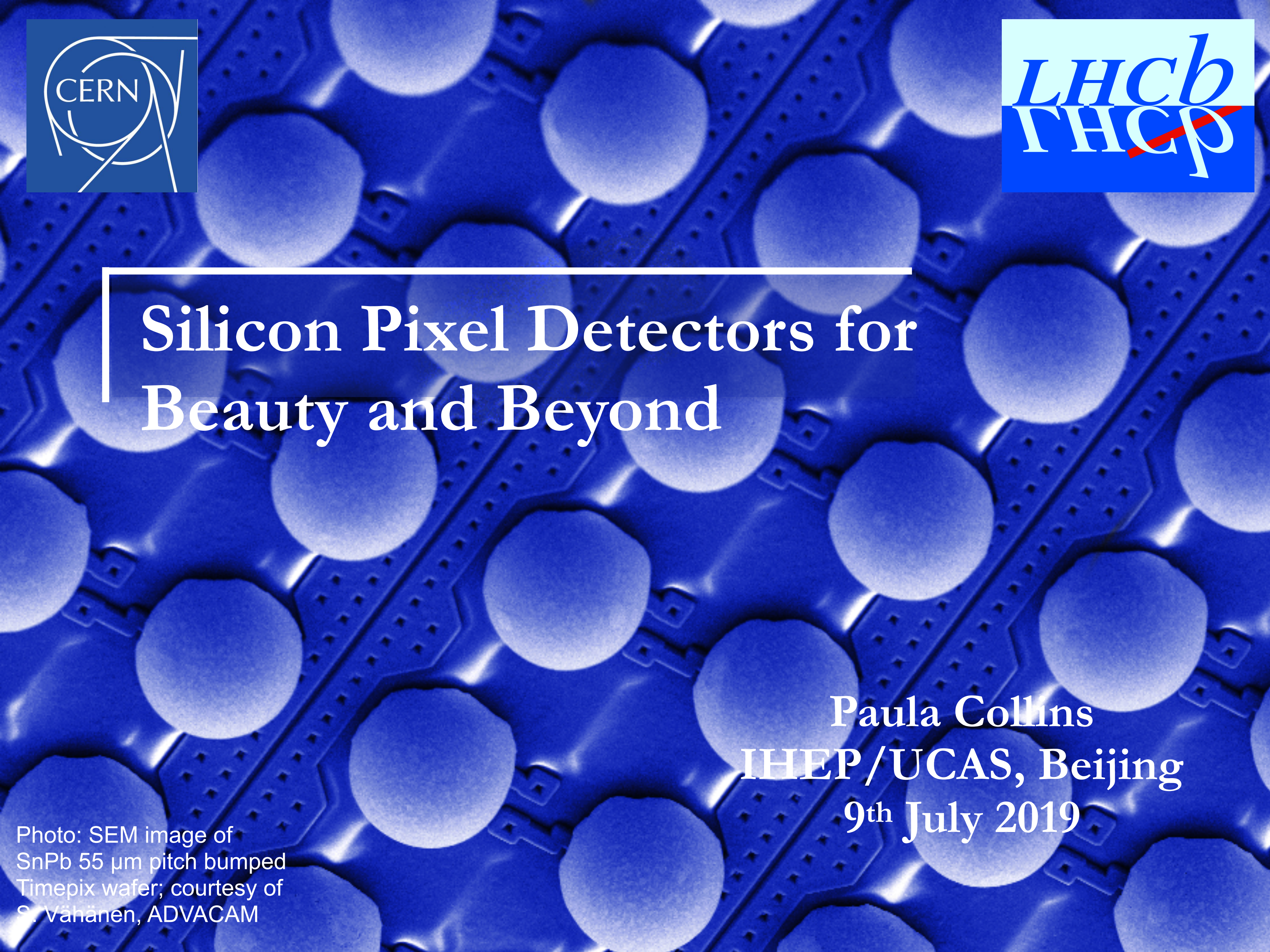
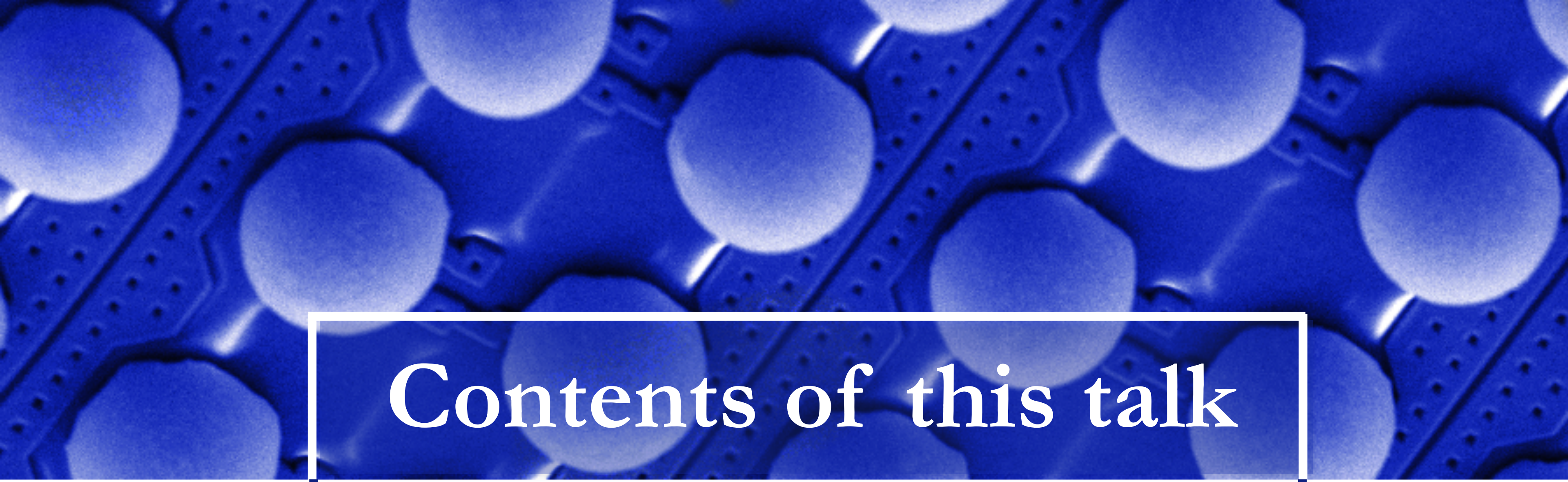


Silicon Pixel Detectors for Beauty and Beyond

Paula Collins
IHEP/UCAS, Beijing
9th July 2019

Photo: SEM image of SnPb 55 µm pitch bumped Timepix wafer; courtesy of S. Vähänen, ADVACAM



Contents of this talk

A brief history of silicon sensors in HEP

- Silicon sensors for LHCb

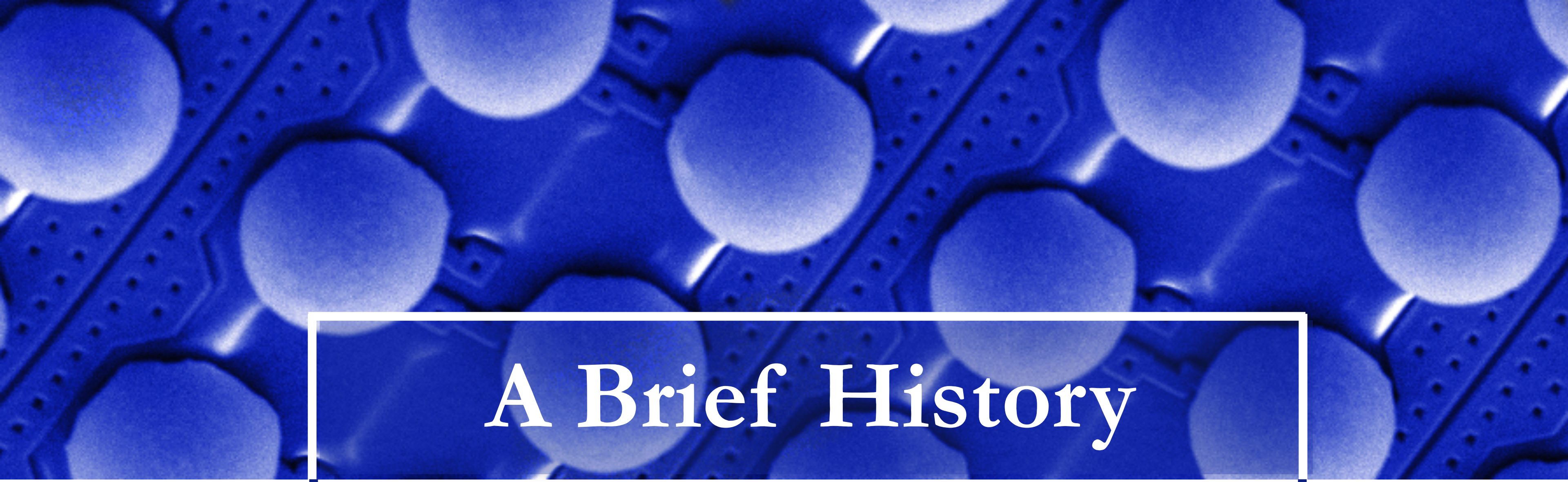
The rise of hybrid pixels

- From HEP to Medicine: Medipix/Timepix for imaging
- From Medicine to HEP: VeloPix for LHCb Upgrade

Further challenges

- Cooling for Pixels
- Radiation Hardness
- Timing

Monolithic pixels



A Brief History

Silicon sensors in HEP

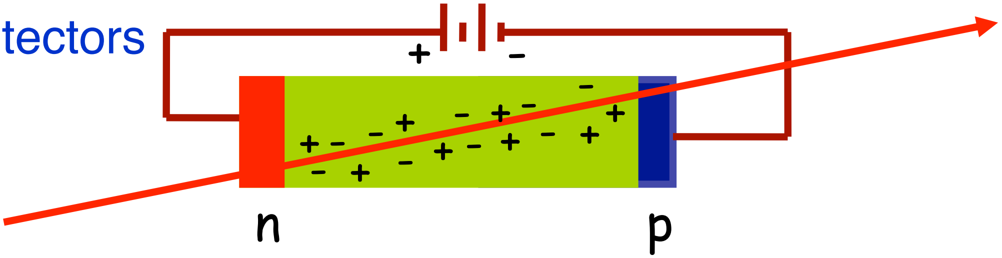
- Silicon sensors for LHCb

Silicon Detectors for HEP

Basic principle: detect electron hole pairs created in reverse biased segmented silicon diode

Originally were not considered for HEP detectors

- Costly, bulky, small signal, challenges of miniaturisation

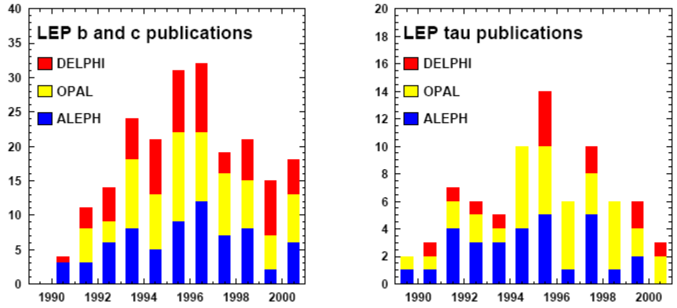


However with the increasing interest in very precise measurements of the vertex position, and the advent of silicon planar processing technology, silicon detectors took

ICHEP Singapore Conference, 1990

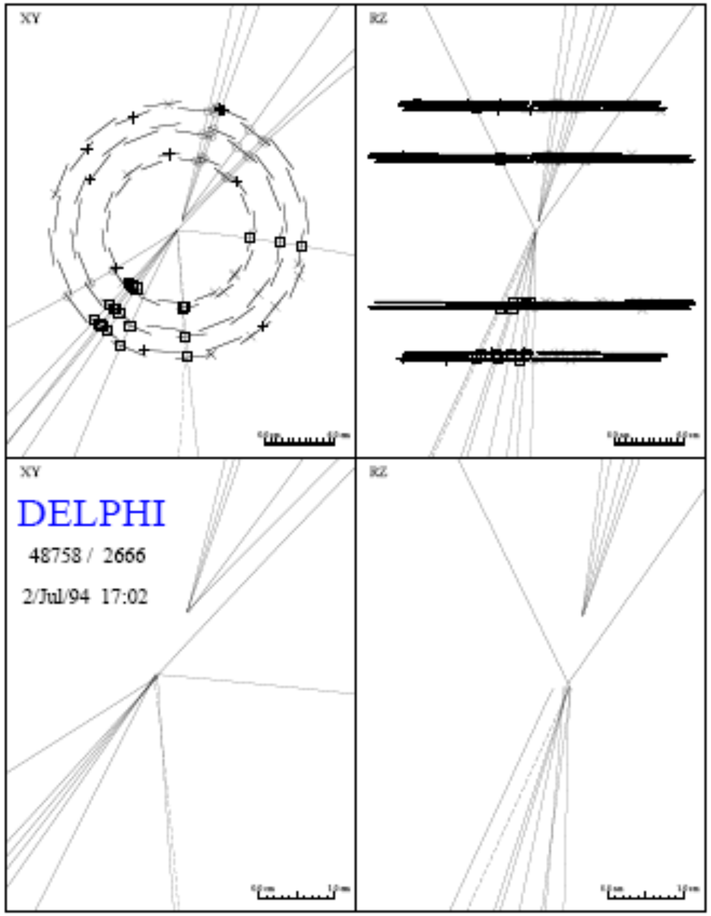
'The LEP experiments are beginning to reconstruct B mesons… It will be interesting to see whether they will be able to use these events'

B. Gittleman, Heavy Flavour Review



10 years later, flavour physics represented 40% of all LEP publications

Silicon Detectors for HEP



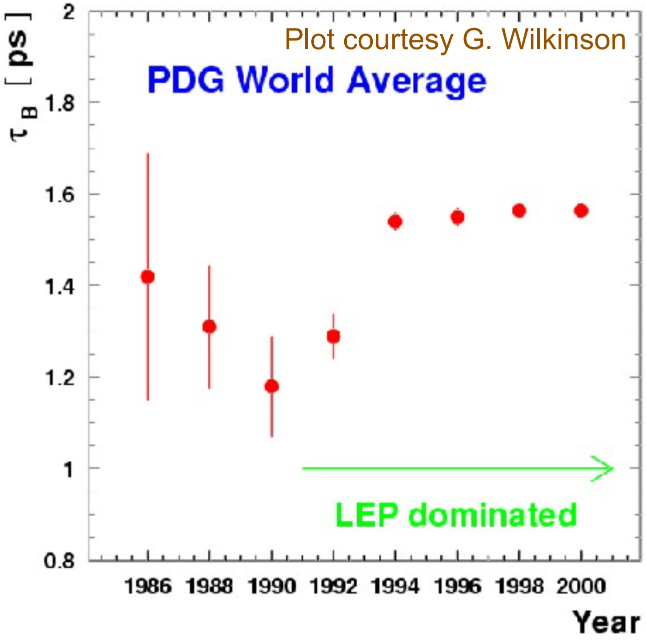
Late 80's MARK II (SLC) and early 90's all LEP experiments had silicon, with continuous upgrades

Pixel detector at SLC in early 90s

The new detectors exploited access to micro-lithography technology, low noise amplifiers to cope with the small silicon signals, and readout with electronics miniaturisation

Silicon Detectors for HEP

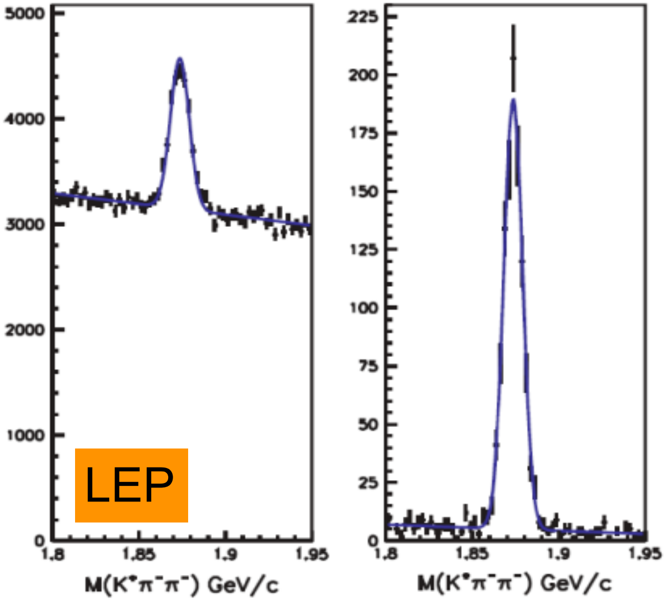
Dramatic effect on measurement precision!



Plot courtesy G. Wilkinson

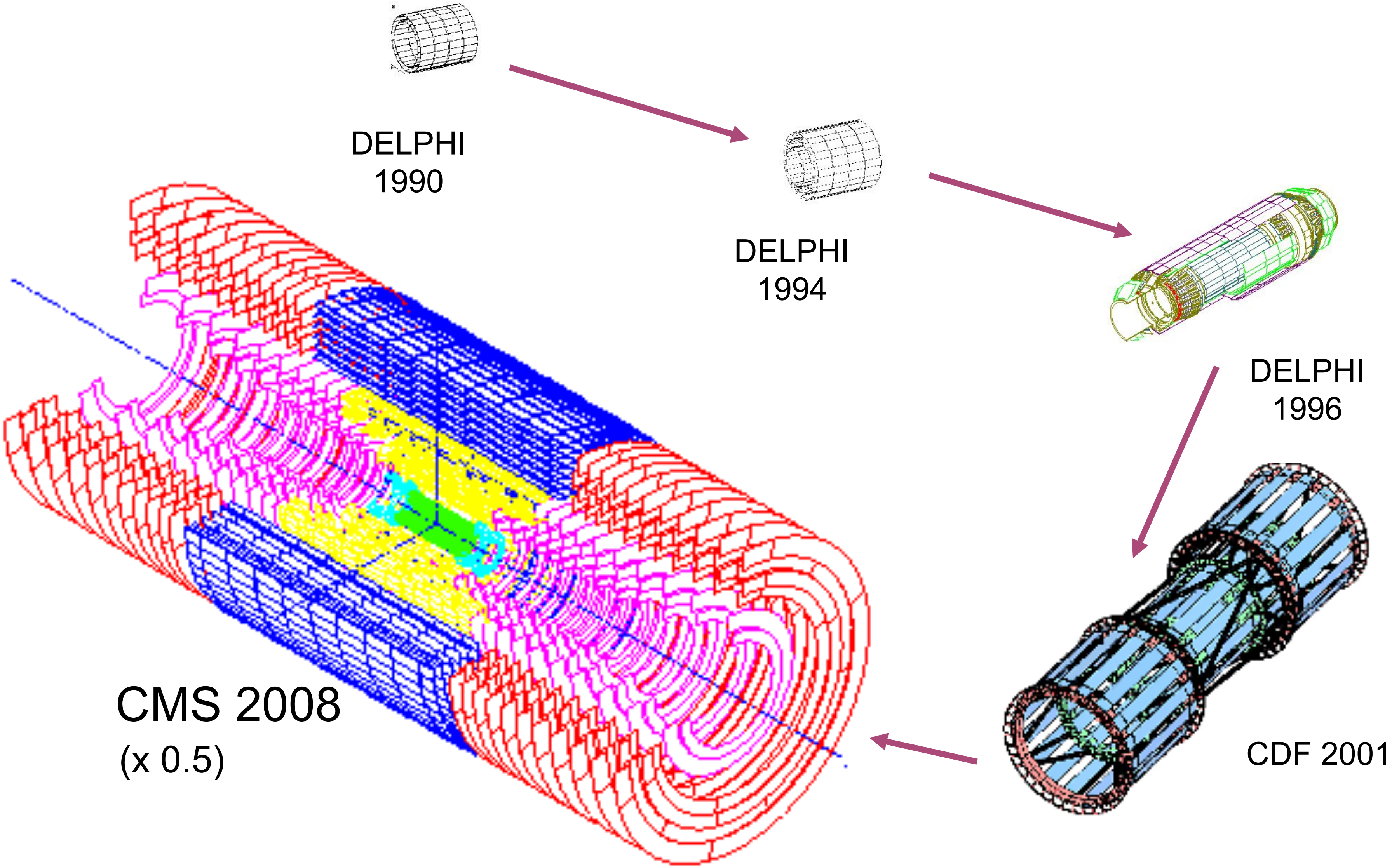
PDG World Average

LEP dominated



LEP

Systems quickly increased in size



DELPHI
1990

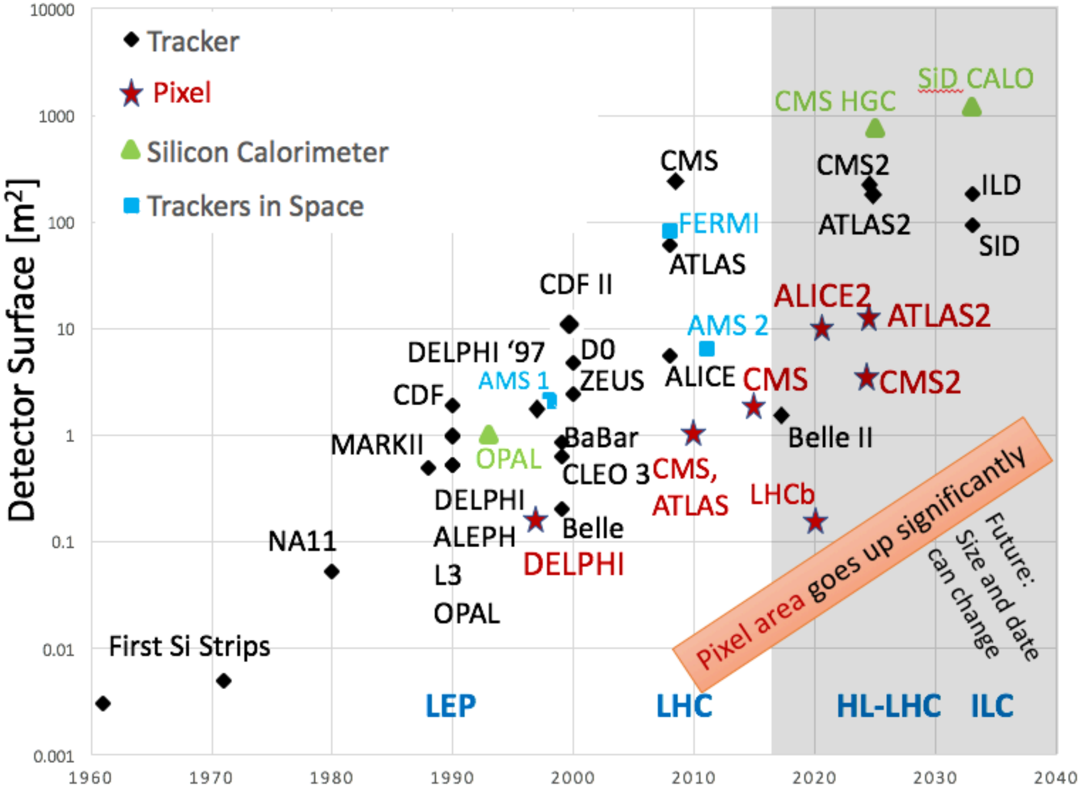
DELPHI
1994

DELPHI
1996

CDF 2001

CMS 2008
(x 0.5)

And became more and more segmented



Based on: Frank Hartmann, HSTD2017

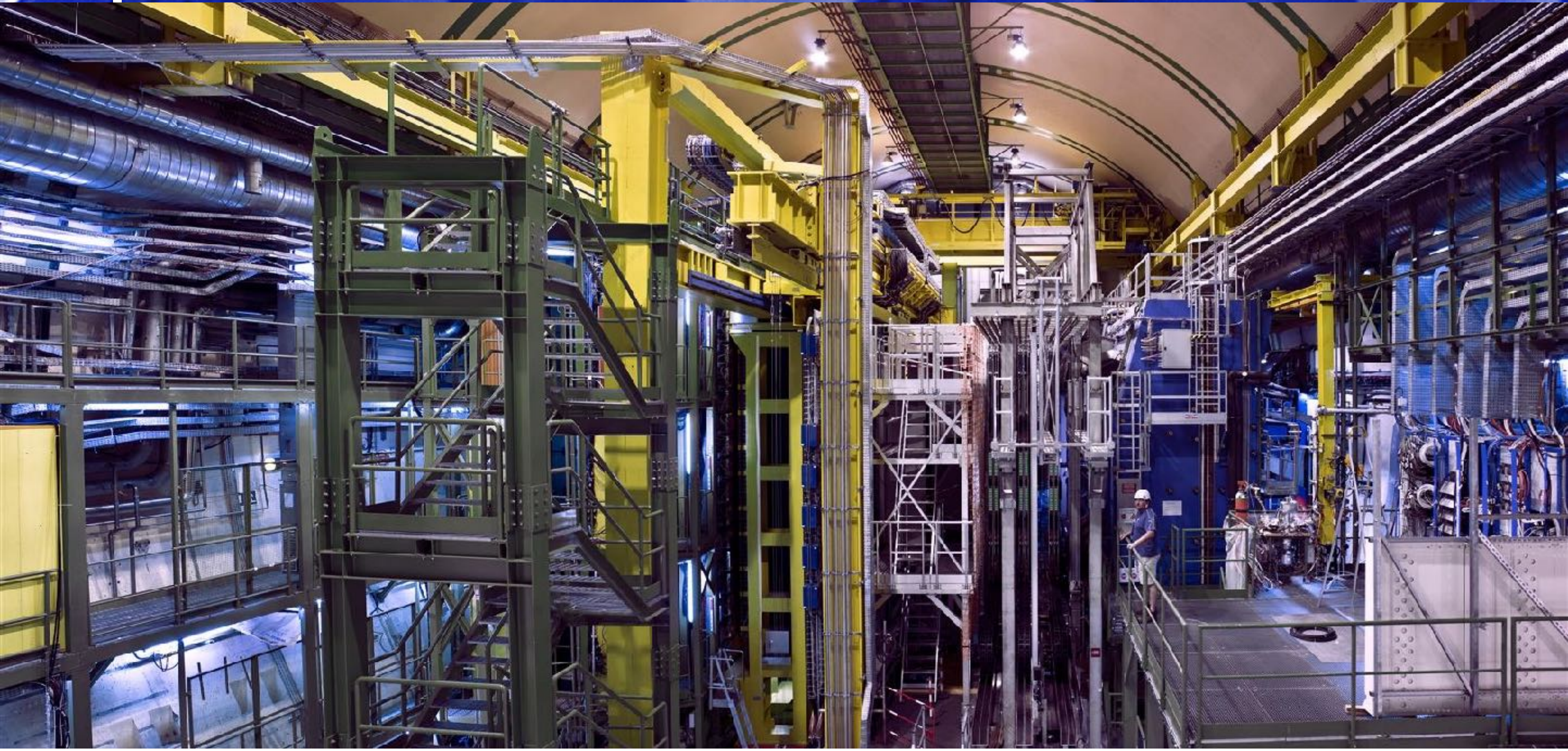
In general global tracker sizes are saturating

However cell sizes and data rates are evolving significantly

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

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

The LHCb Experiment

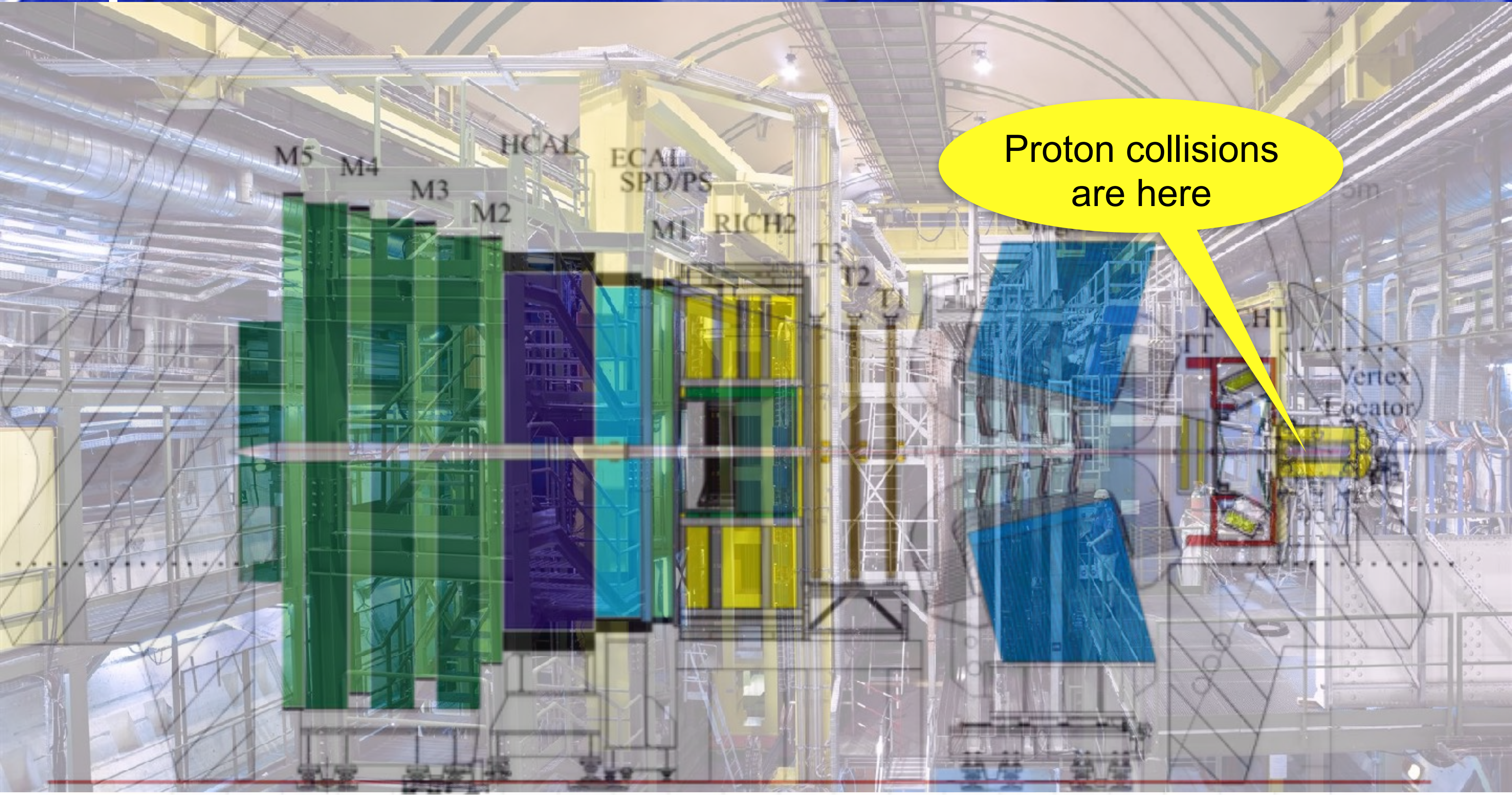


LHCb: Single arm spectrometer optimised for precision flavour physics

Approx 1100 members from 73 institutes in 63 countries

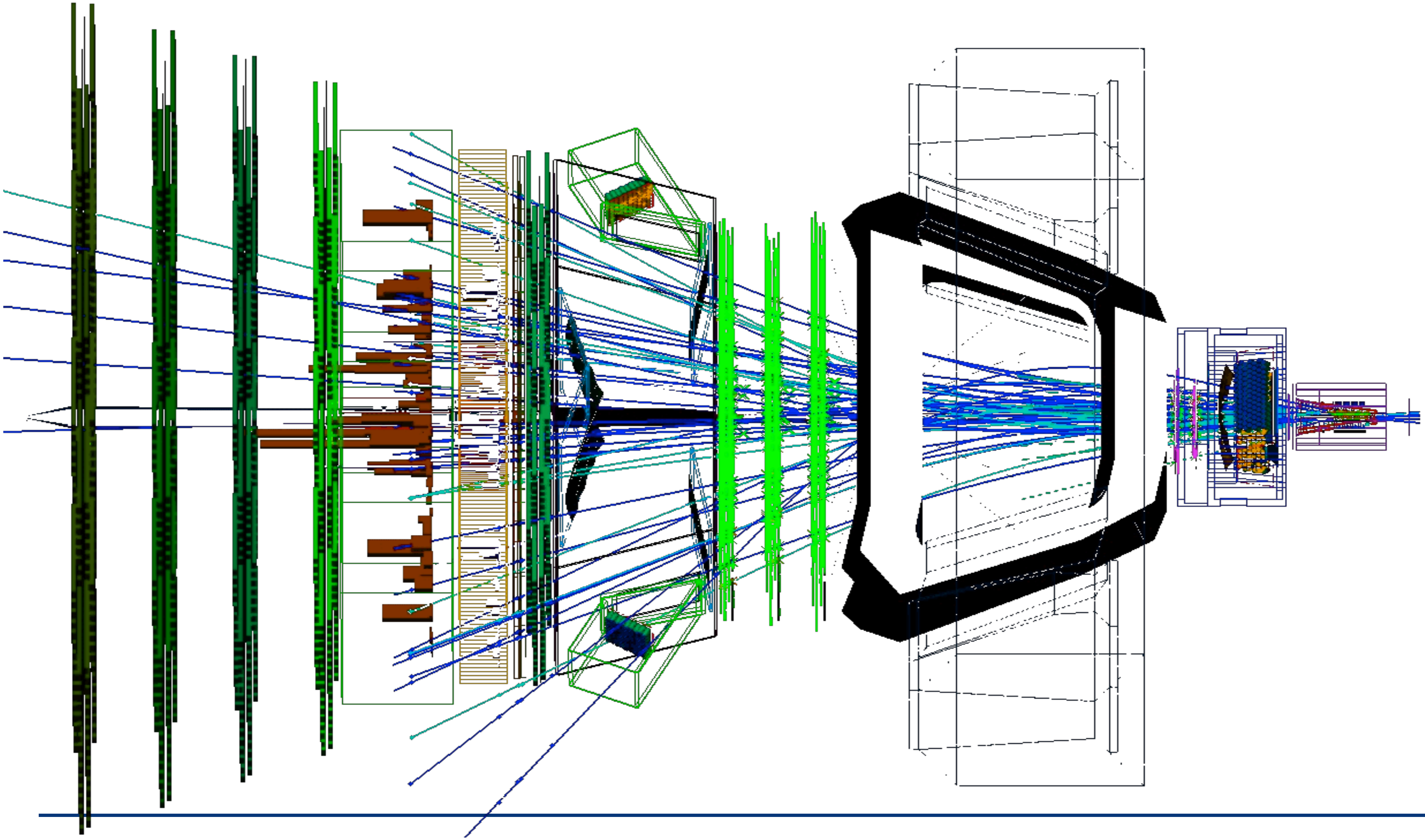
Weight: 5600 Tons
Height: 10 m
Length: 20 m

The LHCb Experiment



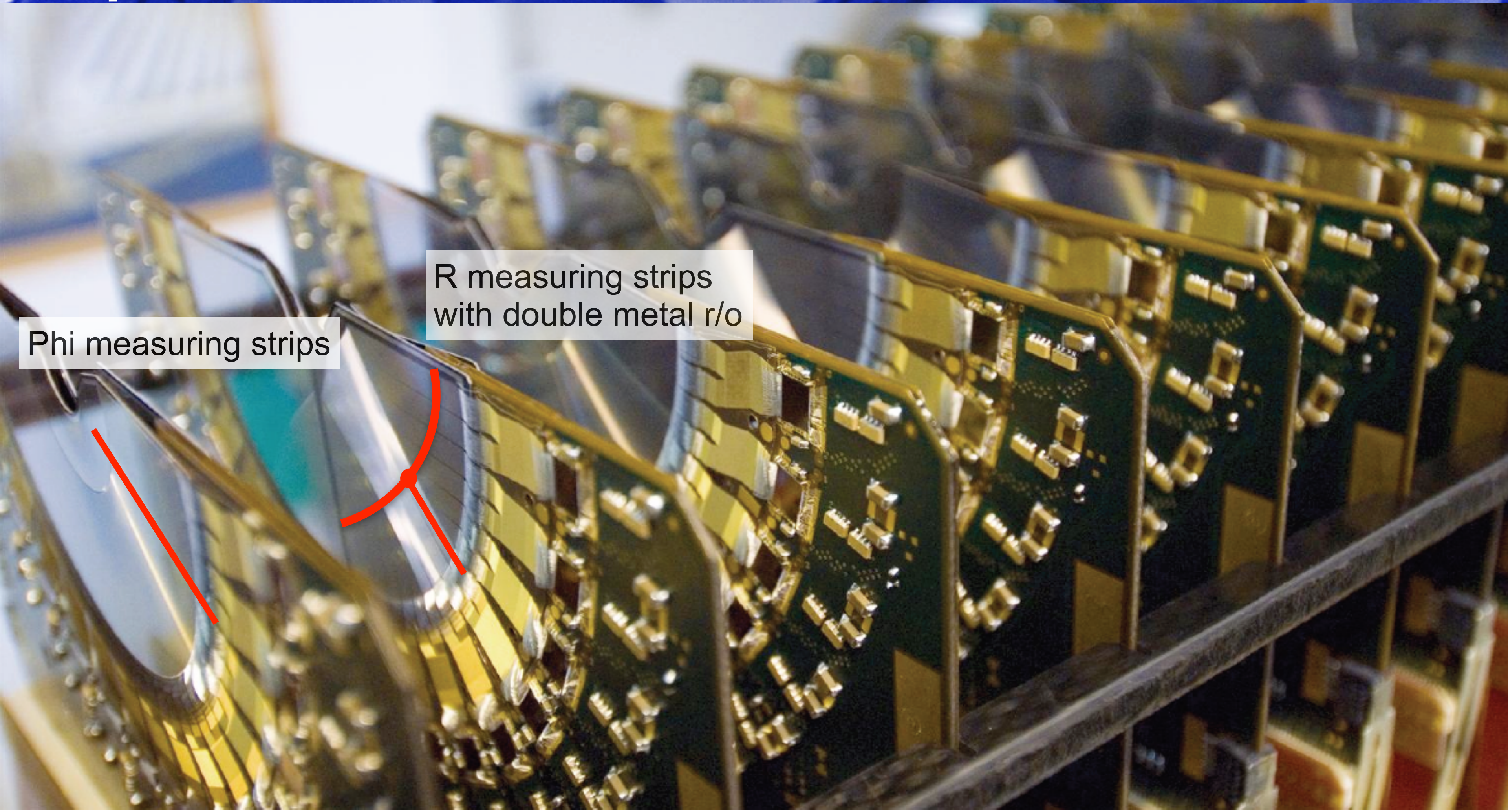
Proton collisions are here

Visualising a Collision



The LHCb Vertex Locator (VELO) 2009-20

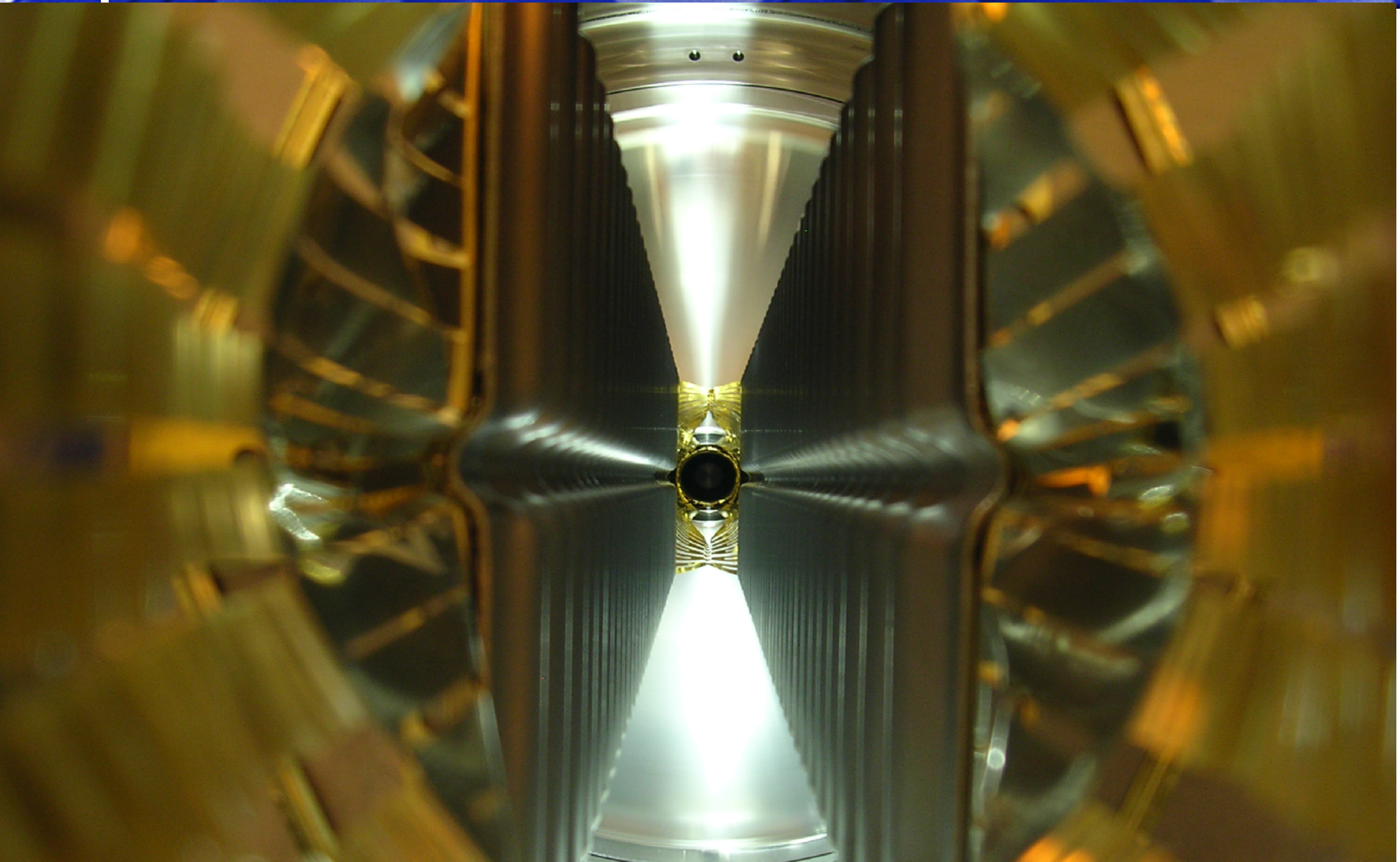
The LHCb Vertex Locator (VELO)



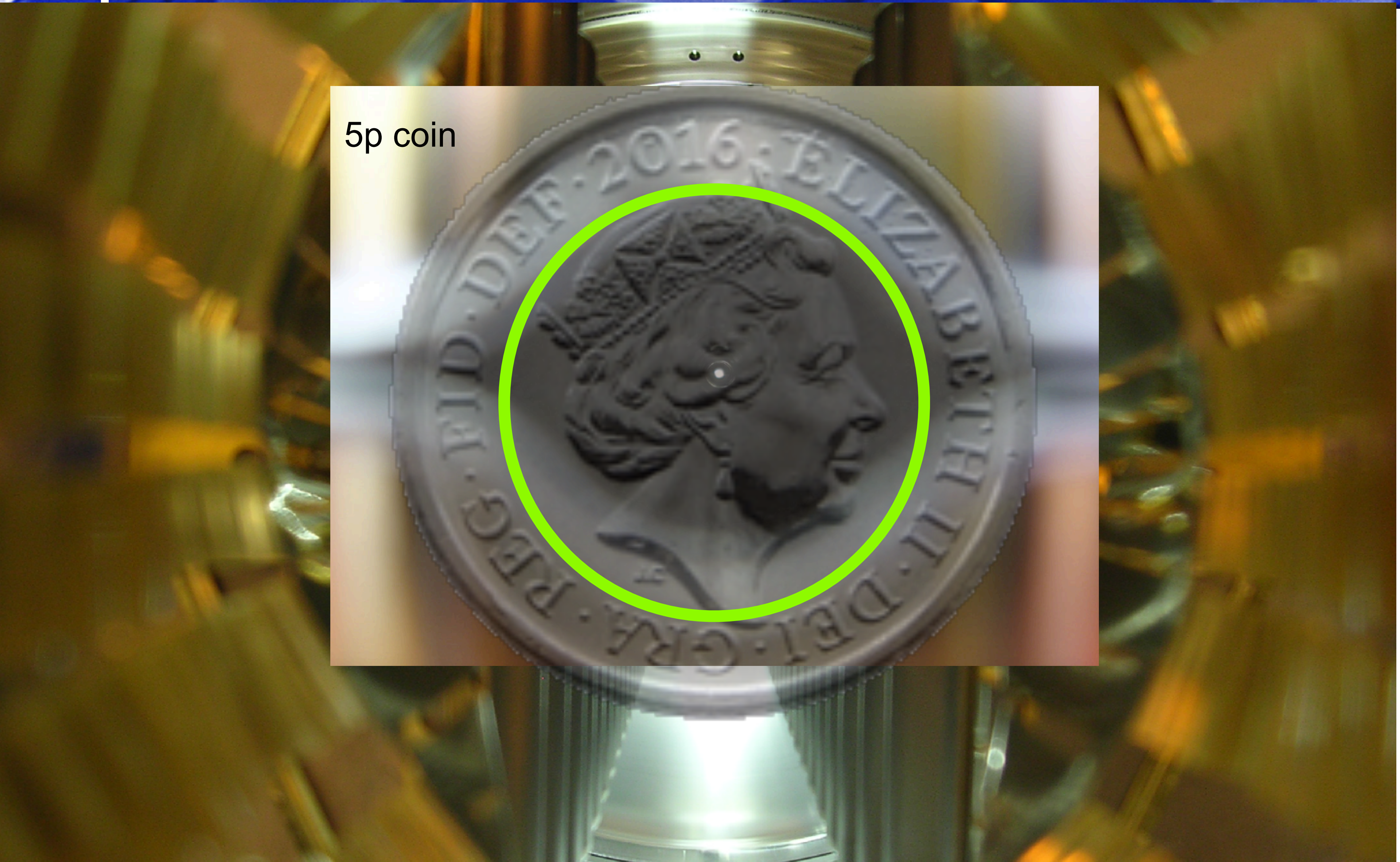
R measuring strips
with double metal r/o

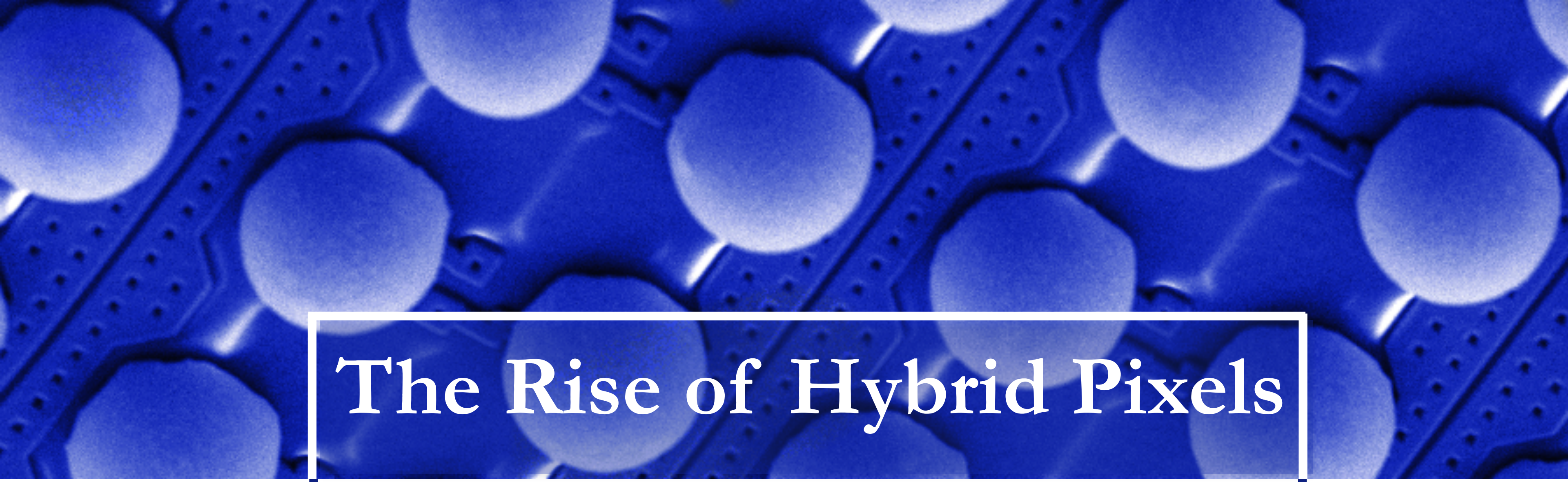
Phi measuring strips

Placed around the LHC beams



Placed around the LHC beams

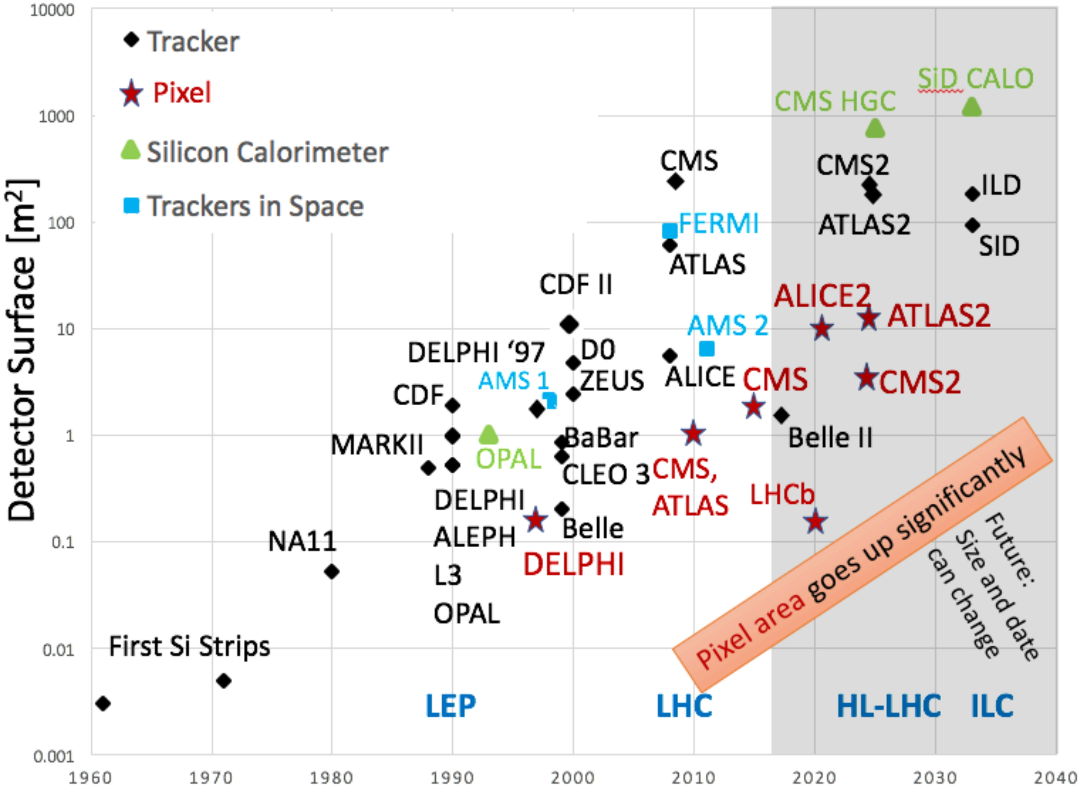




The Rise of Hybrid Pixels

- From HEP to Medicine: Medipix/Timepix for imaging
- From Medicine to HEP: VeloPix for LHCb Upgrade

(previously shown)



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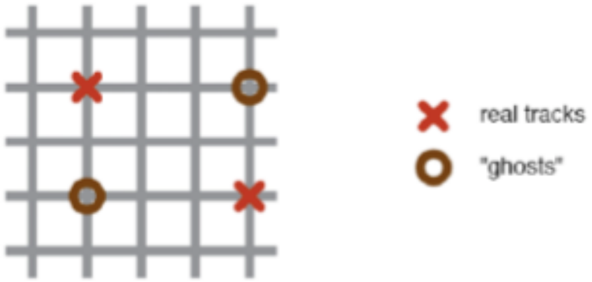
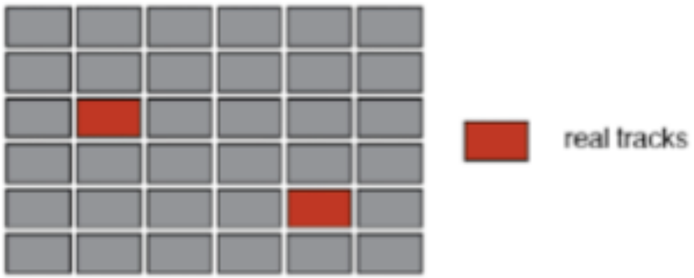
Cell granularity, the weapon against high-PU keeping occupancy at a reasonable level

With the rise of pixel detectors

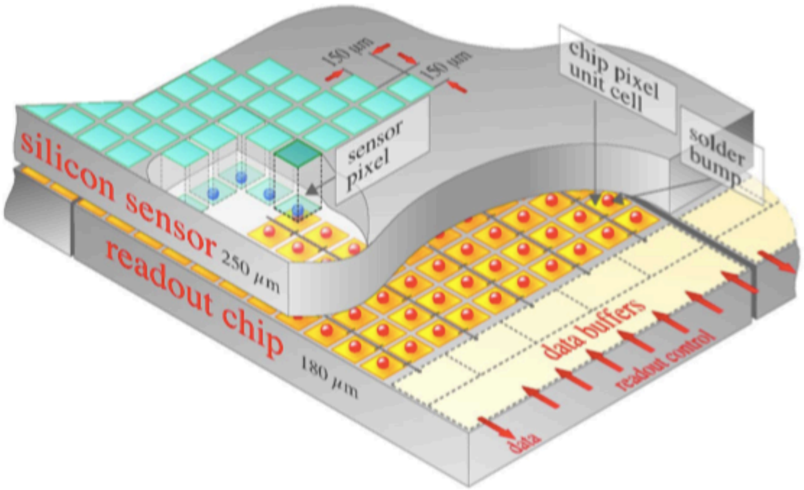




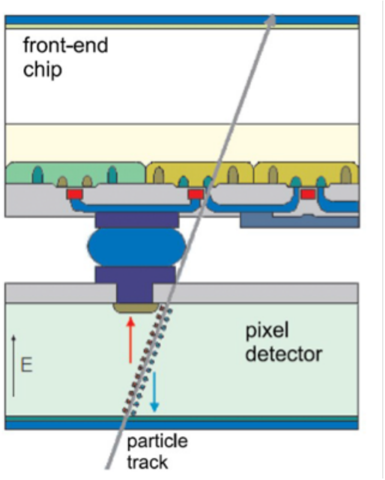
Strip detector measures 1 coordinate only. Two orthogonal detectors give a 2 dimensional position of a particle. However with more than one particle hits the strip detectors the measurement is no longer unambiguous. “Ghost” hits appear!

Pixel detectors produce unambiguous hits

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

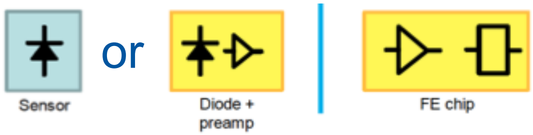


The Hybrid Pixel Detector

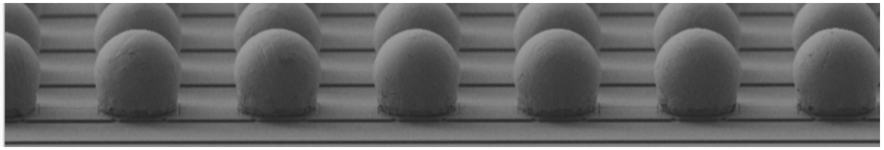


Offer a number of pros due to the split functionality of sensor and readout:

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



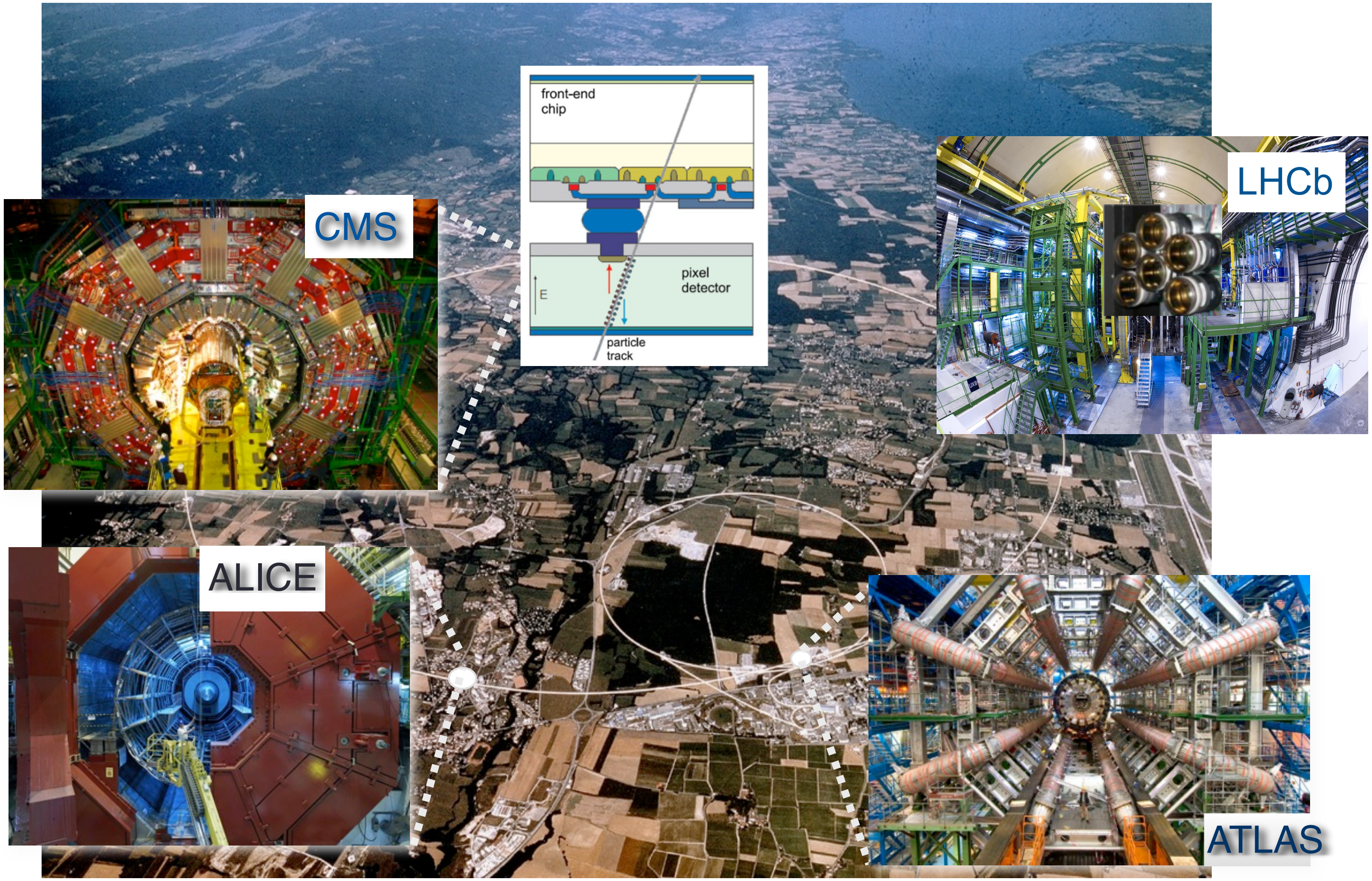
Fine pitch bump bonding to connect sensor and readout chip



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

Hybrid Pixels at the LHC

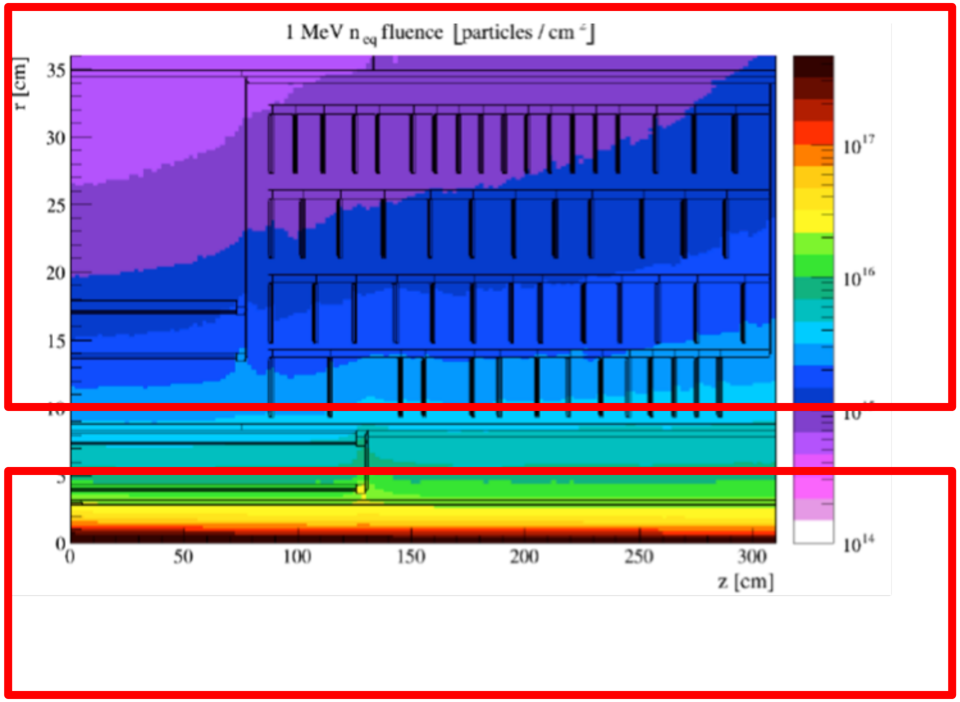
Pixels are typically installed in the regions closest to the IP



And at HL-LHC

Designs governed by LHC radiation levels, hit rates and bunch structure

Example: ATLAS



Outer Pixel layers

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

Inner Pixel layers

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

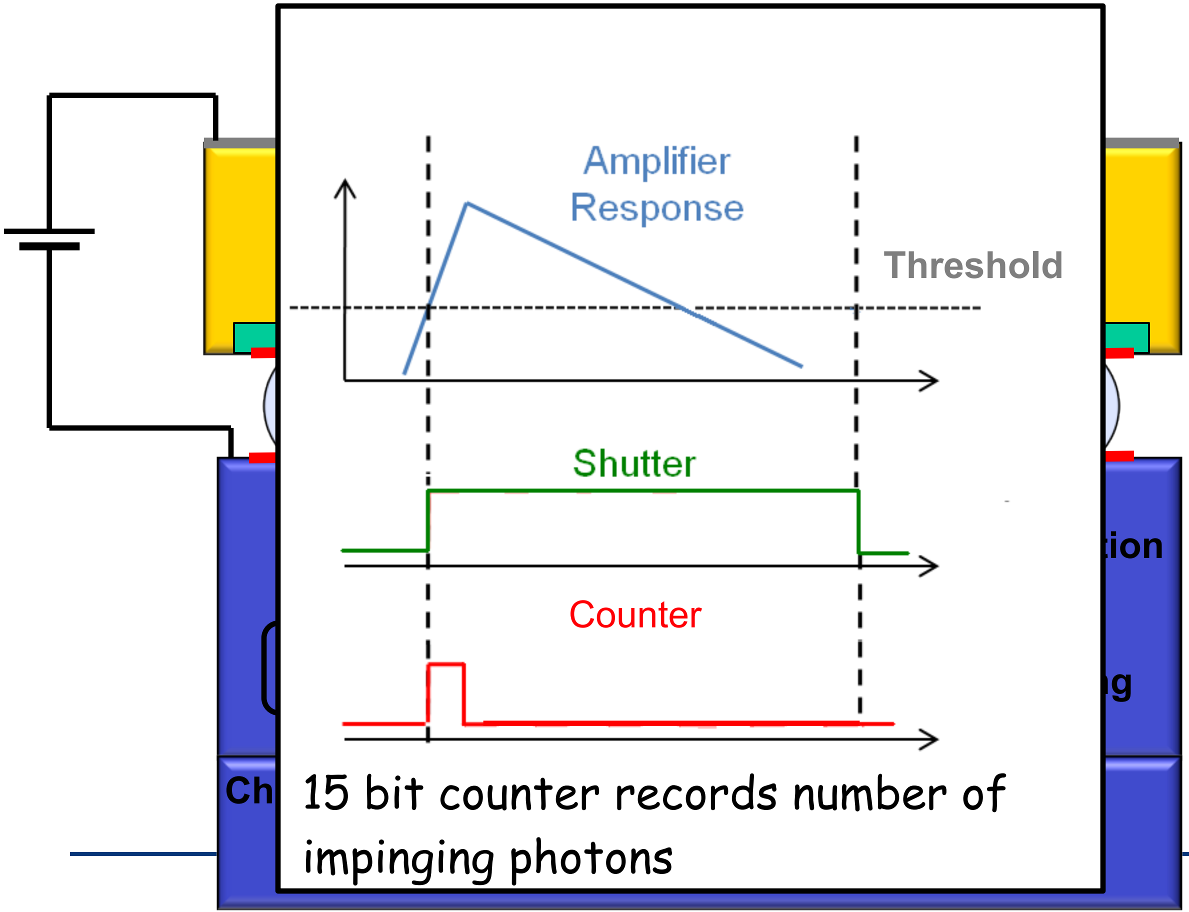
Hybrid Pixels: Medipix/Timepix

Engagement of the detector physics community with difficult detector challenges and with industry has led to wonderful detectors able to go beyond initial goals

Hybrid pixels used in tracking detectors, gaseous detector readouts, RICH, biomedical applications and photon science, space applications etc…

Let's take as an example the Medipix/Timepix family.

Pixels for Medical Imaging



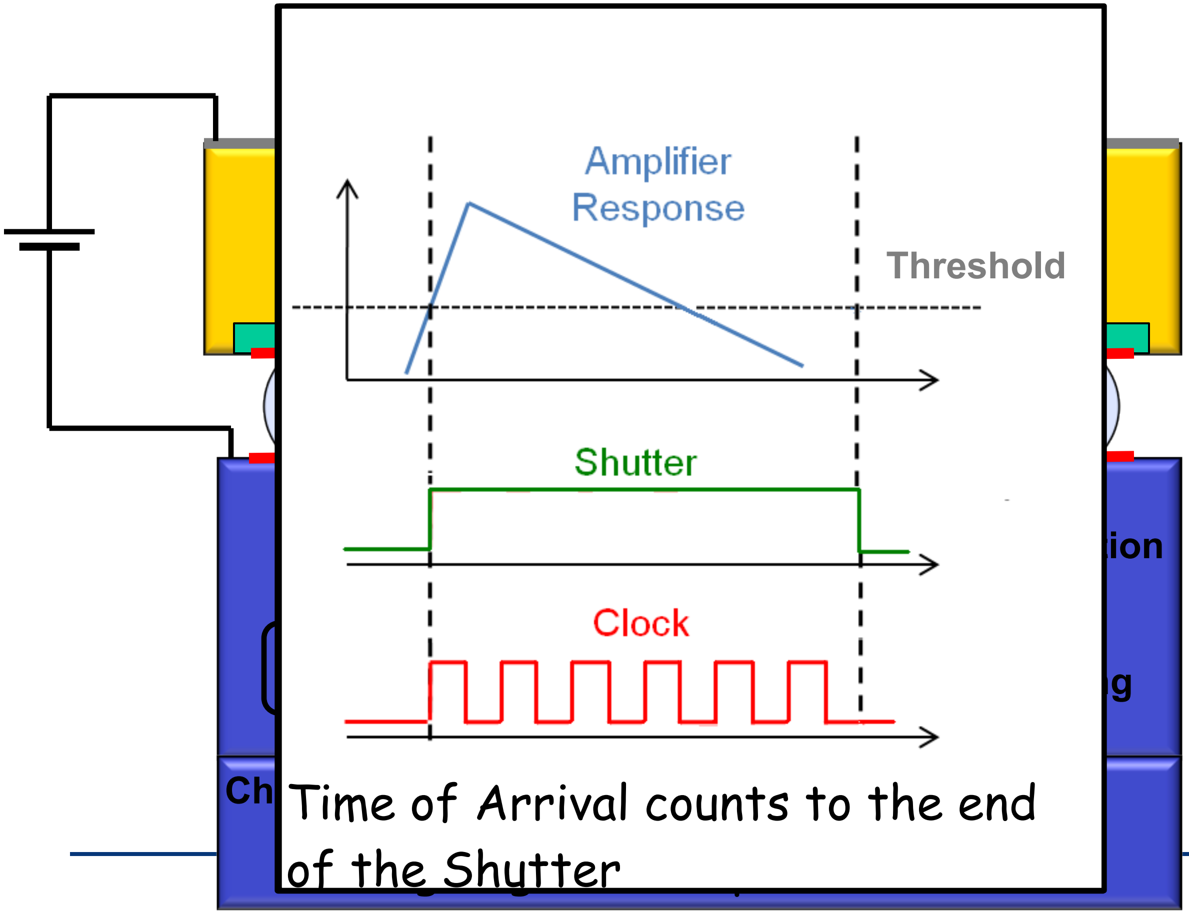
15 bit counter records number of impinging photons

Idea: take advances in HEP and apply them to photon counting for medical physics

Intensity counter for photons, using individual pre-amp, comparator and counter per pixel

Operates in “camera” mode, reading out the entire pixel array when the shutter closes

Pixels for Medical Imaging



Time of Arrival counts to the end of the Shutter

Timepix design requested and funded by EUDET collaboration

Conventional Medipix2 counting mode remains.

Addition of a clock up to 100MHz allows two new modes.

Time over Threshold

Time of Arrival

Pixels can be individually programmed into one of these three modes

Medipix/Timepix Specs

Timepix Specs

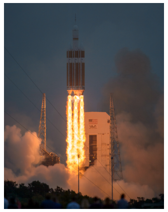
CMOS node	250nm
Pixel Array	256 x 256
Pixel pitch	55μm
Charge collection	e-, h+
Pixel functionality	PC (Particle Counting), TOT (Energy) or TOA (Arrival time)
Preamp Gain	~16.5mV/ke-
ENC	~100e-
FE Linearity	Up to 50ke-
TOT linearity (resolution)	Up to 200ke- (<5%)
TOA resolution	Up to 10ns (@ 100 MHz)
Time-walk	<50ns
Minimum detectable charge	~700e- → 2.5 KeV (Si Sensor)
Counter Depth/Overflow	14-bits(11810)/Yes
Max Analog power (2.2V)	6.5μW/pix 190mA/chip
Static Digital Power (2.2V)	~500mW@100MHz/chip
Readout (@ 100 MHz)	Serial readout → 9.17 ms 32-bit Parallel readout → 287 μs

3 side buttable floor plan
> 36M Transistors

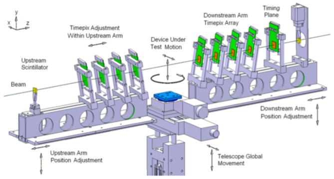
Medipix / Timepix / Medipix3
photon counting/ add time / energy thresholds


miniaturised readout
IEAP/CTU, Prague

Many applications..



including the Timepix particle tracking telescope



Low energy threshold (4 keV) enables imaging of very low contrast media, like flowers, with high resolutions

Medipix3: Convolvulus arvensis
3.1M pixels, 55 μm pixel pitch
Credits: Simon Procz,, Ph.D. Thesis,
University of Freiburg

Advancing Cryo-Electron Microscopy

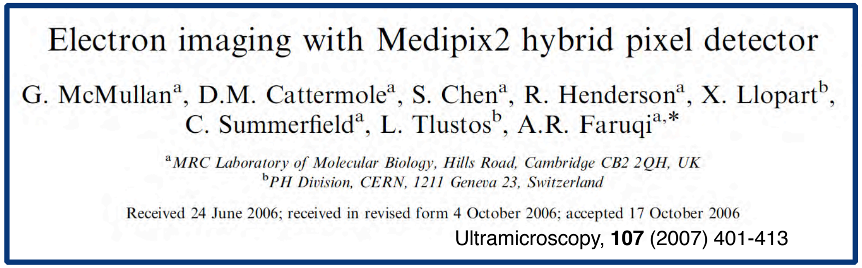

Jacques Dubochet
University of Lausanne


Joachim Frank
Columbia University


Richard Henderson
MRC Lab, Cambridge

2017 Nobel Prize in Chemistry

“For developing cryo-electron microscopy for the high-resolution structure determination of biomolecules in solution”



Electron imaging with Medipix2 hybrid pixel detector

G. McMullan[a], D.M. Cattermole[a], S. Chen[a], R. Henderson[a], X. Llopart[b], C. Summerfield[a], L. Tlustos[b], A.R. Faruqi[a,*]

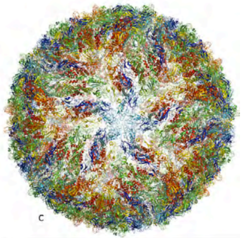
[a] *MRC Laboratory of Molecular Biology, Hills Road, Cambridge CB2 2QH, UK*
[b] *PH Division, CERN, 1211 Geneva 23, Switzerland*

Received 24 June 2006; received in revised form 4 October 2006; accepted 17 October 2006

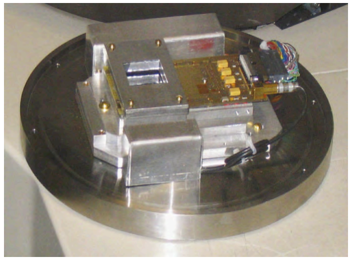
Ultramicroscopy, **107** (2007) 401-413


Protein for circadian rhythm

Ear pressure sensor



The Zika virus



Noiseless direct detection of electrons in Medipix2 for electron microscopy, *NIM* A546 (2005) 160–163

Direct electron detection methods in electron microscopy, *NIM A*513 (2003) 317-321

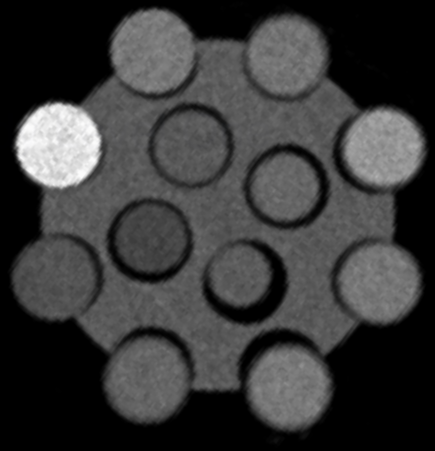
Although CMOS technology is currently being used for cryo-EM imaging, Medipix efforts helped advance the technology

Greyscale to Material Imaging

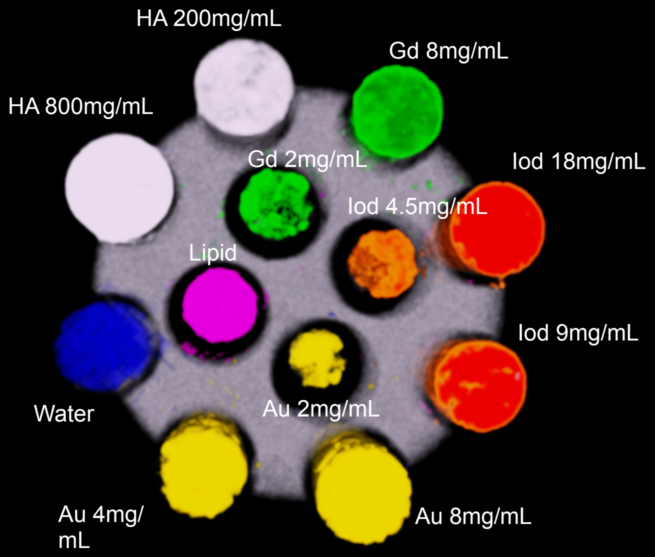
Spectral imaging allows different materials to be identified and quantified

Separate map (data channel) made for each material
Each map gives the partial density (g/cm3) for the material
Each material assigned a colour for easy visualisation

A phantom containing Au, Gd, Iodine, Lipid, Water and hydroxyapatite



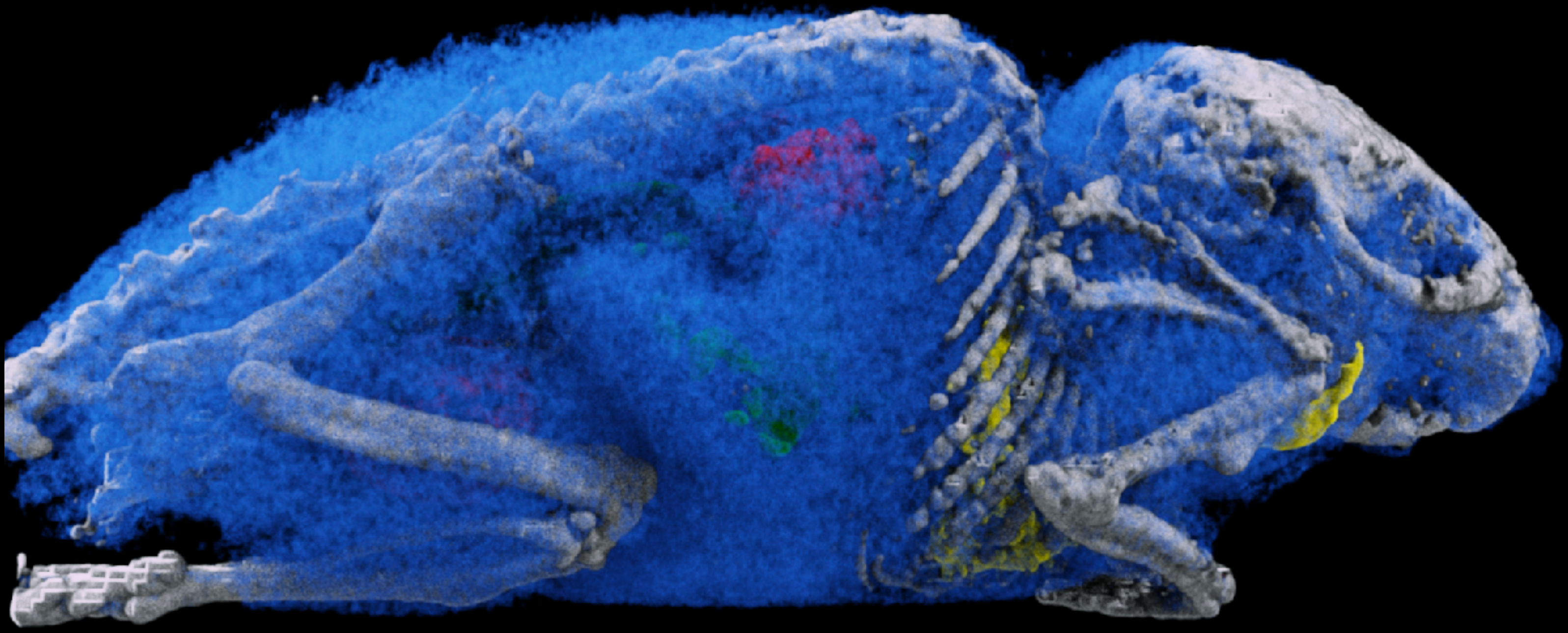
Classic CT image



MARS Spectral Imaging

Greyscale to Material Imaging

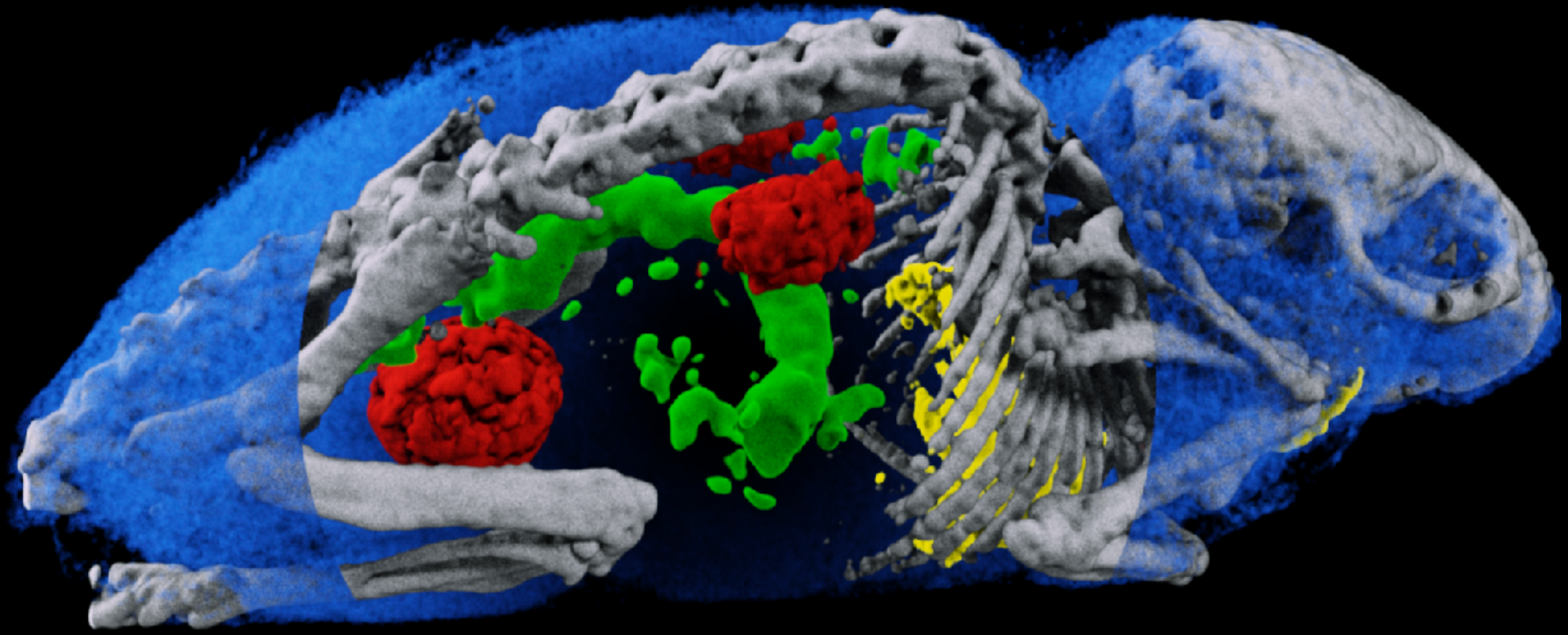
A mouse containing, gold, gadolinium, and iodine



All materials are shown in this image

Images presented and the European Congress of Radiology, Vienna, March 2017.

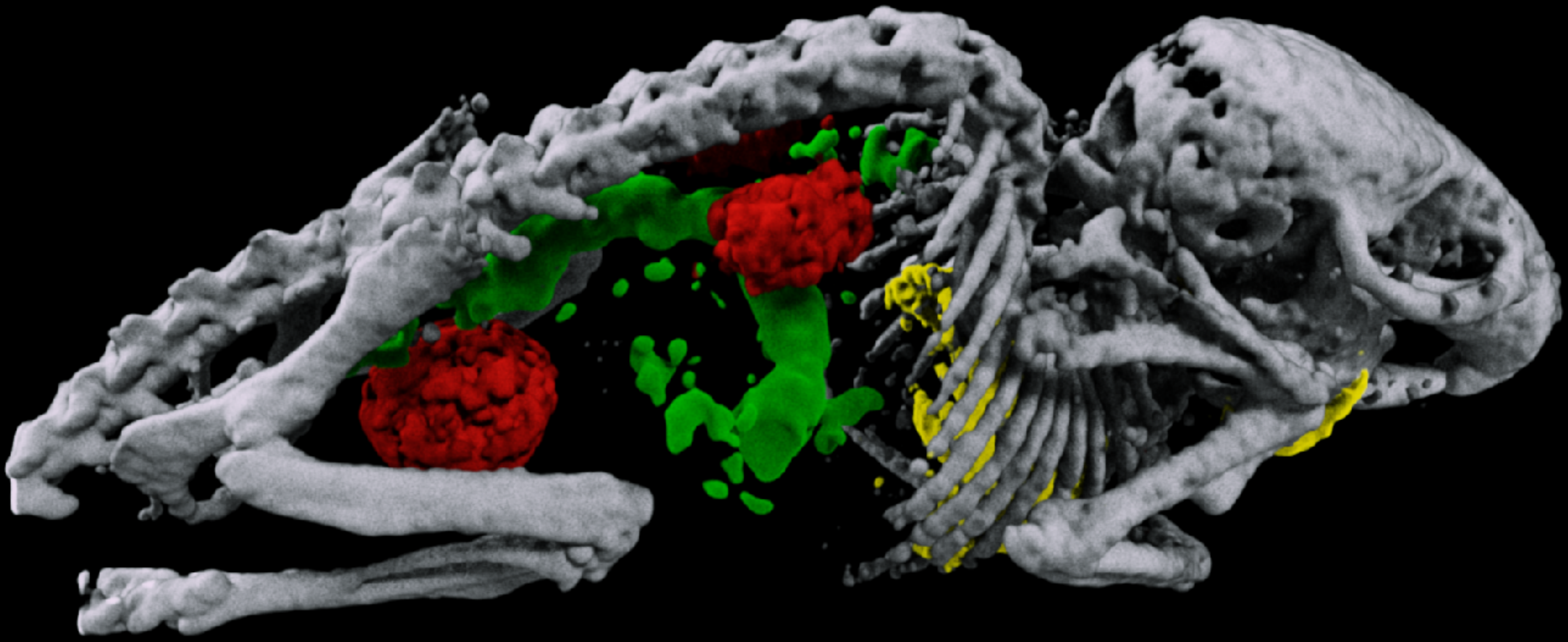
Greyscale to Material Imaging



The water has been partly cut away to reveal the bone, gold, gadolinium and iodine

Images presented and the European Congress of Radiology, Vienna, March 2017.

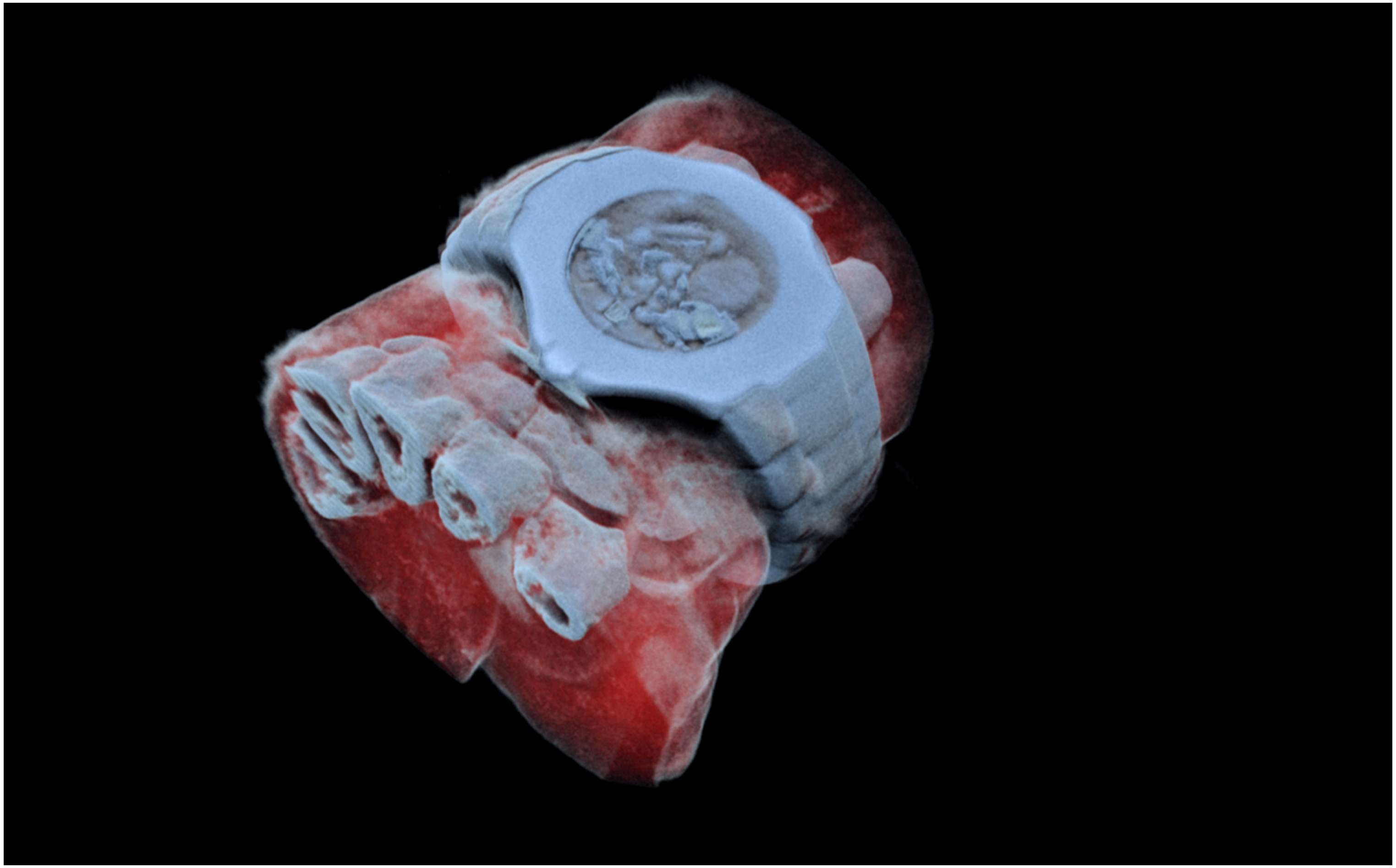
Greyscale to Material Imaging



The water has been completely removed leaving just bone, gold, gadolinium and iodine visible

Images presented and the European Congress of Radiology, Vienna, March 2017.

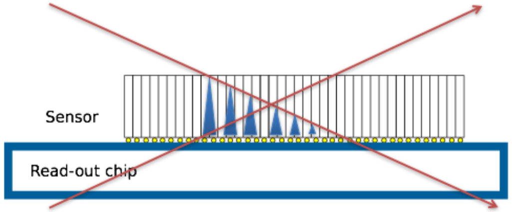
CT image of Phil Butler's wrist



Timepix3

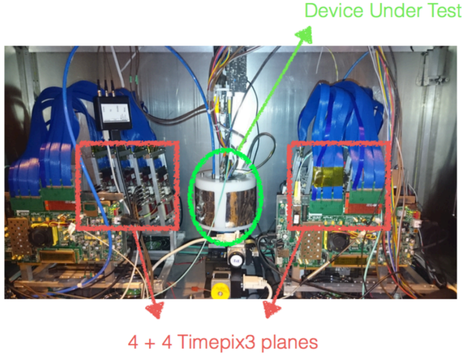
Timepix3 Specs

CMOS node	**130nm**
Pixel Array	**256 x 256**
Pixel pitch	**55μm**
Charge collection	**e^-, h^+**
Pixel functionality	**TOT (Energy) and TOA (Arrival time)**
Preamp Gain	**~47mV/ke$^-$**
ENC	**~60e$^-$**
FE Linearity	**Up to 12ke$^-$**
TOT linearity (resolution)	**Up to 200ke$^-$ (<5%)**
TOA resolution*	**Up to 1.6ns**
Time-walk	**<20ns**
Minimum detectable charge	**~500e$^-$ → 2 KeV (Si Sensor)**
Max Analog power (1.5V)	**500 mA/chip**
Digital Power (1.5V)	**~400mA data driven**
Maximum hit rate	**80Mhits/sec (in data driven)**
Readout	**Data driven (44-bits/hit @ 5Gbps)**

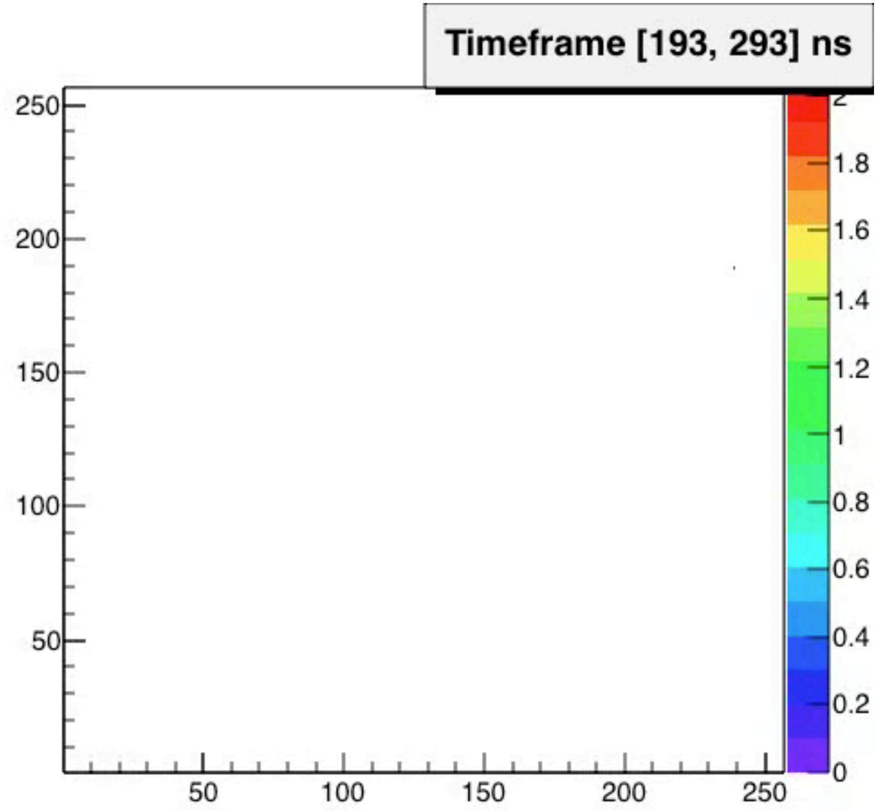


tracking in single Si layer conceivable

X ray materials analysis, gamma camera, compton camera, electron microscopy, neutron and photon imaging… and particle tracking for the Timepix3 telescope



Timepix3 for antimatter

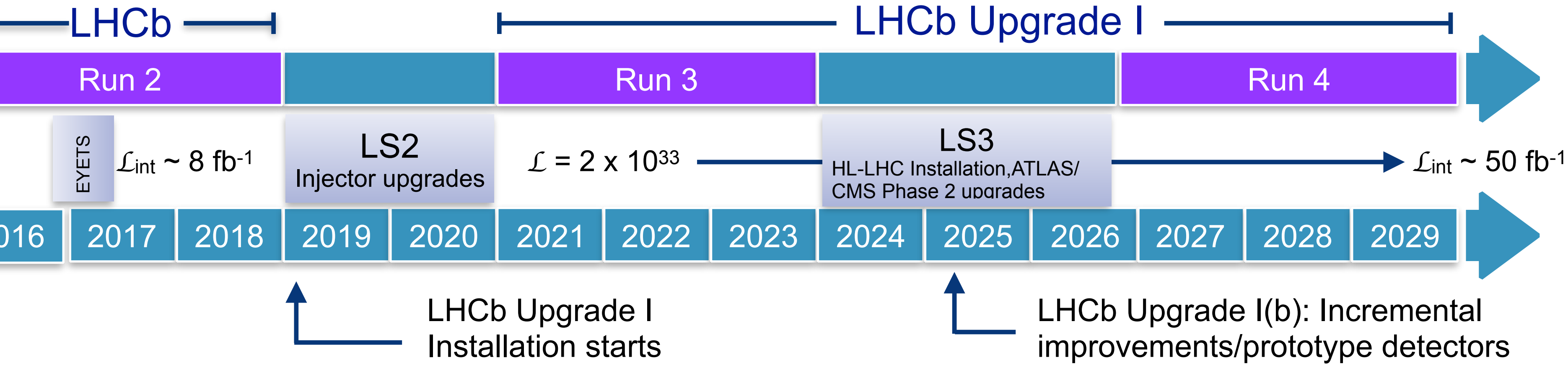


Slide courtesy of N. Pacifico, CERN

AEgIS experiment seeks to measure the pull of gravity on anti-hydrogen

- 300-700 ns: main burst of secondaries coming from annihilation in the moderators, giving fast fragments
- 700-1200 ns: scattered antiprotons
- 1200-1500 ns: Time delay indicates energy of selected antiproton star-like signatures

Applications at LHCb Upgrade I



LHCb

LHCb Upgrade I

Run 2

Run 3

Run 4

EYETS

$\mathcal{L}_{int} \sim 8\ fb^{-1}$

LS2
Injector upgrades

$\mathcal{L} = 2 \times 10^{33}$

LS3
HL-LHC Installation,ATLAS/
CMS Phase 2 upgrades

$\mathcal{L}_{int} \sim 50\ fb^{-1}$

016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029

LHCb Upgrade I
Installation starts

LHCb Upgrade I(b): Incremental
improvements/prototype detectors

Phase I(a) Upgrade - Run 3 and Run 4 (2021 - 2029)
Installation well underway! See http://lhcb-media.web.cern.ch/lhcb-media/
Accumulate 50 fb-1 with upgraded detector, including new pixel detector
Possibilities may exist to install prototype detectors for Upgrade I(b) during LS3 (2024)

Pixels for the LHCb upgrade

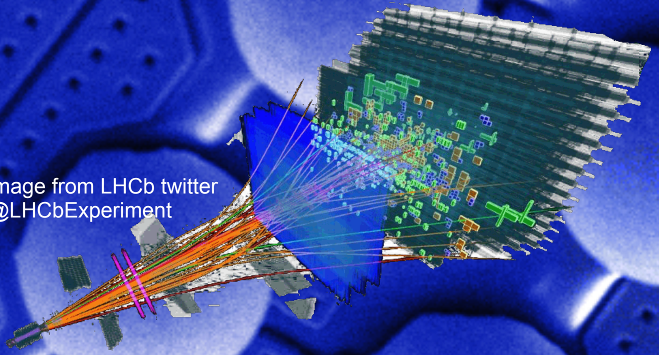


image from LHCb twitter
@LHCbExperiment

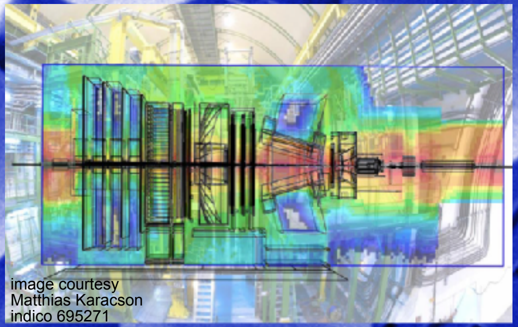


image courtesy
Matthias Karacson
indico 695271

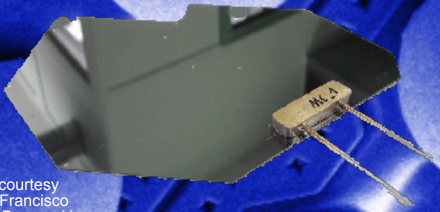


Photo courtesy
Oscar Francisco
Wiktor Byczynski

Maintain Physics Performance in very high occupancy and pile up conditions

- combinatorial complexity and fake tracks
- Pile-up energy
- mitigated by **granularity, high readout speed** and **trigger** innovations (**timing** will be for Upgrade II)

Operate with detector elements exposed to very high radiation doses

- **Radiation hardness** needed for all subdetectors

Control Systematics to match statistics

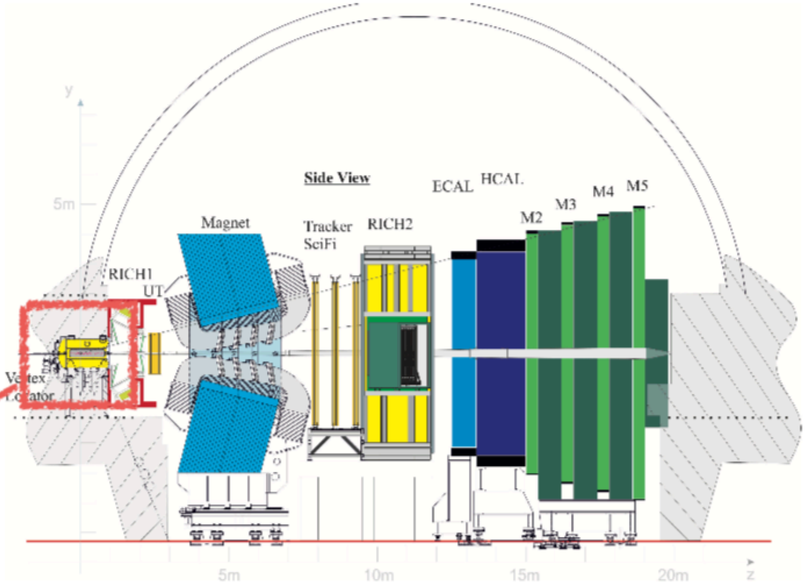
- **low material budget** hence creative solutions needed at mechanics level; support structures, cooling, power delivery, and **thin detectors** for innermost regions

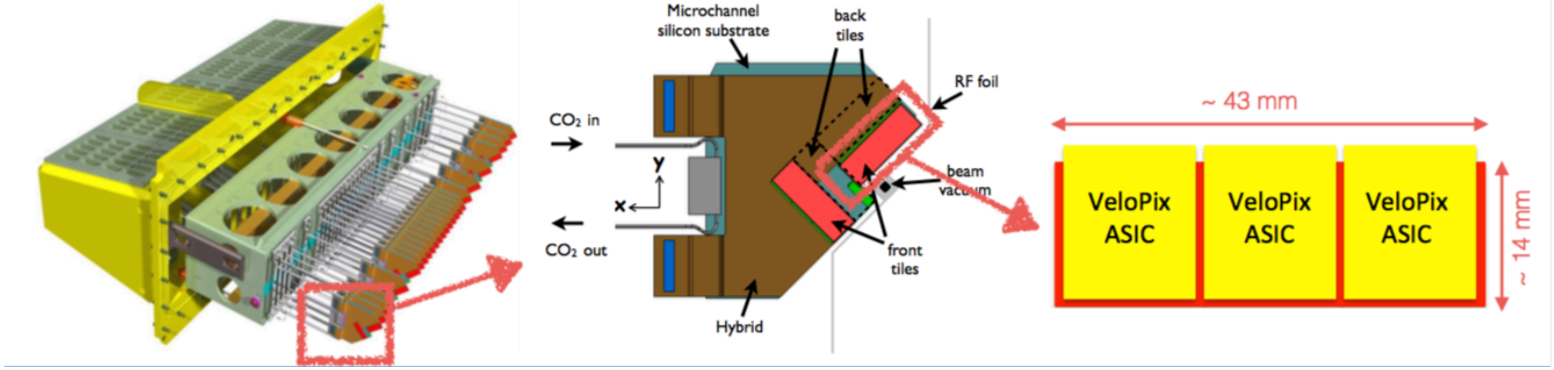
- **Cope with tremendous DAQ and data processing challenges**

VeloPix for the LHCb Upgrade I

LHCb Detector
(Upgrade 2019/2020)

Luminosity: 2 x 10^{33} cm^{-2} s^{-1}

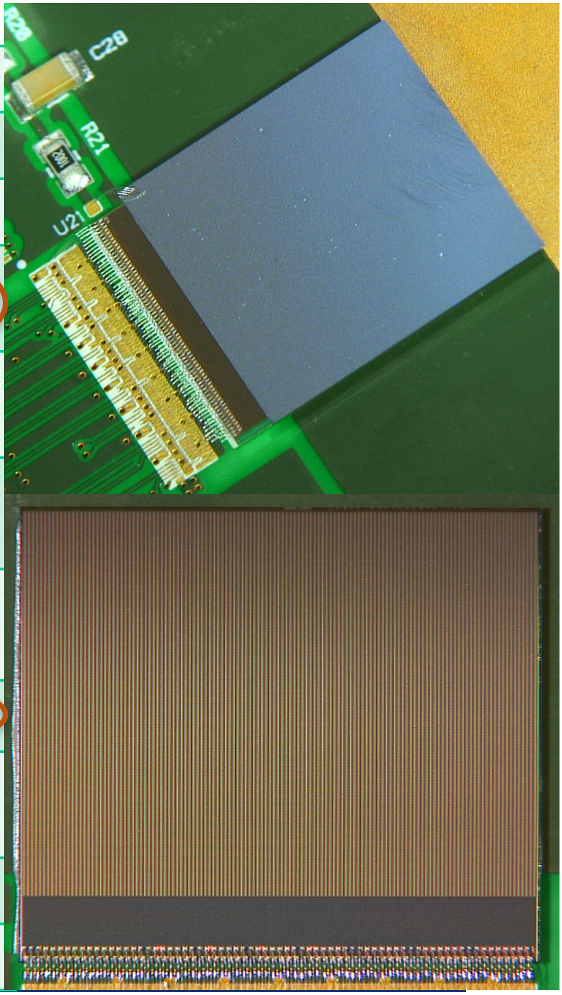




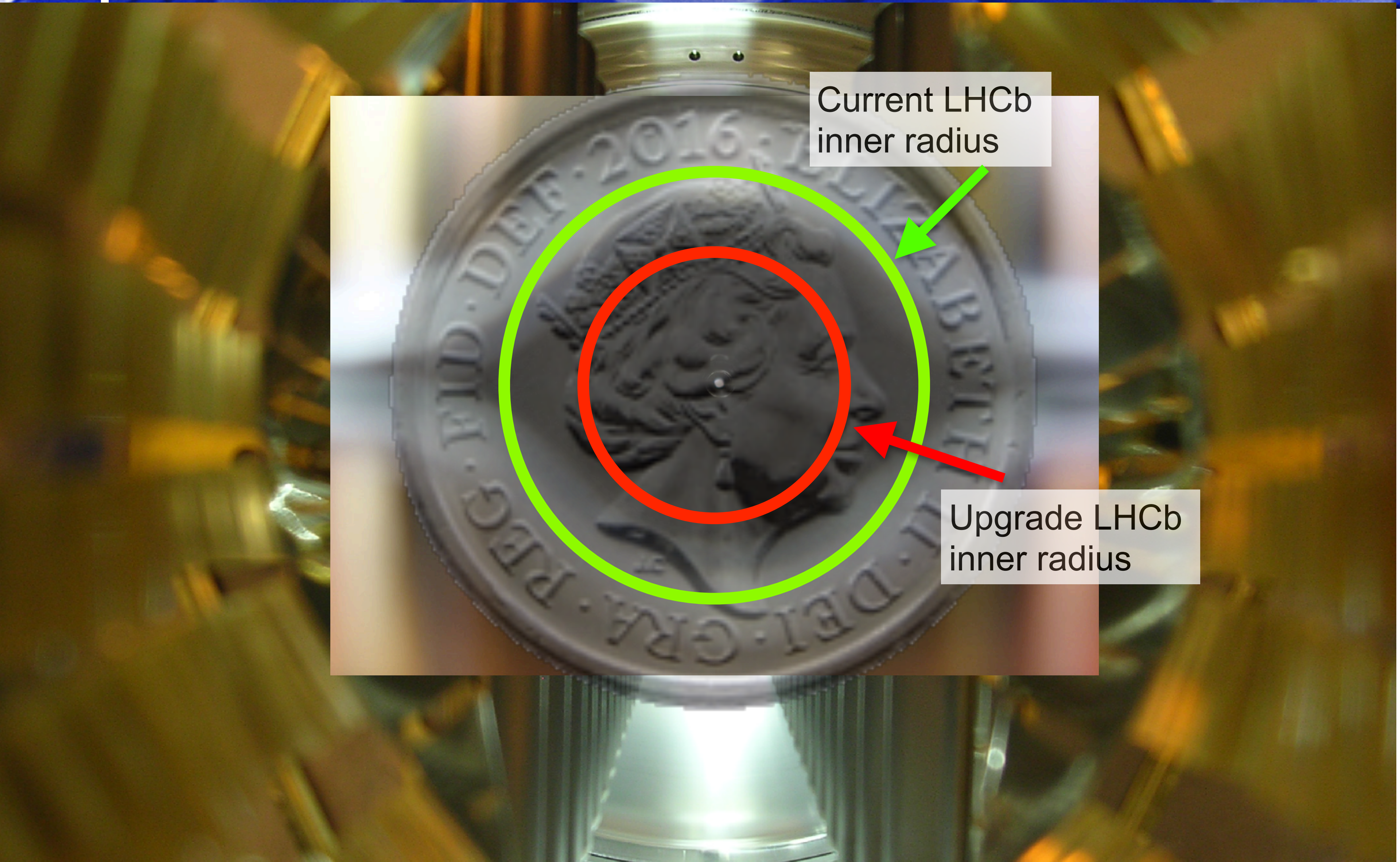
VeloPix for LHCb Upgrade I

Derived from Timepix3 and dedicated to LHCb.

	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



Placed - even closer - around the LHC beams



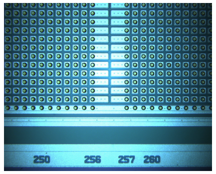
Current LHCb inner radius

Upgrade LHCb inner radius

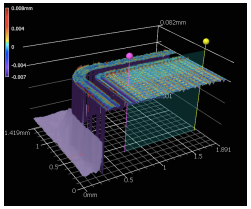
VeloPix for LHCb Upgrade I

The VeloPix ASIC is bonded to 3-chip sensors and module construction is starting now for installation 2020.

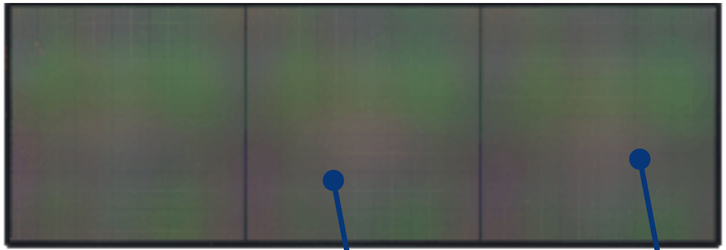
At 20 Gbps readout speed and capable of handling 900 Mhits/chip it is the fastest HEP ASIC, well suited to LHCb Upgrade physics needs

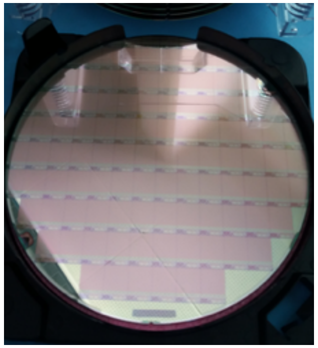


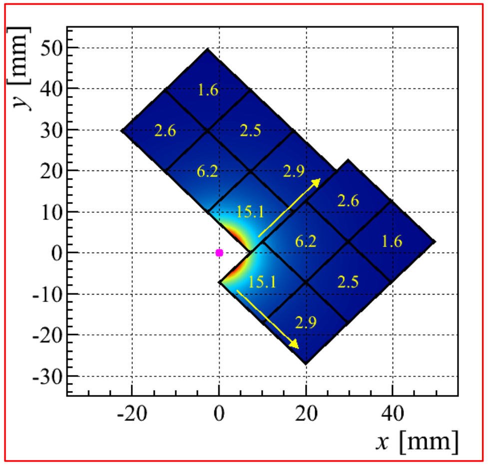
elongated pixels between ASICs

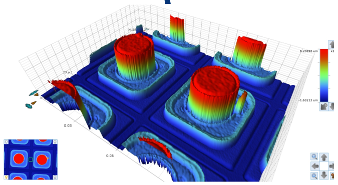


Sensor Thickness 200 µm

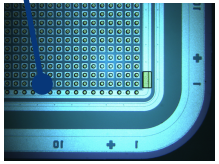








sensor UBM pads



rounded, DRIE etched corners

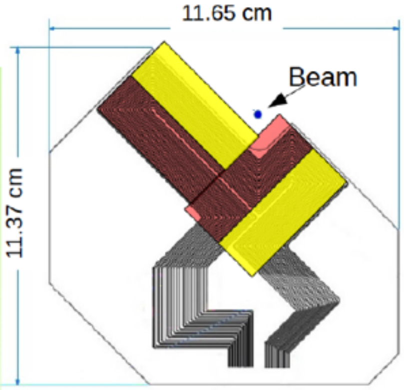
VELO Upgrade I Cooling

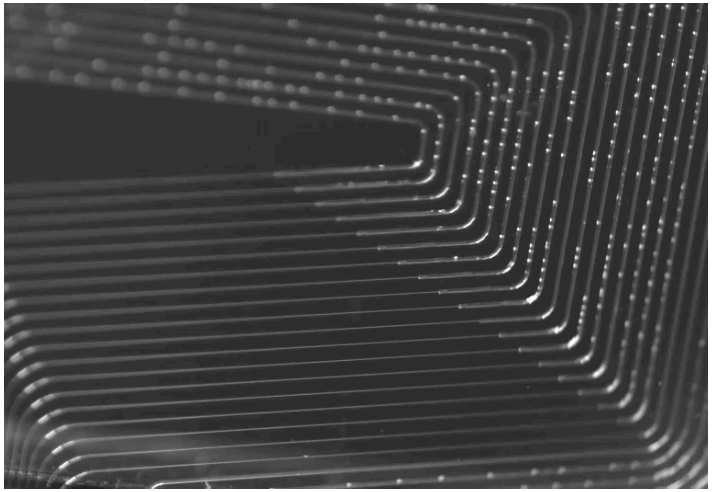
Due to the harsh radiation environment an efficient cooling solution is required to maintain the sensors at < -20°C

This is provided by the novel technique of evaporative CO_2 circulating in 120 µm x 200 µm channels within a silicon substrate.

Total thickness: 500 µm

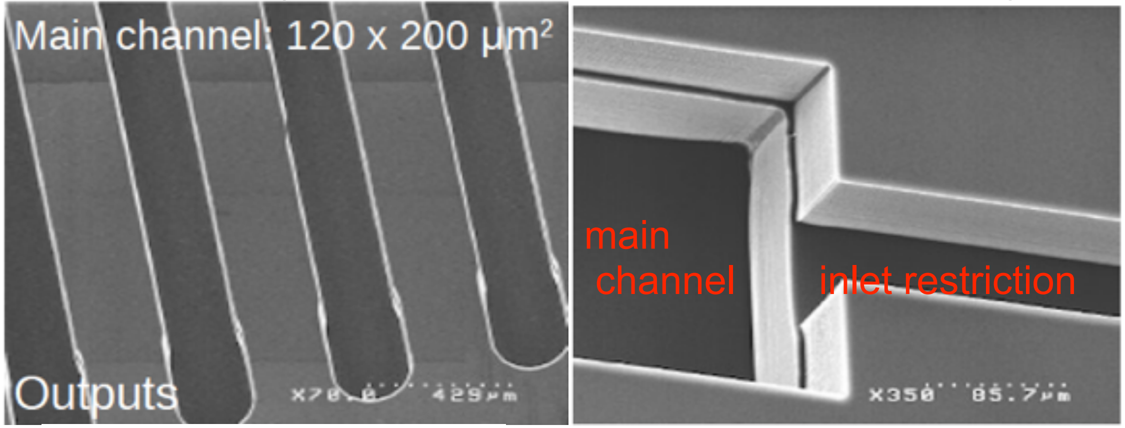
- High thermal efficiency
- CTE match to silicon components
- Minimum and uniform material
- radiation hard





(click for movie)

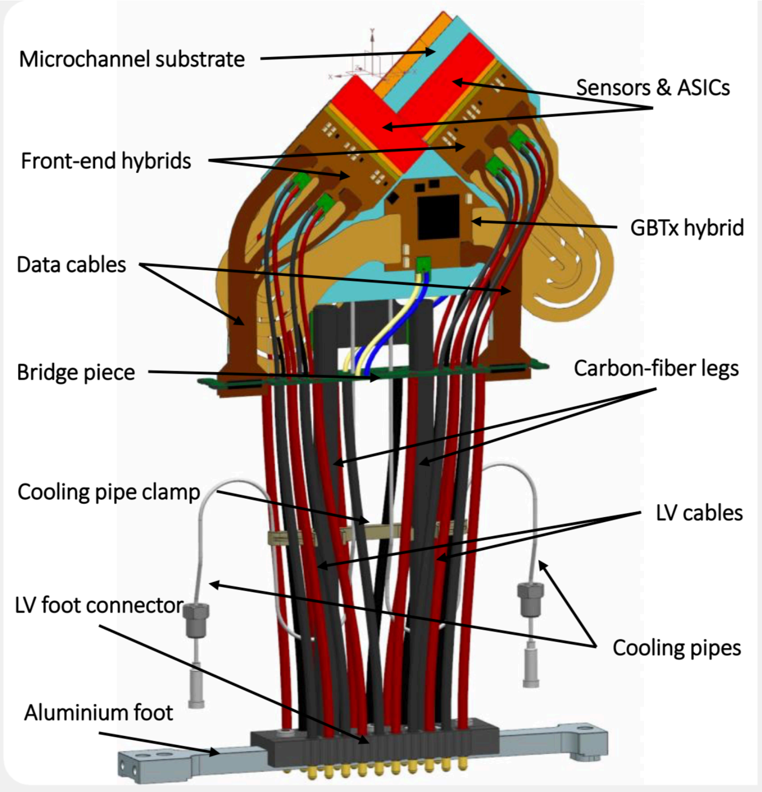
SEM images of etched wafer before bonding



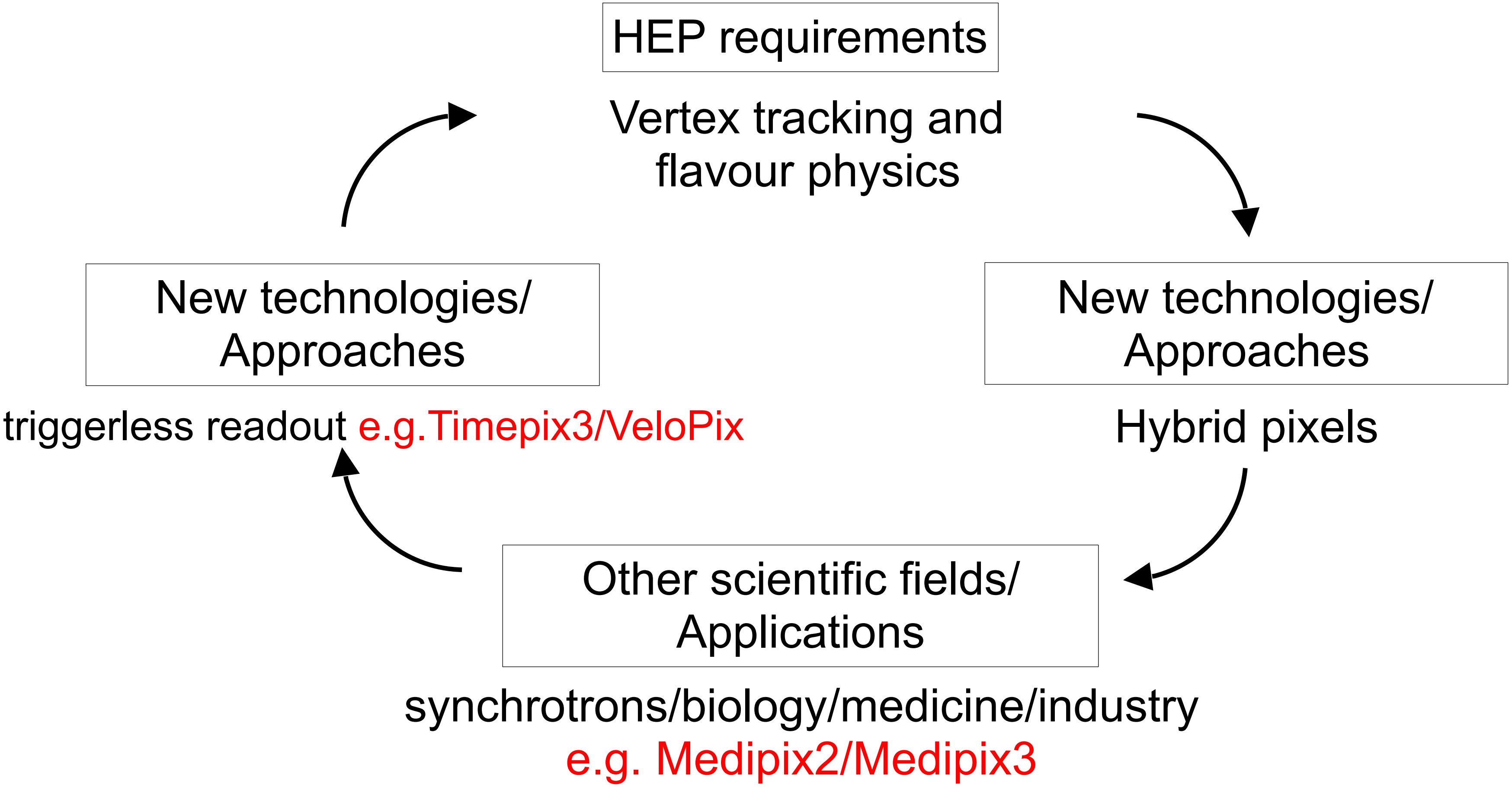
channels output directly to connector

Two step channel etching

VELO Upgrade I module productionn now underway



Timepix / HEP cycle of innovation



HEP requirements

Vertex tracking and flavour physics

New technologies/ Approaches

Hybrid pixels

Other scientific fields/ Applications

synchrotrons/biology/medicine/industry
e.g. Medipix2/Medipix3

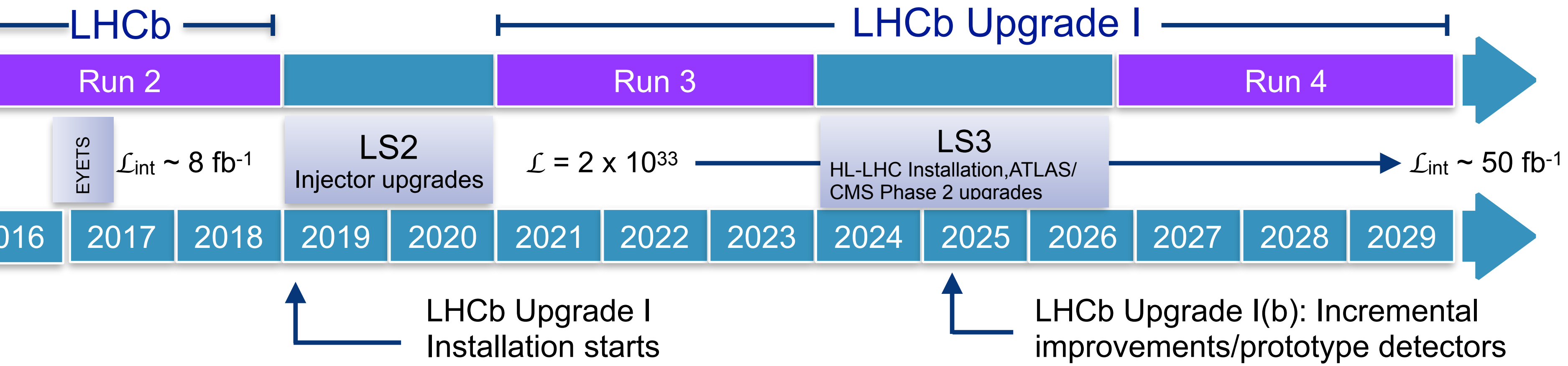
New technologies/ Approaches

triggerless readout e.g.Timepix3/VeloPix

Ultimate Challenges

- LHCb Upgrade II opportunities
  - Advanced Cooling Concepts
  - Radiation Hardness
- Timing
  - Sensors
  - Timepix4/PicoPix

LHCb Upgrade Schedule



LHCb

LHCb Upgrade I

Run 2

Run 3

Run 4

EYETS

$\mathcal{L}_{int} \sim 8\ \mathrm{fb}^{-1}$

LS2
Injector upgrades

$\mathcal{L} = 2 \times 10^{33}$

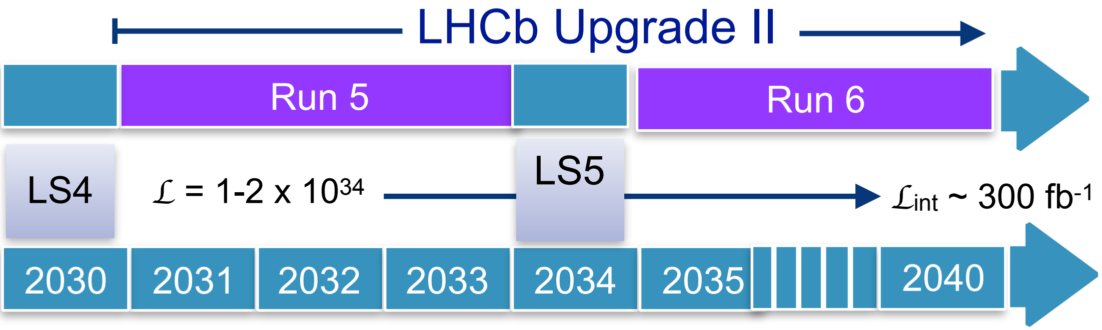
LS3
HL-LHC Installation,ATLAS/
CMS Phase 2 upgrades

$\mathcal{L}_{int} \sim 50\ \mathrm{fb}^{-1}$

016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

LHCb Upgrade I
Installation starts

LHCb Upgrade I(b): Incremental
improvements/prototype detectors



LHCb Upgrade II

Run 5

Run 6

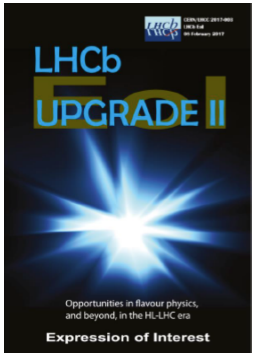
LS4

$\mathcal{L} = 1\text{-}2 \times 10^{34}$

LS5

$\mathcal{L}_{int} \sim 300\ \mathrm{fb}^{-1}$

2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2040



LHCb
UPGRADE II

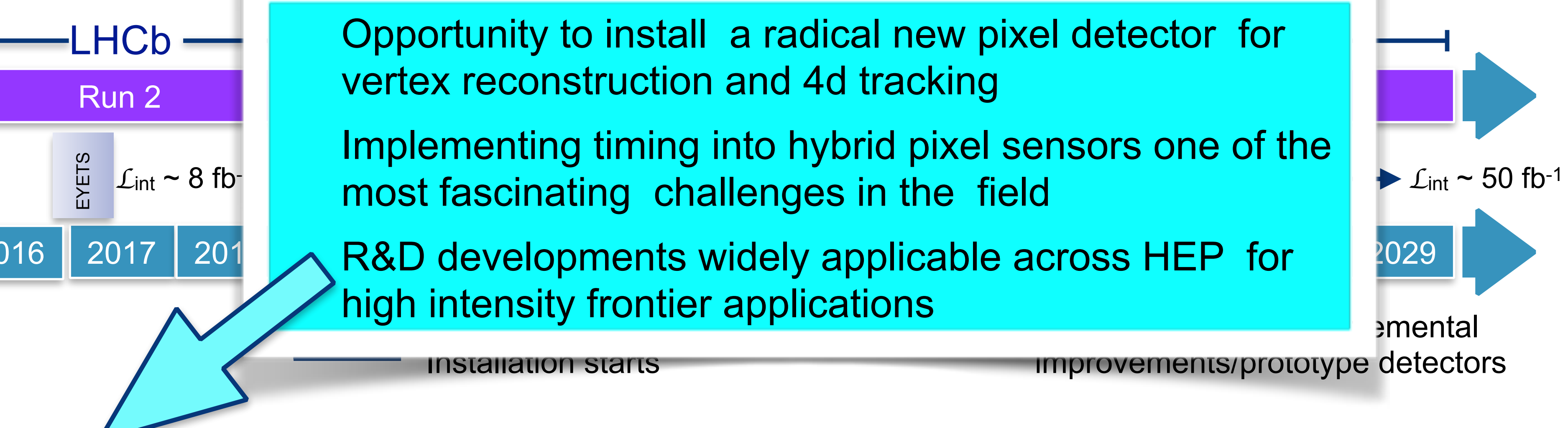
Opportunities in flavour physics,
and beyond, in the HL-LHC era

Expression of Interest

CERN-LHCC-2017-003

LHCb Upgrade II
Run 4 and Run 5
2030 ++
Accumulate 300 fb^{-1}
Pixel timing mandatory

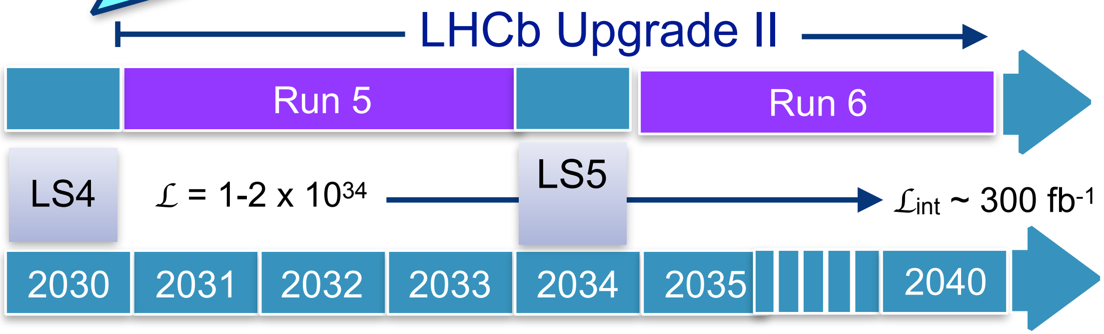
LHCb Upgrade Schedule

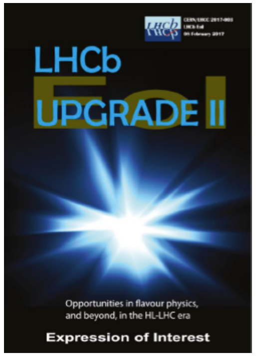


Opportunity to install a radical new pixel detector for vertex reconstruction and 4d tracking

Implementing timing into hybrid pixel sensors one of the most fascinating challenges in the field

R&D developments widely applicable across HEP for high intensity frontier applications





CERN-LHCC-2017-003

LHCb Upgrade II
Run 4 and Run 5
2030 ++
Accumulate 300 fb^{-1}
Pixel timing mandatory

Radiation Hardness (sensors)

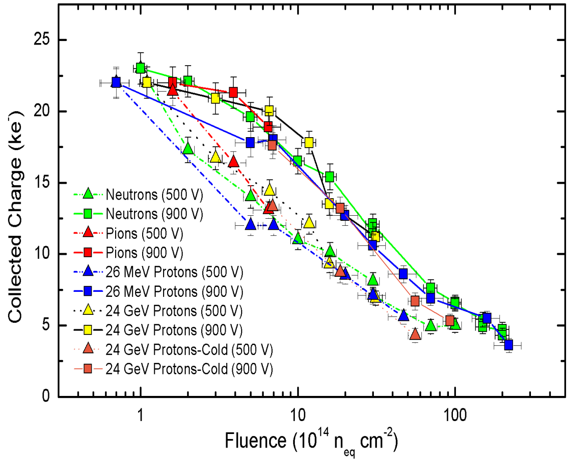
Sunbathers: Viareggio beach
Photo: Bernhard Lang

Radiation Hardness

A lot has been learned about radiation damage

Is it enough to see us through the next 20 years? (G. Hall)

- p-type silicon widely introduced
- n-MCz and oxygenated silicon help in mixed fields
- Double column 3D detectors developments
- Planar segmented sensors optimised thinned
- Improved data and damaged models
- More R&D needed for timing, avalanche modes, HV-CMOS
- Low thresholds of modern pixel ASICs extend the reach
- However, radiation effects and performance constantly evolving - deeper sub micron does not guarantee TID resistance e.g. for 65 nm CMOS technology



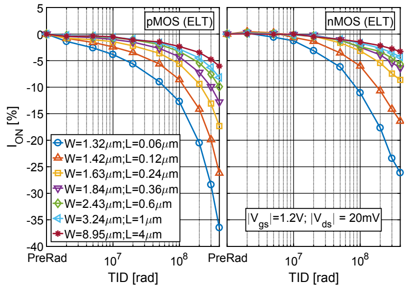
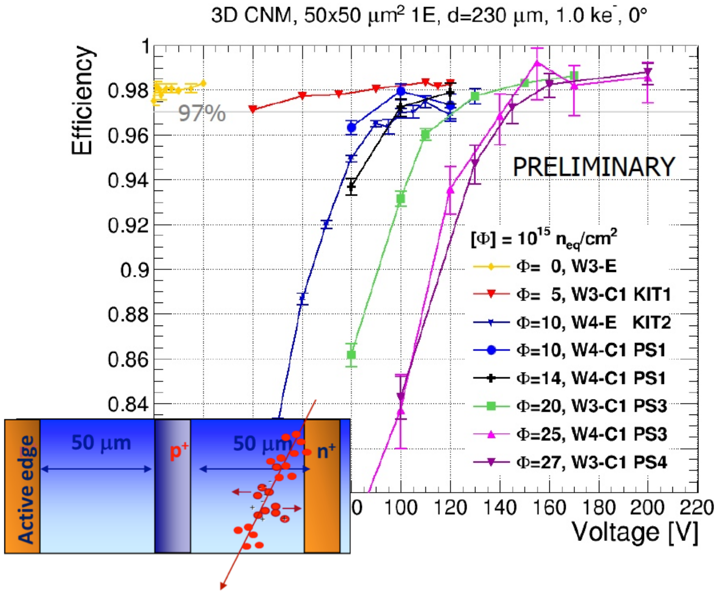
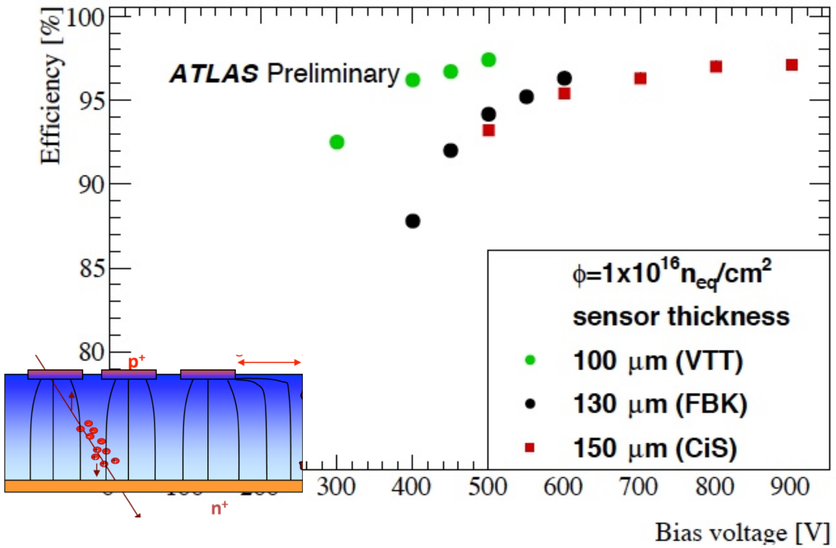


Fig. 1. Radiation-induced degradation of the current in strong inversion ($|V_{gs}| = 1.2$ V) and in the linear regime ($|V_{ds}| = 20$ mV) for PMOS and NMOS ELT transistors “diode”-biased during exposure at room temperature up to 400 Mrad(SiO_2).

after F.Faccio et al., “Influence of LDD spacers and H+ transport on the total-ionizing-dose response of 65 nm MOSFETs irradiated to ultra-high doses”, presented at NSREC 2017, published in IEEE TNS Jan.2018

Radiation Hardness - 3D sensors

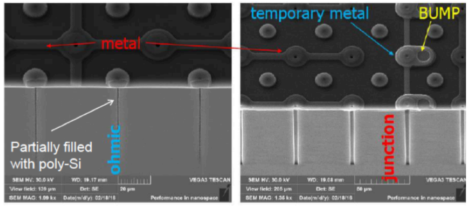




3D sensors are still a very promising technology for the innermost layers

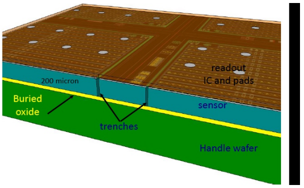
ATLAS measurements show radiation hardness up to 3 x 10^{16}/1 x 10^{16} n_{eq} cm^{-2} for 3D/thin sensors

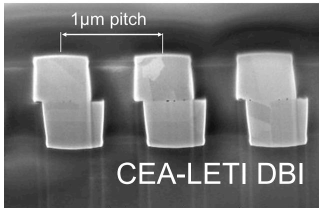
Many process refinements are under investigation



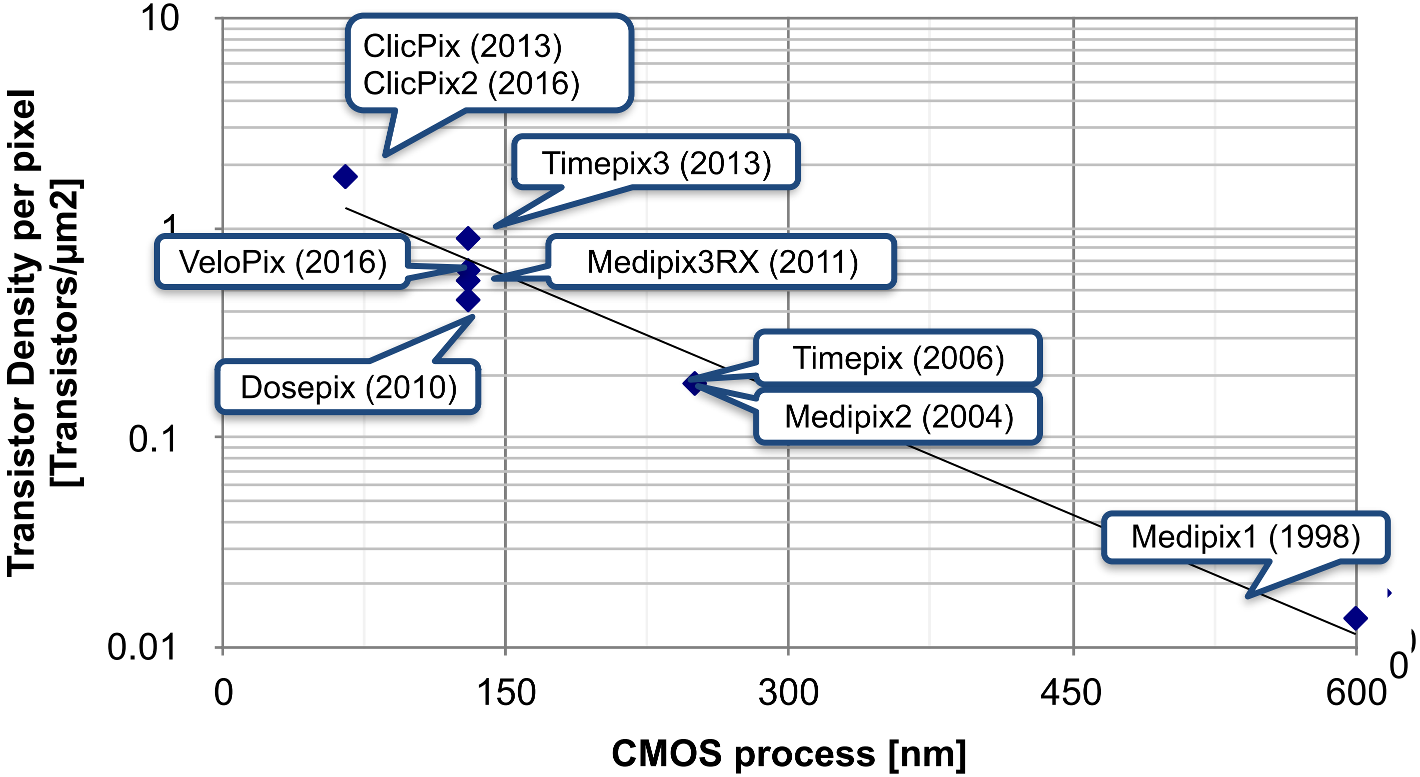
FBK 6" wafer technologies

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





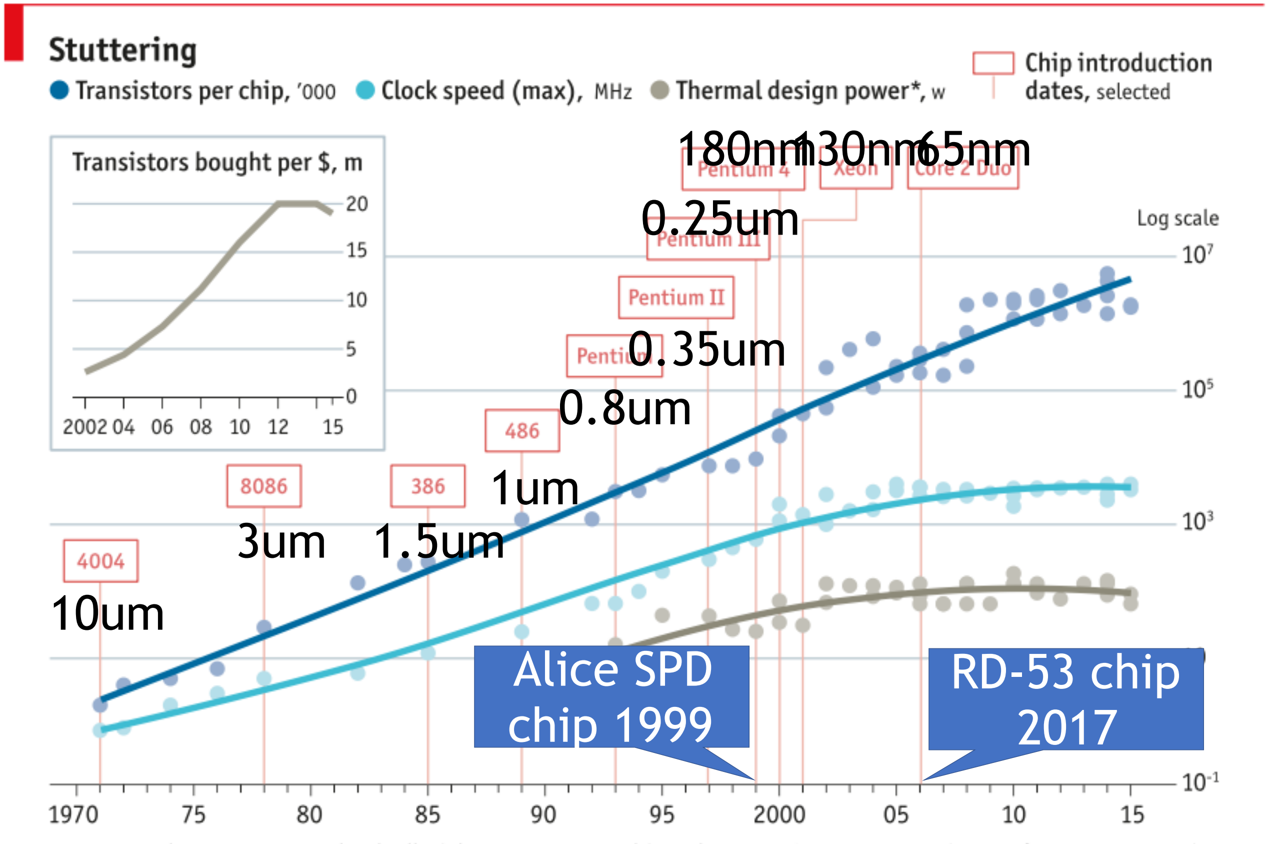
Medipix family “Moore’s Law”



Michael Campbell

Moore's uncertain future

Michael Campbell



10um

3um

1.5um

1um

0.8um

0.35um

0.25um

180nm

130nm

65nm

Alice SPD chip 1999

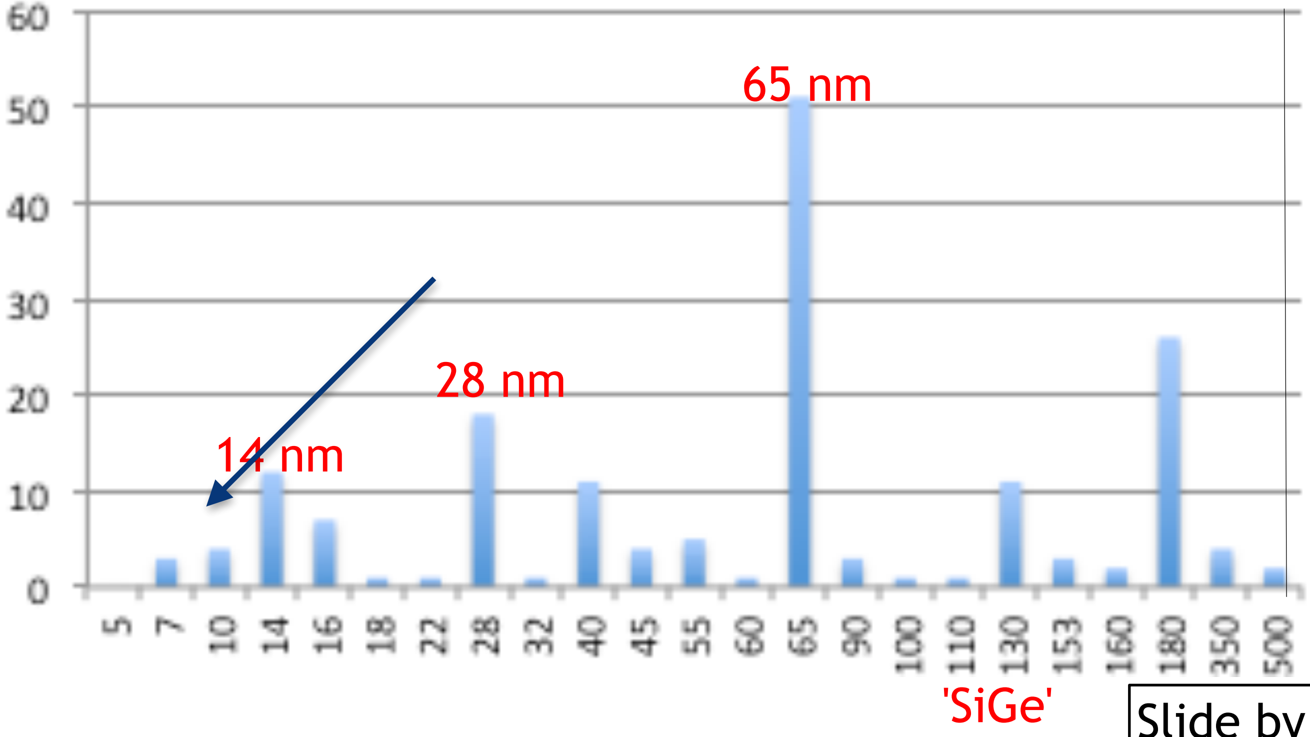
RD-53 chip 2017

Sources: Intel; press reports; Bob Colwell; Linley Group; IB Consulting; *The Economist*

*Maximum safe power consumption

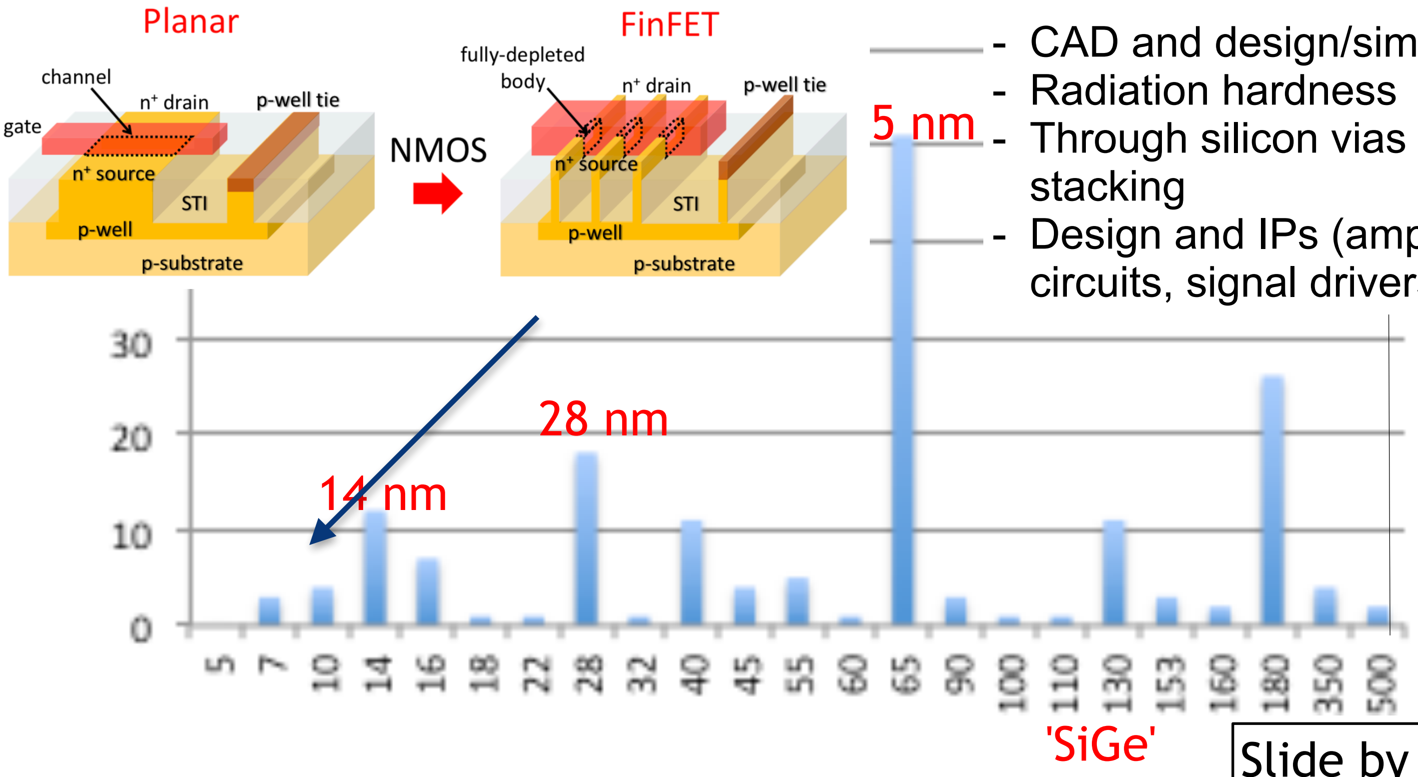
Moore's uncertain future

~300 papers acceptance <40%



Slide by E. Heijne
From ISSCC 2018

Moore’s uncertain future

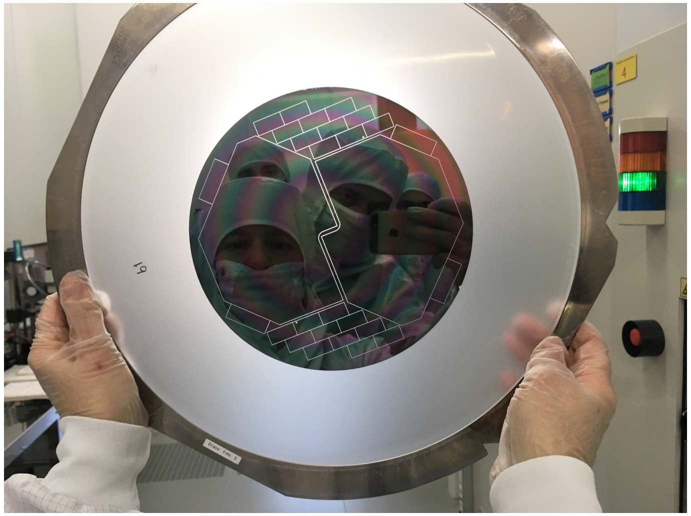


Focus in HEP:

- CAD and design/simulation tools
- Radiation hardness
- Through silicon vias and wafer stacking
- Design and IPs (amplifiers, timing circuits, signal drivers, etc.

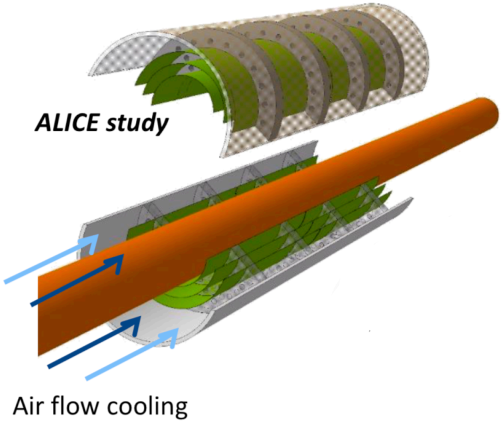
Slide by E. Heijne
From ISSCC 2018

Advanced Cooling Concepts

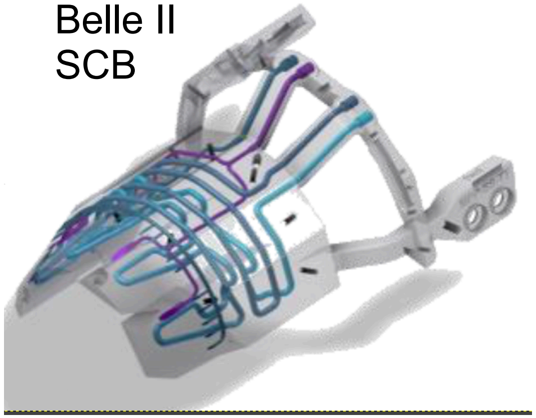


Microchannel cooling in silicon has unrivalled thermal efficiency - vital for hybrid pixel detectors

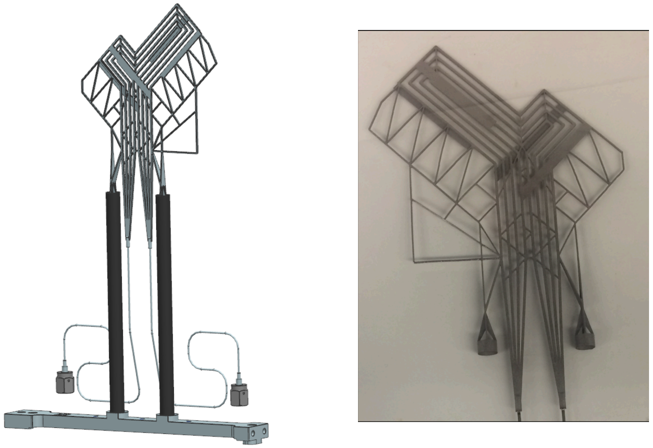
However large scale production challenging; main issue is silicon microfabrication quality control over very large areas - expense implications if replaceable modules are needed



Belle II
SCB

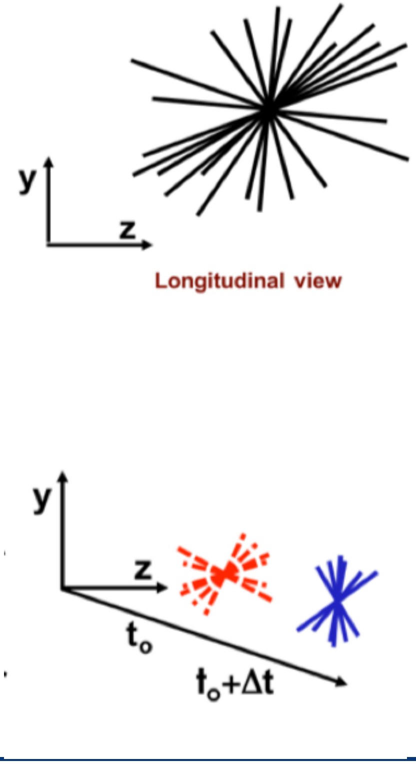


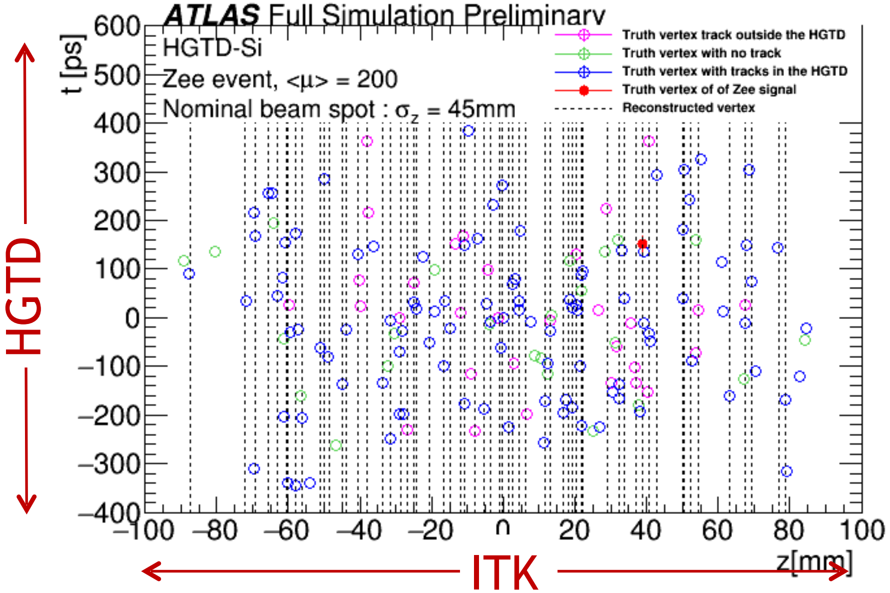
LHCb - 3d printed titanium



Timing sensors for tracking

GPD: Addition of HGTD tracking layer to separate primary vertices; needed when when the tracking resolution along z axis is longer than the distance between vertices

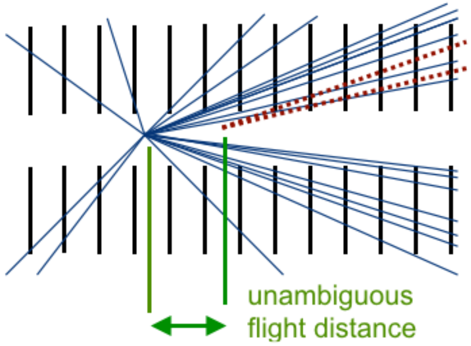




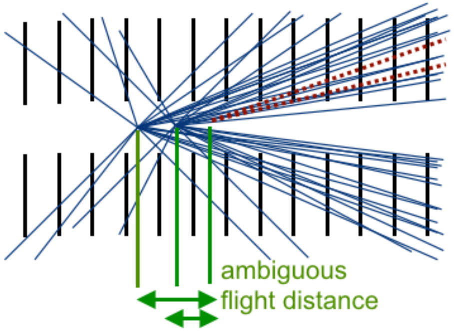
Timing sensors for tracking

LHCb: timing will be needed in future upgrades to associate secondary vertices correctl
to primary vertices

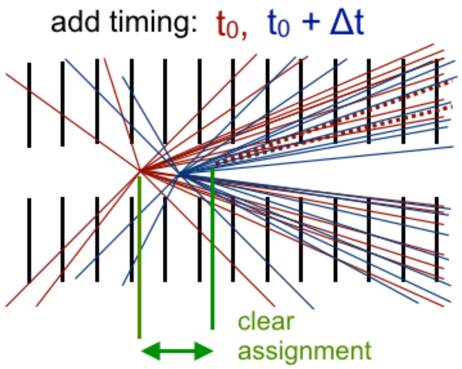
single
primary
vertex:

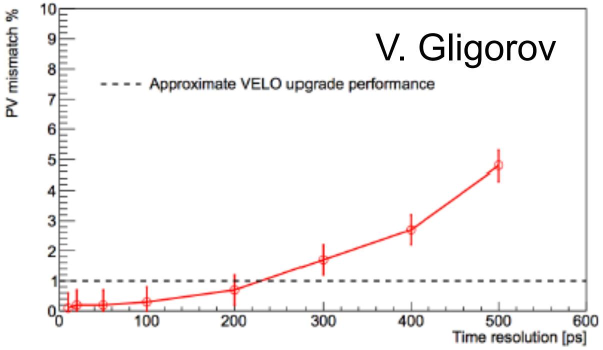


two
primary
vertices:



two
primary
vertices +
time
decoding
$t_0, t_0 + \Delta t$





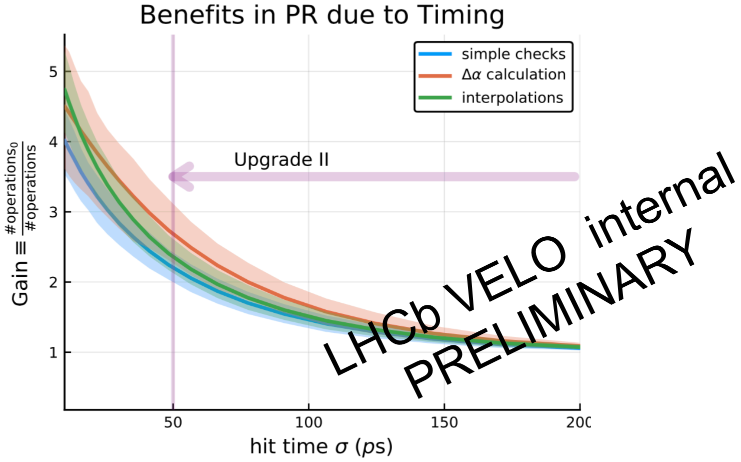
LHCb studies show that with just 200 ps per hit
misassociation rate drops to Phase I levels of < 1%

Timing sensors for tracking

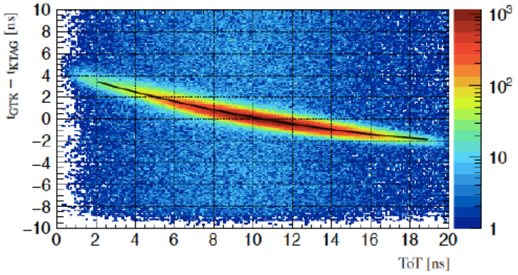
However there are many further benefits of timing

- Timing in the pattern recognition can give dramatic improvements (speed/efficiency)

- PV timing and associations
- Displaced track trigger
- Secondary vertices
- T0 for calo/RICH
- Very precise timing available with suitable phased clock to reference planes
- Beam gas and background pattern recognition

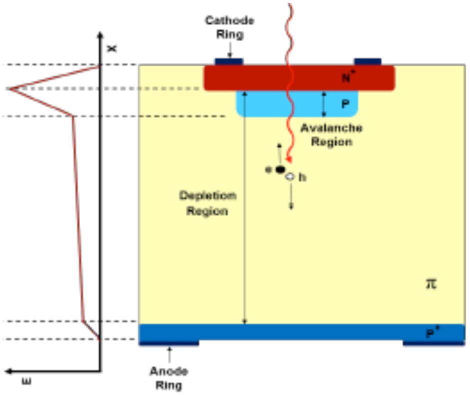


Using just planar silicon, NA62 have already achieved ~115 ps on individual hits and ~65 ps on tracks

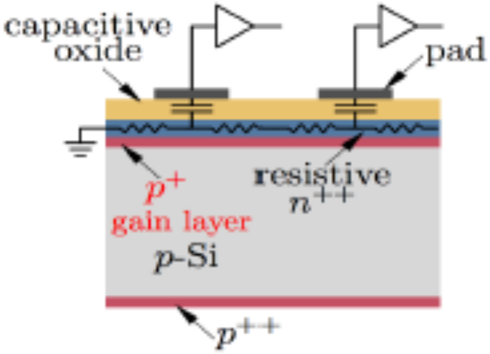


Timing sensors for tracking

Future upgrades - even stricter requirements for 4D tracking to work at pattern recognition level, for small pixels and at high radiation doses



N. Cartiglia, H. Sadrozinski



Low Gain Avalanche Detectors (LGAD)

Multiplication of charges (~10-100x) in thin gain layer

→fast rise time, increased S/N

$$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2$$

Several vendors: CNM, FBK, HPK

Reached ~20 ps for few mm^2 size sensors

→considered for HL-ATLAS/CMS/LHCb timing layers

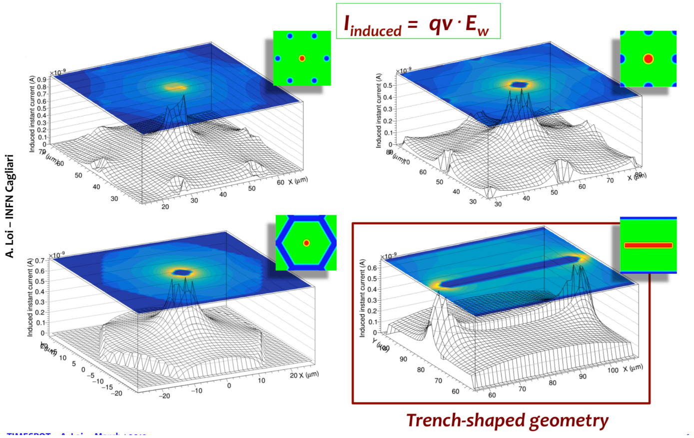
Limiting factors for time resolution:

- Weighting field uniformity →favours larger pixels
- Radidation effects →ok up to 10^{15}, mitigation measures under study for higher fluences
- r/o electronics + clock distribution

R&D to achieve larger fill factors (currently 100 µm inactive region between pixels): e.g.resistive electrodes/3D trench detectors

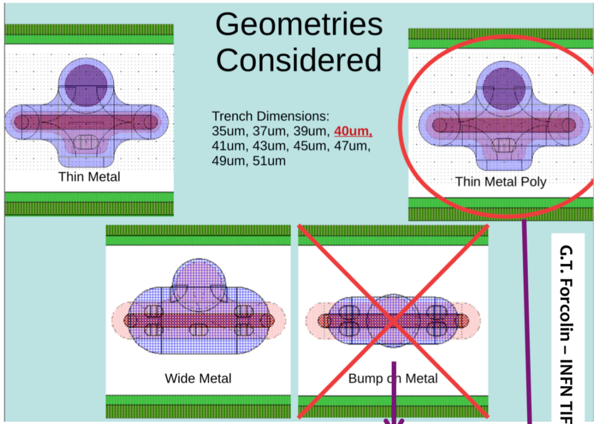
Timing sensors for tracking

Very promising advances for 3d detectors e.g. from TIMESPOT collaboration:



Trench-shaped geometry

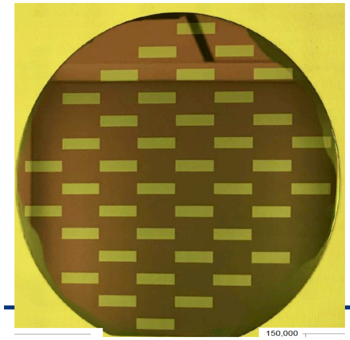
Fast simulation of favoured detector layouts



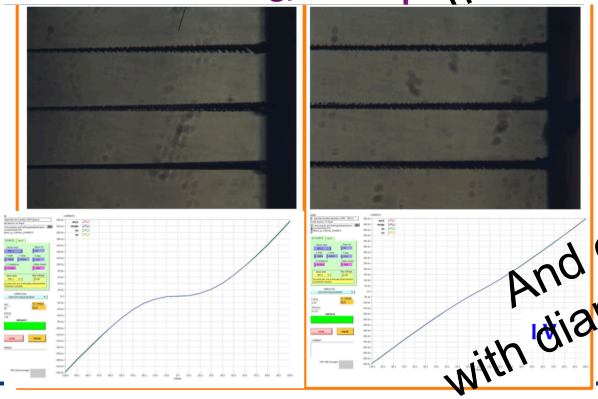
capacitance

Discarded after technology tests

Best choice for minimum capacitance

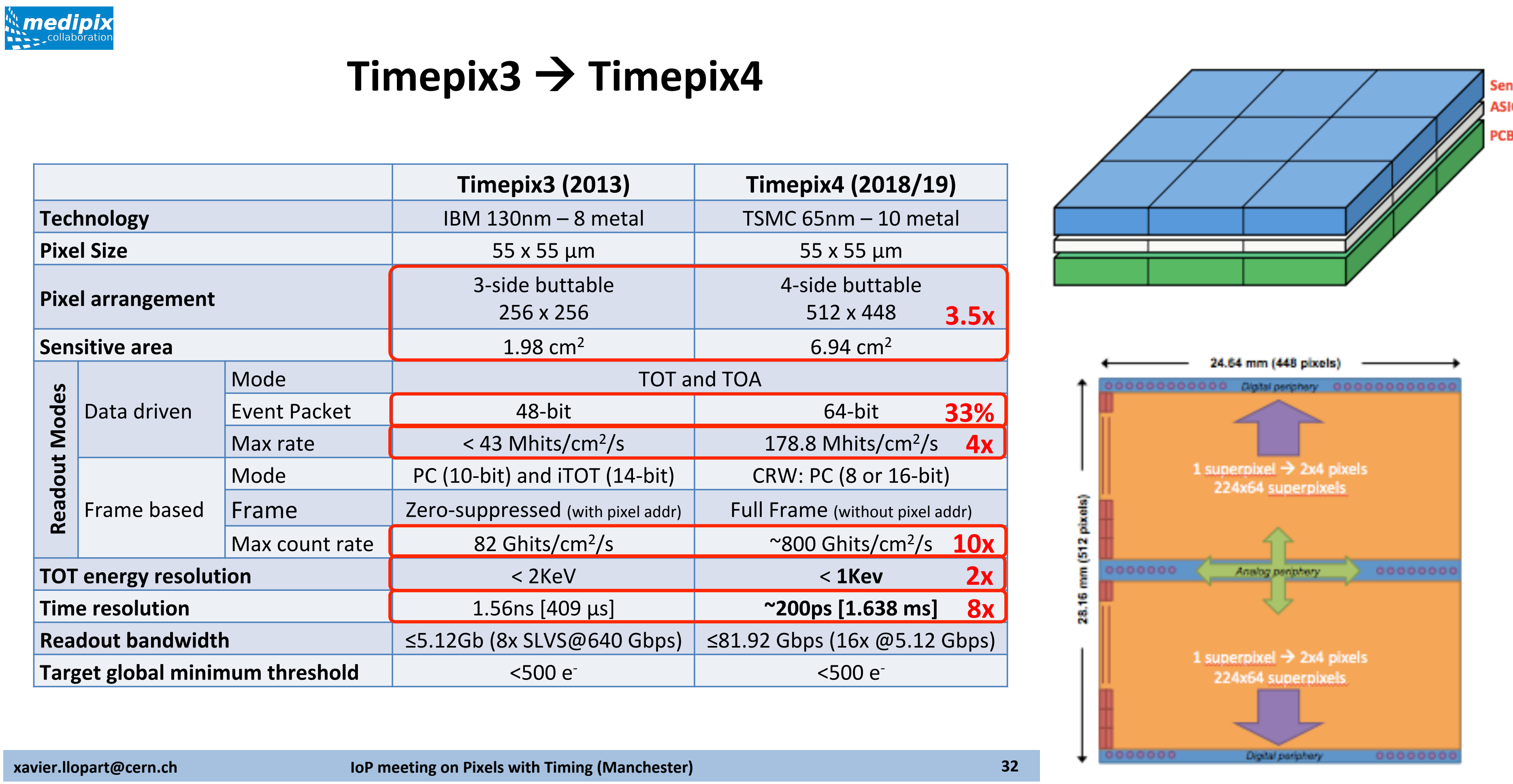


Building up fabrication Experience at FBK



And experience with diamond substrates

Timepix4

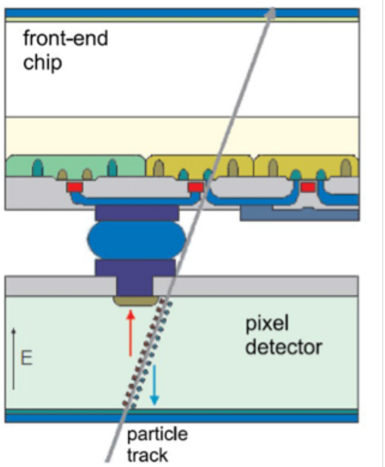


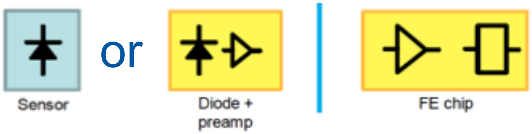
Timepix3 → Timepix4

			Timepix3 (2013)	Timepix4 (2018/19)
Technology			IBM 130nm – 8 metal	TSMC 65nm – 10 metal
Pixel Size			55 x 55 µm	55 x 55 µm
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448 **3.5x**
Sensitive area			1.98 cm^2	6.94 cm^2
Readout Modes	Data driven	Mode	TOT and TOA	
		Event Packet	48-bit	64-bit **33%**
		Max rate	< 43 Mhits/cm^2/s	178.8 Mhits/cm^2/s **4x**
	Frame based	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)
		Max count rate	82 Ghits/cm^2/s	~800 Ghits/cm^2/s **10x**
TOT energy resolution			< 2KeV	**< 1Kev** **2x**
Time resolution			1.56ns [409 µs]	**~200ps [1.638 ms]** **8x**
Readout bandwidth			≤5.12Gb (8x SLVS@640 Gbps)	≤81.92 Gbps (16x @5.12 Gbps)
Target global minimum threshold			<500 e$^-$	<500 e$^-$

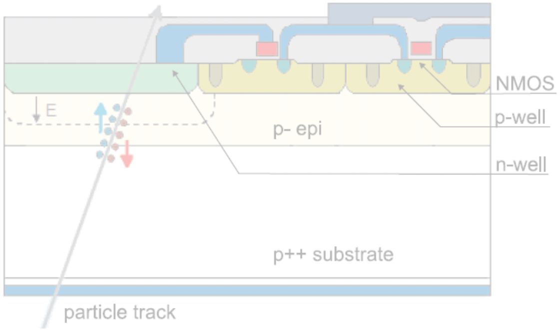
xavier.llopart@cern.ch IoP meeting on Pixels with Timing (Manchester) 32

The Monolithic Pixel Detector





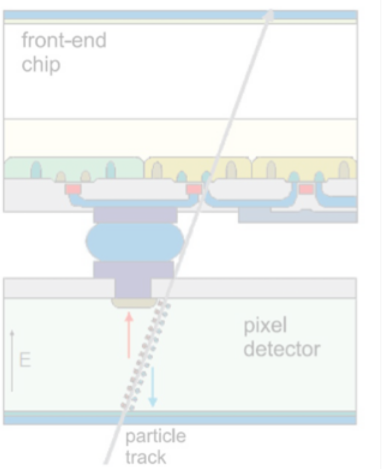
Fine pitch bump bonding to connect sensor and readout chip

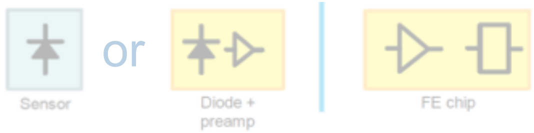


Thin, monolithic CMOS sensor, on-chip digital architecture

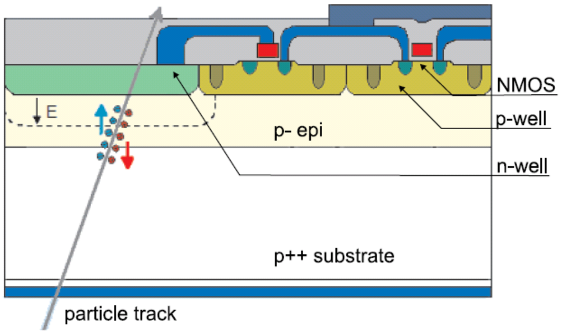
Charge generation volume integrated into ASIC, with a huge number of variants

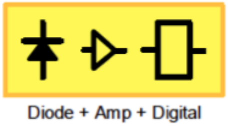
The Monolithic Pixel Detector





Fine pitch bump bonding to connect sensor and readout chip



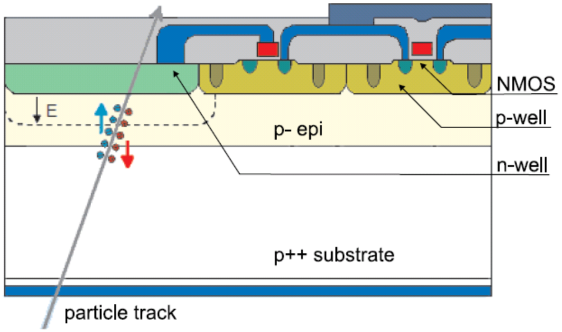


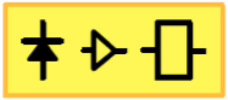
Thin, monolithic CMOS sensor, on-chip digital architecture

Charge generation volume integrated into ASIC, with a huge number of variants

The Monolithic Pixel Detector

- High Granularity →excellent spatial resolution (micron level)
- signal generated in very thin (15-40 µm) epitaxial layer; less material and suited to high eta
- Signal processing circuits integrated on sensor substrate → ease of system integration
- Commercial process with access to 8” and 12” wafers
- Multiple vendors




Diode + Amp + Digital

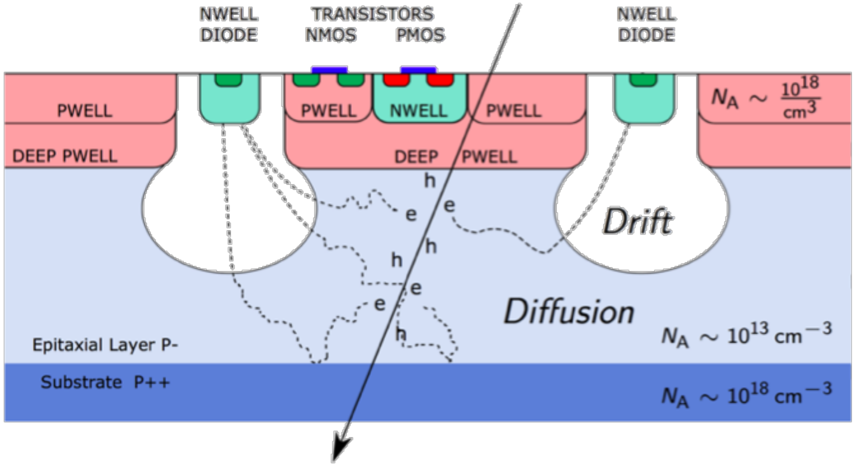
Thin, monolithic CMOS sensor, on-chip digital architecture

Charge generation volume integrated into ASIC, with a huge number of variants

ALICE ITS Upgrade Pixel Technology

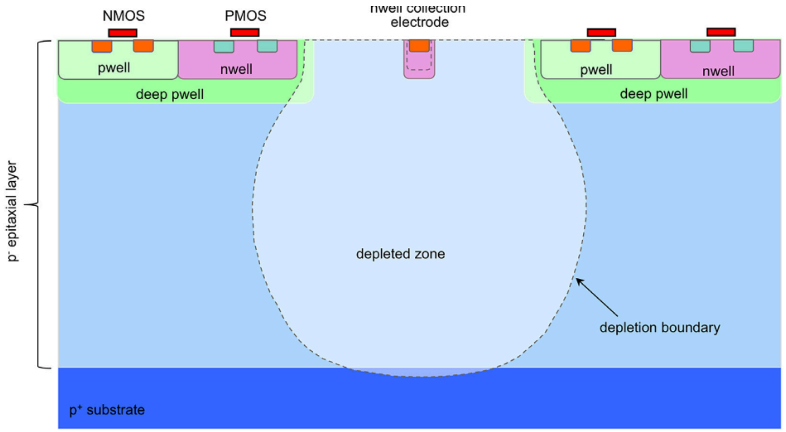
TowerJazz 0.18μm CMOS imaging process

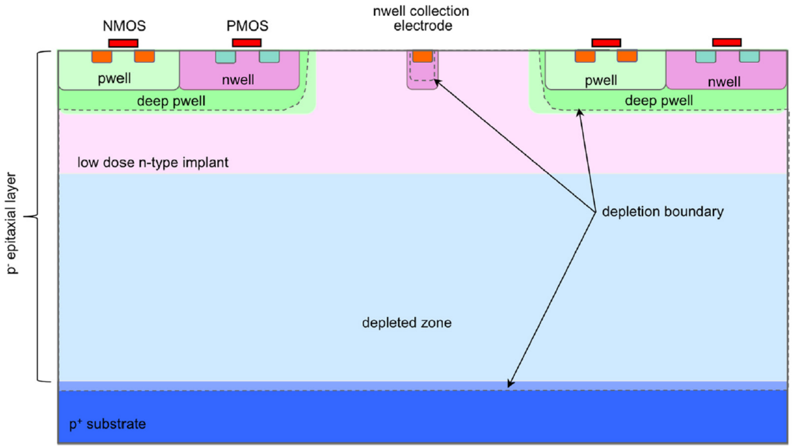
- N-well collection electrode in high resistivity epitaxial layer (>1kOhmcm)
- Present state-of-art based on **quadruple well allows full CMOS**
- **High resistivity (> 1kΩ cm) epi-layer** (p-type, 20-40 μm thick) on p-substrate
- **Moderate reverse bias => increase depletion region** around Nwell collection diode to collect more charges by drift



TJ 180 nm modified process

- Novel modified process developed in collaboration of CERN with TJ foundry in context of ALICE ITS.
- Combined with a small collection diode.

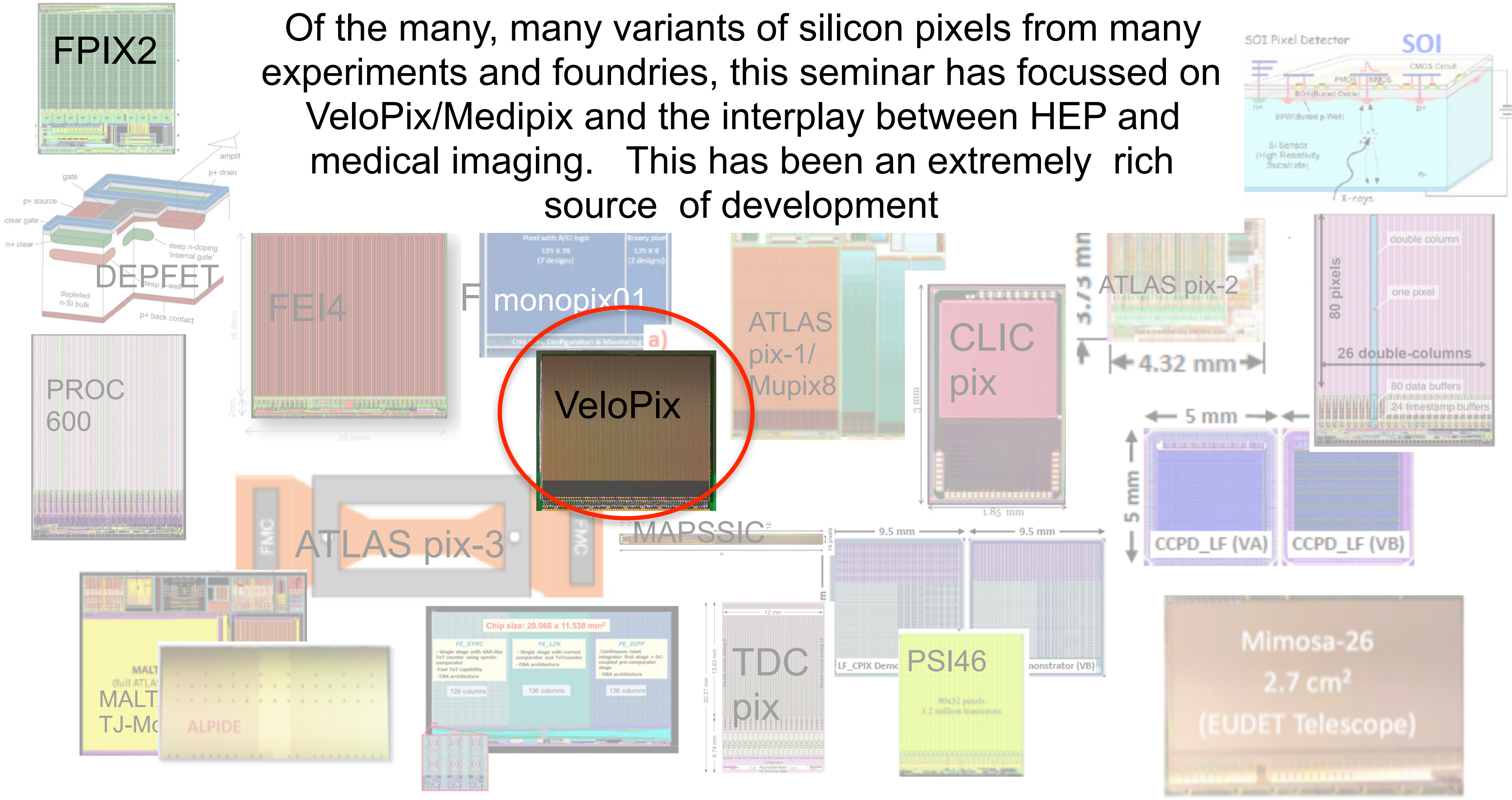




- Adding **a planar n-type layer** significantly improves depletion under deep PWELL
- Increased depletion volume → **fast charge collection by drift**
- better time resolution reduced probability of charge trapping (**radiation hardness**)
- Possibility to fully deplete sensing volume with no significant circuit or layout changes

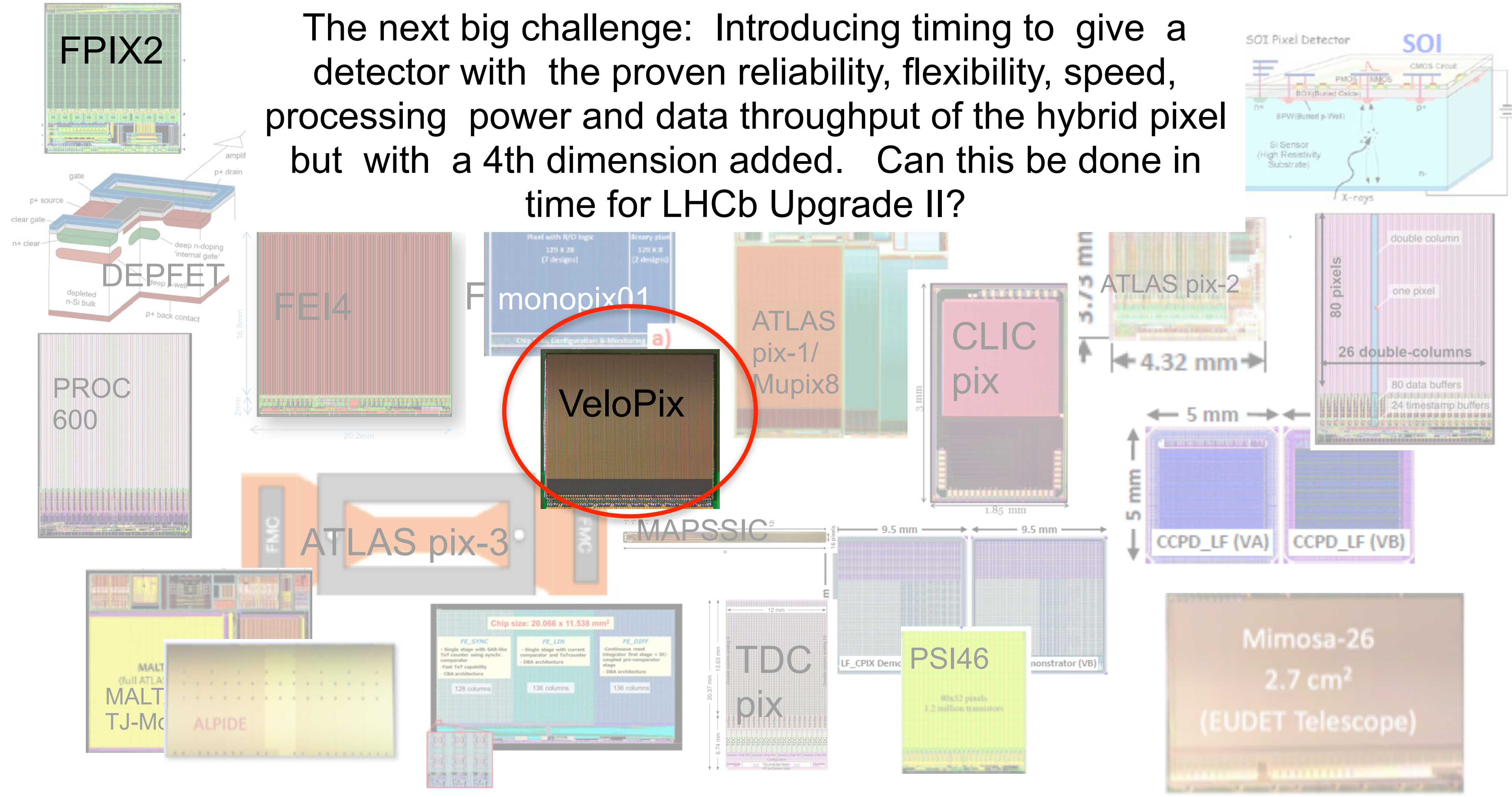
Conclusions

Of the many, many variants of silicon pixels from many experiments and foundries, this seminar has focussed on VeloPix/Medipix and the interplay between HEP and medical imaging. This has been an extremely rich source of development



Conclusions

The next big challenge: Introducing timing to give a detector with the proven reliability, flexibility, speed, processing power and data throughput of the hybrid pixel but with a 4th dimension added. Can this be done in time for LHCb Upgrade II?



Conclusions

Excellent information can be found in (e.g.) the following talks and meetings and references therein

Medipix: Pixel Detectors for Medical Imaging and Other Applications
Michael Campbell, EPS Conference on High Energy Physics, 2017

HV-CMOS: Eva Vilella, VELO Upgrade Retreat, Villars-sur-Ollon, 2018

Monolithic Silicon Pixel Detectors in HEP: Petra Riedler, BTTB 2018, Zurich

Detector++ Applications: Marcel Demarteau, 2017 ICFA Seminar, Ottawa
Silicon Detectors: Pernegger/Dannheim/Riedler, CERN-EP R&D March 2018

NA62 GTK: Massimiliano Fiorini, New Dimensions in Silicon Detectors, Manchester University, October 2017

Monolithic Silicon Pixel Detectors in HEP: Petra Riedler, BTTB 2018, Zurich

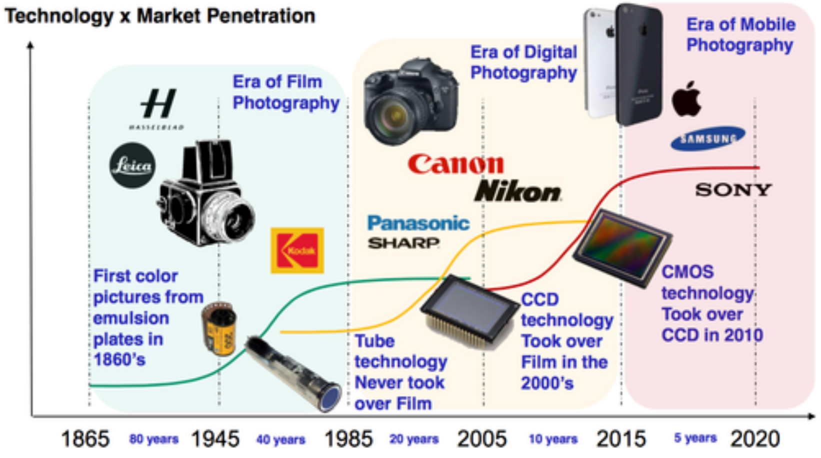
Silicon at the HL-LHC Experiments: Frank Hartmann, HSTD 2017, Okinawa

Technologies for the ATLAS ITK Pixel Detector: Anna Macchiolo, LC Vertex Detector Workshop 2017, Ringberg

Monolithic Active CMOS Pixel Sensors: Mark Winter, LHCb Upgrade II Workshop March 2018, LAPP

CMOS Active Image Pixel Sensors

- CMOS active image pixel sensor developed by NASA/JPL (patents by Caltech) in 1992, plus proposals in HEP
- Used (vanilla) CMOS process available at many foundries→easily accessible
- First versions contained in-pixel source follower amplifier for charge gain, low noise Correlated Double Sampling, basis for camera-on-chip
- Though specialised fab processes are required, the market has driven developments leading to CMOS dominating the field



1980's dominated by CCDs (camcorder market)

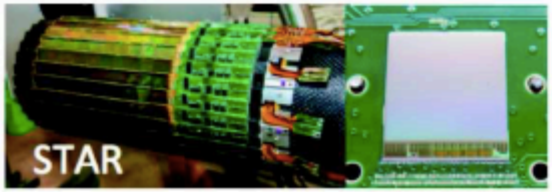
1990s/2000s CMOS take over camera phone market

ER Fossum, CMOS Active Pixel Sensors – Past, Present and Future, 2008
https://pdfs.semanticscholar.org/6d85/af67a846d13b7e7502f7fa96c0729c972590.pdf

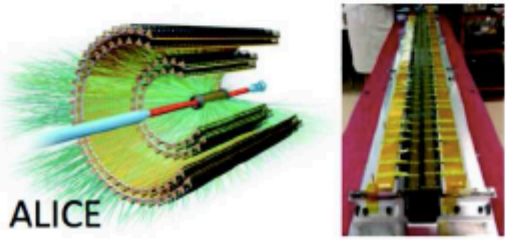
*In HEP, e.g.
S. Parker, A proposed VLSI pixel device for particle detection
NIMA 275 (1989), 494-516

Evolution of Radiation Tolerance and Rate Capability

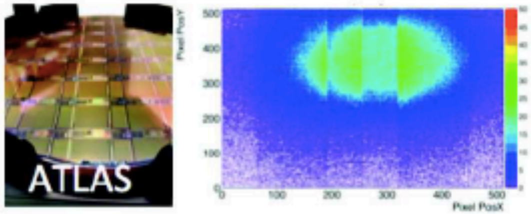
	RHIC STAR	LHC - ALICE ITS	CLIC	HL-LHC Outer Pixel	HL-LHC Inner Pixel	FCC pp
NIEL [n_{eq}/cm^2]	10^{12}	10^{13}	$<10^{12}$	10^{15}	10^{16}	10^{15}-10^{17}
TID	0.2Mrad	<3Mrad	<1Mrad	80 Mrad	2x500Mrad	>1Grad
Hit rate [MHz/cm^2]	0.4	10	<0.3	100-200	2000	200-20000



Ultimate Sensor



Alpide Sensor



MALTA & Monopix & AtlasPix Sensor

Evolution of Process Characteristics:

- starting material: epitaxy thickness and resistivity
- doping profile: from twin-well to quadruple well with buried N-doped brane
- feature size and nb of Metal. Layers

Evolution of Architectures

- rolling shutter with analog readout
- rolling shutter with || readout and EoC disc.
- data driven readout with in-pixel disc.

Timepix/Velopix Trajectory

Timepix3

640 MHz VCO controlled ring oscillators / SP
1.56 ns resolution

→

Timepix4

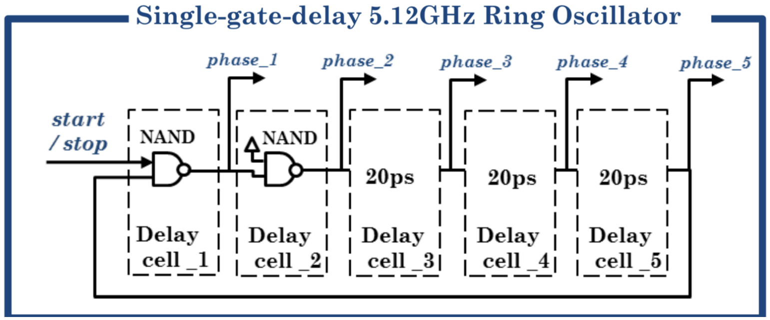
640 MHz VCO controlled ring oscillators / SP
Latch internal phases (4 tap)
195 ps resolution

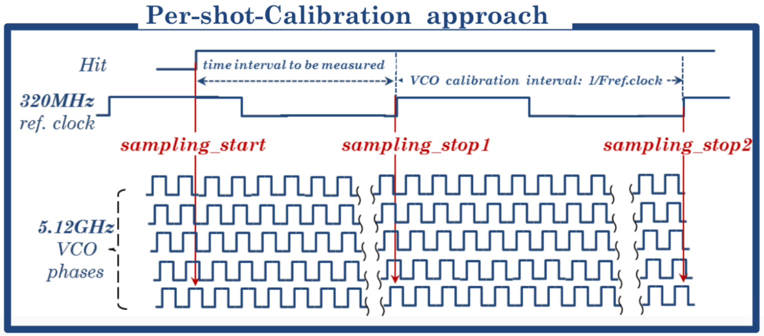
→

VeloPix++ ("pix20" Nikhef proposal)

5 GHz ring oscillator
Latch internal phases (5 tap)
Self calibrating (no reference VCO in periphery): 20 ps resolution

Pix20 concept described in presentation @ Villars of (V. Gromov & M, v. Beuzekom)


Single-gate-delay 5.12GHz Ring Oscillator


Per-shot-Calibration approach

Oscillation frequency varies with temperature, power supply voltage, manufacturing process etc, and is calibrated immediately after each hit

The very successful VeloPix/Timepix4 architecture still the basis of the ASIC; many features could be kept or extended e.g. superpixels, GWT in 65 nm, TSV/buttable design etc.

The relatively short design cycle of the VeloPix/Timepix4 gives great confidence in the design team