LHC project

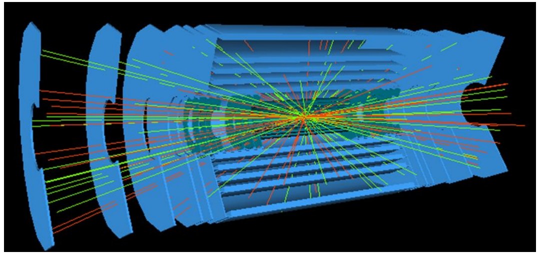
LS = long shutdown: major upgrades!



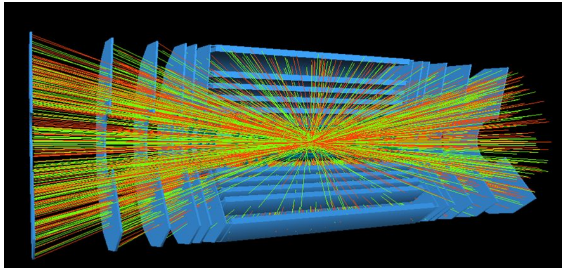
Energy
Data x 6

Data x 2

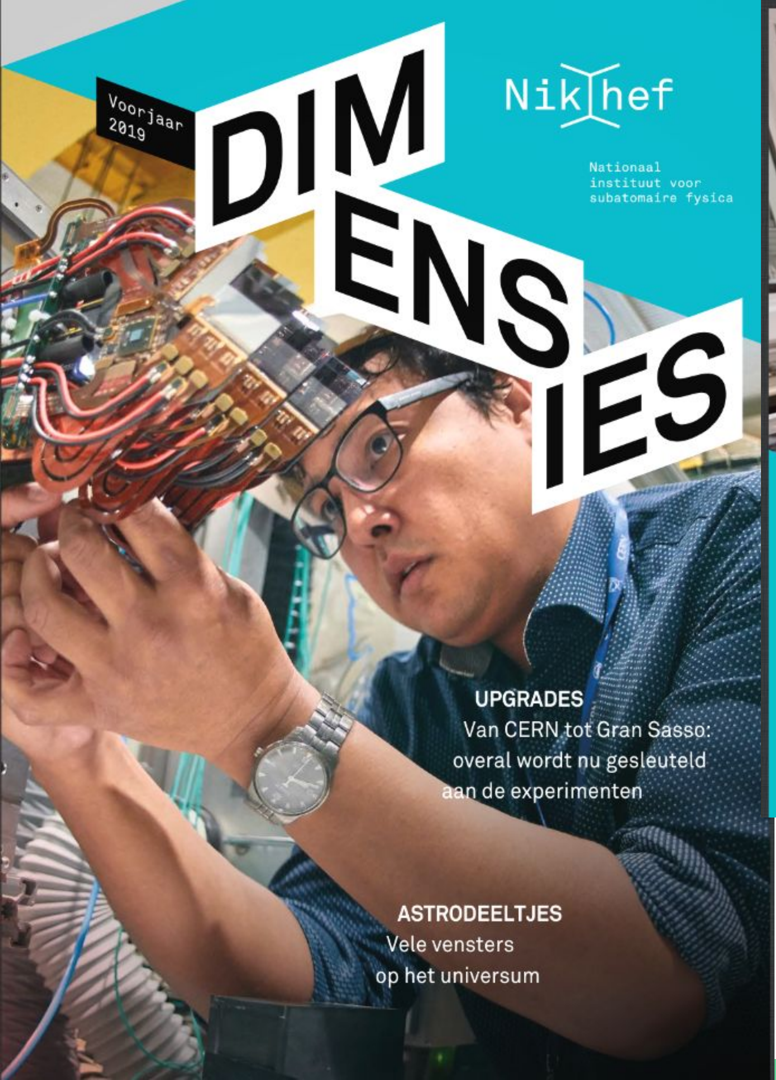
Rate x 5
Data x 11



Pileup x 10

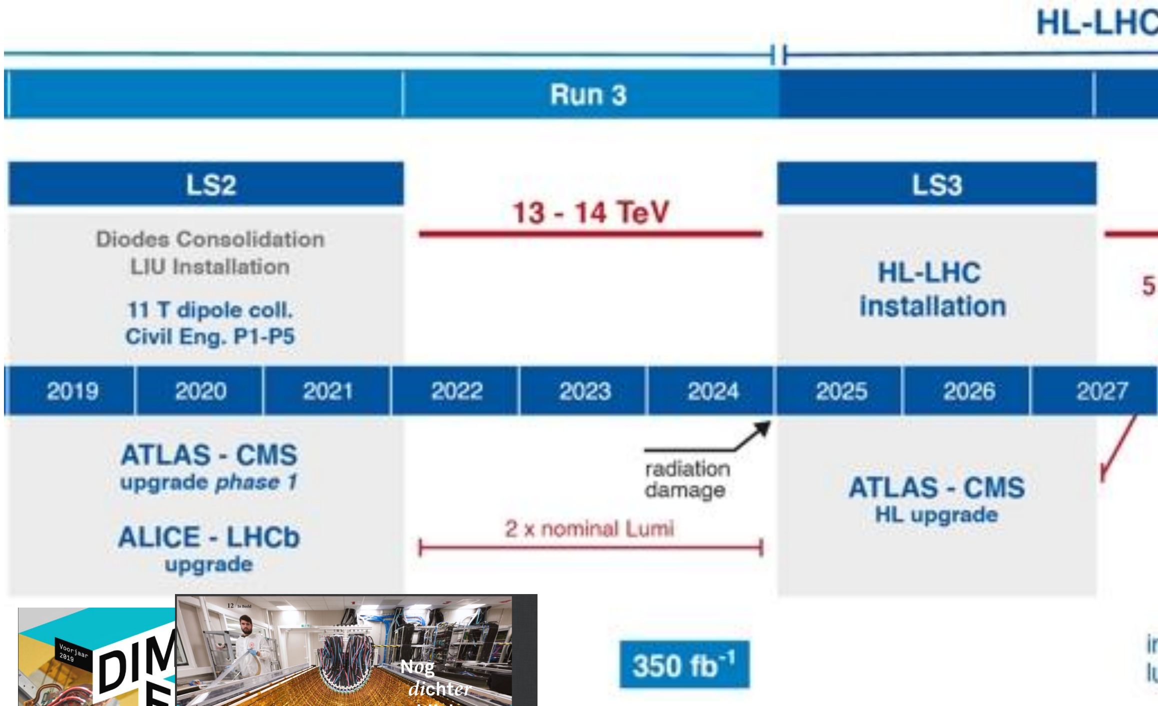


2032: LS4
Rate x 50
for LHCb

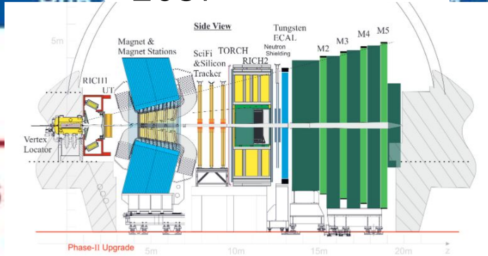


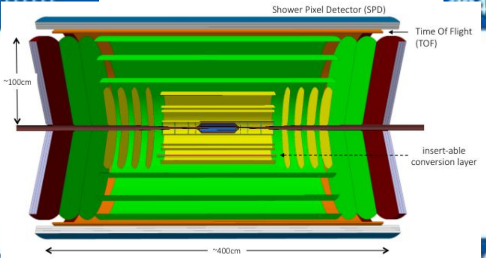
As of NOW!

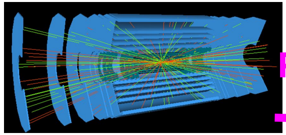
Nikhef R&D group works with LHC experiments and Nikhef electronics group on pixel detectors for future upgrades of experiments



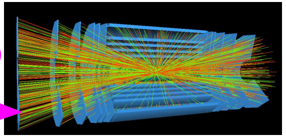
2031







Pileup x 10



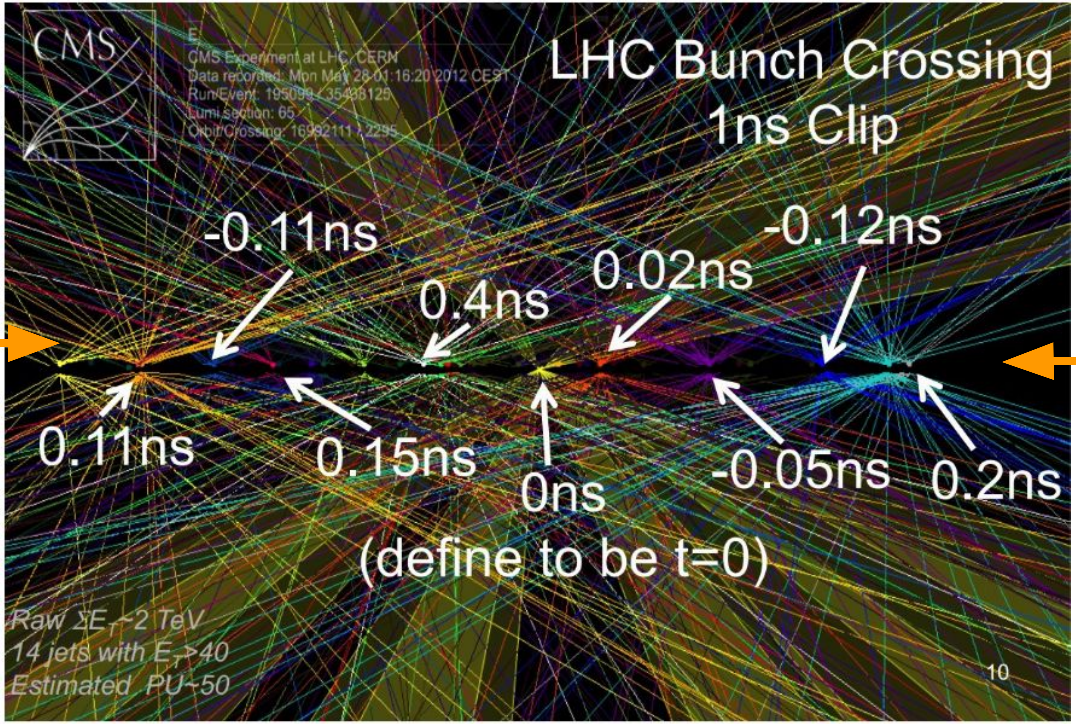
Pileup x 3

Fast timing needed!

How to distinguish between these collisions?

Multiple **primary vertices** per bunch crossing!
Color indicates point in time within bunch crossing

Example: inside the CMS detector



25ns between bunches

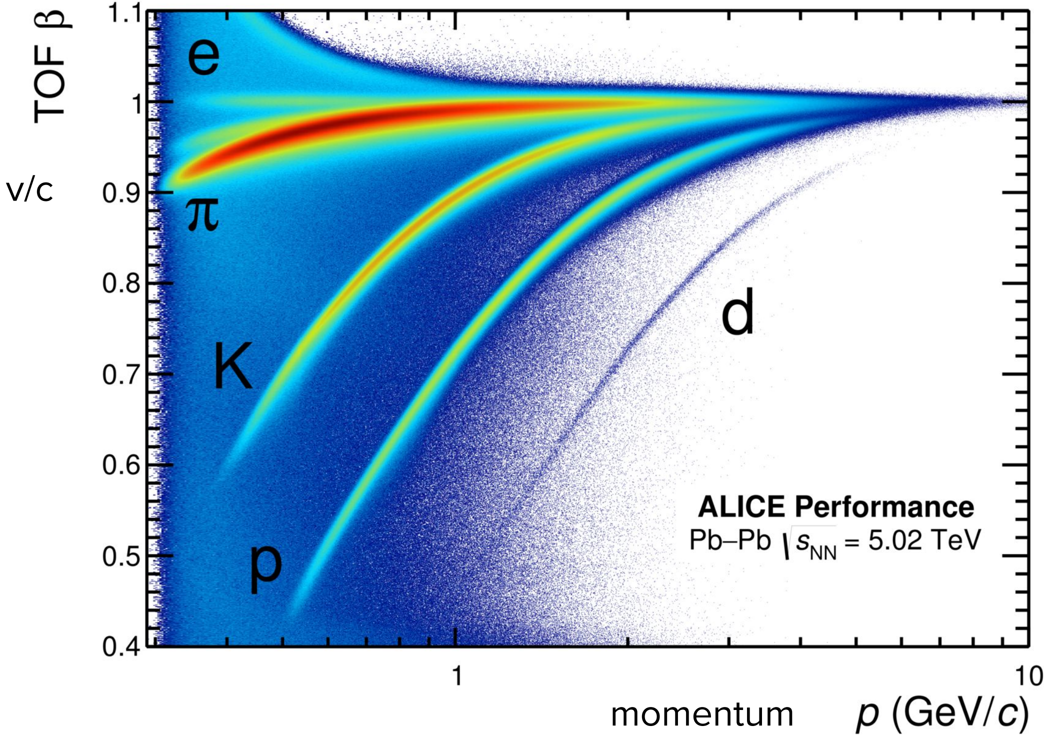
p p

p p p

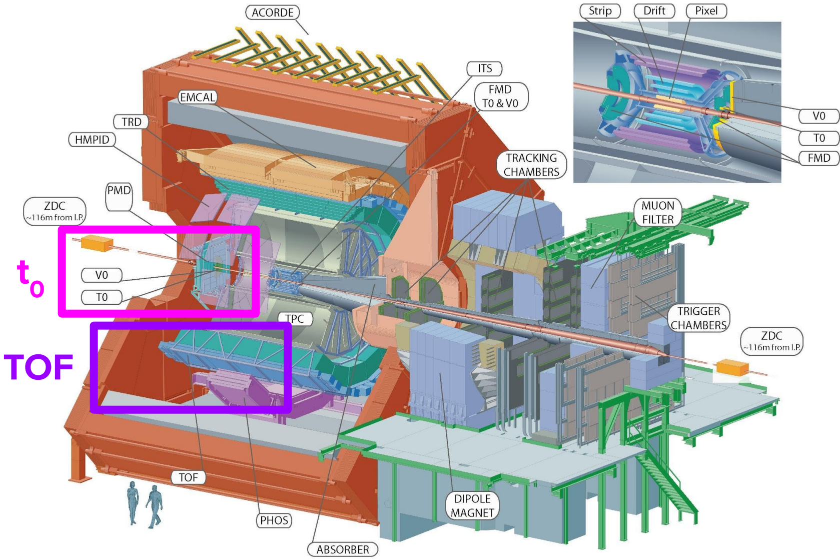
One bunch has $2 \cdot 10^{11}$ protons

From Nicolo Cartiglia (Nikhef colloquium on 2020-10-30)

How to identify particles with time of flight?



ALI-PERF-106336



Measure time at t_0 and TOF

So we need fast silicon pixel detectors. What is a silicon pixel detector anyway?

A silicon tracking detector

200 m^2 CMS silicon strip tracker
The largest tracker ever built

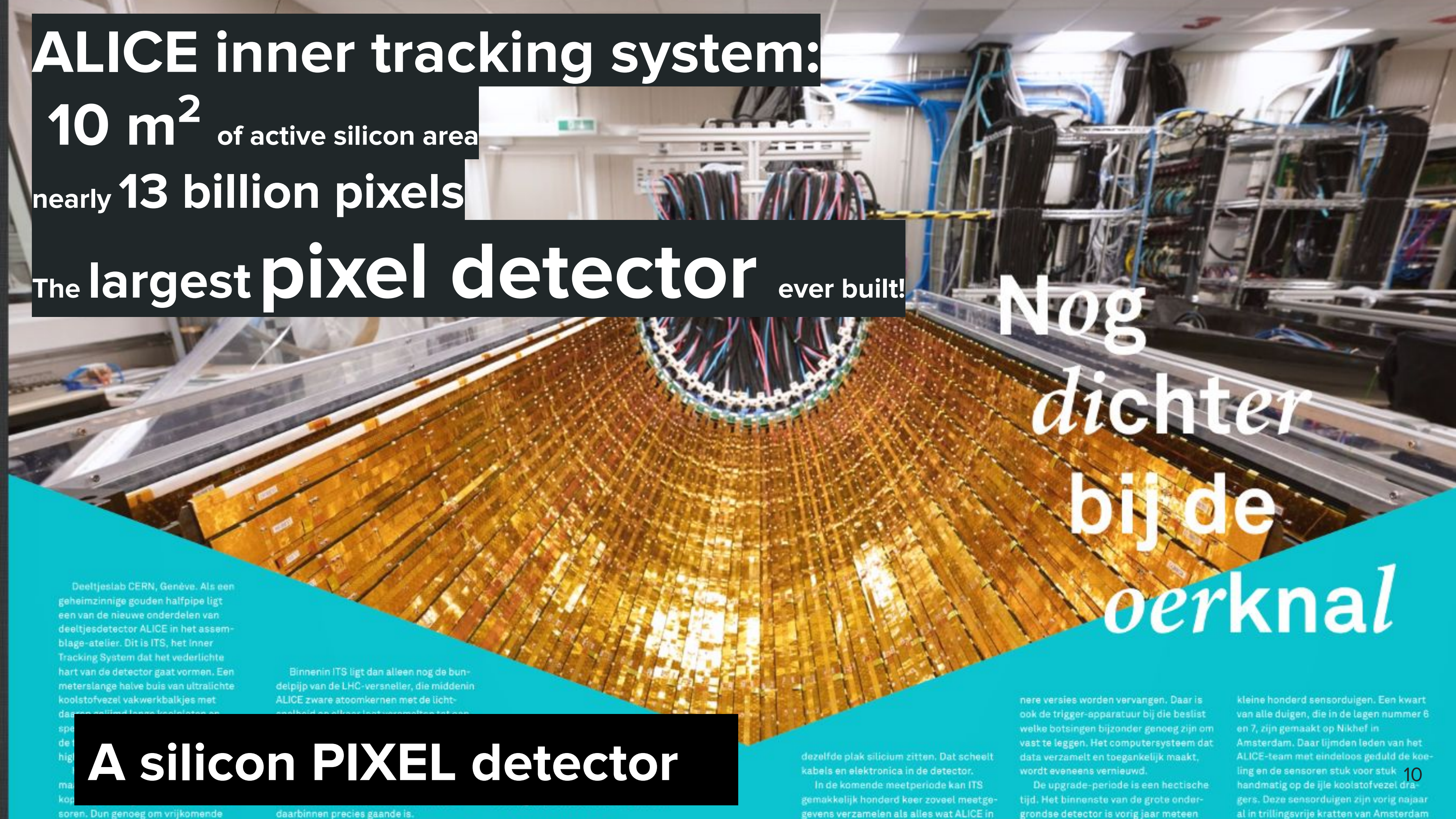
https://www.lhc-epistemologie.uni-wuppertal.de/fileadmin/lhcepistemologie/media/bilder/slider_home1_1200x600.jpg

ALICE inner tracking system:

10 m^2 of active silicon area

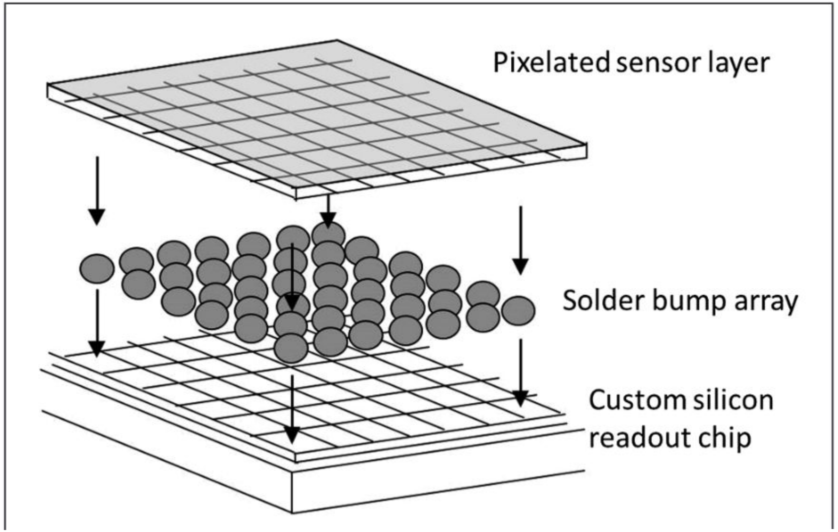
nearly **13 billion pixels**

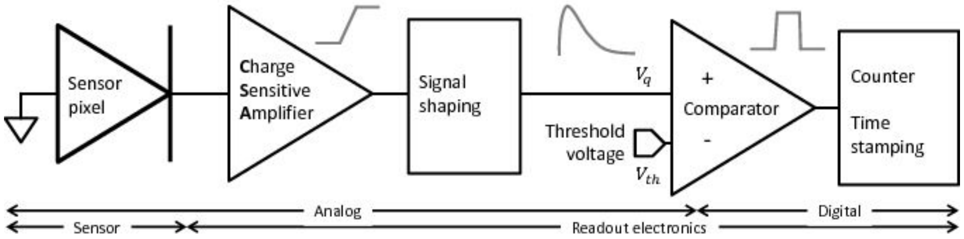
The **largest pixel detector** ever built!

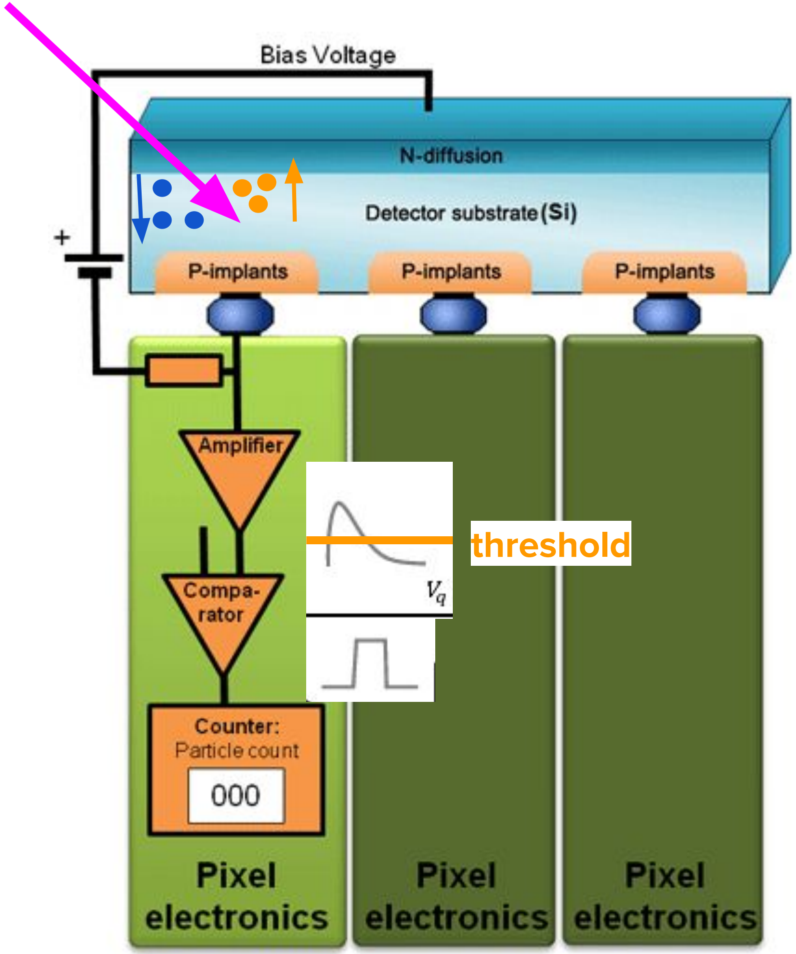


A silicon PIXEL detector

A hybrid pixel detector

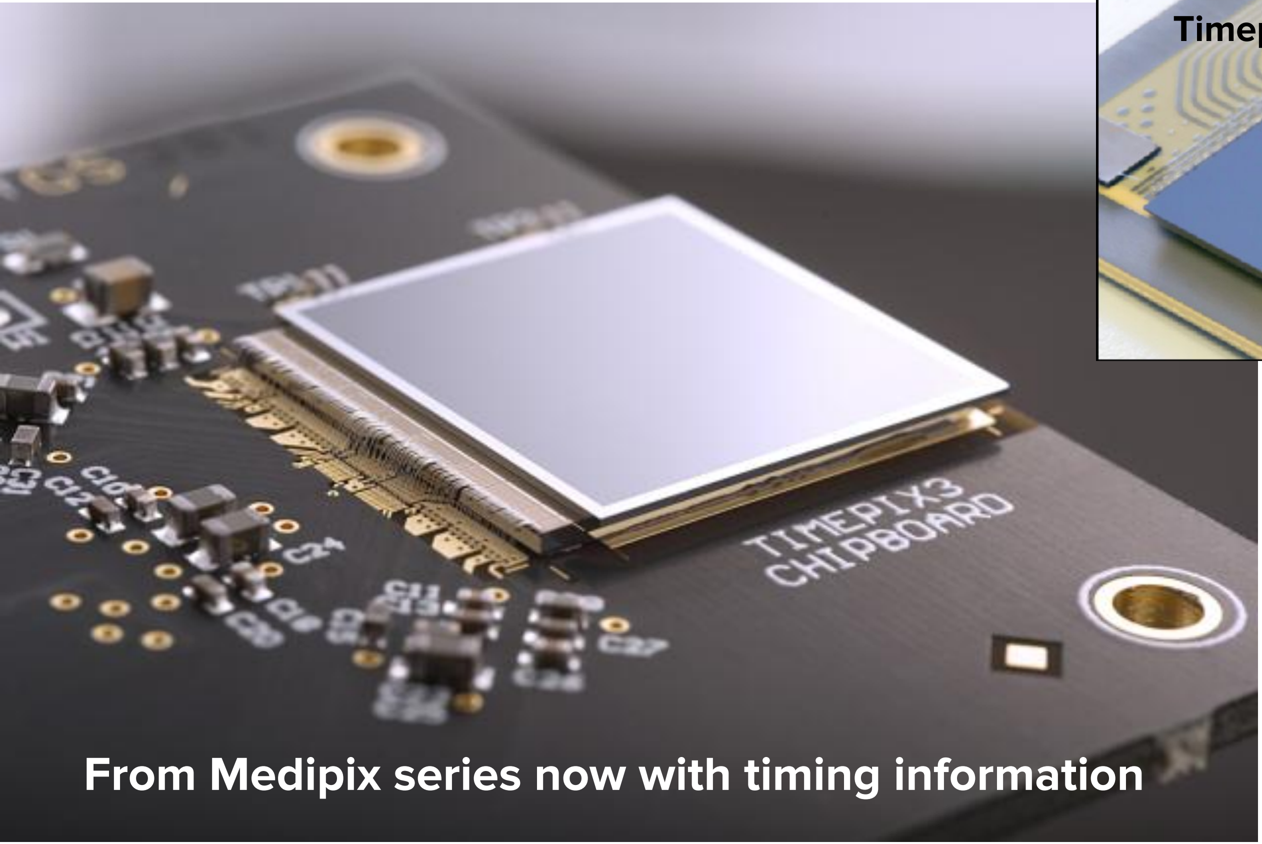


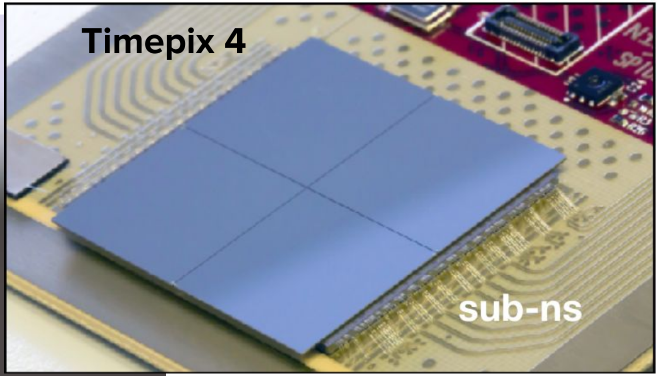




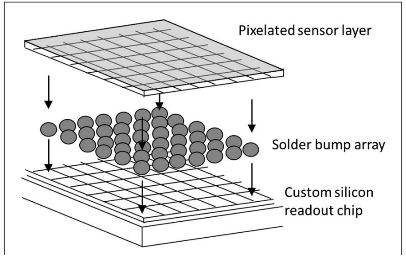
Timepix: an ASIC for hybrid pixel detectors

Here at Nikhef!



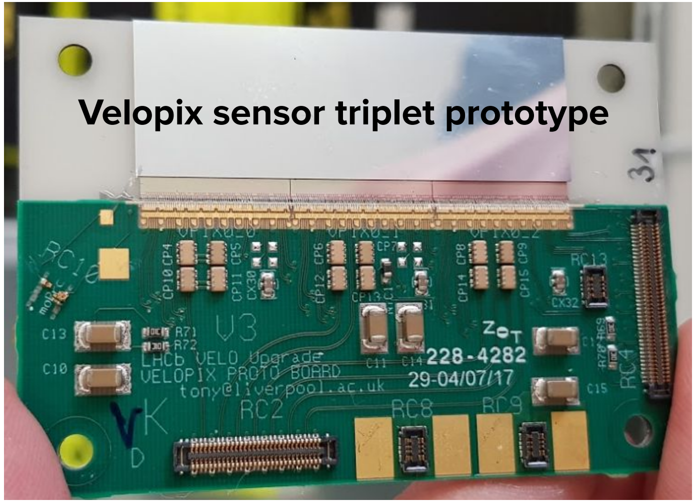


Timepix4 with 200 ps bin size, 73 ps time resolution

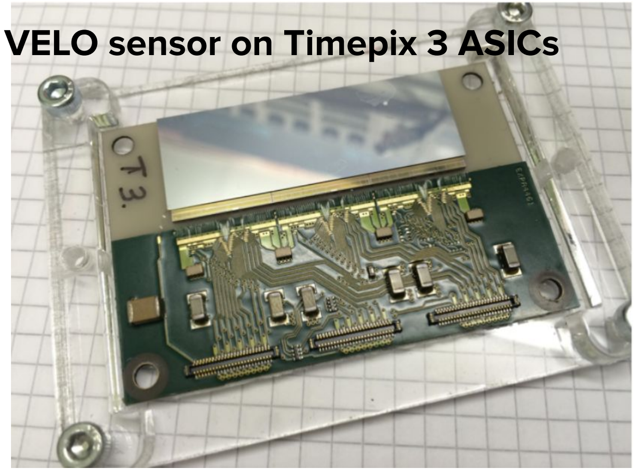


LHCb Vertex Locator (VeLo) upgrade

The Velopix ASIC: based on Timepix, 130nm TSMC, 55x55 μm^2 pixels

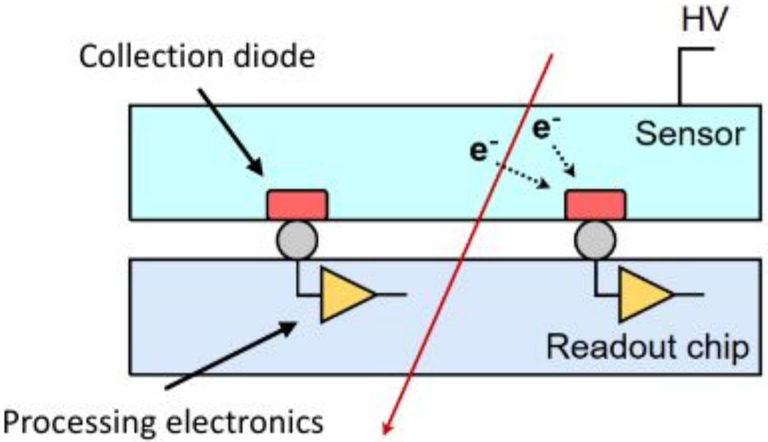


Velopix sensor triplet prototype



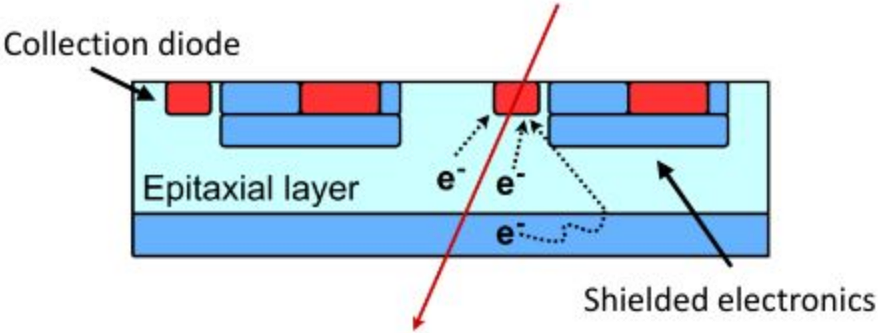
VELO sensor on Timepix 3 ASICs

Integrated sensors



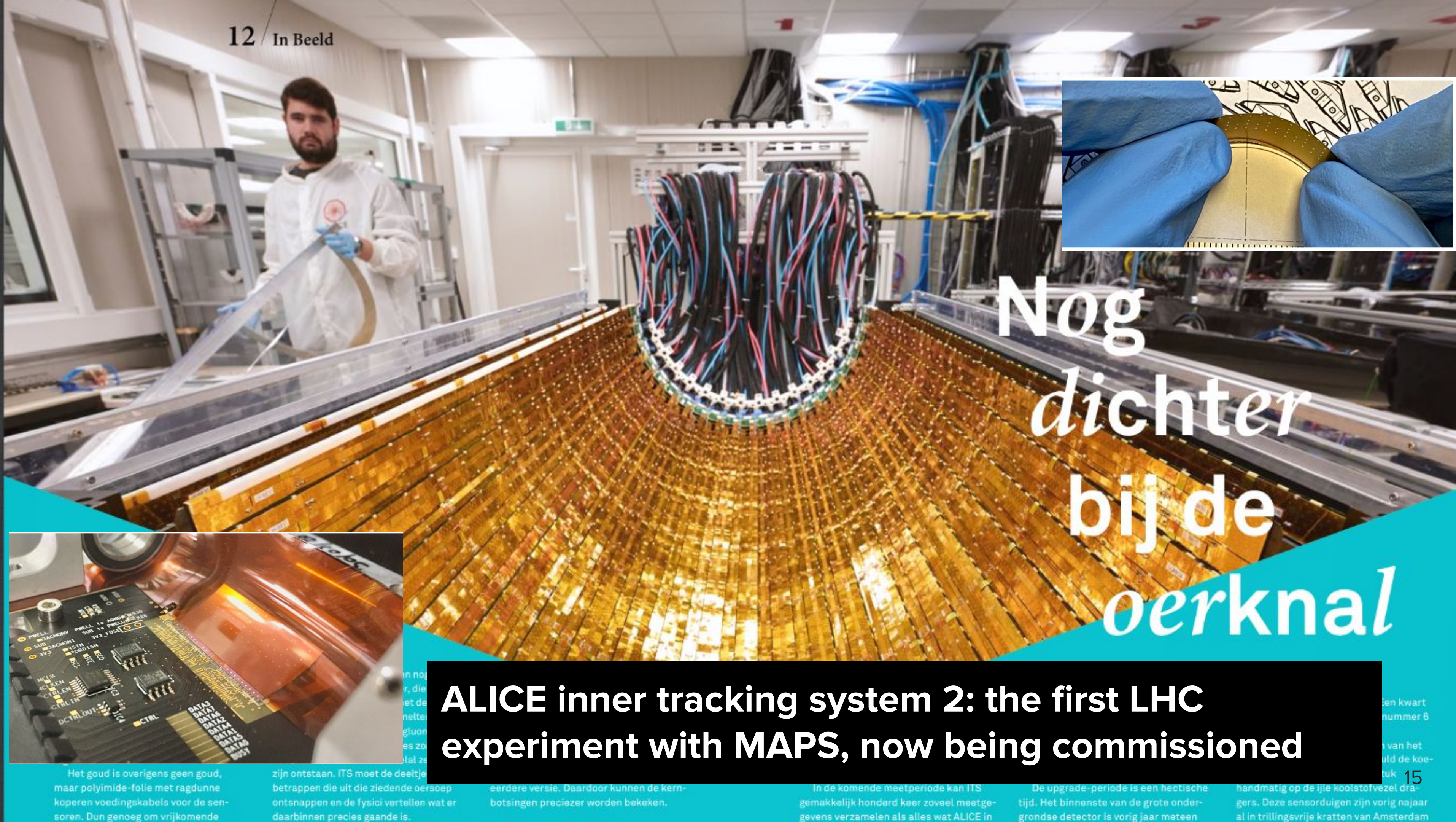
Hybrid pixel detector

CMOS MAPS: in your phone!



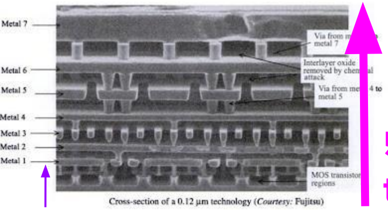
Monolithic Active Pixel Sensors: MAPS

From I. Kremastiotis

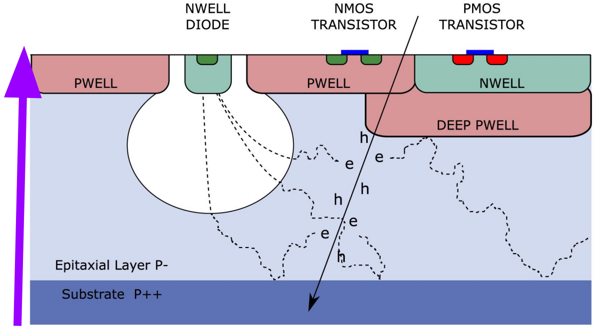


ALICE inner tracking system 2: the first LHC experiment with MAPS, now being commissioned

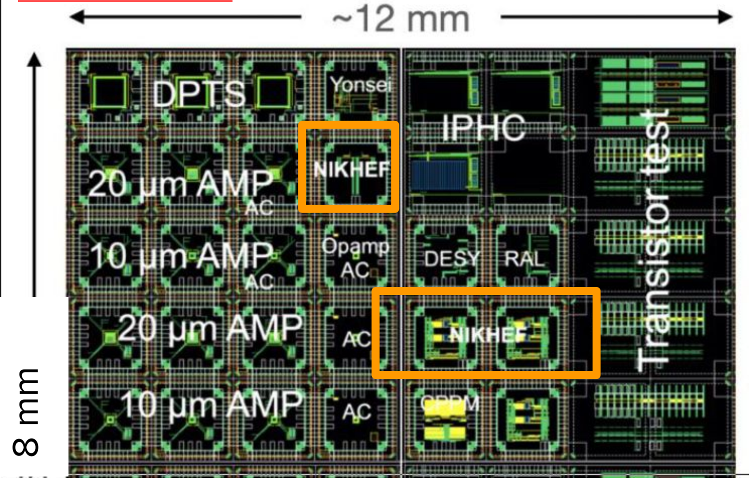
You will find these at Nikhef



50 μm thick sensor

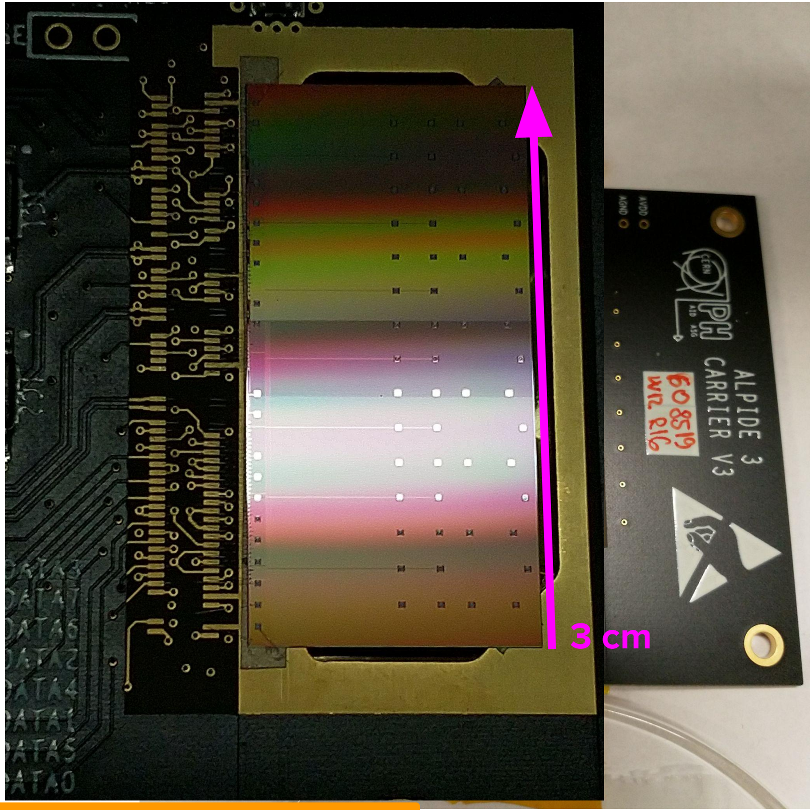


Talk at Vertex2021



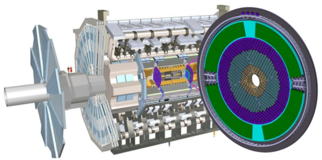
1 pixel: 28 μm x 28 μm

ALICE PIxel DEtector: ALPIDE
TowerJazz 180nm



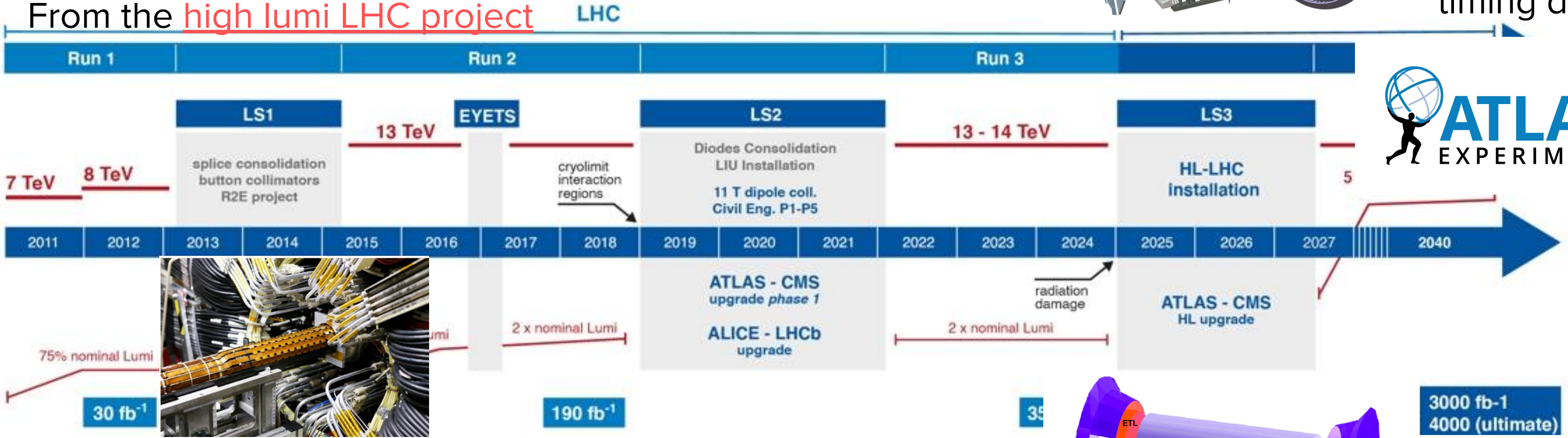
The Nikhef electronics and technology (ET) group designs these chips for the ALICE inner tracking system!

Other timing pixel detectors

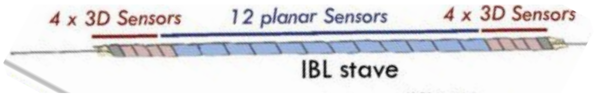


2026: LGADs in ATLAS high granularity timing detector

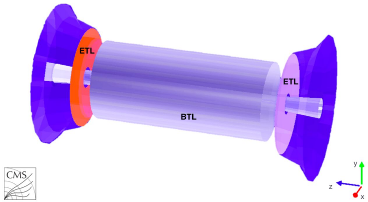
From the high lumi LHC project



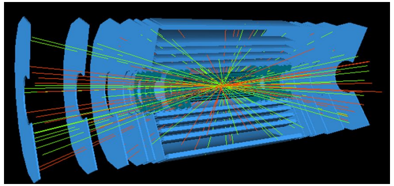
From Kerstin Lantsch



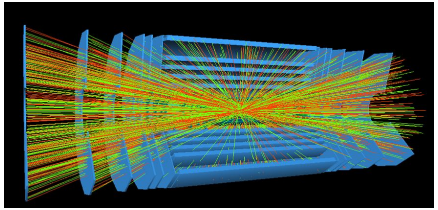
3D sensors now in ATLAS pixel detector



2026: LGADs and SiPMs in CMS timing detectors



Pileup x 10

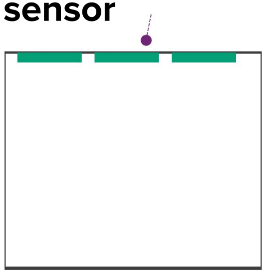


ATLAS High Granularity Timing Detector: a timing layer

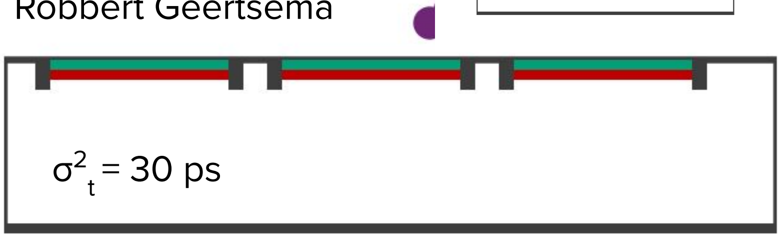
TDR

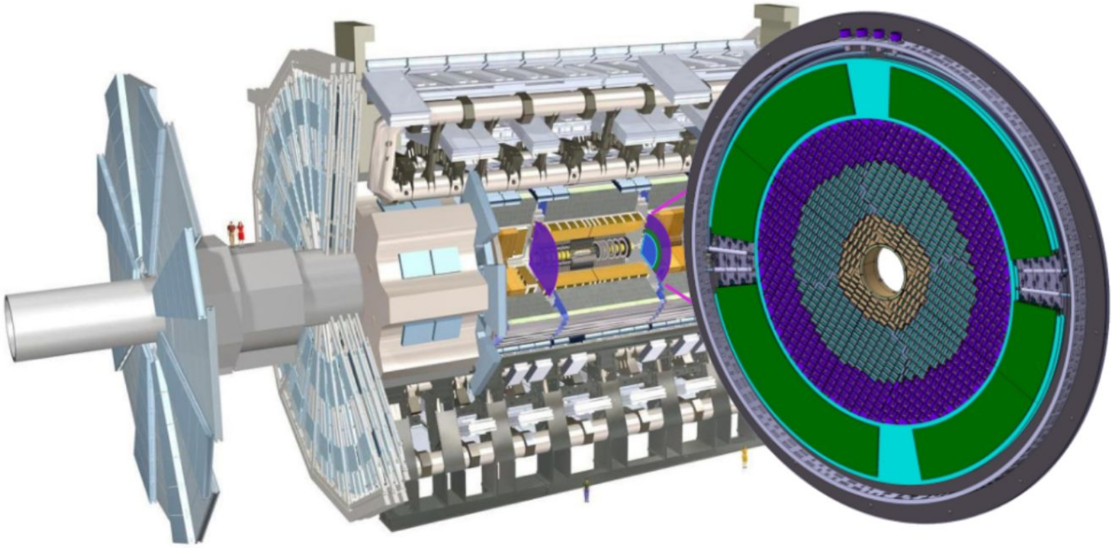
- **LGADs** with time resolution per track (per hit) 25 ps (35 ps) for r = 120 mm
- **Half will be replaced after 1000 fb^{-1}**: timing degrades with radiation damage

Planar sensor signal:



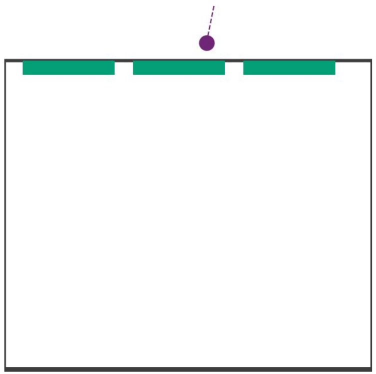
Low Gain Avalanche Diode signal: charge is multiplied in gain layer! Animation by Robbert Geertsema

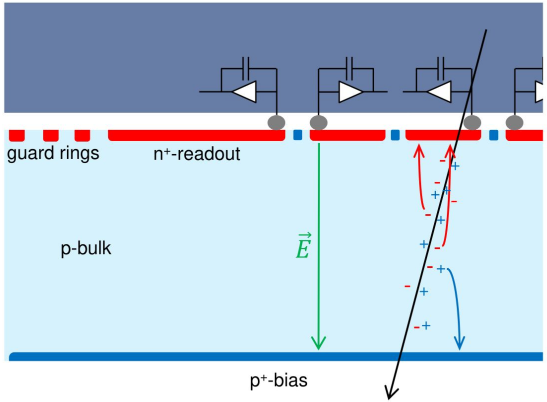




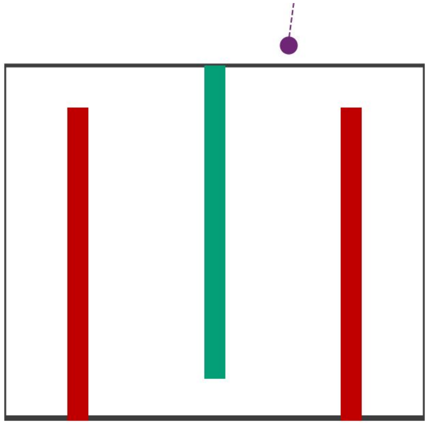
Animations courtesy of Robbert Geertsema

Planar sensors





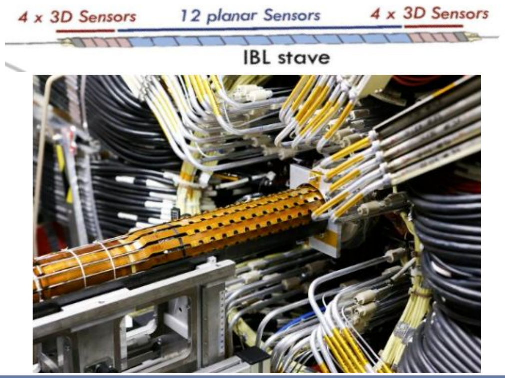
3D sensors

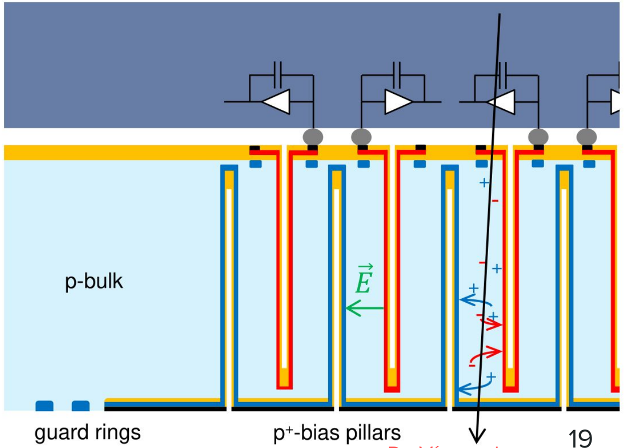


- Fast charge collection: short path!
- Large charge generated
- Radiation hard: in ATLAS at 30mm since 2015

[20 ps time resolution]

Already in ATLAS innermost layer:



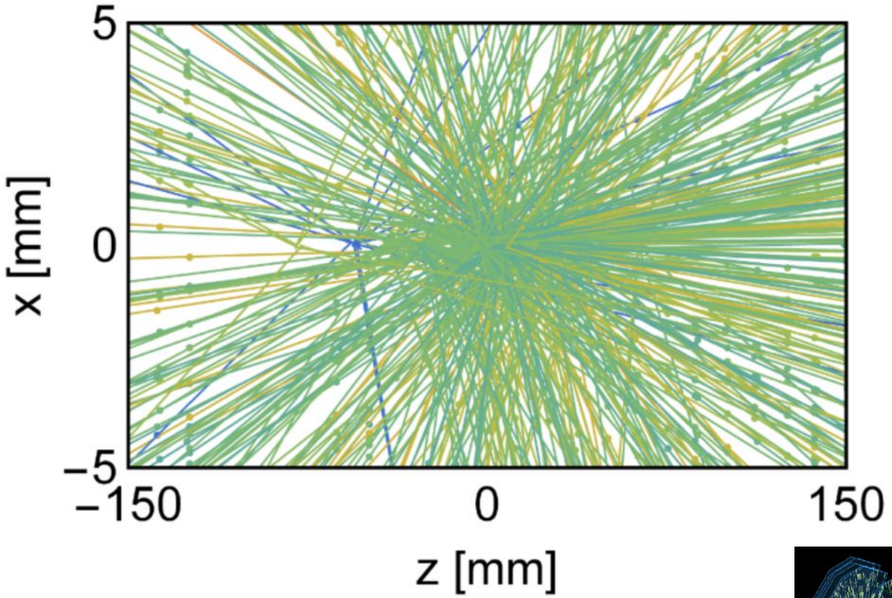


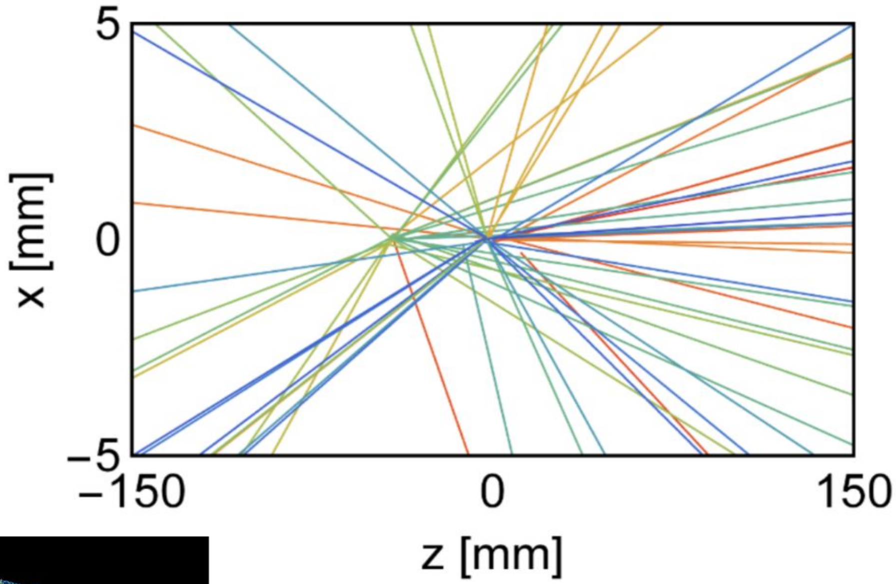
[Da Vía et. al.]

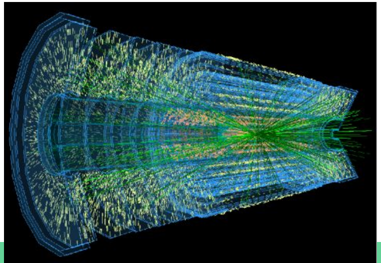
Animations courtesy of Robbert Geertsema

Why ‘fast timing’ and what is it?

Distinguish vertices based on precise timing information







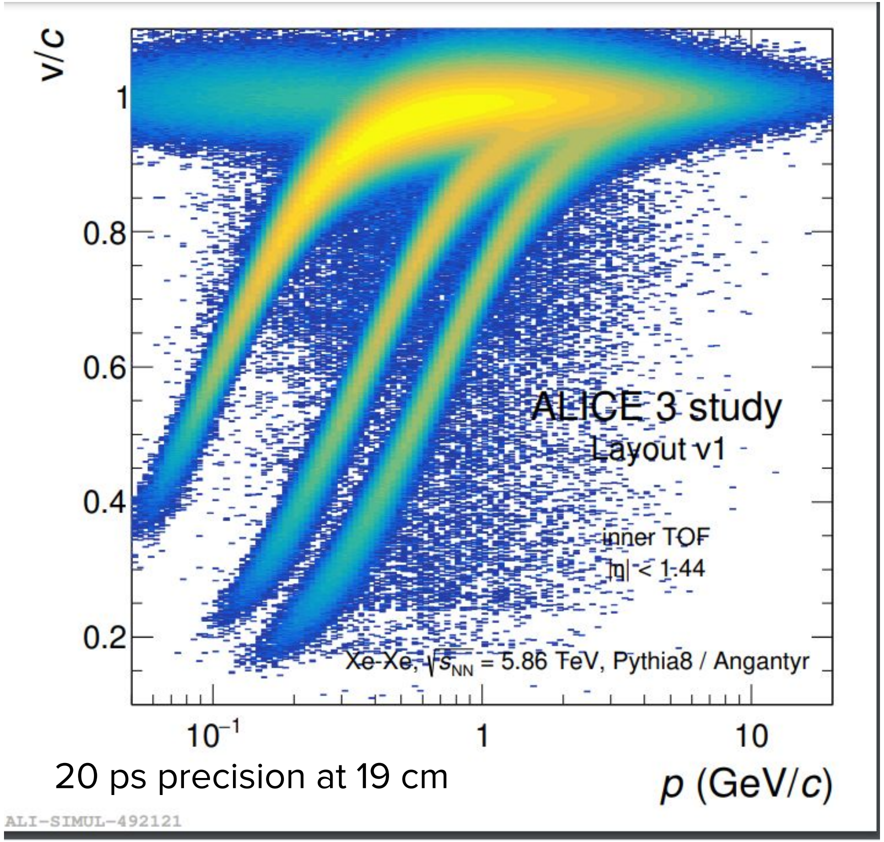
2 nanoseconds window: 2000 picoseconds

20 picoseconds

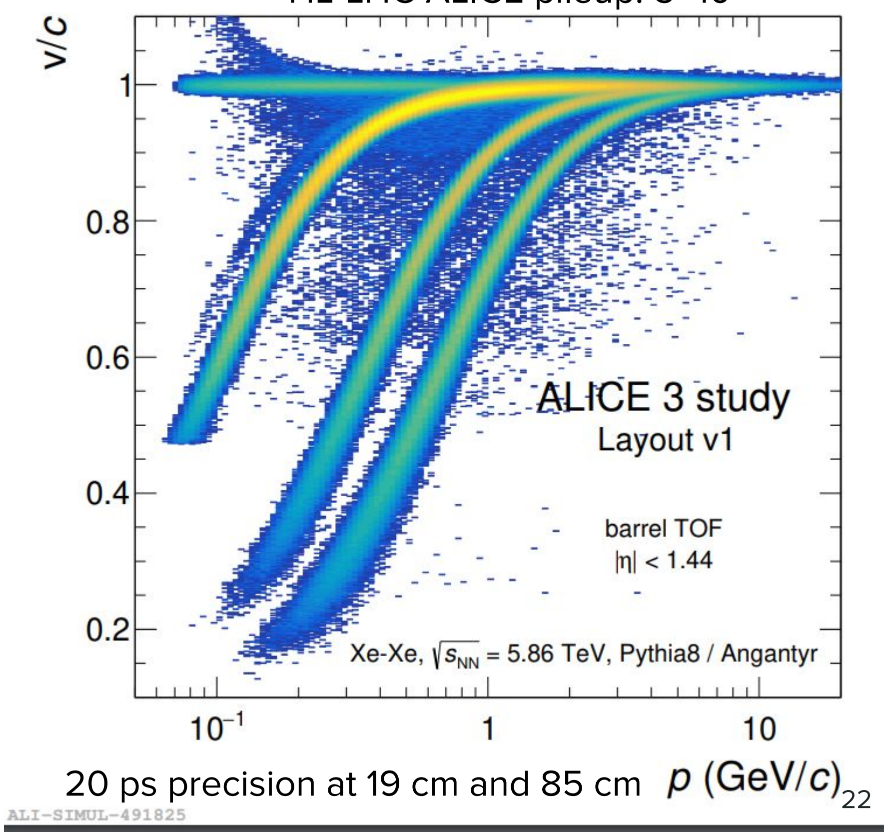
From Robbert Geertsema

Particle identification improves with precise timing

HL-LHC ALICE pileup: 5- 10

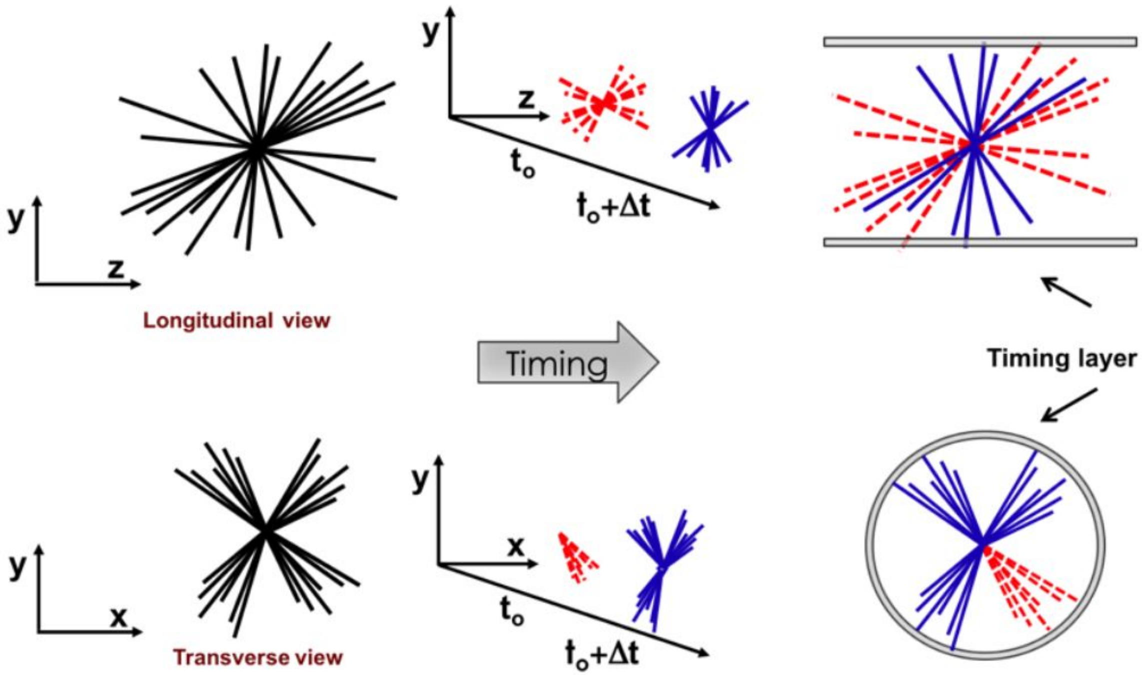


20 ps precision at 19 cm



20 ps precision at 19 cm and 85 cm

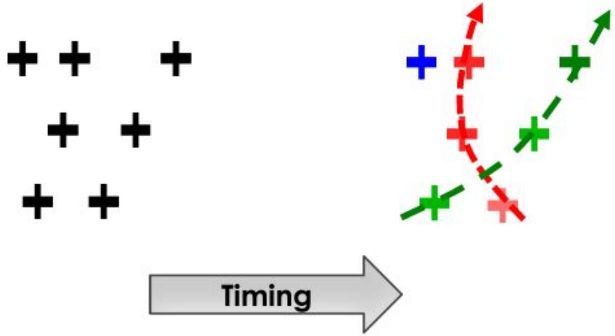
Timing information from a timing layer

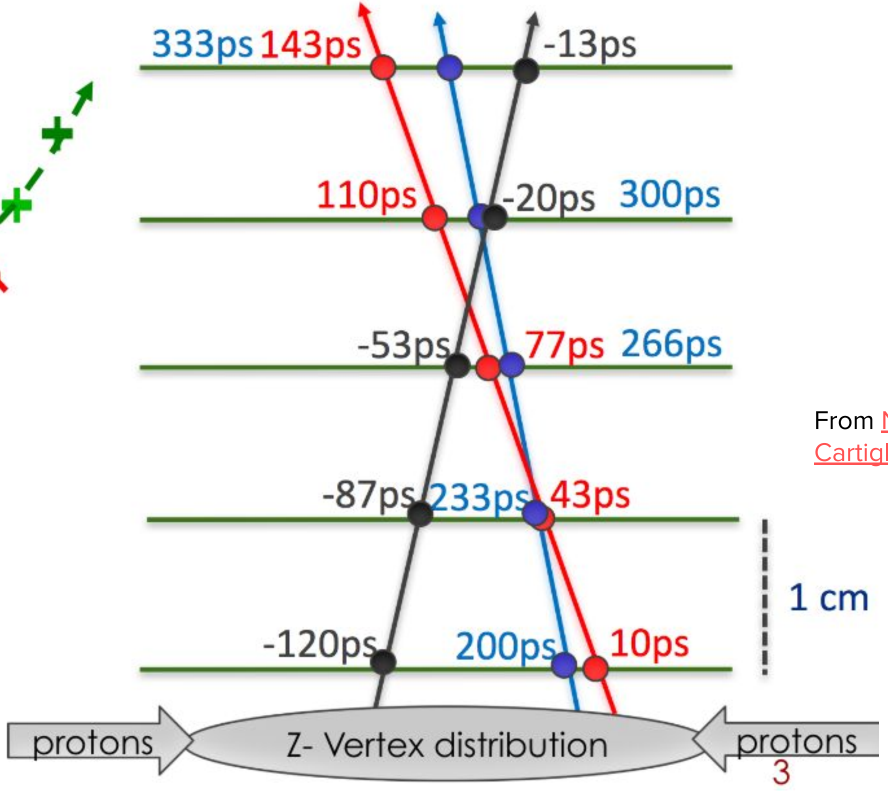


Primary vertex:
Original collision location
LHCb also has many secondary vertices!

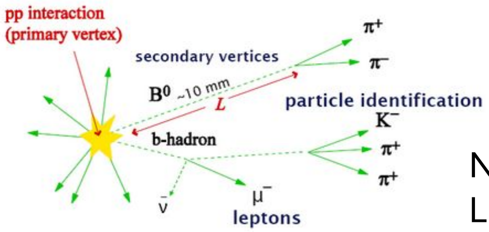
From Nicolo Cartiglia

Timing at points along the track





From [Nicolo Cartiglia]()

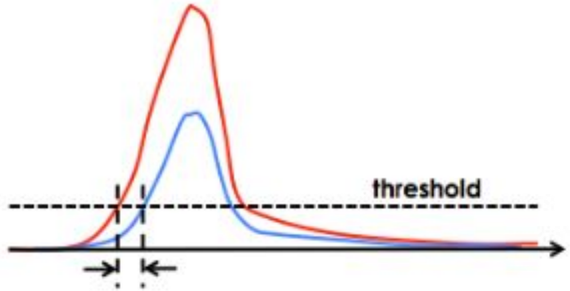


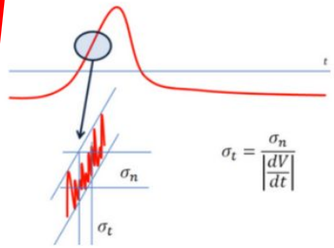
Needed for LHCb: primary and secondary vertices!

How precise, or how good can your time resolution be?

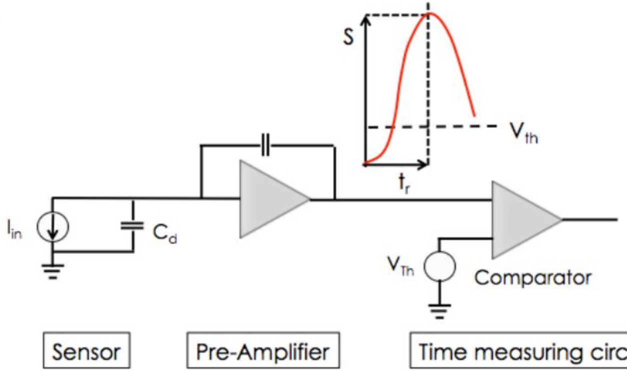
$$\sigma_t^2 = \boxed{\sigma_{timewalk}^2} + \boxed{\sigma_{jitter}^2} + \boxed{\sigma_{TDC}^2}$$

Time walk: smaller signals have a 'time delay'





~ Noise / (dV/dt)
Reduce with faster signal rise time

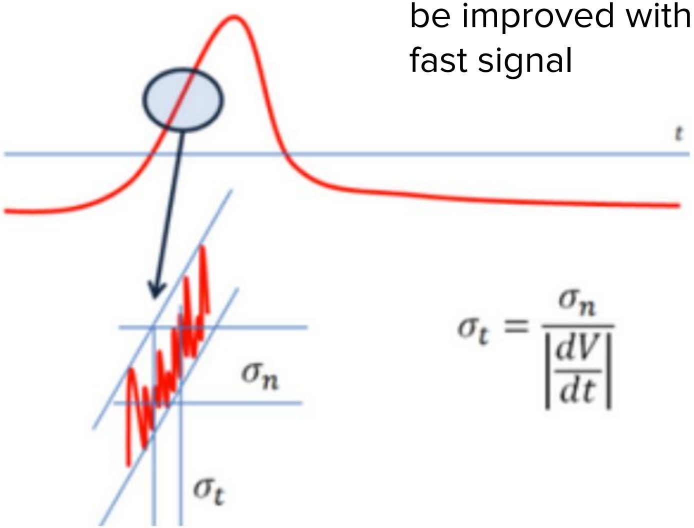


Time to digital converter

From arxiv:1312.1080 -- see also slides by Nicolo Cartiglia

Fast != precise ?

Time resolution can be improved with a fast signal



$$\sigma_t = \frac{\sigma_V}{\left(\frac{dV}{dt}\right)} \cong \frac{t_{\text{rise}}}{(S/N)}$$

RMS noise of amplifier

Slope of output signal

Rise time of output signal

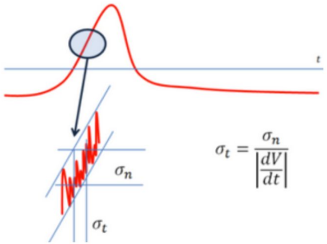
Signal to noise ratio

The fluctuations on the rising signal can also be suppressed with low-noise electronics: not easy!

Fast: more power,
more high frequency,
more noise!

How to make a detector fast?

How to make the time resolution more precise?



Clock jitter also contributes: need to deliver clean clocks!

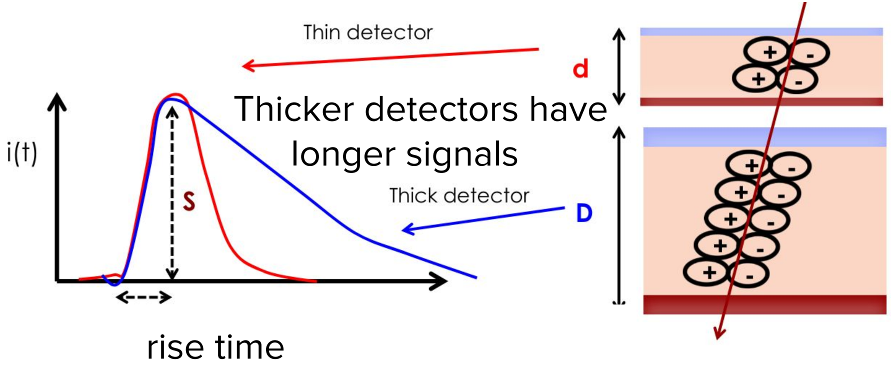
$$\sigma_t = \frac{\sigma_V}{\left(\frac{dV}{dt}\right)} \cong \frac{t_{rise}}{(S/N)}$$

Low input capacitance
Low-noise amplifier

Large signal gain

Short signal rise time
Fast charge collection
Fast amplifier

Very low noise detector!

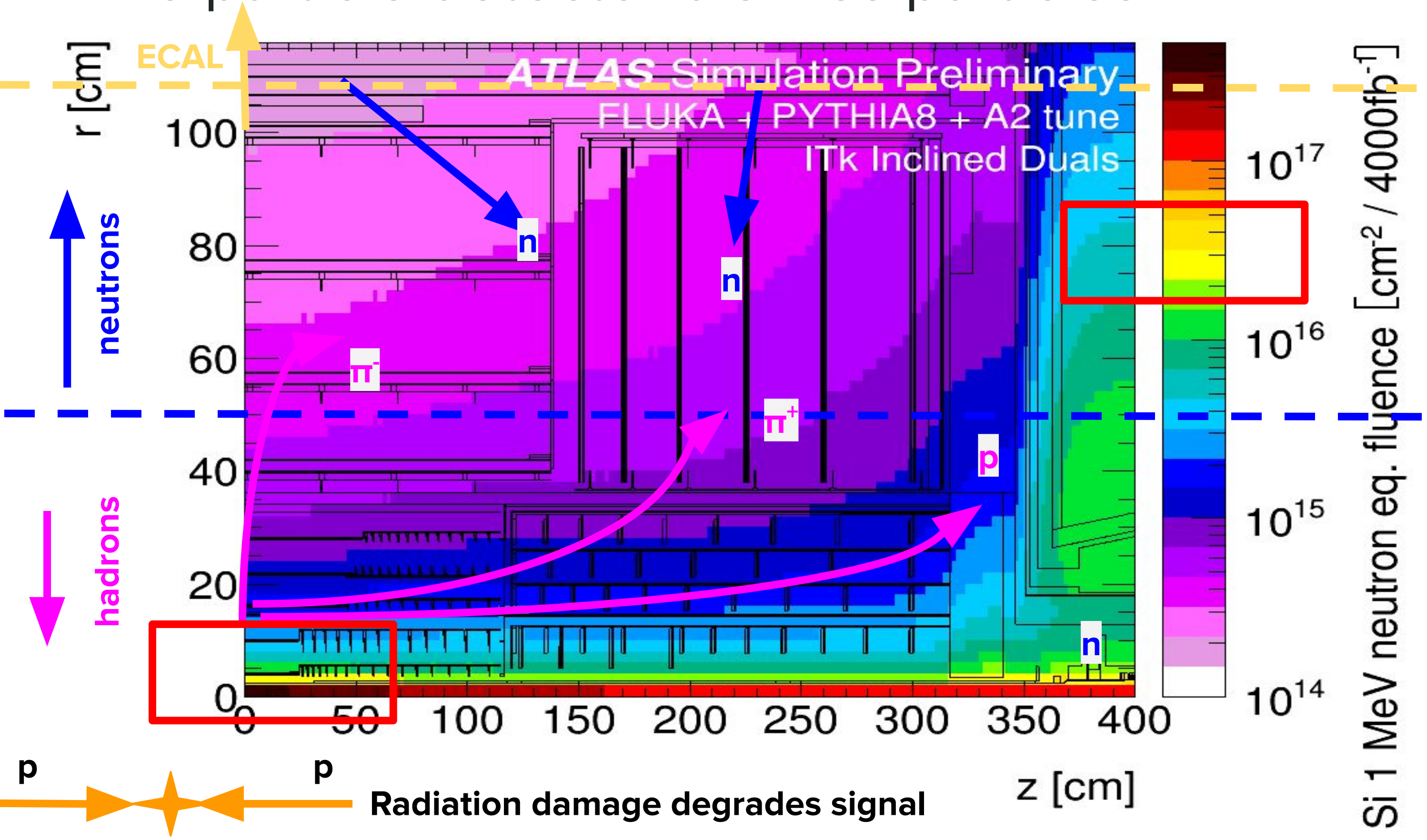


High intensity at HL-LHC
Low noise electronics not easy
➔ need **fast detectors**

The million dollar question:
How to make the detector fast and keep power consumption low?

From Nicolo Cartiglia

The particle detector dislikes particles



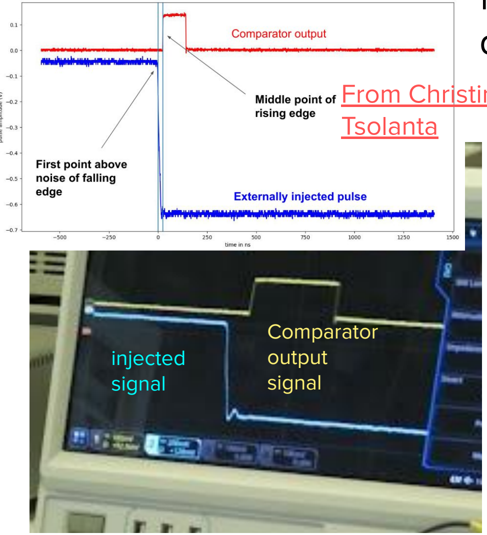
High luminosity LHC: high particle rates!
ATLAS
ITk will see
$\Phi_{eq} = 2.2e16 / cm^2$

Particles damage the silicon sensor

How do you measure time resolution?

Comparison with other signal

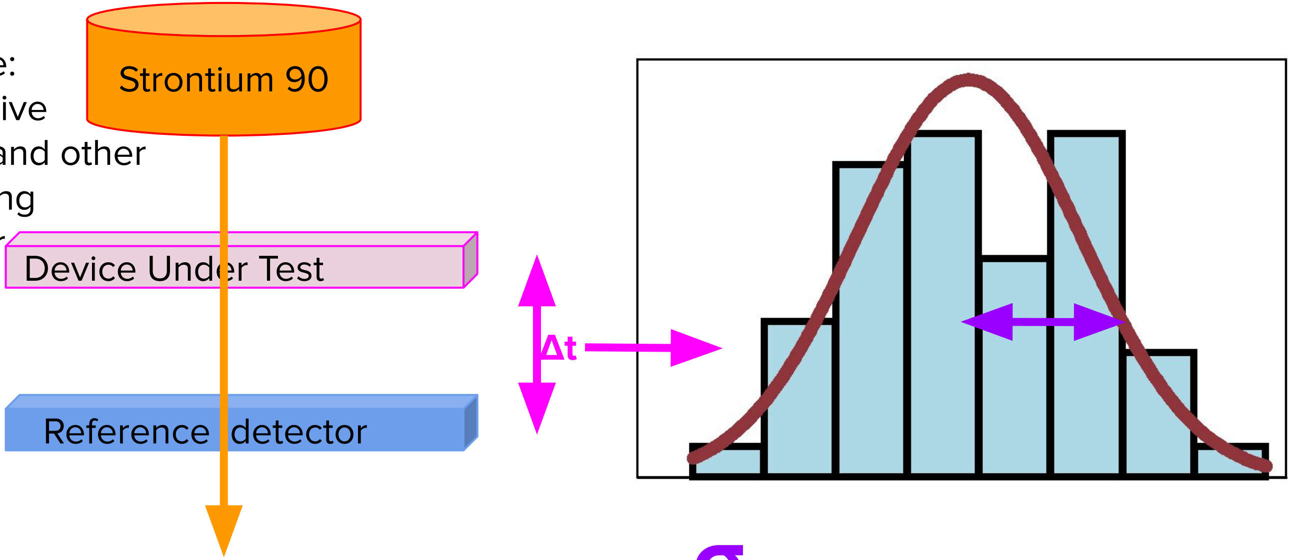
Example:
Waveform
generator



[From Christina Tsolanta]

Can also inject pulses in to DUT electronics: bypass sensor

Example:
radioactive
source and other
fast timing
detector



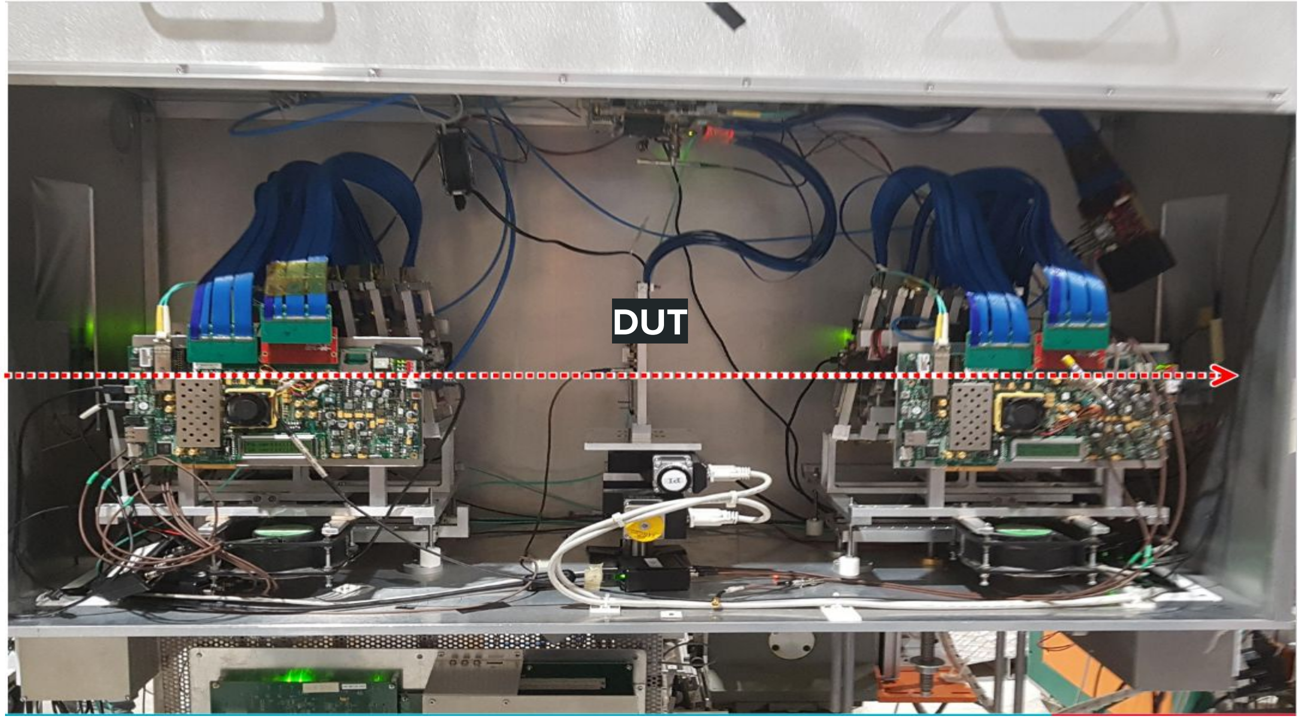
$\sigma_{t,measured}$

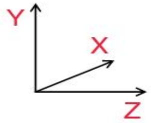
$$\sigma^2_{t,DUT} = \sigma^2_{t,measured} - \sigma^2_{t,ref}$$

Test beam: with the Nikhef Timepix telescopes

Fast Timepix 3 telescope with 1.6 μm spatial and 236 ps track time resolution

Time residuals of DUT compared to track timing

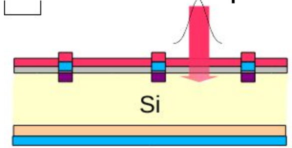




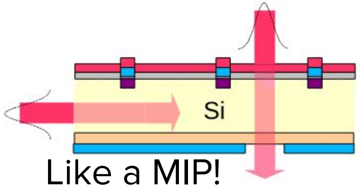
[K. Akiba et al 2019 JINST 14 P05026]
[K. Heijhoff et al 2020 JINST 15 P09035]

Injection of a signal: transient current technique

Red 660nm = 1.9 eV
Penetrates few µm below surface
1 photon = 1 electron-hole pair



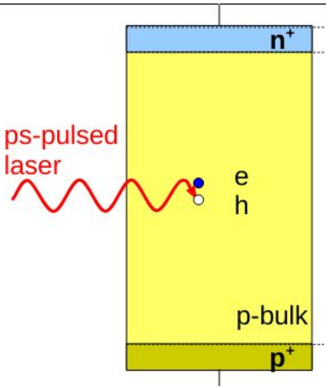
Infrared 1060nm = 1.17 eV
Penetrates deep into sensor
1 photon = 1 eh pair

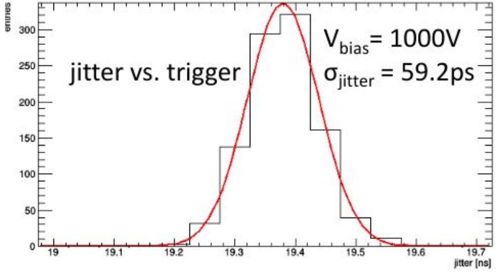


Like a MIP!

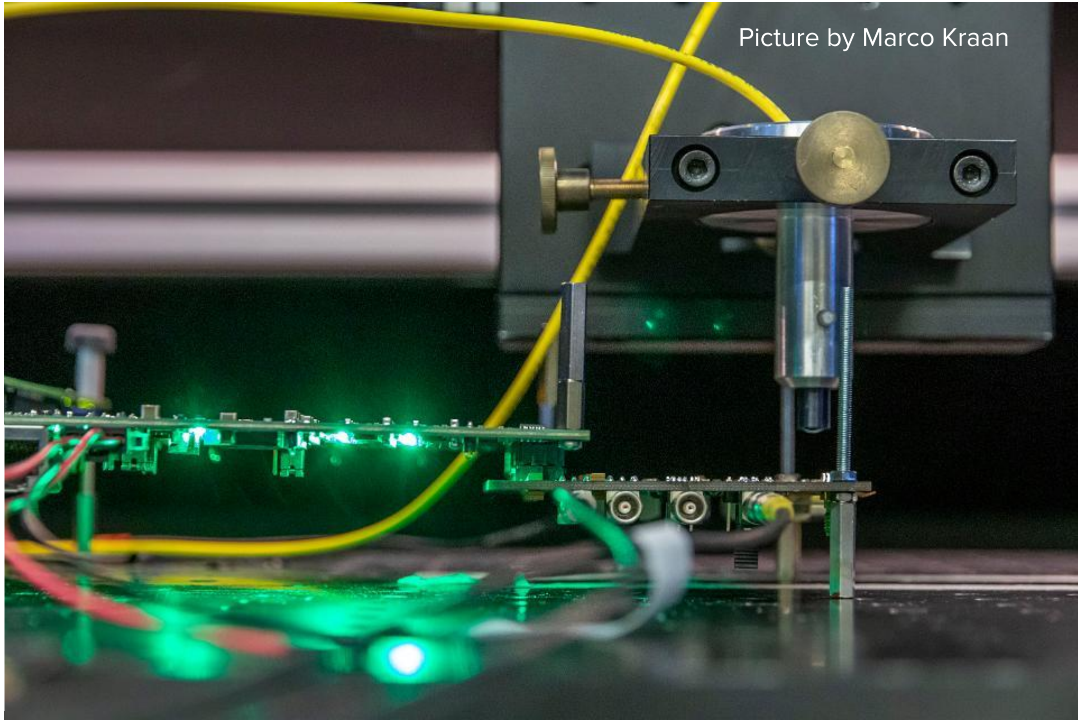
From C. Gallrap

2D spatial resolution





From Marco Fernandez

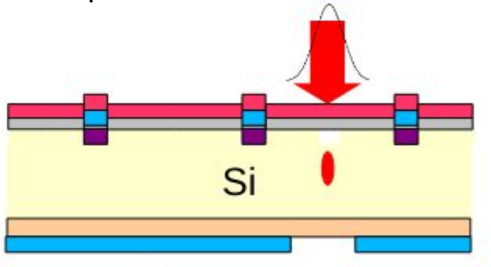


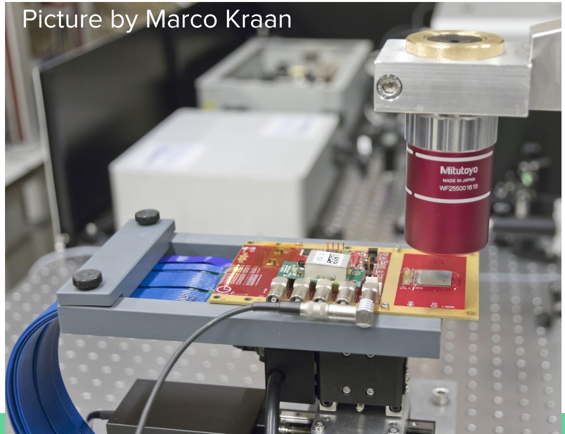
Single photon absorption laser and RD50 HR-HV MAPS at Nikhef

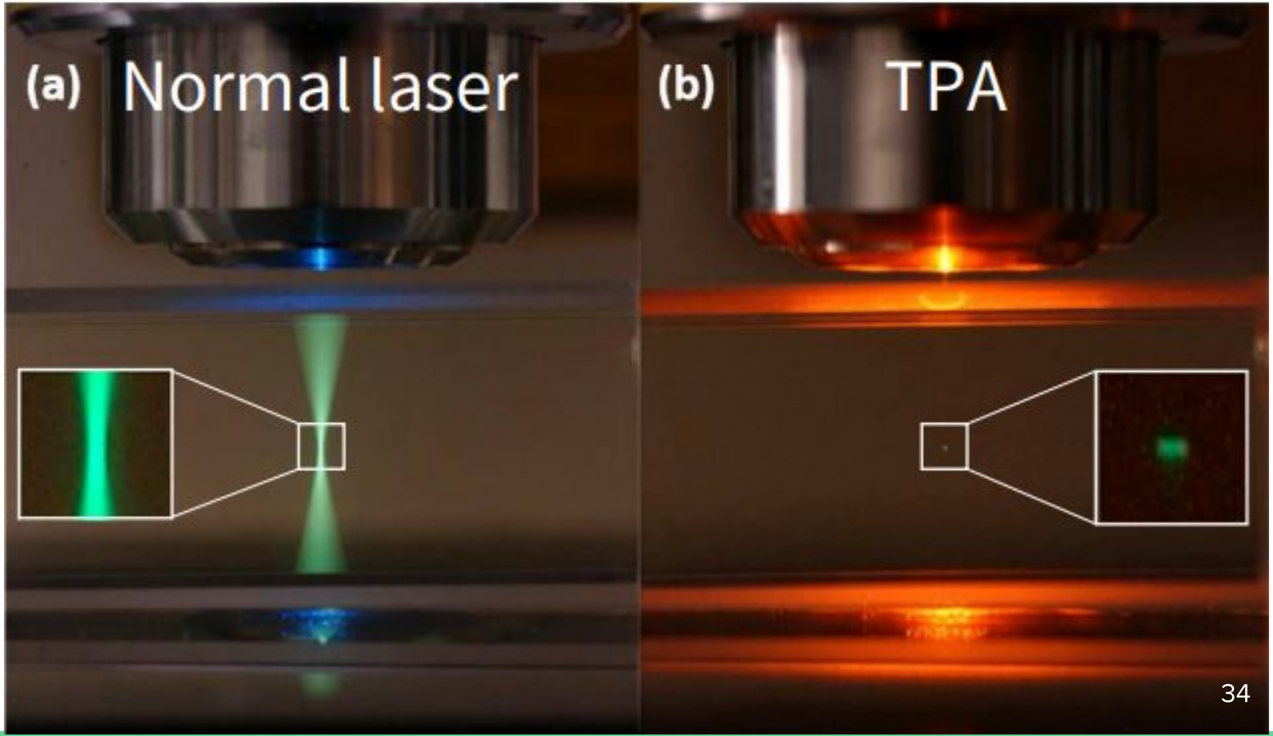
Two-photon absorption transient current technique

3D spatial resolution
1550 nm = 0.8 eV: smaller than silicon band gap!
➔ 2 photons = 1 electron-hole pair

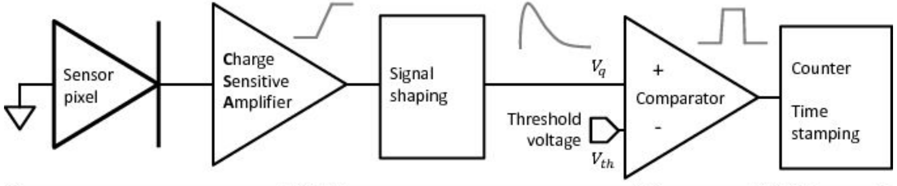
NEW at Nikhef!
380 fs – 5.5 nJ – 1 µm wide spot
fast – powerful – precise

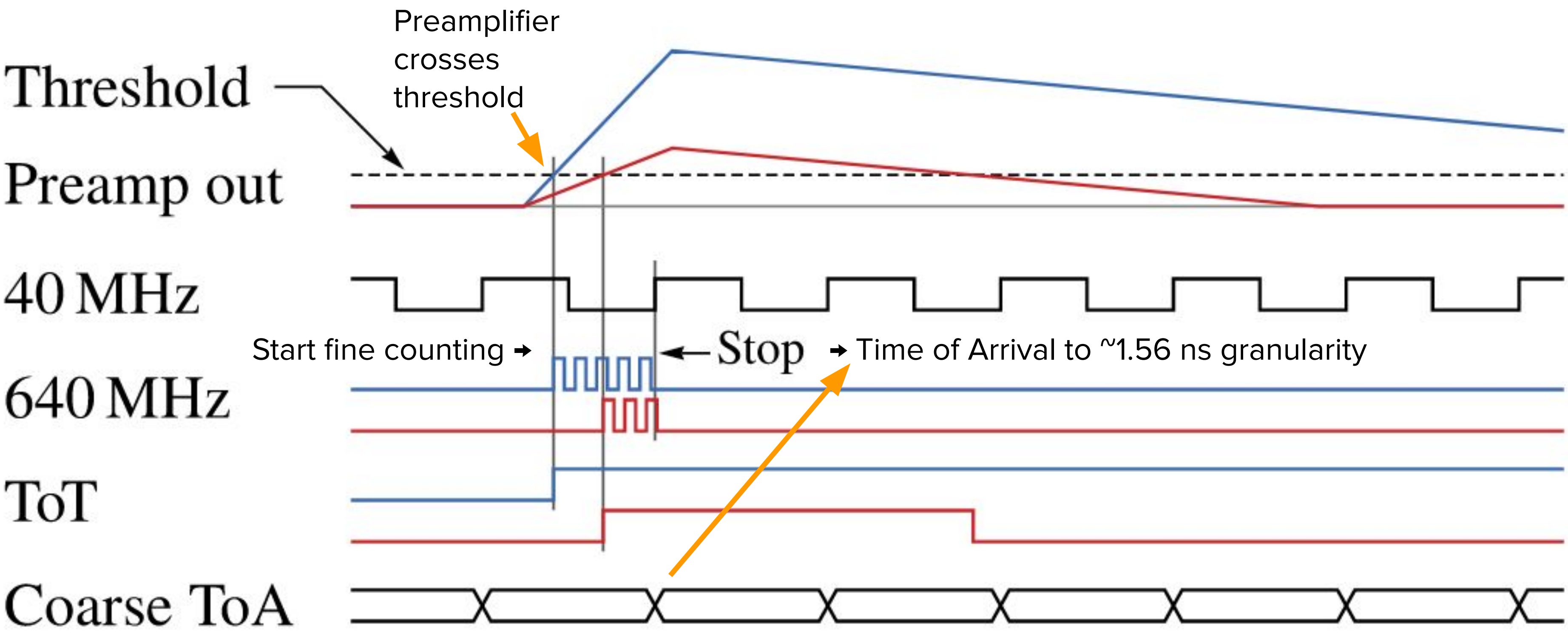






Timepix 3 time measurement



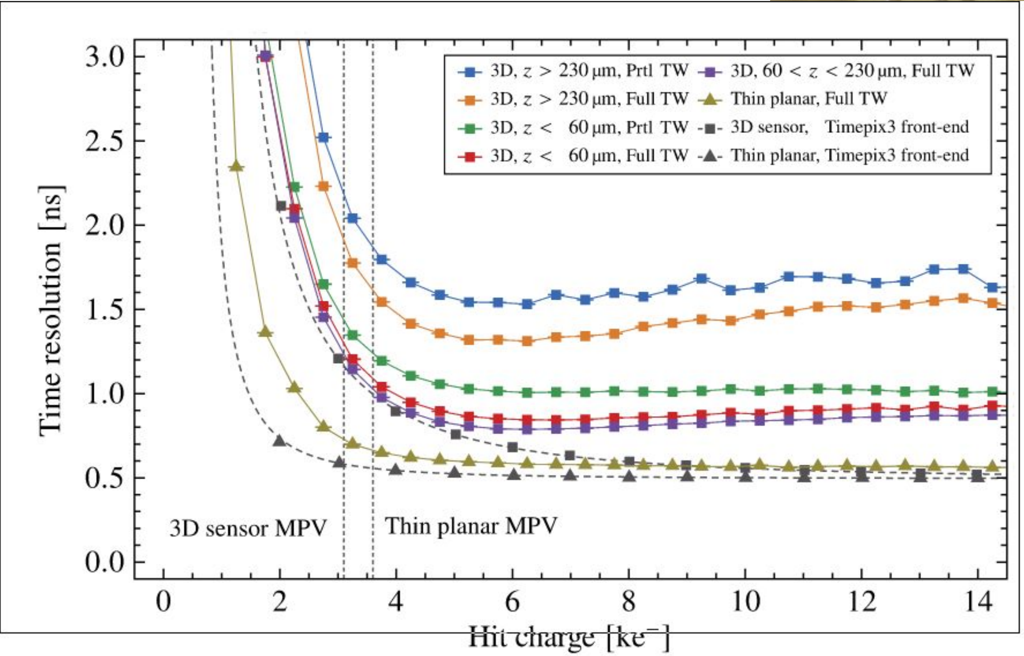


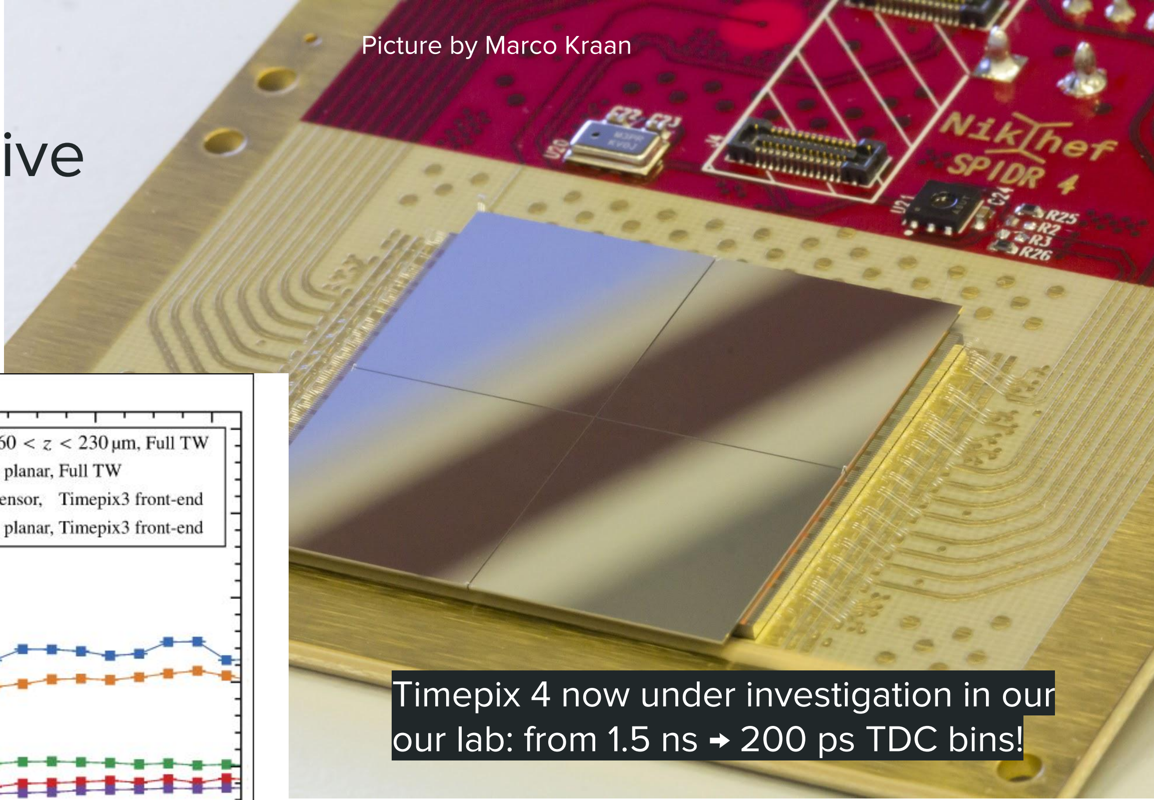
K. Heijhoff et al 2021 JINST 16 P08009 [DOI: 10.1088/1748-0221/16/08/P08009]

Some more examples of fast timing at Nikhef

Timepix: a Nikhef initiative

Timepix 3 with sensor: σ_t = 500-600 ps



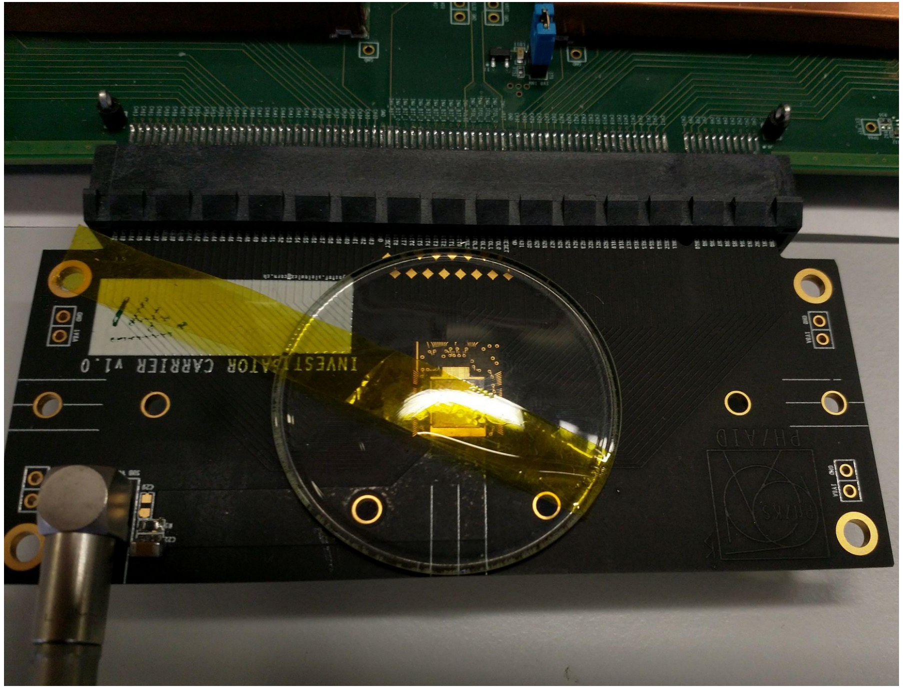


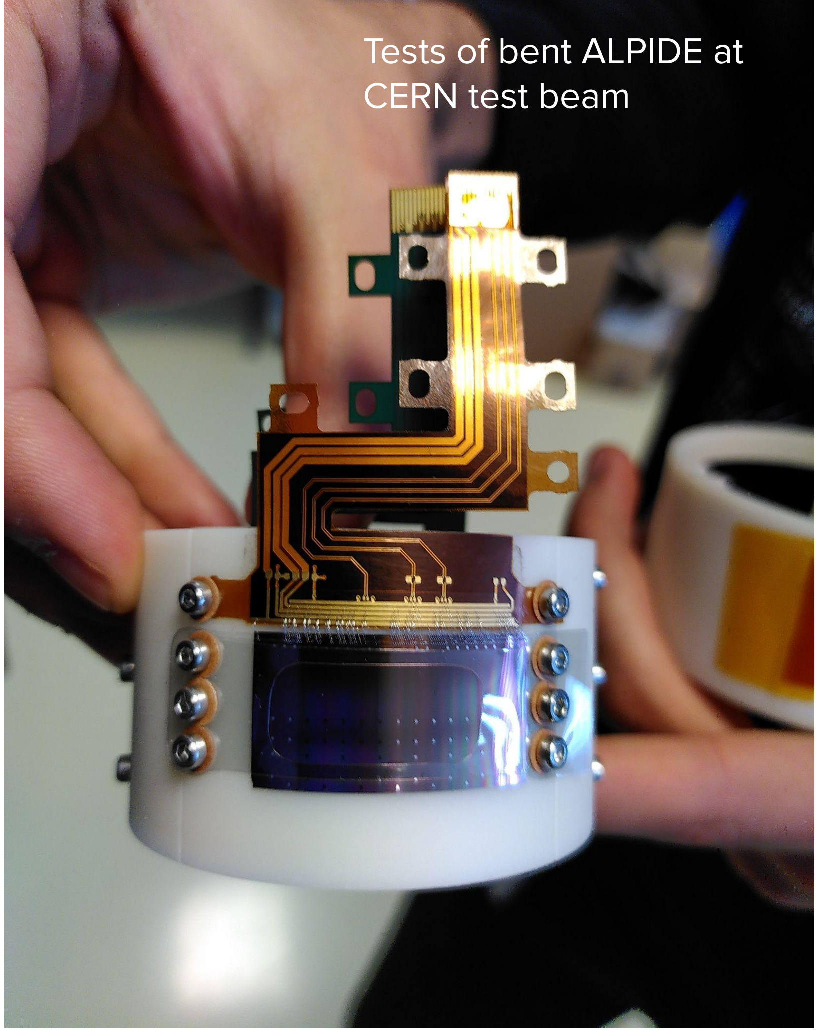
Timepix 4 now under investigation in our our lab: from 1.5 ns → 200 ps TDC bins!

K. Heijhoff et al 2021 JINST 16 P08009
doi:10.1088/1748-0221/16/08/P08009

ALICE3 fast timing with MAPS

Timing measurements: <u>unoptimized</u> chip already has only the order of 800 ps in the lab, O(ns) at test eam.

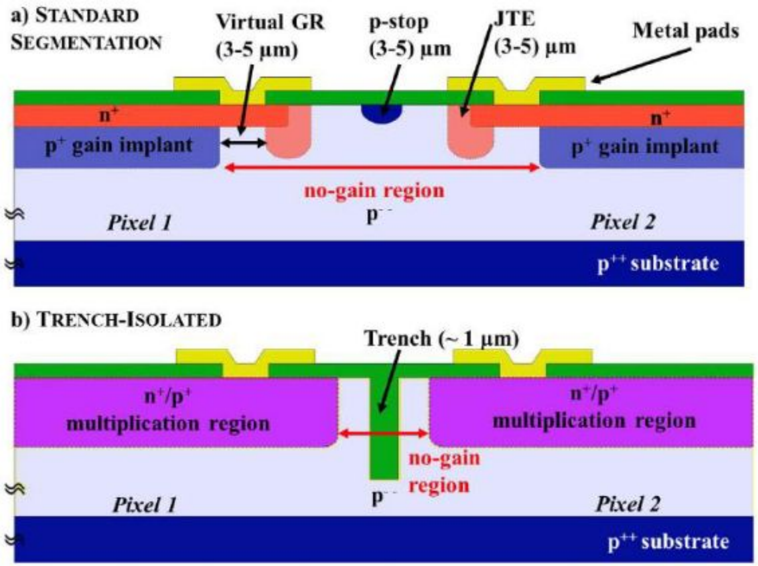




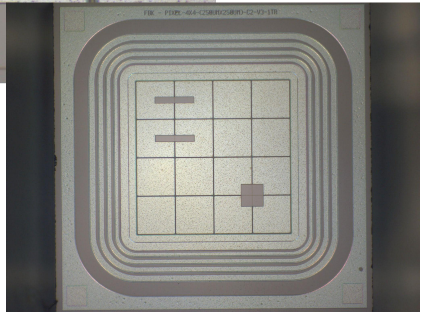
Tests of bent ALPIDE at CERN test beam

Trench isolated Low Gain Avalanche Diodes

Larger sensitive area in the detector than standard LGADs: larger **fill factor**



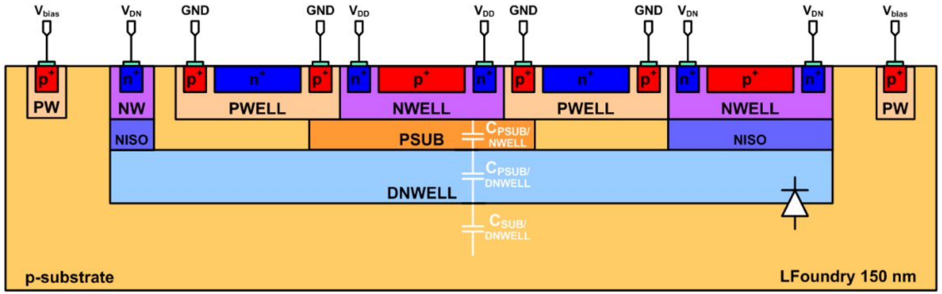
See also this talk at Vertex2021

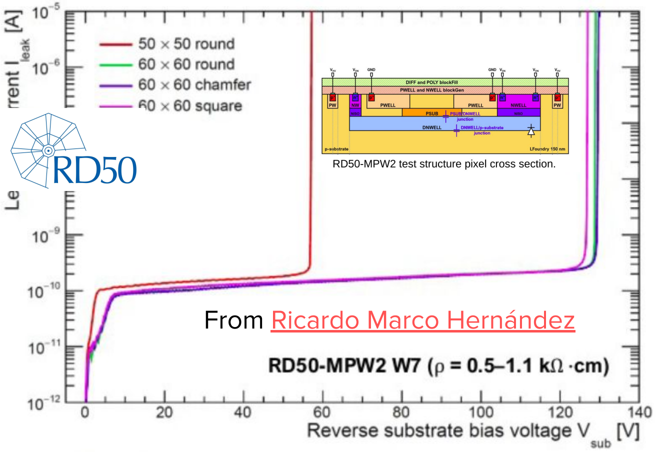


Trench isolated LGAD will be bonded to Timepix4 ASIC

Need resolutions better than 10 um and 50 ps

Radiation hard depleted MAPS

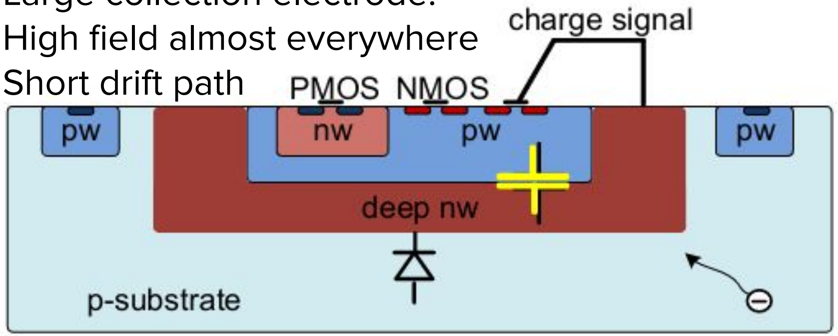




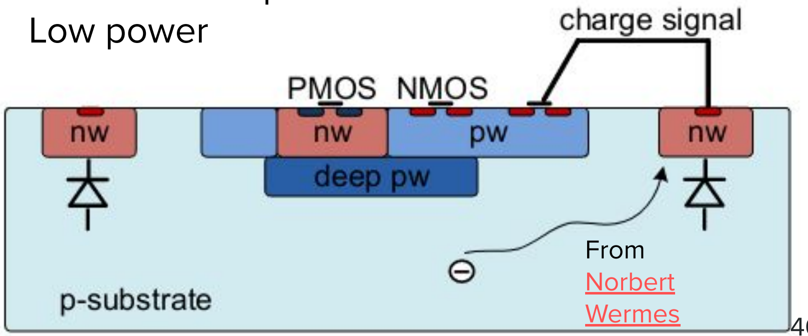
From Ricardo Marco Hernández

HV CMOS with a **larger collection electrode**:
fast collection time and **radiation tolerant.**

Large collection electrode:
High field almost everywhere
Short drift path



Smaller collection electrode:
Low sensor capacitance
Low power

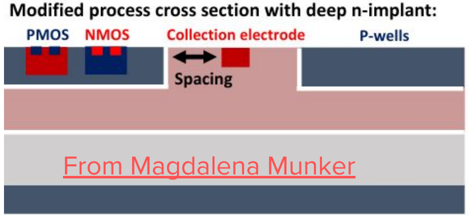


From Norbert Wermes

Other fast timing examples

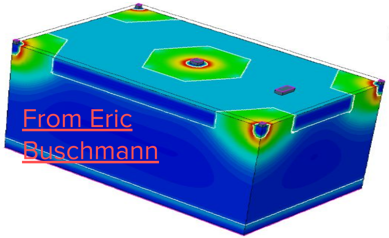
Many more possibilities for fast timing detectors

- With avalanche gain
  - Sub-geiger mode (LGADs, APDs)
    - DC-coupled
    - AC-coupled
  - Geiger mode (SPADs)
- Without avalanche gain
  - Hybrid
    - Planar
    - 3D electrodes
  - Monolithic
    - BiCMOS (SiGe)
    - CMOS
    - HV-CMOS



From Magdalena Munker

Larger spacing for fast charge collection but low capacitance



From Eric Buschmann

Hexagonal pixels

MonPicoAD

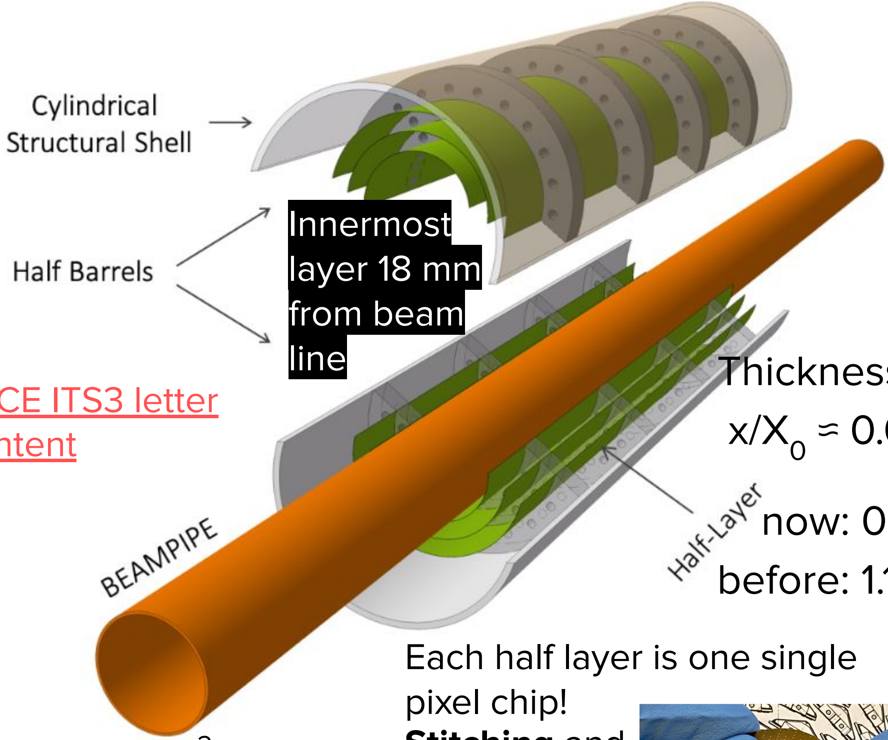
FASTPIX

ARCADIA

RD50

Applications

ALICE ITS3: 2025



Innermost layer 18 mm from beam line

[ALICE ITS3 letter of intent]()

Thickness:

$x/X_0 \approxeq 0.05\%$

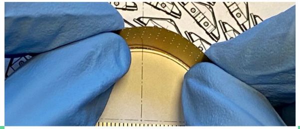
now: 0.35%

before: 1.14%

Φ_{eq} = 1e13 cm^{-2}, 10 kGy

Much less than ATLAS!

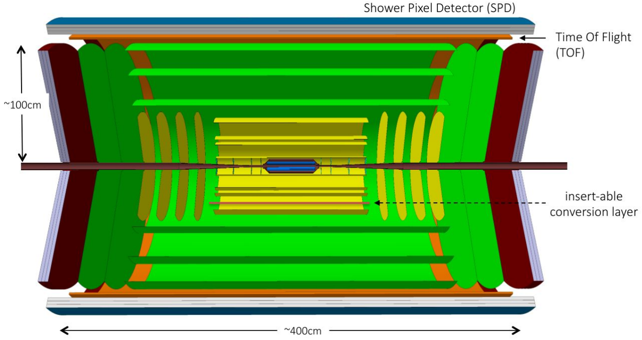
Each half layer is one single pixel chip! **Stitching** and **bending**

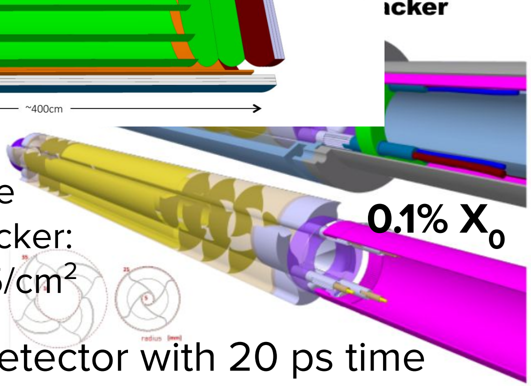


ALICE3: 2032

ALICE3 expression of interest

https://arxiv.org/pdf/1902.01211.pdf





Retractable vertex tracker:

Φ_{eq} = 5e15/cm^2

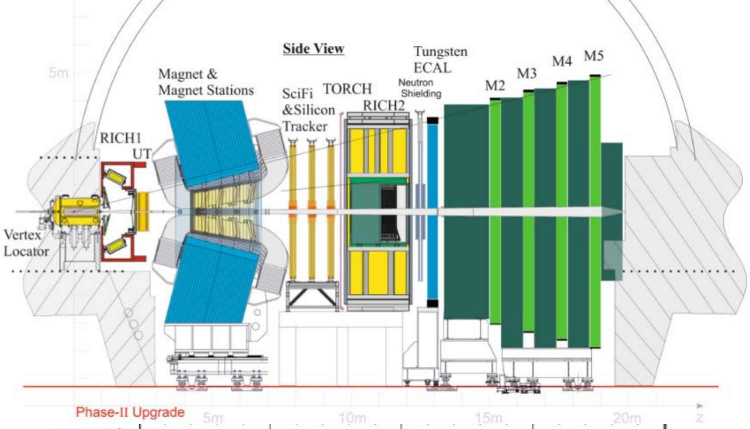
0.1% X_0

Time of flight detector with 20 ps time resolution -- possibly depleted MAPS:

Φ_{eq} = 1e12 cm^{-2} **1% X_0**

Fast timing detectors for LHCb

LHCb expression of interest:
[CERN-LHCC-2017-003]

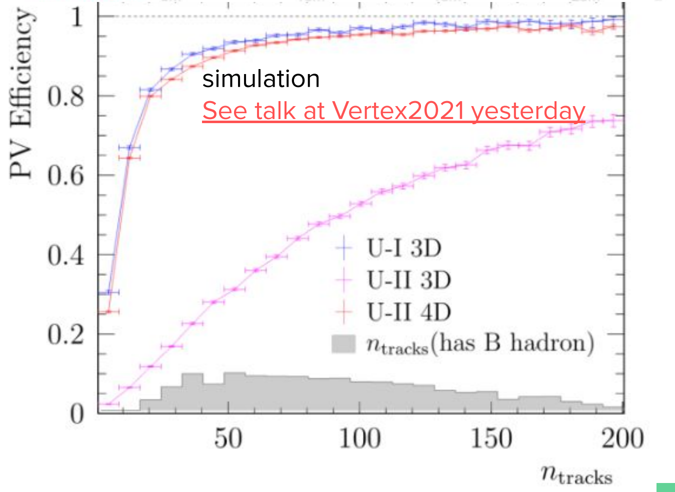


Environment and requirements

- 250fb^{-1} up to 350fb^{-1}
- fluence of Φ_{eq} = 6e16 / cm^2 at 5.1 mm
- Expected pileup 50: 25 times that of today!
- Need a track time resolution of 20ps
- Collision rate: 2e34 /cm^2/s: 50 times that of today!
- Now upgrading for 5x collision rate

Good time resolution from one of:

- Thin planar hybrid
- 3D hybrid
- MAPS
- LGADs

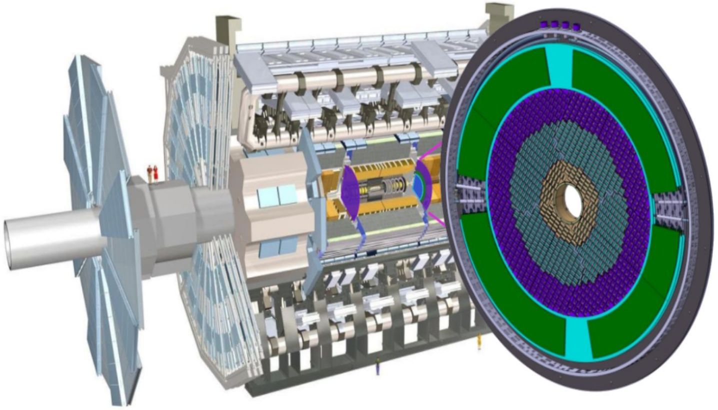


simulation
[See talk at Vertex2021 yesterday]

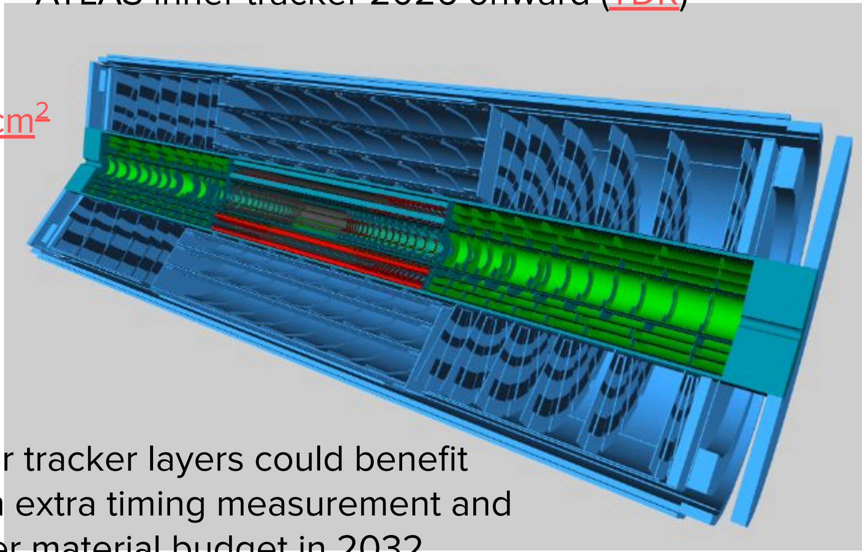
ATLAS

High luminosity LHC: high particle rates!
ATLAS ITk will see Φ_{eq} = 2.2e16 / cm^2

High granularity timing detector: LGADs from 2026
Replacements in 2032
TDR



ATLAS inner tracker 2026 onward (TDR)



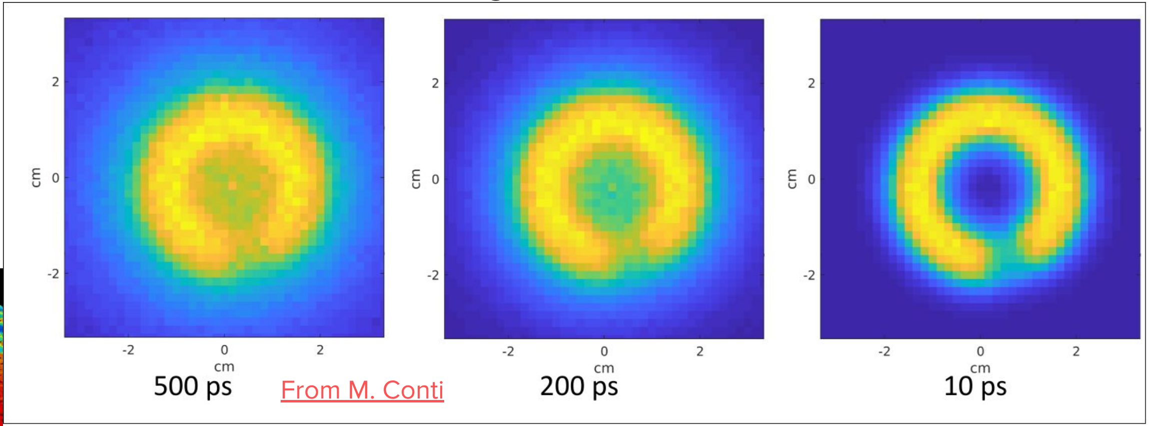
Inner tracker layers could benefit from extra timing measurement and lower material budget in 2032

Material budget of ITk per layer ~3% X_0
ALICE material budget per layer **now**: 0.35% **planned**: 0.05%

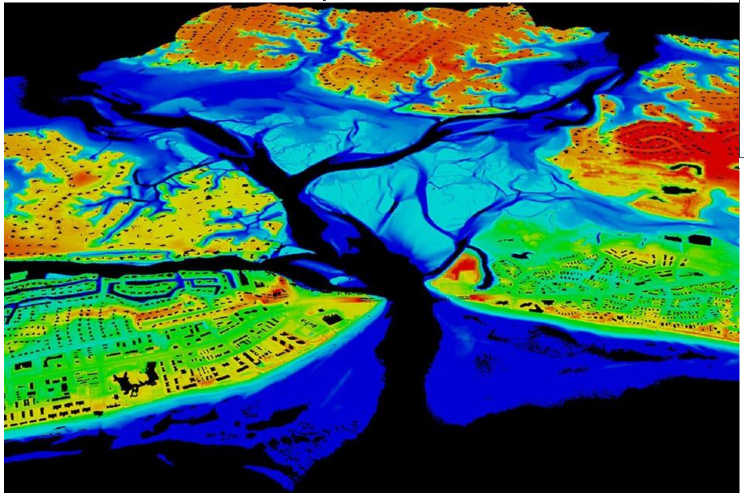
Applications beyond high energy physics

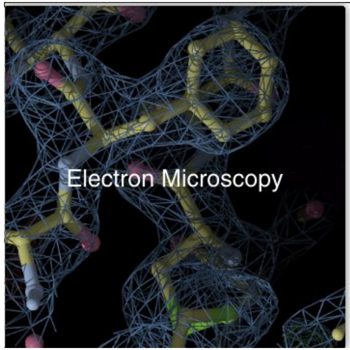
LiDAR, TOFPET, FLIM

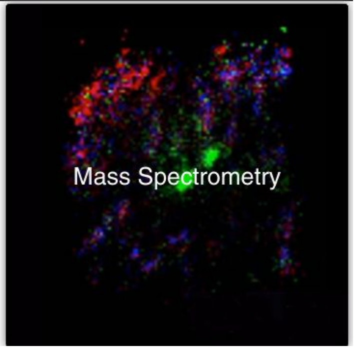
Time of flight positron emission tomography:
cardiac effect simulation
with a 4 cm diameter ring, 1 cm thick , with on 1 cm defect



Light detection and ranging (LiDAR) for
e.g. imaging earth's biomass
905 nm ➔ 20-50 µm active thickness







Fluorescence
lifetime
imaging
microscopy

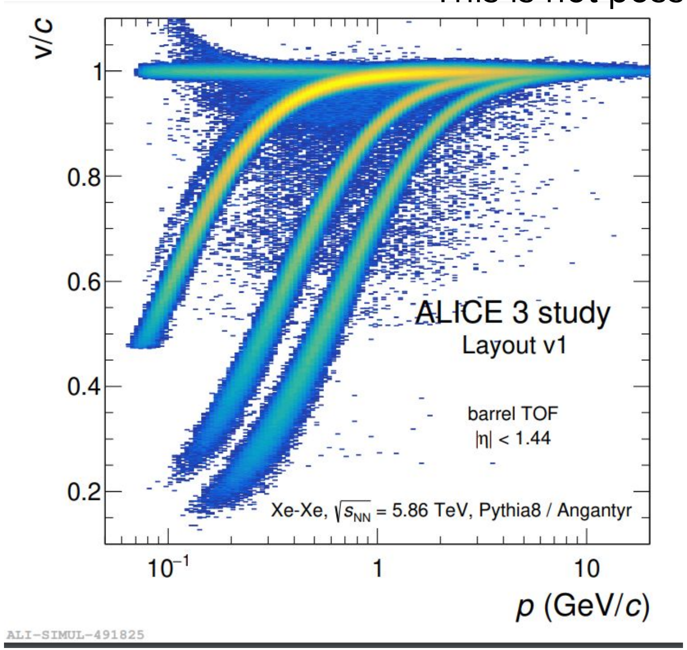
https://velodynelidar.com Velodyne Lidar

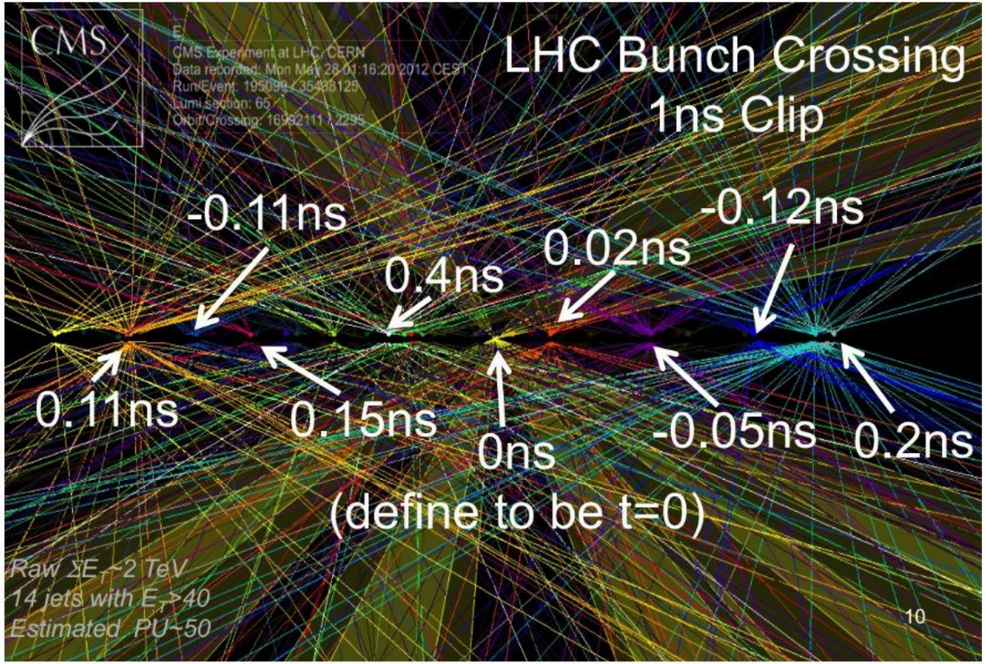
AMSTERDAM SCIENTIFIC INSTRUMENTS https://www.amscins.com

Towards picosecond timing with thin silicon pixel detectors

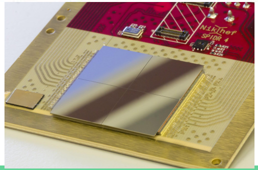
Fast, thin, and low power!

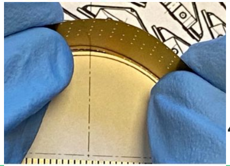
This is not possible now.





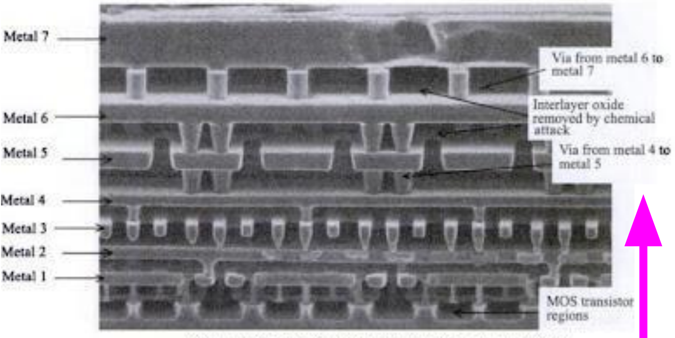
Not yet -- but we will make this possible with R&D in the coming years!



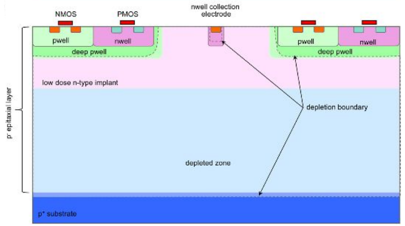


Additional material

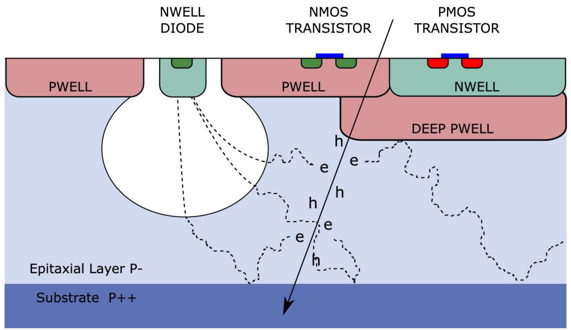
Interconnected metal layers on top

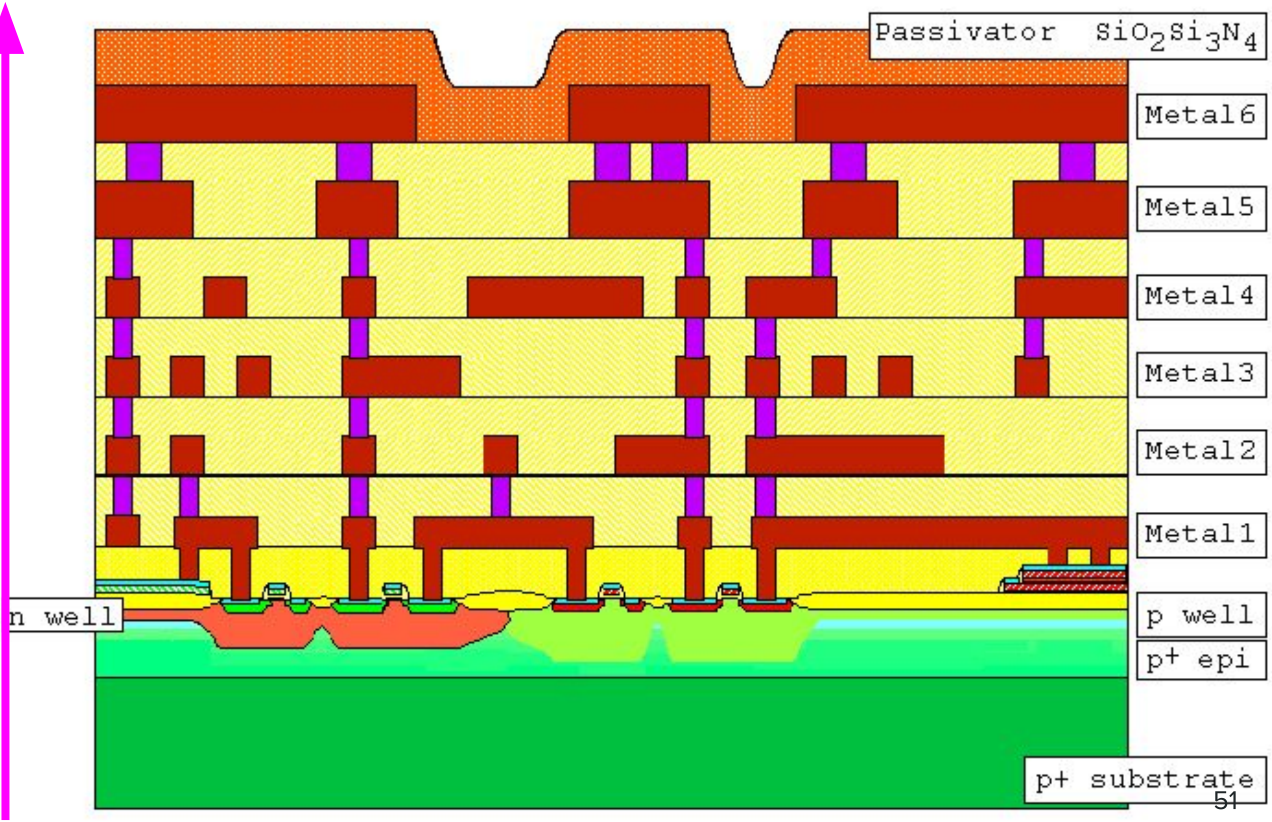


Cross-section of a 0.12 µm technology (*Courtesy:* Fujitsu)



50 µm thick MAPS

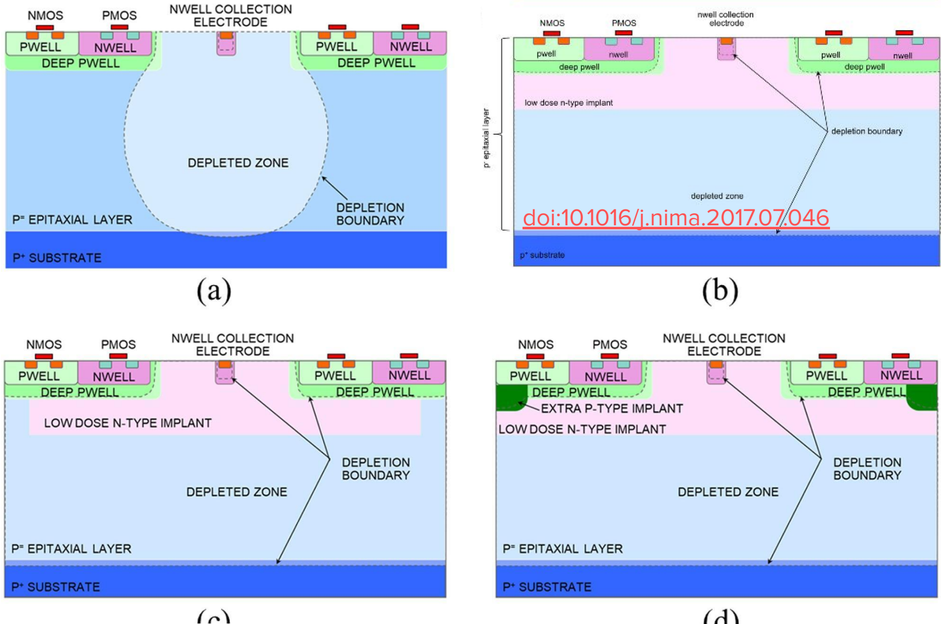




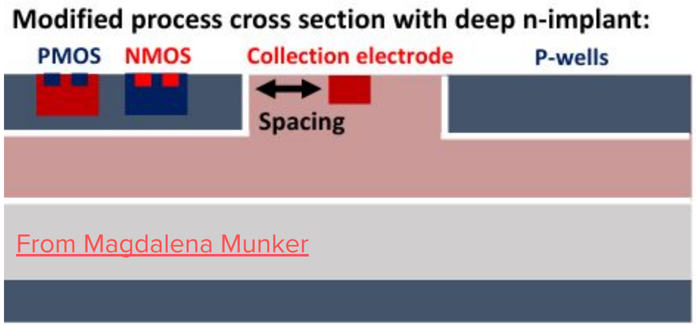
Fast MAPS example: FASTPIX

FASTPIX ATTRACT project:

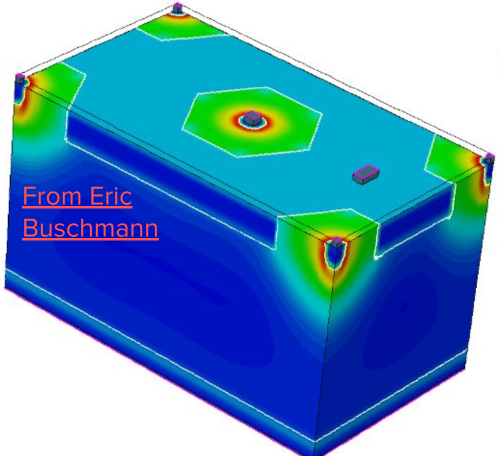
- Designed for tens of ps; measured 120-130 ps time resolution
- Designed for 20 uW power consumption
- Process optimization
- Larger spacing for fast charge collection but low capacitance
- Hexagonal pixels to reduce edge effects



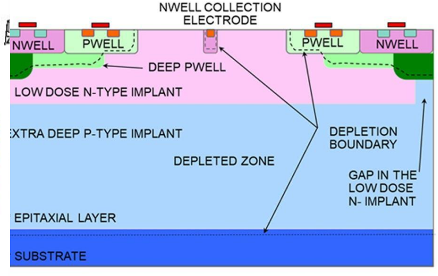
doi:10.1016/j.nima.2017.07.046



From Magdalena Munker



From Eric Buschmann



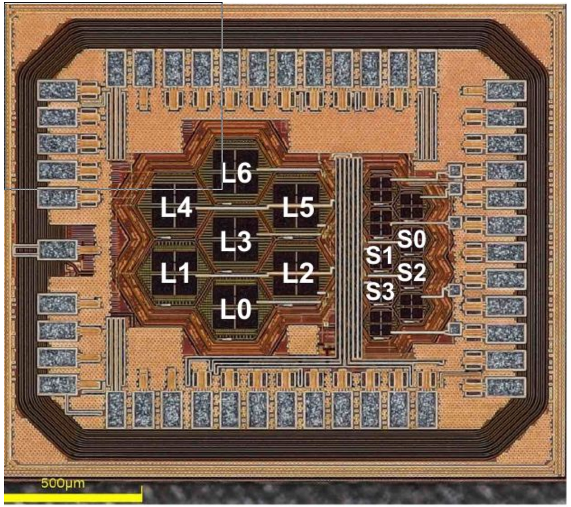
(e)

Kugathasan et al., Nucl. Instr. Meth. A 979 (2020), doi:10.1016/j.nima.2020.164461

MonPicoAD ATTRACT project

- 140 ps at an amplifier current of 7 μA
- 45 ps at 150 μA

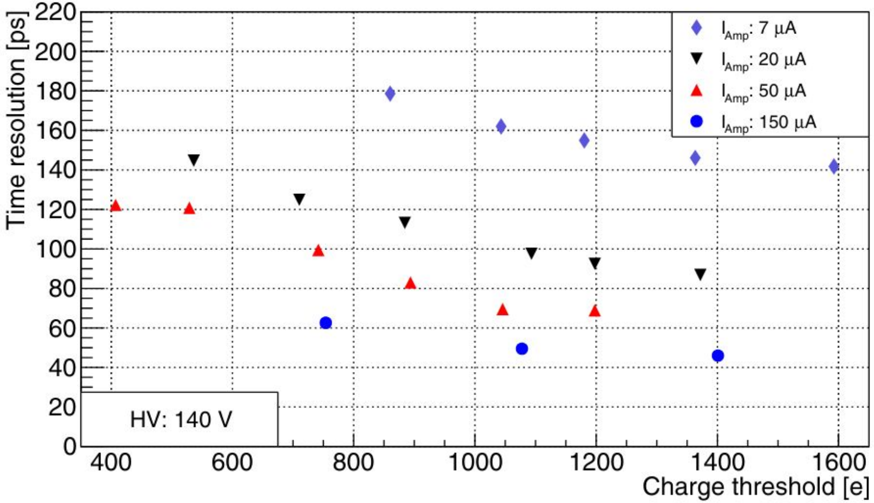
BiCMOS silicon germanium: SG13G2 technology from IHP Microelectronics

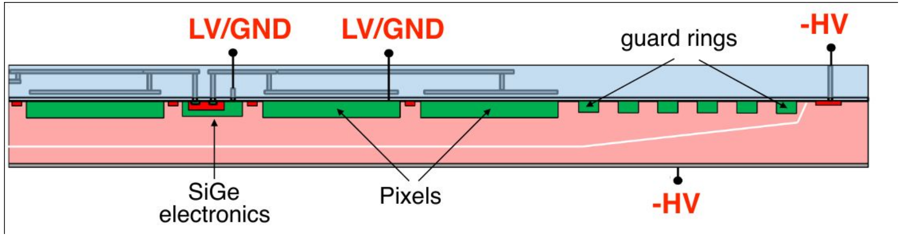


MonPicoAD

See also:

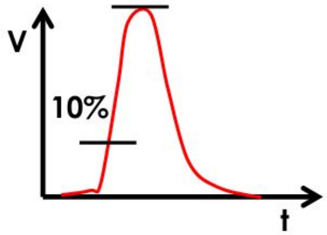
ARCADIA





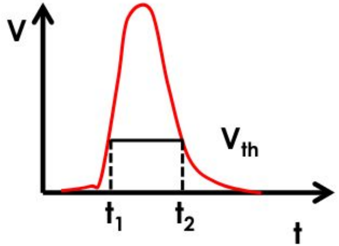
L. Paolozzi et al 2020 JINST 15 P11025
doi:10.1088/1748-0221/15/11/P11025

Different circuits for measuring time



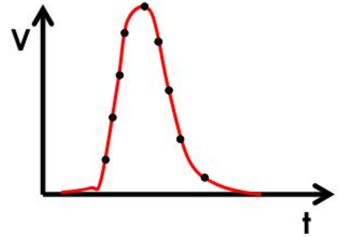
Constant Fraction Discriminator

The time is set when a fixed fraction of the amplitude is reached



Time over Threshold

The amount of time over the threshold is used to correct for time walk



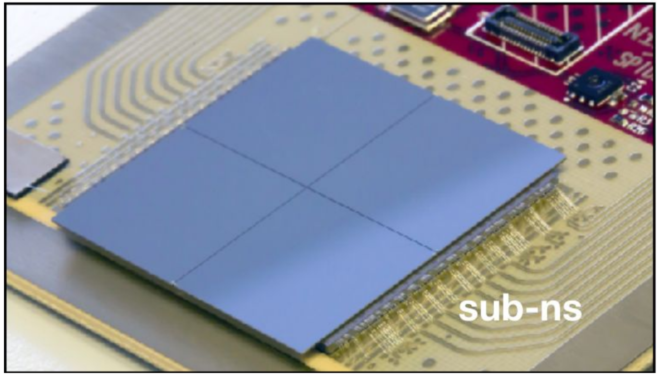
Multiple sampling

Most accurate method, needs a lot of computing power

44

Nikhef experience with fast ASICs and fast readout

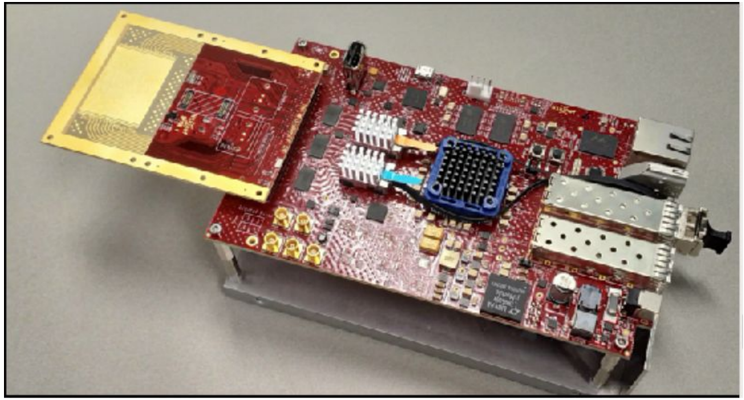
Experience with development of
fast timing



New Timepix 4 with 200 ps TDC time bins ➔ ≃ 60 ps RMS time resolution
Developments continue to further improve time resolution

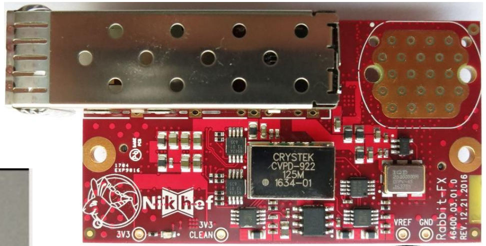
Nikhef in collaboration with CERN

Nikhef
Experience with **Gigabit readout**



SPIDR4: Speedy PIxel Detector Readout developed for Timepix and Medipix chips

Nikhef in collaboration with CERN
Experience with **subnanosecond synchronization**

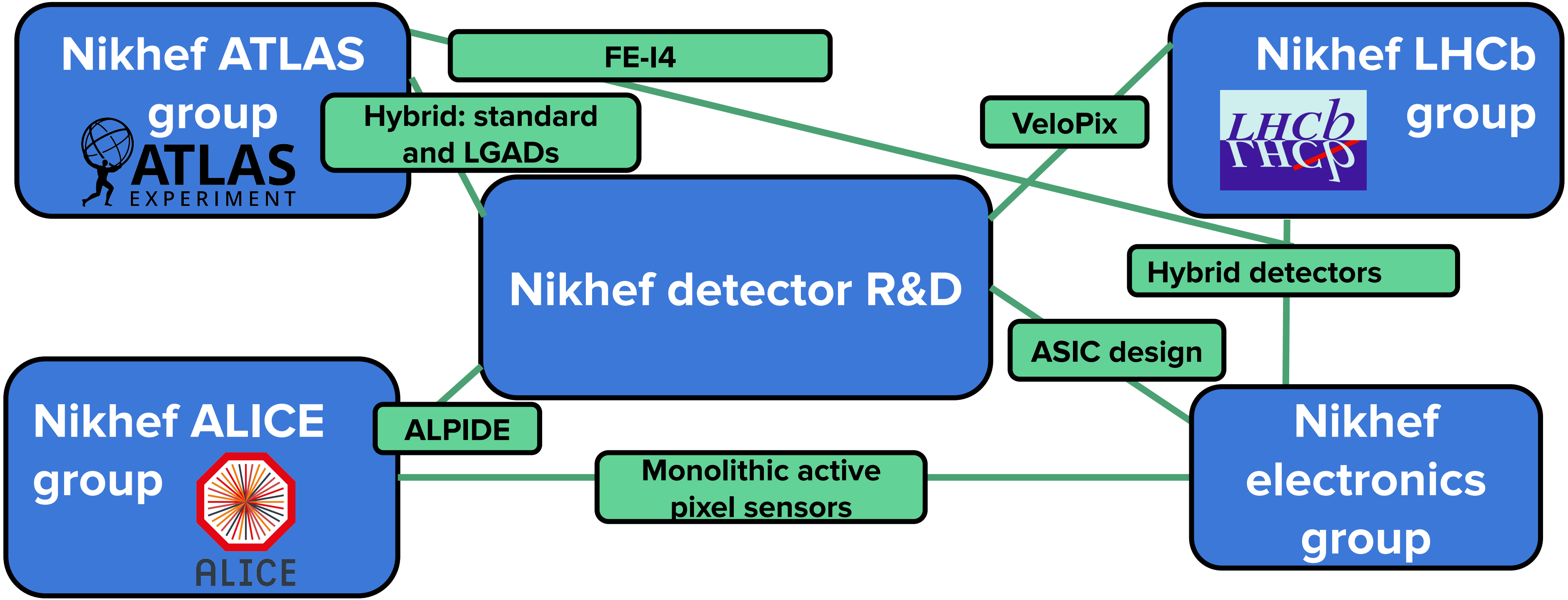


White Rabbit for subnanosecond synchronization over ethernet -- used by KM3Net, possibly ATLAS, ET-pathfinder

	Timepix3 (2013)	VeloPix (2016)
Pixel arrangement	256 x 256	
Pixel size	55 x 55 μm²	
Peak hit rate	80 Mhits/s/ASIC	800 Mhits/s/ASIC 50 khits/s/pixel
Readout type	Continuous, trigger-less, TOT	Continuous, trigger-less, binary
Timing resolution/range	1.5625 ns, 18 bits	25 ns, 9 bits
Total Power consumption	<1.5 W	< 3 W
Radiation hardness		400 Mrad, SEU tolerant
Sensor type	Various, e- and h+ collection	Planar silicon, e- collection
Max. data rate	5.12 Gbps	20.48 Gbps
Technology	IBM 130 nm CMOS	TSMC 130 nm CMOS

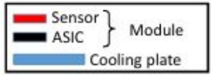
From X. Llopart

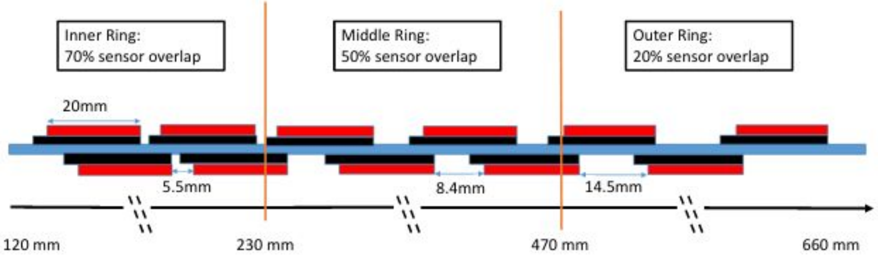
Nikhef detector R&D with Nikhef LHC groups



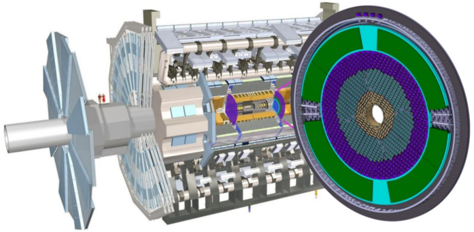
Work on fast timing in both MAPS and hybrid detectors

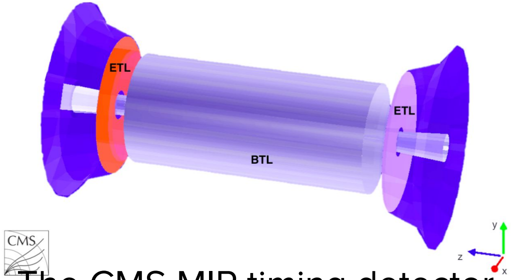
ATLAS High Granularity Timing Detector





- High lumi LHC: 4000 fb^{-1}
- $z = \pm 3.5$ m
- Outside ITk
- In front of endcap calorimeters
- r = 120-640 mm
- CO_2 cooling @ -30 °C
- Overlapping double modules
- Time resolution per track (per hit)
  25 ps (35 ps) for r = 120 mm
- After 4000 fb^{-1}: 42 ps (60 ps)
- Φ_{eq} = (5.5) 8.3e15 cm^{-2} , 7.5 (3.3) MGy
- **Half will be replaced**: < 230 mm after 1000 fb^{-1}, < 470 after 2000 fb^{-1}

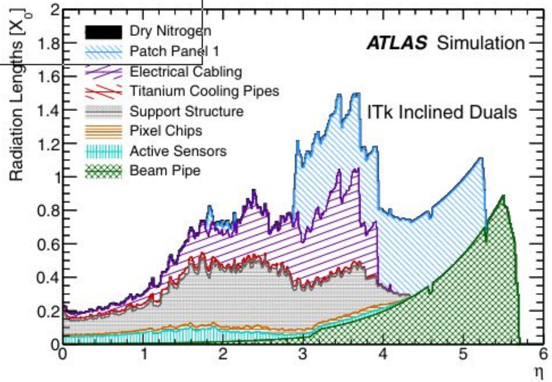


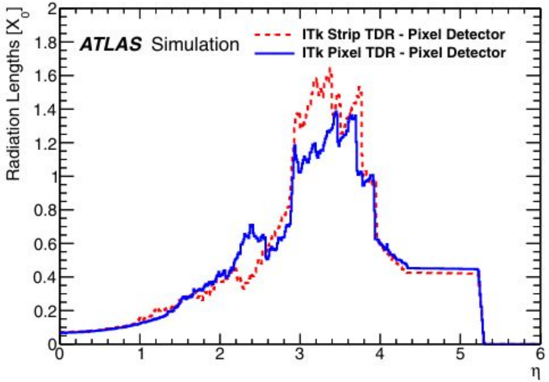


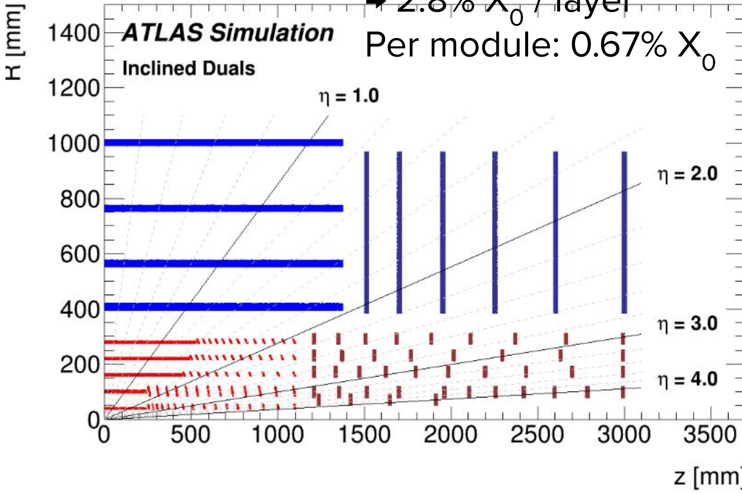
The CMS MIP timing detector also has a barrel layer with silicon photomultipliers

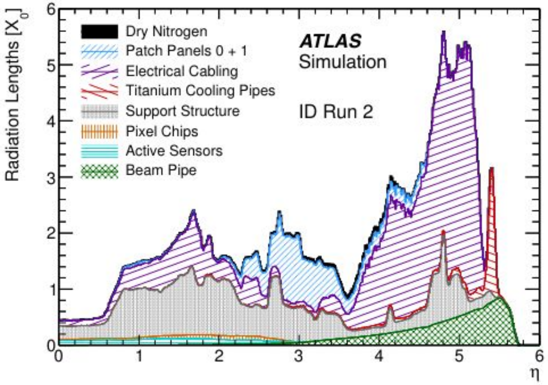
ATLAS 2026 Inner Tracker (ITk) material budget

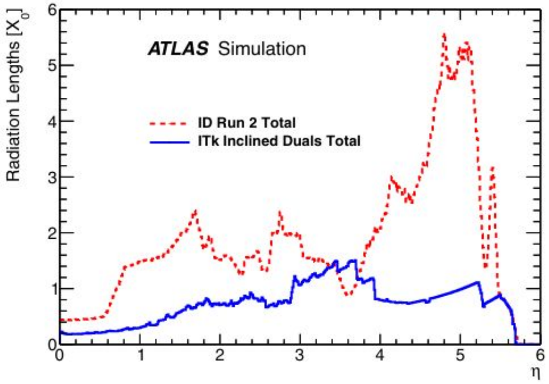
ITk: 9 layers, ~25%X_0
➔ 2.8% X_0 / layer
Per module: 0.67% X_0

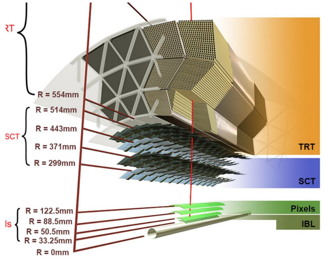




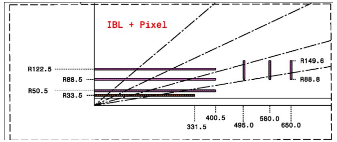


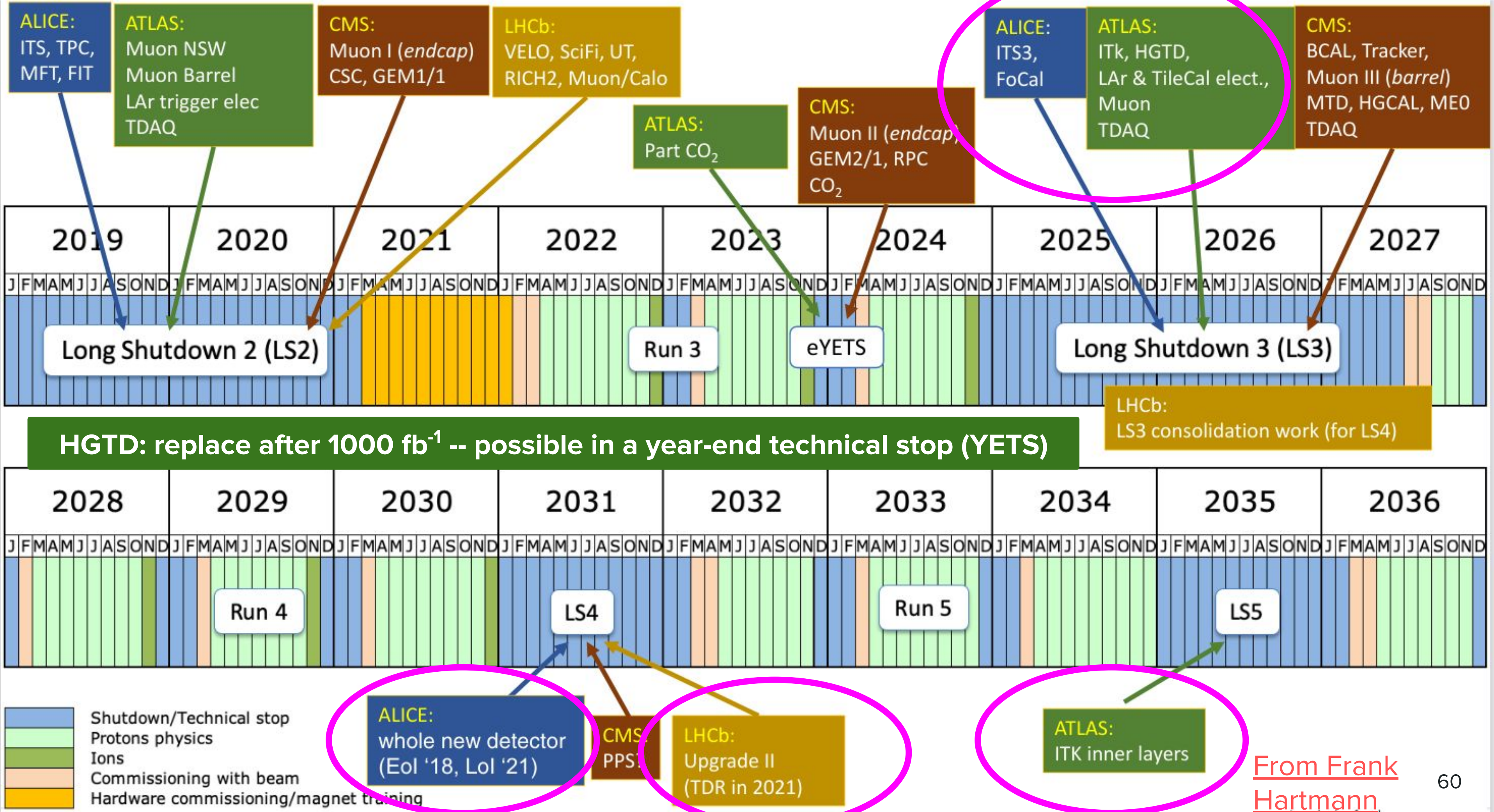






Inner detector now:
4 layers, ~40%X_0
➔ 8% X_0 / layer





[From Frank Hartmann]