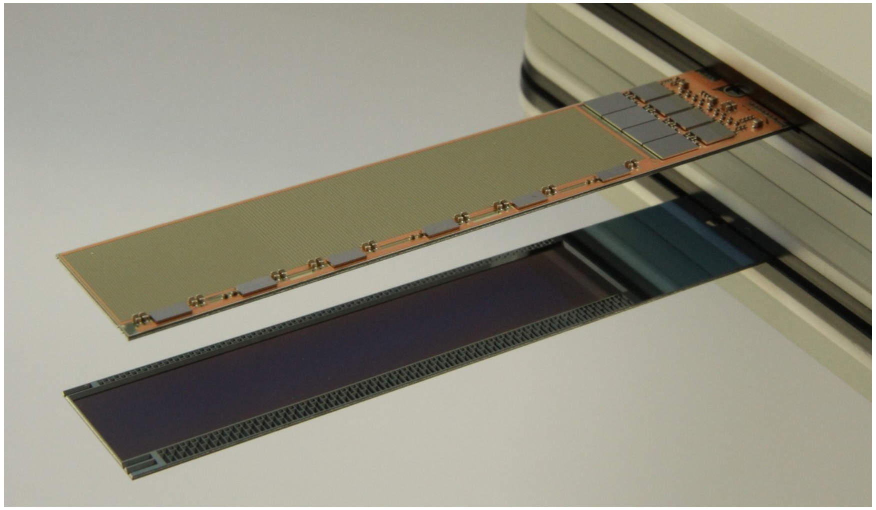
Integrated silicon sensors for Higgs factory experiments

CEPC workshop, Nov 2021

Marcel Vos, IFIC (UV/CSIC) Valencia

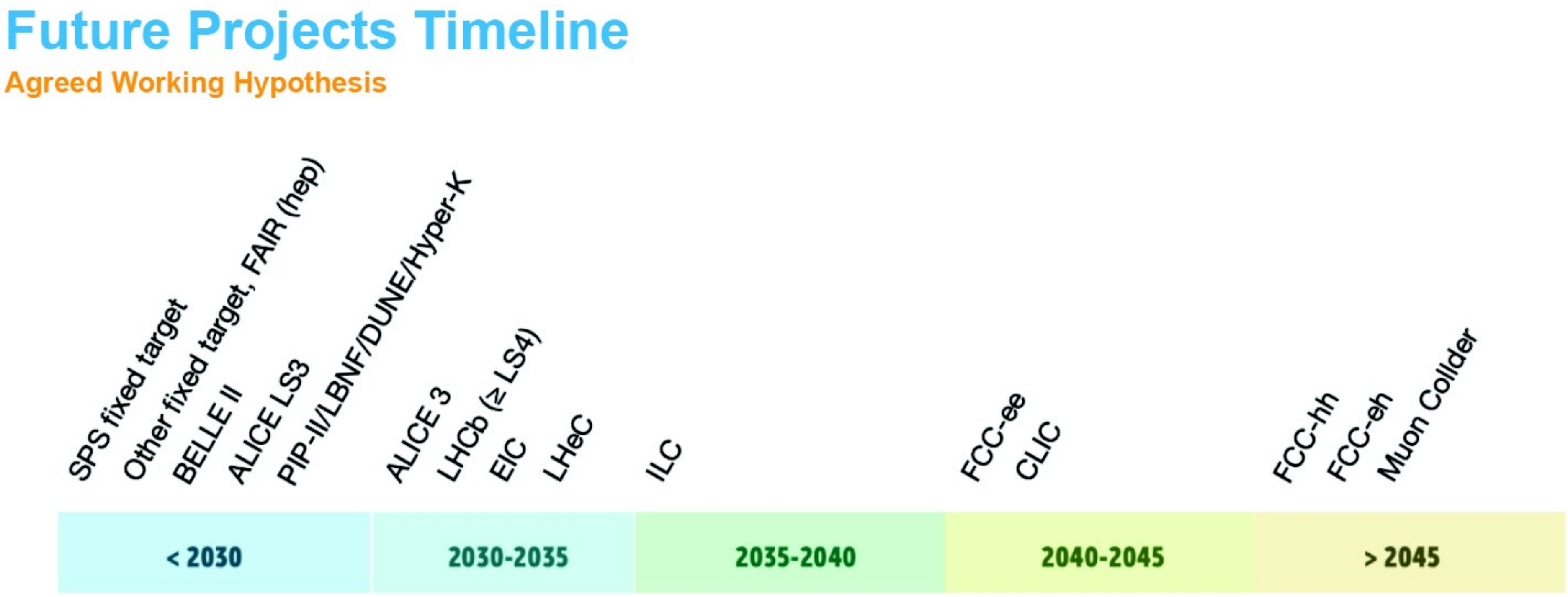
Loosely based on recent contributions to ILCX2021 and Queen Mary, London



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004761.

Global R&D landscape

- Higgs factory detector R&D in the global R&D landscape



- Funding for “future” projects and “blue sky” R&D is scarce

Global R&D landscape

Find synergies with “stepping stone” projects that are in the construction stage to advance new detector technologies

++ Collateral benefit: validate new ideas in exp. reality
-- Potential risk: only applicable to nearly-mature ideas

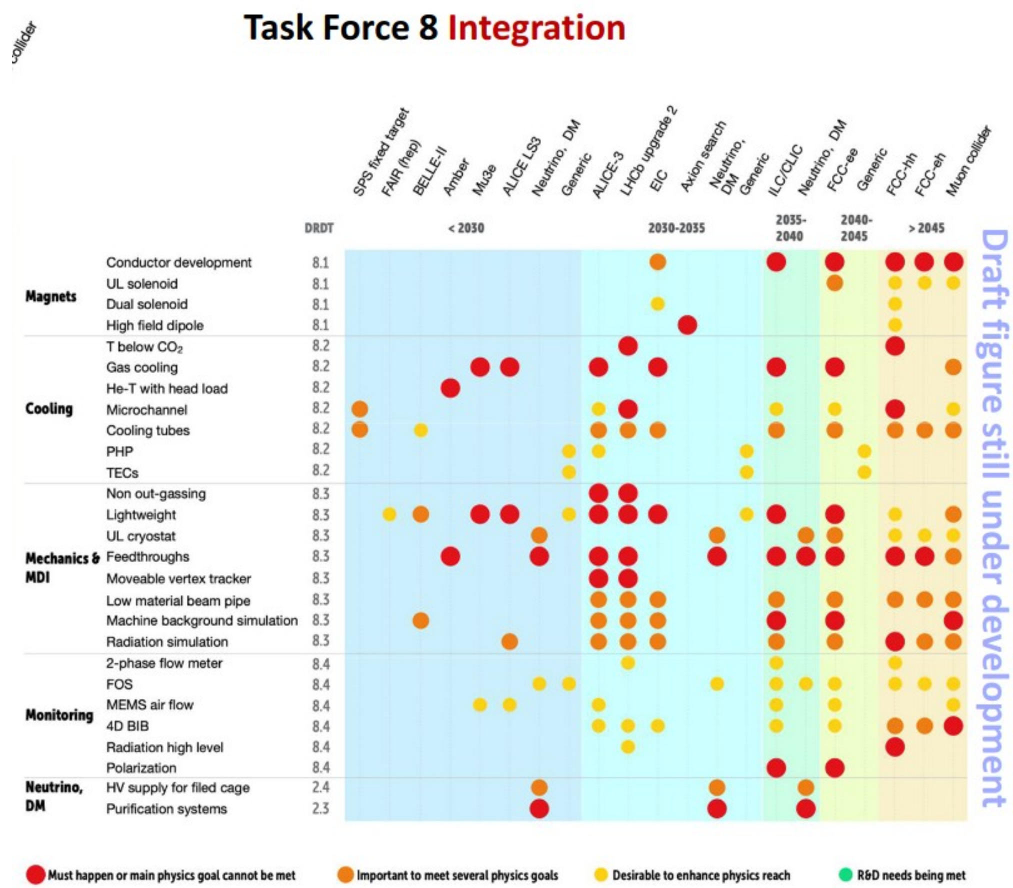
Examples: CMS HGTD, Belle 2 PXD,…

Future: ATLAS+CMS timing detectors, LHCb, ALICE, FAIR, EIC…

ECFA R&D panel

Important effort in Europe to inventorize detector R&D needs of upcoming experiments in particle physics

Snowmass detector R&D



See talks in ECFA R&D symposium:
https://indico.cern.ch/event/999825/

AIDAInnova

AIDAinnova project funded by EU H2020 programme
H2020-INFRAINNOV-2020-2, https://cordis.europa.eu/project/id/101004761

focus on Strategic R&D in the pre-TDR phase

++ Forces groups to collaborate with similar projects
-- Specific funding rather limited

Eventually, projects need ear-marked funding

Tracking requirements

From key requirements from physics:

- **p_t resolution** (total ZH x-section)

  $\sigma(1/p_t) = 2 \times 10^{-5}\ \text{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$ — ≈ CMS / 40

- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)

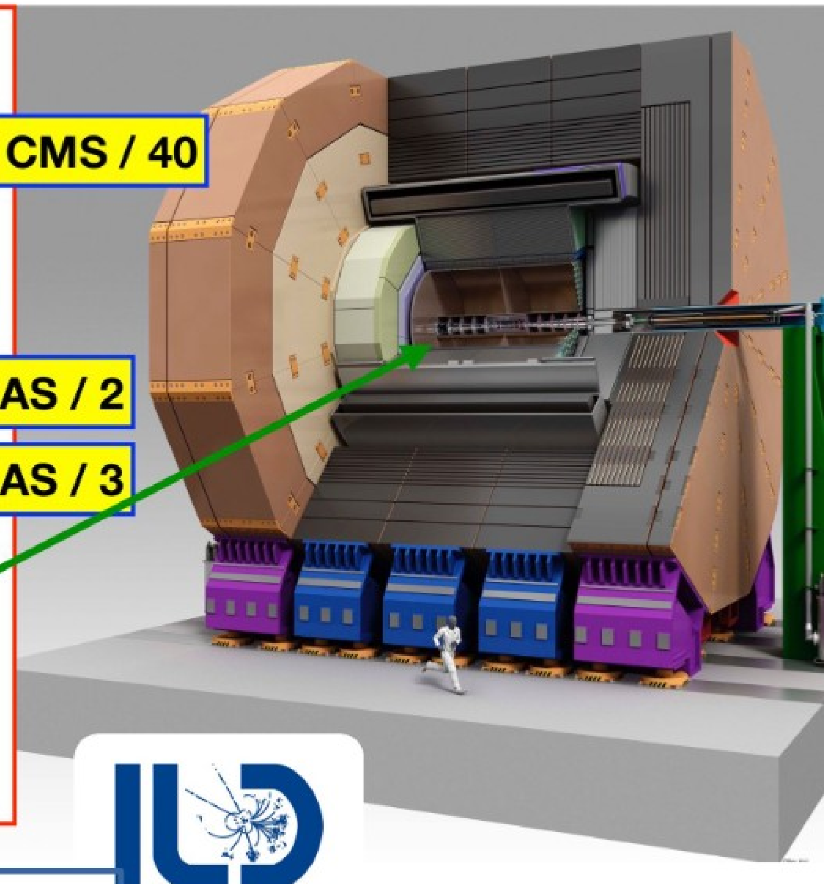
  $\sigma(d_0) < 5 \oplus 10 / (p[\text{GeV}] \sin^{3/2}\theta)\ \mu m$ — ≈ CMS / 4

- **jet energy resolution** ($H \rightarrow$ invisible) 3-4% — ≈ ATLAS / 2
- **hermeticity** ($H \rightarrow$ invis, BSM) θ_{min} = 5 mrad — ≈ ATLAS / 3

To key features of the detector:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow

~x1000 more r/o cells than LHC exps.
~x10-100 more than HL-LHC exps.



A. Irles, ILCX2021

Borrowed from J. List

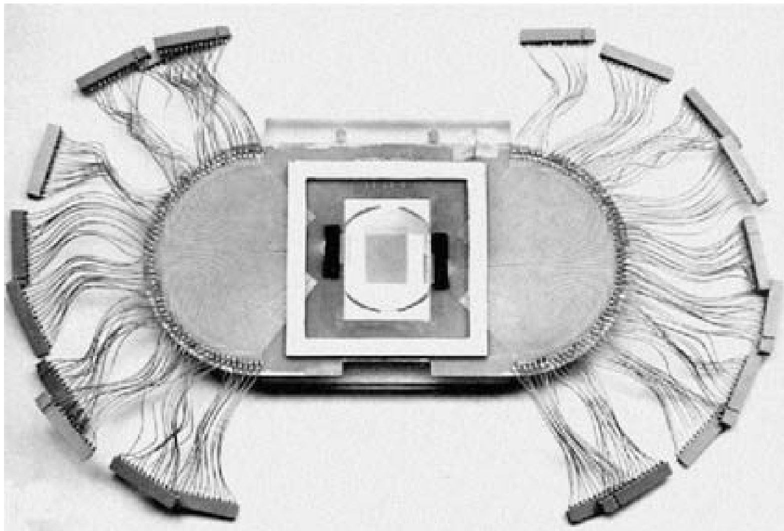
Tracking requirements

Higgs factory silicon requirements:
- excellent spatial resolution (3-10 μm)
- virtually no material (VXD: 100 μm of Si/layer)
- time resolution (CLIC 1 ns, TOF 10s of ps)

Cooling at ILC/CLIC aided by pulsed structure of the beam
→ up to factor 1/100 in average power consumption
→ well within “air cooling” regime with typical power consumption

Circular colliders must reassess trade-off between material and power

Silicon detectors



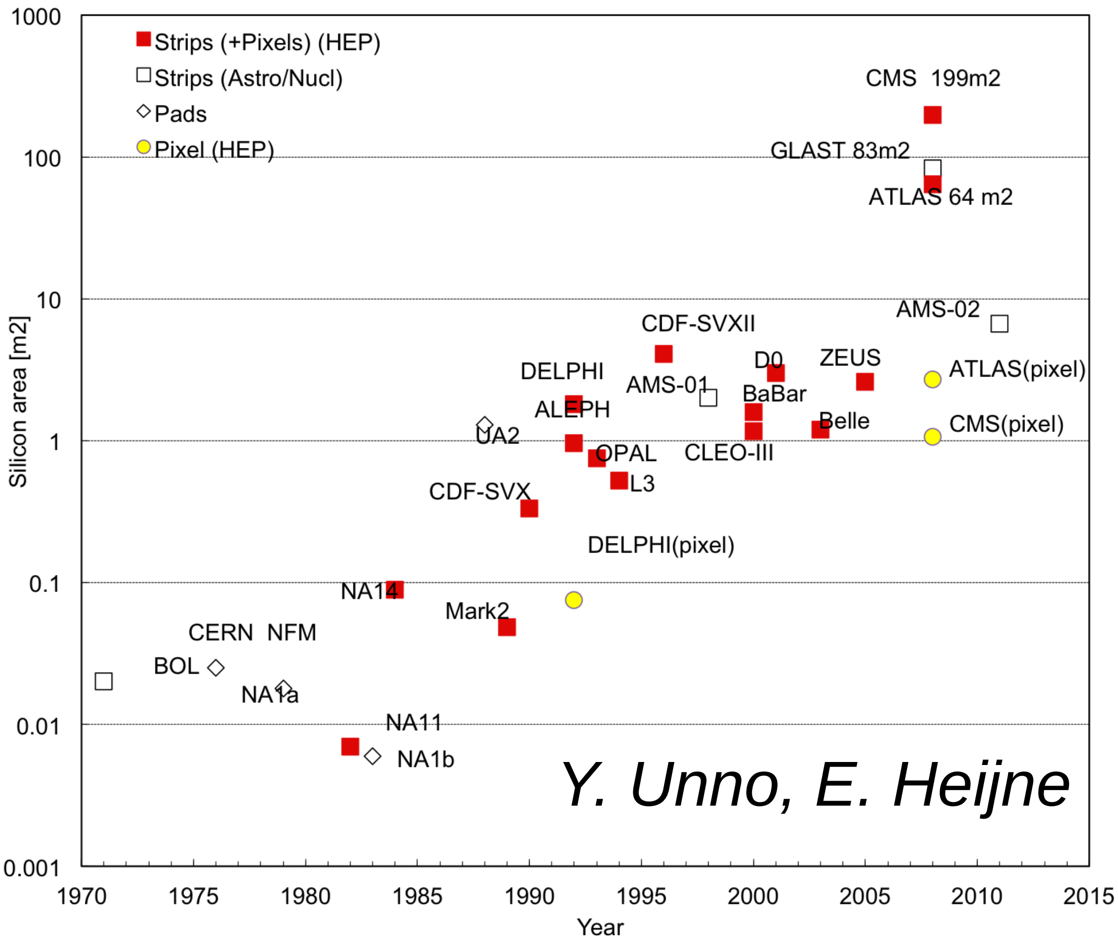
NIM217 (1983):

1200 diode strips on a 2” wafer

Very bulky support and ancillary systems

The 2017 HEP Prize of the EPS awarded to **Erik Heijne & Robert Klanner**

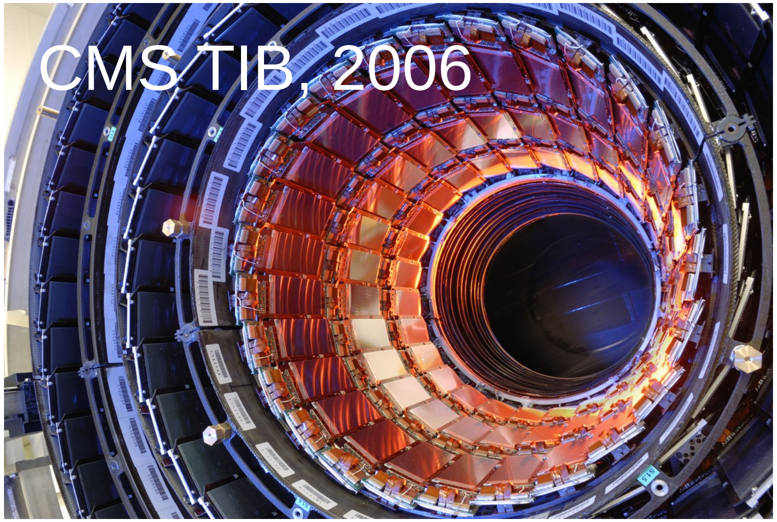
Silicon detectors



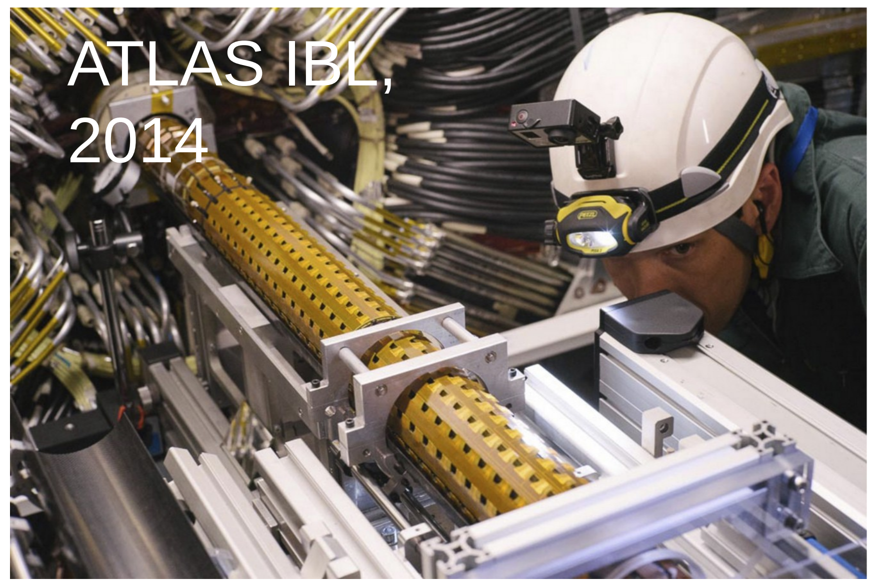
Trends for the next decade:

- monolithic CMOS sensors to replace hybrid detectors
- pixels to displace micro-strips → O(10-100) m^2
- Integrated solutions for mechanics, power/signal bus and cooling

Silicon detectors



Still pretty much the same planar process
Industrial scale: 2” wafers → 8”
Segmentation: pixels 100 x 100 μm^2
Micro-electronics: compact FE/interconnect



So, what's next?

Integrated pixel detectors

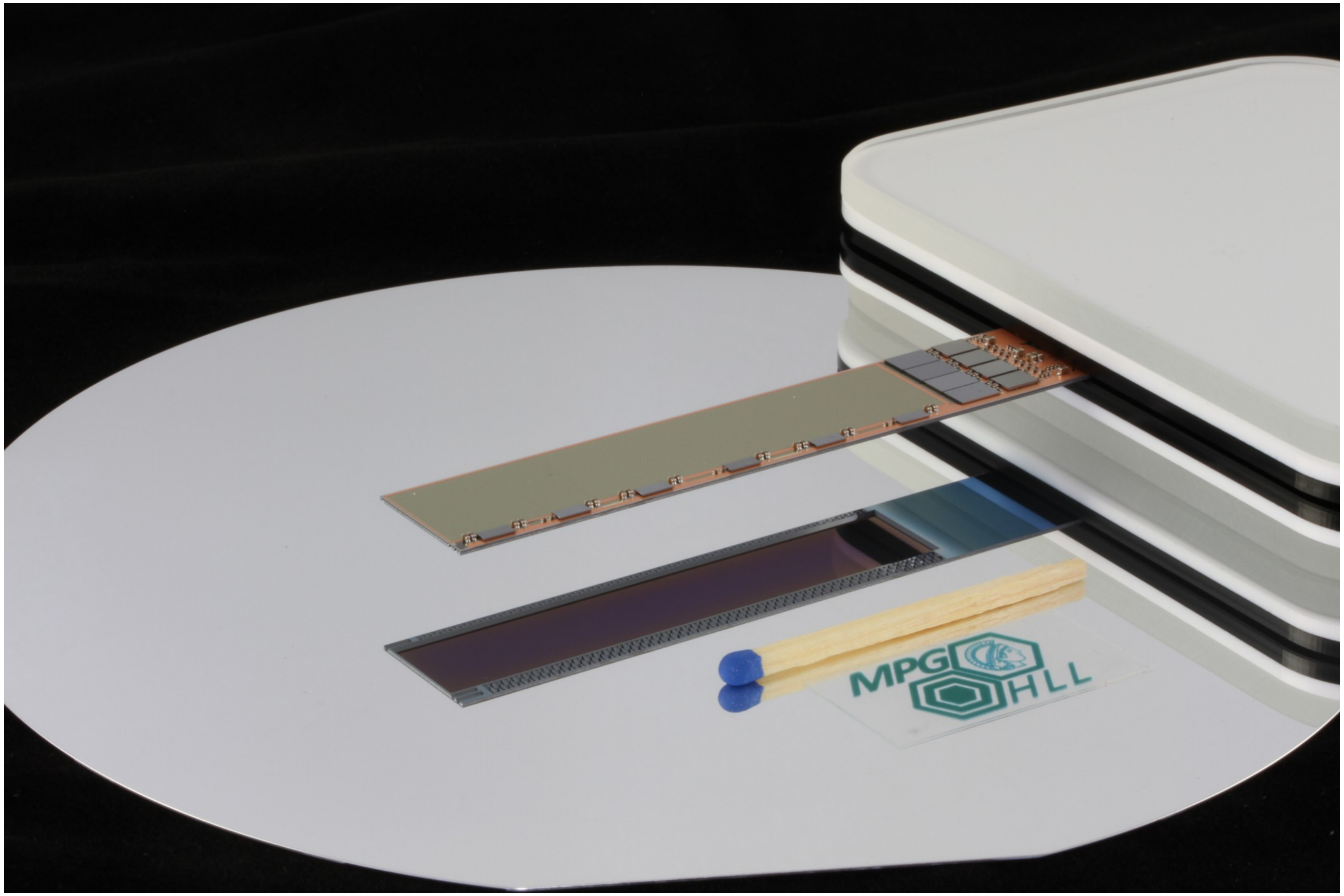
Precision tracking & vertexing requires further integration

Sensor is still pretty much the same high-R silicon

read-out electronics:
on the silicon

Power & signal lines:
on the silicon

Support structure:
= the silicon

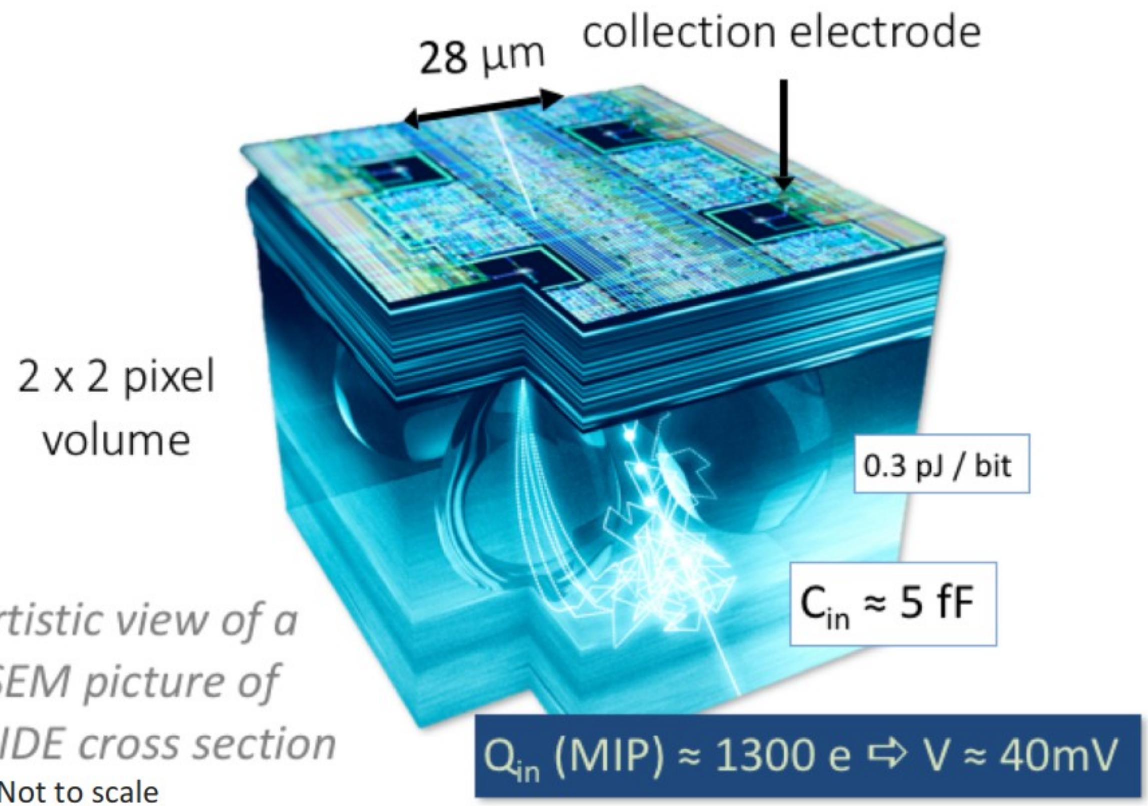


Silicon pixel sensors

Several groups/collaborations have developed Silicon sensors for the ILC vertex detector and tracking system

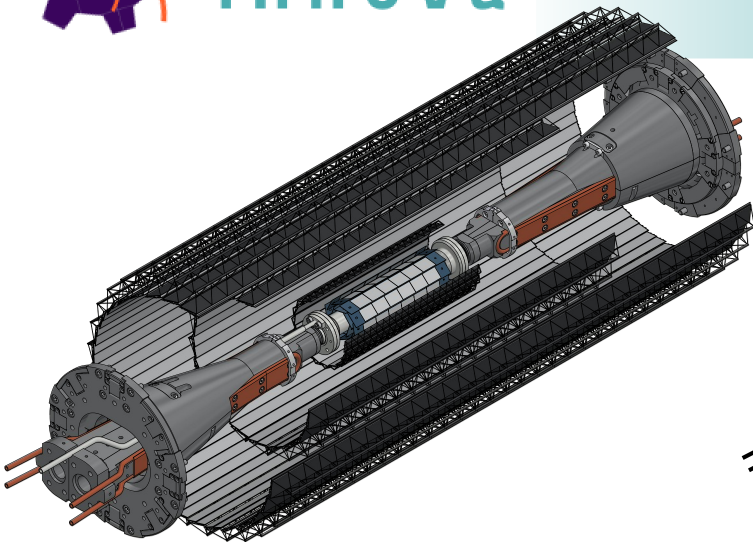
Recent focus on CMOS

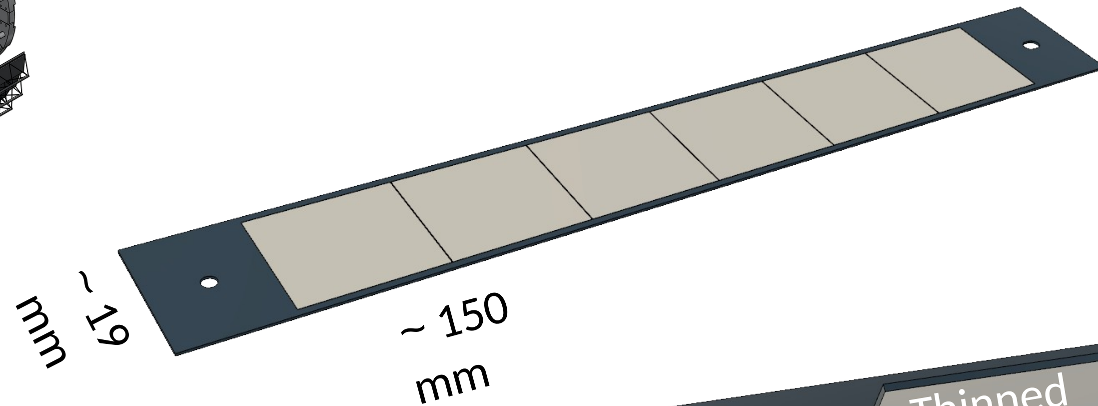
Today's CMOS sensors *(MIMOSA, ALPIDE, MonoPix,...)* can meet ILC requirements.
I will focus on engineering & integration in the following

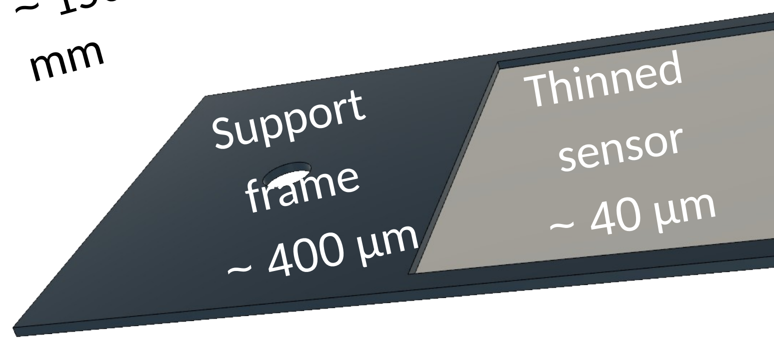


Artistic view of a SEM picture of ALPIDE cross section
Not to scale

Silicon pixel sensors

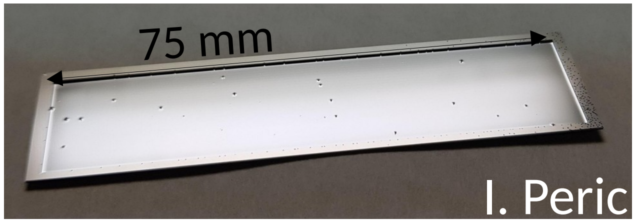






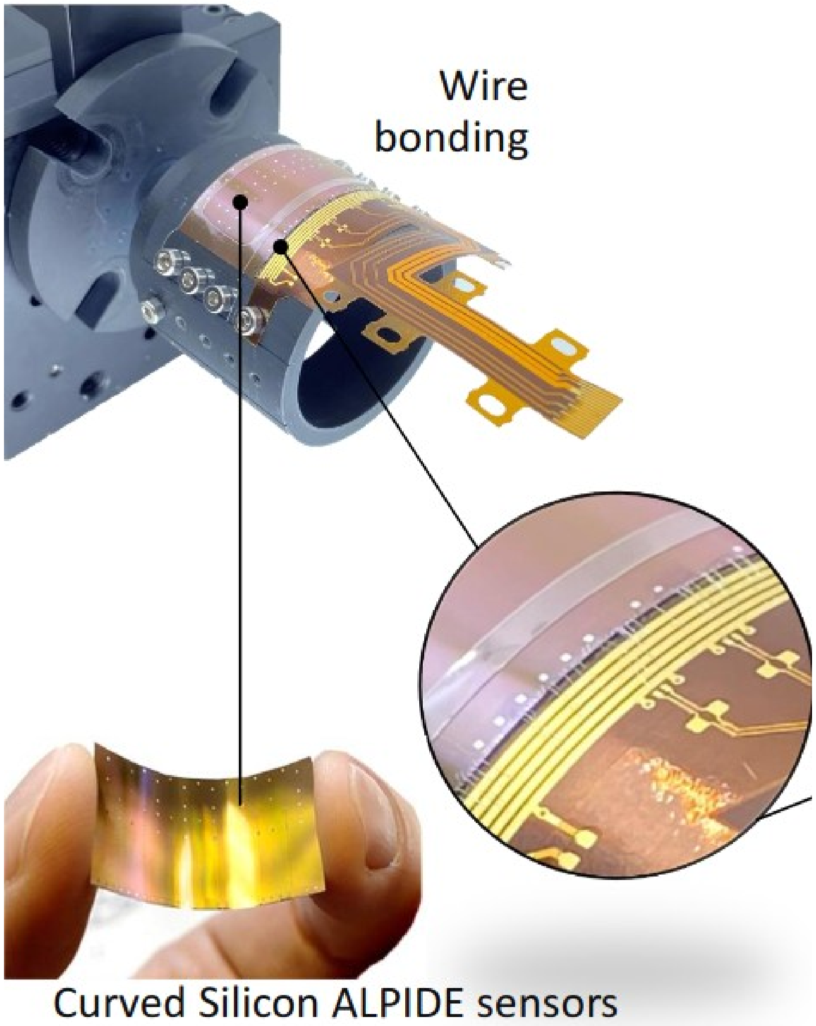
A Belle 2 VXD upgrade (~2026) is foreseen with OBELIX (TJ-monopix) CMOS sensors

Adapt the all-silicon ladder concept



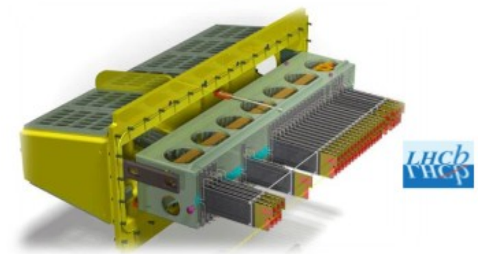
Promising steps towards all-CMOS ladder by I. Peric/IZM HV35DEMO.

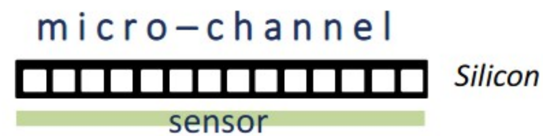
Ultra-light mechanics

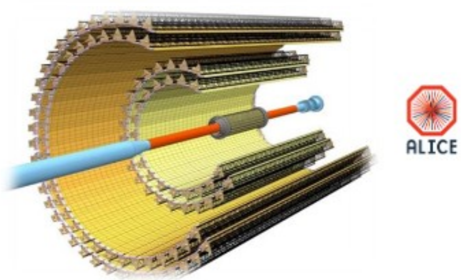


The Mu3e experiment and ALICE have aggressive plans to reduce detector material (Kapton support structures, bent sensors)

Ultra-light cooling







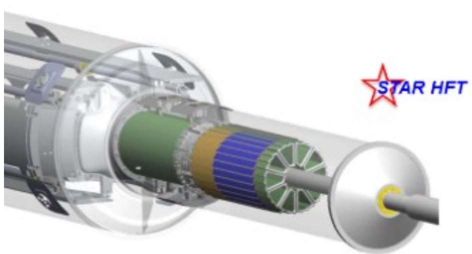
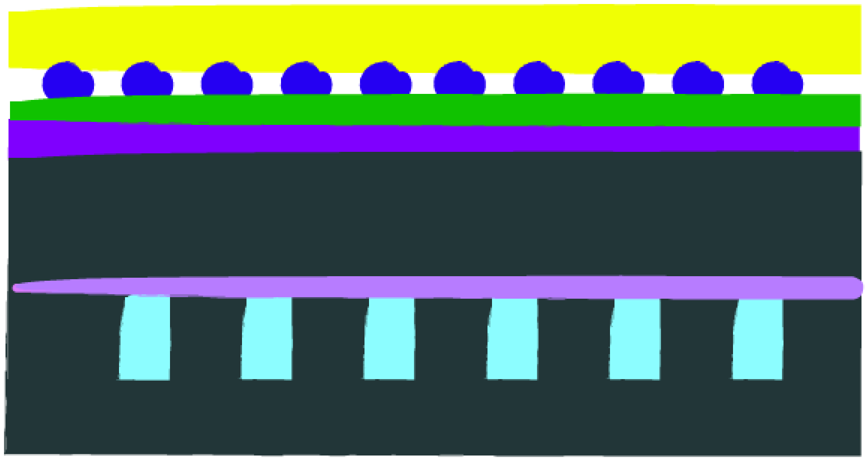


Image from Corrado Gargiulo

Note: first two options may benefit from R&D into novel room-temperature refrigerants, including studies of super-critical CO_2 by CERN and NTNU

Micro-channel cooling



Active cold plates used by NA62 GTK and (soon) LHCb VELO

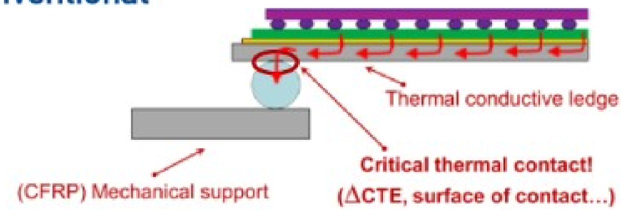
μ-channel rationale

Minimize thermal resistance between heat source and heat sink

Crucial to keep FCChh detectors feasible within CO_2 temperature range

Can also reduce the material involved in systems based on liquid or bi-phase coolant

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

<table>
<tr><th>approach</th><th>TFM</th></tr>
<tr><td>conventional

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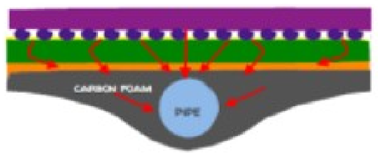
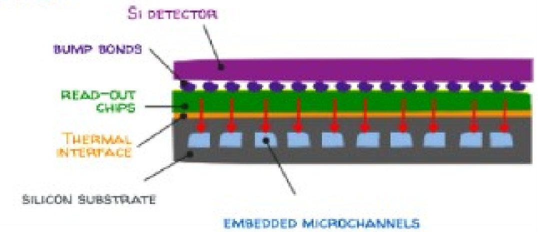
<tr><td>integrated

</td><td>12</td></tr>
<tr><td rowspan="2">microchannels

</td><td>5-8
liquid</td></tr>
<tr><td>3
bi-phase</td></tr>
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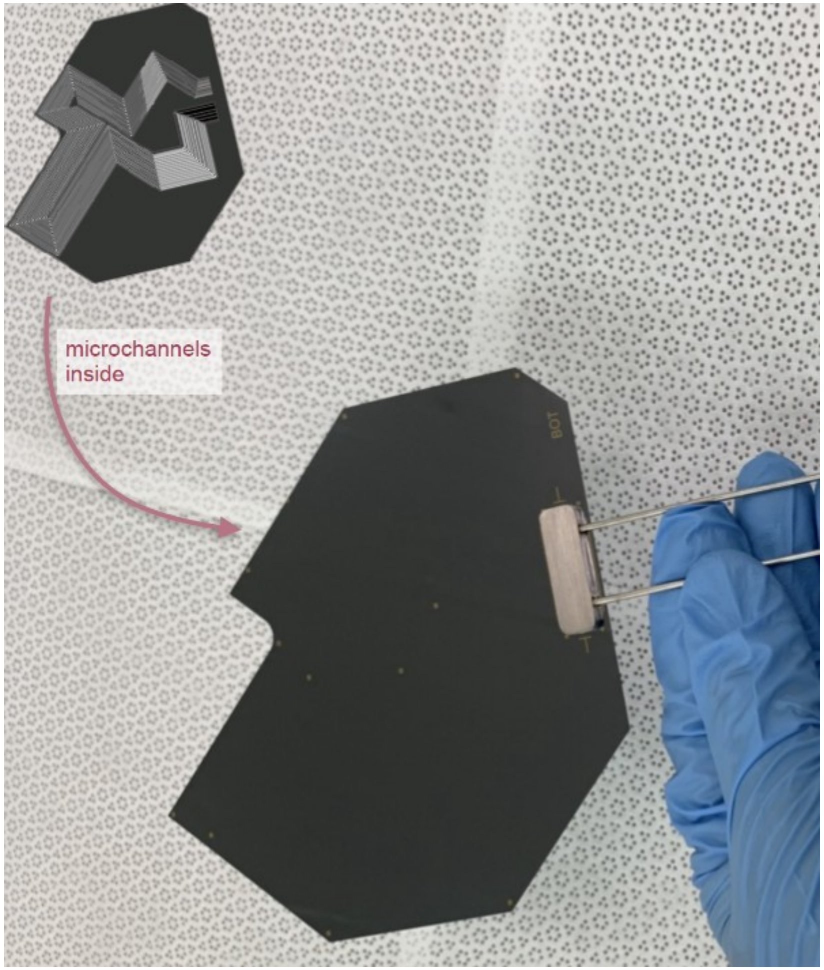
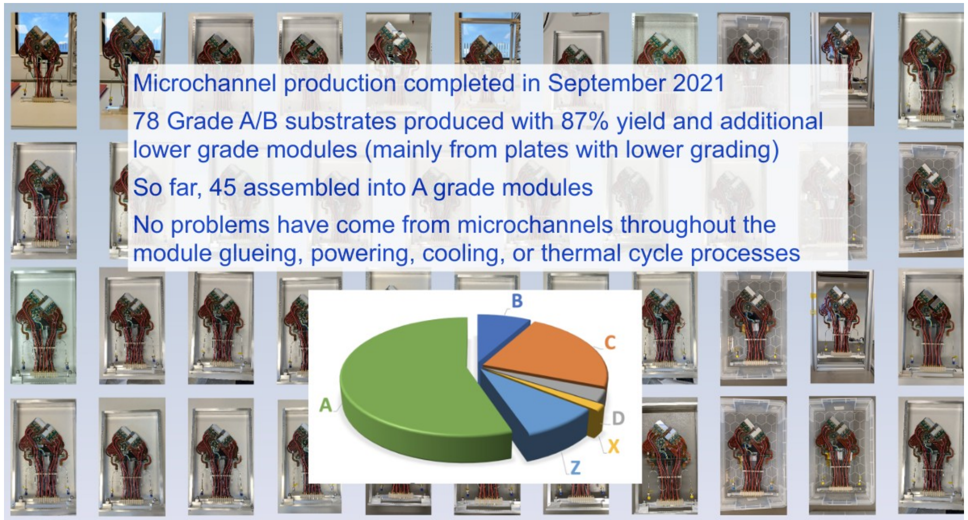
see P.Petagna, presentation, EIC tracking Workshop, Jul 24th 2018, A. Mapelli, presentation, 3rd FCC Physics and Experiments Workshop

μ-channel experience



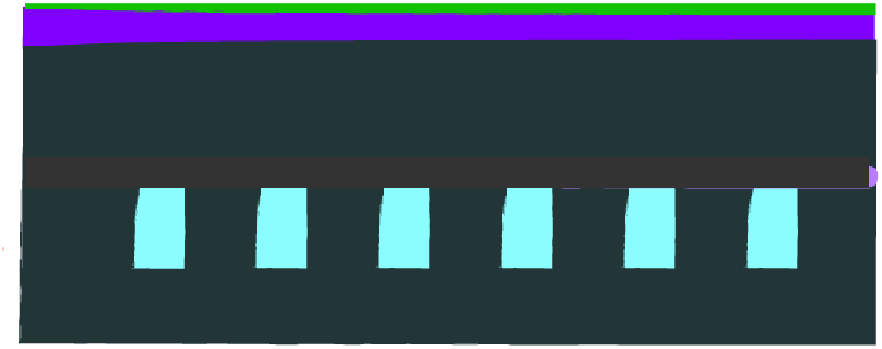
Pioneered by NA62 GTK, in operation since several years

LHCb module production managed to produce 45 grade A VELO modules, engineered to handle operation with bi-phase CO_2 at 60 bar in the LHC secondary vacuum



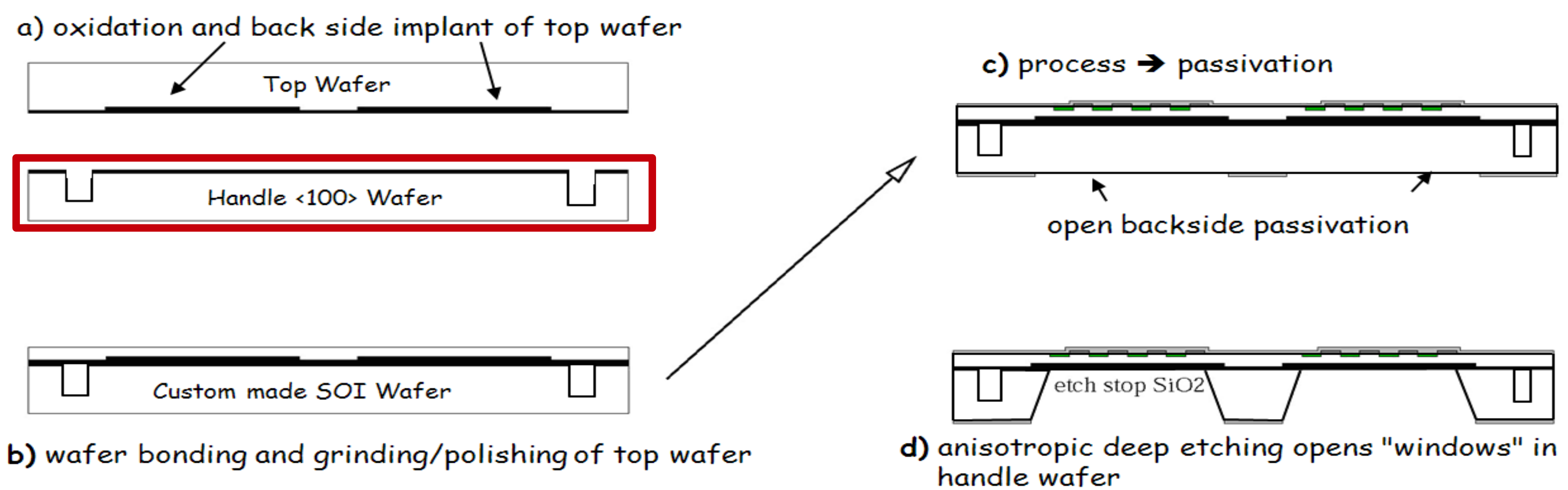
See: Paula Collins, ILCX2021

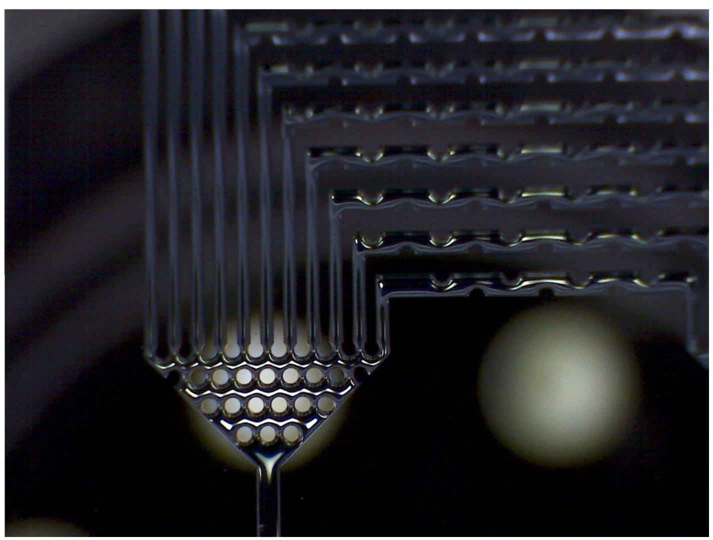
The next frontier: integrated ladders

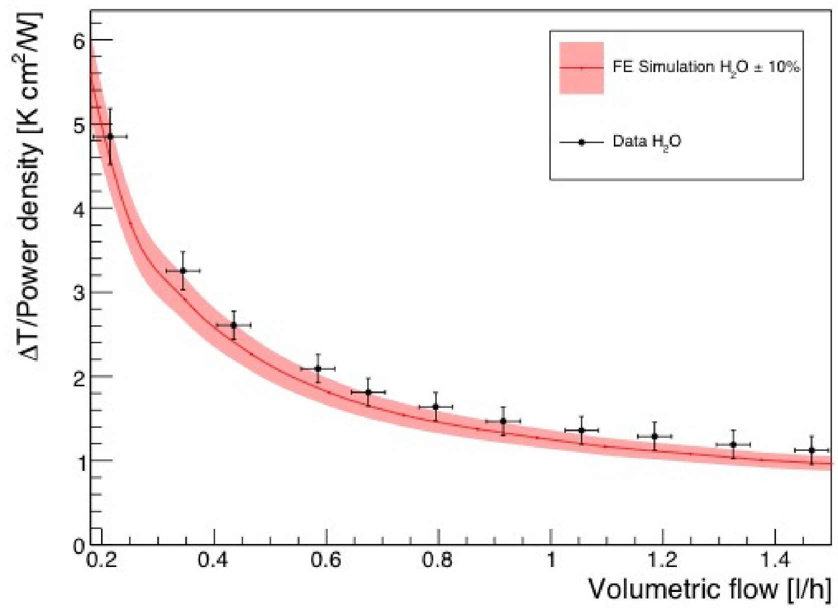


Silicon sensors with integrated support and cooling structures

Ultra-light cooling

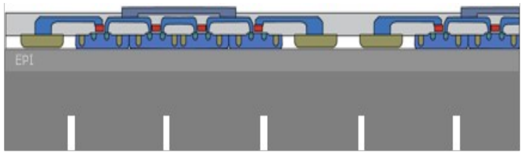






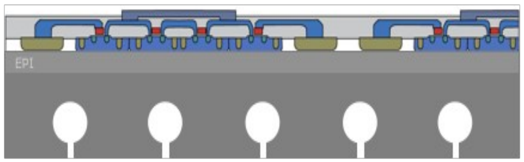
L. Andricek et al., JINST 11 (2016) P06018

Ultra-light cooling



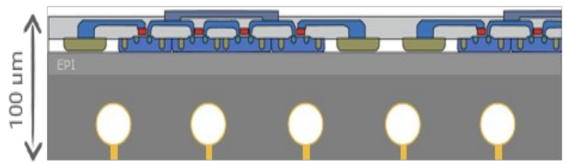
DRIE of small trenches (anisotropic)

A pattern of small trenches (3 x 10 µm) is etched on the backside of the pixel detector



XeF_2 etching of microchannels (isotropic)

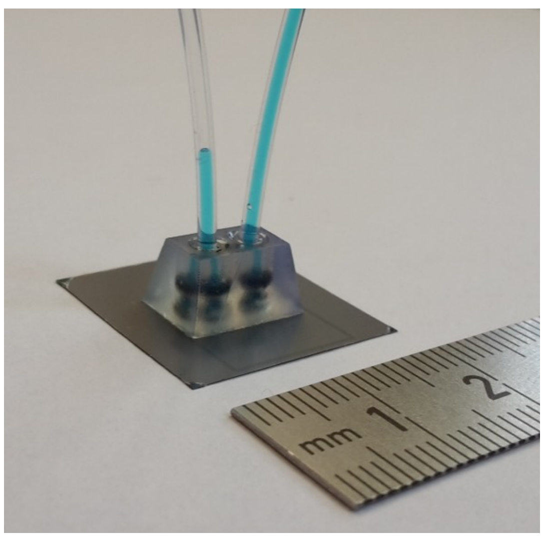
Microchannels are etched isotropically with XeF2.



Filling of trenches (e.g. PECVD, Parylene)

A thin film of parylene (5 µm) seals the microchannels. It is finally cured by a thermal cycle.

M. Boscardin et al., NIM A, 2013
C. Lipp, MSc Thesis, EPFL, 2017
I. Berdalovic et al., JINST 13 (2018) C01023

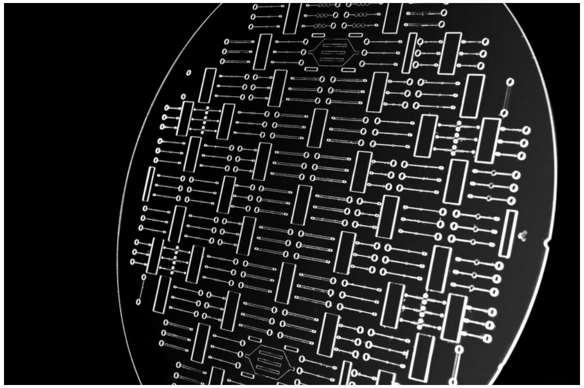


Working MALTA CMOS sensor with integrated µ-channels

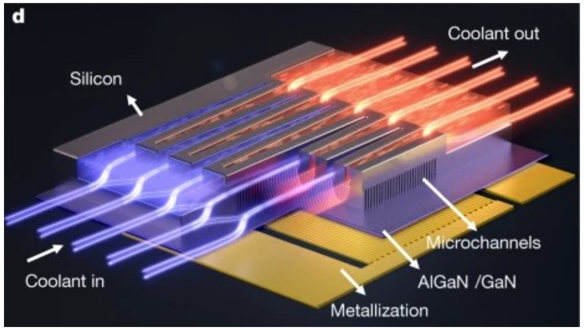
From A. Mapelli (CERN+EPFL)

Beyond HEP

- Beyond HEP, a LOT is going on!



- Glass wafer with micro-fluidics, available
- in Europractice as standard CMOS post-process
- (IMT through IMEC, thanks to Riet Labie)



- Co-designed electronics and micro-fluidics
- for thermal management of data centers
- R. van Erp et al., Nature 585, 211–216 (2020)

Summary

Detector R&D has made tremendous progress,
but Higgs factory requirements remain pretty daunting

Detector R&D must advance as much as possible
now to be ready for an approved Higgs factory!

Integrated silicon sensors – with integrated supports,
power and signal lines and cooling – are a real
possibility