Oak Ridge National Laboratory

Linear Collider Detectors for Many Decades

Linear Collider Vision
Community Meeting
CERN , January 9, 2025

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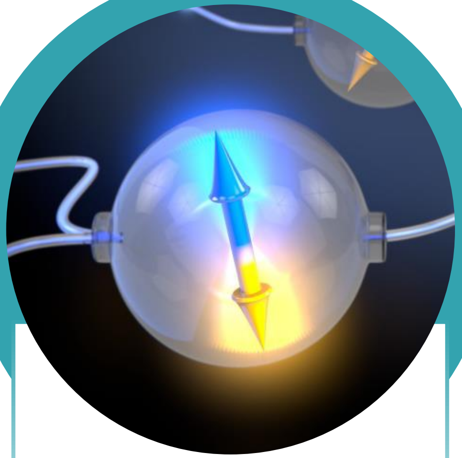
U.S. DEPARTMENT OF ENERGY

Outline:

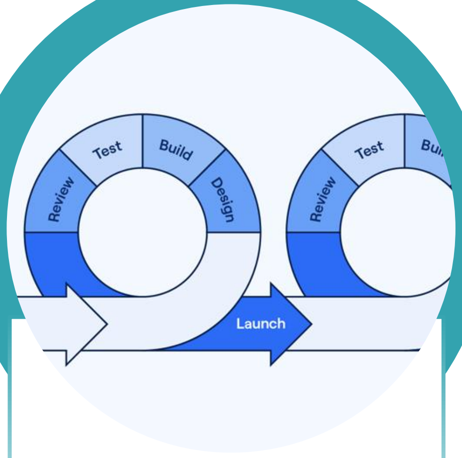
Revolutions

The Unexpected



Technologies

Current and future technologies and their challenges



Agility

Multi-decade Requirements

Summary

Learning from History

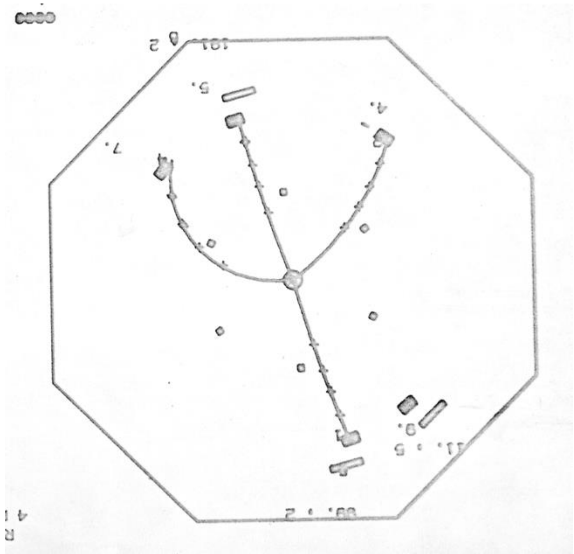
Revolutions

- The Standard Model is incomplete; we pretty much don't quite know where to look; expect revolutions (or measure ever and ever so precisely).
- **Revolution through Instrumentation; breaking with tradition.**

Revolutions

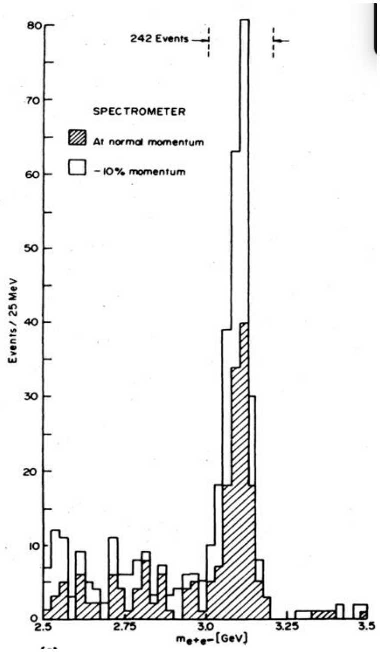
- The Standard Model is incomplete; we pretty much don't quite know where to look; expect revolutions (or measure ever and ever so precisely).
- **Revolution through Instrumentation; breaking with tradition.**
- Last year (2024) saw two 50^{th} Birthday Anniversaries: J/Psi Discovery

MARK-I at SPEAR



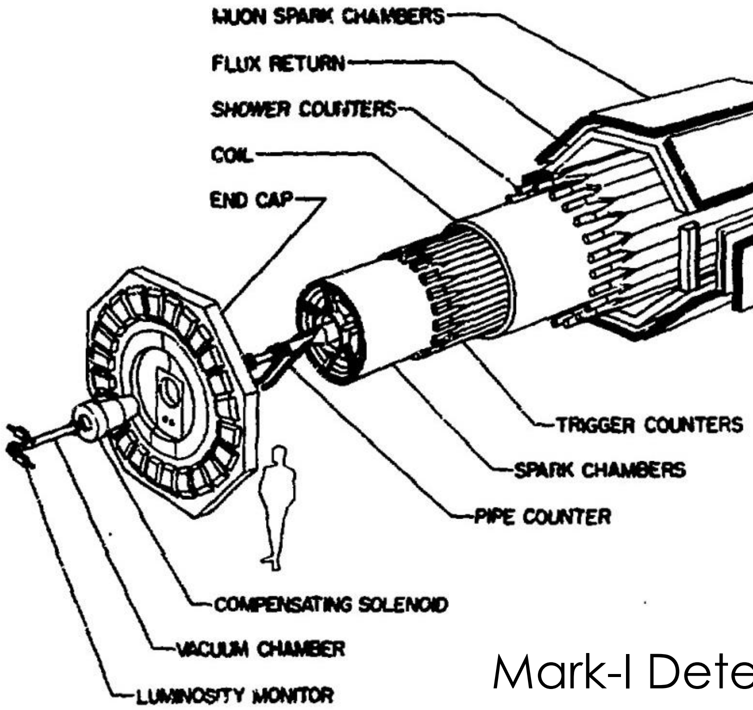
https://indico.slac.stanford.edu/event/9040/

E598 at AGS



https://indico.bnl.gov/event/25016/

November Revolution 1974



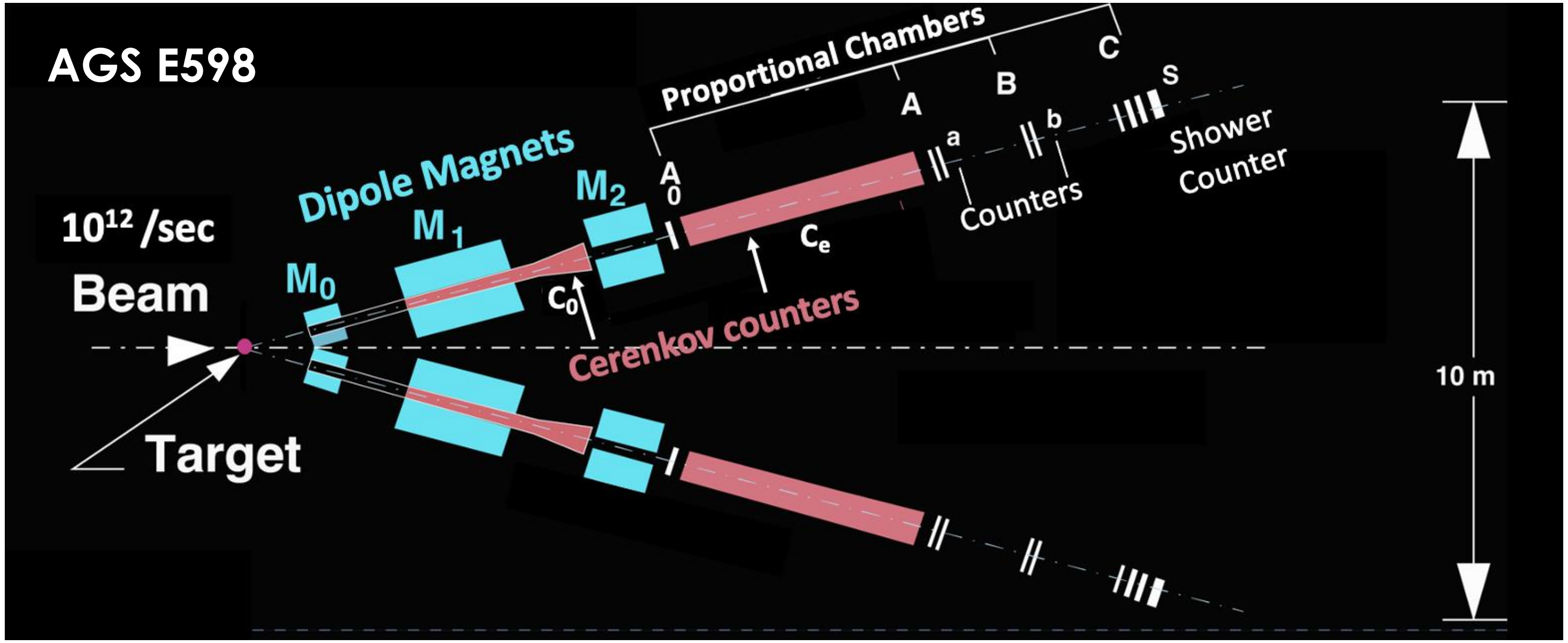
Mark-I Detector

- The first of the ~4π, cylindrical, electronic detectors with tracking in an axial B field (B. Richter).
- Critically different from spectrometers then (ISR @ CERN or DORIS @ DESY).
- Measured exclusive reactions with large acceptance and micro-sec time resolution with tracking technology with low-mass cylindrical layout.
- About all collider detectors followed this model.
- Ready for data in February 1973

Marty Breidenbach

https://indico.slac.stanford.edu/event/9040/contributions/10265/attachments/4779/12897/Breidenbach.pdf

November Revolution 1974



- Very high resolution (and expensive) spectrometer

- Against conventional wisdom:

  "This type of spectrometer is only good for looking for narrow resonances —and there are no narrow resonances."

Sam Ting

https://indico.bnl.gov/event/25016/contributions/97268/attachments/58730/100855/BNL-50-years.pdf

Discoveries in High Energy Physics

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	p N interactions	Neutral Currents -> Z,W
AGS BNL (1960)	p N interactions	Two kinds of neutrinos Time reversal non-symmetry charm quark
FNAL Batavia (1970)	Neutrino Physics	bottom quark top quark
SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
Telescopes (2000)	SN Cosmology	Curvature of the universe Dark energy

Precision instruments are key to discovery when exploring new territory.

- It is far more than just precision; the purpose is to make **discoveries** and should be prepared for the unexpected.

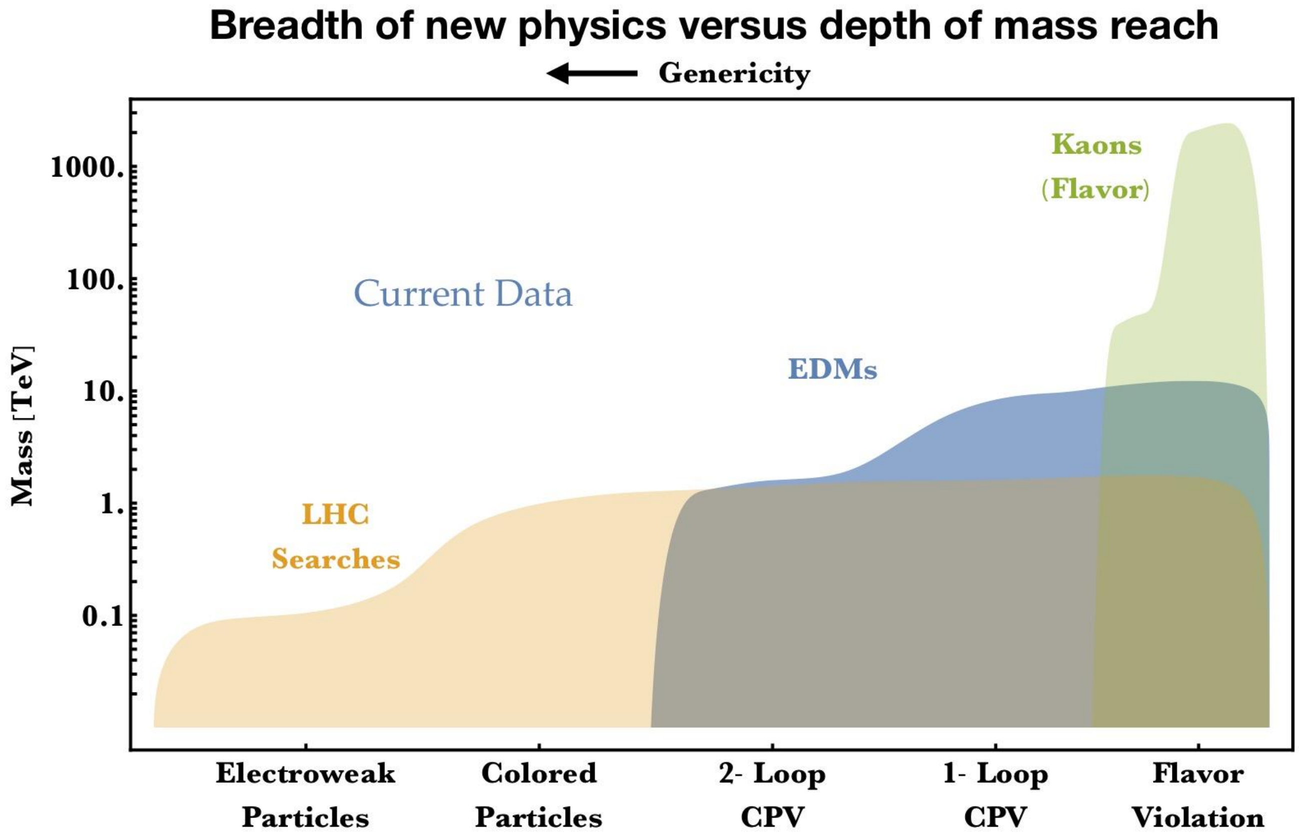
"The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' but, 'That's funny ... ' "

-- Isaac Asimov

Adapted from Sam Ting

Precision Experiments

- Future colliders have direct discovery potential but are not the only source to explore very high energy scales.

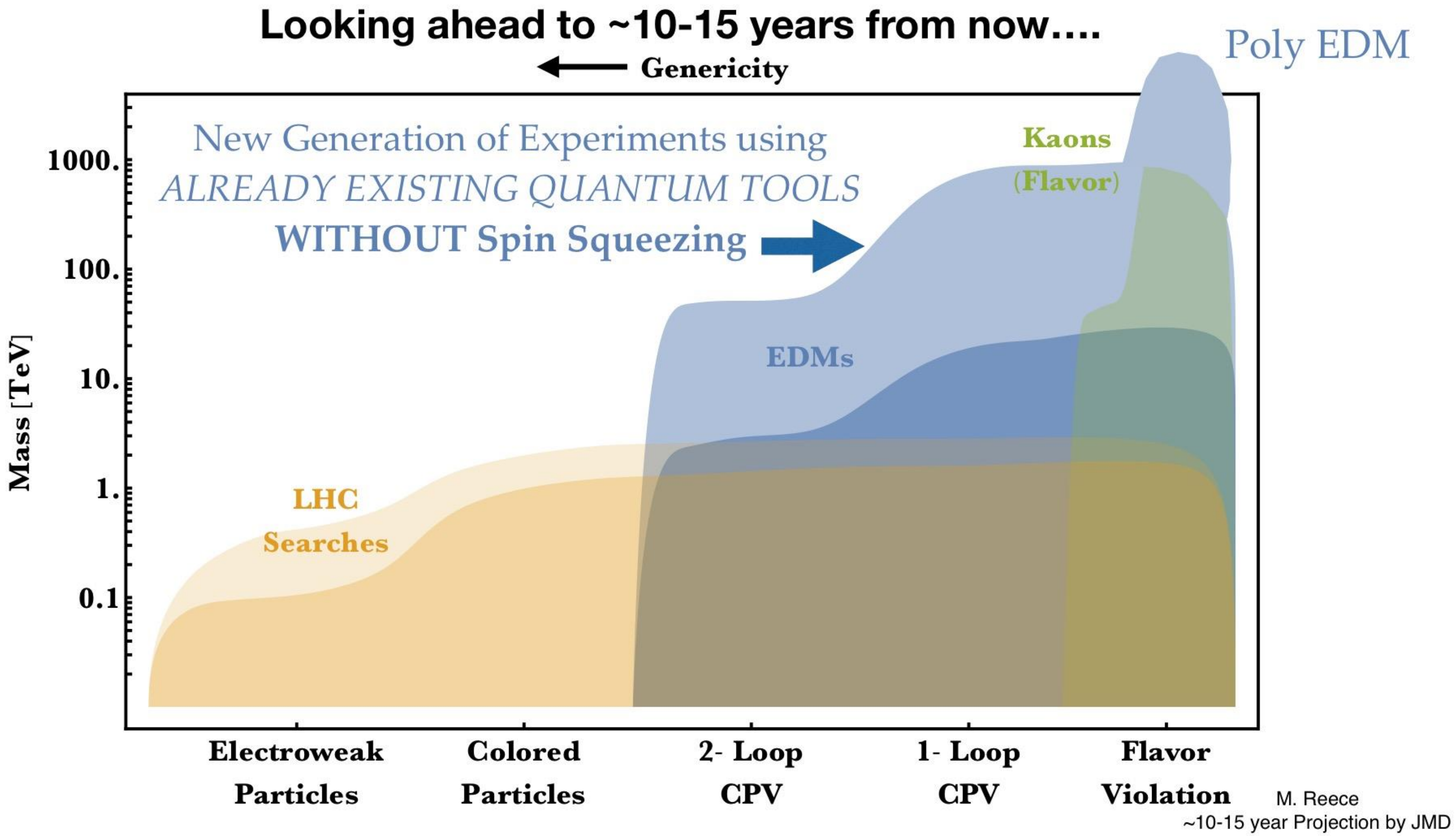


M. Reece

Y. Nakai, M. Reece: Physics Today, Nov. 2018
DOI:10.1063/PT.6.3.20181114a

Squeezed Precision Experiments

- Nascent Quantum techniques provide a compelling reason



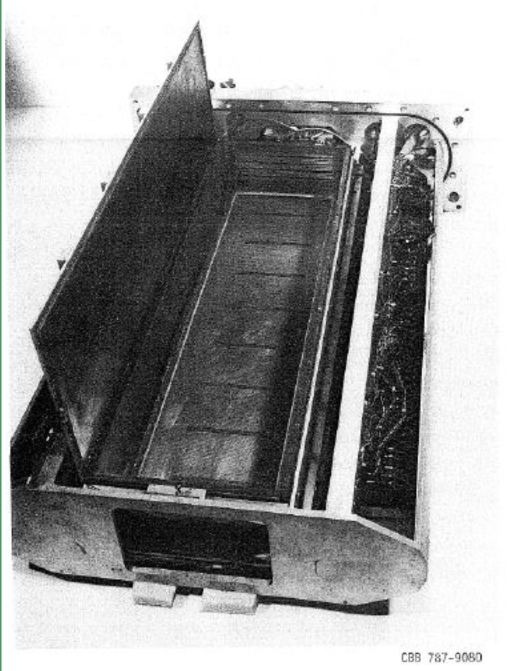
J. Doyle, Argonne workshop, Dec. 2017,
Y. Nakai, M. Reece: Physics Today, Nov. 2018
DOI:10.1063/PT.6.3.20181114a

Take Away Messages

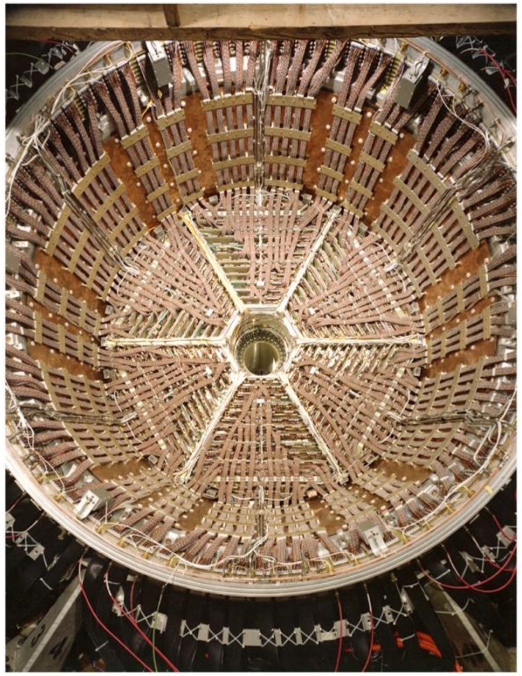
- Expect the unexpected.
- Build with the highest (affordable) precision.
- Ignore, within reason, conventional wisdom.

The Underpinning Of Scientific Progress

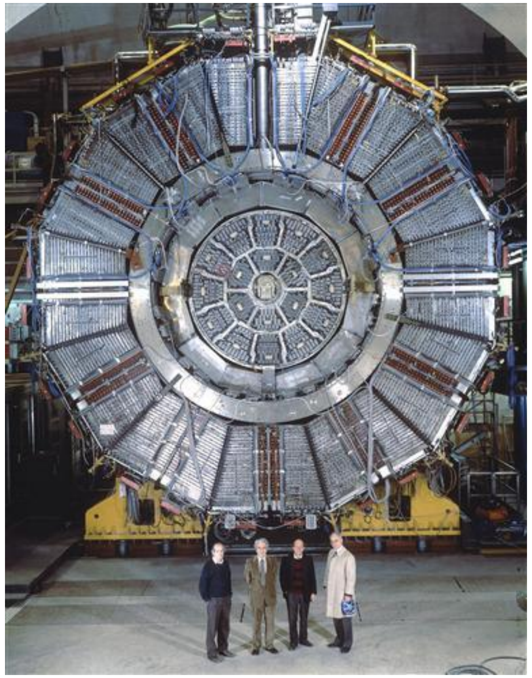
Bevatron (1974)



PEP-4 TPC (1976)



ALEPH TPC (1983)



ALICE TPC (2003)

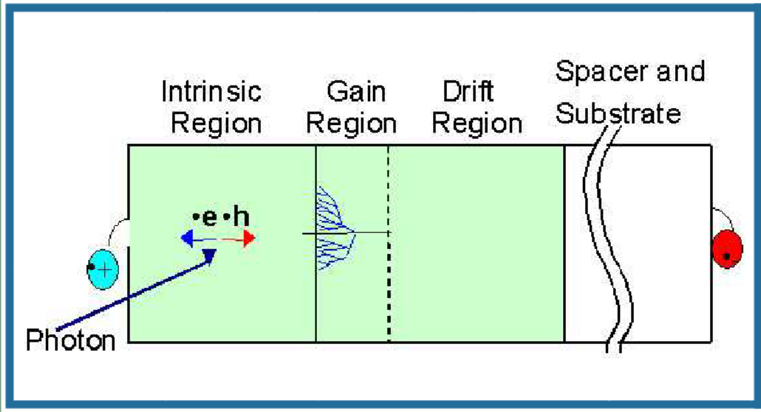
Dave Nygren has said the idea for the TPC came to him after he realized that real improvements in particle detection could not be achieved without a radical departure from the old ways.

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

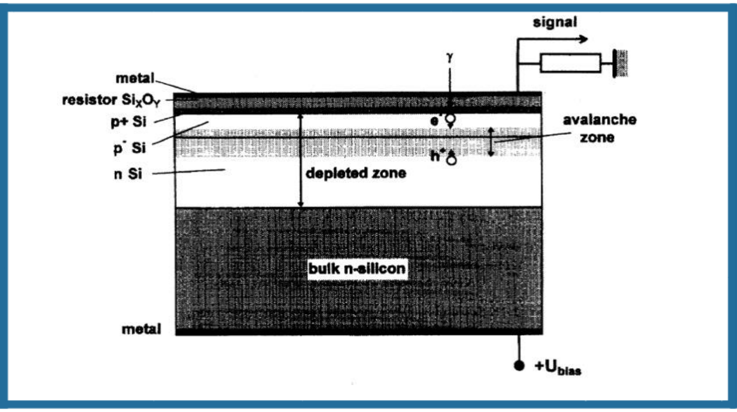
The Underpinning Of Scientific Progress

VLPC
(Rockwell, 1987)



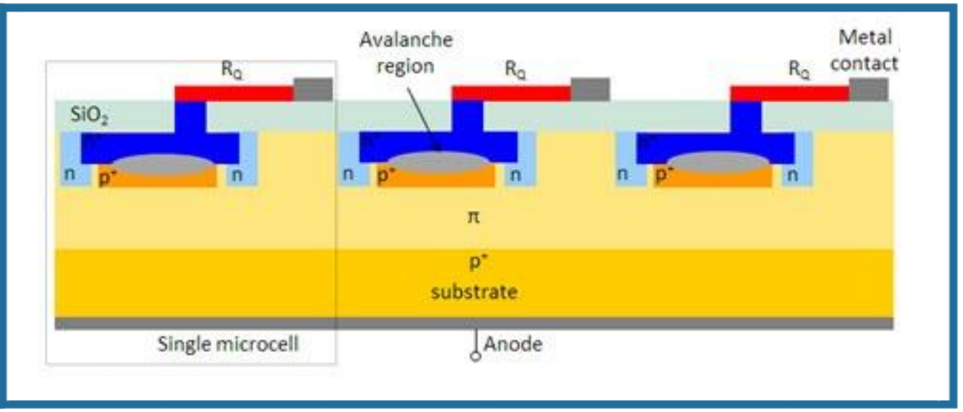
Bross et al., NIM A477, 172 (2002)

MRS APD
(Russia, ~1995)



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

MPPC
(Russia, ~2003)



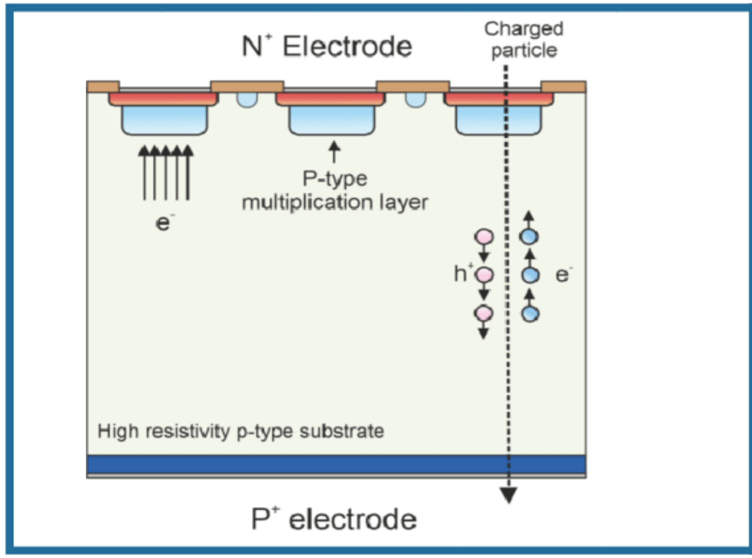
Dolgoshein et al., NIM A 504 (2003) 48
Sadygov patent (1998)

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

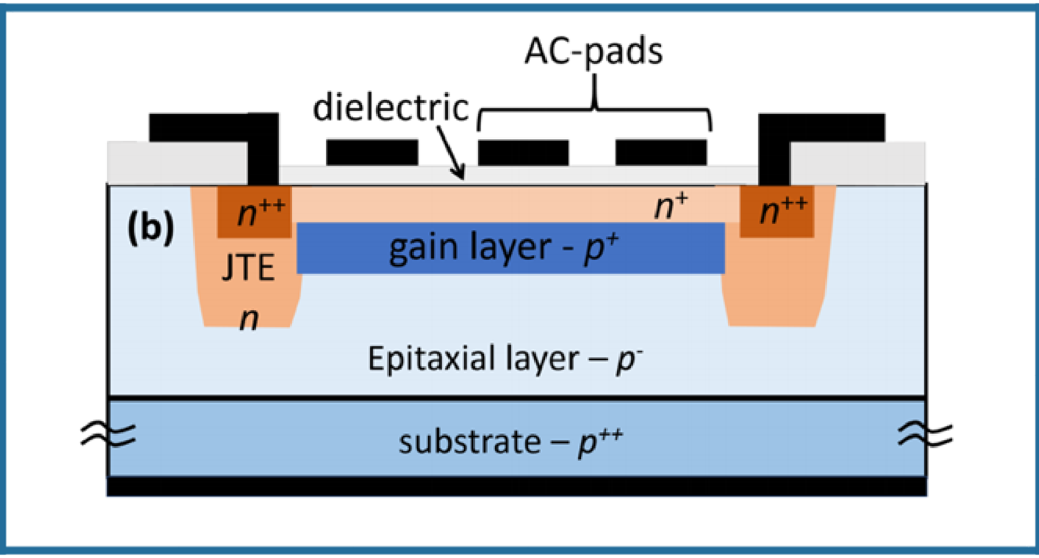
VLPC: Visible Light Photon Counter
MRS: Metal- Resistor-Semiconductor
MPPC: Multi-Pixel Photon Counter (SiPM)

The Underpinning Of Scientific Progress

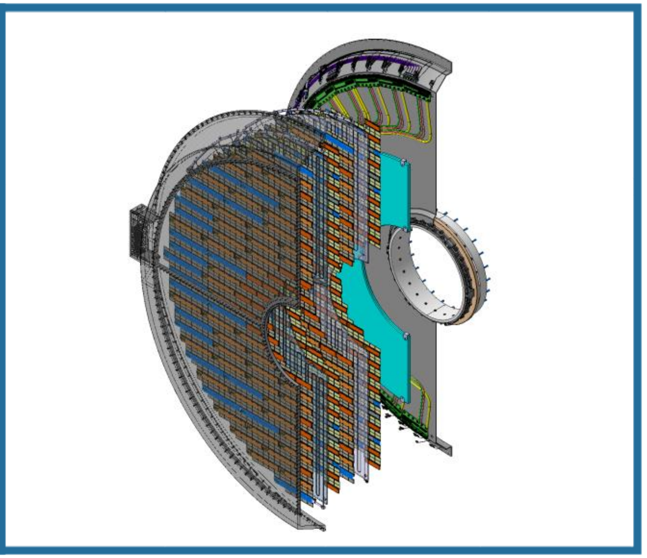
LGAD
(UCSC, 2012)



AC-LGAD (RSD)
(UCSC/INFN, ~2019)



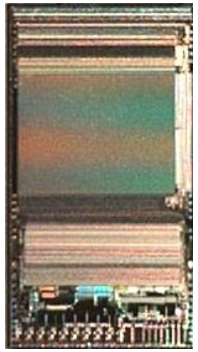
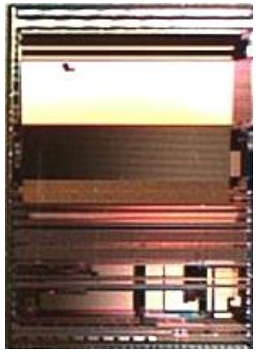
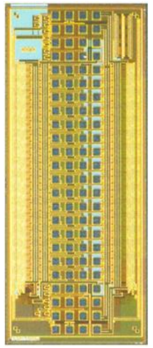
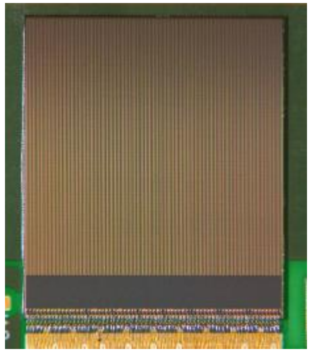
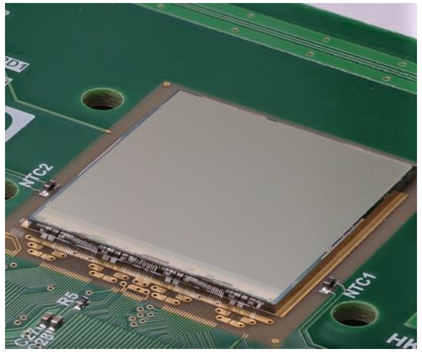
CMS ETL (2023)
ATLAS HGTD (2023)



- From inception to development to full-scale detector in a short **10 years**.

LGAD: Low-Gain Avalanche Diode
RSD: Resistive Silicon Detector
UFSD: Ultra-Fast Silicon Detector

The Underpinning Of Scientific Progress

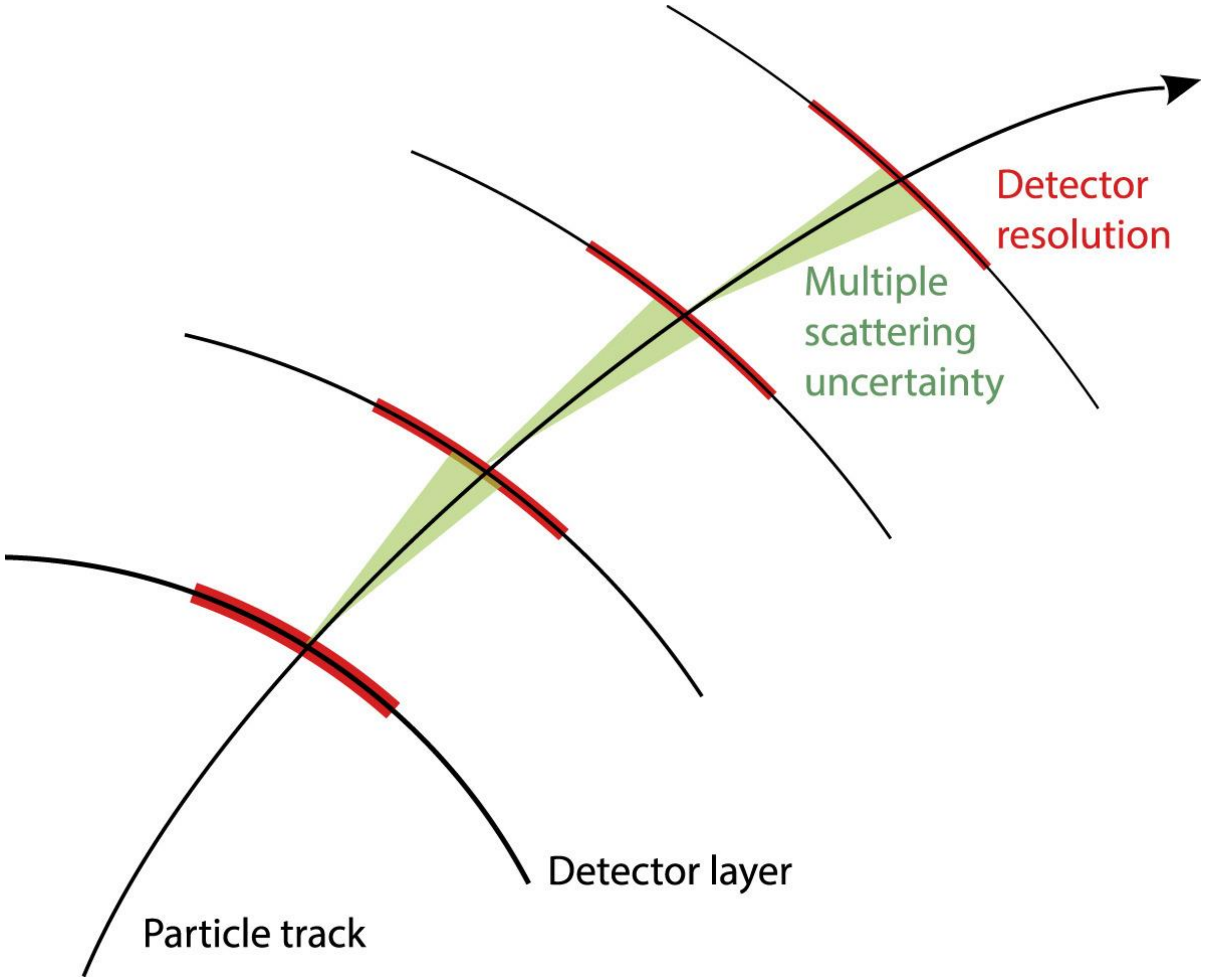
SVX (CDF 1990)	**SVX3 (Fermi 1998)**	**SVX4 (Fermi 2002)**	**DCDB (Belle 2015)**	**Velopix (LHCb 2022)**	**RD53 (HL-LHC 2022)**
					
UTMC 1.2 µm rad-hard CMOS	Honeywell 0.8 µm Mixed-signal CMOS	TSMC 0.25 µm mixed-signal CMOS	TSMC 180nm CMOS	TSMC 130nm CMOS, 20.5 Gbps	TSMC 65nm CMOS, noise <100 e;
Doi: 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

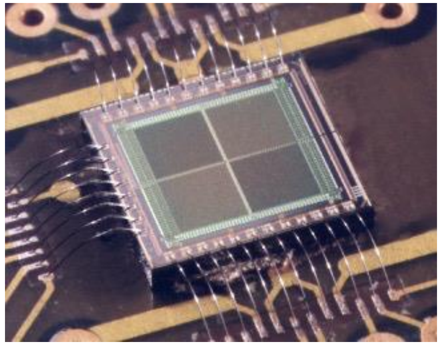
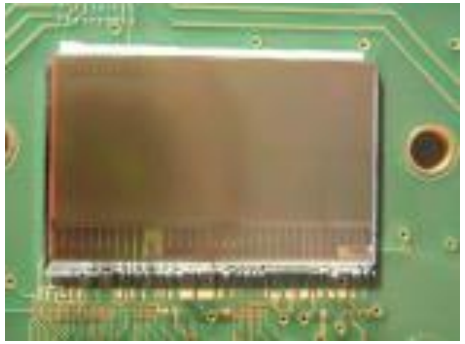
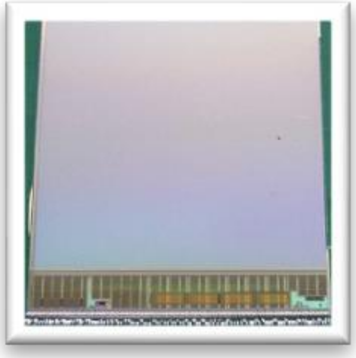
Note: not keeping up with industry

Transparency in Tracking

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



The Underpinning Of Scientific Progress

MIMOSA 1 (1999) (AMS 0.6 μm)	MIMOSA 2 (2000) (MIETEC 0.35 μm)	MIMOSA 3 (2001) (IBM 0.25 μm)	MIMOSA 26 (2008) (AMS 0.35 μm)	MIMOSA 28 (2011) (AMS 0.35 μm)
				

NIM A 458 (2001) 677-689

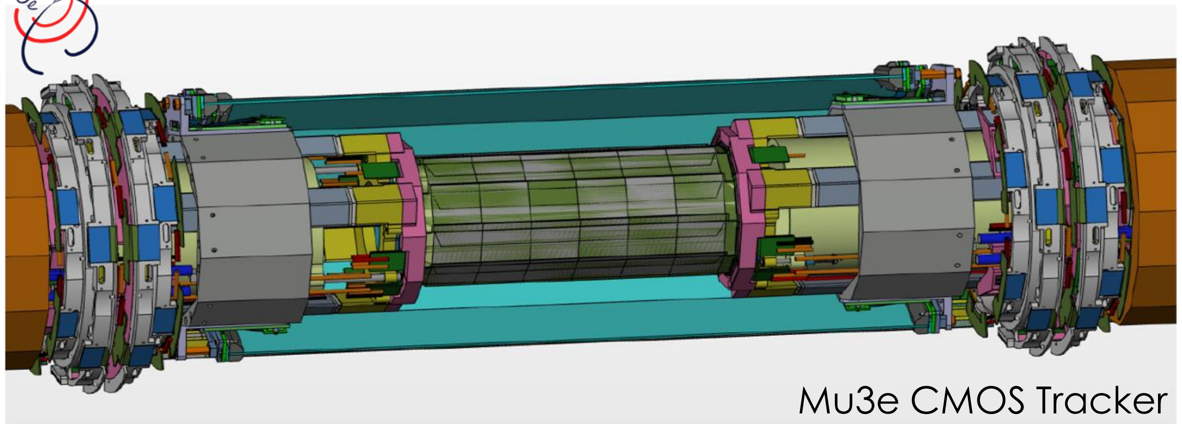
DOI:10.3390/s8095336

- Implementation **within a decade**.

EUDET Telescope (2008)

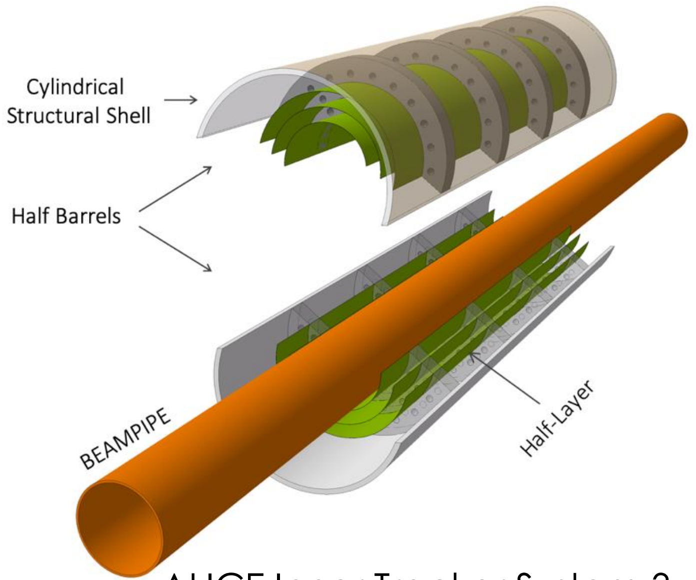
STAR (2014)

Next Generation CMOS Trackers and Vertex Detectors

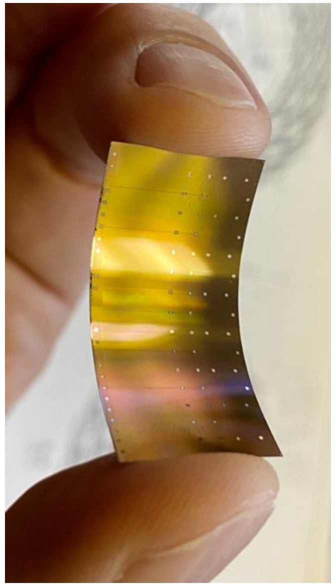


Mu3e CMOS Tracker

- 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



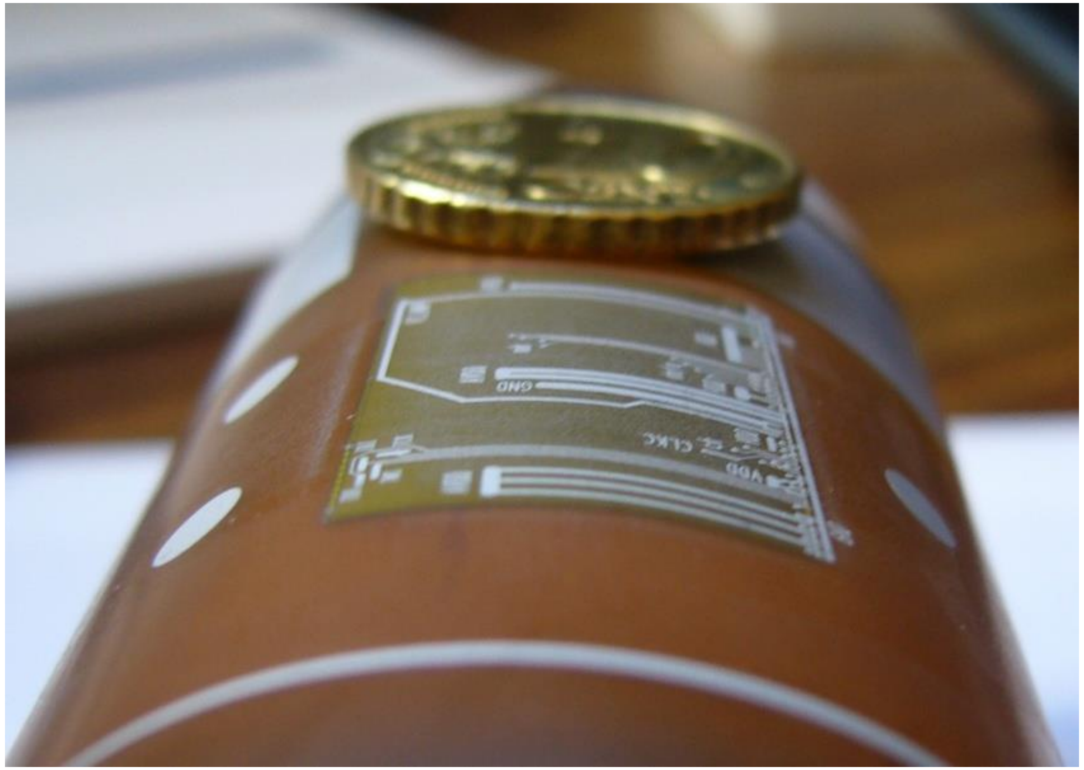
ALICE Inner Tracker System 3



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

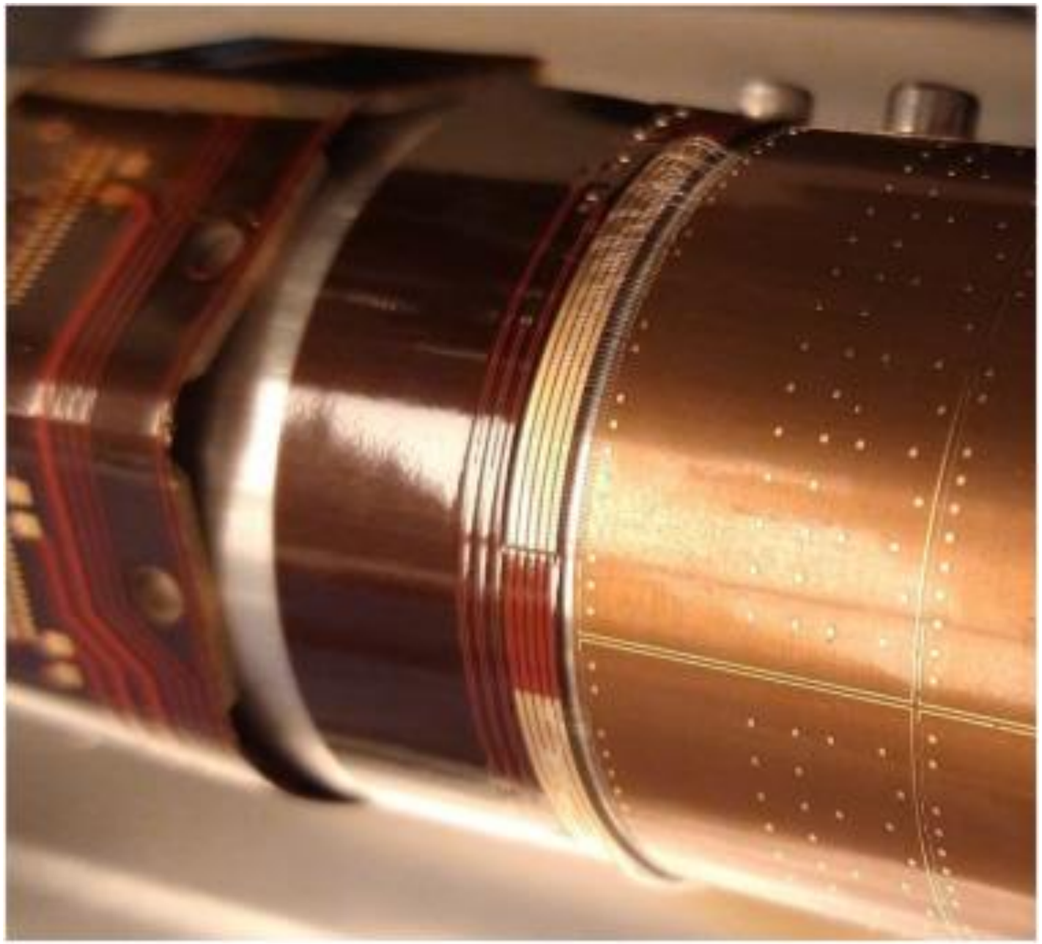


Already more than a decade ago, PLUME, SERVIETTE and PLUMETTE collaboration investigated and succeeded at **embedding thin MAPS sensors in Kapton flex**

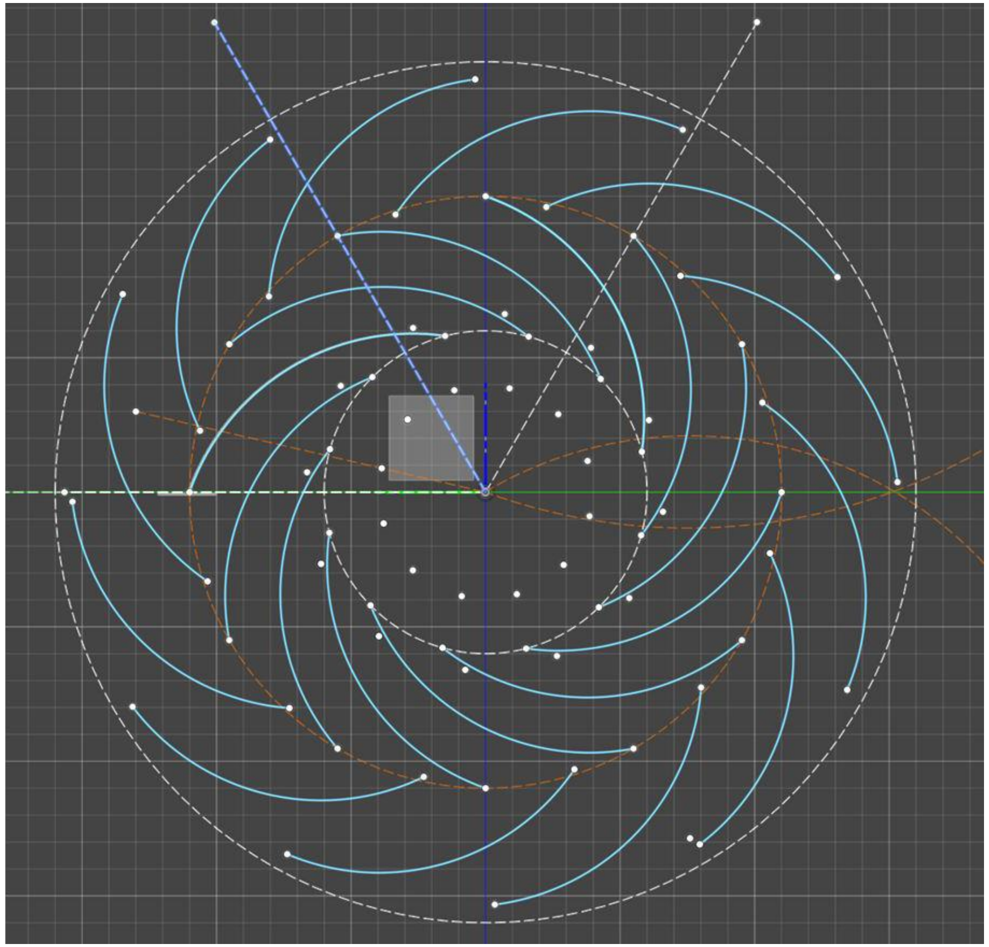
New fabrication and packaging technologies for CMOS pixel sensors are **closing the gap between hybrid and monolithic**

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

Alternate Geometries

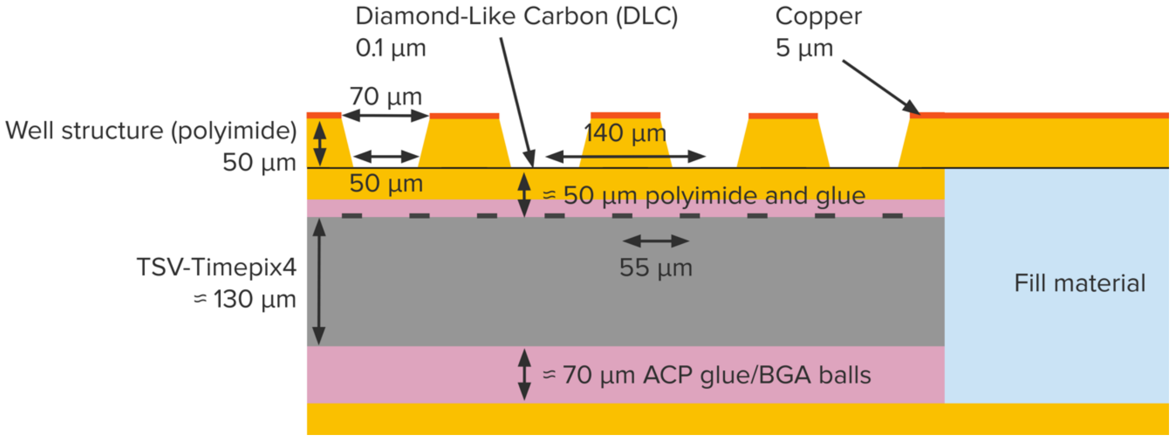


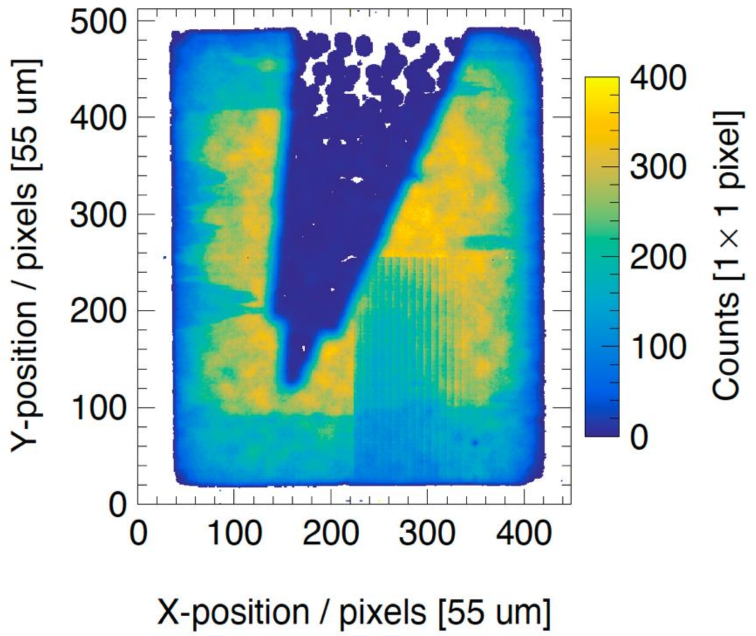
ALICE ITS3 mechanical bent prototype



Gaseous Tracking

- Embedded TSV-Timepix4 laminated into a polyimide μRWELL flex-PCB, with the connection to the readout system on one side and the amplification stage on the other side



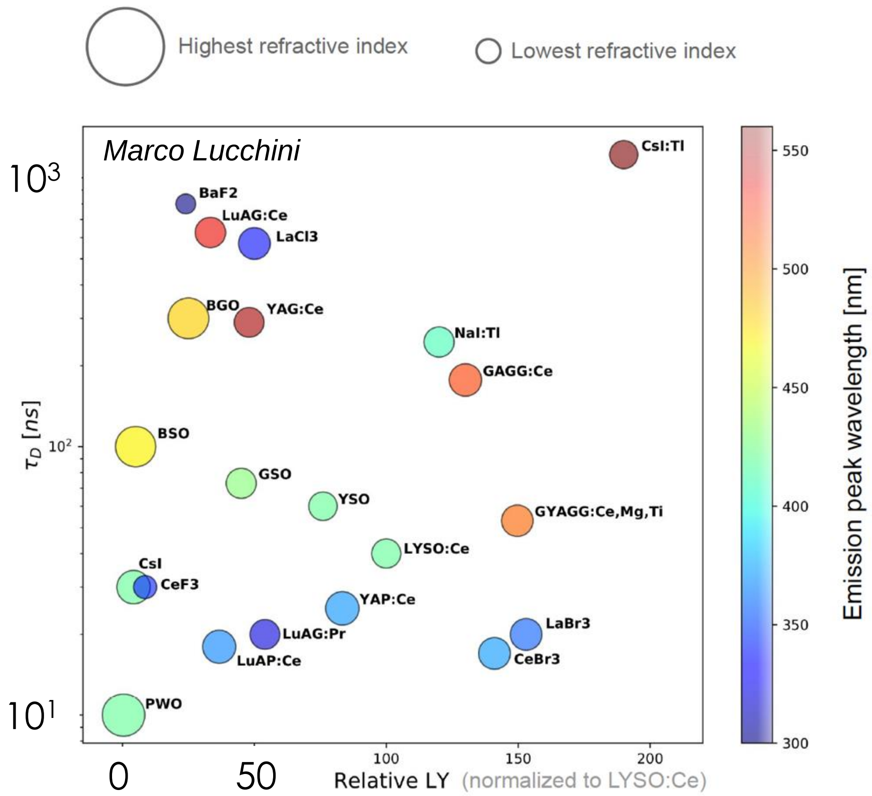


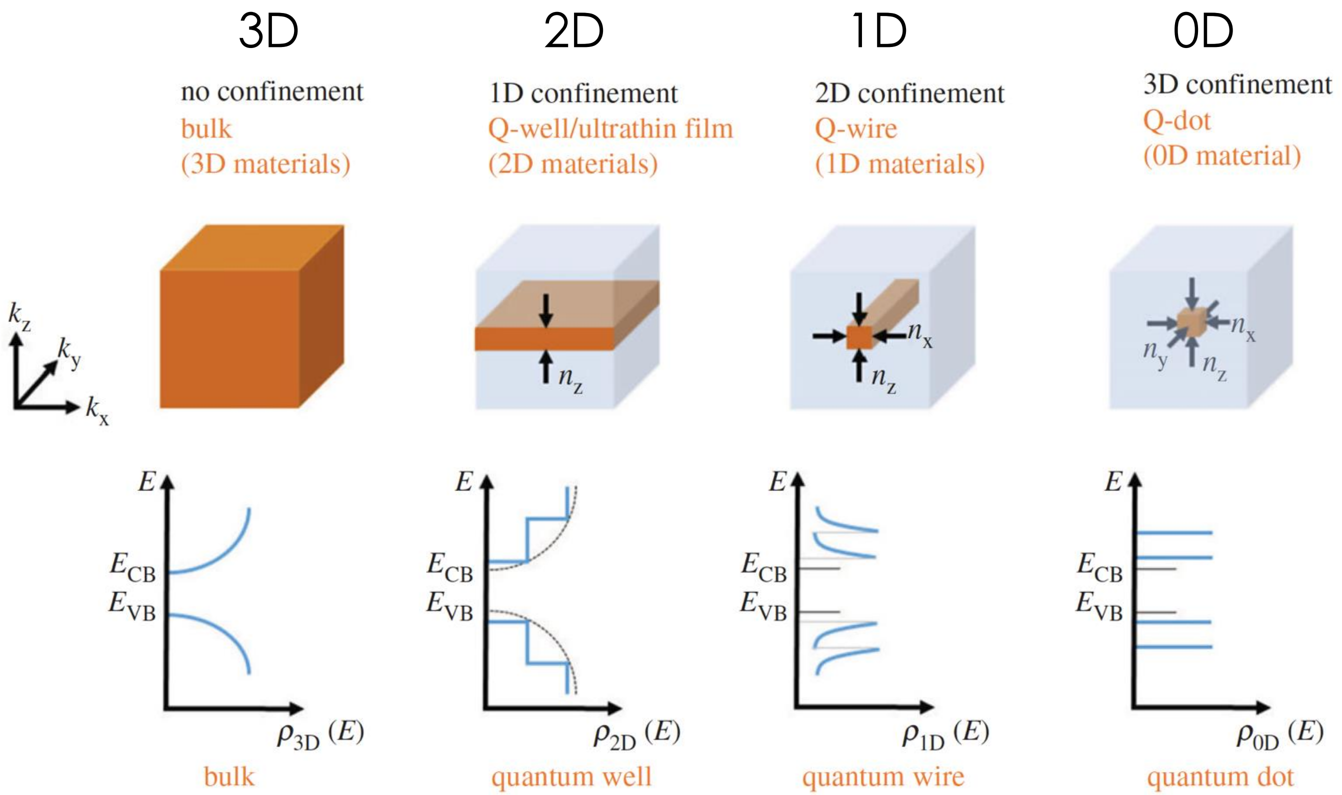
- Combining advanced 3D ASIC technology with cost-efficient gaseous detector technology

arXiv:2412.16950

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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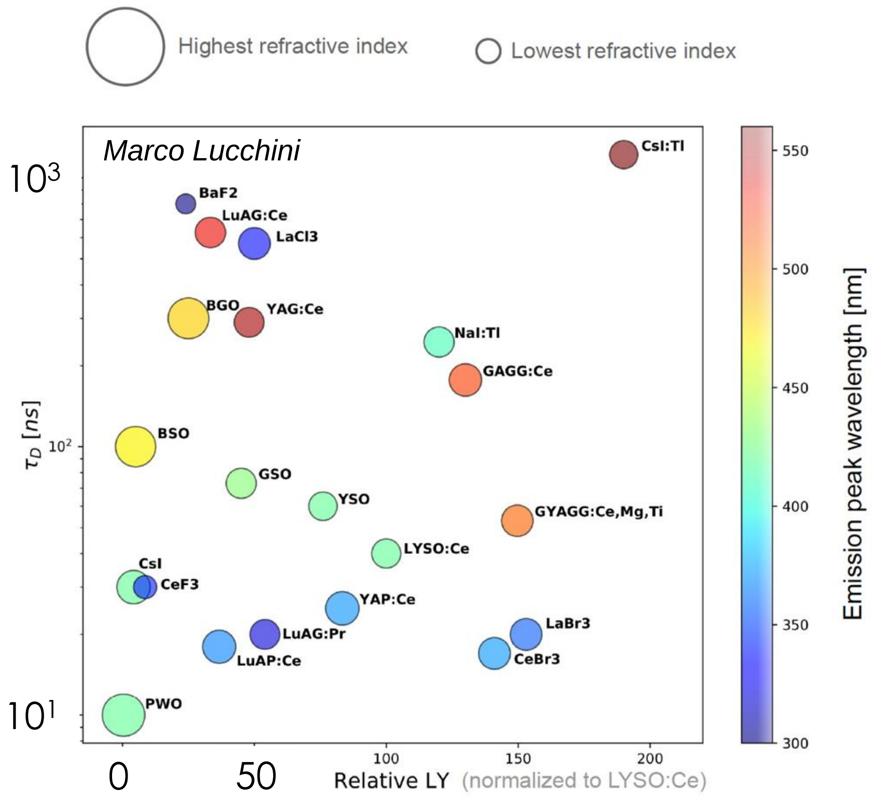
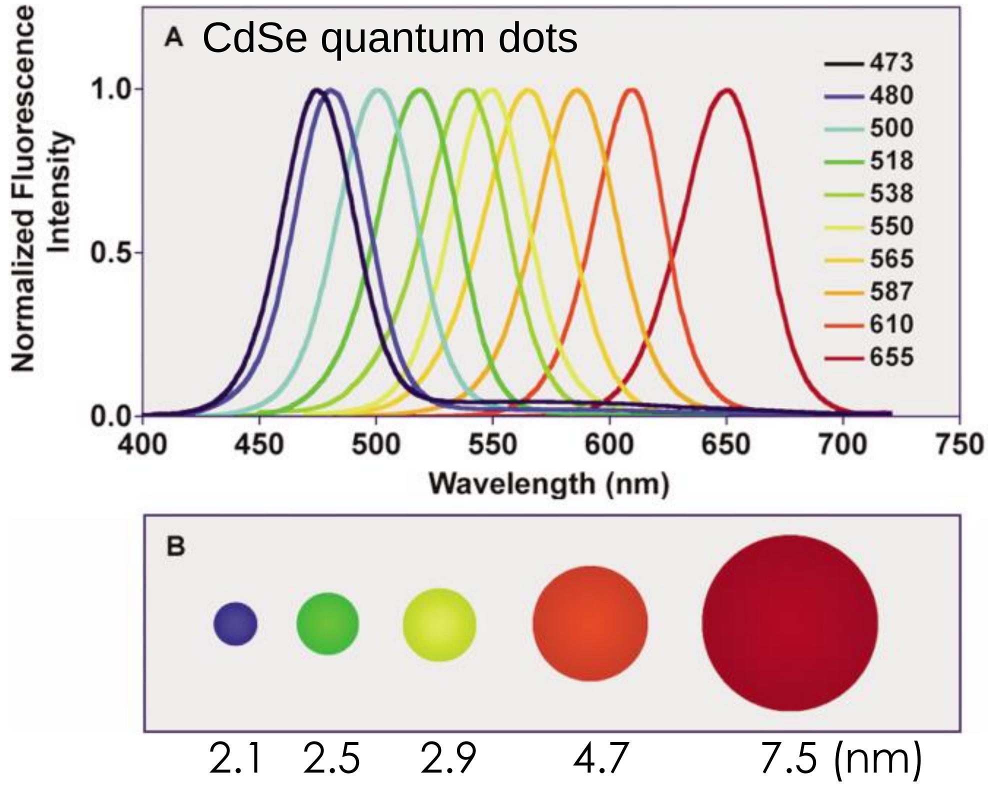
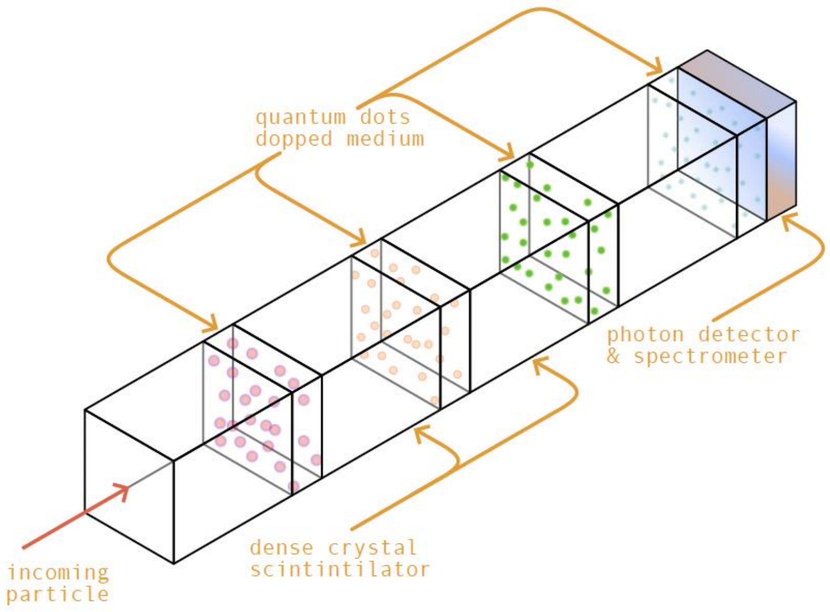


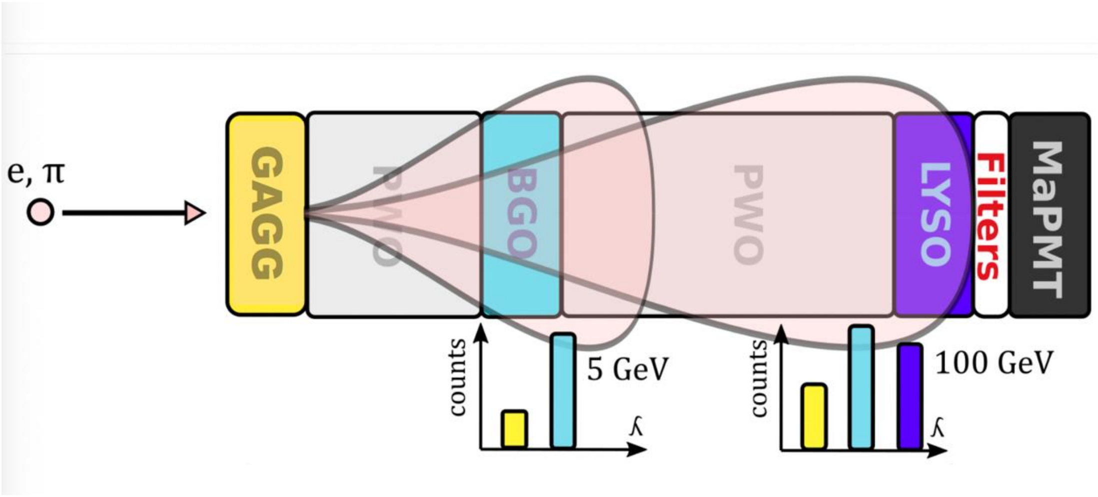


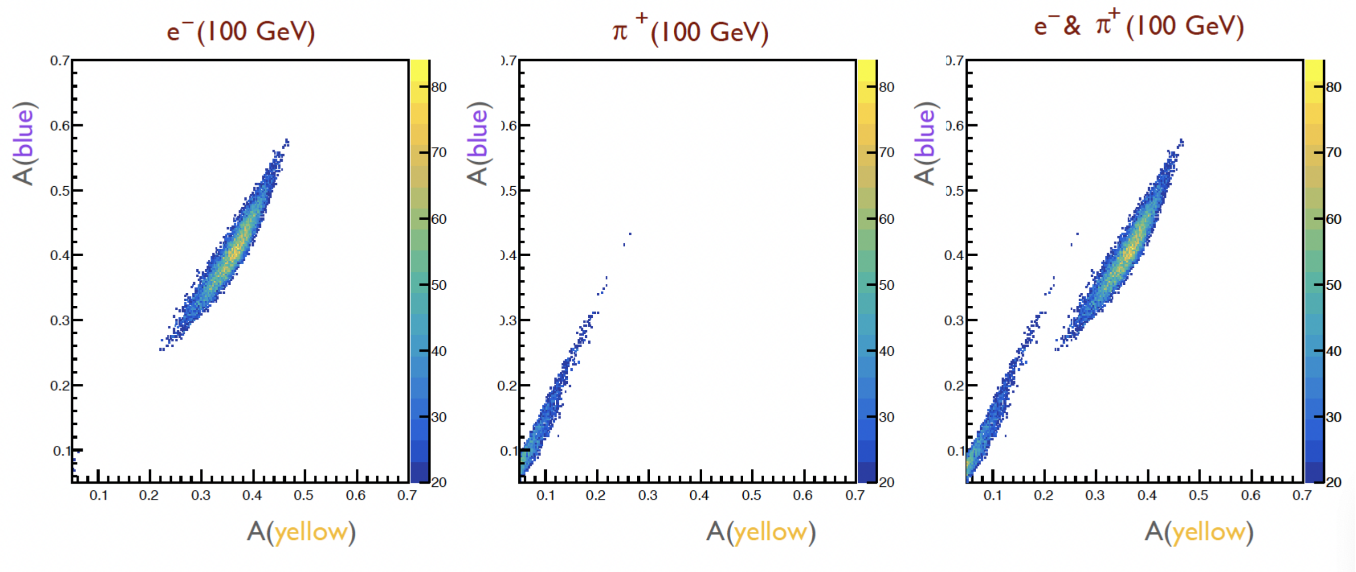
A. Smith, https://doi.org/10.1039/B404498N

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

Quantum Dot Crystal Calorimetry



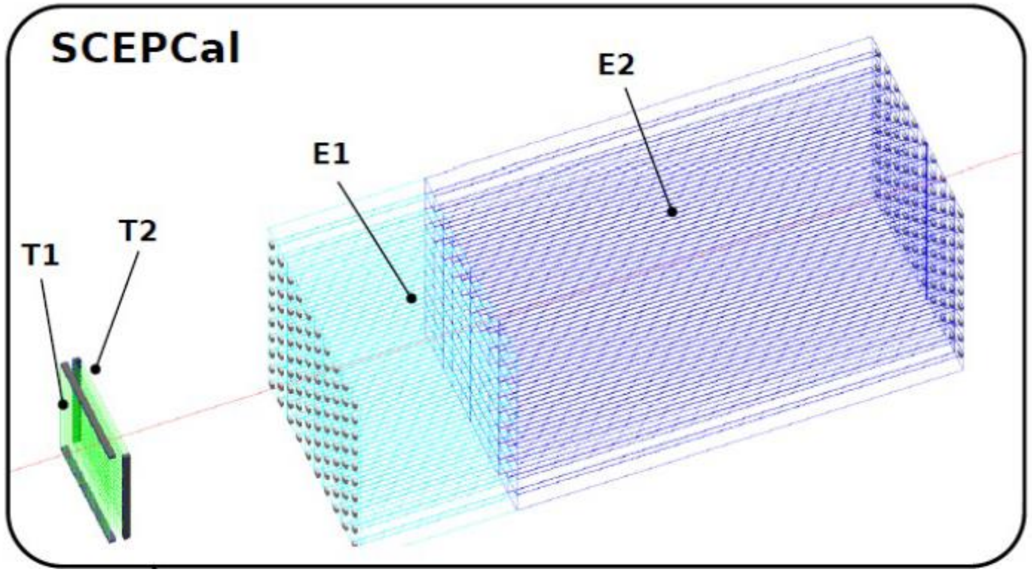


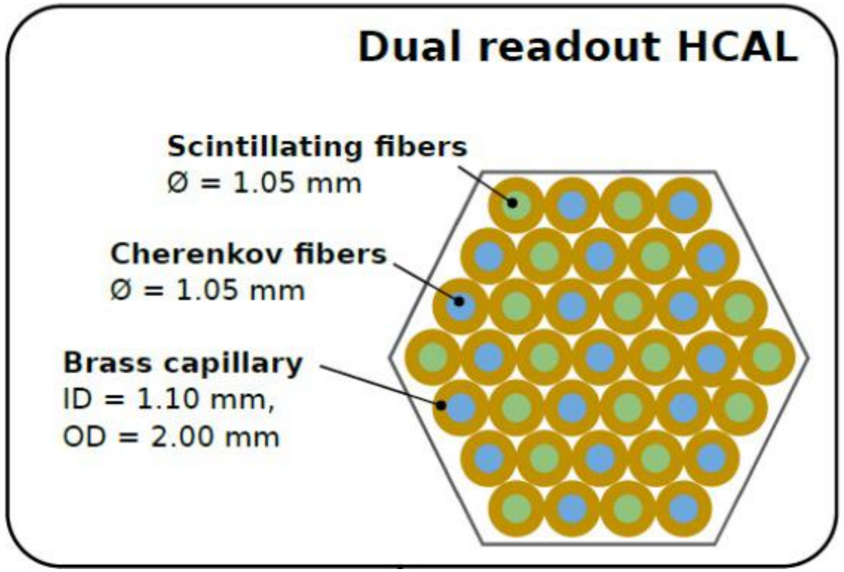


Chromatic Calorimetry

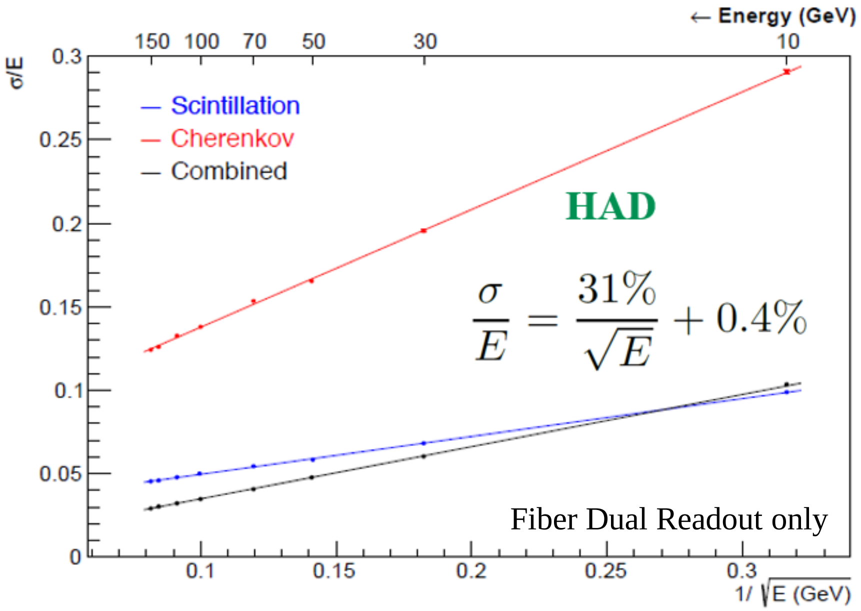
From: Devanshi Arora, CALOR'24

Dual Readout Calorimetry





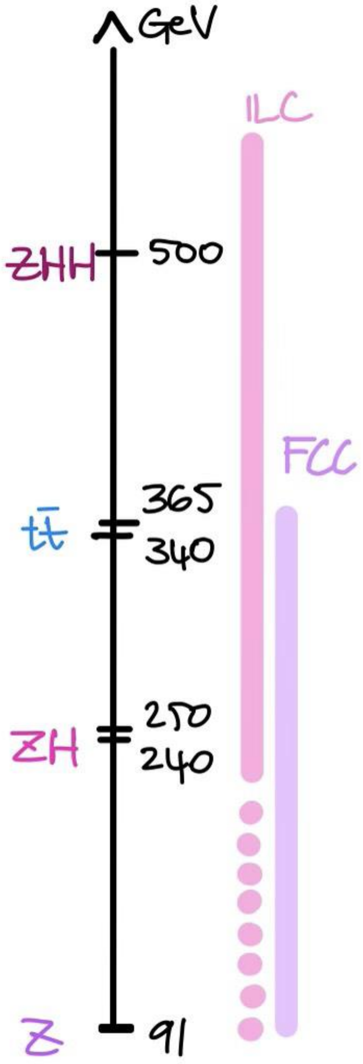
- Segmented Crystal EM Precision Calorimeter with dual readout, preceded by precision timing detector, followed by fiber-based dual readout hadron calorimeter.



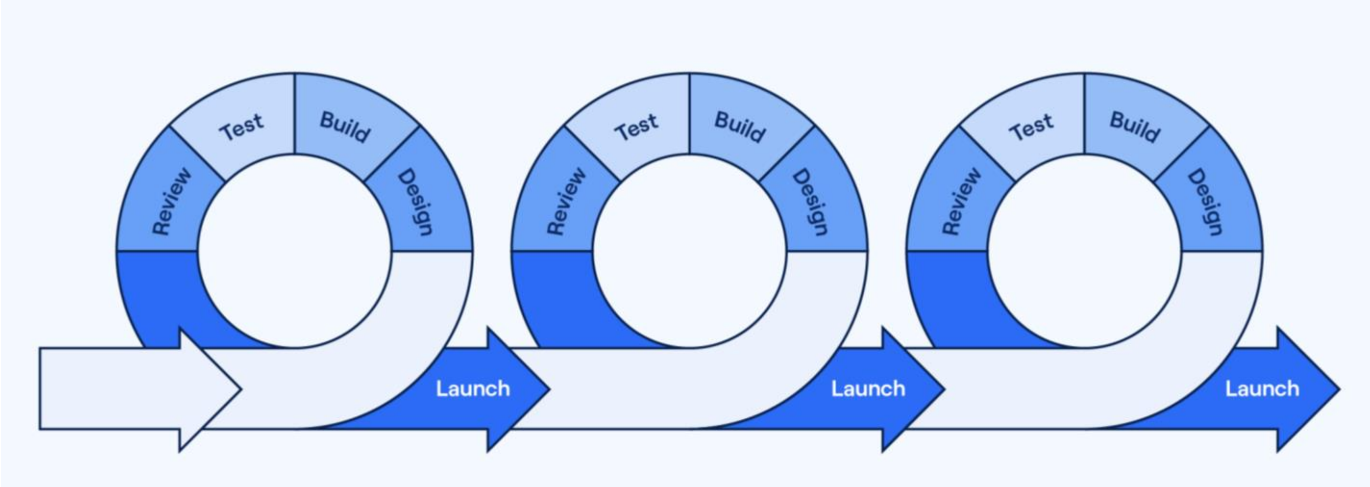
Take Away Messages

- Expect the unexpected.
- Build with the highest (affordable) precision.
- Ignore, within reason, conventional wisdom.
- There is plenty of time for innovation; think out of the box!

Agility



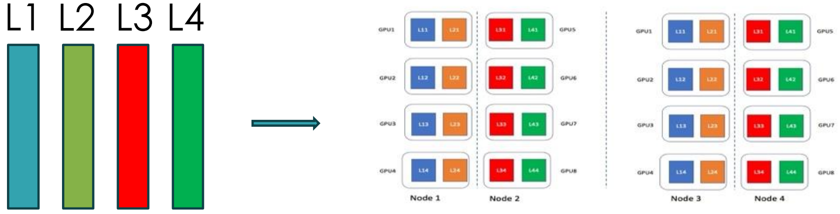
- The current modus operandi of a detector is that it gets upgraded.
- Upgrades have to live within certain constraints of the original detector: invariants.
- Given decades of running at different center of mass energies with **different physics signatures**, and the evolving technologies, detectors needs to be designed in a 'modular' fashion, retaining the integrated physics performance.



Integrating AI

ChatGPT

Scalable training on OLCF



A model is too large to fit in one GPU's memory. ORNL developed capabilities to automatically distribute the model across multiple GPUs

Frontier trained a ChatGPT-sized large language model with only 3,000 of its 37,888 Radeon GPUs — the world's fastest supercomputer blasts through one trillion parameter model with only 8 percent of its MI250X GPUs

News By Matthew Connatser published January 07, 2024

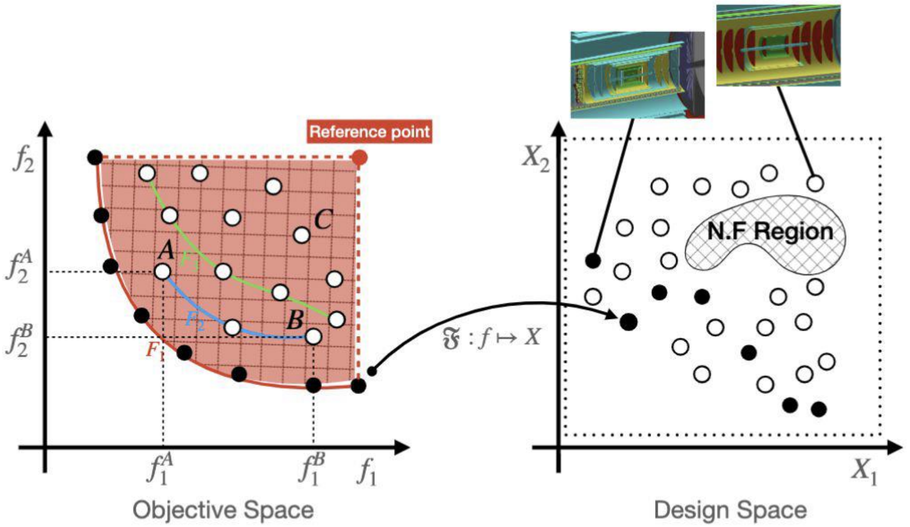
Now you're playing with AI power!

Comments (19)

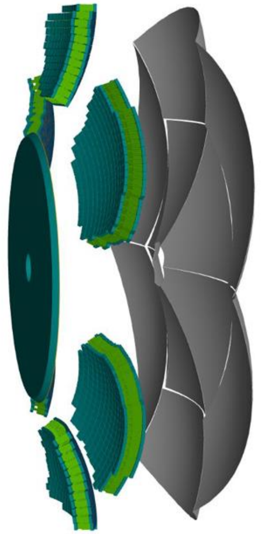
(Image credit: ORNL)

Researchers at Oak Ridge National Laboratory trained a large language model (LLM) the size of ChatGPT on the Frontier supercomputer and only needed 3,072 of its 37,888 GPUs to do it. The team published a research paper that details

AI: Multi-Objective Optimization



- Traditionally, sub-detector systems are optimized individually, using single-objective criteria per sub-detector, within overall constraints.
- Multi-Objective Optimization with 3 types of Objectives
  - Intrinsic detector performance (resolutions, efficiencies) for each sub-detector
    - Tracking, calorimetry, PID
  - Physics-performance
    - Multiple physics channels, equally important in the EIC physics program
  - Costs (e.g., material costs, provided a reliable parametrization)
- Objectives can be competing with each other

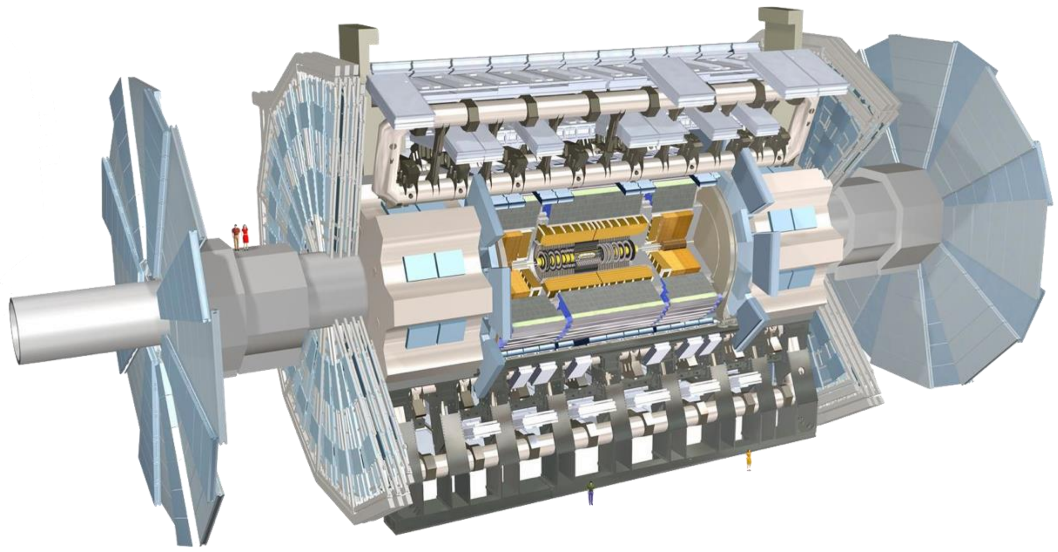


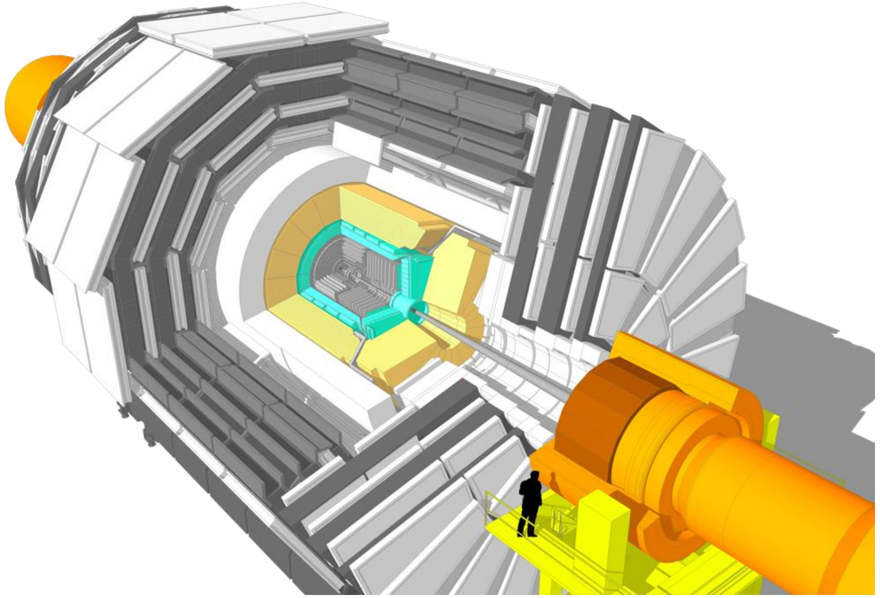
Example: dual-rich for EIC

NIM-A 1047 (2023): 167748
2024 JINST 19 C07001

Agile: the LHC Experiments

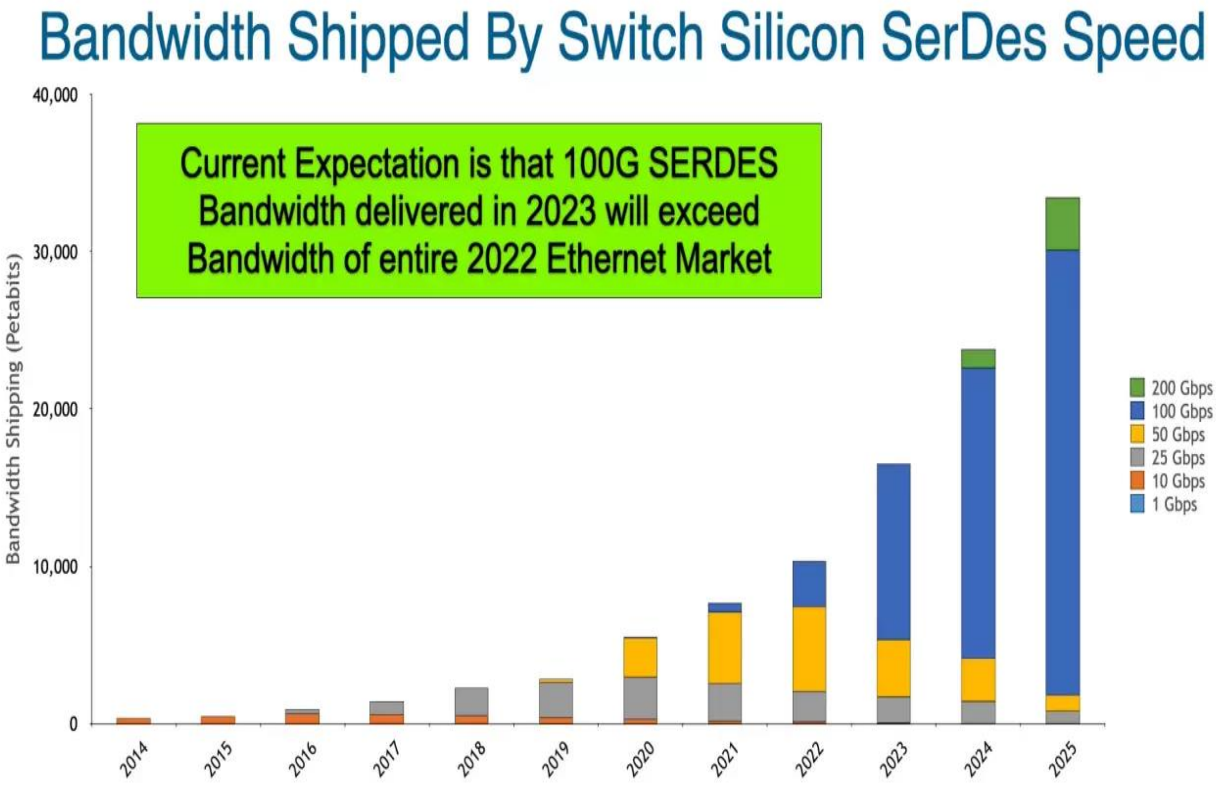
- Very different mechanical design philosophy, with CMS being much more ‘modular’ than the more monolithic ATLAS detector.

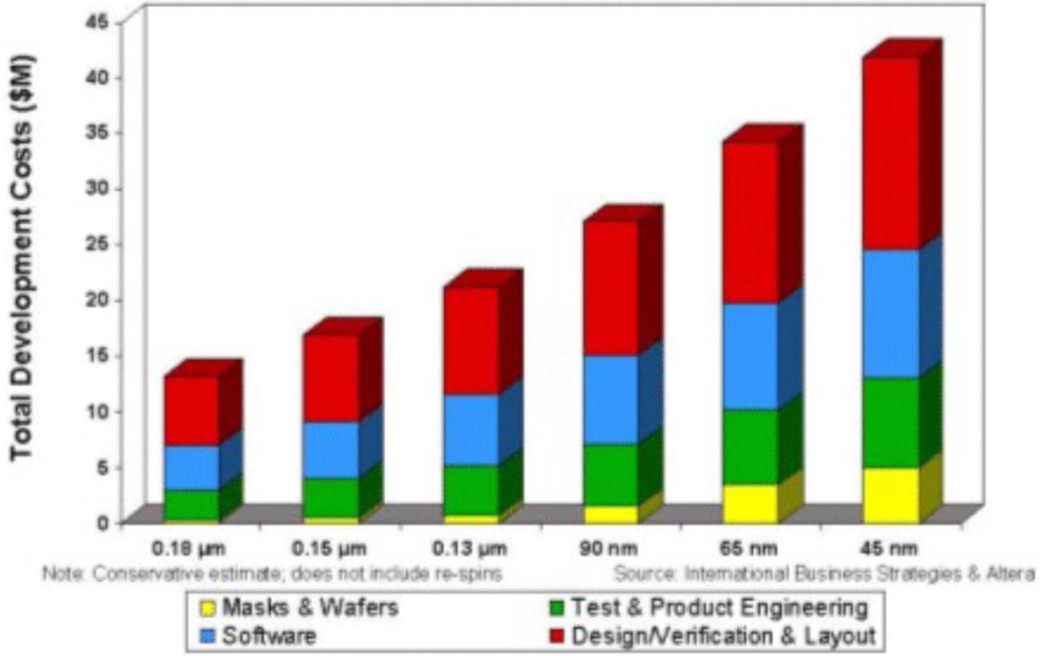




- Need to integrate substantial “upgrades” from the start.

Expect Some Exponential Technology Development



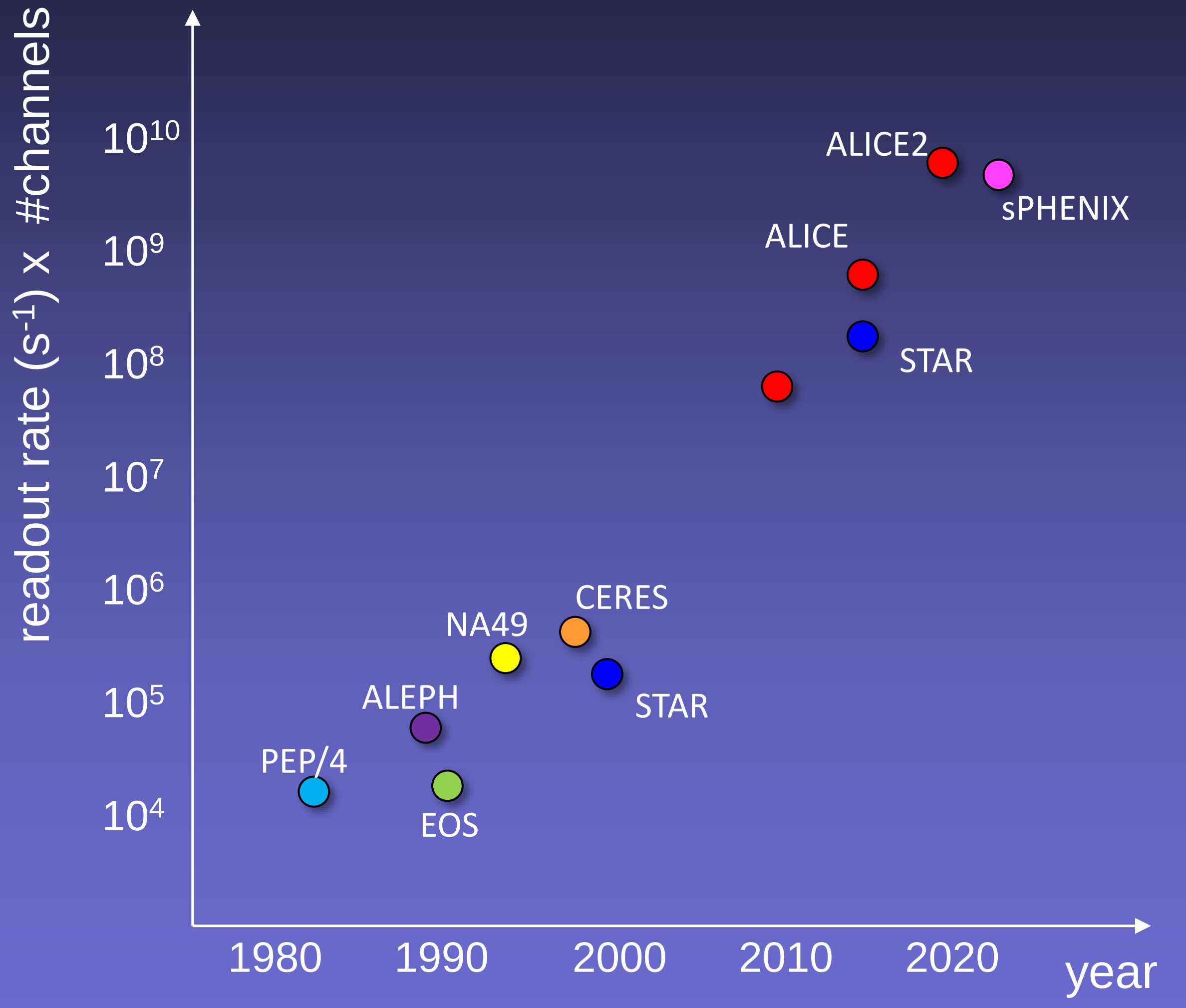


https://www.design-reuse.com/articles/12360/fpgas-and-structured-asics-low-risk-soc-for-the-masses.html

Source: https://ascentoptics.com/

Source: Walter Snoeijs

TPC evolution



One order of magnitude improvement in this metric per decade.

From Harald Appelshäuser (CPAD 2024)

Take Away Messages

- Expect the unexpected.
- Build with the highest (affordable) precision.
- Ignore, within reason, conventional wisdom.
- There is plenty of time for innovation; think out of the box!
- Detector design should be modular, but performance integrated.
- Assume healthy improvements in commercial components.
- Closely follow and connect with technology developments.

J.N. Marx and D.R. Nygren
Physics Today **31** (10), 46–53 (1978)

Detecting Particles

The Time Projection Chamber

By combining the particle-identification function in the same detector volume as the tracking and momentum-measurement functions, this device achieves substantial reduction in overall size.

Jay N. Marx and David R. Nygren

Progress in experimental high-energy physics is limited in practice by two complementary aspects: the types of beam particles available with useful intensities and energies, and the charac-

Stanford and the Lawrence Berkeley Laboratory, stands for "Positron–Electron Project." PETRA, nearing completion at Hamburg, Germany, stands for "Positron-Electron Tandem Ring Accel-

has been in operation in a charged-particle beam for the past ten years, and has shown performance in agreement with expectations (figure 1).

PEP and PEP physics

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Here, in particular, it may be risky to speculate on the future, but as the reader may have concluded by now, we are not afraid to make projections in time.

Summary

- The next-generation experiments will not – and should not – be your grandfather's experiment!
- The time-scale of "many decades" provides for interesting challenges and opportunities.
  - Many decades of operation at different energies with different physics topologies creates tension with single detector design.
  - Many decades for technology development that is advancing at break-neck pace, needs to be followed and will impact the detector design.
  - The community needs to be nimble, creative and work towards experimental transformational developments.
- The "**many decades**" should provide for at least one "**revolution**". We could not be at a better time for transformational detector designs.