Detector Technologies For Higgs Factories

LCWS 2024
University of Tokyo
July 11, 2024

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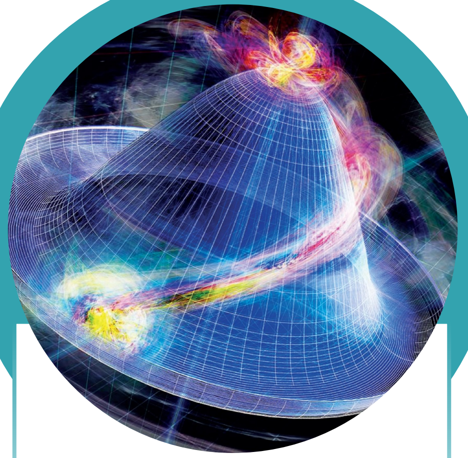
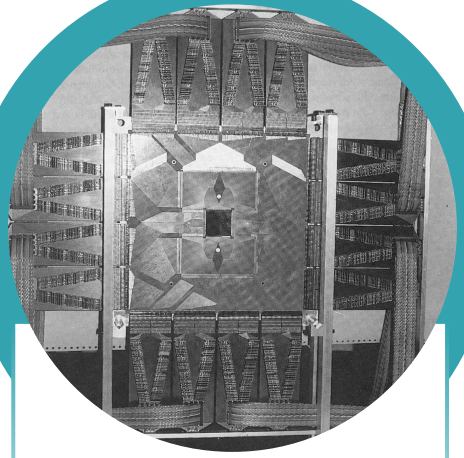
Outline: Technologies toward the realization of a Higgs Factory



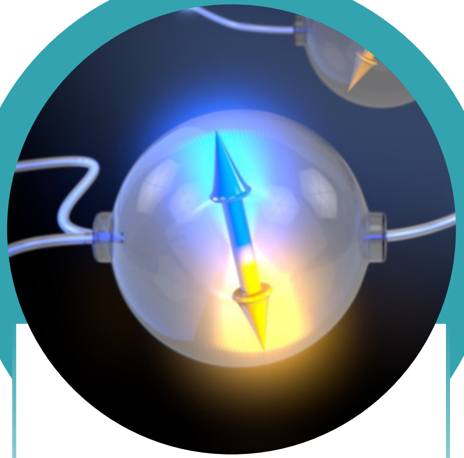
Physics Landscape

The Higgs boson is special



Historical Perspective

New paradigms through novel instrumentation



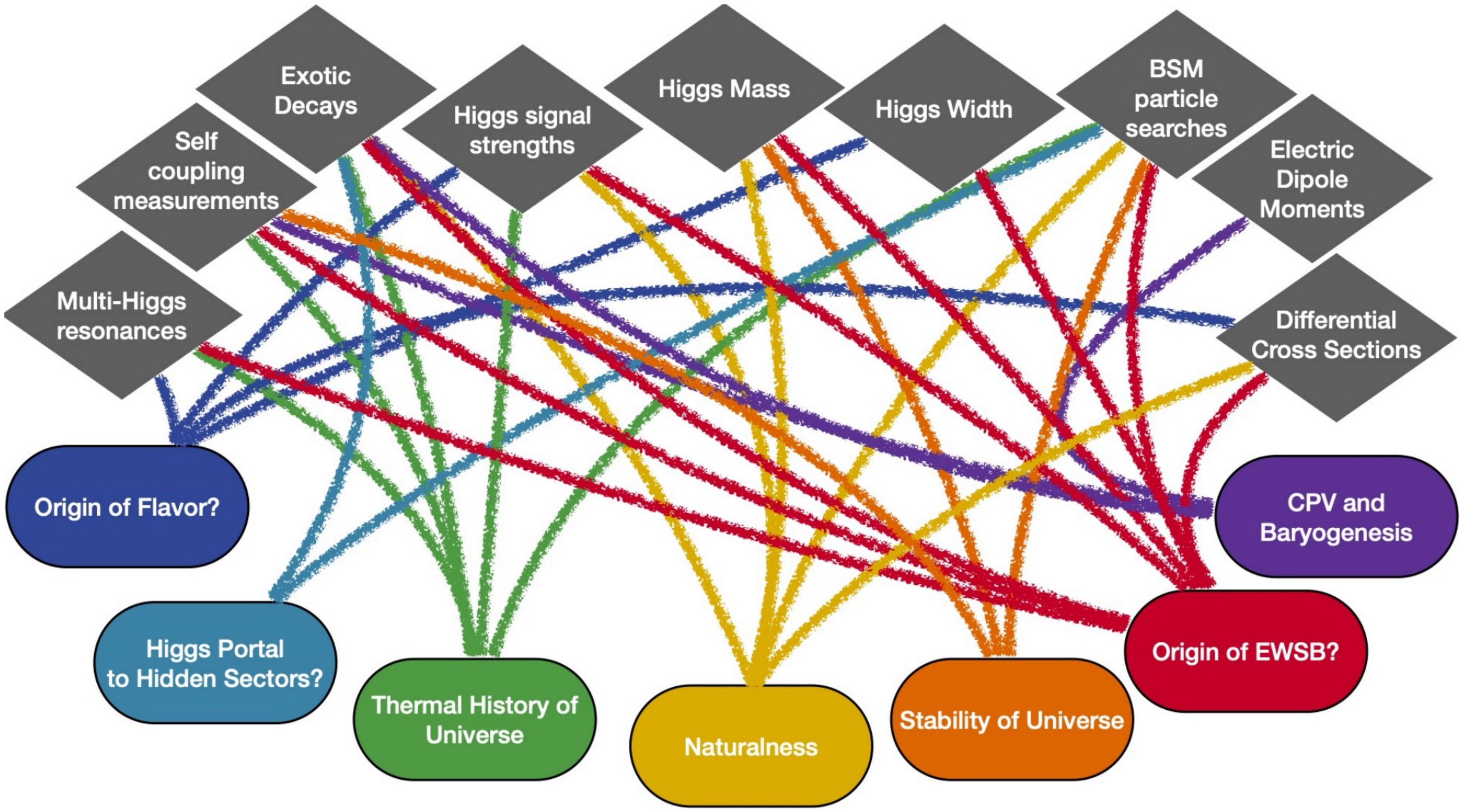
Technologies

Current and future technologies and their challenges

Global Roadmap

Realizing a Higgs Factory

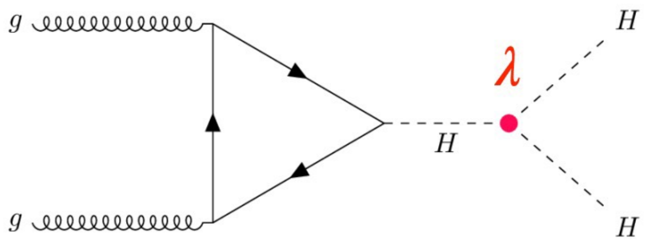
Precision Studies of the Higgs Will Lead To New Insights

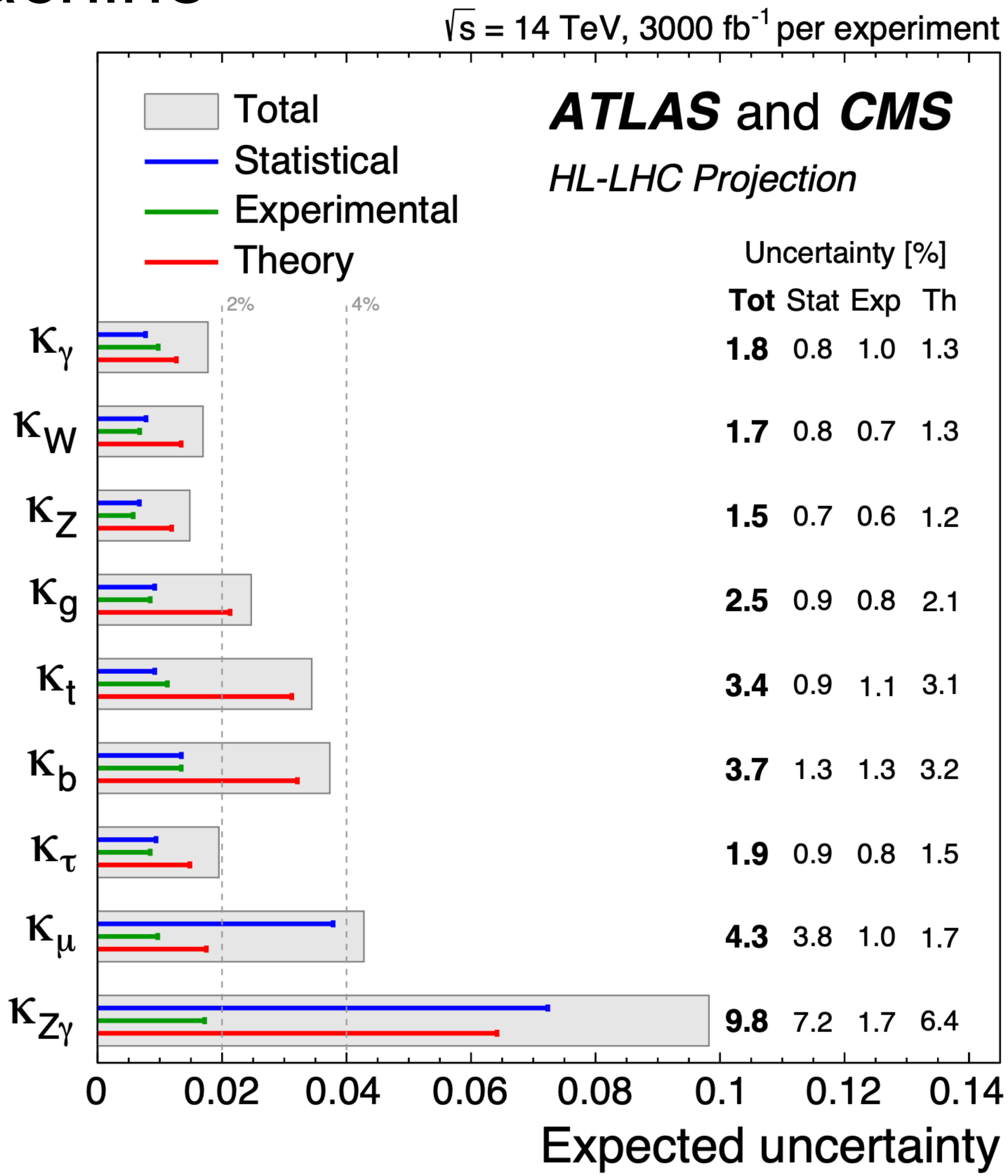


https://www.slac.stanford.edu/econf/C210711/reports/Energy.pdf

The HL-LHC is a most powerful machine

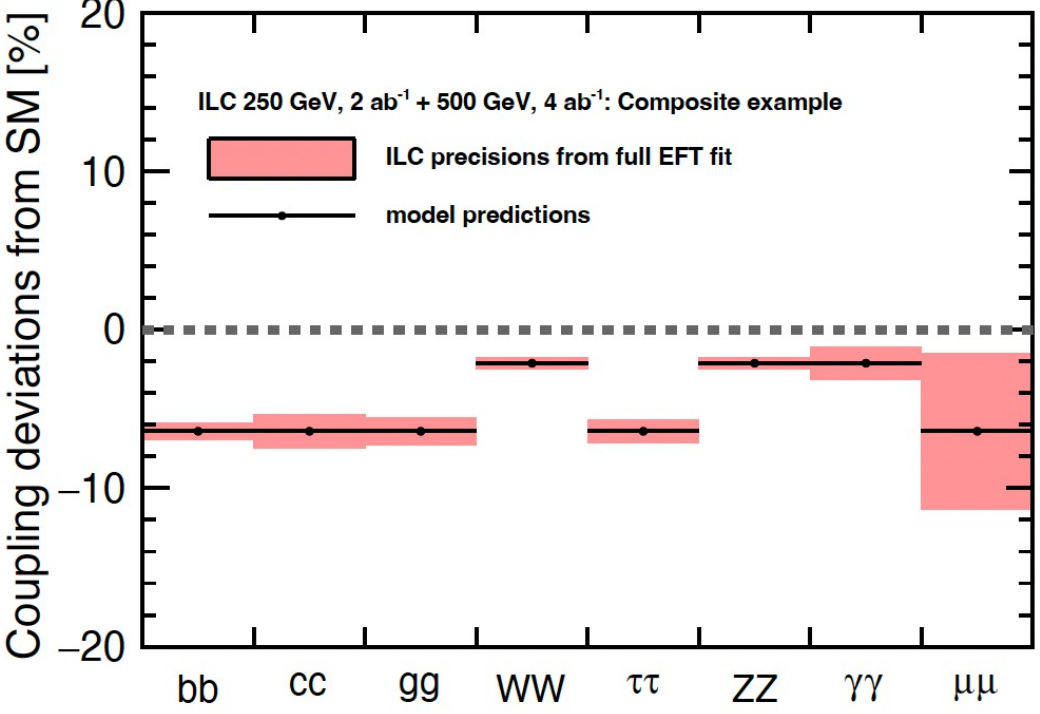
- At the start of a new Higgs Factory, the HL-LHC program will have been completed
- With a luminosity of 3 ab^{-1} at 14 TeV:
  - 190M Higgs bosons produced!
  - 120k Higgs boson pairs produced
  - Tri-linear coupling a science driver: Observe pp --> HH @ 3.4σ



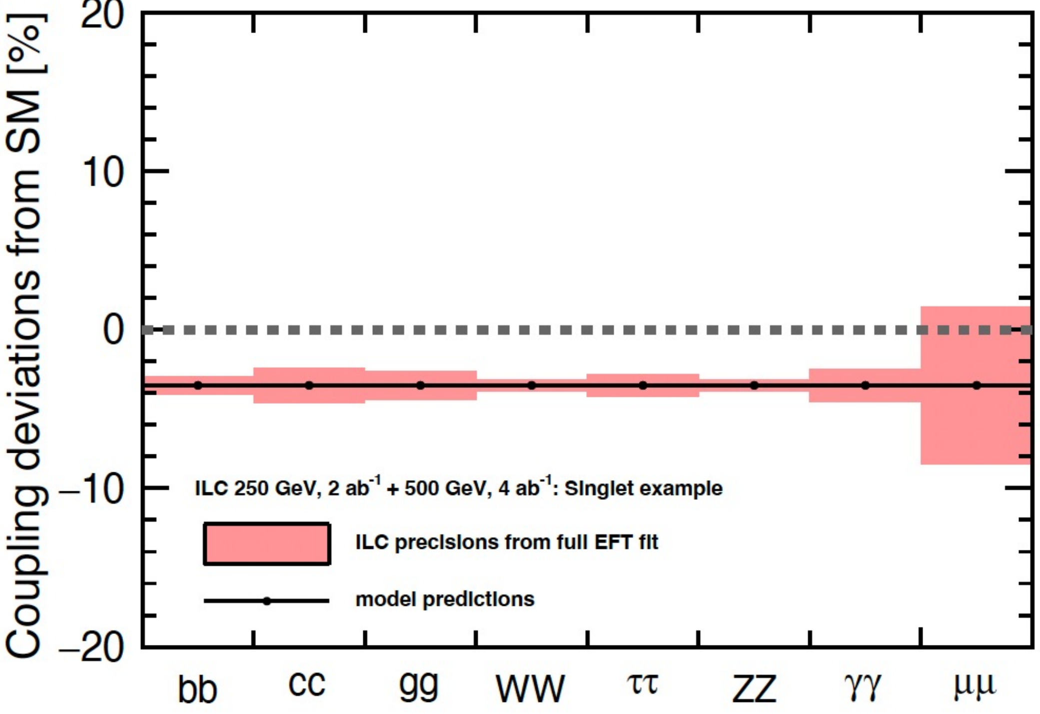


Manifestation of New Physics Could Be Subtle

Composite Higgs Model

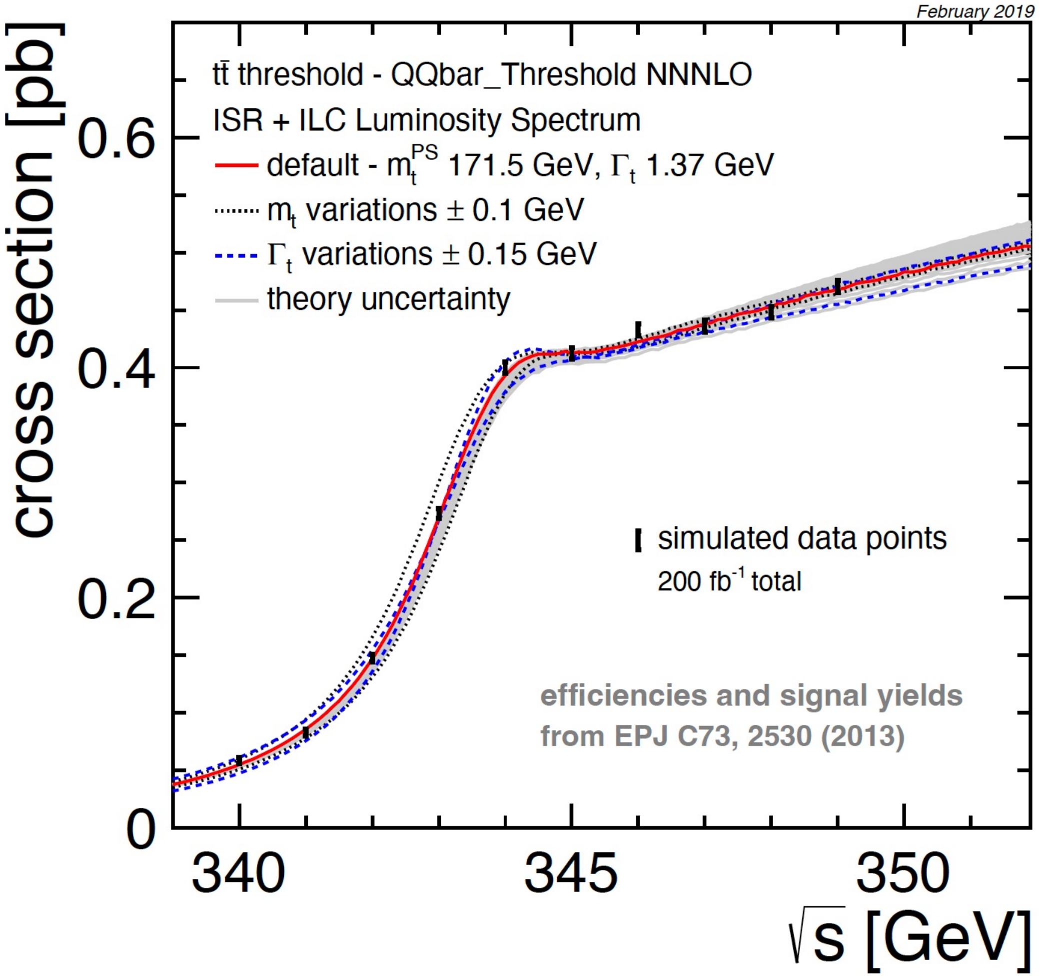


Scalar Singlet Model



Phys. Rev. D97 (2018) 053003 [1708.08912]

High Precision Is Needed



- Measurements of the machine conditions and theoretical predictions are equally important

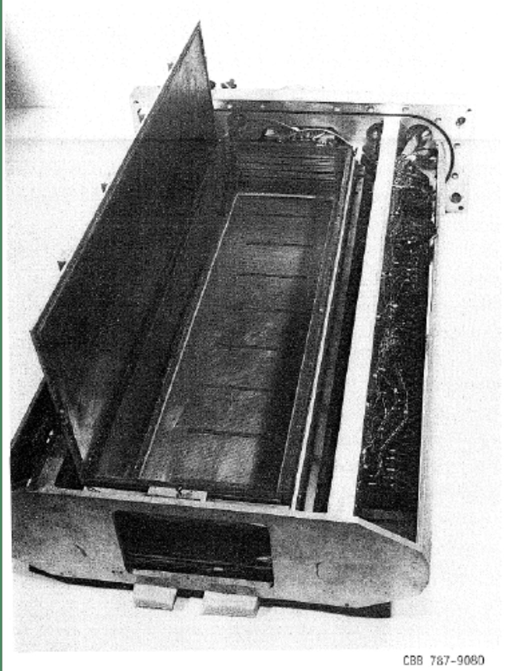
$$\left.\frac{\partial m}{\partial\sqrt{s}}\right|_{\sqrt{s}\,=\,343\ \mathrm{GeV}} = 0.5$$

$$\left.\frac{\partial \sigma}{\partial m}\right|_{\sqrt{s}\,=\,343\ \mathrm{GeV}} = 0.12\ \frac{\mathrm{fb}}{\mathrm{MeV}}$$

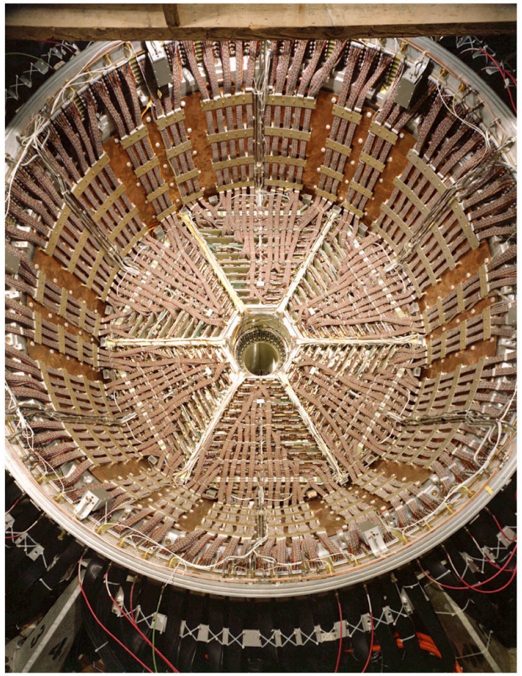
Required Detector Technologies
For Higgs Factories and Discoveries

The Underpinning Of Scientific Progress

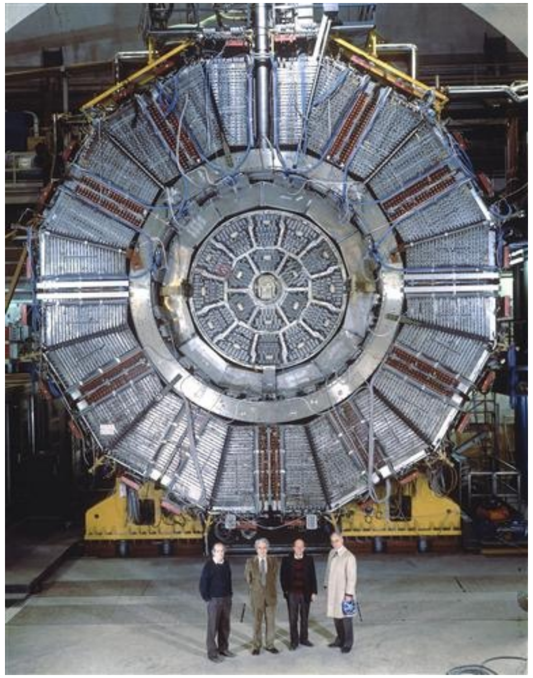
Bevatron (1974)



PEP-4 TPC (1976)



ALEPH TPC (1983)



ALICE TPC (2003)

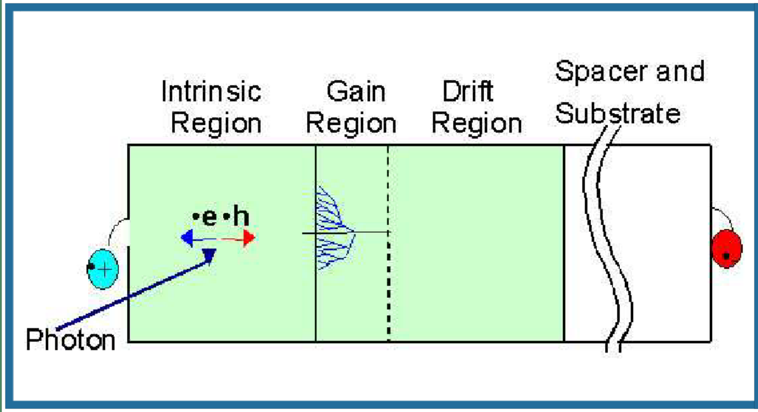
Dave Nygren has said the idea for the TPC came to him after he realized that real improvements in particle detection could not be achieved without a radical departure from the old ways.

https://doi-org.ornl.idm.oclc.org/10.1016/j.nima.2018.07.015

PEP-4: https://inspirehep.net/literature/114399
ALEPH: https://cds.cern.ch/record/300680/files/cer-0222458.pdf
ALICE: https://edms.cern.ch/ui/file/398930/1/ALICE-DOC-2003-011.pdf

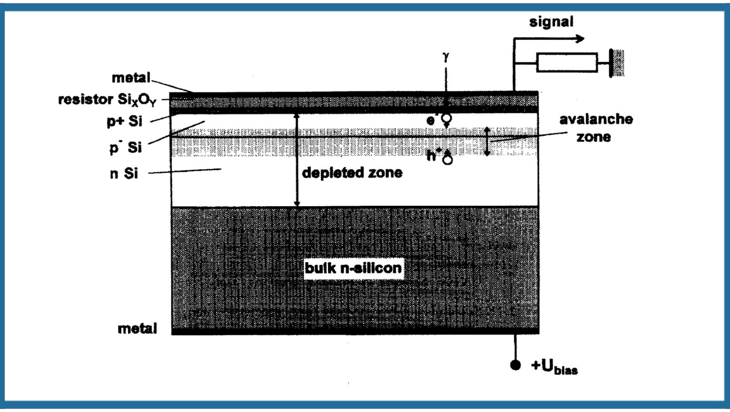
The Underpinning Of Scientific Progress

VLPC (Rockwell, 1987)



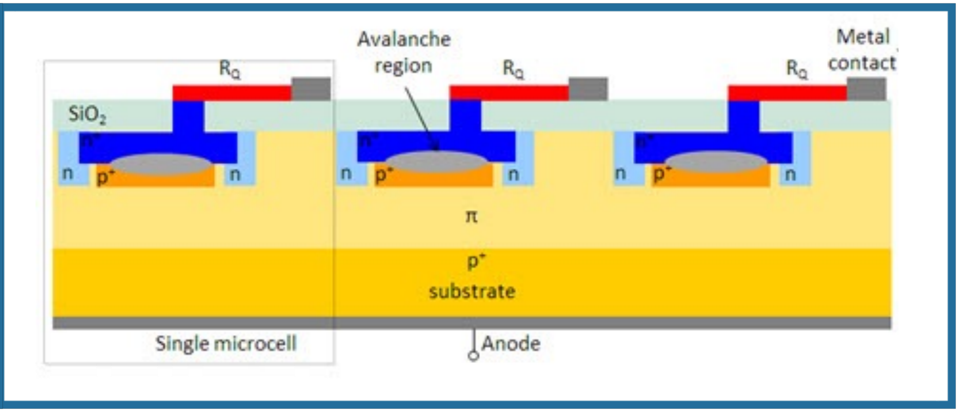
Bross et al., NIM A477, 172 (2002)

MRS APD (Russia, ~1995)



Antich et al., NIM A 389 (1997) 491

MPPC (Russia, ~2003)

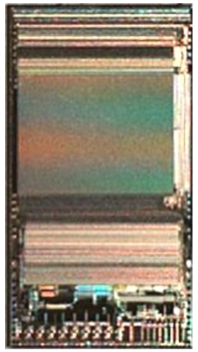
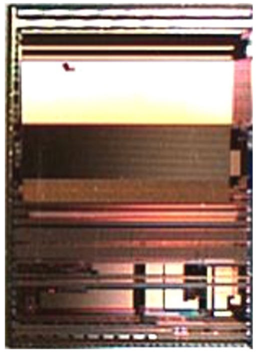
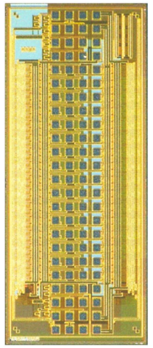
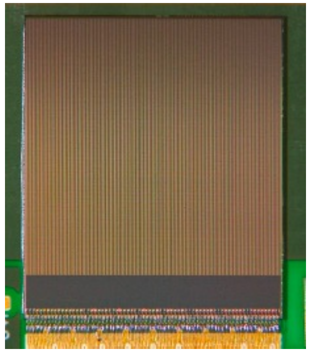
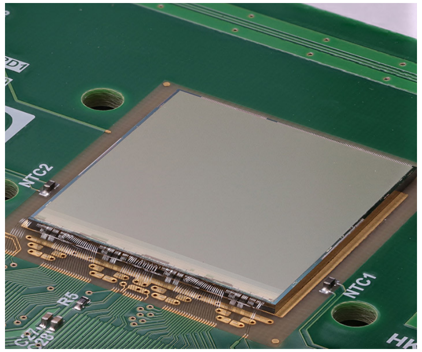


Dolgoshein et al., NIM A 504 (2003) 48
Sadygov patent (1998)

- From difficult beginnings (VLPC operated at 7K for Dzero scintillating fiber tracker) to being a workhorse for the field in a mere twenty years.

VLPC: Visible Light Photon Counter
MRS: Metal- Resistor-Semiconductor
MPPC: Multi-Pixel Photon Counter (SiPM)

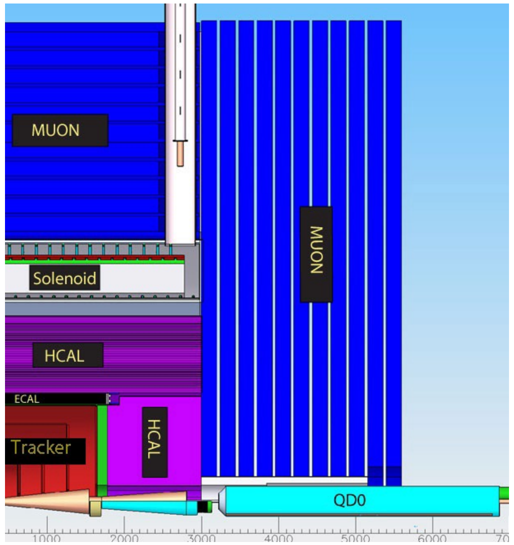
The Underpinning Of Scientific Progress

SVX (CDF 1990)	**SVX3 (Fermi 1998)**	**SVX4 (Fermi 2002)**	**DCDB (Belle 2015)**	**Velopix (LHCb 2022)**	**RD53 (HL-LHC 2022)**
					
UTMC 1.2 µm rad-hard CMOS	Honeywell 0.8 µm Mixed-signal CMOS	TSMC 0.25 µm mixed-signal CMOS	TSMC 180nm CMOS	TSMC 130nm CMOS, 20.5 Gbps	TSMC 65nm CMOS, noise <100 e;
Doi: 10.1109/23.12699	*Doi.org/10.1016/S0168-9002(97)01301-6*	*Doi:10.1109/TNS.2004.836027*	*Doi:10.1109/NSSMIC.2011.6154365*	*Doi: 10.1088/1748-0221/10/01/C01057*	*Doi: /10.22323/1.343.0157*

- Continued through progress with MAPS technology and parallel progress in opto-transceivers by industry

Detector Concepts Today

SiD



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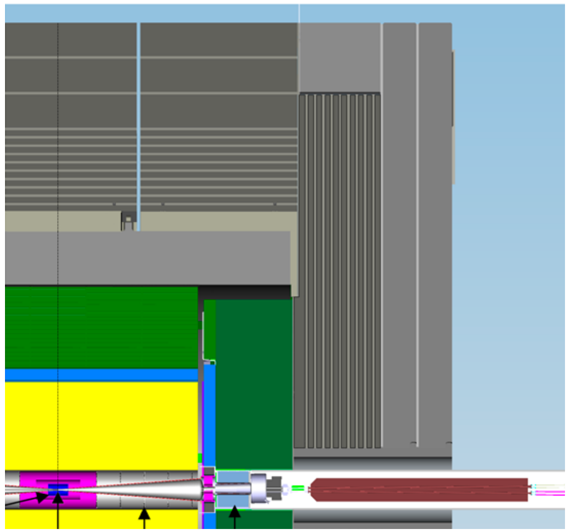
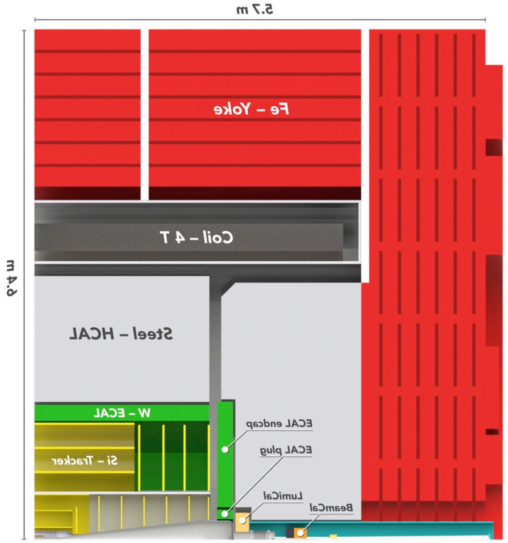
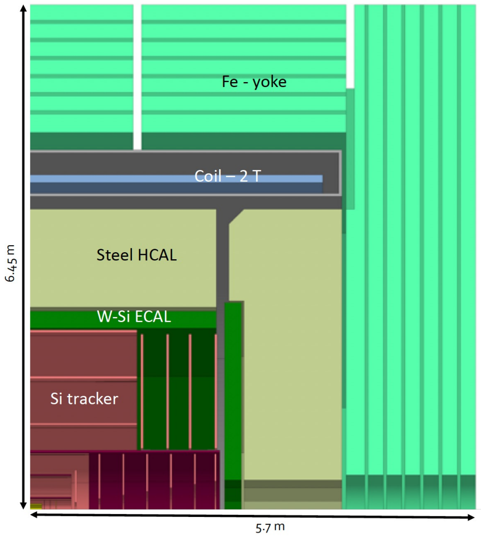
ILD



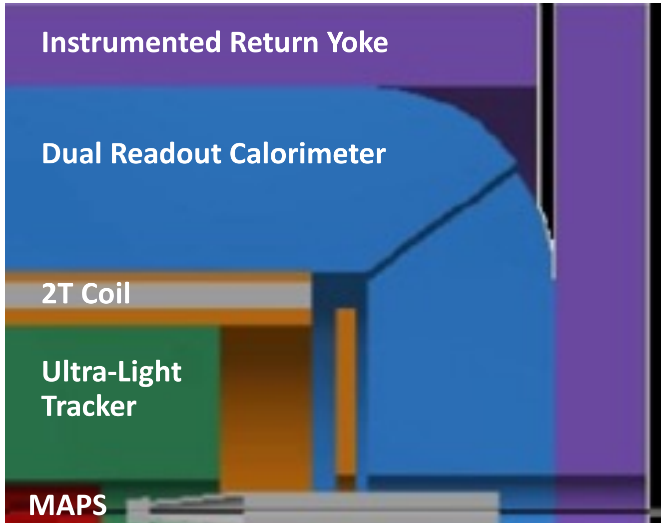
CLIC



CLD



IDEA

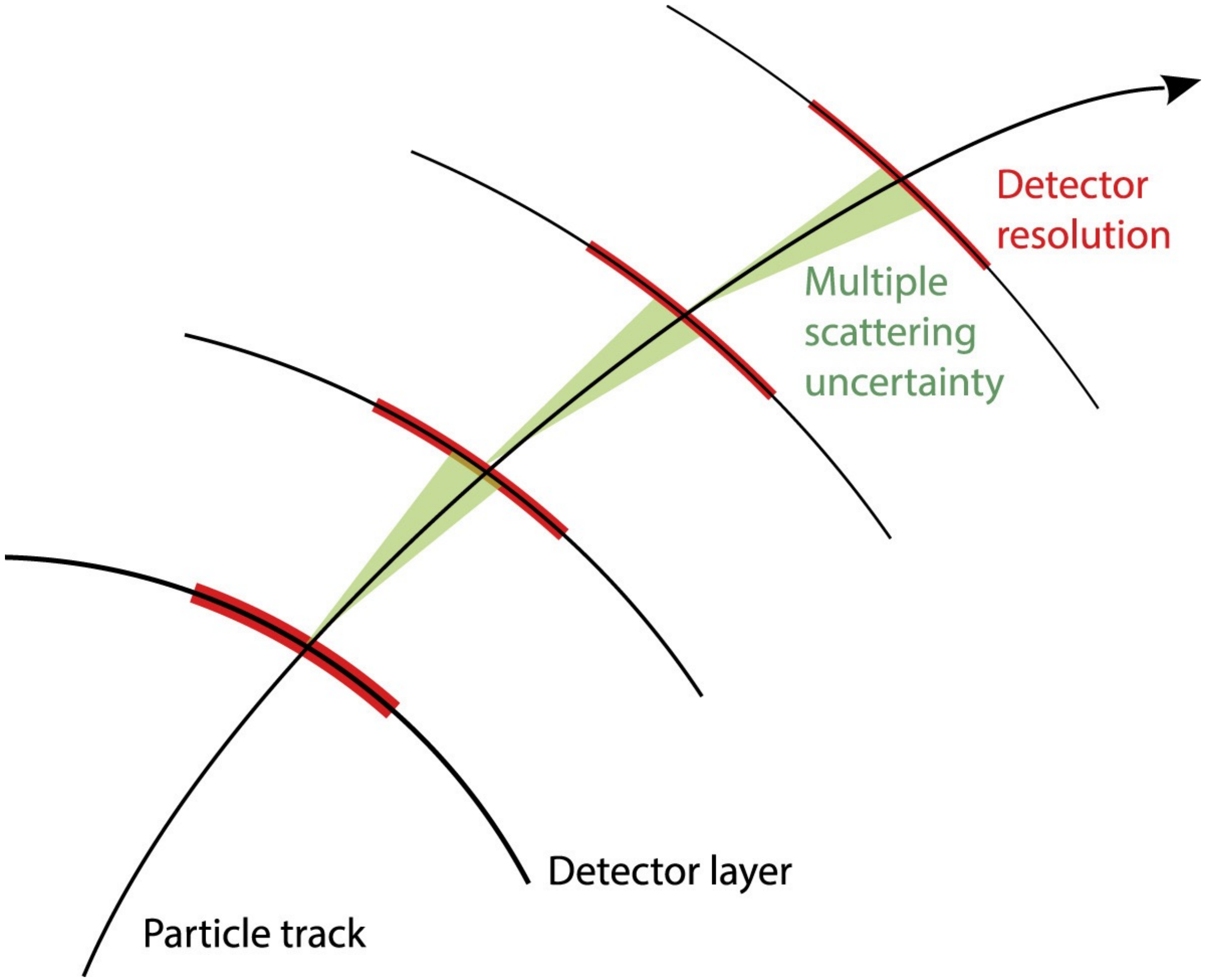


ALLEGRO

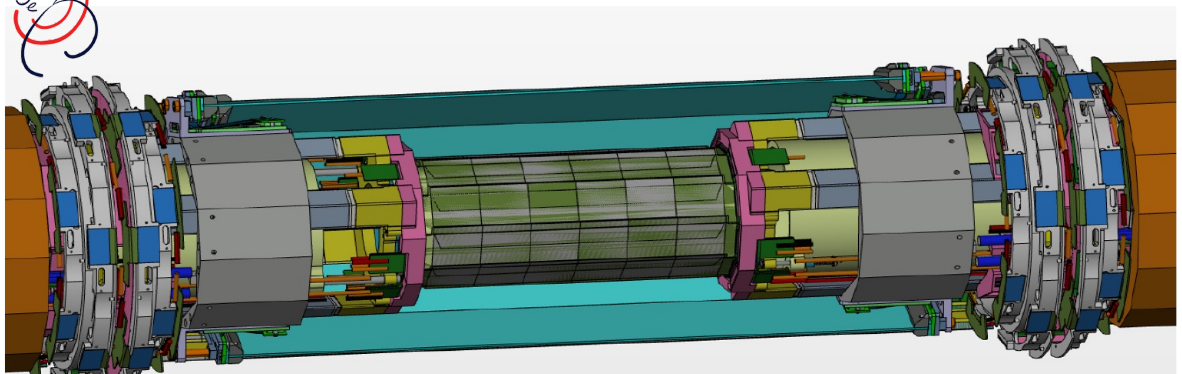
+ .....

Transparency in Tracking

- Critical requirements:
  - High spatial resolution
  - Low mass budget
  - No active cooling
  - Low power
  - Hermetic with redundancy

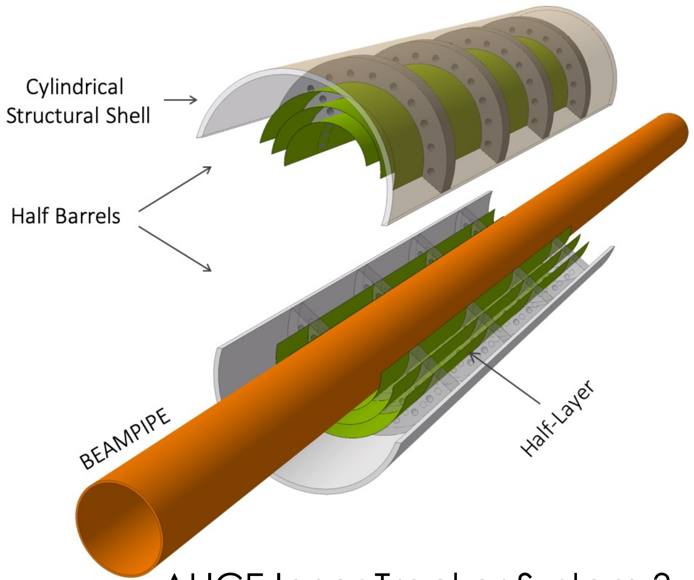


Next Generation CMOS Trackers and Vertex Detectors

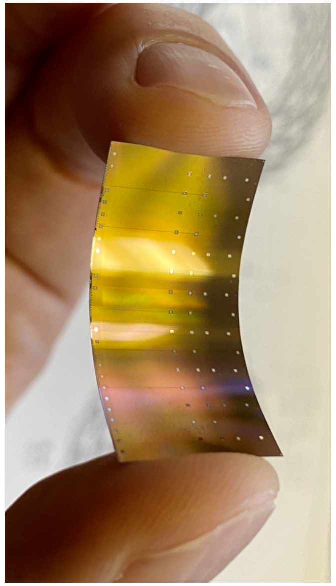


Mu3e CMOS Tracker

- Mu3e:
  - Ultra-thin, 50 µm, wafer-scale HV-CMOS Monolithic Active Pixel Sensor.
  - 180 nm technology, chip size 20.6 x 23.2 mm^2; pixel size 80x80 $µm^2$
  - **0.5 ‰ X_0** per layer, <30 µm resolution



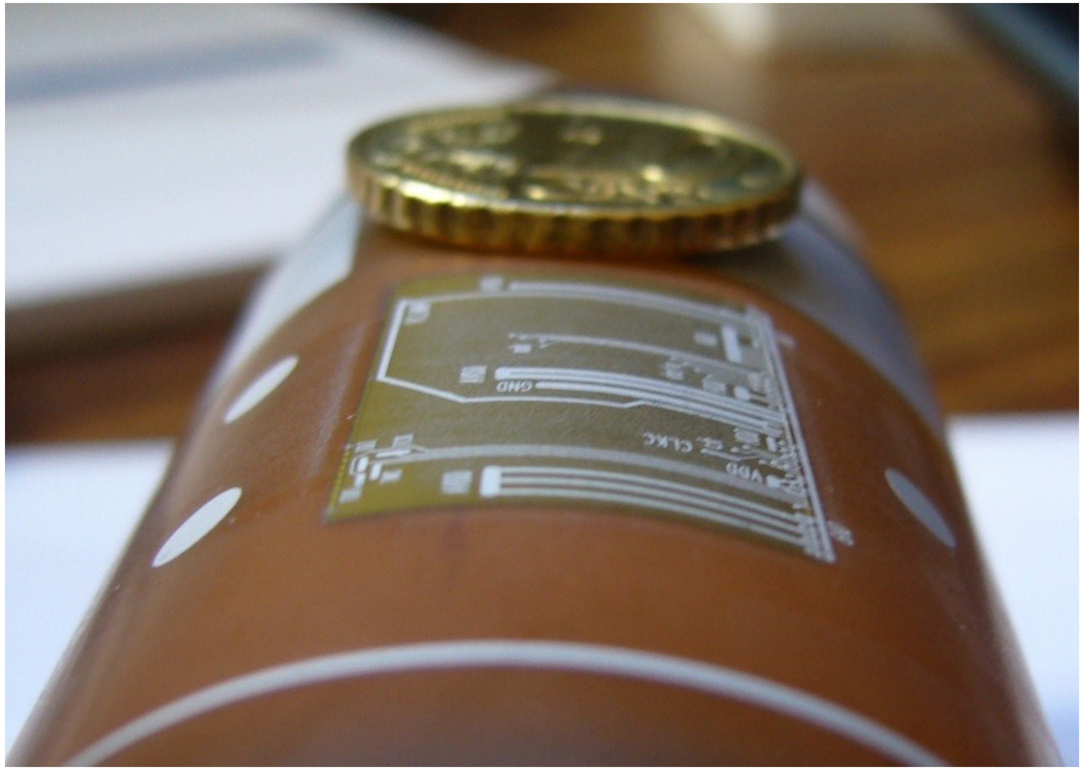
ALICE Inner Tracker System 3



ALIPIDE thinned readout chip

- ALICE ITS-3:
  - Ultra-thin (20 µm to 40 µm), wafer-scale **HV-CMOS** Monolithic Active Pixel Sensor.
  - 65 nm technology, chip size 280 x 94 mm^2, stitched,
  - 0.5 ‰ X_0 per layer, <5 µm resolution
  - **Flexible!**

Flex embedded sensors

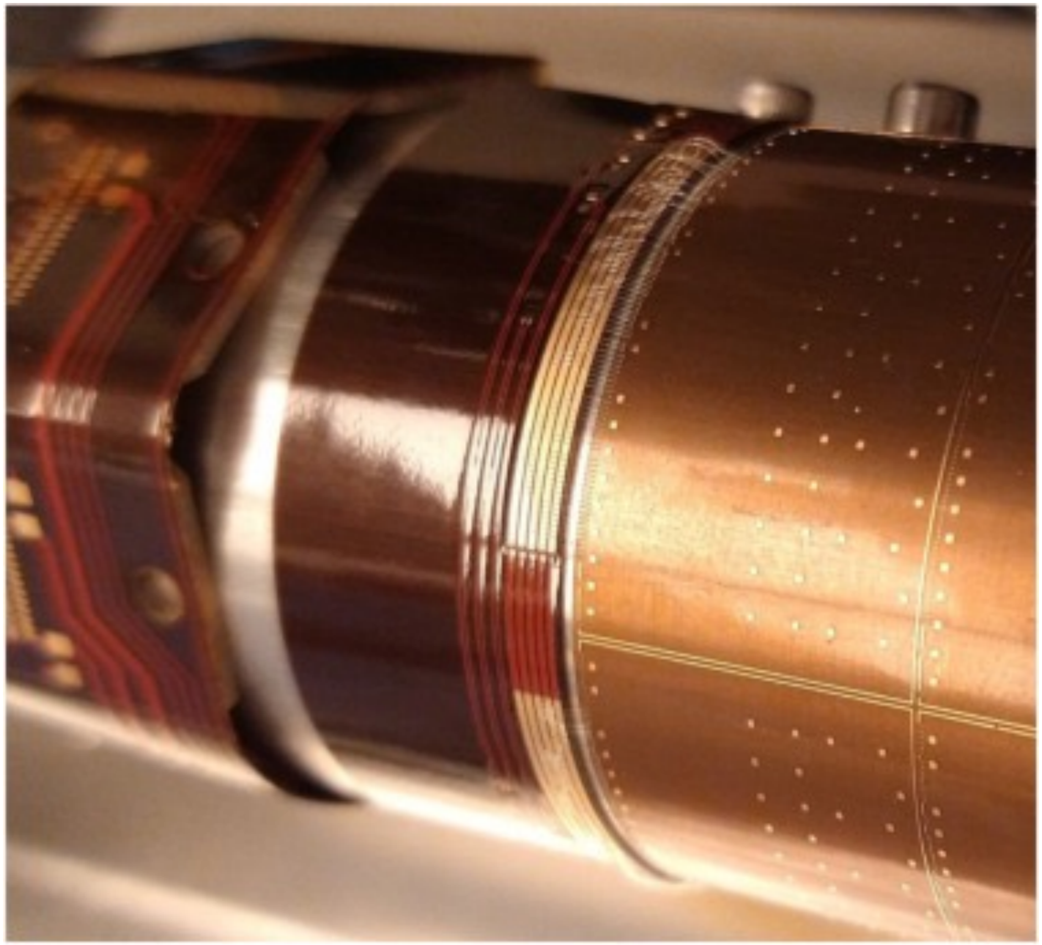


Already more than a decade ago, PLUME, SERVIETTE and PLUMETTE collaboration investigated and succeeded at **embedding thin MAPS sensors in Kapton flex**

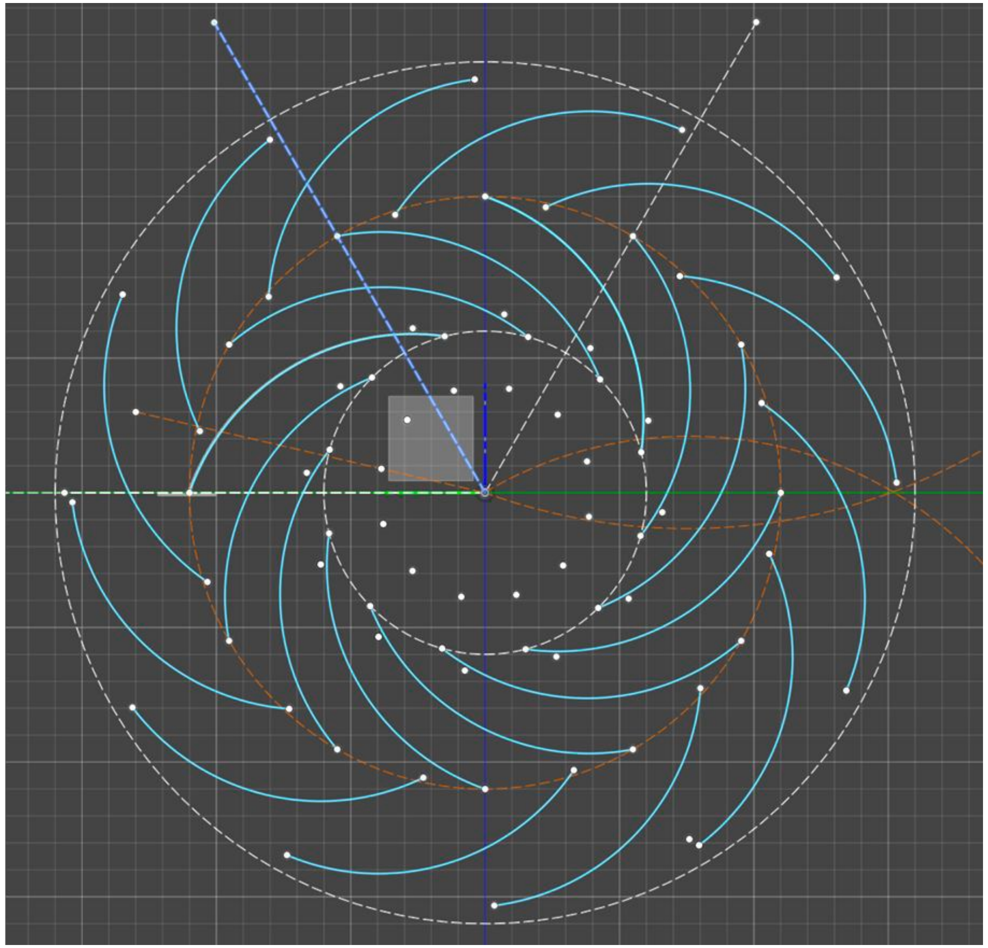
New fabrication and packaging technologies for CMOS pixel sensors are **closing the gap between hybrid and monolithic**

https://indico.cern.ch/event/276611/contributions/622863/attachments/502969/694527/dulinski_FEE-2014.pdf

Alternate Geometries

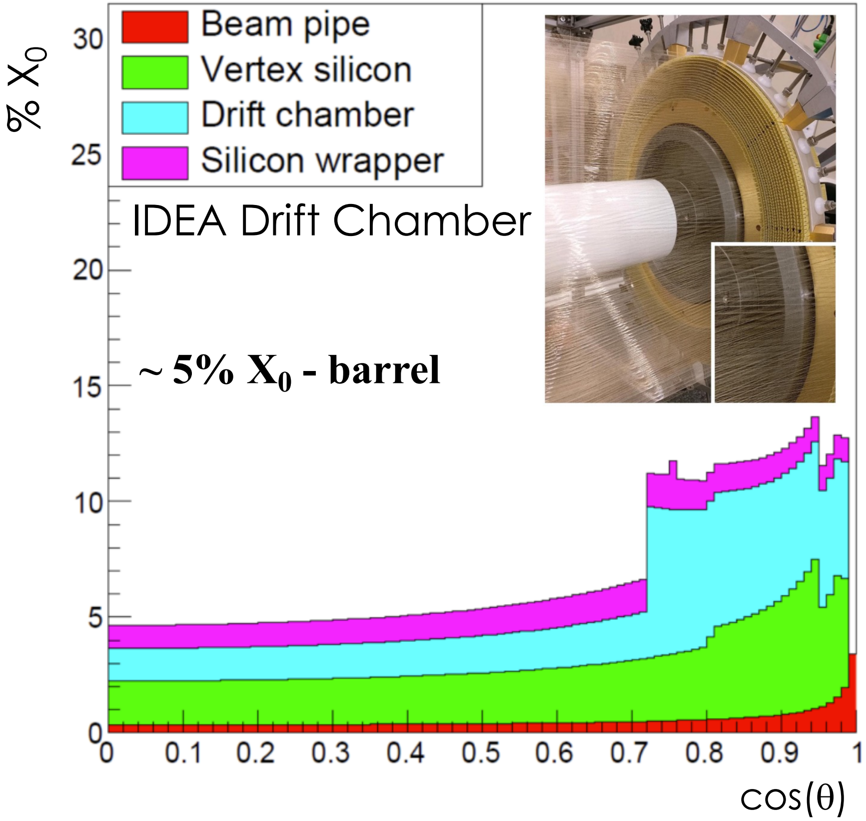


ALICE ITS3 mechanical bent prototype



Gaseous Tracking

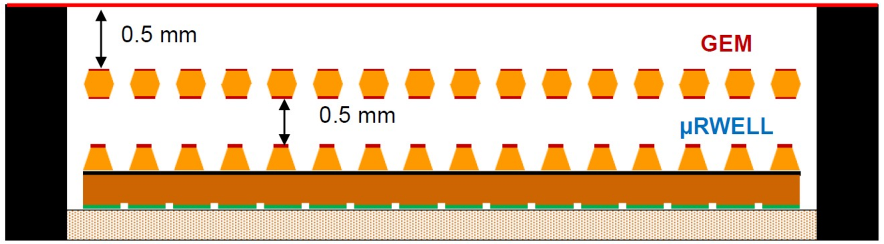
Revival of an old technology with modern readout: drift chamber with cluster counting

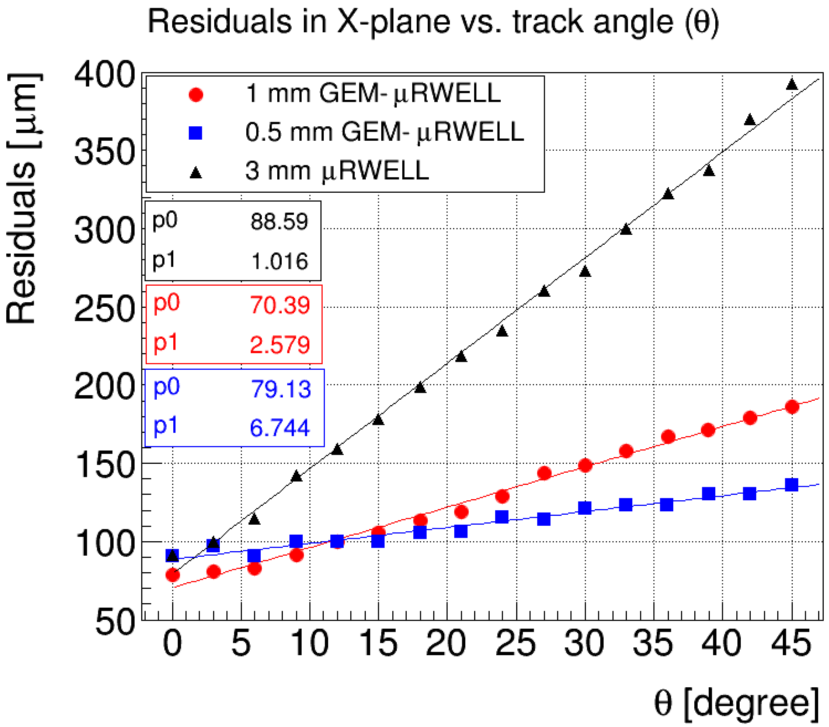


Nicola De Filippis, this workshop

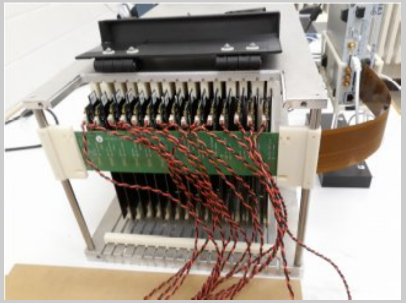
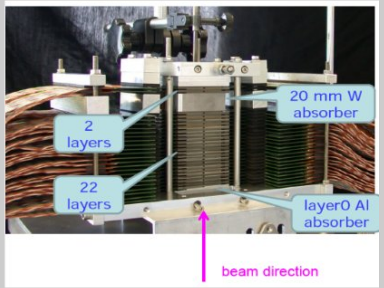
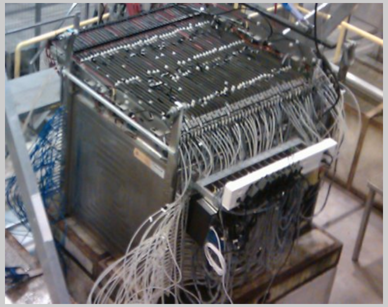
Combining **old with new ideas** for cost-effective large-area tracking detectors

hybrid amplification GEM-μRWELL with 0.5 mm drift gap





Imaging Calorimetry

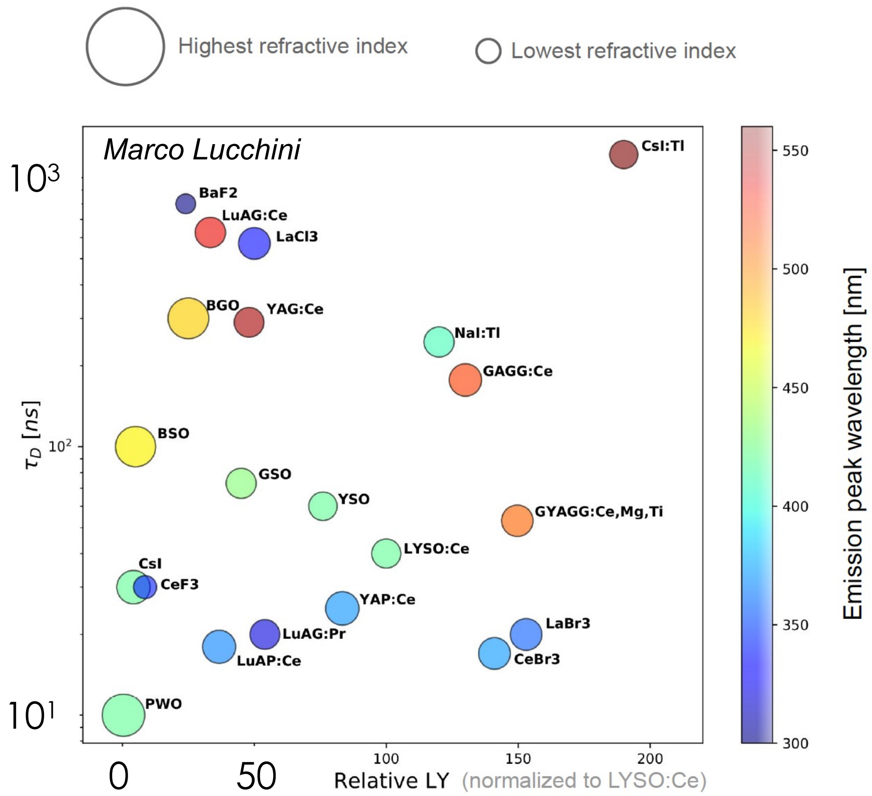
Si-W ECAL	(ALICE FoCAL)	Scint-W ECAL	AHCAL	SDHCAL
				
0,5×0,5 cm² ×15 (➞30) Si layers + W	0,003×0,003 cm² × 24 MIMOSA layers + W	0,5×4,5 cm² ×30 Scint+SiPM lay. + SS	3×3 cm² × 38 Scint+SiPM lay. + SS	1×1 cm² × 48 layers GRPC + SS

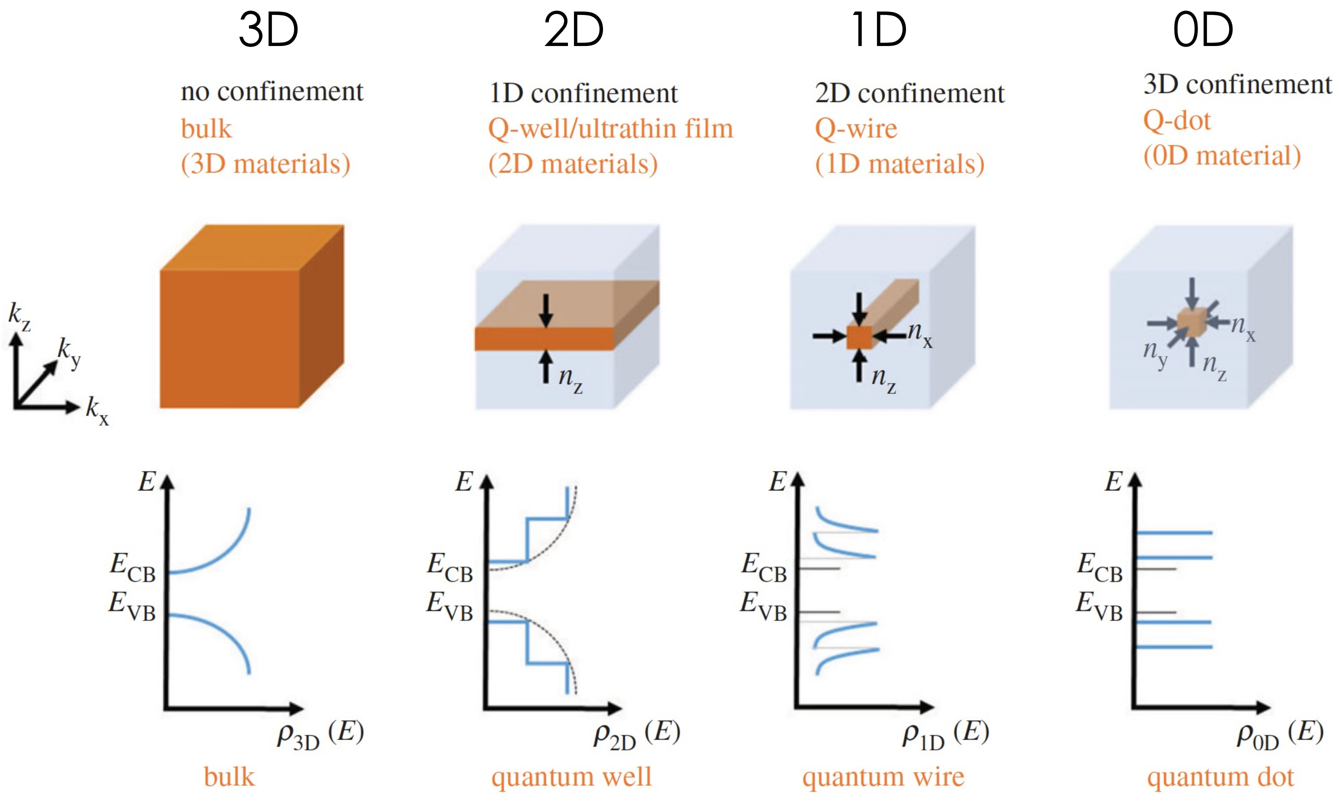
From V. Boudry, Calor 2024

- Many technology options being pursued for imaging calorimeters, with analog, digital or semi-digital readout.
- First true fully imaging calorimeter is the HGCAL of CMS.

Crystal Calorimetry

- Traditionally, crystal – fully absorbing – calorimetry has obtained the best energy resolution





rsos.royalsocietypublishing.org R. Soc. open sci. 5: 180387

- Huge range of possibilities through **quantum engineering** of materials

Crystal Calorimetry

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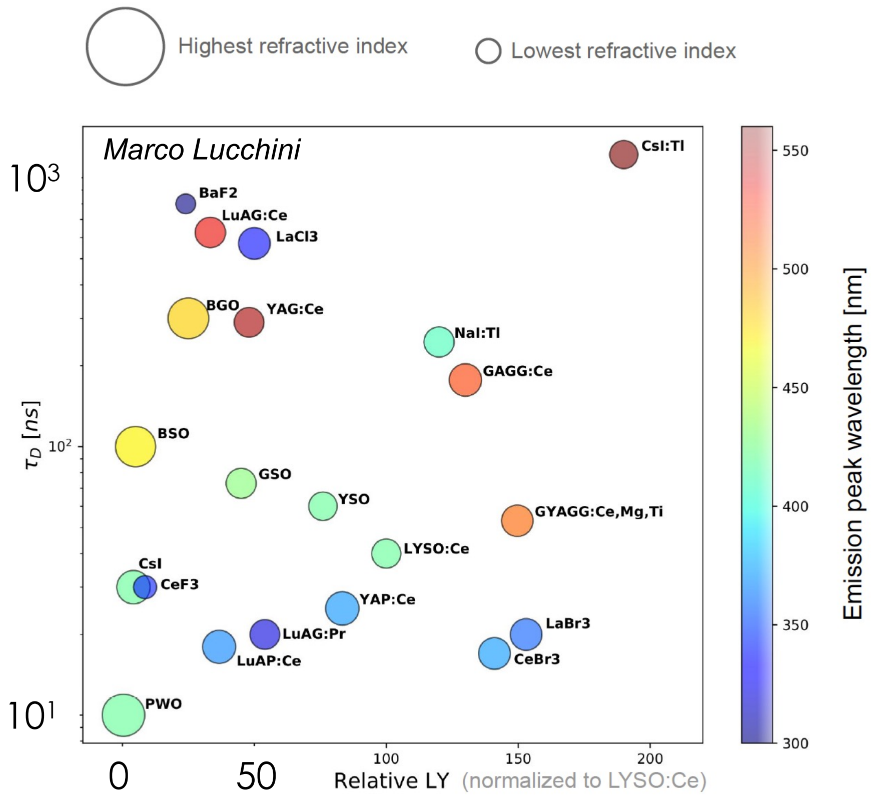
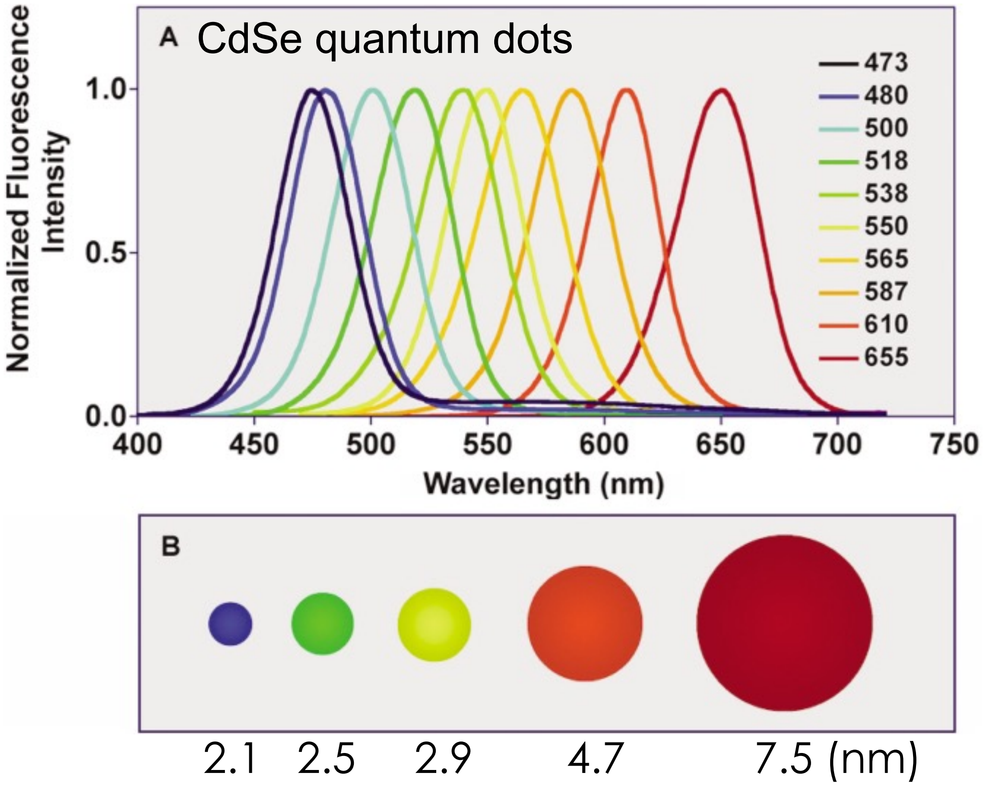
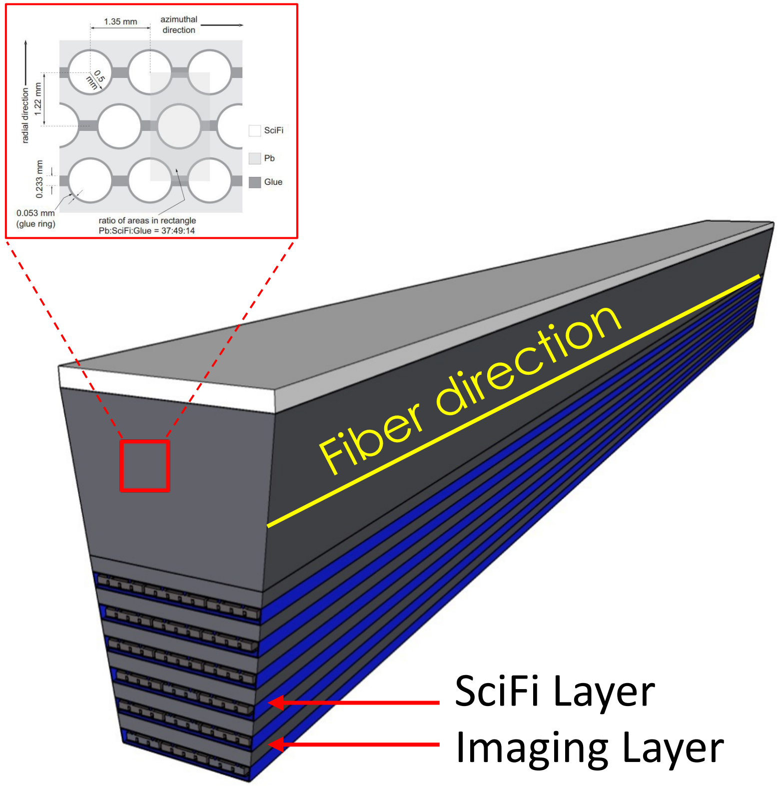




A. Smith, https://doi.org/10.1039/B404498N

- Huge range of possibilities through **quantum engineering** of materials

Hybrid Calorimetry



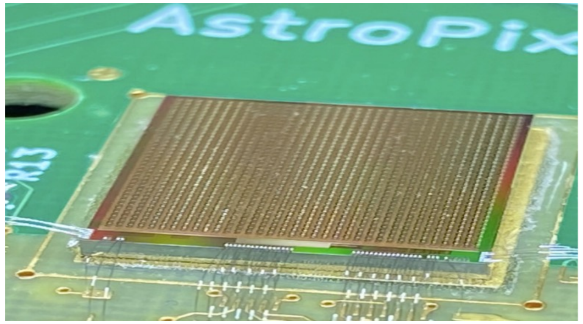
SciFi Layer

Imaging Layer

⌀ 1mm fibers embedded in Pb

Incident particle

Imaging



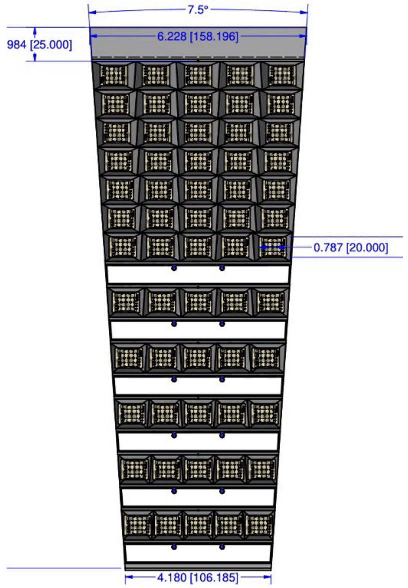
AstroPix MAPS sensor based on ATLASpix3

- 500 μm pixel size
- Time resolution 3.25 ns
- Low power dissipation (~1.5mW/cm2)

Sampling

Pb/SciFi 5+1 Layers (1.4X_0)

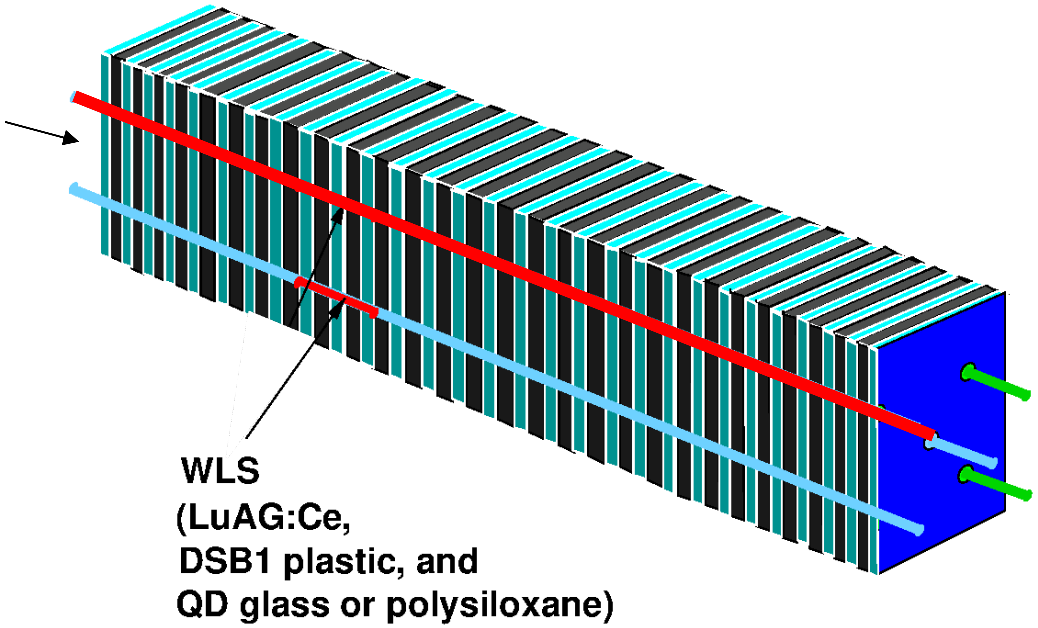
- 5 readout cells per layer
- 1 light-guide per cell
- Two side readout
- Each readout by 4x4 SiPMs of 3x3mm^2

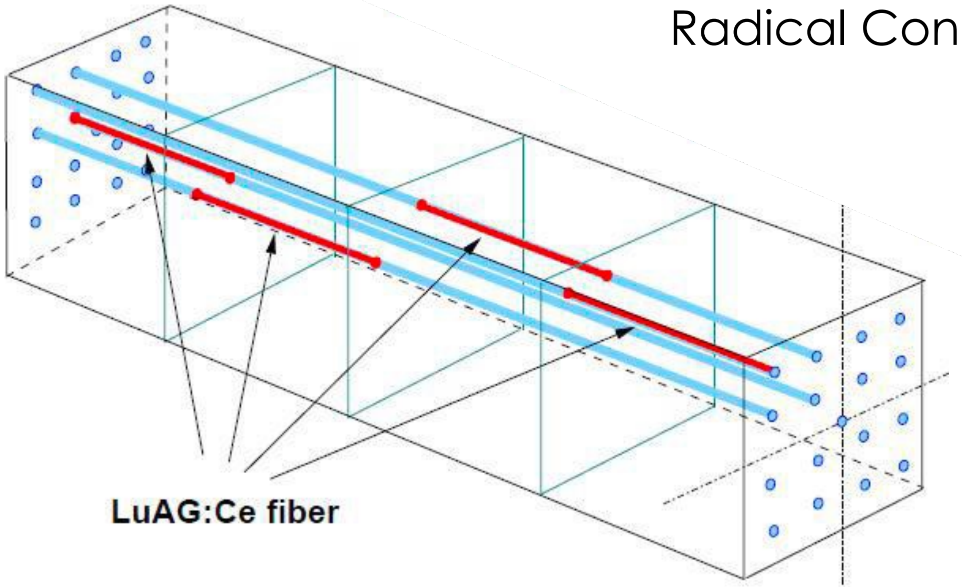


Baseline for ePIC

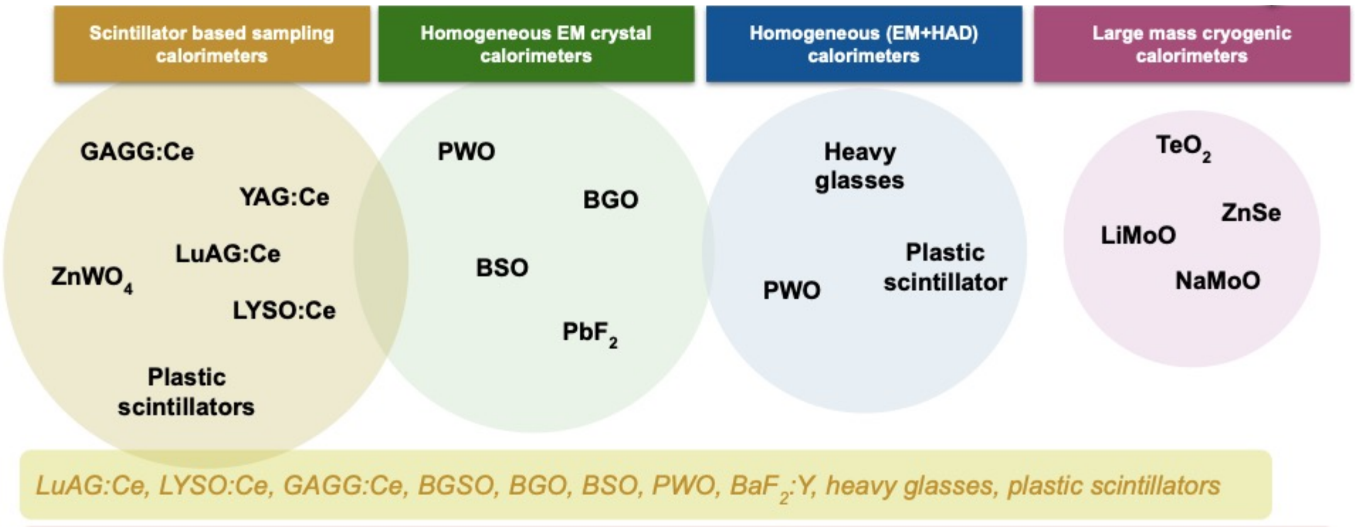
5D Calorimetry

Radical Concept



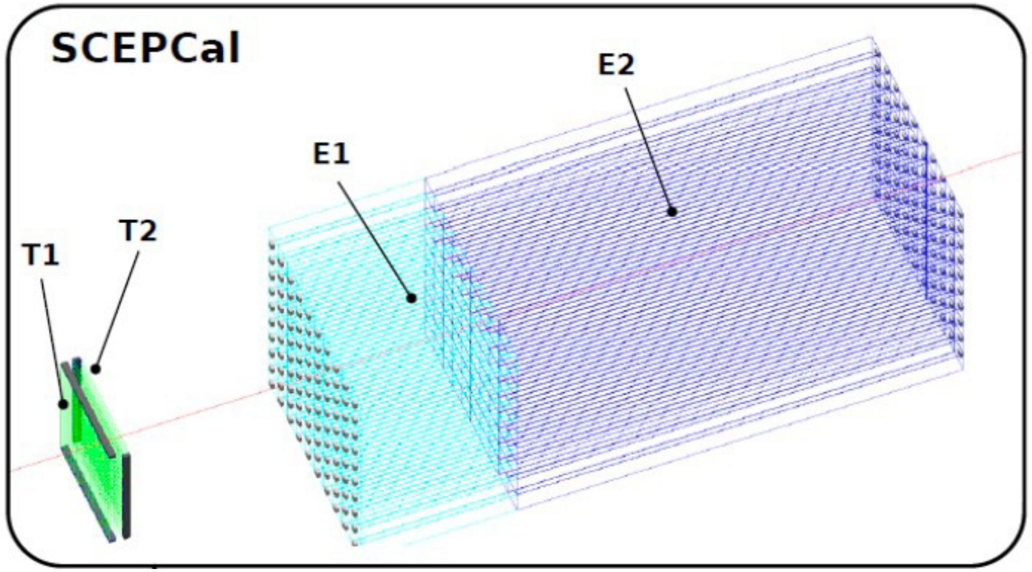


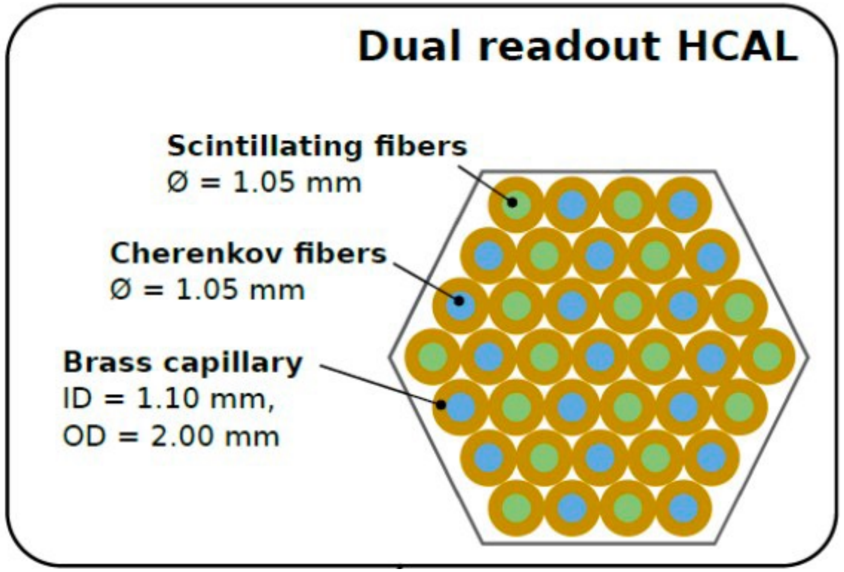
- Energy Measurement:
  – WLS fiber extends over full length of module
- Timing Measurement:
  – WLS are positioned at strategic locations, such as shower maximum



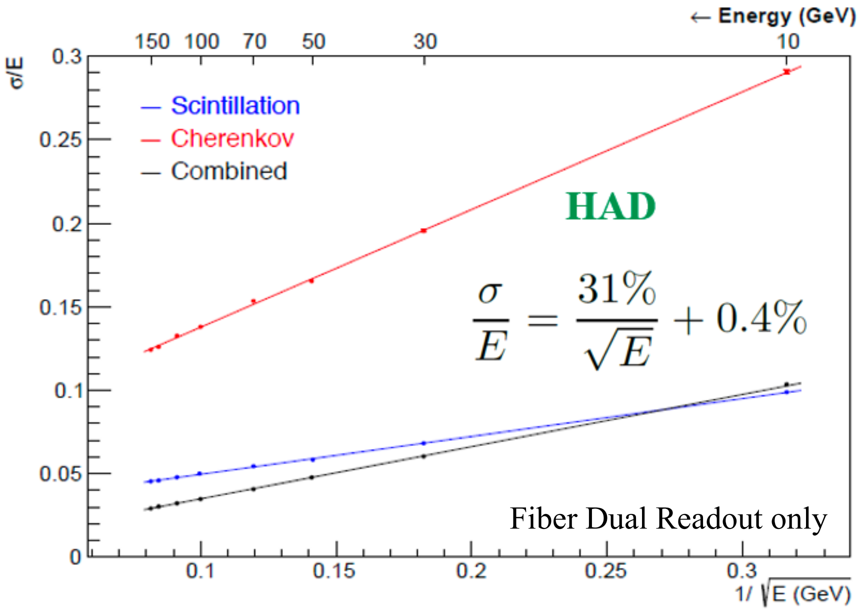
Large parameter space + matching of fiber materials

Dual Readout Calorimetry

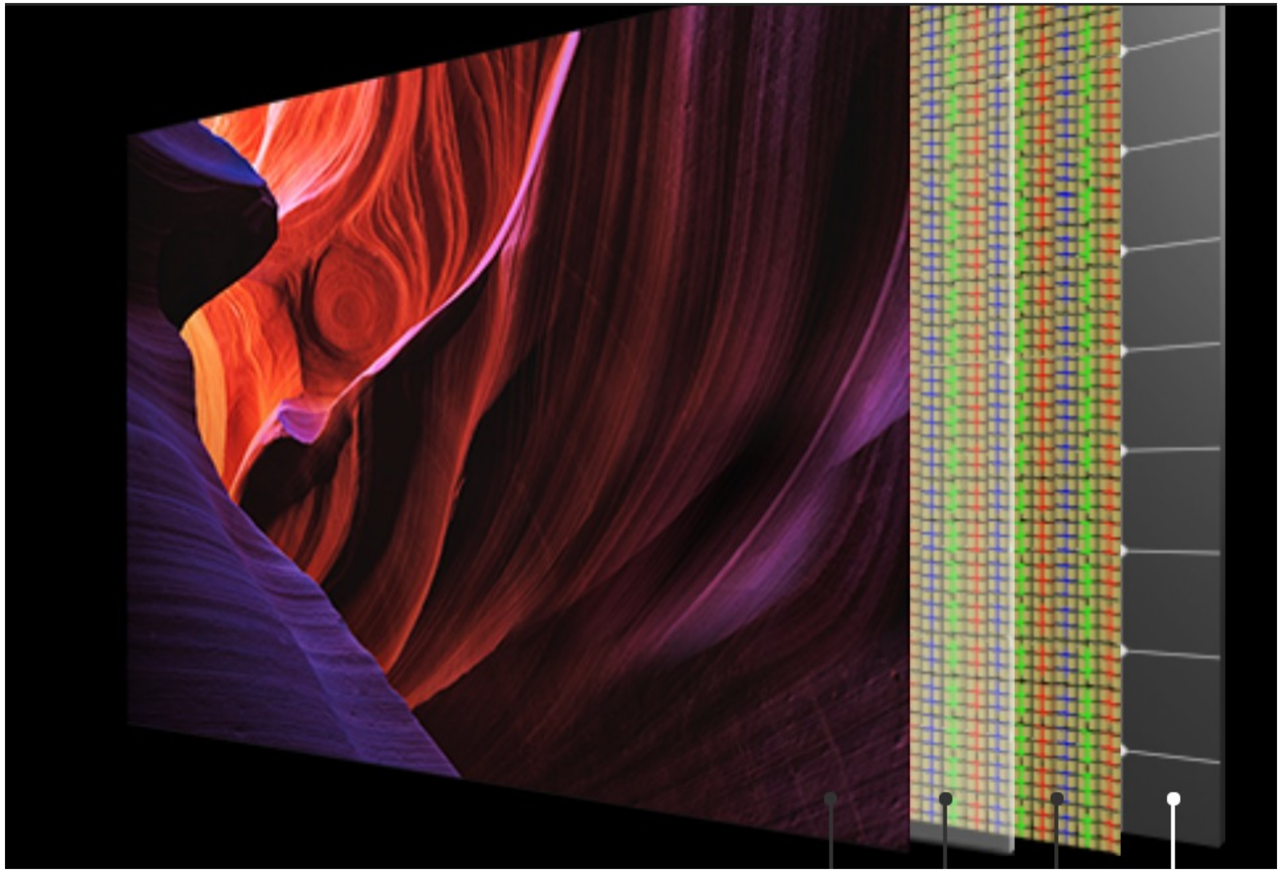




- Segmented Crystal EM Precision Calorimeter with dual readout, preceded by precision timing detector, followed by fiber-based dual readout hadron calorimeter.



Photodetector – Reverse OLED?

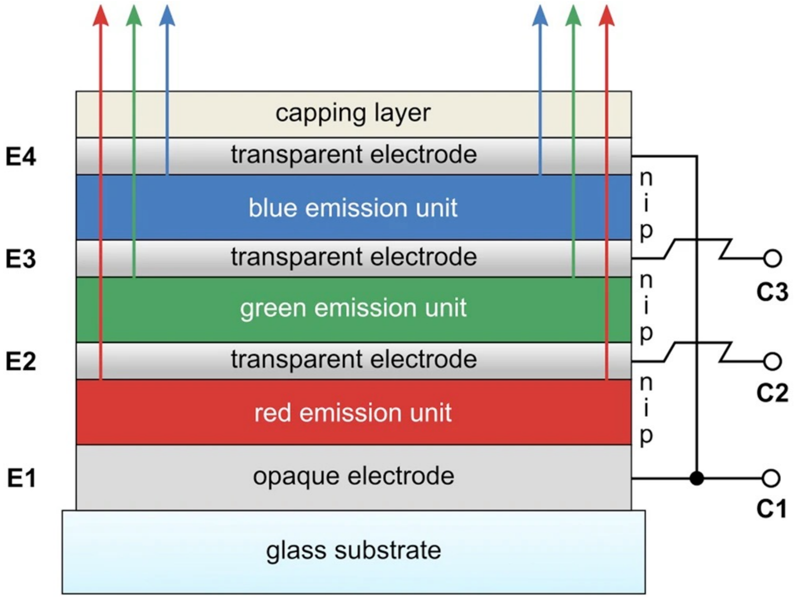


iPhone,, iPad, Macbook:

- Pixel size: ~50x50 μm^2
- Driven by electronics on periphery

Photodetector – Reverse OLED?

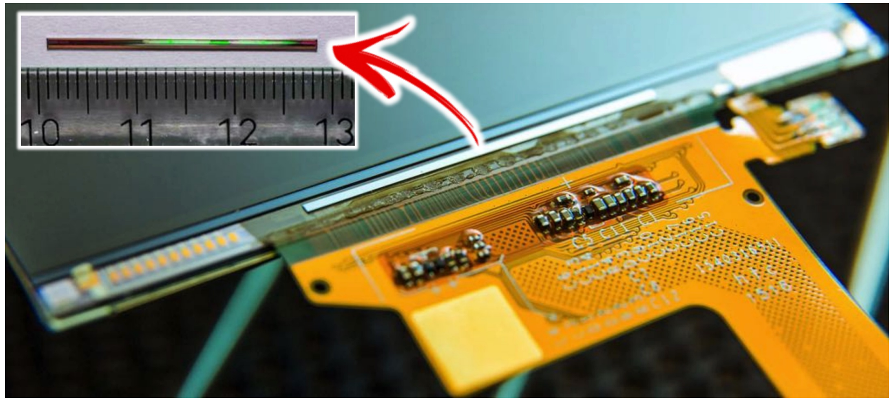
Stacked OLED



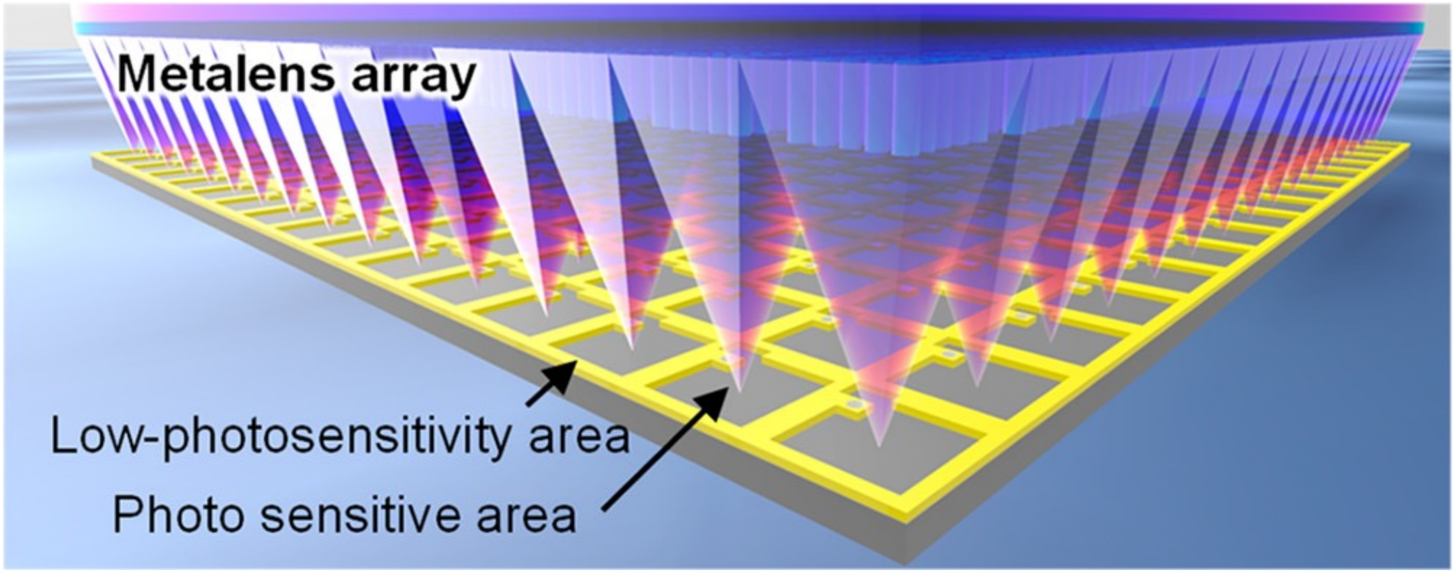
https://www.nature.com/articles/s41598-018-27976-z

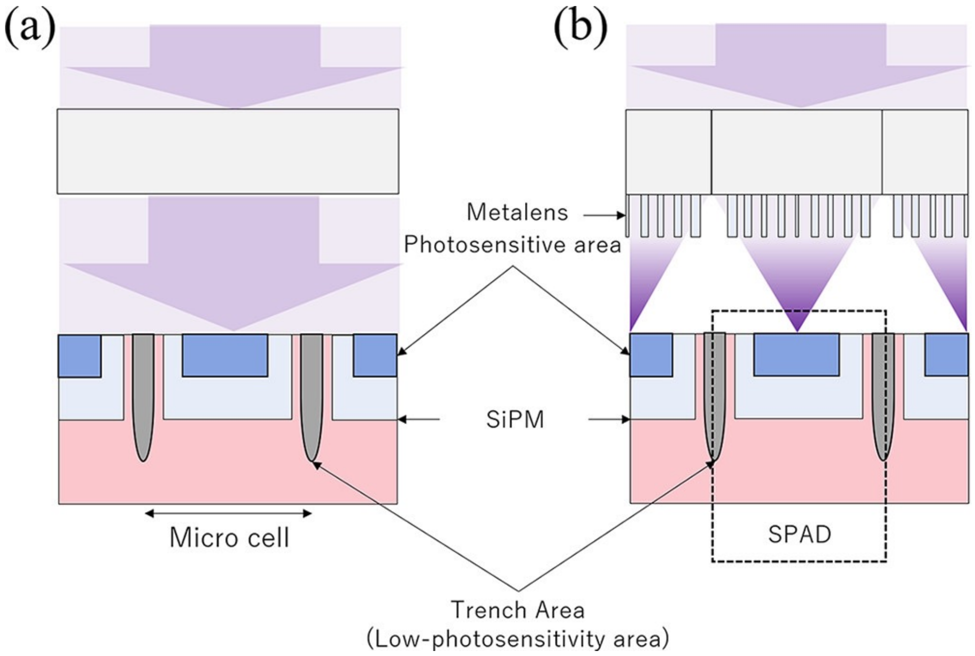
https://www.sammobile.com/news/samsungs-new-foldable-and-udc-panels-reveal-an-exciting-future/

- Reverse the OLED design: spectroscopic photodetectors
  - Engineer organic materials that absorb the light with a specific wavelength
  - Cherenkov vs. scintillation separation
  - No loss of photosensor coverage
- Integrate with 3D printed scintillators
- Electrical connections through Anisotropic Conductive Films (ACF)



Nanophotonics





S. Uenoyama, R. Ota, ACS Photonics 2021, 1548–1555
https://doi.org/10.1021/acsphotonics.1c00257

- Improved detection efficiency, timing resolution.
- Possibility for wavelength sensitivity?

Impact of ILC Related Detector Development

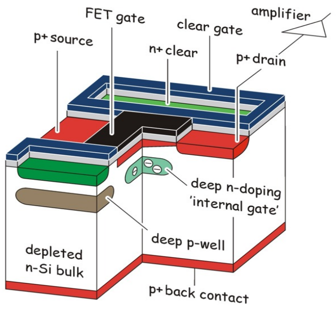
Show me !

ALCPG 2011, Eugene, March 19-23, 2011 -- M. Demarteau *Slide 47*

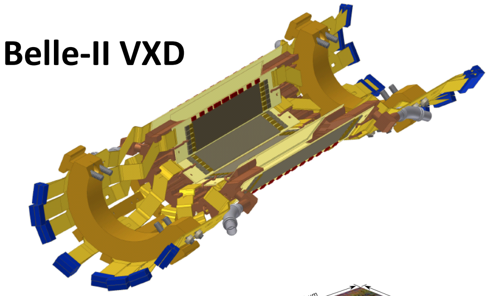
- At the ALCPG meeting, March 2011 in Eugene Oregon, I presented the slide shown on the left.
- The work within the ILC framework has had significant positive impact on the field and advanced the overall program.

Impact of ILC Related Detector Development

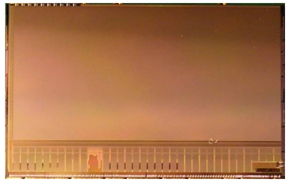
DEPFET



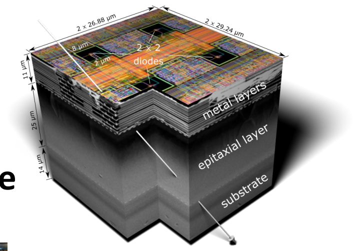
Belle-II VXD



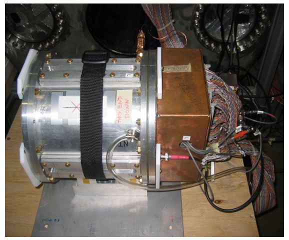
MIMOSA



ALICE Alpide

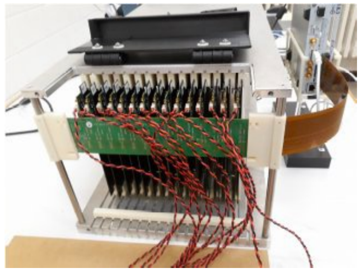


Cosmo-TPC

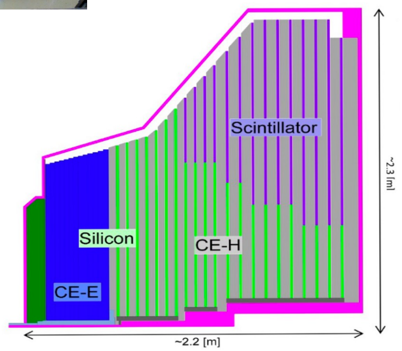


T2K TPC

Si-W ECAL



CMS HGCAL



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Some Observations

- The LC community has advanced detector technologies in a significant way for particle physics and should continue to work towards advancing technologies for **a** Higgs factory.
- The challenges for a linear or circular collider are quite different (circular with continuous beam, magnetic field, high data rates, power and cooling, …). Let's accept the challenge to design a detector that works for either!
- Aim for a discovery machine; this will require **novel technologies and new ideas**.

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2021- 25: Feasibility Study	**2027/2028:** project approval by CERN Council	**2032:** construction starts	**2041:** HL-LHC ends	**2045:** Operation of FCC-ee	**2070:** Operation of FCC-hh

- There is plenty of time to explore new ideas; think of of the box and **rethink current paradigms**.

A Higgs Factory is an Ambitious Goal

かたつぶり
そろそろ登れ
富士の山

小林一茶

Snail
It Is Time To
Climb Mount Fuji
— Issa Kobayashi

From: Makoto C. Fujiwara

A Higgs Factory is an Ambitious Goal To Be Realized

2021- 25: Feasibility Study → **2027/2028:** project approval by CERN Council → **2032:** construction starts → **2041:** HL-LHC ends → **2045:** Operation of FCC-ee → **2070:** Operation of FCC-hh

- The outcome of the process proposed will depend on many factors, with some important ones not under our control.
- The international scientific community can assist in this process by providing the necessary input for these to enable informed derisions to be made.
- We should build the strongest science case and demonstrate that we can meet the physics challenges with the **most advanced detectors** that we can design, to improve the likelihood that this very ambitious process be realized.
- We need to work together in a unified and objective way, leading with the science. **The ask is huge**; we need to be unified.

Conclusion

- The linear collider community has been a driving force towards the realization of a next collider.

- Let's continue to "bounce ideas" for **new detector technologies** to strengthen the case for **a** Higgs Factory; we will all benefit.