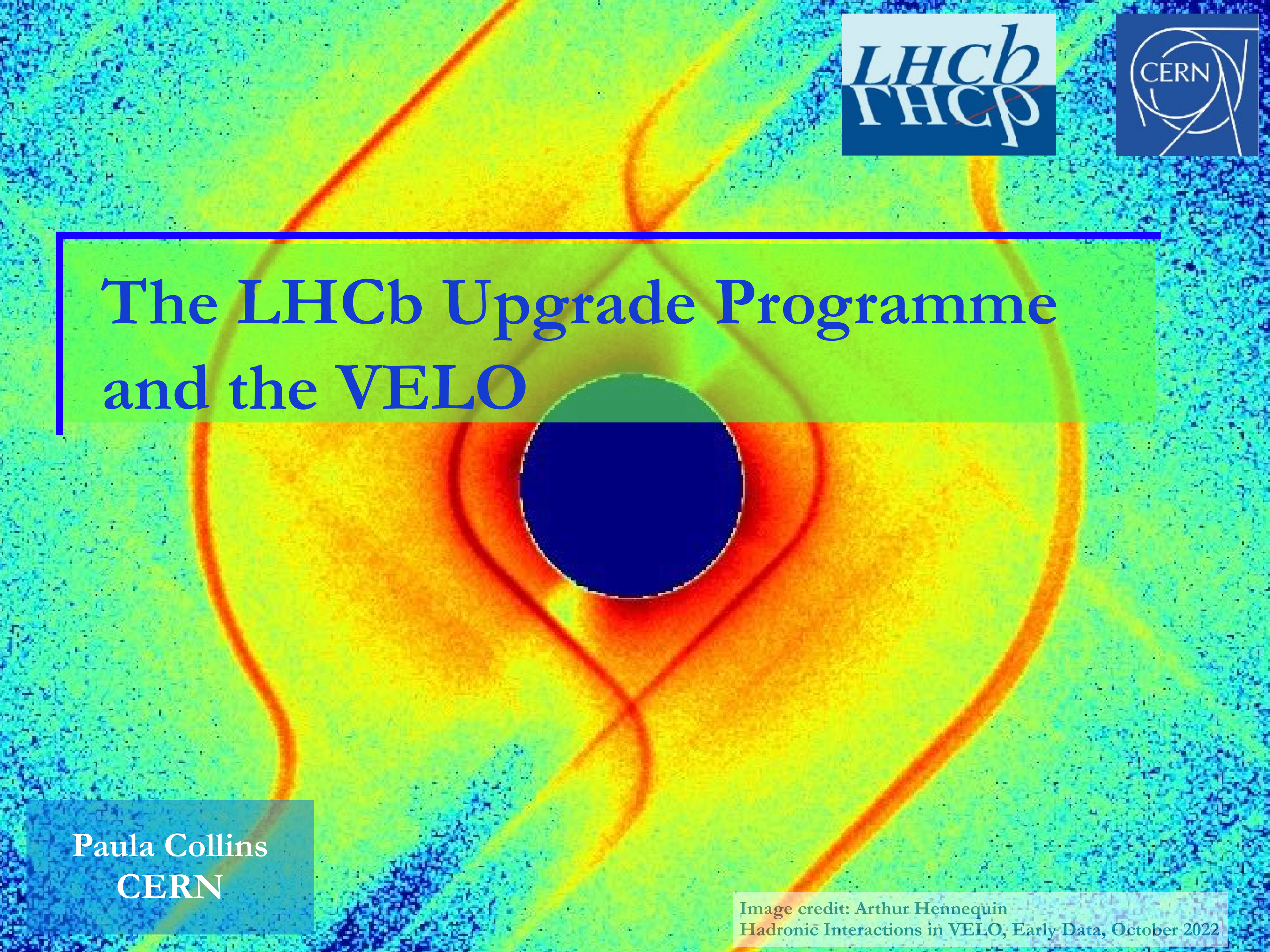
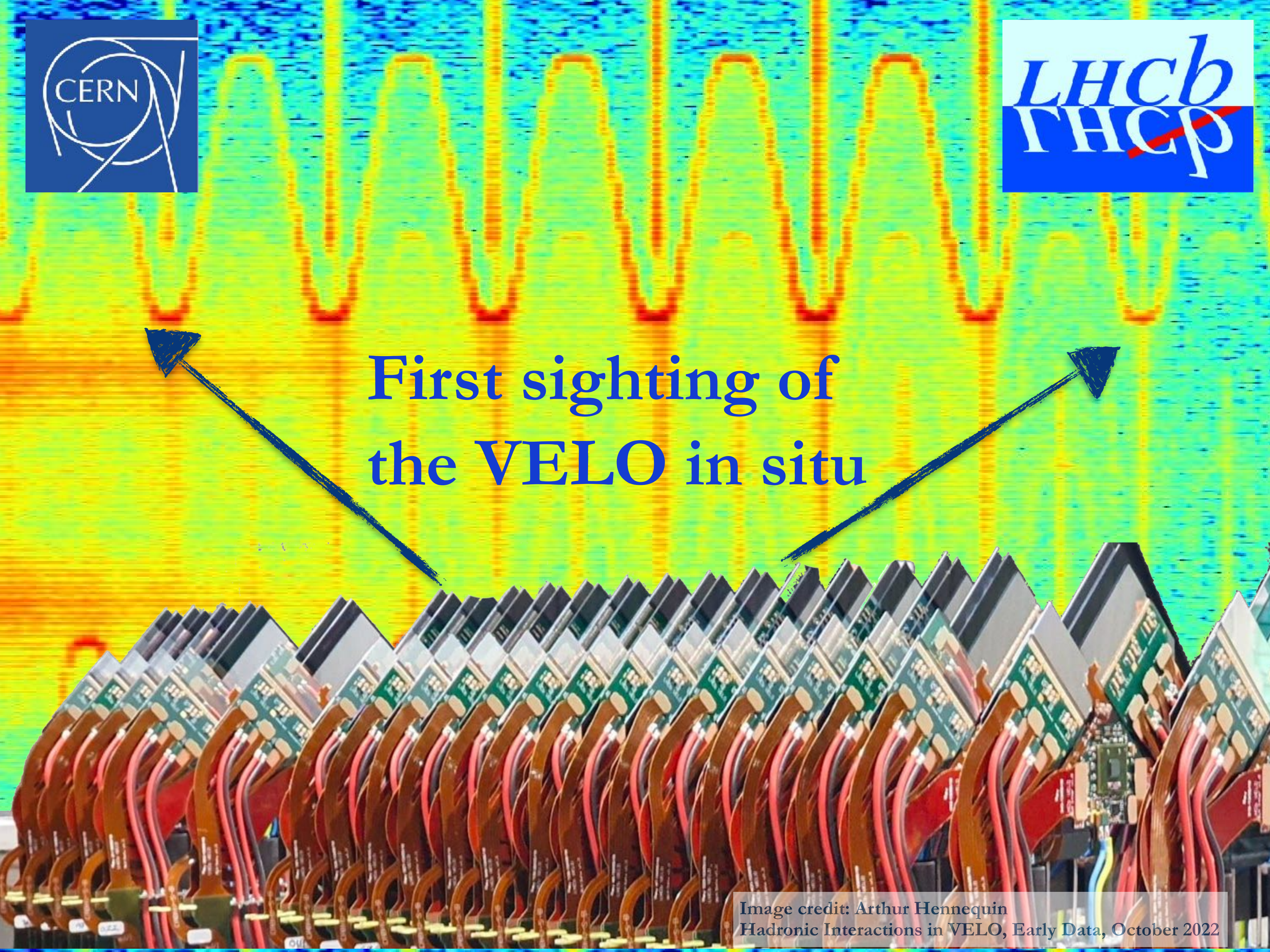
The LHCb Upgrade Programme and the VELO



Paula Collins
CERN

Image credit: Arthur Hennequin
Hadronic Interactions in VELO, Early Data, October 2022


First sighting of
the VELO in situ
Image credit: Arthur Hennequin
Hadronic Interactions in VELO, Early Data, October 2022

LHC Page1 | Fill: 8288 | E: 450 GeV | 19-10-22 08:09:02

PROTON PHYSICS: CYCLING

Energy: 450 GeV

Post Mortem Information

PM event ID:	Wed Oct 19 03:04:00 CEST 2022
PM event category:	PROTECTION_DUMP
PM event classification:	MULTIPLE_SYSTEM_DUMP
PM BIS Analysis result:	First USR_PERMIT change: Ch 8-RF-b1: B T -> F on CIB.UA47.R4.B1
PM comment:	MD

Comments (19-Oct-2022 08:06:29)

Preparing for precycle
Next: 300b fill for first VELO full closure

BIS status and SMP flags

	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	false	false
Setup Beam	true	true
Beam Presence	false	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

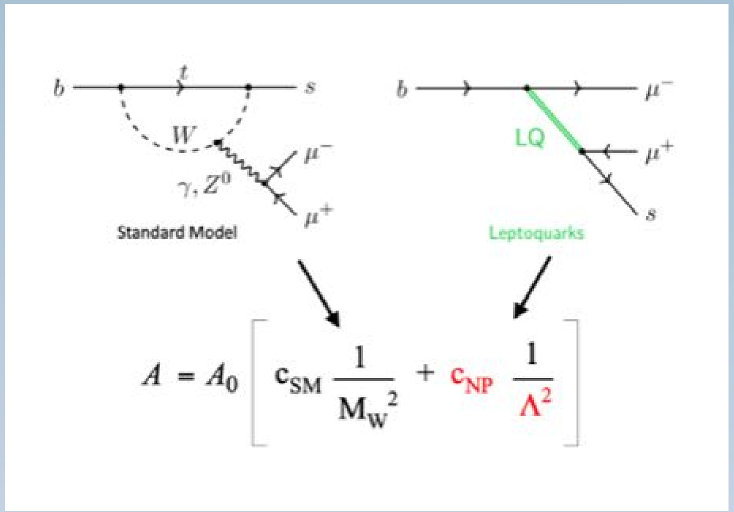
AFS: Single_42b_0_0_0_noHOnoLR

PM Status B1: ENABLED | PM Status B2: ENABLED

Contents

Flavour Physics at LHCb

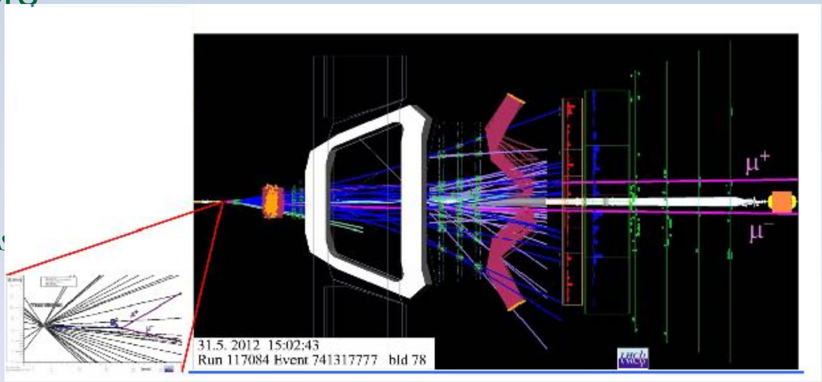
New physics searches with flavour look for the indirect effects on low energy processes, for instance rare b-hadron decays, probing mass scales not directly accessible at the LHC



The LHC provides huge statistics and access to all c- and b-hadrons - but **event topology is challenging**; need low material, ability to trigger on low p_T, and particle identification to flavour tag and distinguish topologically similar decays e.g. $B \to \pi\pi$, $B \to K\pi$

LHCb is a **general-purpose forward detector** at the LHC which is **particularly suited** to precision measurements in the beauty and charm sectors

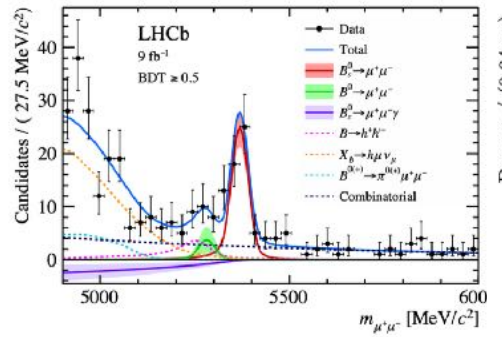
- ✓ $\Delta p / p$ = 0.5% at < 20 GeV/c, 1.0% at 200 GeV/c
- ✓ IP resolution = 15 + 29/p_T [GeV/c] μm
- ✓ decay time resolution 45 fs for $B_s \to J/\psi\phi$ and $B_s \to D$
- ✓ Kaon ID ~ 95% for 5% $\pi \to K$ mis-id probability
- ✓ full real time reconstruction in the high level trigger



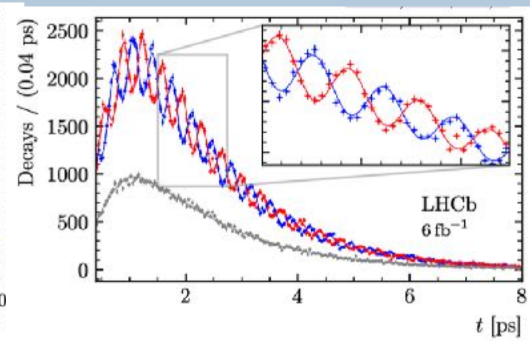
LHCb Detector Performance

LHCb accumulated 9 fb^{-1} of integrated luminosity during LHC Runs 1 & 2 yielding **precision measurements including**:

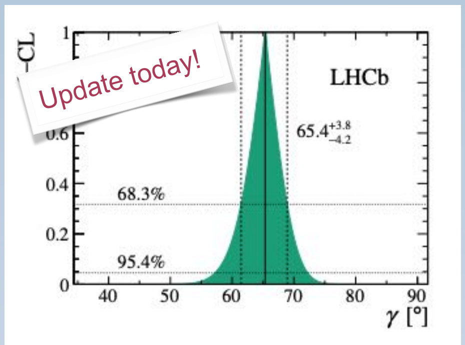
$B_s^o \to \mu^+\mu^-$



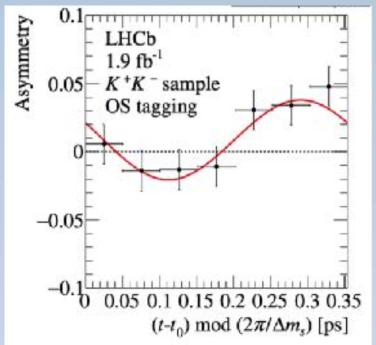
Δm_s



CKM angle γ

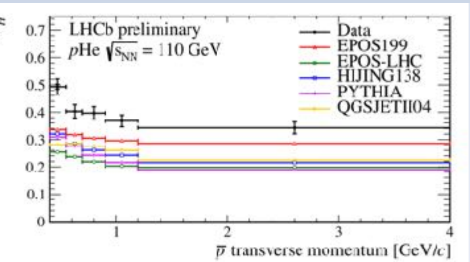


B_s time dependent CPV

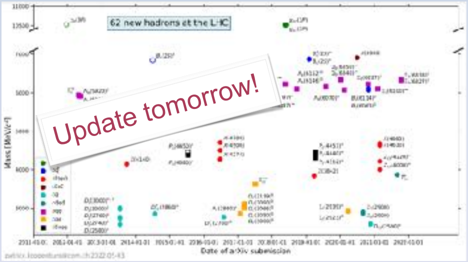


a wealth of f**urther measurements and discoveries** including:

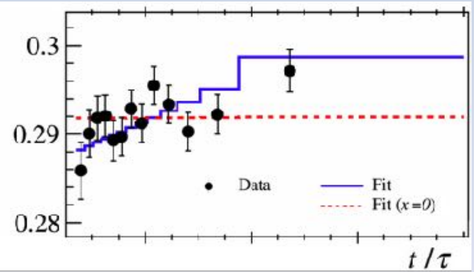
pHe physics



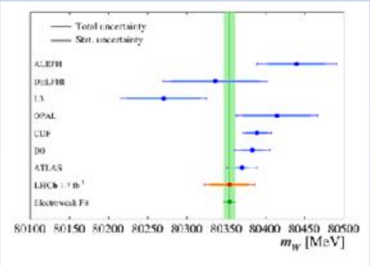
>55 new hadrons



$D^o\overline{D^o}$ mass difference



EW physics

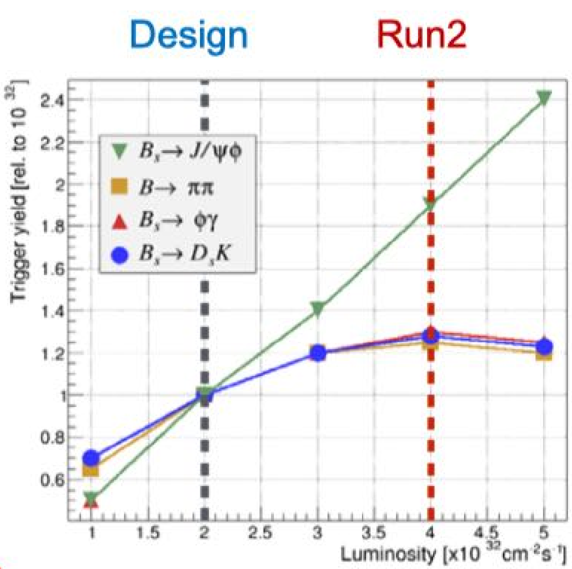


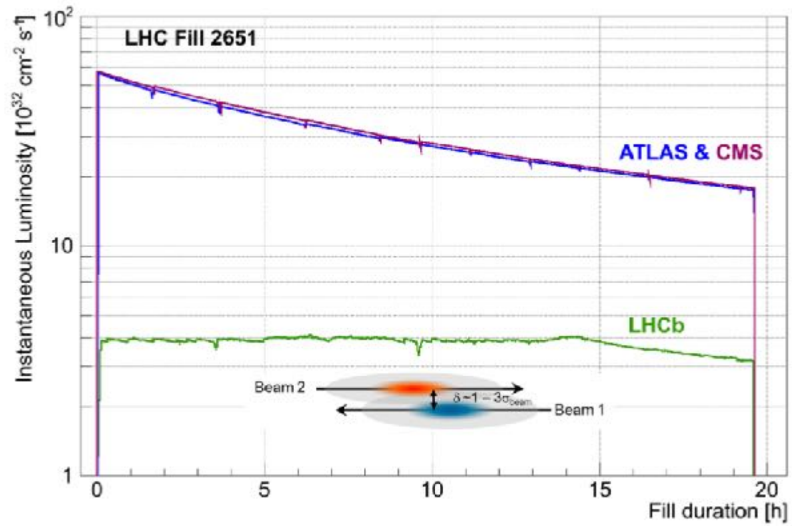
and also **intriguing anomalies**: R(D*), R(K), R(K*), angular analysis of $K^*\mu^+\mu^-$ …

LHCb Detector Performance

This was all achieved running at lower luminosity than LHC could provide

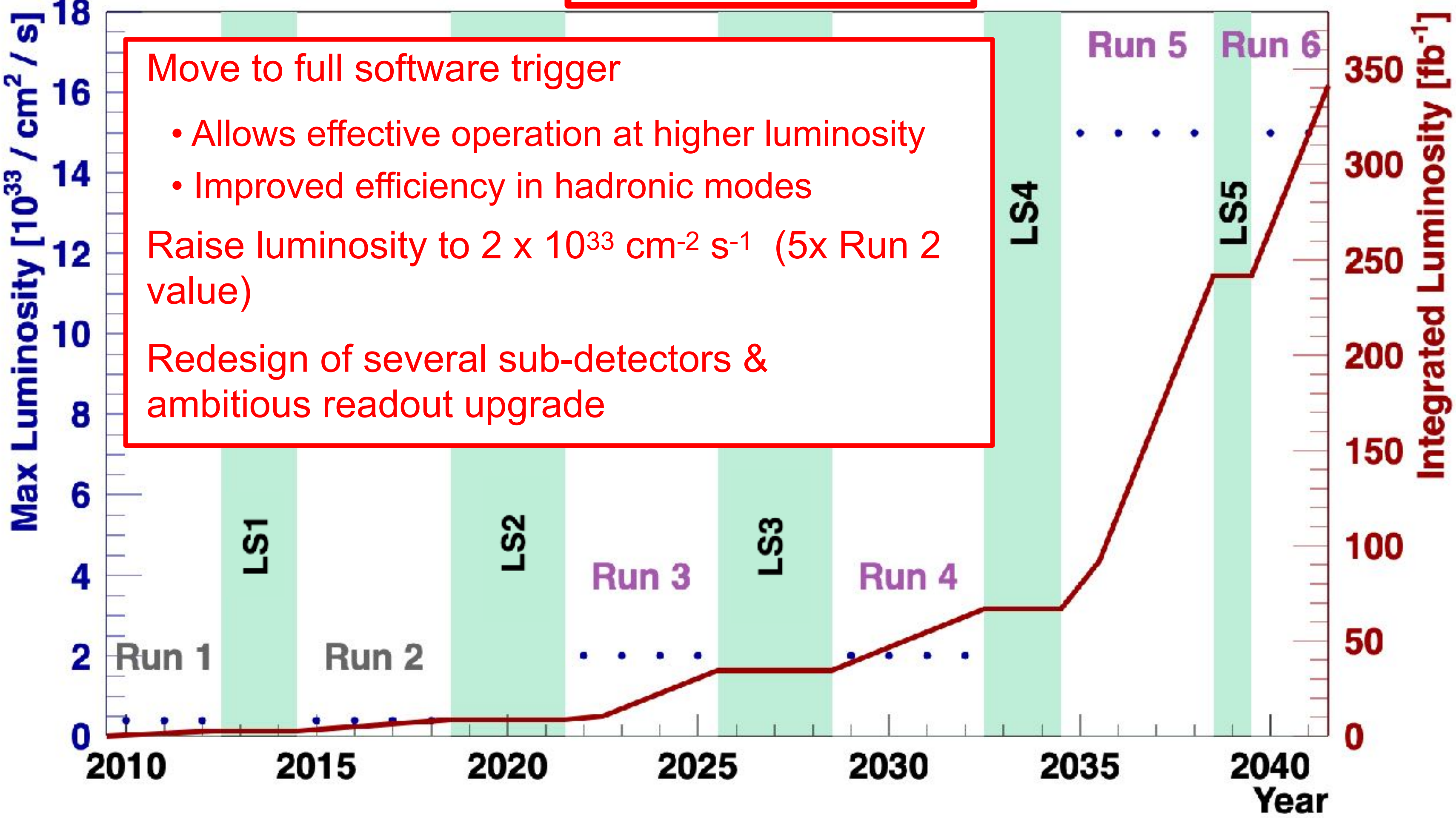
- $L_{peak} \sim 4 \times 10^{32} cm^{-2} s^{-1}$ levelled, ~ 1 visible interaction / crossing
- ATLAS/CMS have $L_{peak} \sim 2 \times 10^{34} cm^{-2} s^{-1}$, ~ 40 visible interactions / crossing
- Programme not limited by available luminosity - but by limitation on readout!





LHCb Upgrade I in a nutshell

Original LHCb | Upgrade I → | Upgrade II →



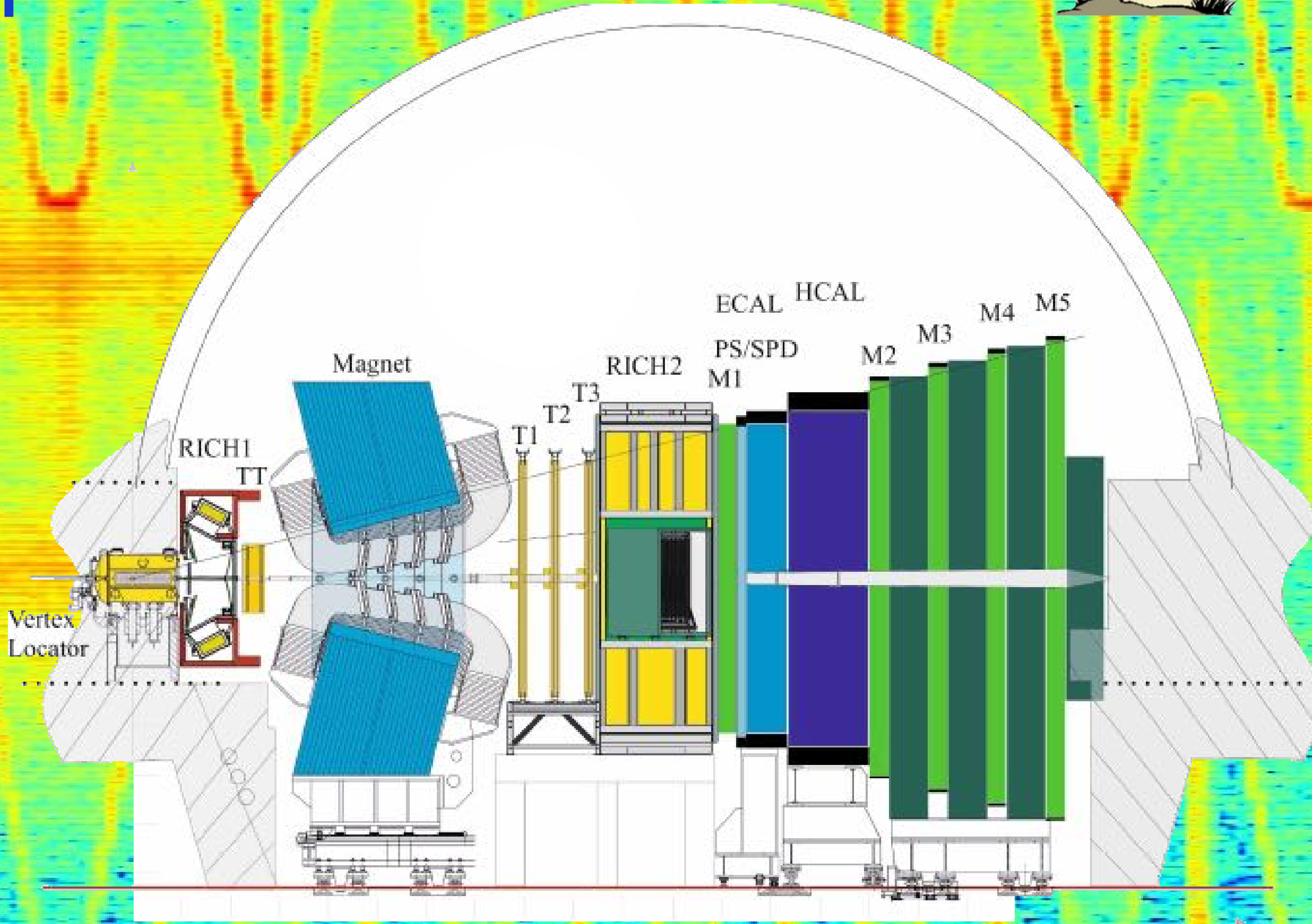
Move to full software trigger

- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

Raise luminosity to 2 x 10^{33} cm^{-2} s^{-1} (5x Run 2 value)

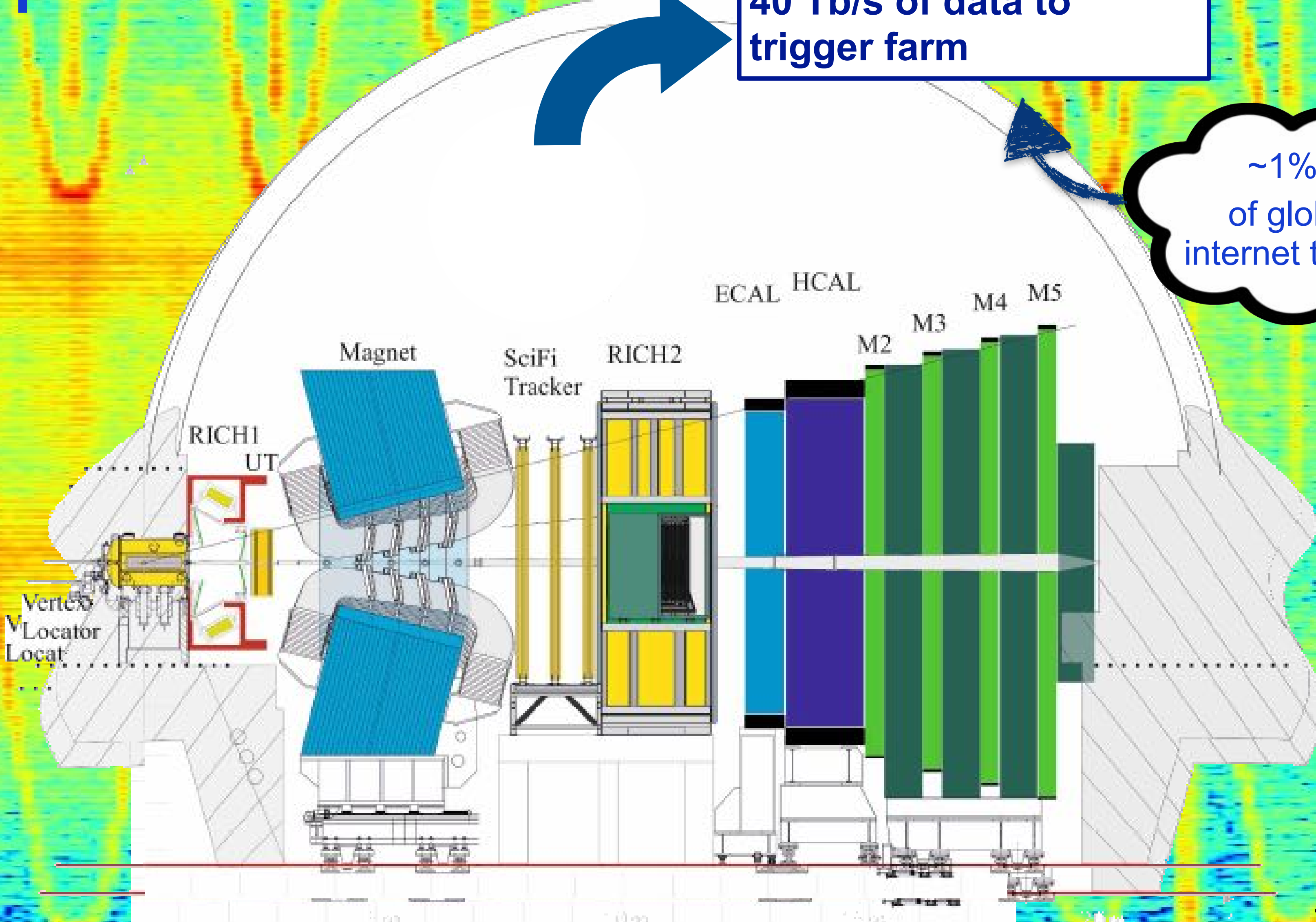
Redesign of several sub-detectors & ambitious readout upgrade

Pre-Upgrade Detector



Upgrade I

40 Tb/s of data to trigger farm

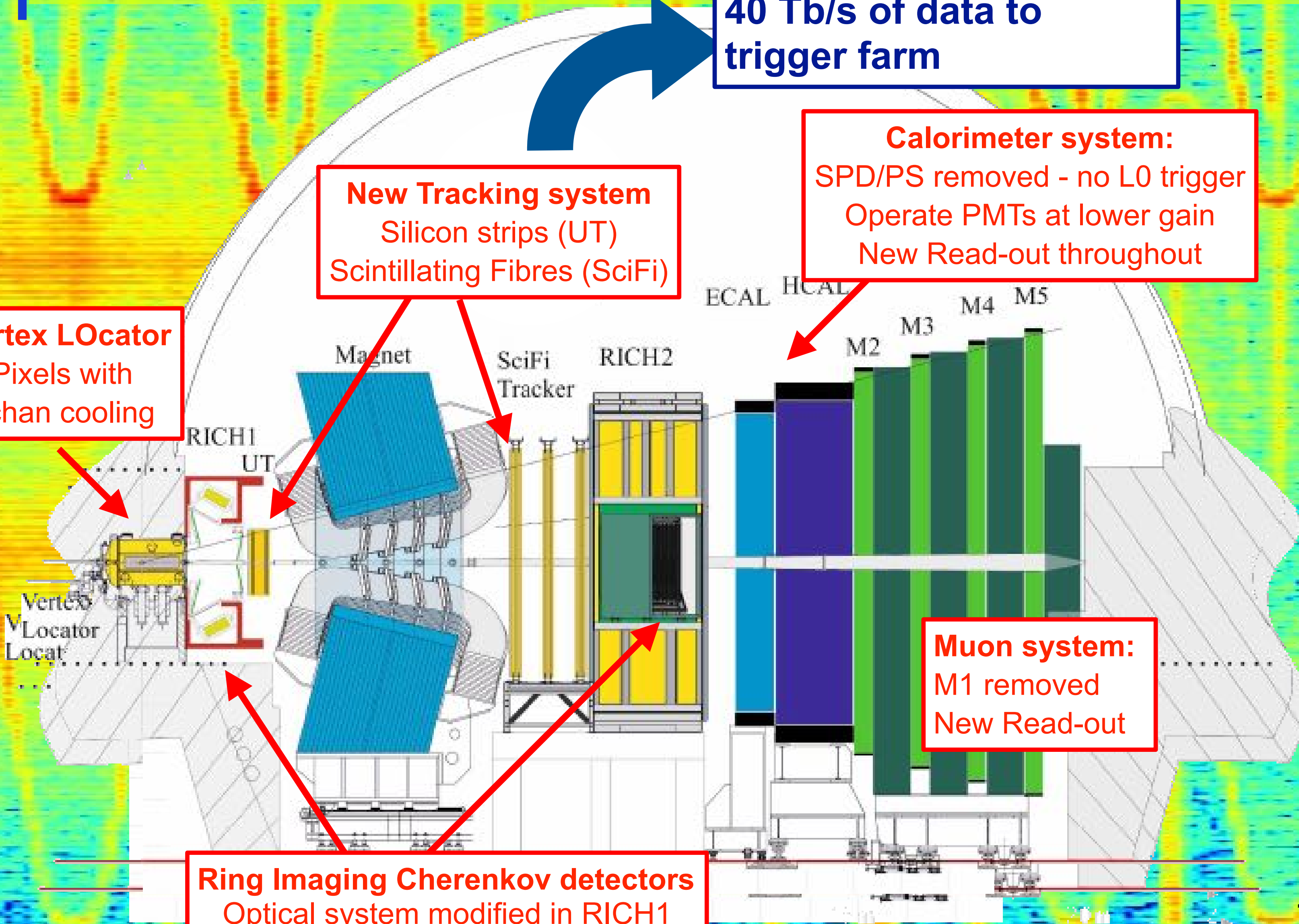


~1%
of global
internet traffic!

Upgrade I

Full s/w trigger →
Replace read-out boards and DAQ

40 Tb/s of data to trigger farm



New Tracking system
Silicon strips (UT)
Scintillating Fibres (SciFi)

Calorimeter system:
SPD/PS removed - no L0 trigger
Operate PMTs at lower gain
New Read-out throughout

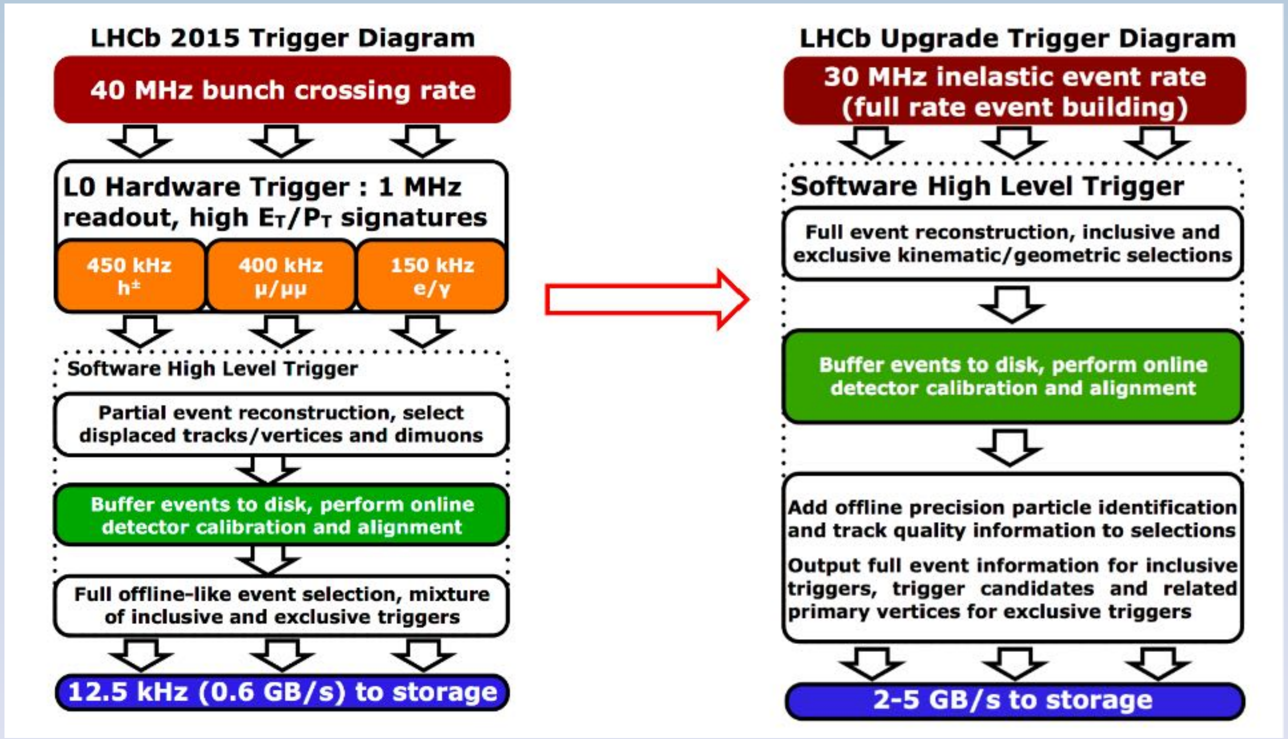
VErtex LOcator
Pixels with
μchan cooling

Muon system:
M1 removed
New Read-out

Ring Imaging Cherenkov detectors
Optical system modified in RICH1
New photon detectors and Read-out

Trigger Transformation

Goal: Achieve same reconstruction performance in harsher environment
Record all bunch crossings with full software trigger



Pioneering Use of GPUs

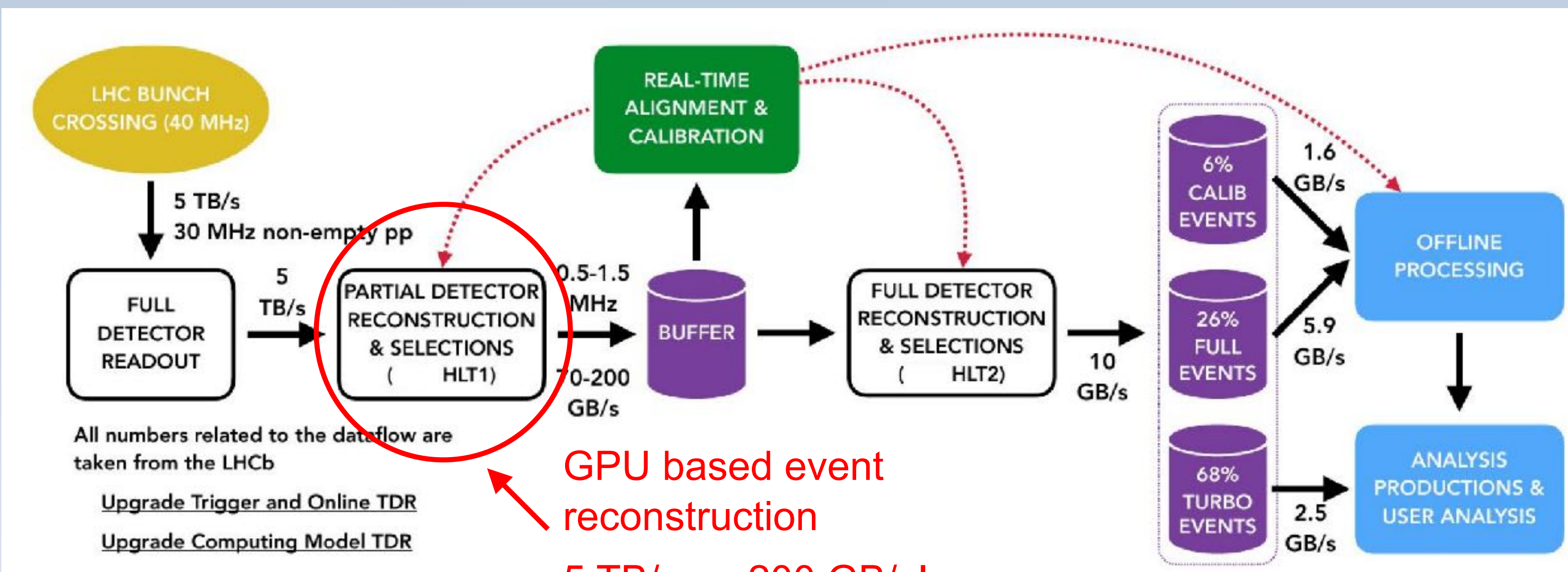
Backend electronics on surface in data center

~19000 long distance optical fibres (99.75% yield)

- Common backend boards (PCIe40) housing large FPGAs and optical links (48 x 10 Gbps)

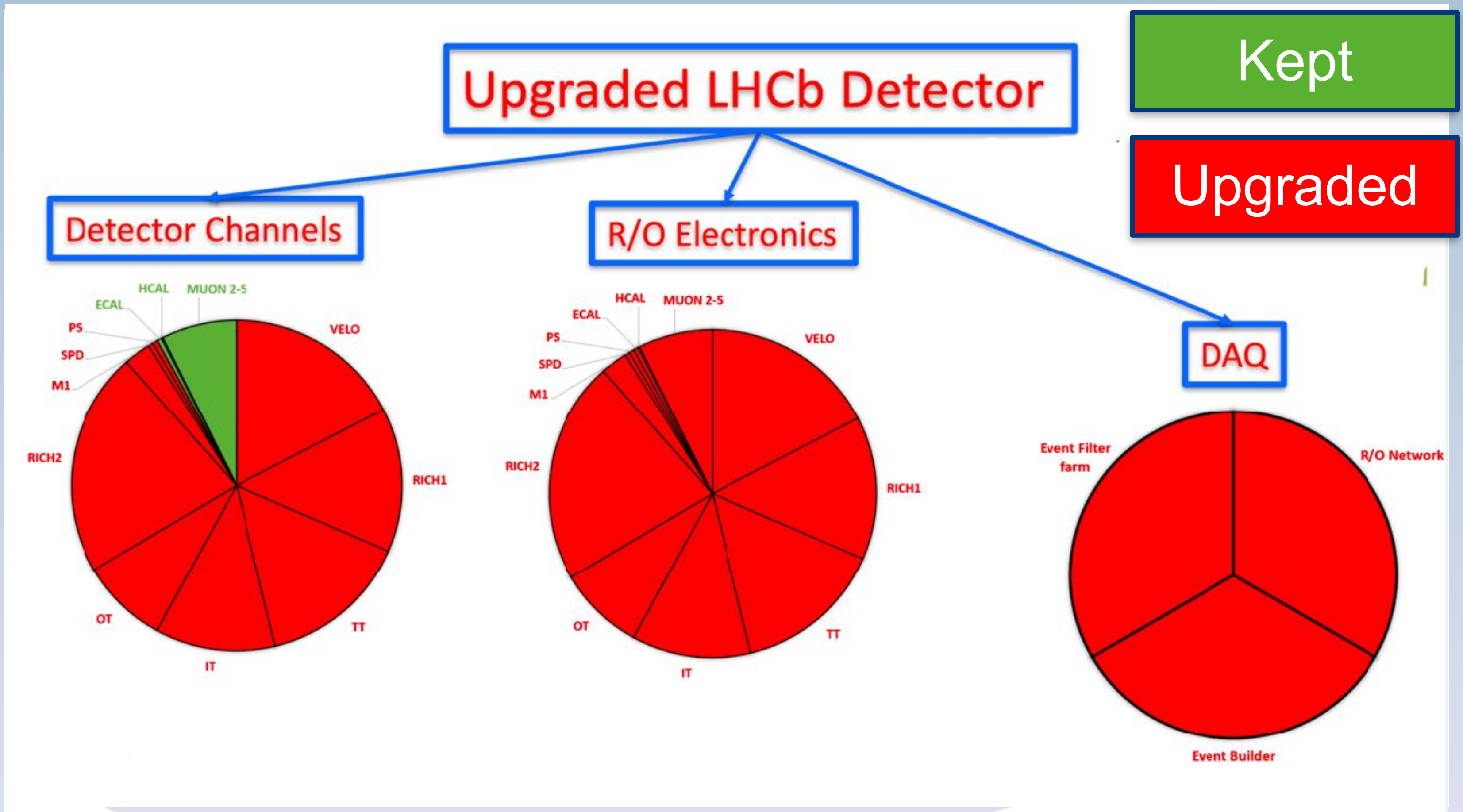
Flavour of firmware defines functionality

Total effective bandwitdh of **up to 40 Tbps**



5 TB/s → 200 GB/s!

Putting it all together



Major Upgrade → it's an all together new detector!

New VErtex LOcator

CERN-LHCC-2013-013

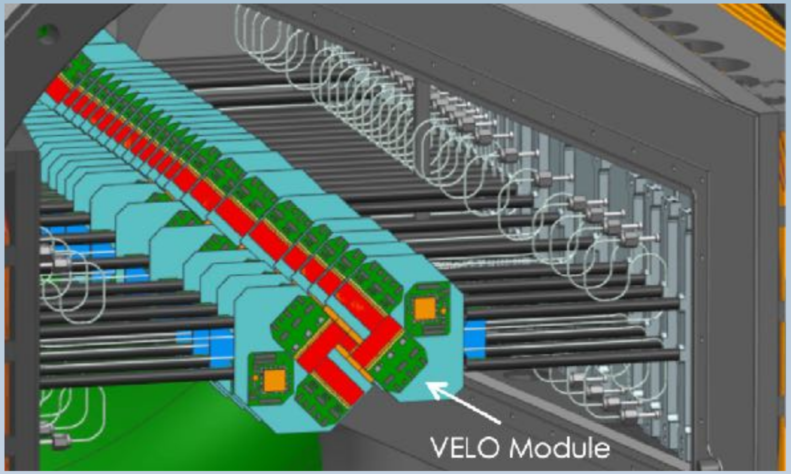
L-shape hybrid pixel silicon detector modules cooled by bi-phase CO_2 which passes under the chips in etched microchannels within a silicon wafer cooler (T~-30˚C)

- ~ 3 % X_0 radiation length before second measured point on track

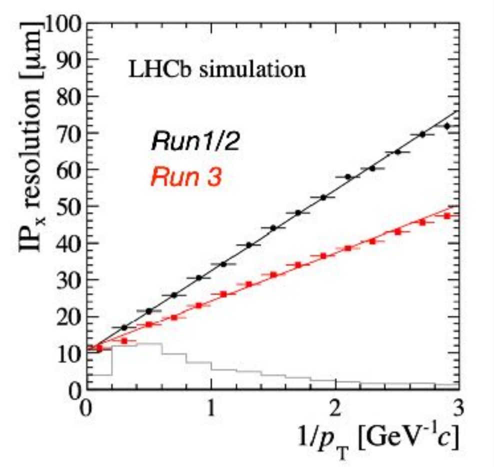
Two moveable halves: closer to beam line (R = 8.2mm → R = 5.1 mm) for improved IP resolution

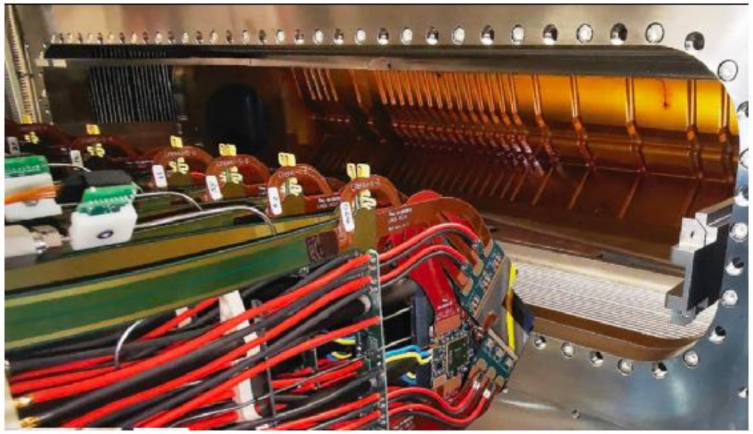
- 52 modules, 41M pixels, 208 x 200 µm sensor tiles

New ASIC: VeloPix ~ 20 Gb/s in hottest ASIC for a total of 3 Tb/s for whole VELO



Improved impact parameter and decay time resolution

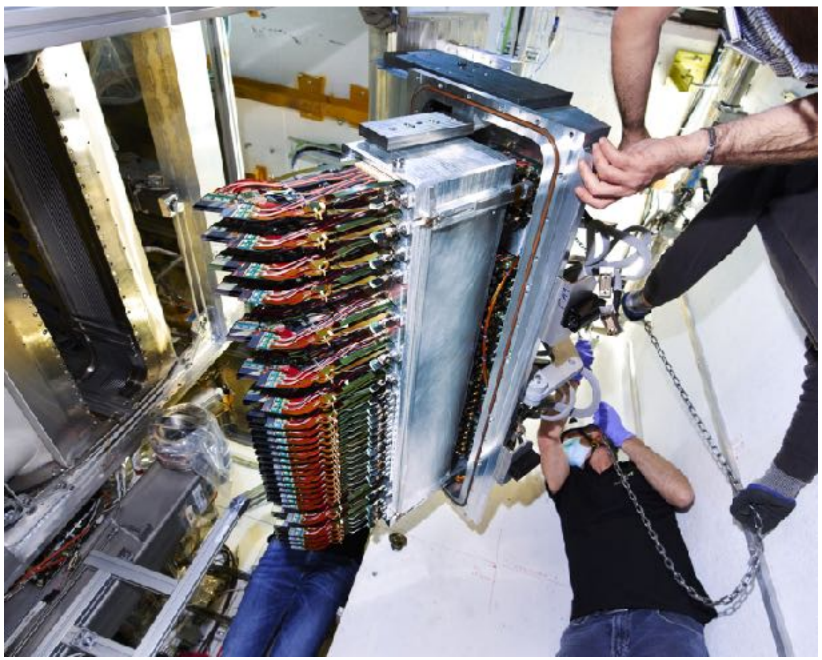


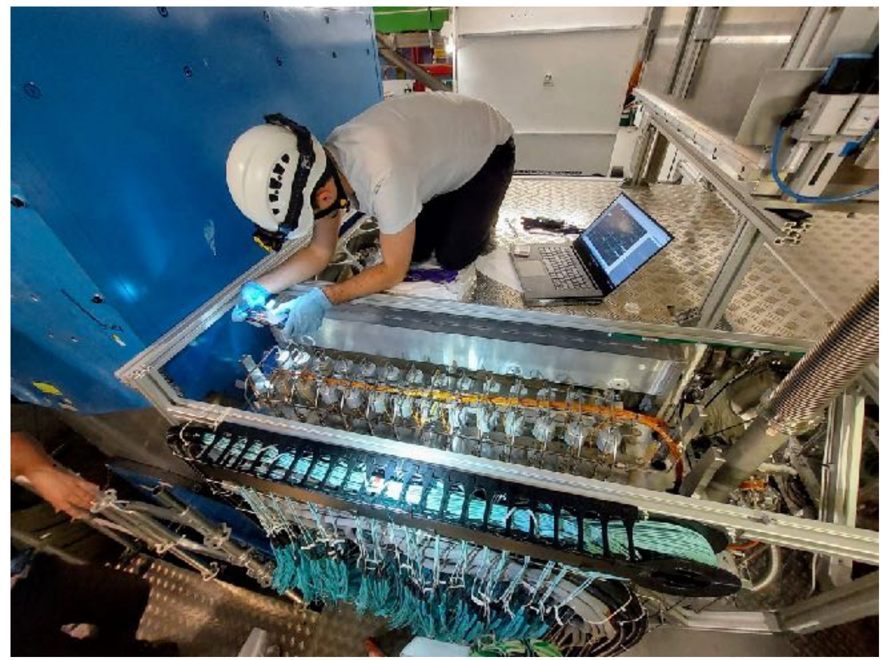


VELO half being installed

New VErtex LOcator

Second half of VELO installed in May 2022





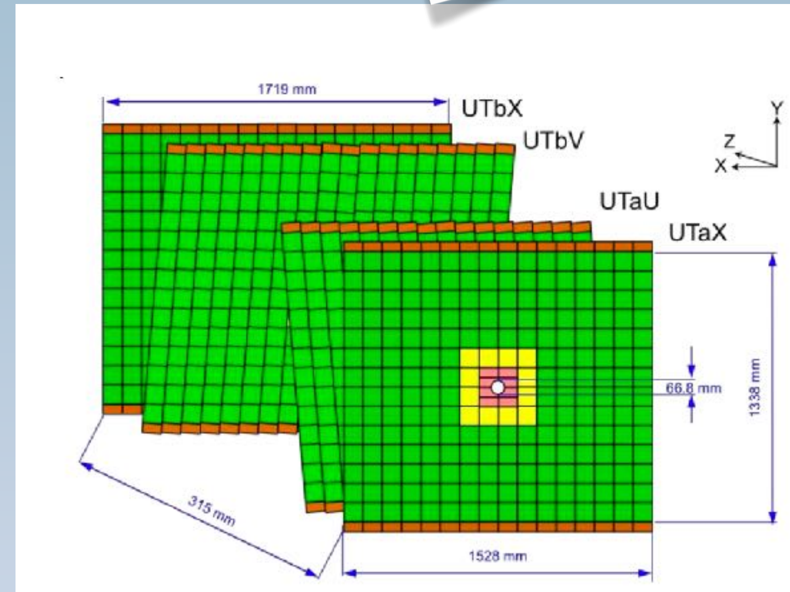
1/p_T [GeV^{-1}c]

Tracking Detectors

CERN-LHCC-2014-001

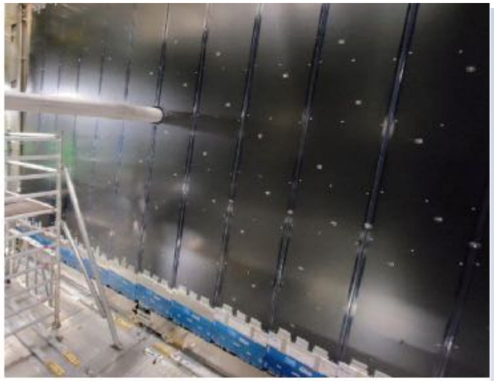
Upstream Tracker (UT) : 4 planes made of silicon strips, with finer segmentation and improved acceptance

- fast p_T determination for track extrapolation - reduce ghost tracks and improved trigger bandwidth
- Long lived particles decaying after VELO (K_s, Λ)



SciFi : downstream tracker made of 12 planes of scintillating fibres read out by SiPMs, to cope with increased occupancy

- each plane, with dimensions 6 x 5 m2, is made of scintillating fibres with 2.5 m length and 250 μm diameter
- Spatial resolution is better than 80 μm and hit efficiency better than 99%
- Readout with linear arrays of SiPMs cooled to -40˚C



SciFi plane fully installed and aligned

PID detectors: RICH

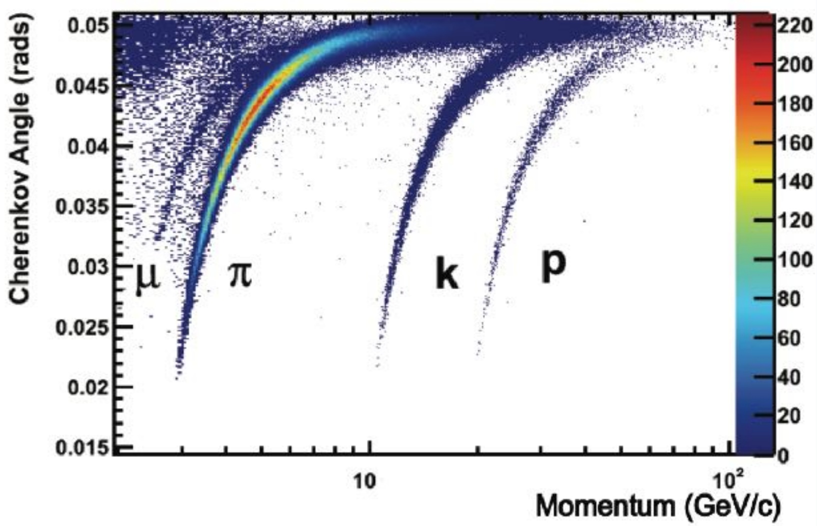
CERN-LHCC-2013-022

Goal is to maintain the excellent Run 1/2 performance with the increased occupancy foreseen at Run 3

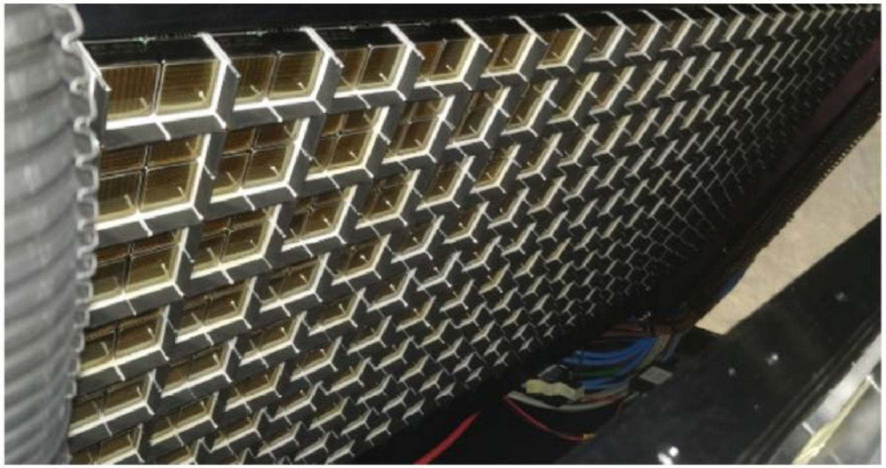
RICH1 (closer to the IP); new mirrors with $\times\sqrt{2}$ focal length, to halve the occupancy

RICH 1 & 2; new photodetectors; MaPMTs with increased granularity and 40 MHz readout

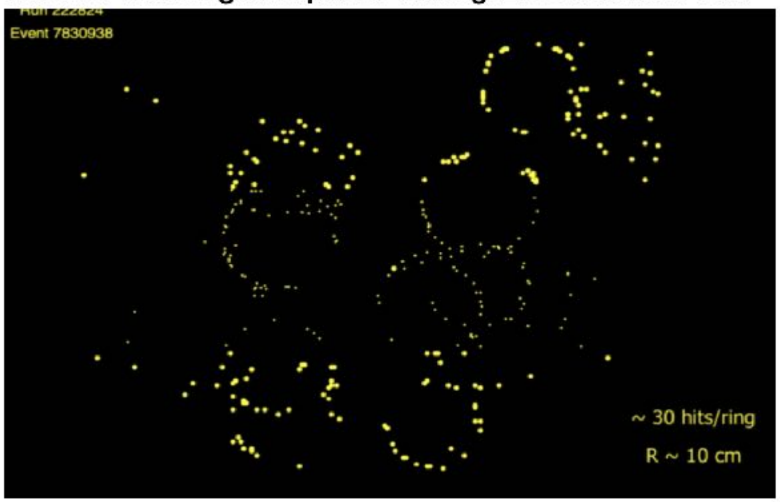
Run 1/2 performance of the RICH system



RICH1: MaPMTs installed upper side



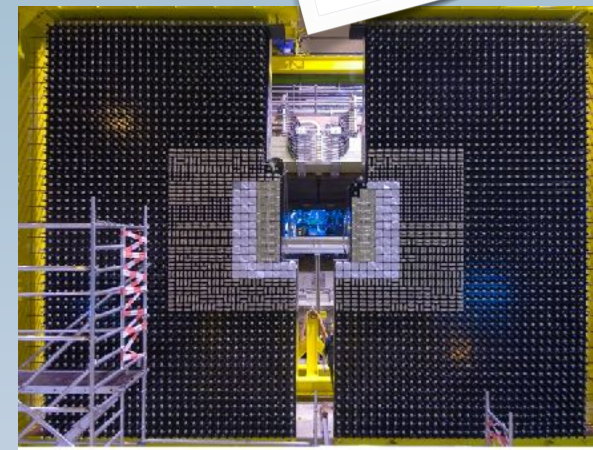
RICH2: first rings acquired during LHC october test



PID Detectors: CALO and MUON

CERN-LHCC-2013-022

Present calorimetry system can withstand the increased luminosity of Run 3/4



Shashlik calorimeters

- ECAL = Pb+Sci ~25X_0, HCAL = Fe+Sci $\sim 5\lambda_I$
- PMT gain reduced to stand the higher occupancy
- new front-end electronics with improved S/N and 40 MHz readout

Muon stations

- 4 walls equipped with MWPCs, and interleaved with iron filters
- front-end electronics upgraded for 40 MHz readout, granularity increased on first station to reduce occupancy

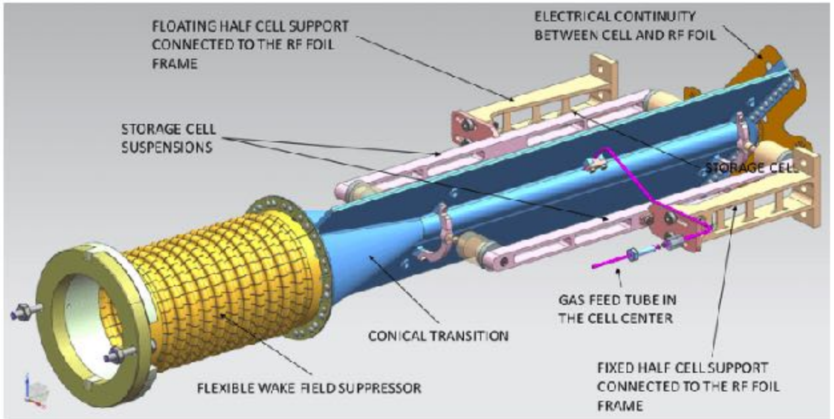
Large improvements expected from software trigger

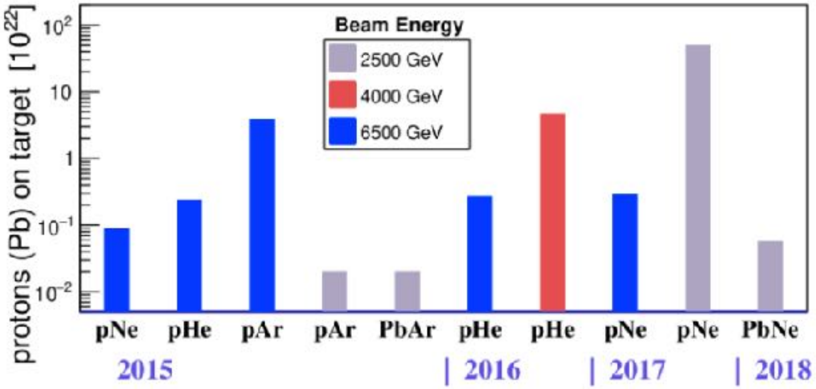
- reduced p_T threshold on electrons after removal of hardware L0
- improved muon software selection will allow to reject a factor of ~2 more bkg at trigger level
- more improvements in high-level electron and muon PID selections will allow to compensate the occupancy increase

SMOG2 and Fixed Target Physics

New SMOG2 system installed to inject various gas species in the LHCb IP

- Fixed Target physics at the LHC collider: in // with pp data taking
- Gas cell attached to VELO, displaced p-gas IP for easy distinction from pp data



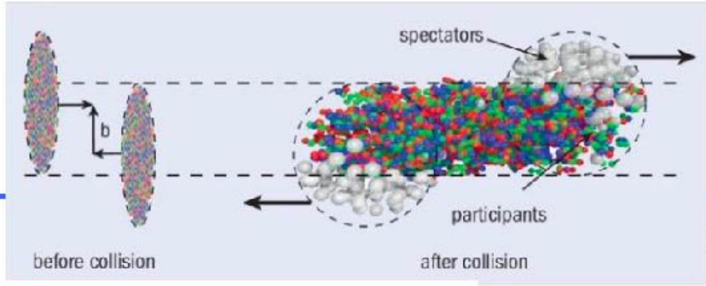


Physics program spans over:

- anti-proton production
- Central exclusive production
- X(3872)/ψ(2S)
- ψ(2S) / J/ψ
- Strangeness production
- $\Lambda_c \rightarrow pK\pi$

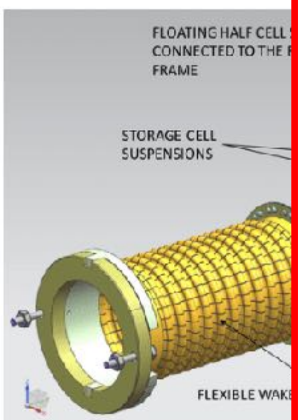
+ LHCb participation in Heavy Ion runs (PbPb and pPb data taking)

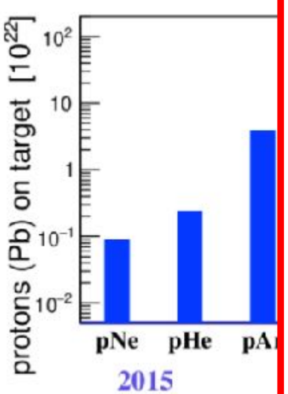
✓ Down to 30% centrality in LHCb in Run3!



SMOG2 and Fixed Target Physics

New SMOG2 system installed to inject various gas species in the LHCb IP
- Fixed Ta
- Gas cell ... ata

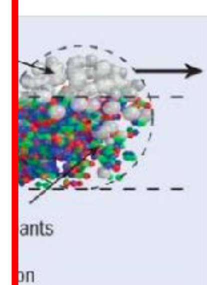




on

Ion runs

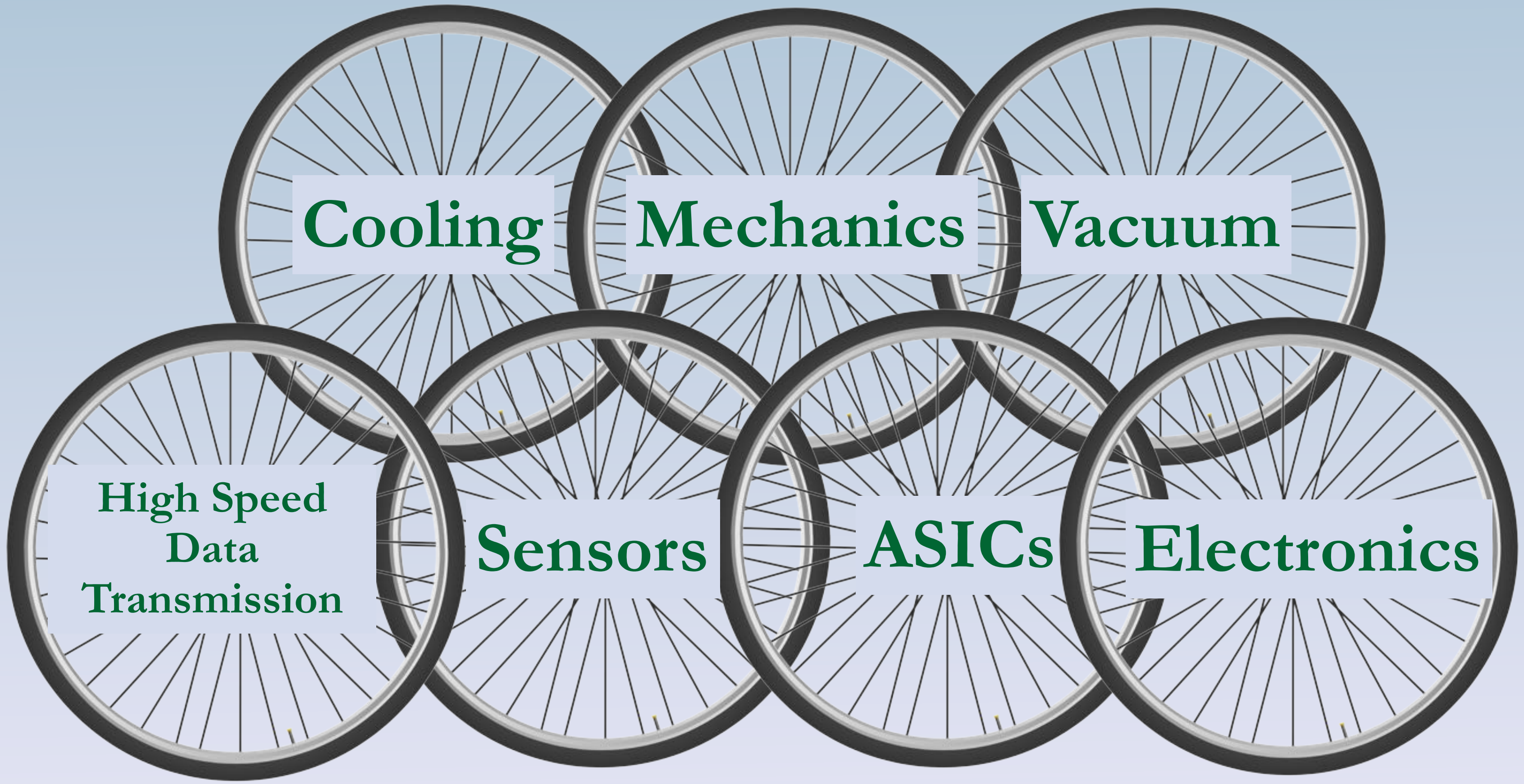
in Run3!



Last view of the cavern before commissioning started, upgrade is almost complete! The final sub-detector, the UT, will be installed in the upcoming shutdown

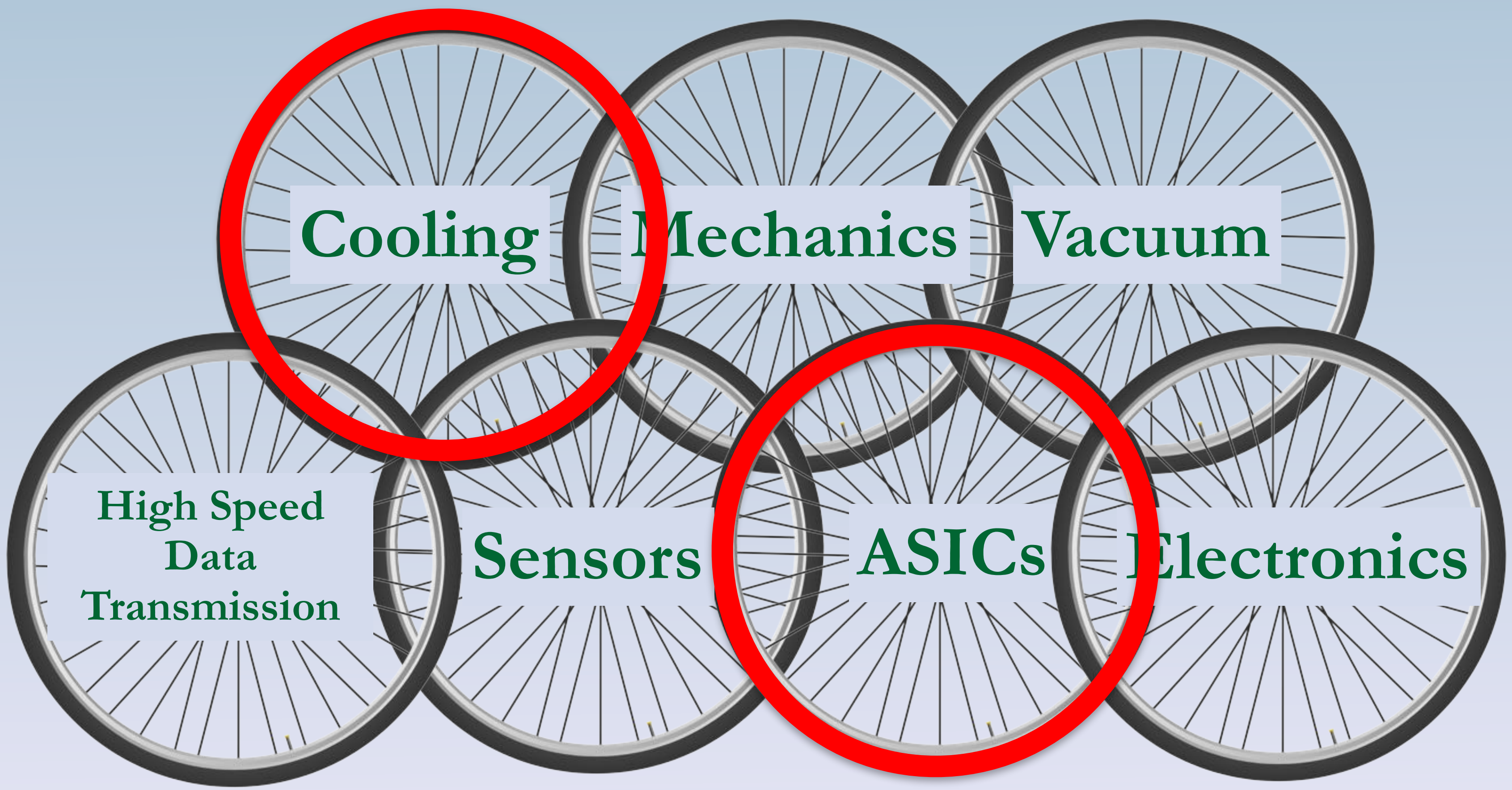
Focus on the VELO

VELO runs on many technologies

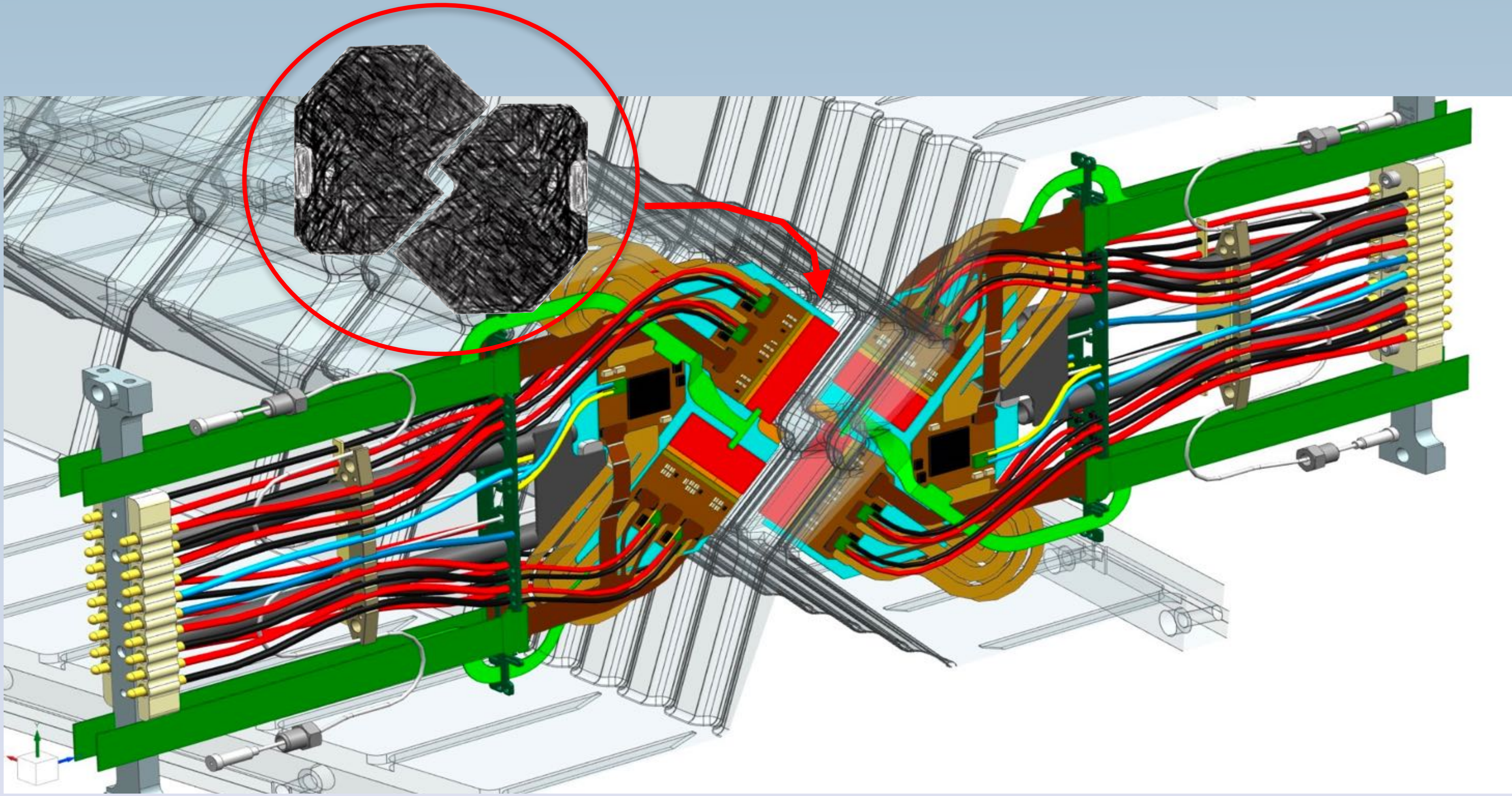


Focus on the VELO

Today will take a deep dive into two of these



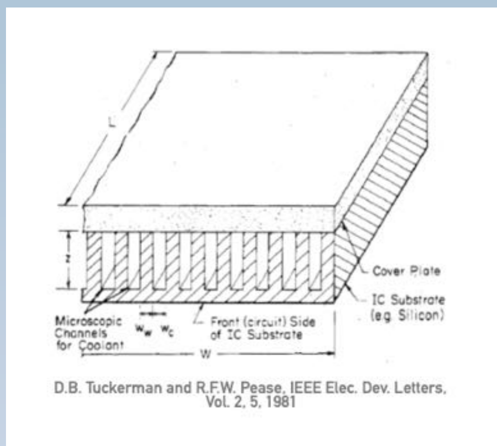
Microchannel Cooling



What is "microchannel cooling"?

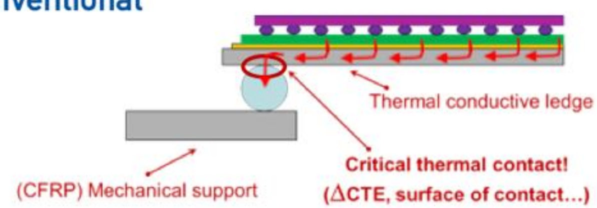
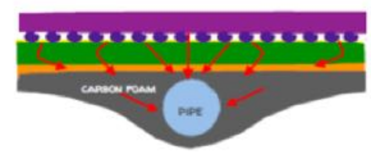
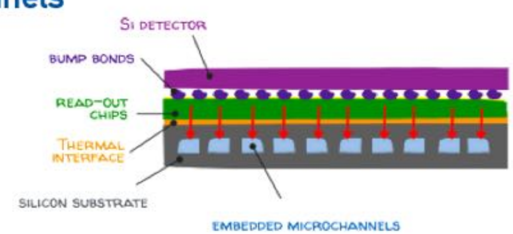
$$\text{TFM} = \frac{(\Delta T \text{ fluid - sensor})}{\text{power density}}$$

Original idea (liquid H_2O)



D.B. Tuckerman, R.F.W.Pease,: High performance heat sinking for VLSI, IEEE Electron Device Letters Vol. 2, Issue 5, pages 126-129,1981

- No CTE mismatch
- Low Material budget
- Active/distributed cooling
- Radiation resistance
- Great integration potential
- Great Thermal Figure of Merit

approach	TFM
conventional 	20
integrated 	12
microchannels 	5-8 liquid
	3 bi-phase

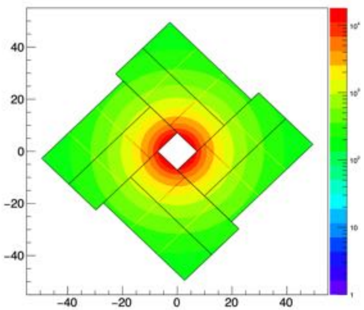
see P.Petagna, presentation, EIC tracking Workshop, Jul 24th 2018, A. Mapelli, presentation, 3rd FCC Physics and Experiments Workshop

VELO Pixel Cooling Requirements

Silicon pixel modules will accumulate ~ 50 fb^{-1} at a closest distance of 5.1 mm from the beam

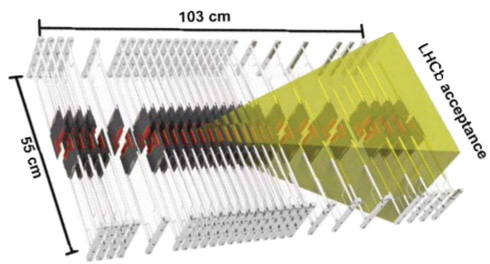
non-uniform Irradiation up to 8×10^{15} MeV n_{eq} / cm^2

Sensor tips must be kept **< -20°C** (almost) permanently while bump bonded directly to heat source



Cooling partially in acceptance for physics tracks

Vital to minimise material over entire cooling plate

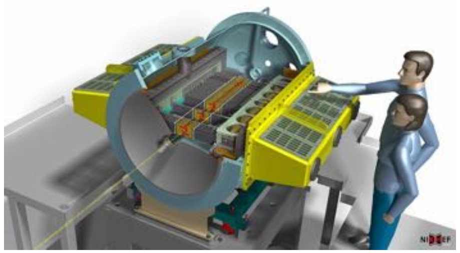


Modules dissipate 30W **<u>in vacuum</u>**

Total power:1.5 kW

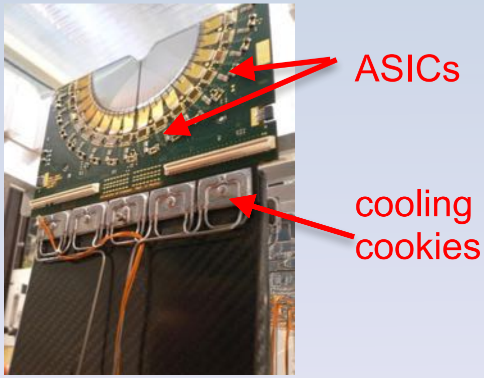
silicon tip: 1W/cm^2 after irradiation

High thermal efficiency mandatory

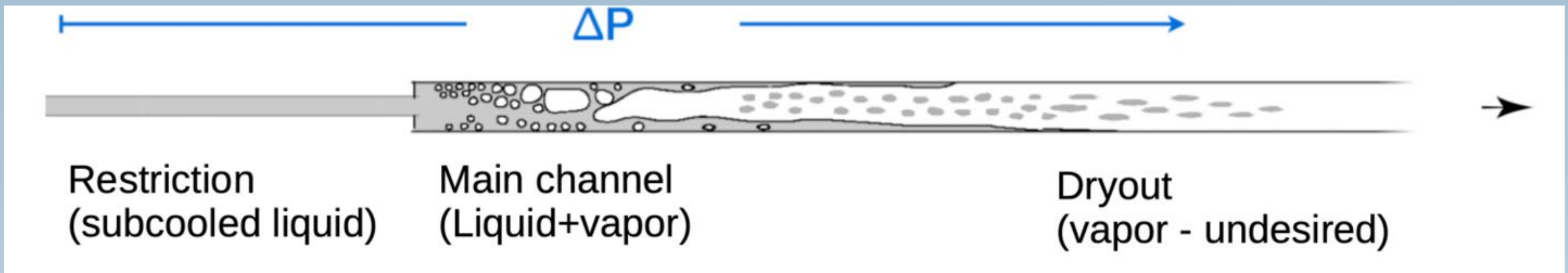


Ideal to find a solution which uses the CO_2 evaporative cooling already developed for LHCb (-35°C)

However the previous solution of cooling pipes embedded in aluminium “cookie” heat spreaders does not satisfy the pixel upgrade requirements



Microchannel Evaporative Cooling



- CO_2 has high latent heat capacity, low viscosity and is radiation hard
- The heat from the electronics is absorbed by the liquid CO_2, that evaporates
- Structures of the orders of 10s of μm are accessible
- The coolant temperature decreases from the input to the output
- The restriction dominates the fluidic resistance and so provides excellent control
  - Instabilities are avoided and the channels have even flow
- The system must withstand operational pressures
  - normal operation at -30°C → 20 bar
  - at room temperature → 65 bar
  - entire system must be validated to > 186 bar for safety reasons

LHCb Implementation

Channels integrated in silicon substrate under hybrid pixel tiles

Material budget: 500 µm Si + coolant

Very homogenous material distribution

Cooling delivered directly under heat sources

Thermal contact over flat area

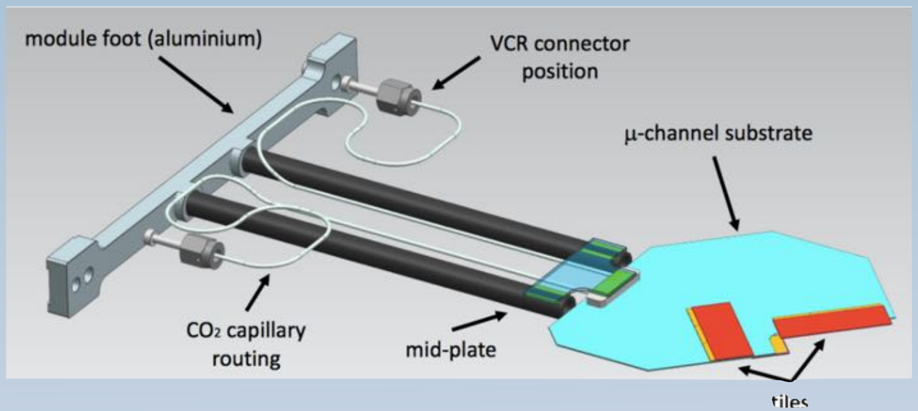
No CTE mismatch wrt ASICs and sensor

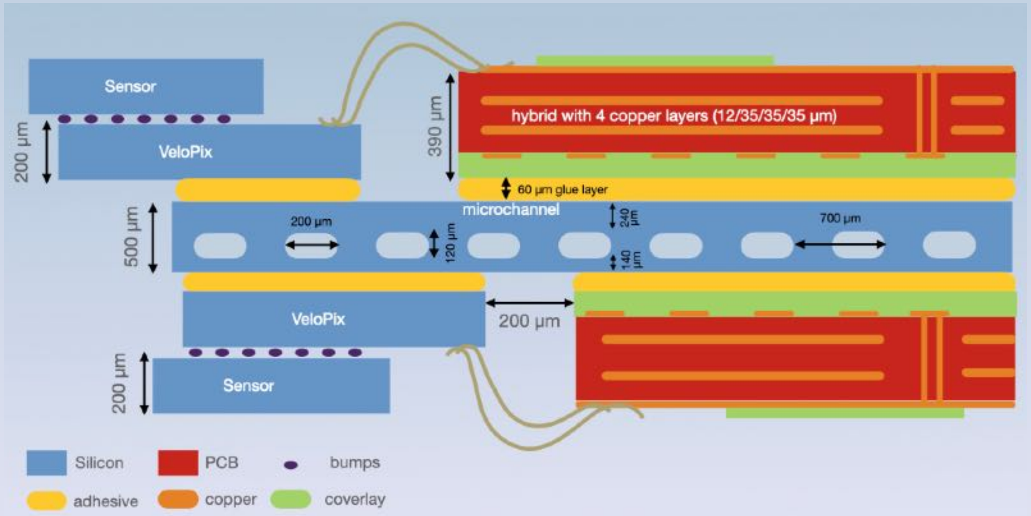
Very efficient cooling performance

- 60 µm glue interface only
- 120/240 µm Si between coolant and electronics
- Very high thermal conductivity (Si 150 W/m.K)
- Very low temperature gradients over substrate

Evaporative cooling → fast response to changes in power dissipation

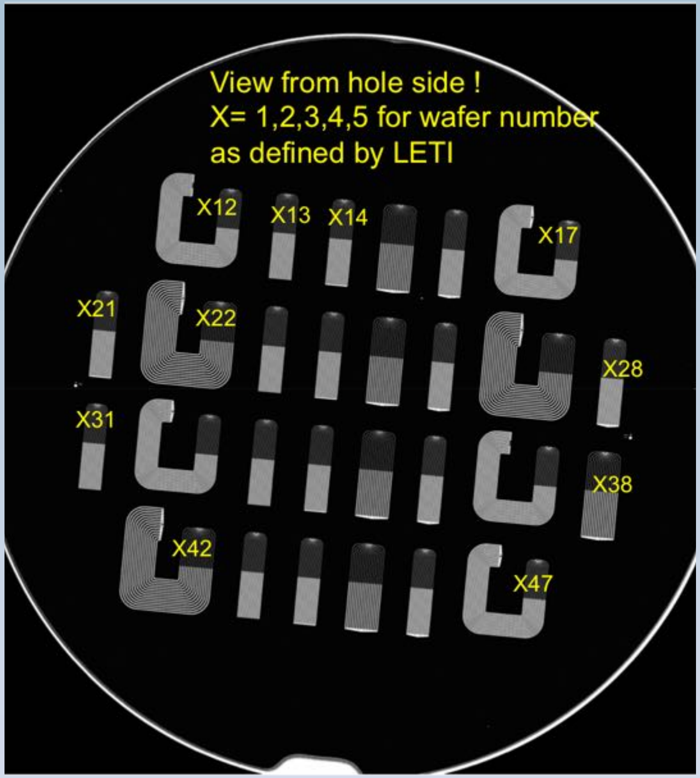
Cooling is so effective that the microchannel can be withdrawn 5 mm from module tip





Challenges: Production (large size of device), Mastery of full silicon process (DRIE, Direct Wafer Bonding), Fluidic connector attachment, QA for proven long term mechanical stability

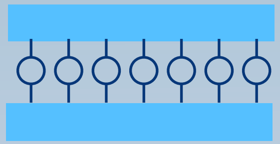
Bonding Layer Options

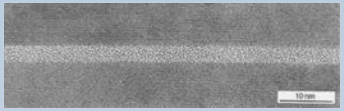


Scanning Acoustic Microscope image of bonded wafers with test structures

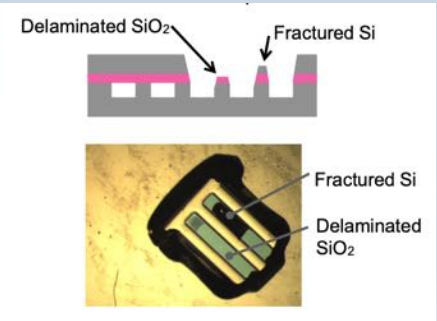
Hydrophilic bonding

- water molecules coat the surface
- T_{anneal} = 1050°C, P_{max} 400 bar
- Gives a good quality, even bond



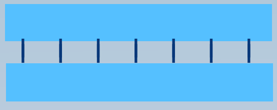


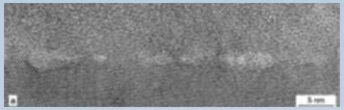
When tested to very high pressure:
Tendency to delamination + rupture



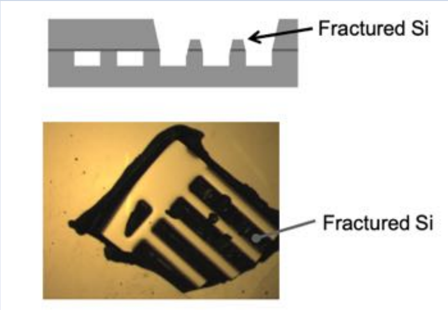
Hydrophobic bonding

- Highest quality bond with no oxide layer
- T_{anneal} = 1050°C, P_{max} 700 bar
- but more sensitive surface preparation





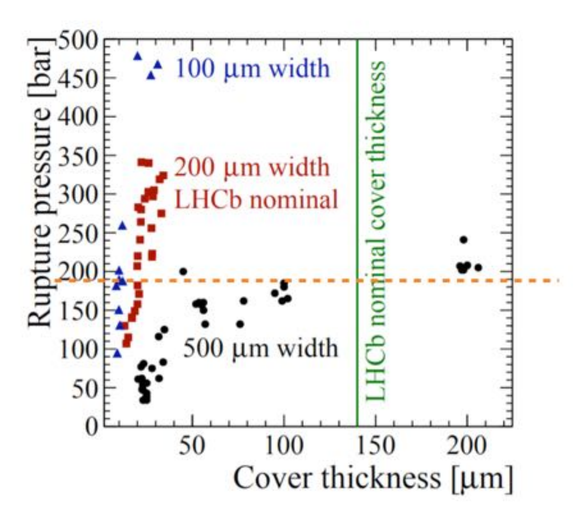
When tested to very high pressure:
Tendency to rupture without delamination

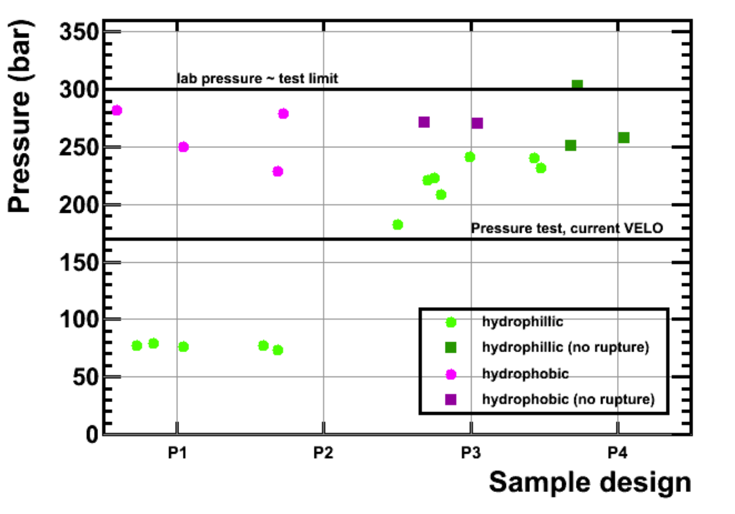


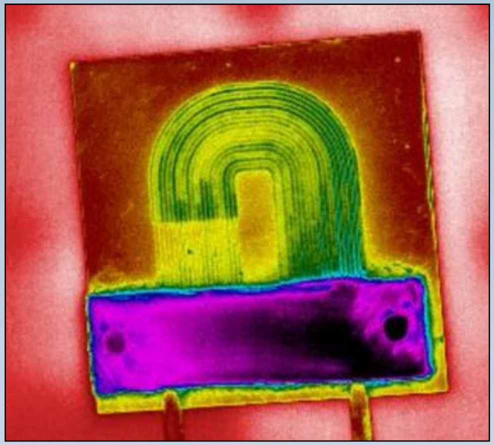
See A. Mapelli: Microfabricated silicon substrates for pixel detectors assembly and thermal management, presentation at 15th Vienna Conference on Instrumentation

Test Results I

At room temperature, saturation pressure of CO_2 is around 65 bar
For safety reasons, the system must be validated to 186 bar







Cover test

Layout test

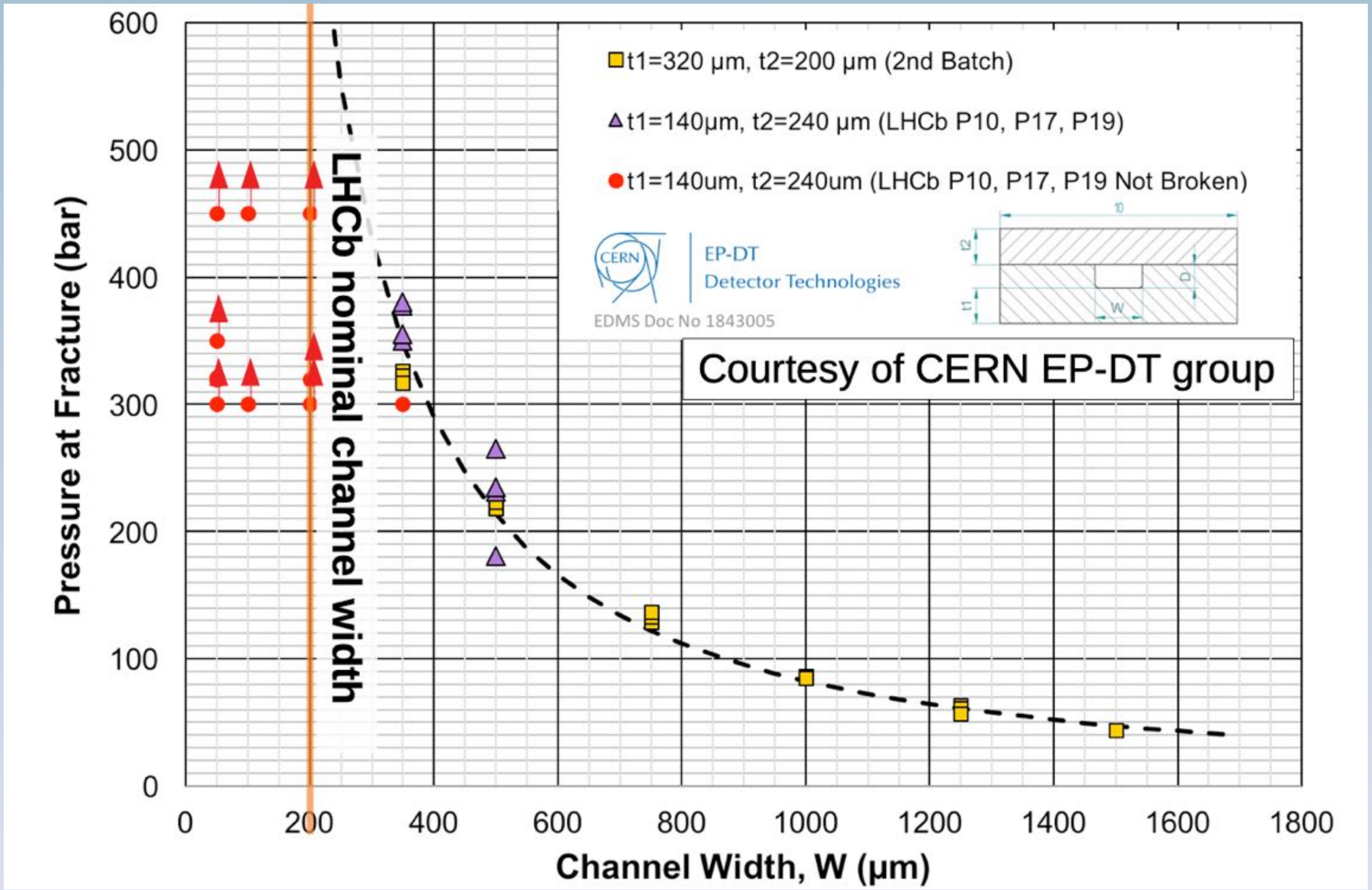
Cooling test
(with different prototype)

Even with a silicon cover << nominal, the safety requirements are surpassed

As long as the large manifolds are avoided, the samples surpass the safety test for both hydrophilic and hydrophobic bonding

Qualitative results show expected behaviour

Test Results II



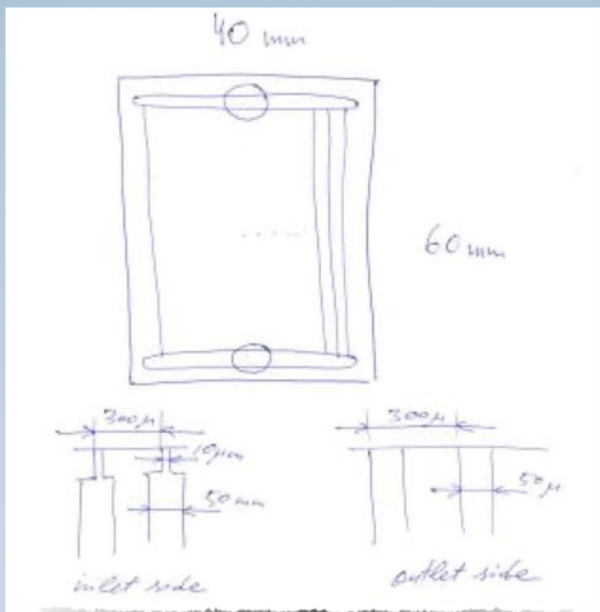
Measurements made in collaboration with NA62 and fitted to a theoretical curve, demonstrating role of the channel width

No LHCb sample with nominal geometry broke, up to maximum test pressures of 400 bar

Microchannels are proven to be small, but very strong!

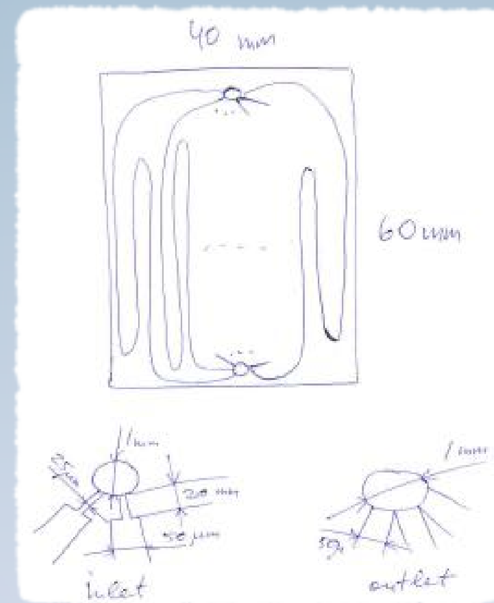
Initial Designs

‘Simple Design’



- 75 parallel channels on 300 μm pitch
- 10 μm x 5 mm inlet
- 50 μm x 45 μm boiling channel
- 100 μm etching depth (channels and manifold)
- 1 mm wide manifold

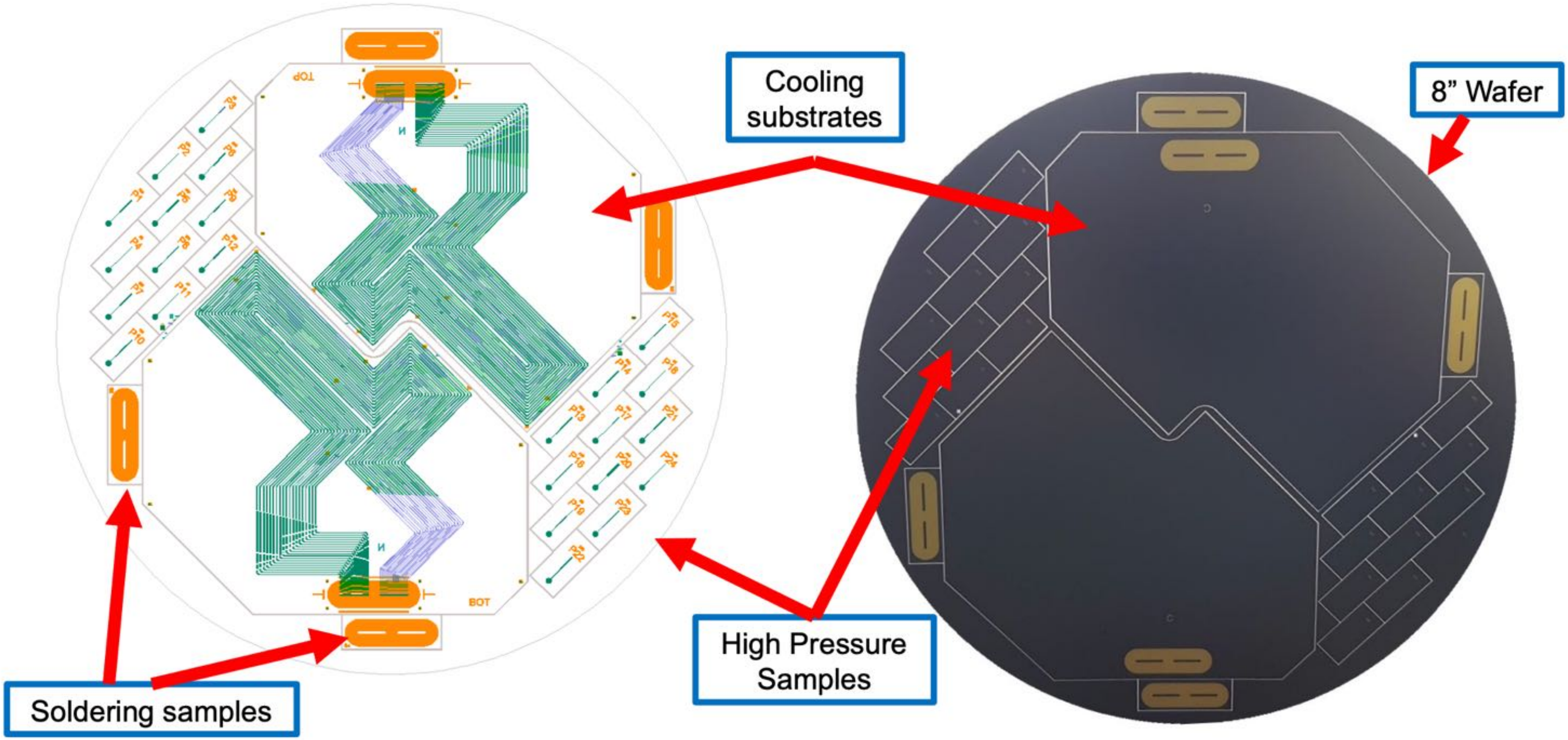
‘Spider Design’



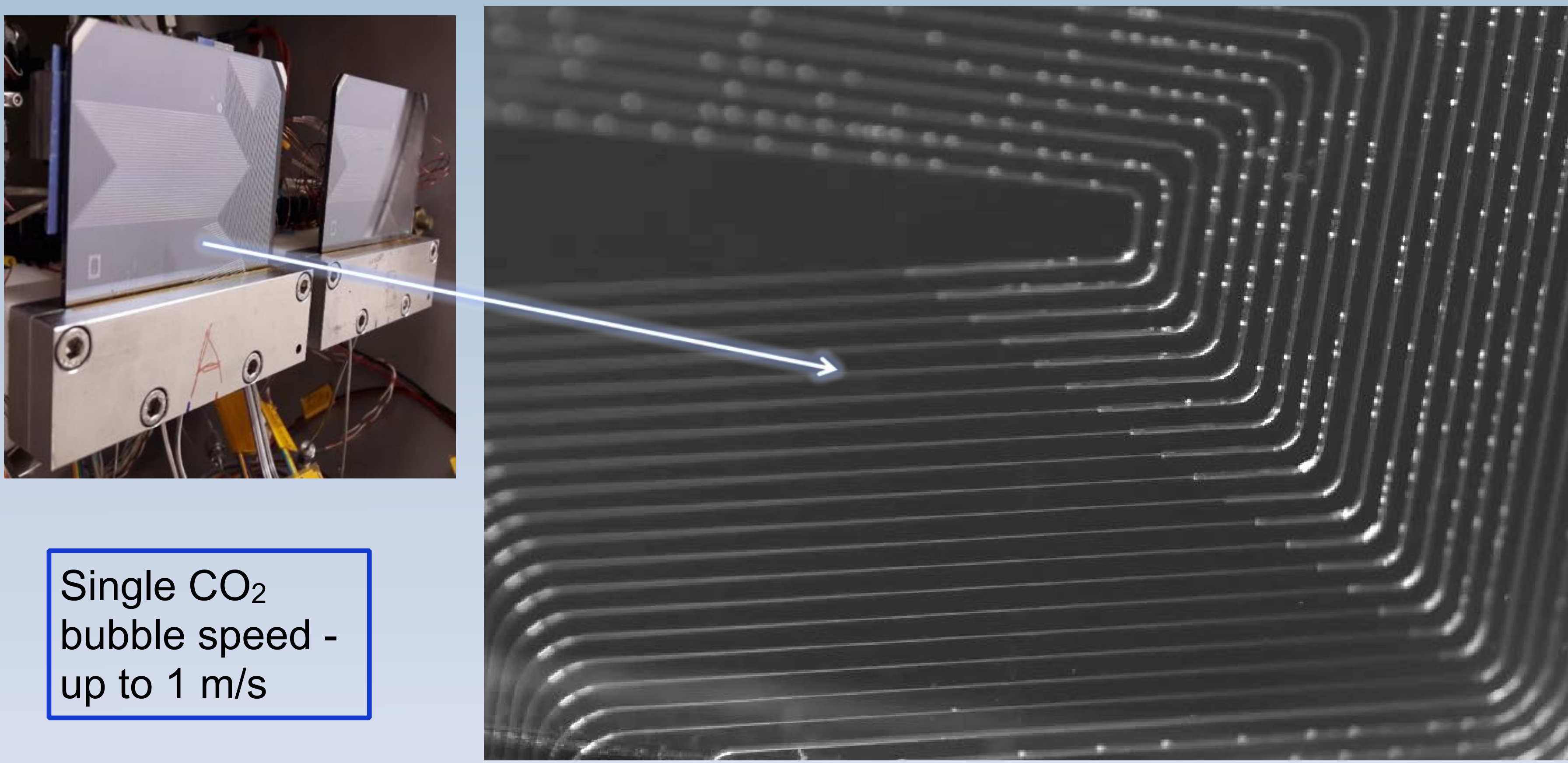
- 15 parallel channels on 200 μm pitch
- 25 μm x 20 mm inlet
- 200 μm x 135 μm boiling channel
- 100 μm etching depth (channels and manifold)
- manifold is small and can be located anywhere

see A. Nomerotski et al, “Evaporative CO_2 cooling using microchannels etched in silicon for the future LHCb vertex detector” link

Contents


Cooling substrates
8” Wafer
High Pressure Samples
Soldering samples

Demonstrator



Single CO_2 bubble speed - up to 1 m/s

Final Design

Race track like layout

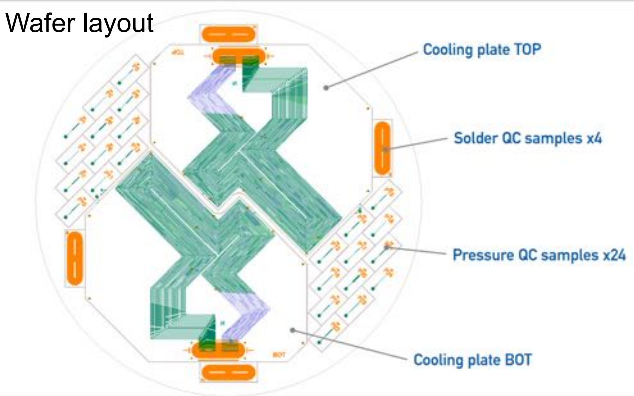
Restrictions: 60 x 60 μm²

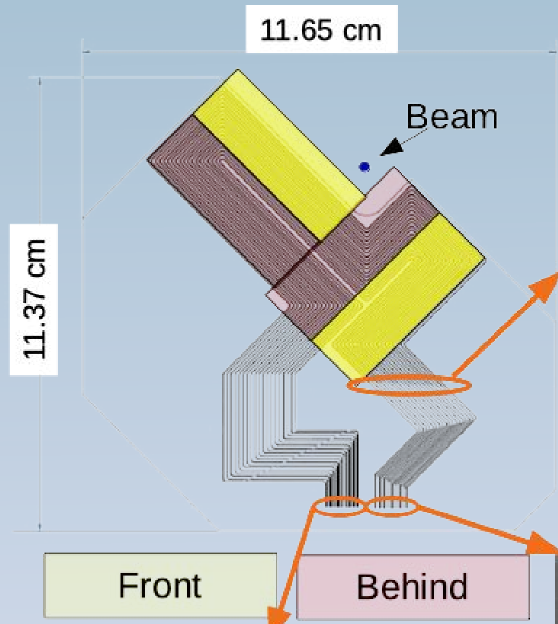
Main channels: 120 x 200 μm²

19 channels with approximately the same total length (~ 30 cm)

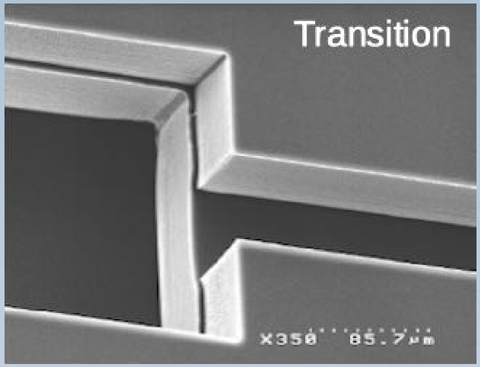
Each channel has its own inlet and outlet hole (200 x 600 μm²)

CO_2 distribution among channels done by connector





©CEA



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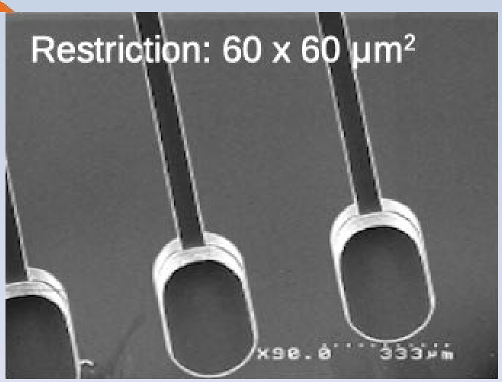

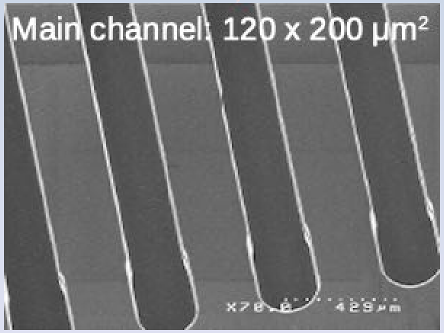

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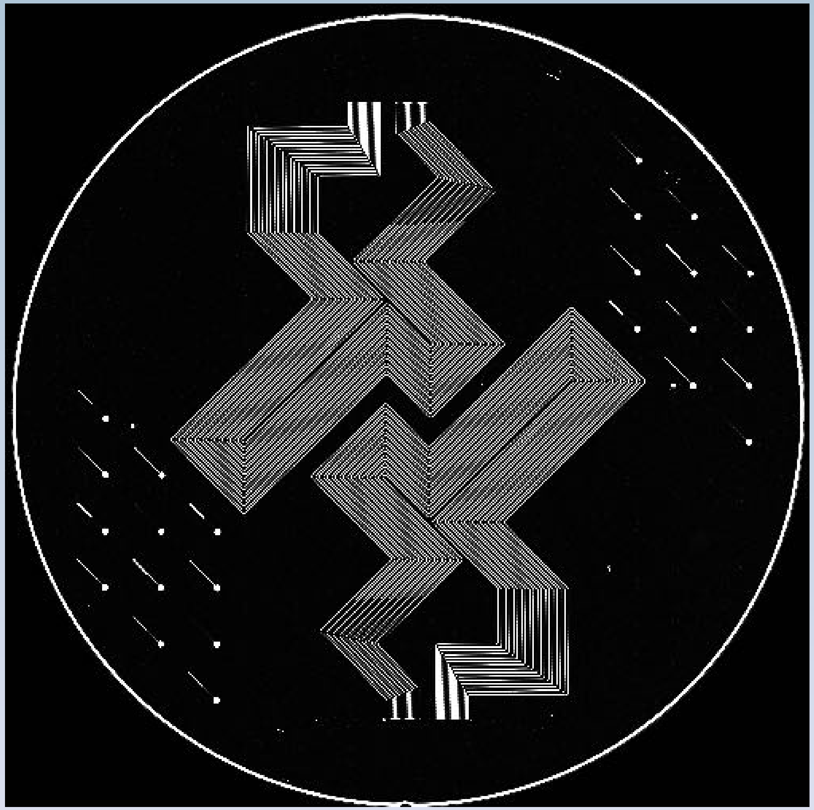
Grading and Quality Control

Major part of grading based on high resolution scanning acoustic microscope images (resolution < 50 μm) taken at wafer level after bonding, and again after thermal annealing



Grade A: no defects

Grade B: defects close to input/output

Grade C: defect near channels

Grade P: dicing defects

See presentation of C. Bertella, 28th International Conference on Vertex Detectors, October 2019

Guiding principle, limiting channel width (see slide 13)
Additional grading added for surface quality, planarity etc.

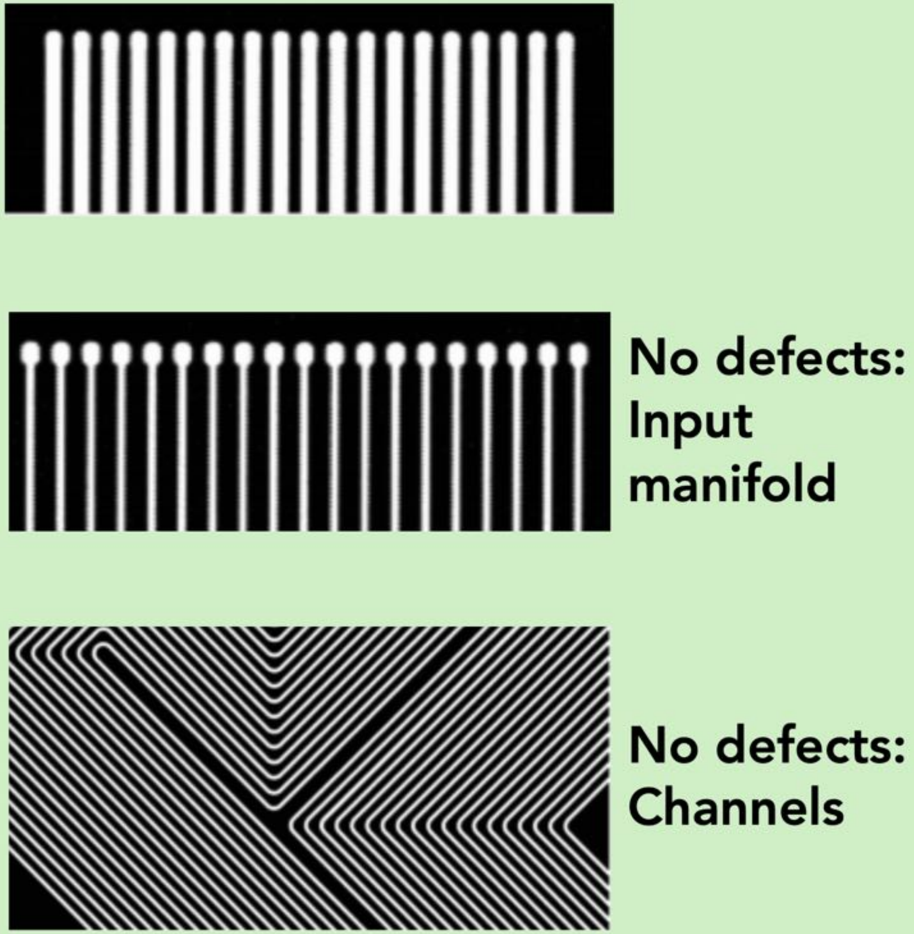
Grading and Quality Control

Grade A: no defects

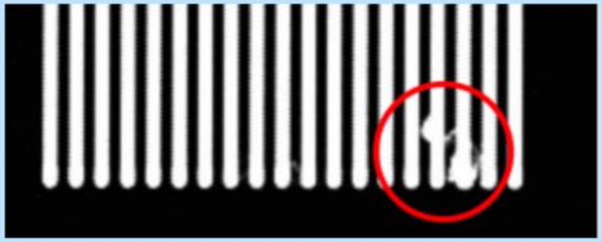
Grade B: defects close to input/output

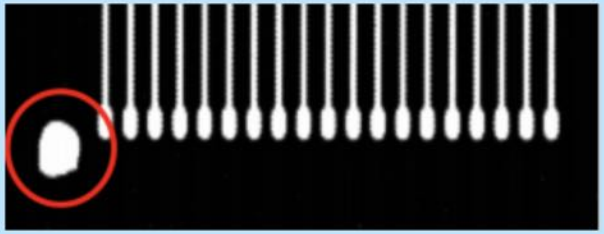
Grade C: defect near channels

Grade P: dicing defects



Grading and Quality Control





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Grading and Quality Control

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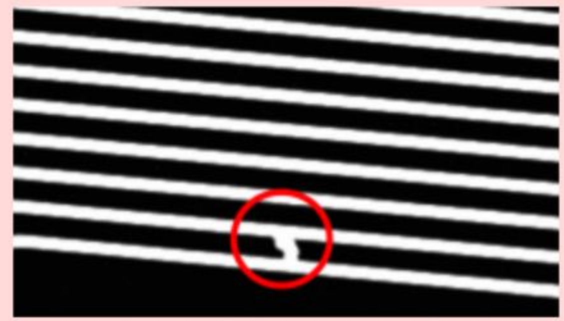
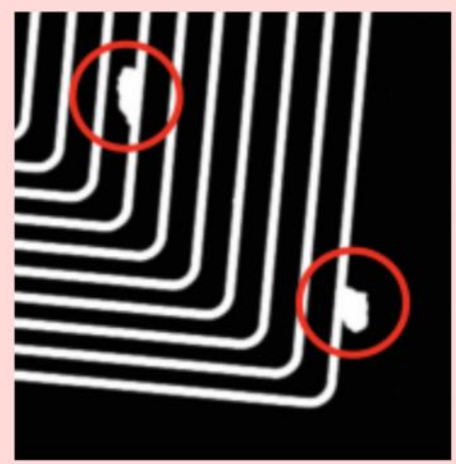
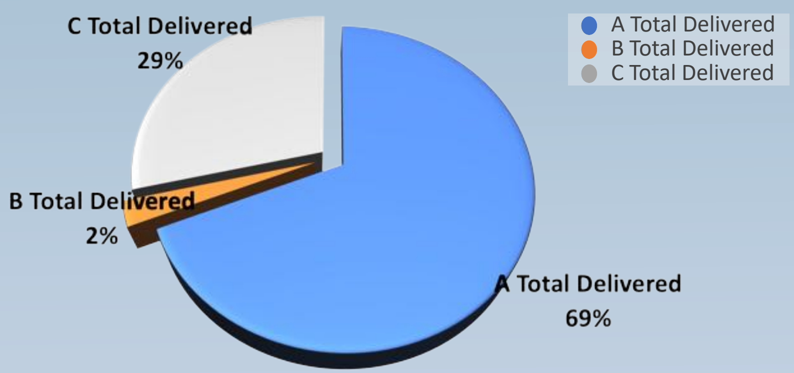


Connected channels



Defects connected to the channels

Grading and Quality Control



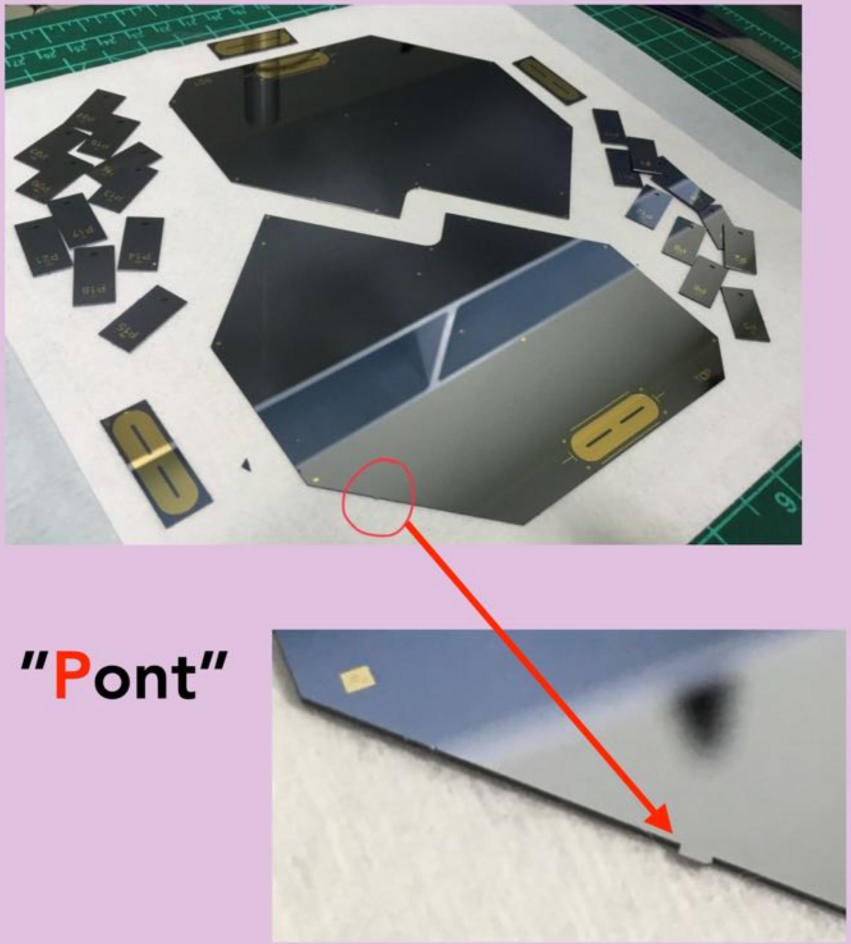
Grade A: no defects

Grade B: defects close to input/output

Grade C: defect near channels

Grade P: dicing defects

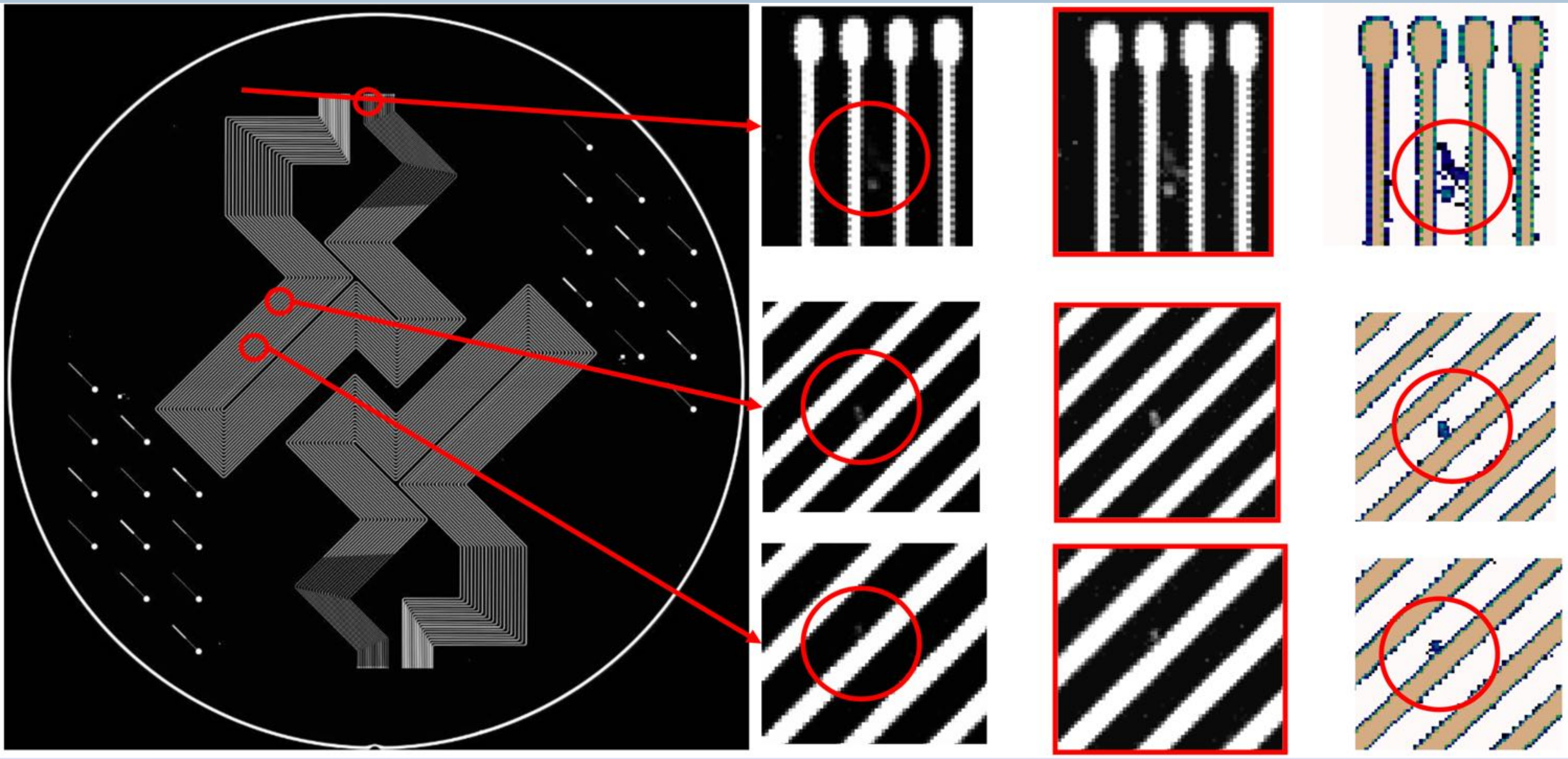
Bonding grading most challenging component of overall yield



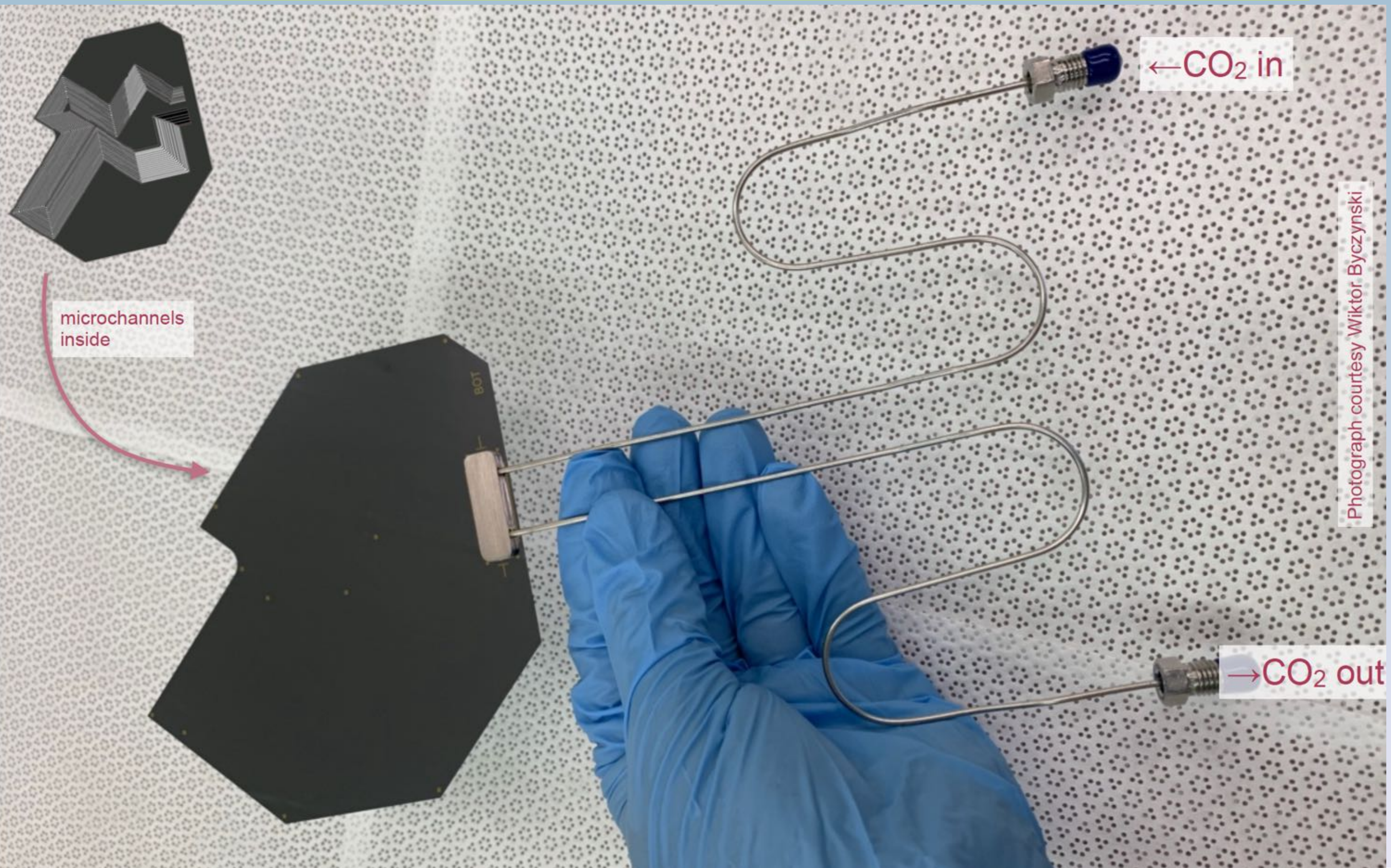
Grading and Quality Control

Analysis of images very time consuming and tiring: new technique developed to process the images

- Grey scale transformed to colour map with background suppression
- Algorithm useful to assist visual inspection - all features found verified in original SAM



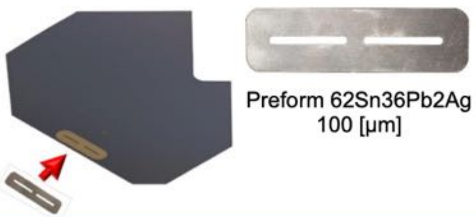
Assembly of Connector and Susbstrate

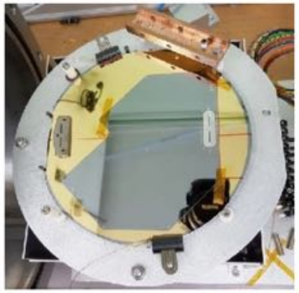


Fluxless Connector Soldering

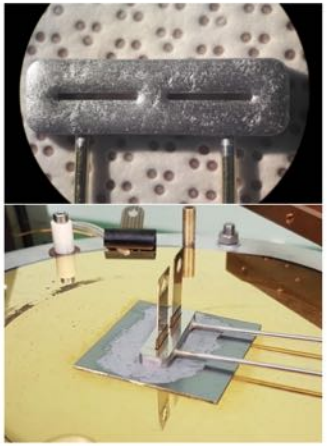
Fluxless process to avoid long term corrosive effects in the cooling system

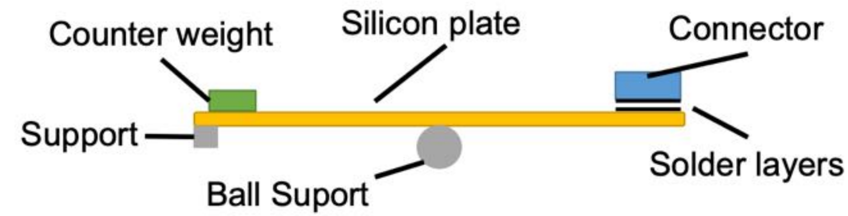
Silicon pretinning

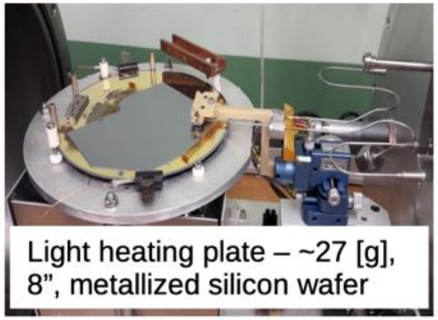


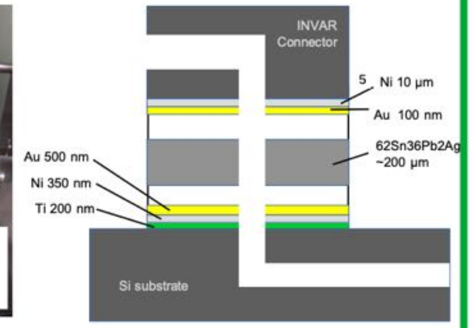


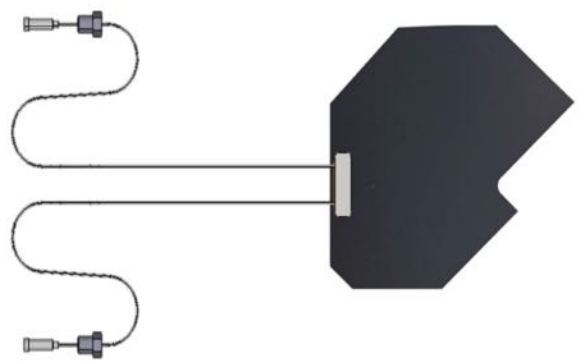
Connector pretinning



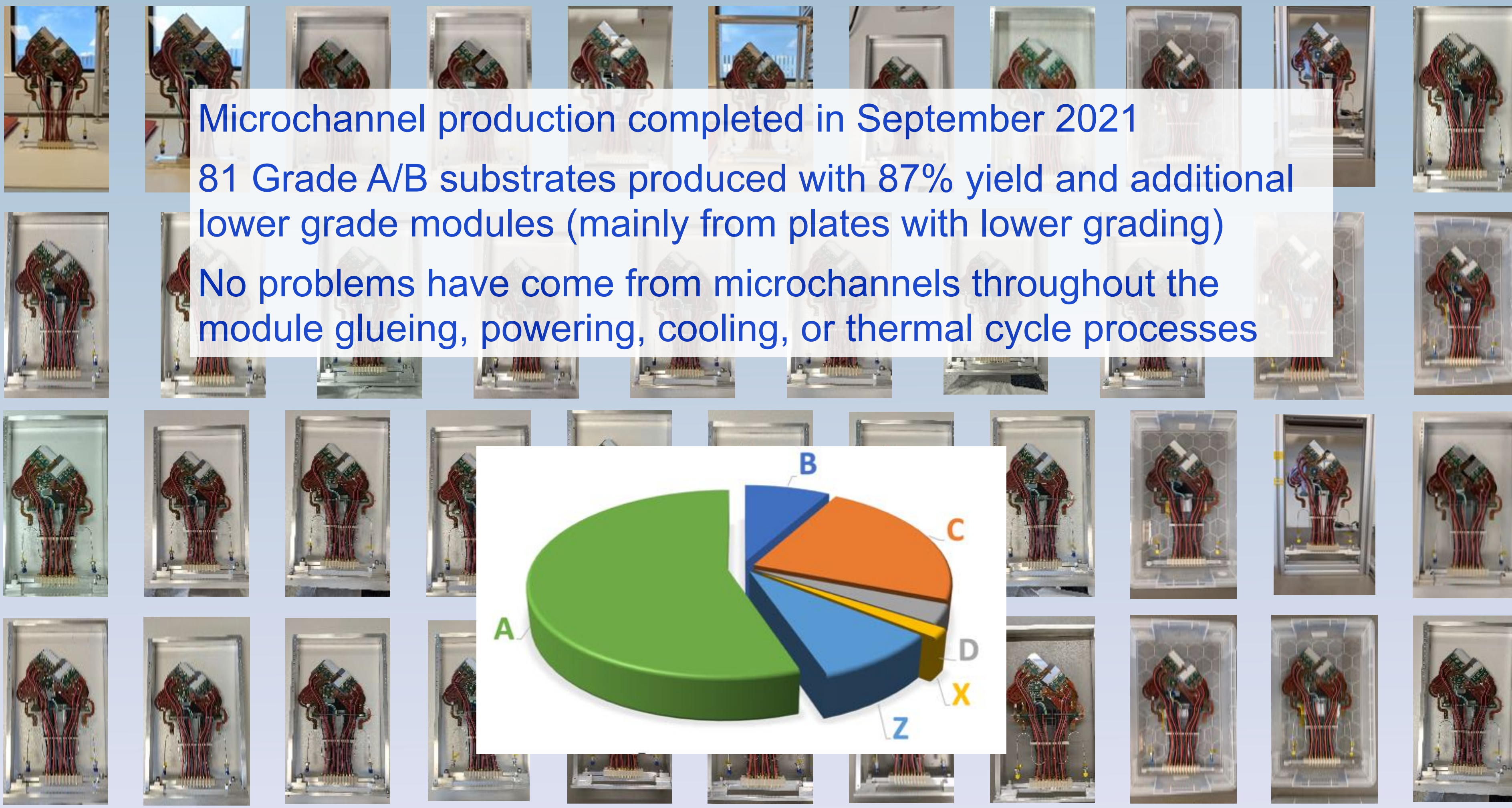








Production Yield



Microchannel production completed in September 2021

81 Grade A/B substrates produced with 87% yield and additional lower grade modules (mainly from plates with lower grading)

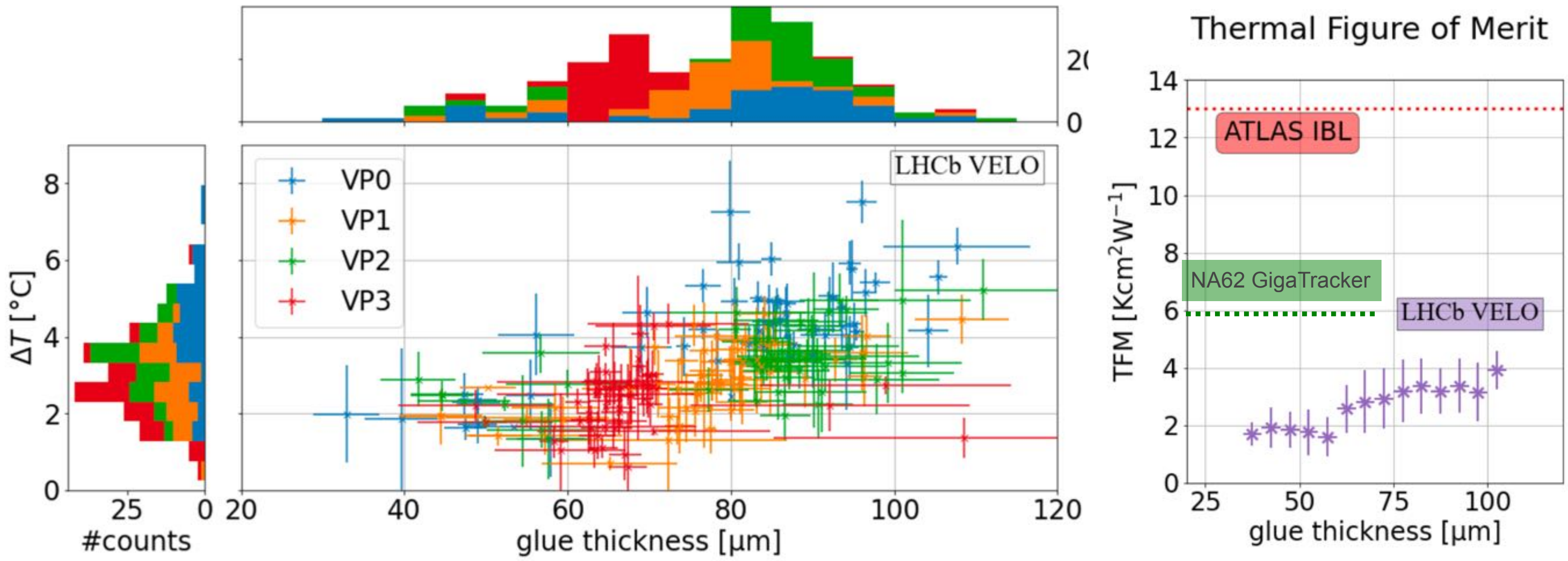
No problems have come from microchannels throughout the module glueing, powering, cooling, or thermal cycle processes

Cooling Performance

The performance of a cooling system can be characterised by the Thermal Figure of Merit;

$$\text{TFM} = \frac{\text{Difference in temperature between coolant and power dissipating element}}{\text{Power Density}}$$

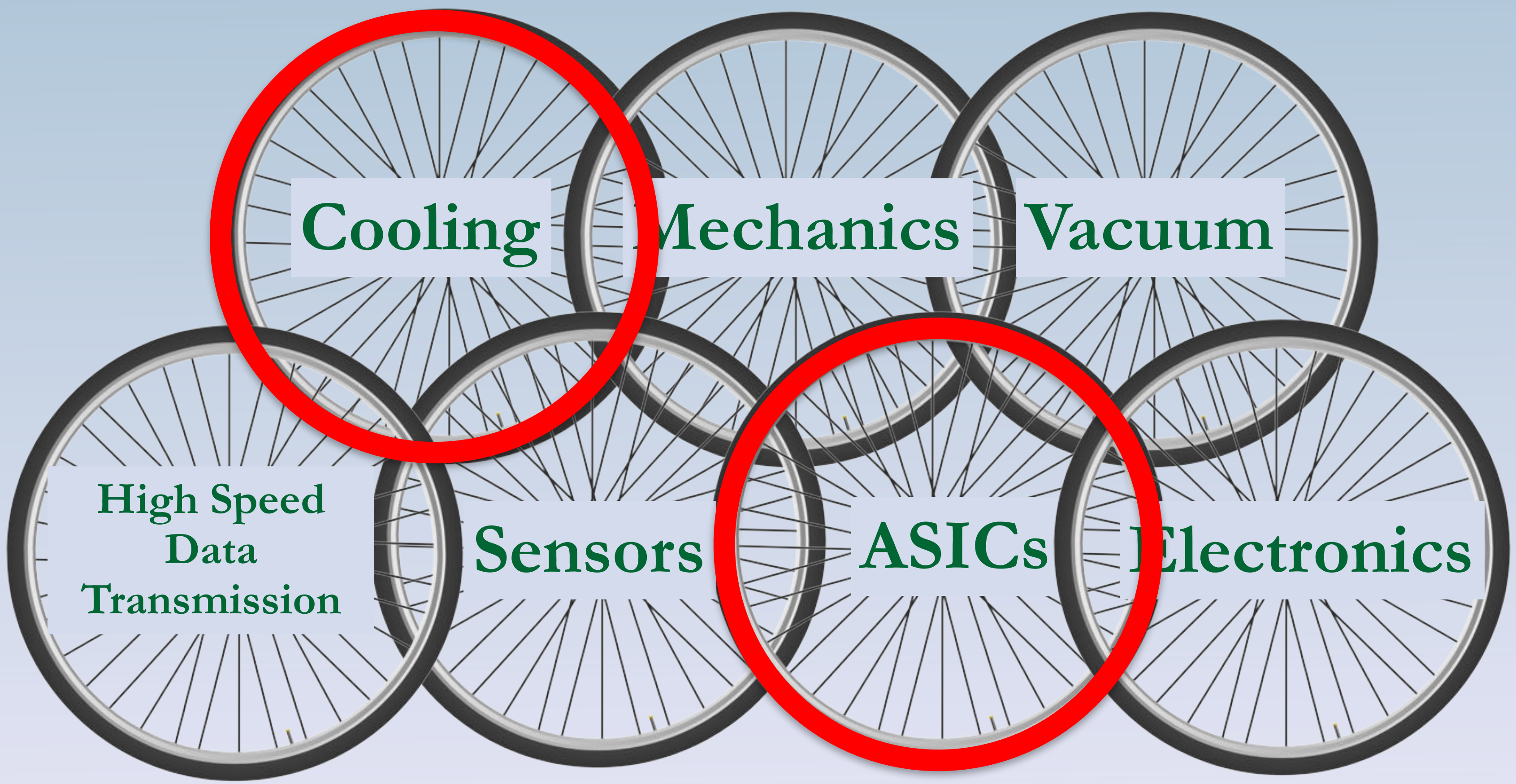
Expected values: ~ 20 for classical systems, ~12-13 for integrated pipe systems, ~5-6 for single phase microchannels



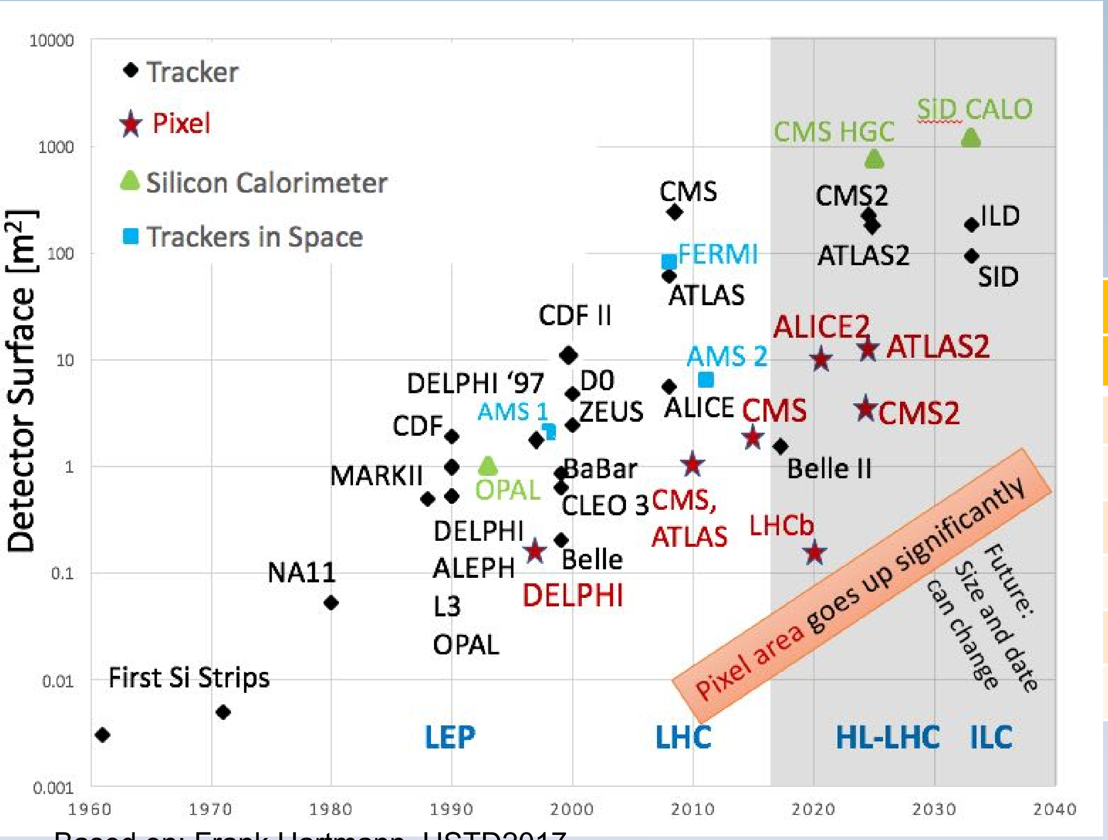
TFM measured value for all produced VELO modules between 2 and 3 (dependent on glue thickness)

Focus on the VELO

Today will take a deep dive into two of these



VELO in line with rise of hybrid pixels



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**

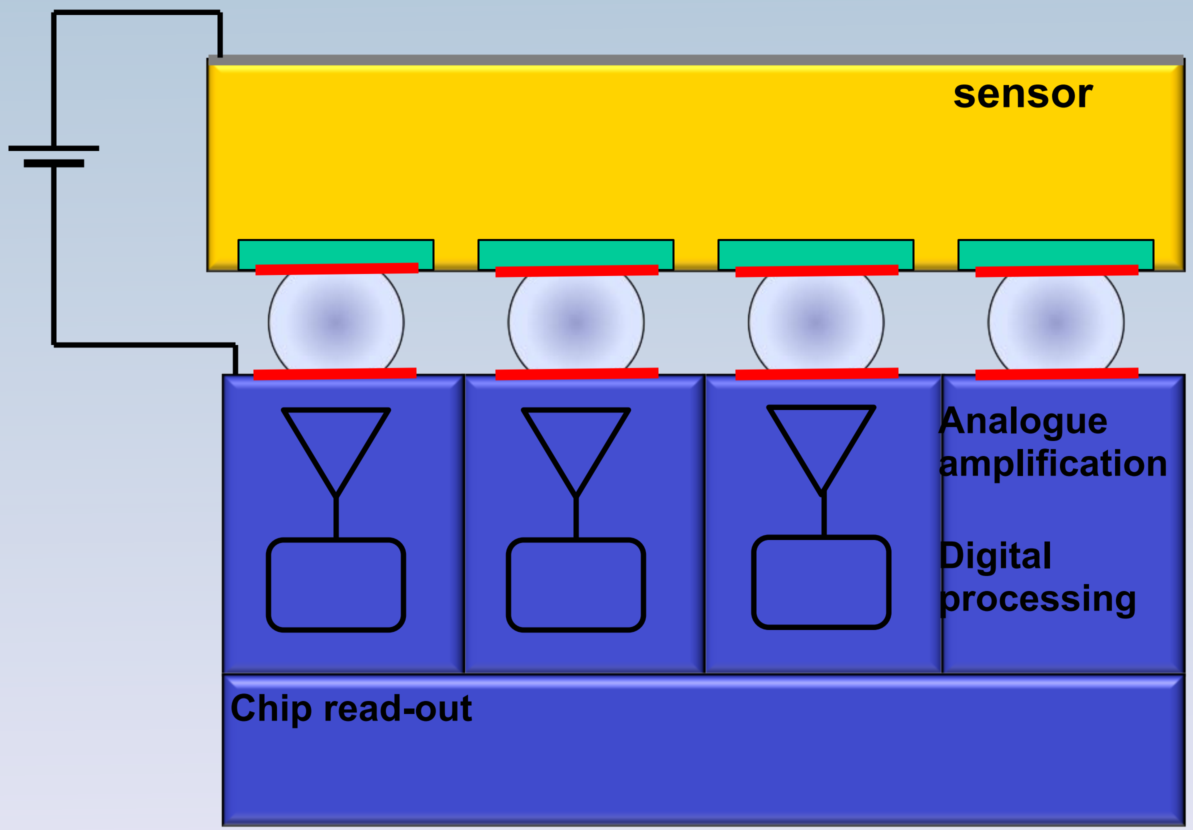
Cell granularity, the weapon against high-PU keeping occupancy at a reasonable level

Hybrid Pixels: Medipix/Timepix

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

In the case of the VELO close integration with Medipix/Timepix family.

Pixels for Medical Imaging

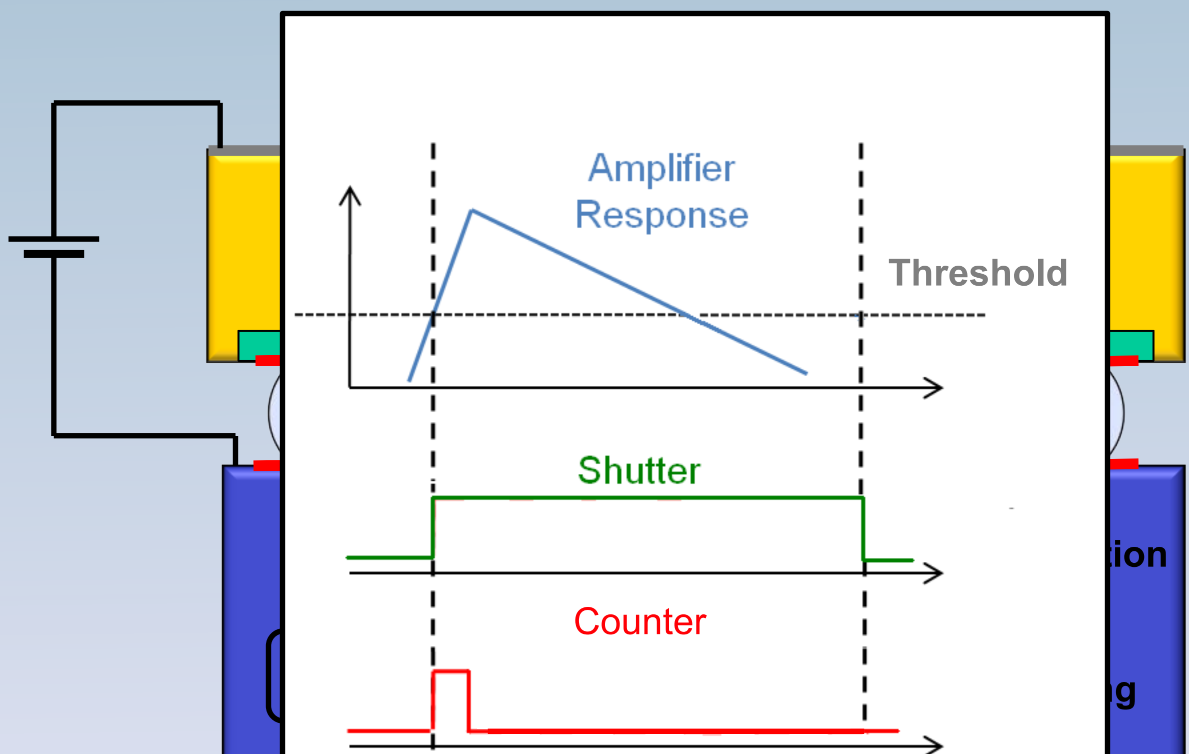


Idea: take advances in HEP and apply them to photon counting for medical physics

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



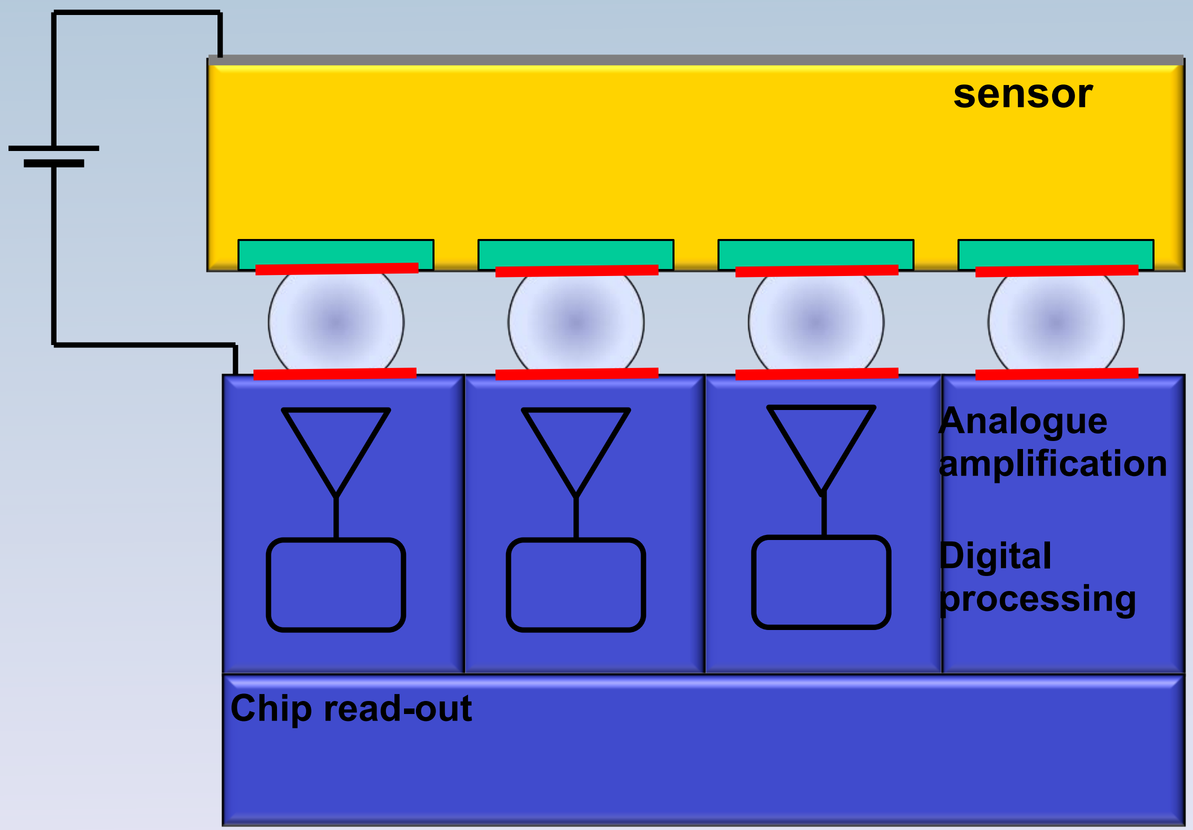
15 bit counter records number of impinging photons

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



Timepix design requested and funded by EUDET collaboration

Conventional Medipix2 counting mode remains.

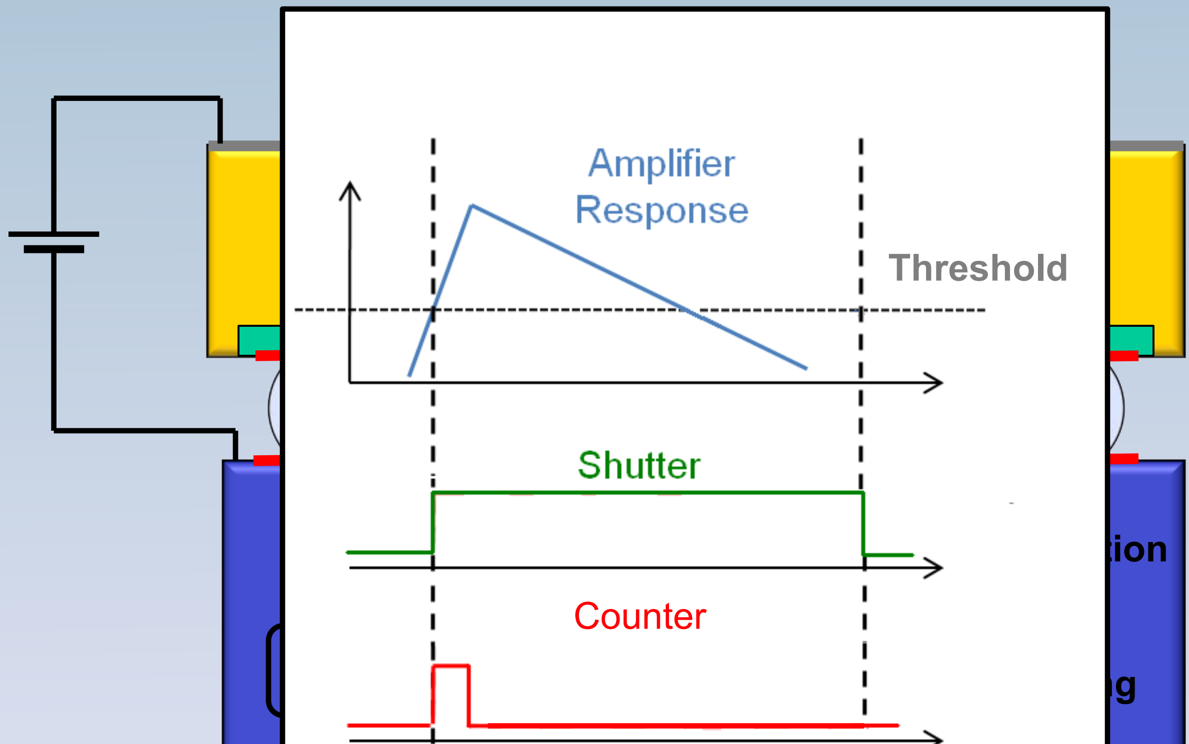
Addition of a clock up to 100MHz allows two new modes.

Time over Threshold

Time of Arrival

Pixels can be individually programmed into one of these three modes

Pixels for Medical Imaging



13 bit counter records number of impinging photons

Timepix design requested and funded by EUDET collaboration

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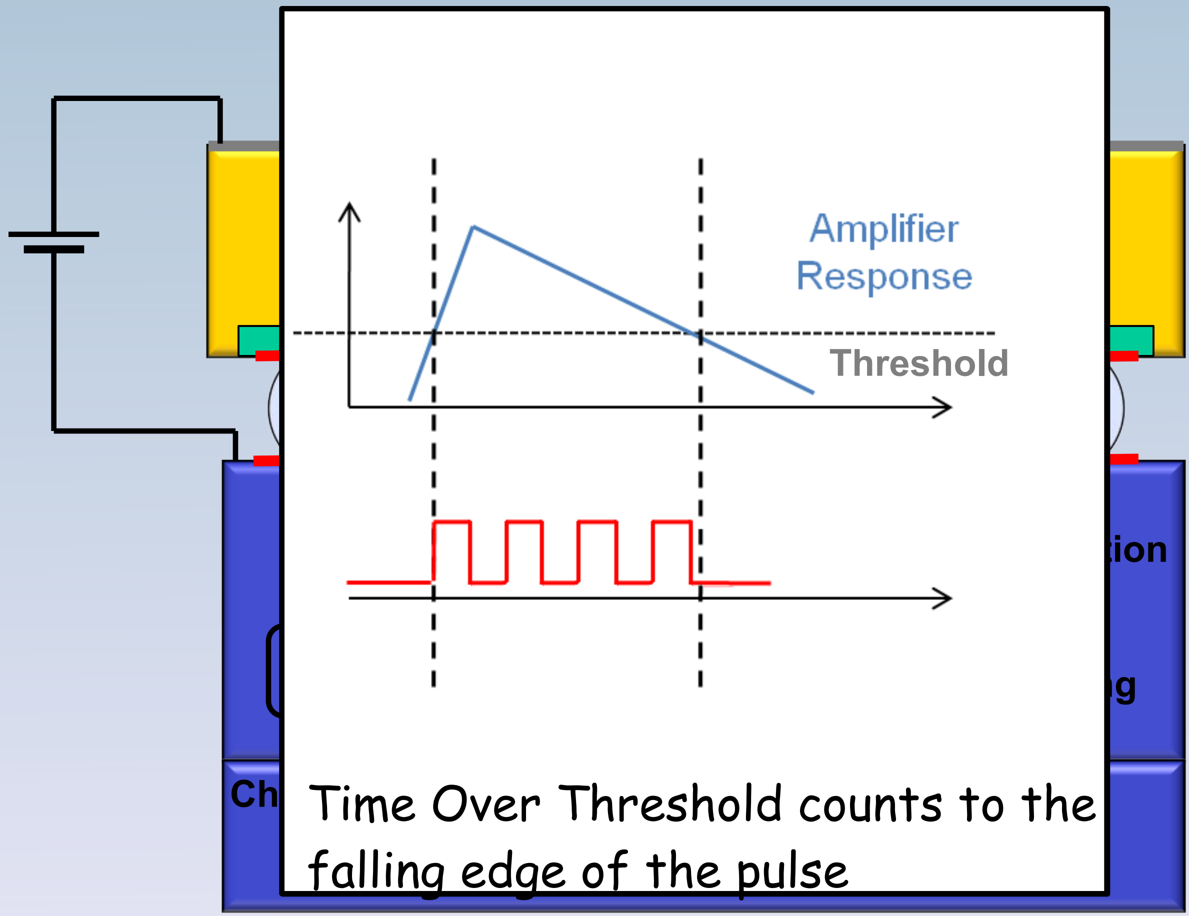
Pixels for Medical Imaging



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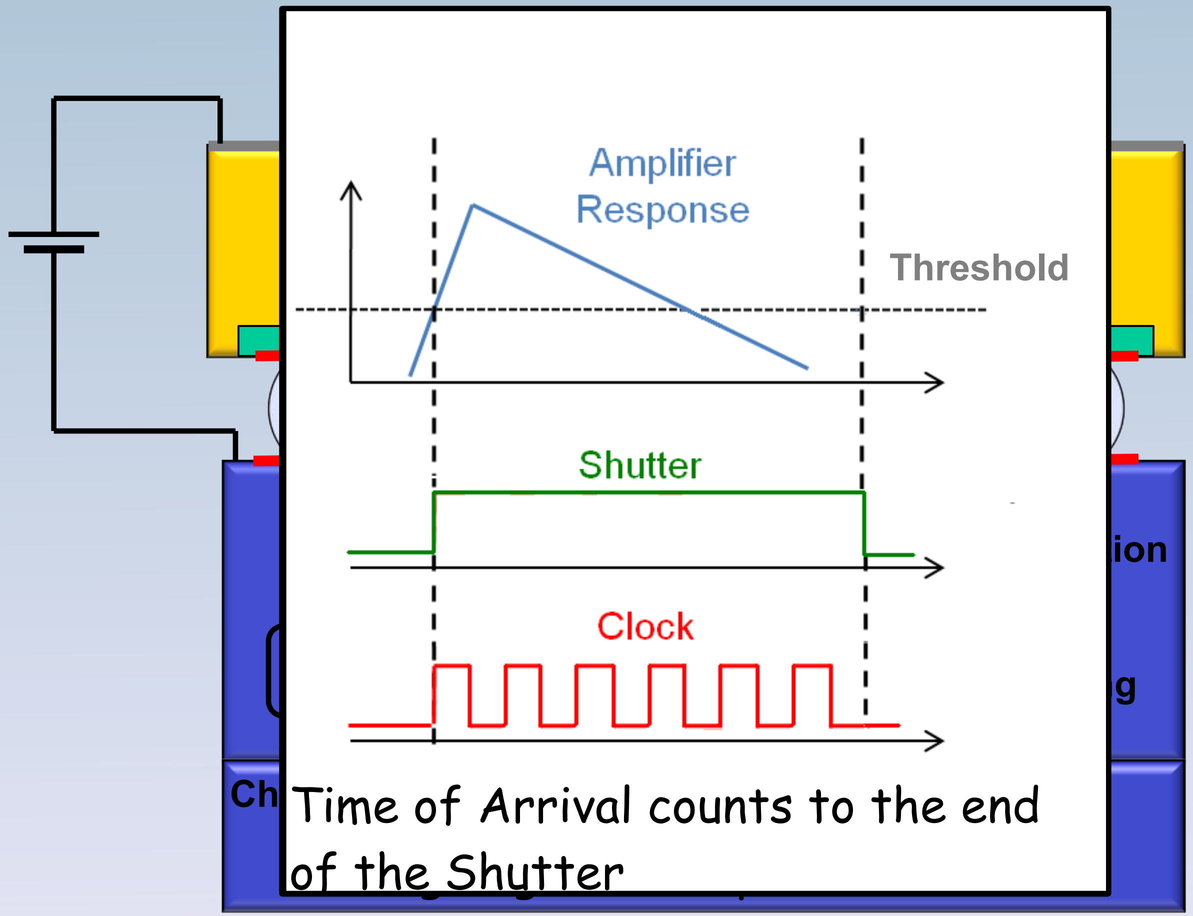

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Conventional Medipix2 counting mode remains.

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

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

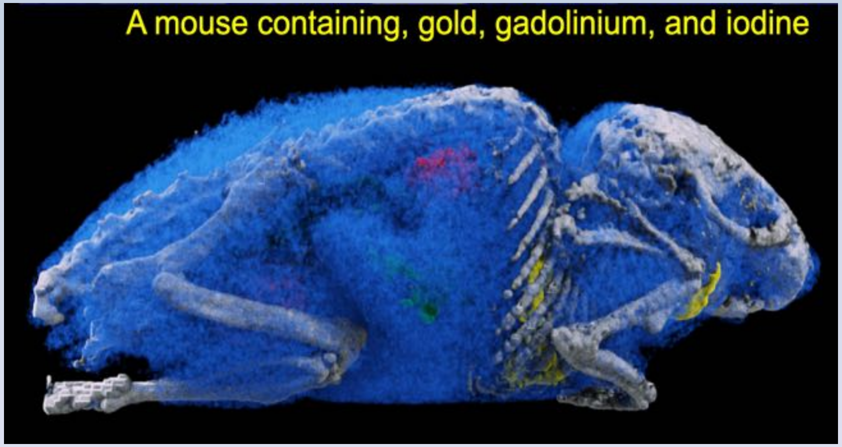
Medipix3: Convolvulus arvensis
3.1M pixels, 55 μm pixel pitch
Credits: Simon Procz,, Ph.D. Thesis, University of Freiburg

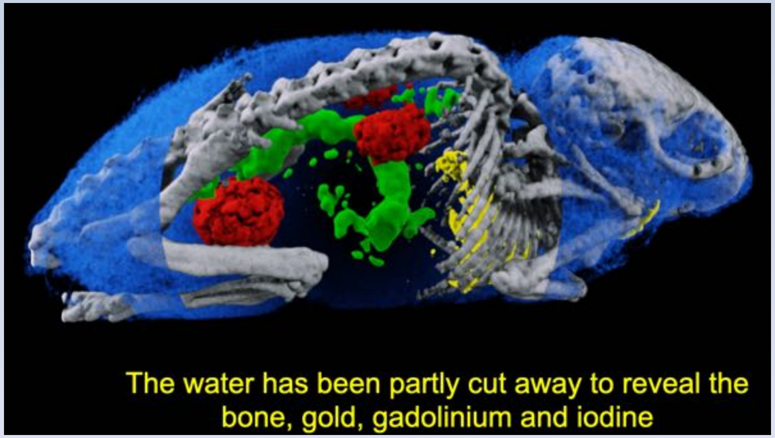
Spectral Imaging with MARS

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

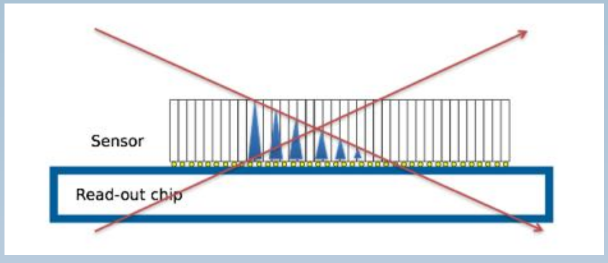




Timepix3 Specs - particle tracking

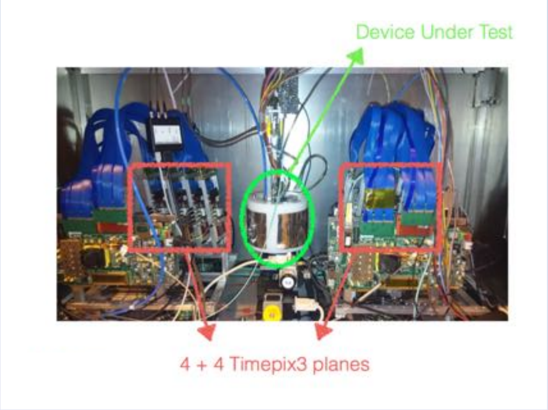
Timepix, and then Timepix3, applied to particle tracking

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



VELOPix for LHCb Upgrade I

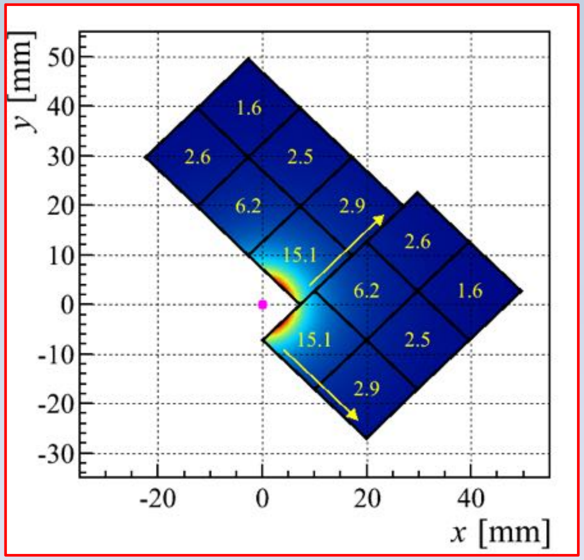
ASIC challenges: data rate & radiation hardness

- Sensor and ASIC exposed to high, non-homogeneous, radiation fluence
  - Only part of the pixel matrix gets the full dose of ~ 370 Mrad
  - TID at periphery of chip is factor 10 lower

- For data rates calc. we assume collisions in every LHCb bunch crossing
  - in reality only 2/3 of bunches collide
  - would require a lot of memory to level out
  - → assume peak rates for ASIC design
- Data flow simulations using physics Monte Carlo data

- No trigger, all data sent off chip
- Hottest ASIC gives ~20 Gbps

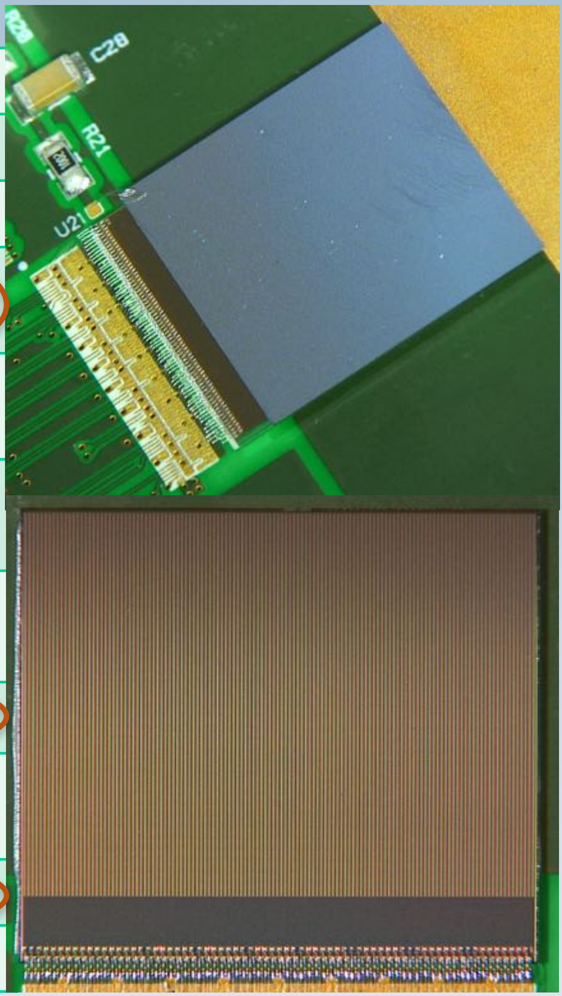
- ASIC design starting point: Timepix3



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 μm^2	
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



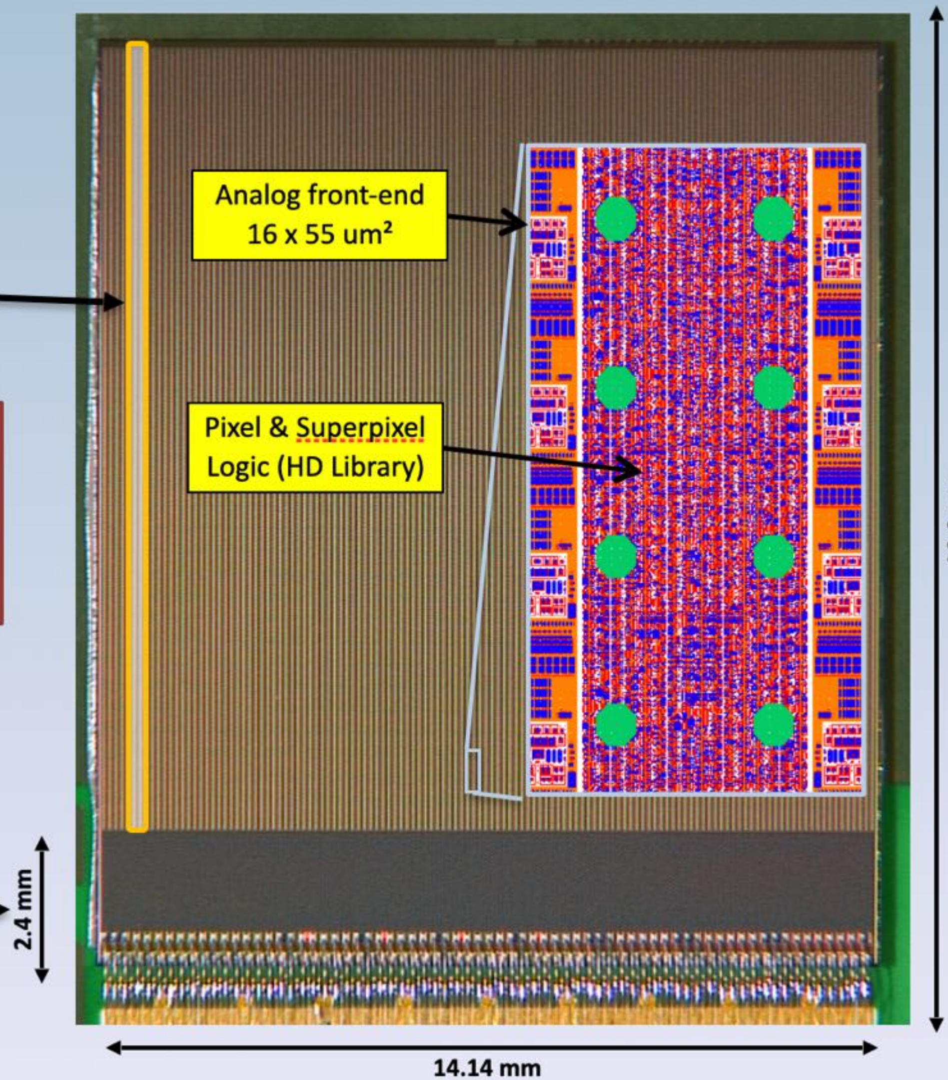
VeloPix

Design started 2013
Engineering runs 2016/2017

Double column:
- 512 pixels
- 64 super pixels

Full matrix:
- 128 Double columns
- ~190 Mtransistors
- 14.8nF digital decoupling (thick gate)

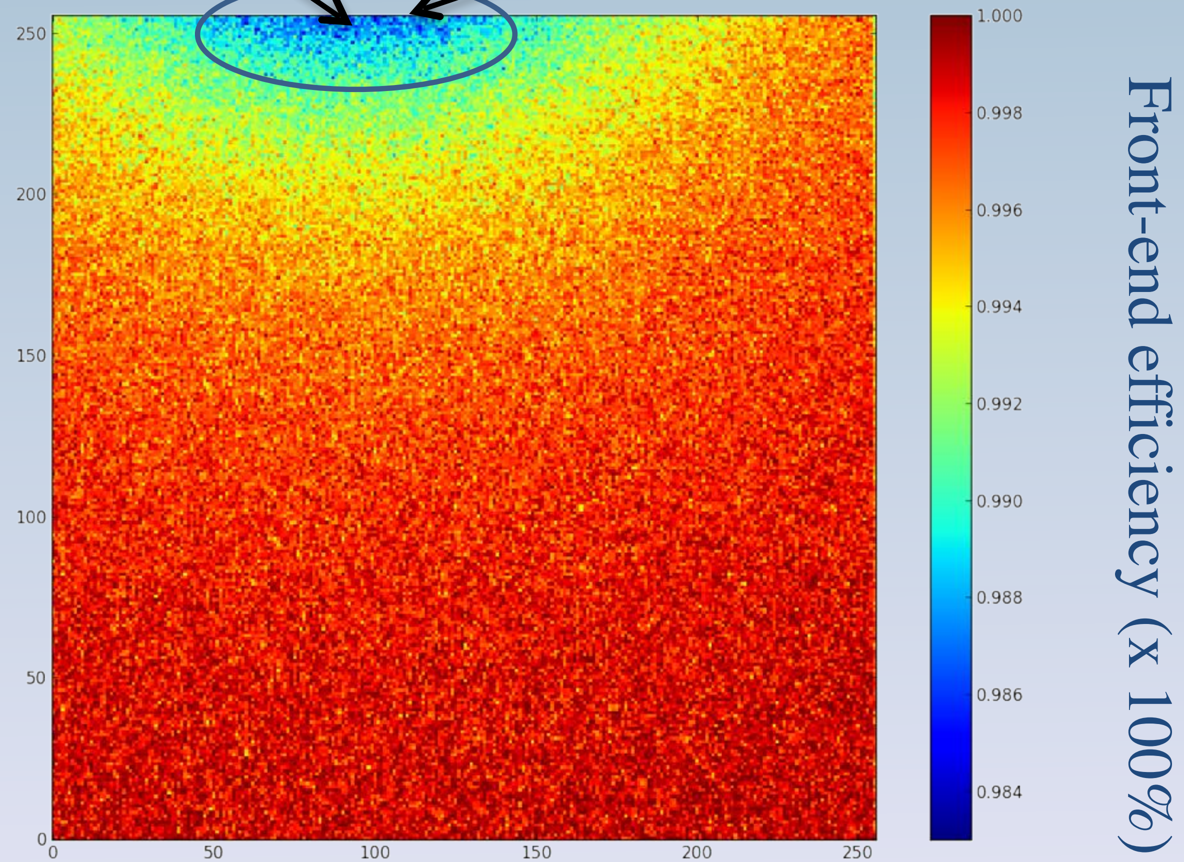
Active Periphery:
- 40, 80, 160 and 320 TMR clocks
- HVT TSMC (tcb013ghphvt library)
- 4nF digital decoupling (thin gate)



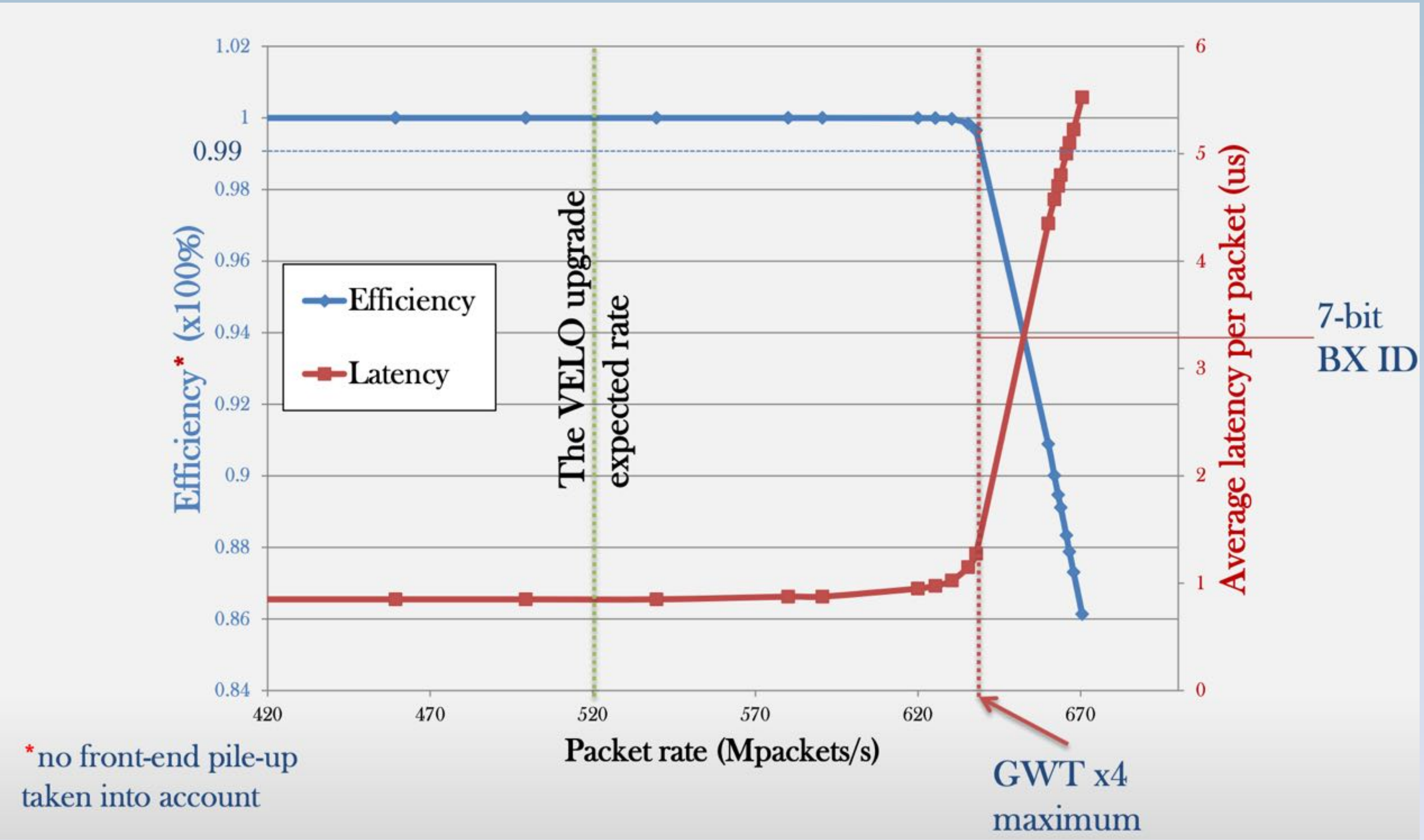
Analog Front End Pileup (simulated)

Up to 1.6% losses

Rates up to 50 kHz per pixel



Data Transfer Efficiency (simulated)

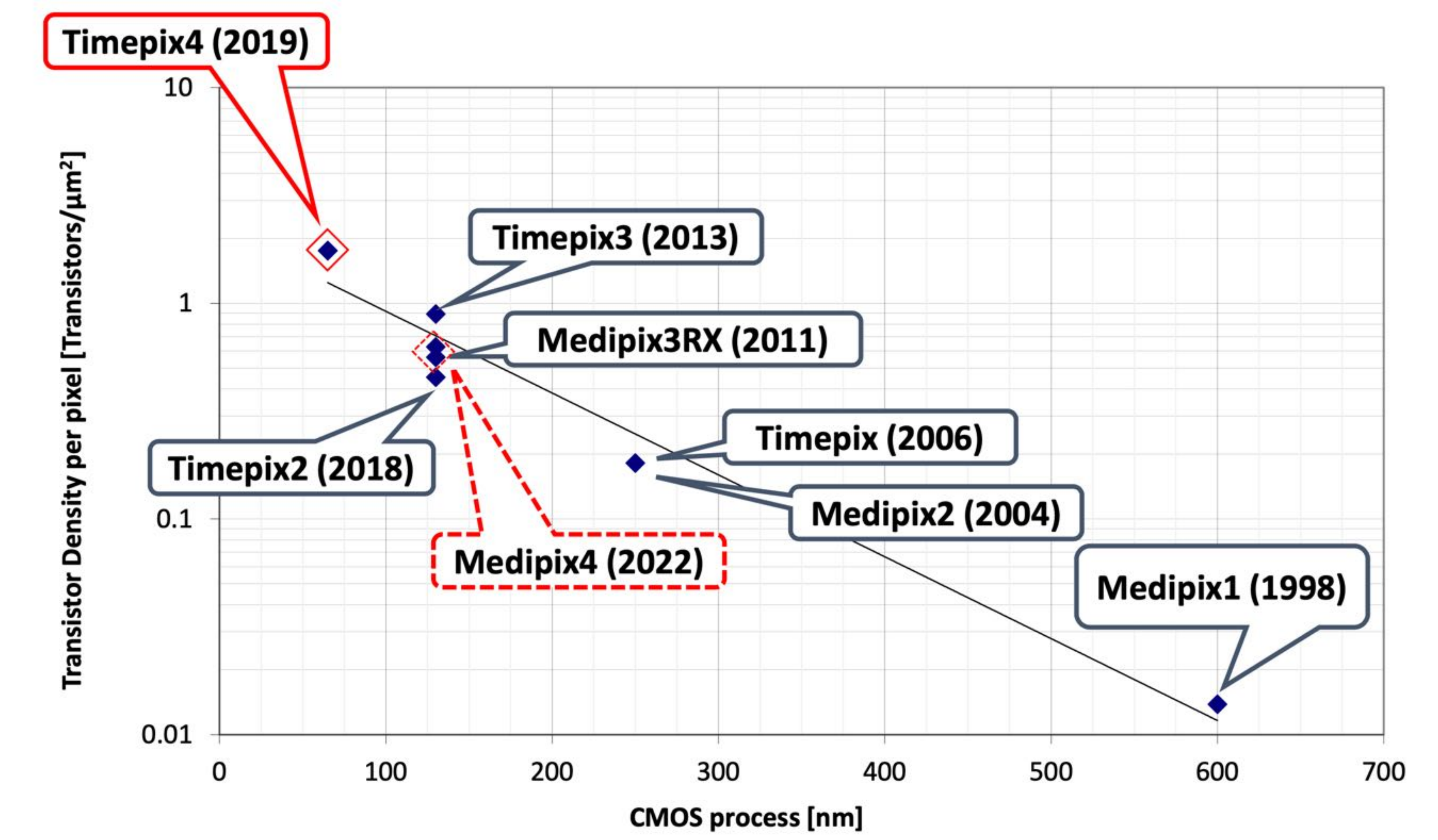


VELO pix lab performance (ECS)

- Measured power consumption (@nominal settings):
  - Analog supply < 480 mW
  - Digital: Periphery < 380mW, matrix ~ 300 mW at high rate (simulated)
  - Total= ~1.5W @High rate

Pixel gain	~24.6 mV/Ke$^-$
Pixel to pixel gain variation	~3.3%
Pixel ENC	62.9 e$^-$
Pixel to pixel threshold mismatch	410 e$^-$rms
Pixel to pixel threshold mismatch calibrated (Threq)	40.3 e$^-$rms
Expected minimum threshold	> 450 e-

Timepix4



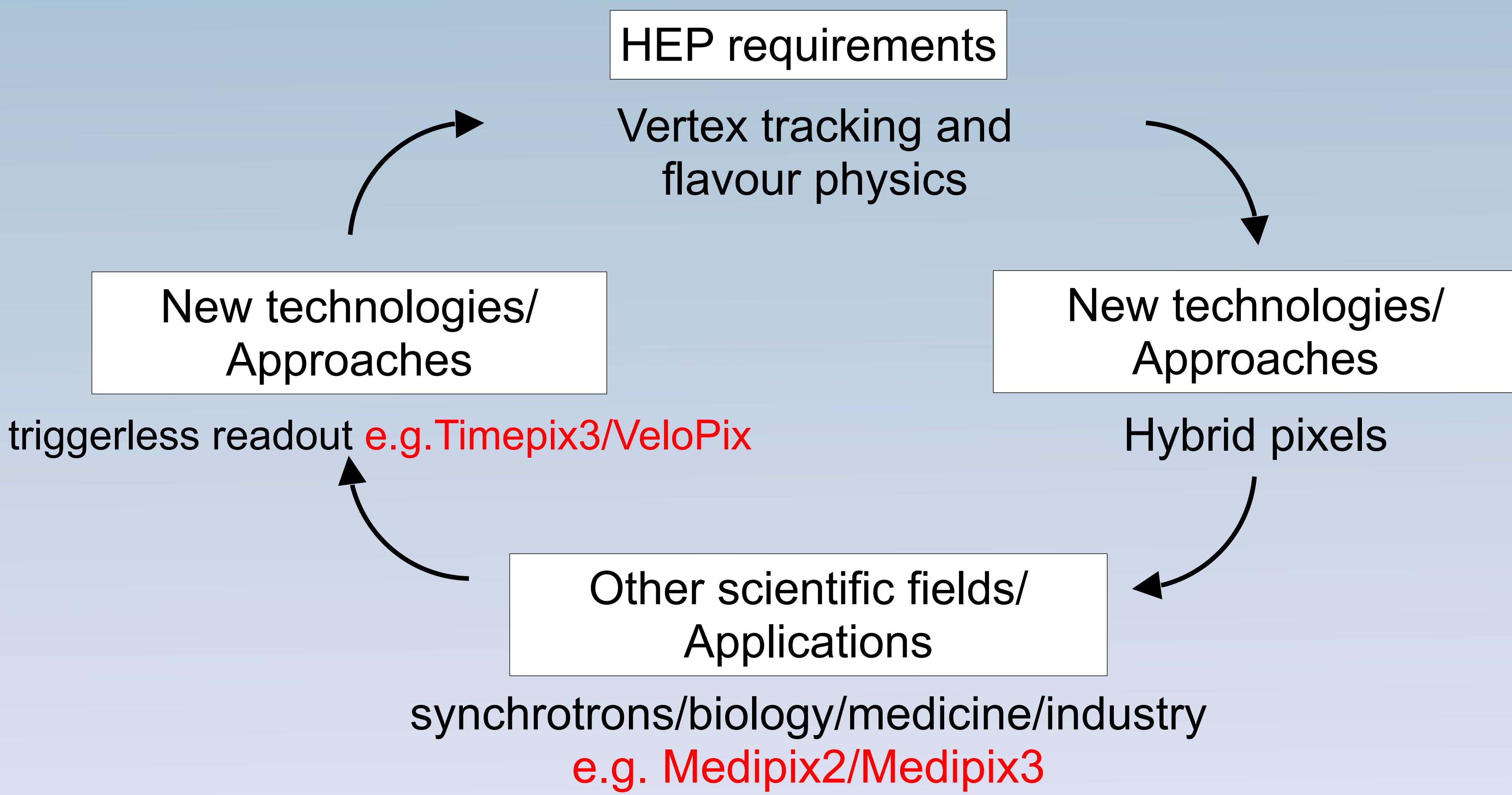
Timepix4 (2019)
Timepix3 (2013)
Medipix3RX (2011)
Timepix2 (2018)
Medipix4 (2022)
Timepix (2006)
Medipix2 (2004)
Medipix1 (1998)
Transistor Density per pixel [Transistors/µm²]
10
1
0.1
0.01
0
100
200
300
400
500
600
700
CMOS process [nm]

Timepix4

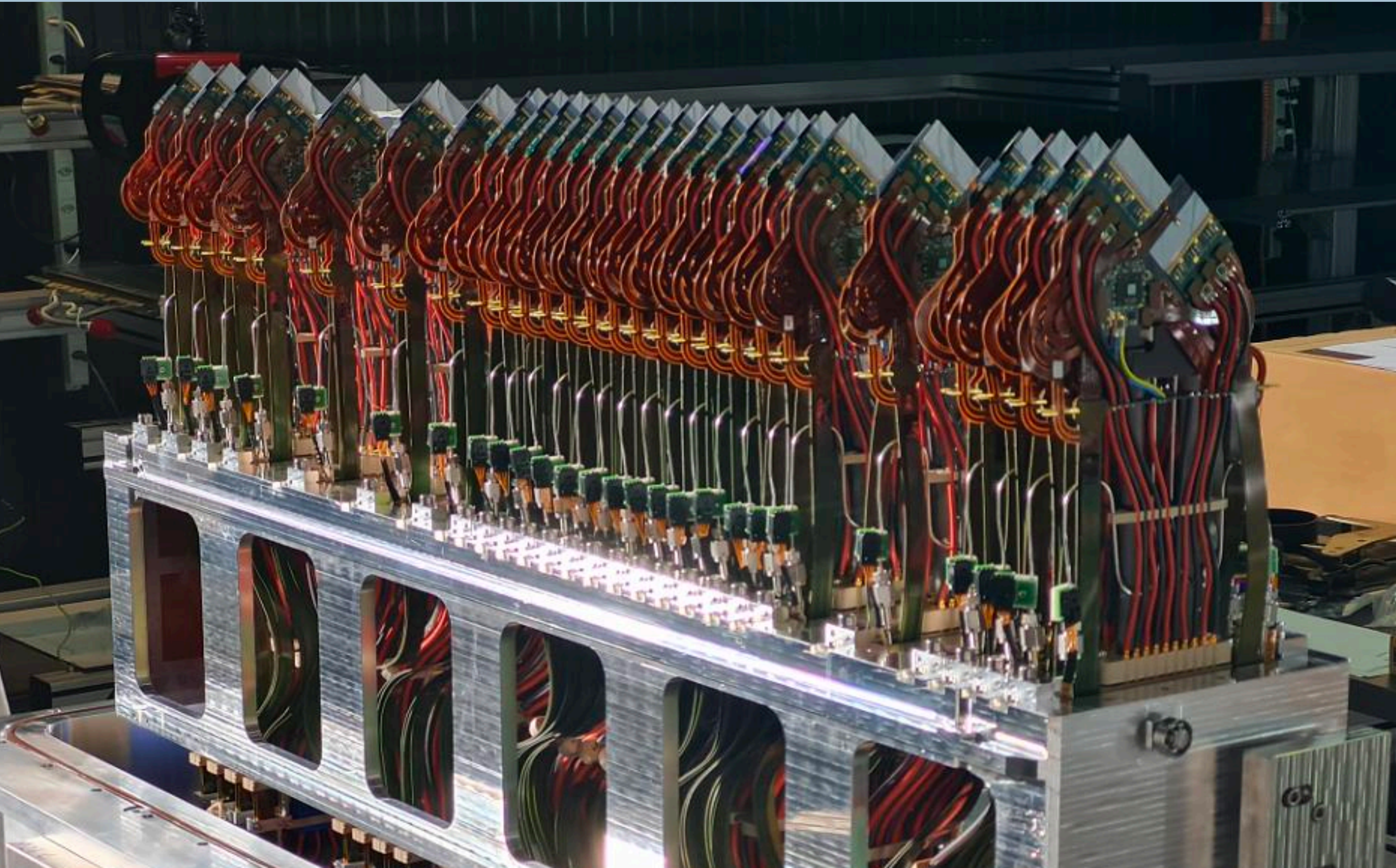
Timepix4: A 4-side tillable large single threshold particle detector chip with improved energy and time resolution and with high-rate imaging capabilities

			Timepix3 (2013)	Timepix4 (2019)	
Technology			130nm – 8 metal	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 (Tracking)	Mode	TOT and TOA		
		Event Packet	48-bit	64-bit	**33%**
		Max rate	0.43×10^6 hits/mm^2/s	**3.58×10^6 hits/mm^2/s**	**8x**
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**	
	Frame based (Imaging)	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	~0.82×10^9 hits/mm^2/s	~5×10^9 hits/mm^2/s	**6x**
TOT energy resolution			< 2KeV	**< 1Kev**	**2x**
Time resolution			1.56ns	**195.3125ps**	**8x**
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	≤163.84 Gbps (16x @10.24 Gbps)	**32x**
Target global minimum threshold			<500 e^-	<500 e^-	

Timepix / HEP cycle of innovation

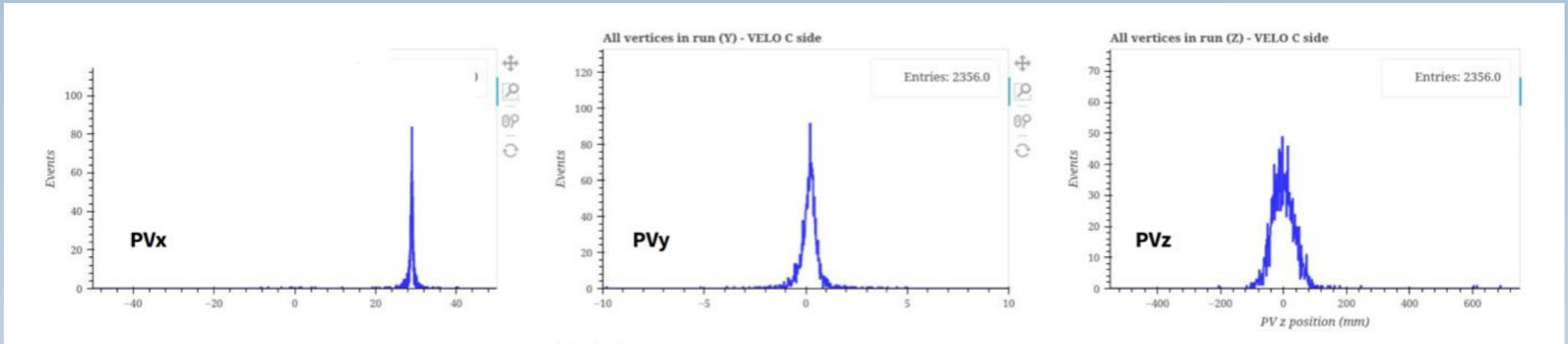


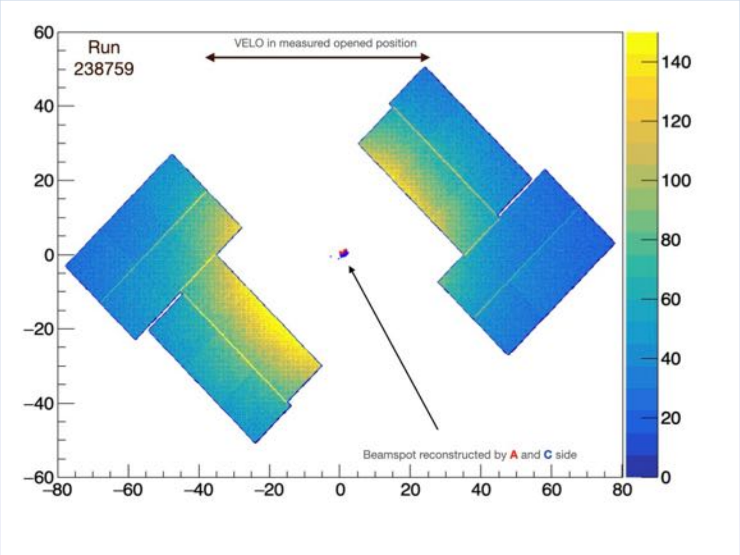
VELO Commissioning



VELO Commissioning

VELO is 98% up and running, and reconstructing tracks and vertices independently from the two halves. Pixel calibrations and time alignment being finalised to bring efficiency up to 100%



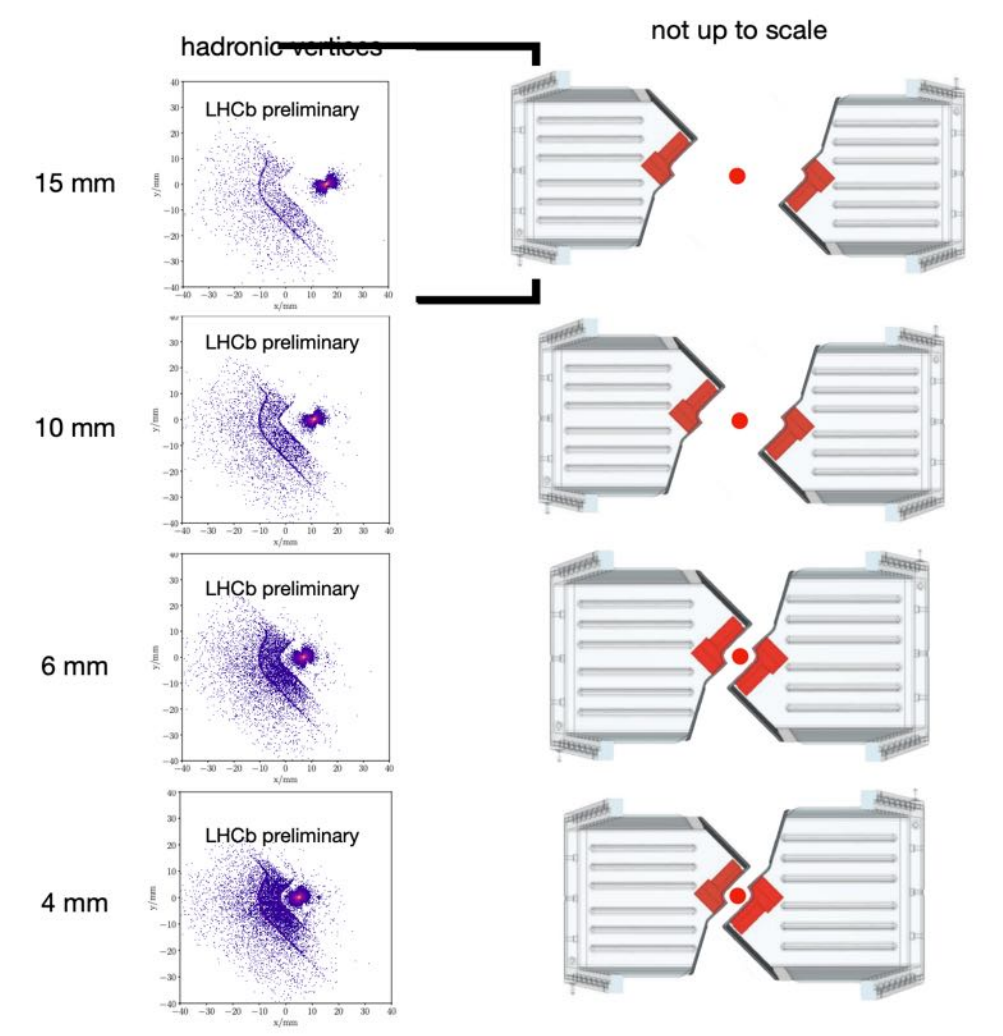


VELO Commissioning

First test closure to within 2 mm of nominal position: October 2022

Image credit: Rizwaan Mohammed, Valeria Lukashenko
Hadronic Interactions in VELO, Early Data, October 2022

First full closure scheduled for today! The 400 MJoule LHC beams will have to thread their way through a meter long tube no thicker than a pencil

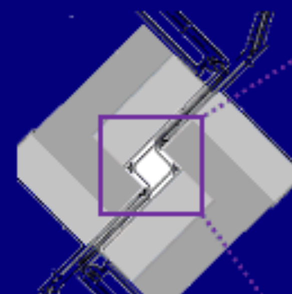


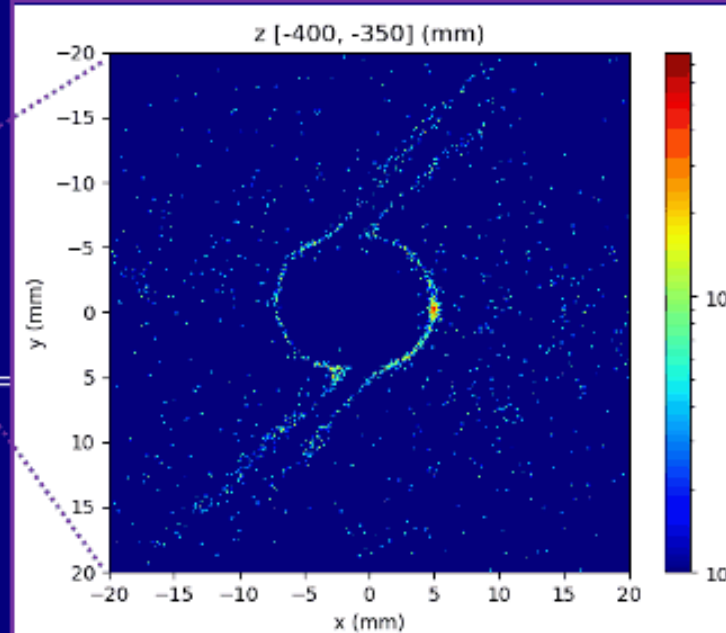
VELO Commissioning

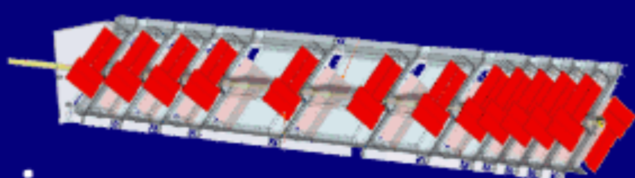
Material scan by reconstructed hadronic interactions

Image/gif credit: Arthur Hennequin, Silvia Borghi
Hadronic Interactions in VELO, Early Data, October 2022

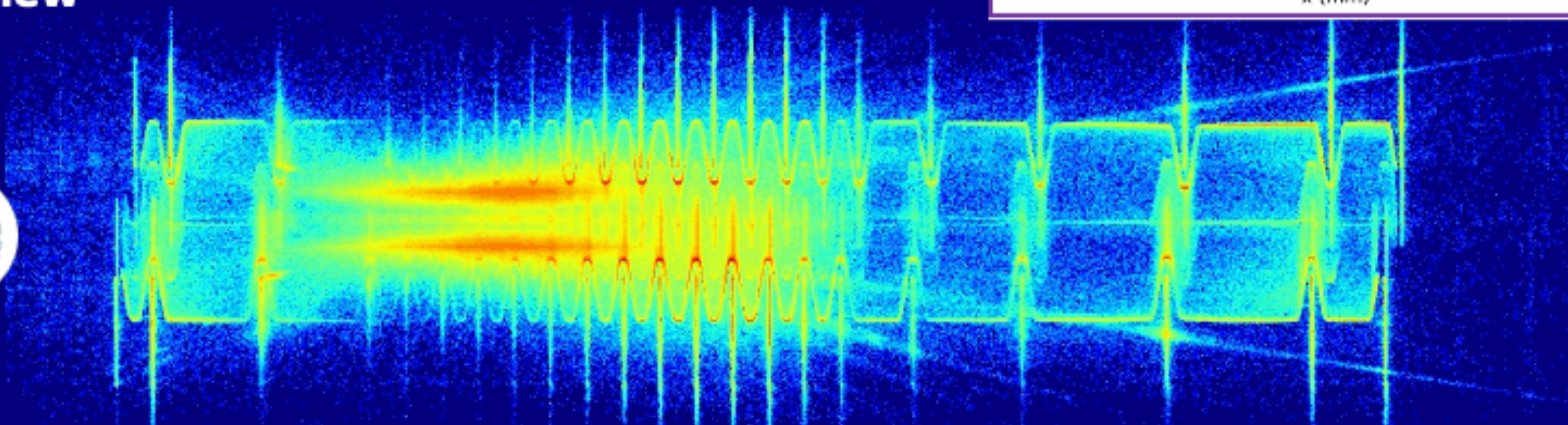
Front view







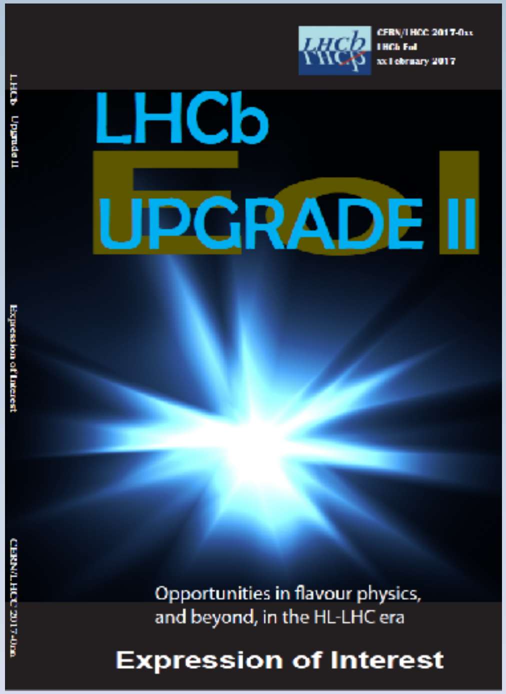
45° view



LHCb Upgrade II

Upgrade I will not saturate precision in many key observables → a further upgrade is necessary to fully realise the flavour-physics potential of the HL-LHC

There is steady progress towards plans for an Upgrade II, that will operate in Runs 5 and 6.



[CERN-LHCC-2017-003] [CERN-LHCC-2018-027] [CERN-LHCC-2021-012]

Now part of the CERN baseline plan. Framework TDR recently approved by LHCC.

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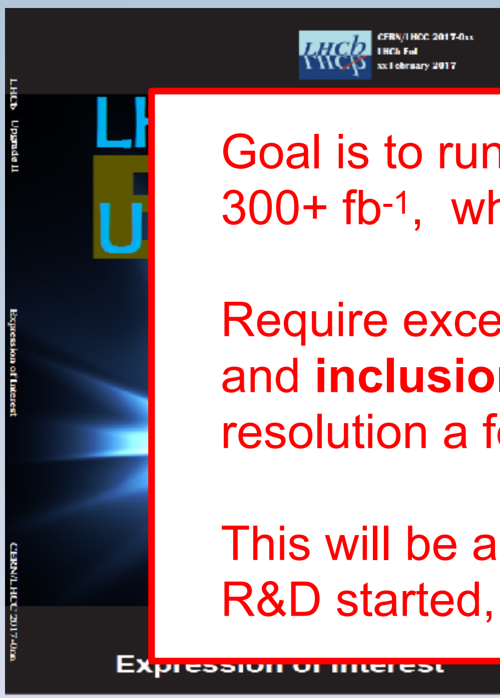
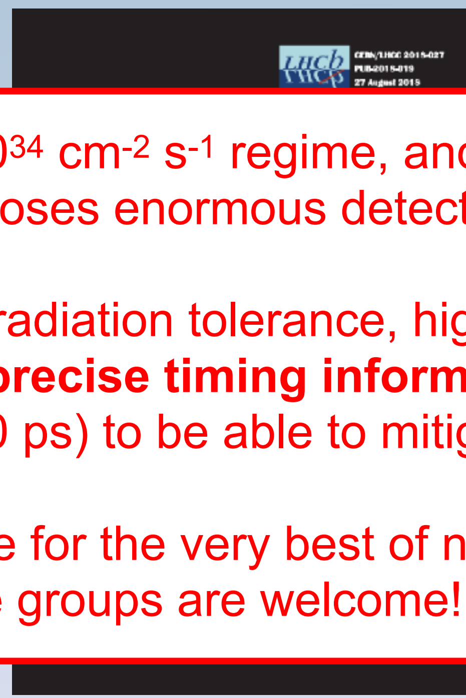




Goal is to run in 10^{34} cm^{-2} s^{-1} regime, and integrate 300+ fb^{-1}, which poses enormous detector challenges.

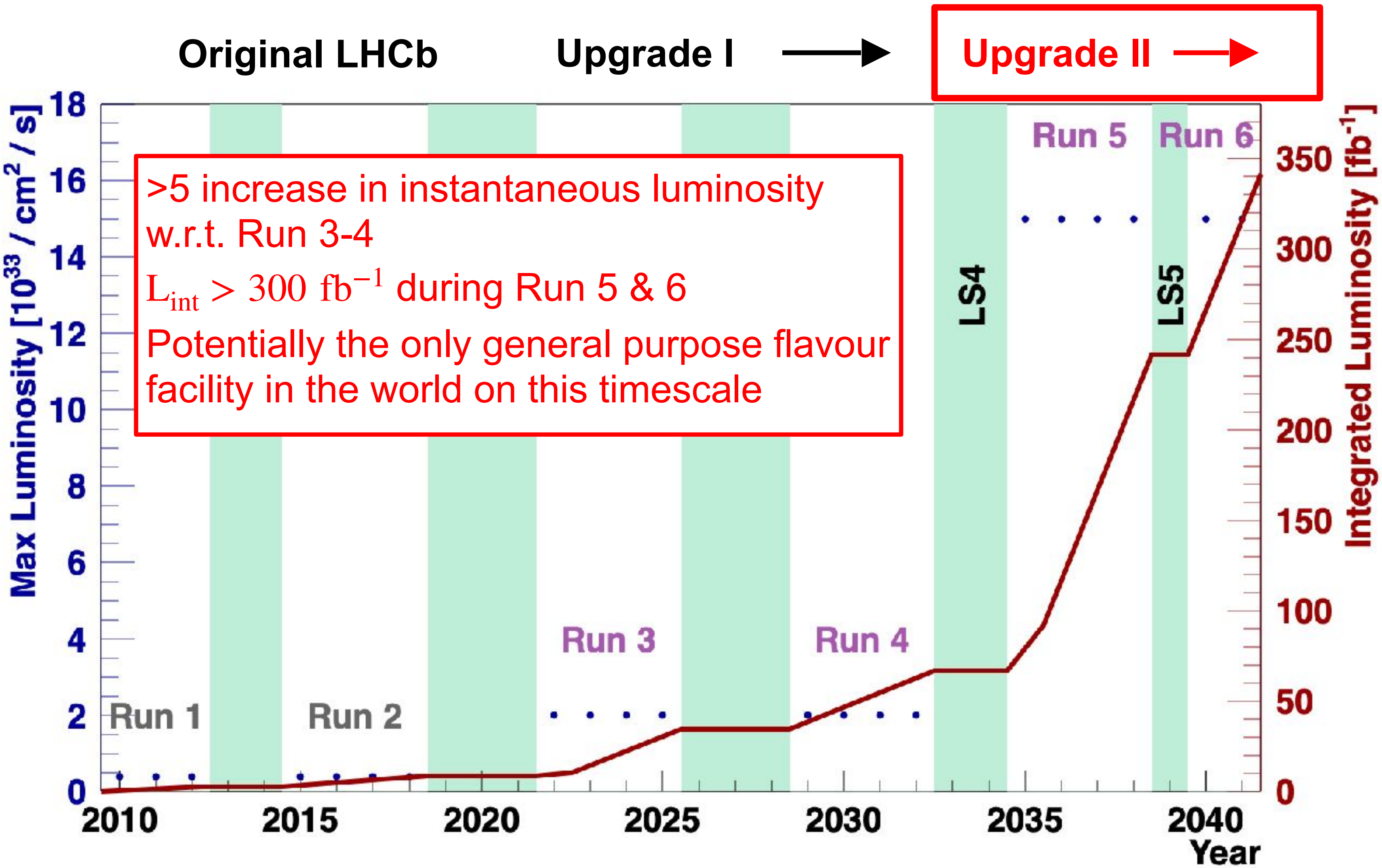
Require excellent radiation tolerance, higher granularity and **inclusion of precise timing information** (*i.e.* of resolution a few 10 ps) to be able to mitigate pileup

This will be a home for the very best of new technology. R&D started, more groups are welcome!

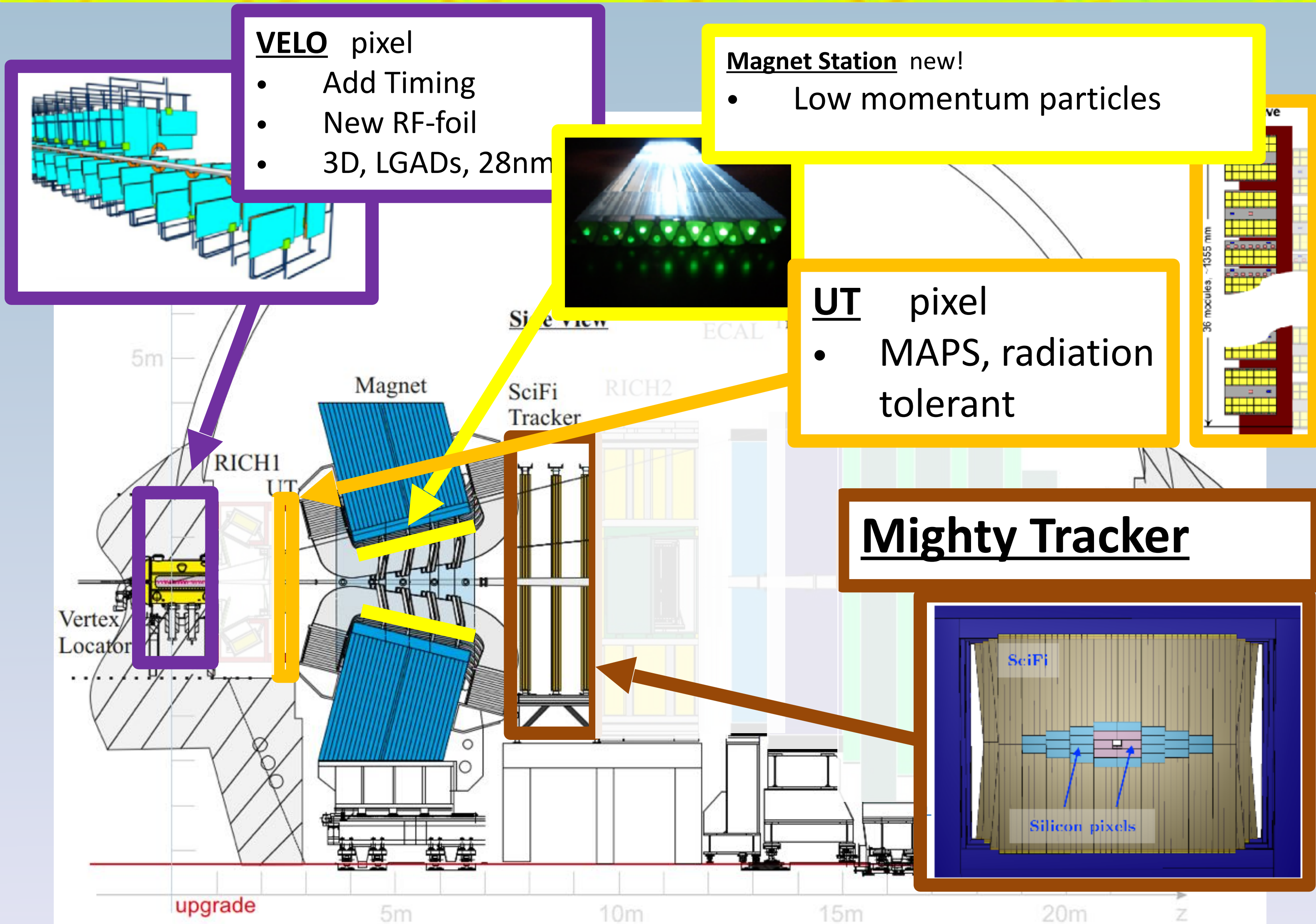
[CERN-LHCC-2017-003] [CERN-LHCC-2018-027] [CERN-LHCC-2021-012]

Now part of the CERN baseline plan. Framework TDR recently approved by LHCC.

Upgrade II Timeline



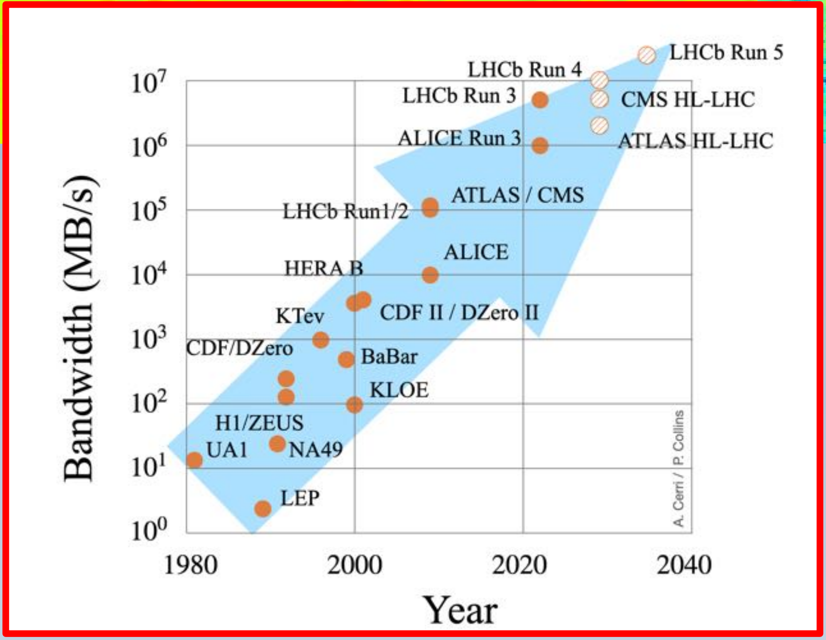
Upgrade II Tracking System



UII Detector

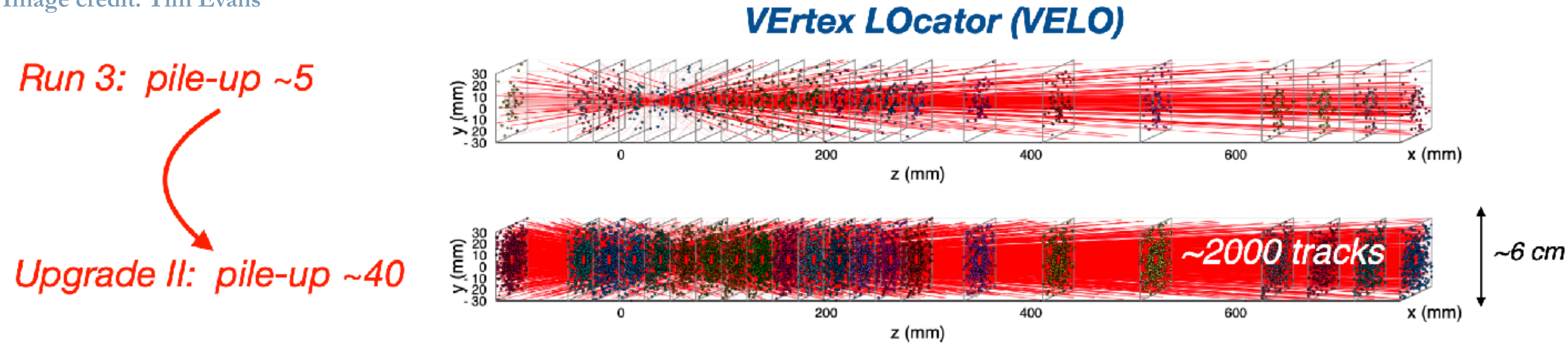
Upgrade II performance must equal or surpass that of Upgrade I, with

- Pile-up reaching values of 40
- 200 Tb/s of produced data
- charged particle densities up to $1 \times 10^{12}/\mathrm{cm}^2$



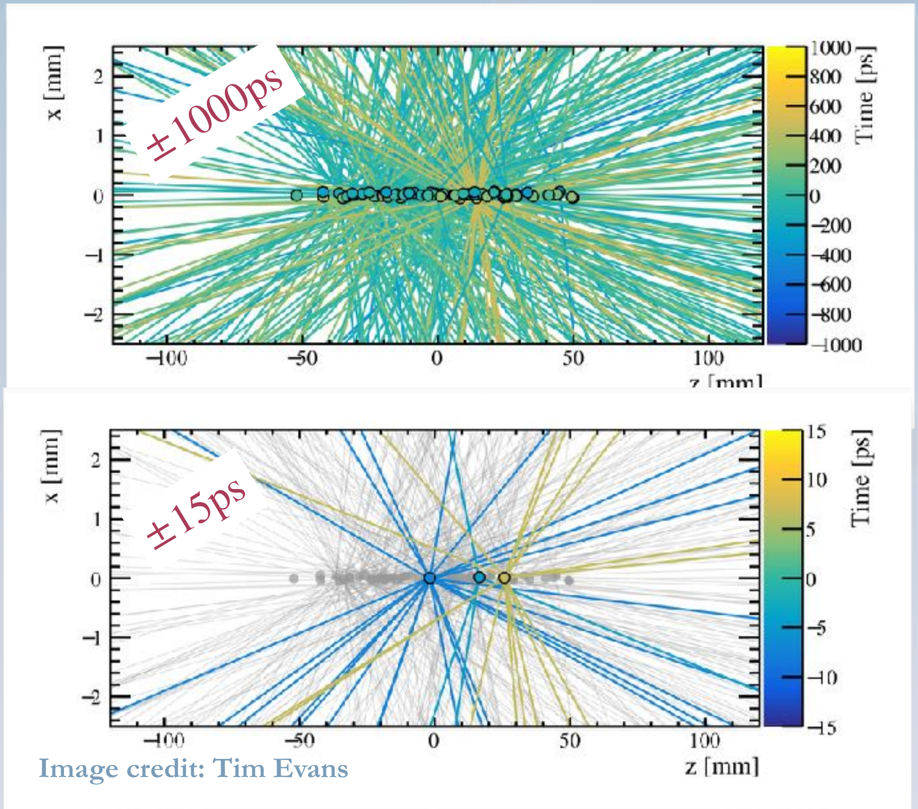
This is the **intensity frontier**! New, lightweight technologies with high granularity, timing, radiation resistance and innovative data processing all necessary to go to $\mathscr{L} \sim 1 \times 10^{34}\ \mathrm{sec}^{-1}\mathrm{cm}^{-2}$

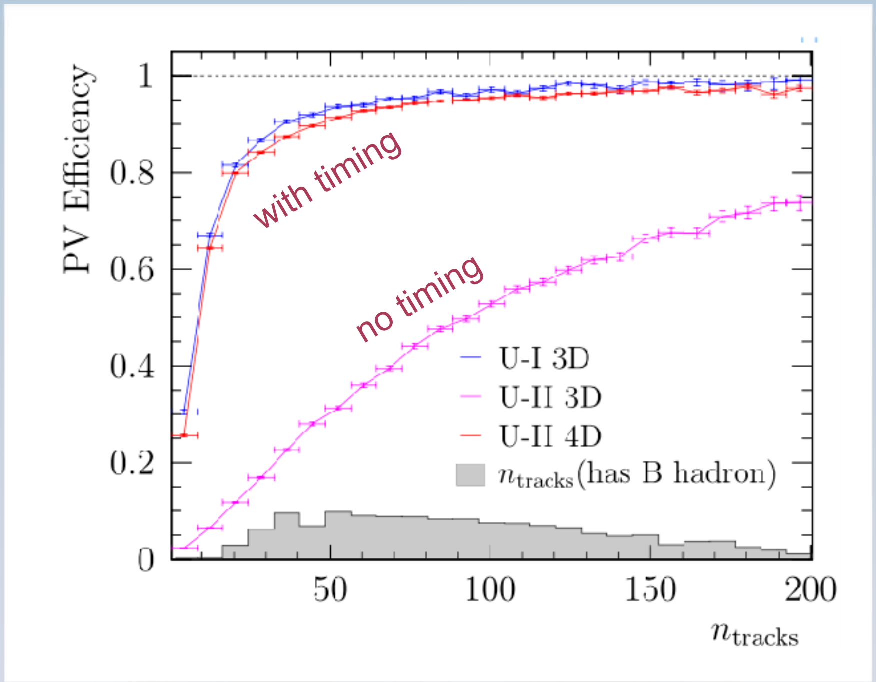
Image credit: Tim Evans



Upgrade II Detector Opportunity

Timing to the Rescue





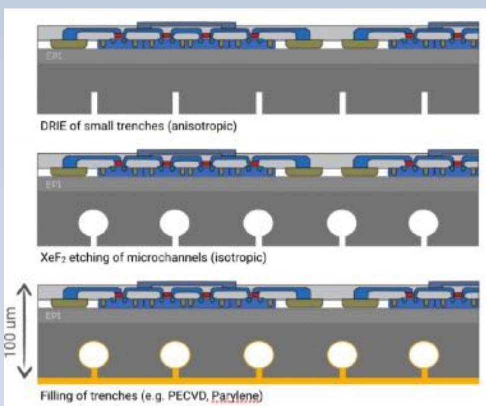
Alternatives to microchannels

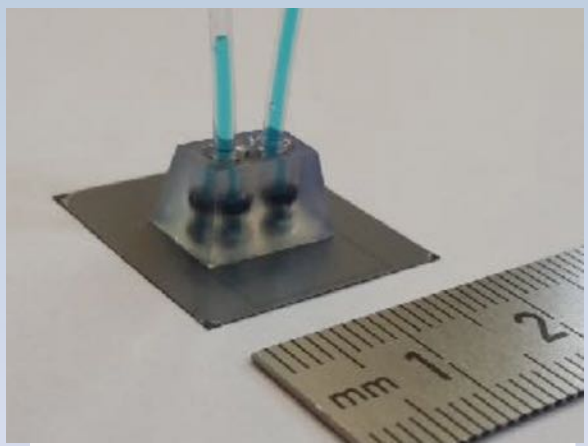
Address production cost (yield related)

- Alternative Bonding (anodic bonding..)
- Avoid mask based photolithographic techniques
- Smaller cooling plates

- Handle wafer bonded to active silicon (IFIC/MPI-HLL)
- Buried microchannels (CERN/.EPFL)

AIDA-2020-NOTE-2020-003



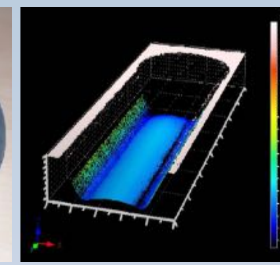


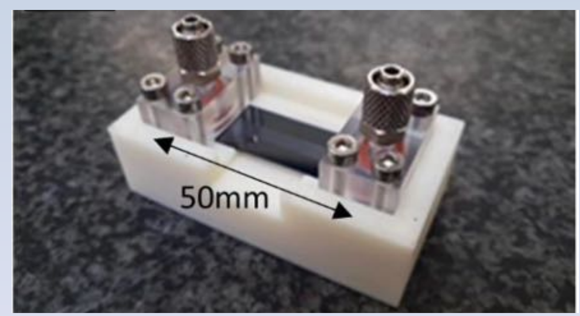
CMOS compatible process
potential post processing step
Holds 110 bars, leak tight to 10^{-8} mbar l/s

Most ambitious approach: bring the cooling to the tiles

R&D @ CPPM

- Laser etching and anodic bonding
- 5 x 10 channels per wafer
- 200µm x 70µm x 4.5cm per channel
- Next step: connector with anodic bonding





Alexandros Mouskeftaras, Stephan Beurthey, Julien Cogan, Gregory Hallewell, Olivier Leroy, et al.. Short-Pulse Laser-Assisted Fabrication of a Si-SiO2 Microcooling Device. Micromachines, MDPI, 2021, 12 (9), pp.1054. 10.3390/mi12091054 . hal-03356892

Alternatives to microchannels

Grade 2 printed Ti: a lot of experience in industry (medical, dental)

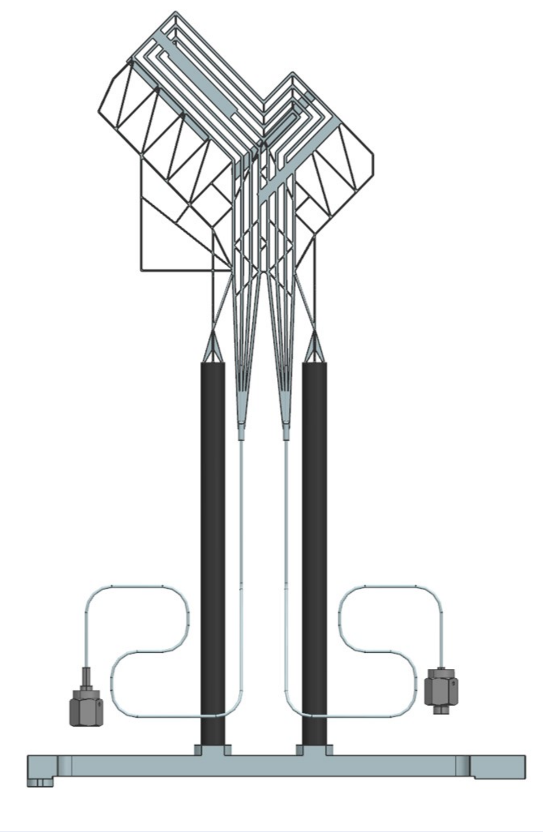
Advantages

- strong, easy to handle, will not break
- easier to connect CO_2 pipes (welding, brazing)
- Restrictions integrated into inlet
- Fast turnaround for design changes (order of weeks)
- Fast production 25/batch, 1 batch/few days
- cheap (<500 Euro / module, including welding capillaries)

Challenges

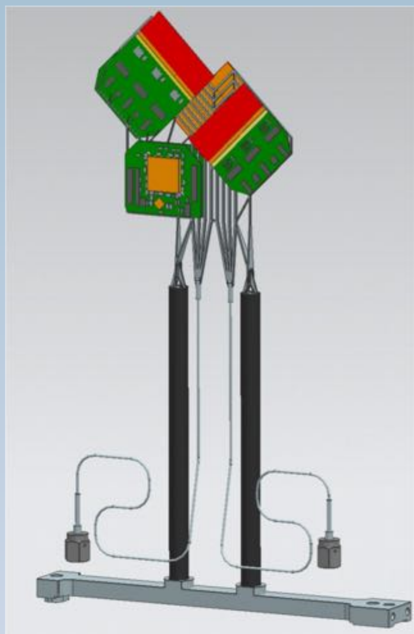
- CTE match with silicon is worse (8.6 vs 2.6 ppm/K)
- smaller thermal conductivity (16 vs 150 W/mK)
- smaller radiation length (3.6 vs 9.4 cm)
- irregularities in printing; less flat surfaces?

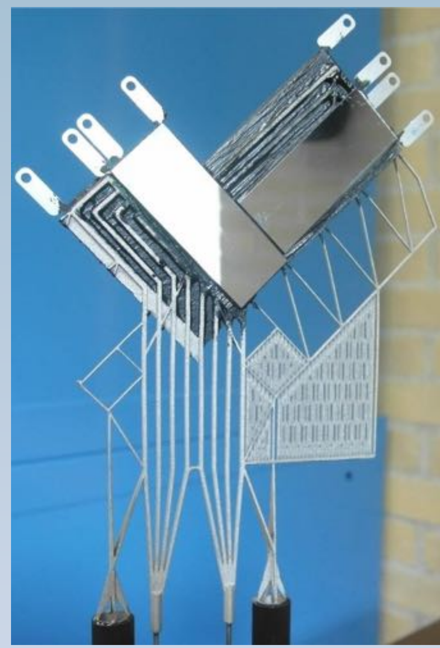
3d printed cooling design



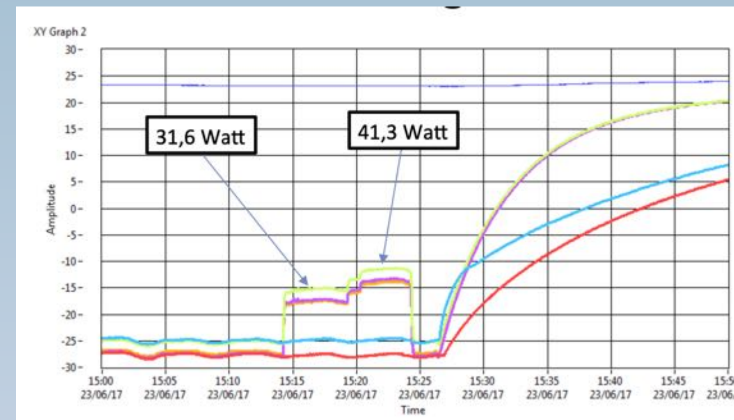
See presentation by Freek Sanders, “Design and Production challenges for the LHCb VELO Upgrade Modules”, CERN Detector Seminar, February 2019

Alternatives to microchannels

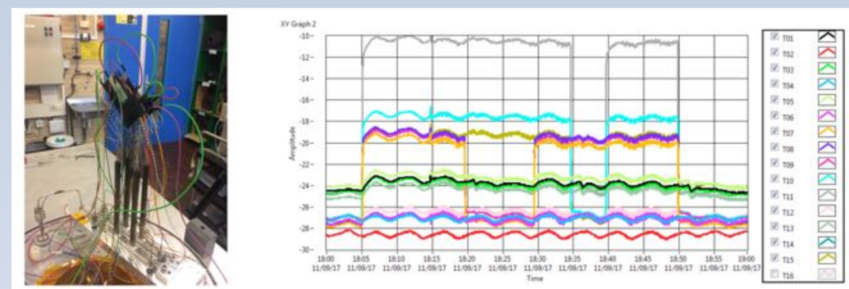




prototype fitted with heaters
- high pressure test to 250 bar
- Leak tight with 250 μm wall



successful cooling test (ΔT~13^{o}C)

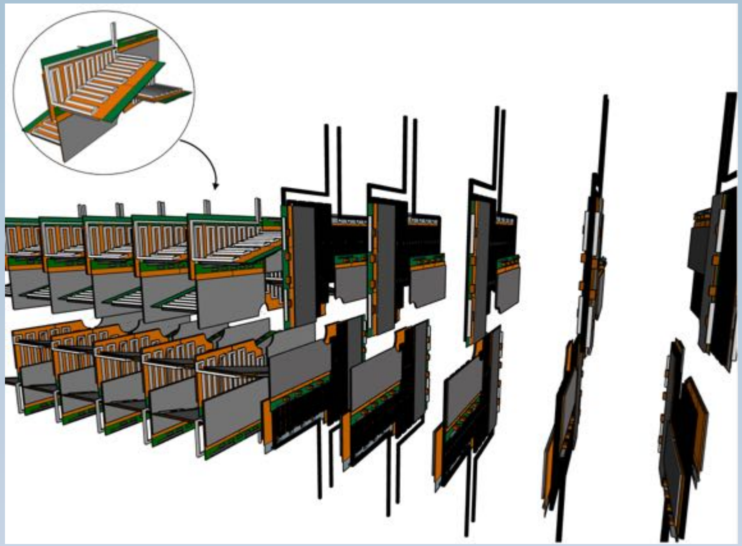


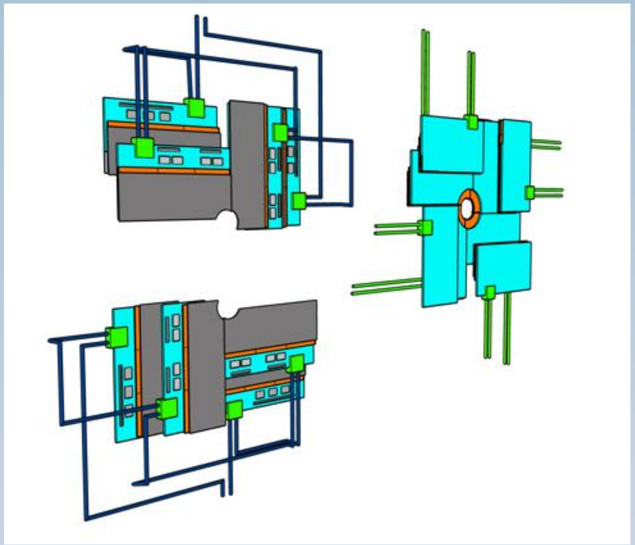
successful flow and stability test (ΔT~13^{o}C)

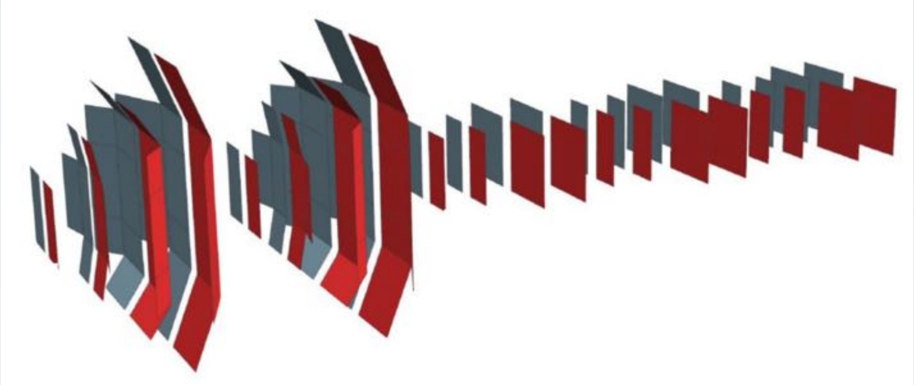
A bit of history

R&D 3d printed substrates made extremely rapid progress and were a credible backup alternative for LHCb. At the time of development the microchannels were sufficiently mature to be chosen as the implementation for Run3

Many types of geometry possible…



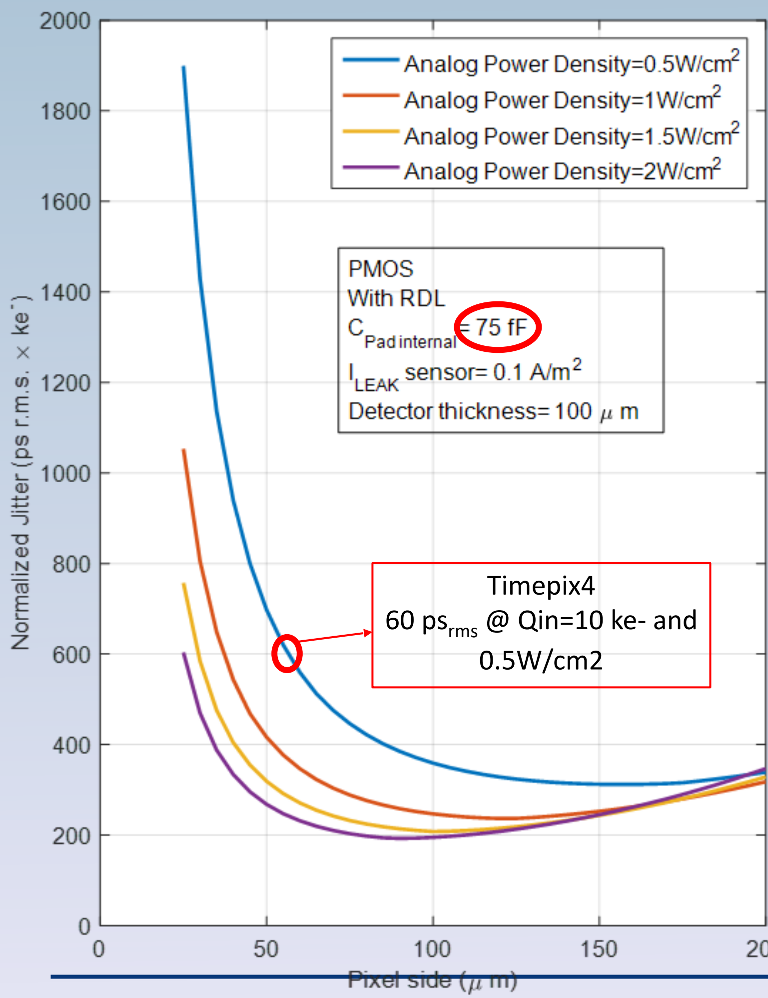




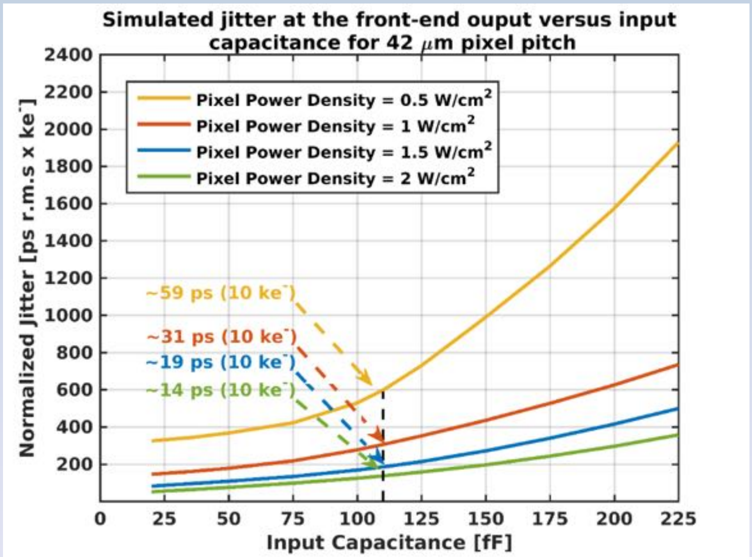
3d printed technology already in active development for UII
May give the flexibility required for a cooling "skeleton"
Many issues of connectivity to be solved

ASIC requirements & Limits

Slide complied by Vagelis Gkougkousis



Requirement	scenario S_A	scenario S_B
Pixel pitch [µm]	≤55	≤42
Matrix size	256×256	335×335
Time resolution RMS [ps]	≤ 30	≤ 30
Loss of hits [%]	≤ 1	≤ 1
TID lifetime [MGy]	> 24	> 3
ToT resolution/range [bits]	6	8
Max latency, BXID range [bits]	9	9
Power budget [W/cm²]	1.5	1.5
Power per pixel [µW]	23	14
Threshold level [e⁻]	≤ 500	≤ 500
Pixel rate hottest pixel [kHz]	> 350	> 40
Max discharge time [ns]	< 29	< 250
Bandwidth per ASIC of 2 cm² [Gb/s]	> 250	> 94

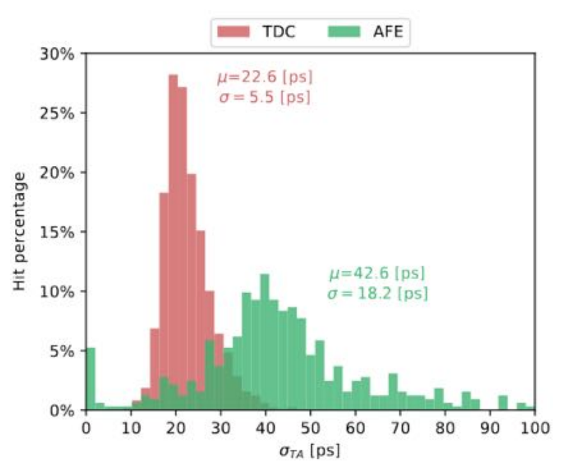


ASIC precursors

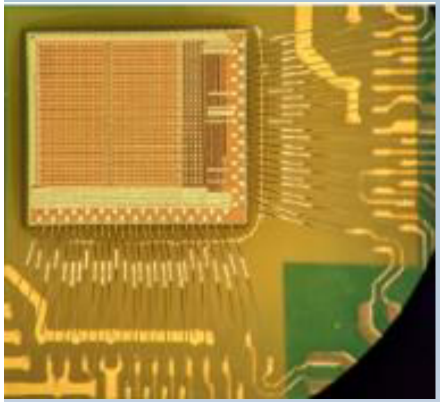
Slide complied by Jakob Heimberger

Timespot:

- **28nm** technology
- Minimum pixel size **< 40 μm**
- TDC: ~**23 ps** resolution
- AFE**: ~43 ps** resolution
- Power: **~1.2** W/cm²



Timespot1 time resolution



Timespot1 ASIC

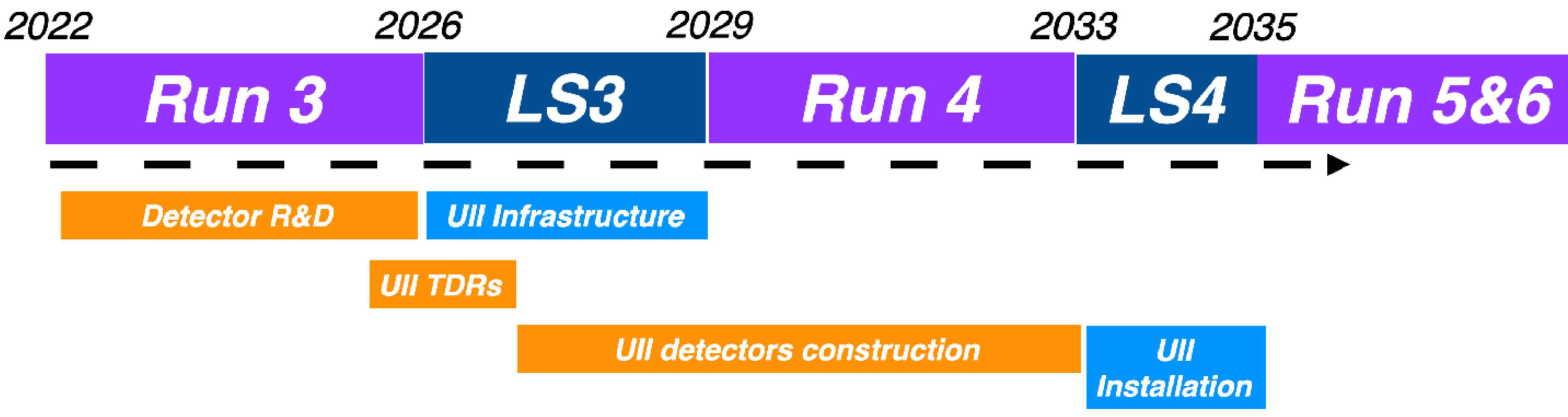
Timepix4:

- **65nm** technology
- **23** Gbps/cm²
- Minimum pixel size **55 μm**
- TDC: ~**62 ps** resolution
- AFE**: ~ 70 ps** resolution
- Power: <**0.5** W/cm²

PicoPix:

- **In development**
- **Goals:**
  - **28nm** technology
  - **>125** Gbps/cm²
  - Minimum pixel size **42-55 μm**
  - Total time resolution < **30 ps**
  - Power: **<1.5** W/cm²

Upgrade II Timeline



- *~4 year period for detector R&D, make technology choices and optimise the detector design*
- *TDRs expected at beginning of LS3, then ~6 year period for detector construction → being ready for LS4 installation is of primary importance*
- *Significant infrastructure preparation during LS3, to optimise LS4 duration*
- *Limited size detector consolidations also proposed for LS3 as anticipation of Upgrade II*

Upgrade II needs a significant expansion of the collaboration

Conclusions

LHCb Upgrade I: Commissioning NOW!

VELO is fully installed and operational, first full closure TODAY!

LHCb Upgrade II: unique opportunity for an ultimate precision flavour physics and general purpose experiment in the forward region.

EOI, Physics Case and FTDR approved by LHCC/RB
Strong support received in European strategy

Very challenging project ⇒ lots of R&D ongoing on all sub-systems

New technologies needed, now is a great time to join the collaboration

Conclusions