NEW DETECTOR TECHNOLOGIES

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PRELUDE

This presentation is a brief glimpse of the very broad and interesting topic of new detector technologies. Trying here to summarise the impressive common effort among our scientific community and beyond through collaborative work with industries.

Thanks for this opportunity to talk on behalf of all the people contributing to shaping the future of instrumentation in high-energy physics.

OUTLINE

- Introduction: What are we after? What are the requirements and how do these translate into detector specifications? We really need new technologies, we can't we just scale up what we have. Concentrating mostly on FCC (appropriate extreme baseline case).

- Detector evolution: ongoing developments in various detector areas: Tracking & Vertexing, Calorimetry, Muon detection, particle identification, readout electronics, etc. What are the challenges and how new material are introduced to match specifications.

- Beyond HEP: perspectives and collaboration beyond HEP

Lots of very interesting developments, impossible to go through all of them, try to avoid the catalogue of technology available on the market, focusing here on the main trend. Suggested link for more:
ECFA detector roadmap (building on previous RD collaboration models). Working Groups in all R&D aspects with worldwide expertise (including outside HEP).
https://indico.cern.ch/event/957057/program

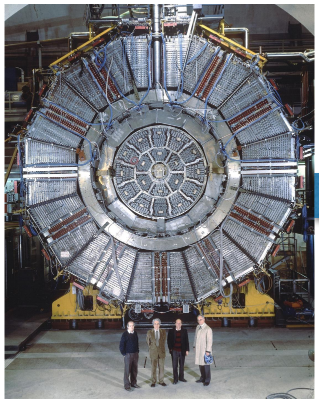
INTRODUCTION

FUTURE OF DETECTORS

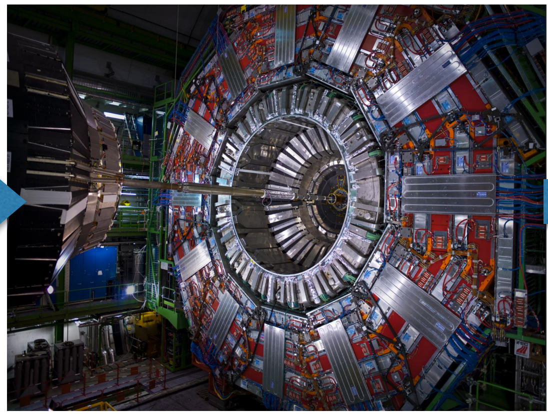
new era of physics measurements

FUTURE OF PARTICLE DETECTION

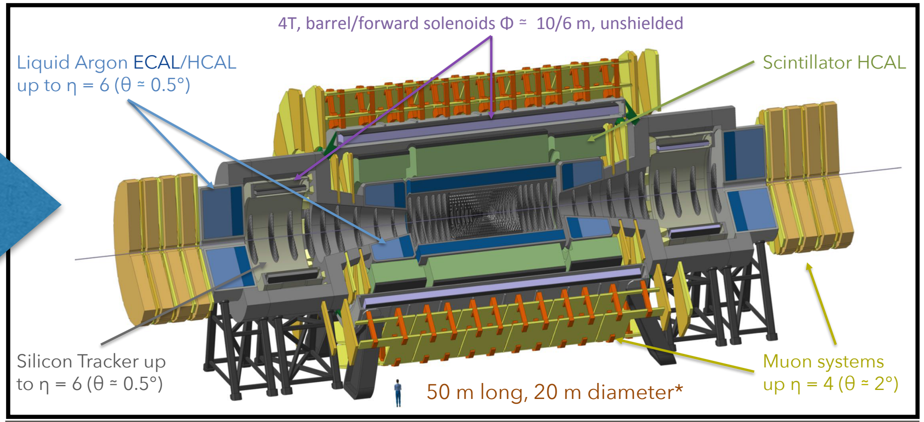
- What physics are we after ?* *"Higgs is really new physics, put it under a microscope and study it to death !" N. Arkani-Hamed, Higgs boson's anniversary 4th July 2022.* The Higgs boson is a portal → **Higgs boson factories** → unprecedented precision measurements → detectors uncertainties brought to statistical levels! & knowledge of beam energy O(10^{-6}), luminosity O(10^{-4}), detector acceptance O(10^{-5}), B-field to O(10^{-6}).
- Detector requirements: Incredible precision on all detector components operating at high energy / luminosity colliders. FCCee: Vertex 5-7 μm, O(15%) Muons@50GeV, 15-20%/√E → O(3%)Jet@50GeV (W/Z/H sep), latency RO ~10μs



ALEPH 12x16m



CMS 15m x 28m 14kT



FCC-hh Detector 20m x 50m

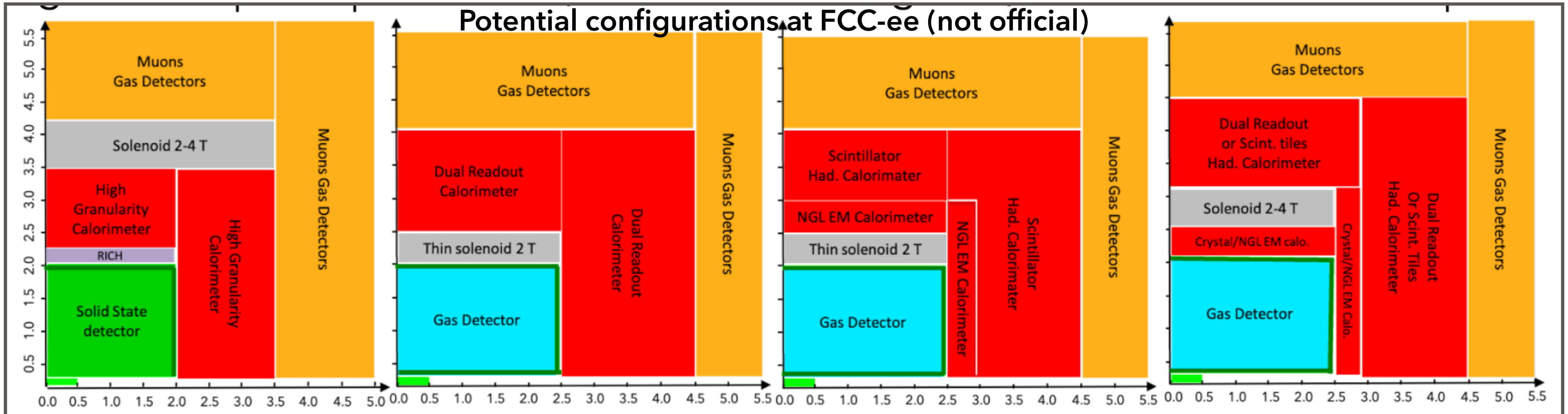
*Talk by J. Ellis on Particle Physics Today

Challenge of precision on a massive scale!

FUTURE OF PARTICLE DETECTION

- **Detector designs:** detector conceptual designs are motivated by the **physics case and the environment** in which they operate. Of course compromise remains the driver to balance performance, cost, construction time and technical risks.
- **Design optimisation:** complex in itself, must **anticipate the experiment from end-to-end in simulation**. Common software framework developments to facilitate comparison of design scenarios (first attempt at Machine Learning to link detector design parameters to physics reach*)

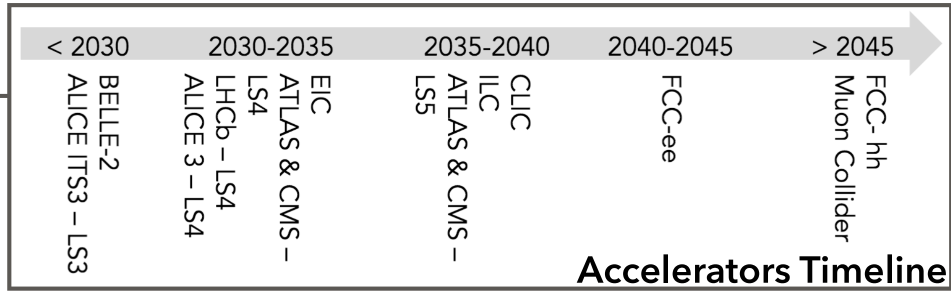
Potential configurations at FCC-ee (not official)



Detection techniques traditionally used in certain detector areas make their way to other ones (Tracking - Muon - Calorimetry)

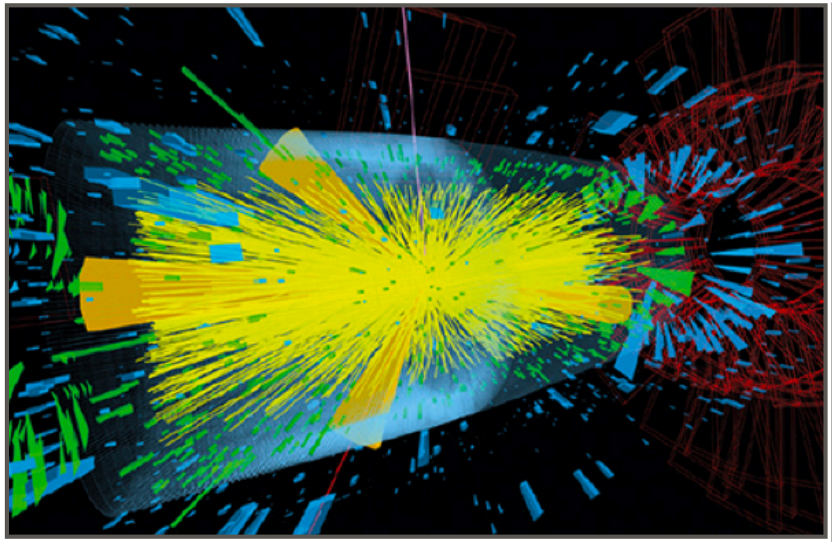
*Joint ECFA-NuPPEC-APPEC Activities

FUTURE OF PARTICLE DETECTION



- Many directions explored*
  - Linear colliders (CLIC, ILC)
  - Circular Collider (FCC, etc.)
  - FCC-hh: Luminosity ~ 30.0x10^{34} cm^{-2} s^{-1} (x15 LHC) & Pile-Up ~ 1000(x20 LHC)

→ Detector Environment: very large particle multiplicity. The goal is to visualise all particles: global event reconstruction**.



HL-LHC: particle multiplicity in CMS

"Particle Flow" paradigm emerging as baseline for future detector design: high-granularity & timing information. Challenges ahead:

- Millions of channels: readout / power consomption
- Particule rates / **radiation damage**
- Large tracking volume + timing
- Imagining calorimetry + timing
- Extended acceptance up to η~6 (particle boost)
- Sophisticated reconstruction software (ML)

Some options rely on long term R&D, combining forces among the community and strong ties with industrials

*Talk by F. Zimmermann on Innovative Accelerator Technologies

**May not even be the future of data analysis. New approaches are explored, such as graphic recognition etc.

FUTURE OF PARTICLE DETECTION

‣ Radiation tolerance

Major challenge at the FCC-hh, most radiation tolerant technology design today would not survive below R=30cm: sensors & ASICs

Note: it is already an issue at HL-LHC at relatively large radii

→ Neutron fluence tolerance needs to increase from O(10^{16}) to O(10^{18}) neq/cm^2

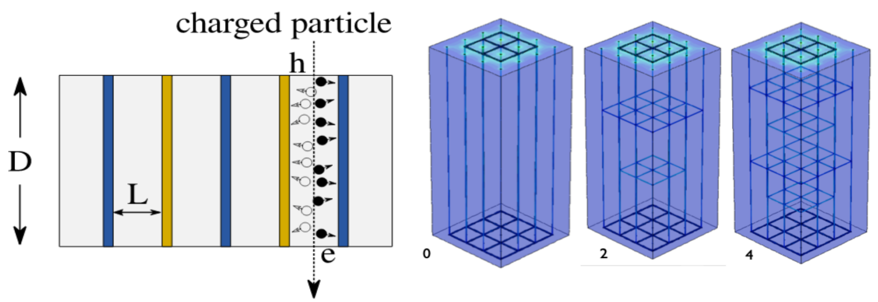
→ Total Integrated Dose (TID) affects electronics, tolerance needs to increase from O(1) GRad to O(30) GRad

Note 1: *Behaviour beyond @ 10^{17} neq/cm^2 not really known, current ageing models may be pessimistic.*

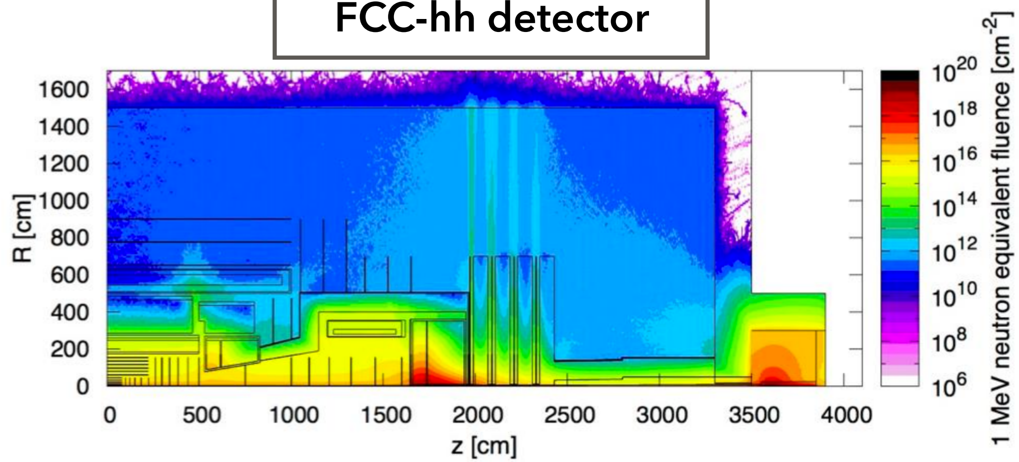
Note 2: 3D sensors may still work al lowest radii with replacement O(year).

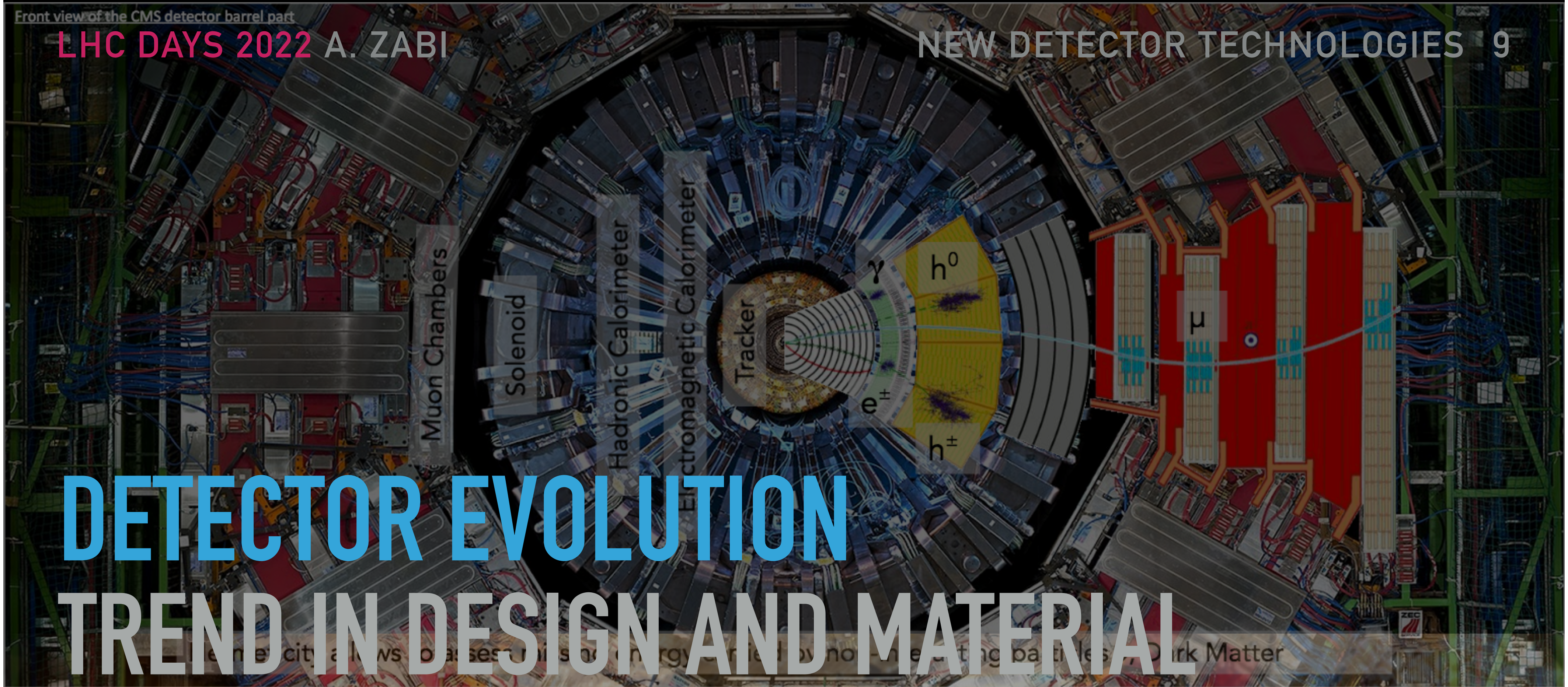
New types of semiconductors → CVD-diamond semiconductor pixel sensors. These are already used by ATLAS for their luminosity detectors and CMS for beam abort and timing measurements (PPS)

ex. CVD-diamond 3D pixel sensors



FCC-hh detector





DETECTOR EVOLUTION

TREND IN DESIGN AND MATERIAL

more with HEP detectors

DETECTOR EVOLUTION

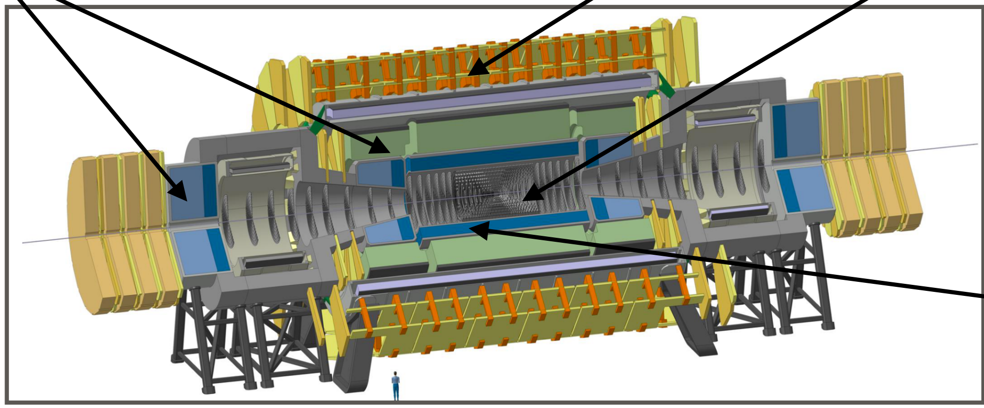
HL-LHC are used as stepping stones towards FCC detector technologies. Note: progress in material and engineering over more than 20 years are hardly predictable.

Calorimetry
best e/γ/h and jets resolution / shower separation (high-granularity $\Delta\eta \times \Delta\phi$ = 0.01x0.01, XM channels); timing ~ 10-20 ps
@Higgs Factory = separation of W/Z/H
Tech: Solid State, Fibers, Noble Liquid, xtals.

Muons
High muon rate 10kHz/cm^2 in forward region
Tech: Gas, MicroPattern Gas Detectors (MPGD)

Tracking & Vertexing
pT O(0.3%) @ 10 GeV
Vertex position O(1 µm)
hit position 10 µm
timing 10 ps (provide Particle ID, also FCCee)
lowest X/Xo (0.4%)
Tech: Solid State or Gas

Tech transfer:
Muon MPGDs → Tracking, Calorimetry
Tracker SiPixels → Calorimetry



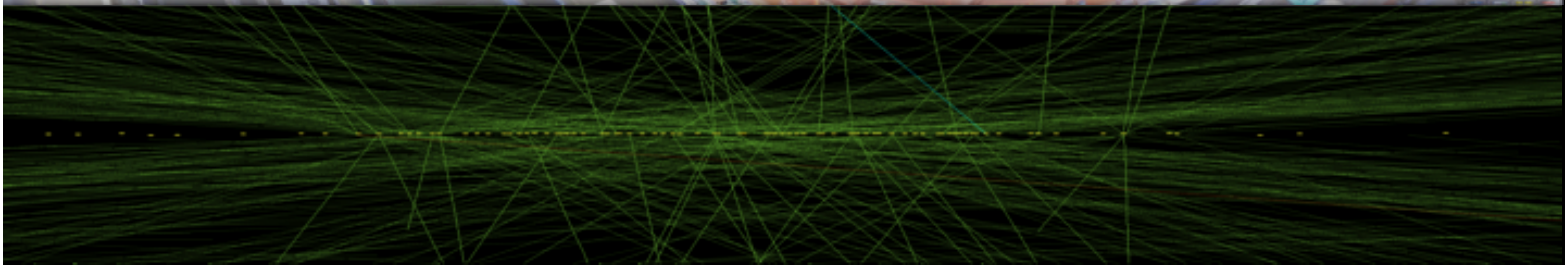
Particle ID (FCCee)
e/π/K/p identification to cover O[1-50] GeV/c
ToF Layers ~ 10ps
Tech: Solid State, Gas, Scintillators, Radiators

@FCC-hh: Vertices are 170 µm away (1000 PU) → timing 5~10 ps

Progress in Solid State Detector (SSD) benefiting from CMOS imaging sensor technologies
MGPDs approaching solid state performance: Exploit PCB technology with single amplification stage

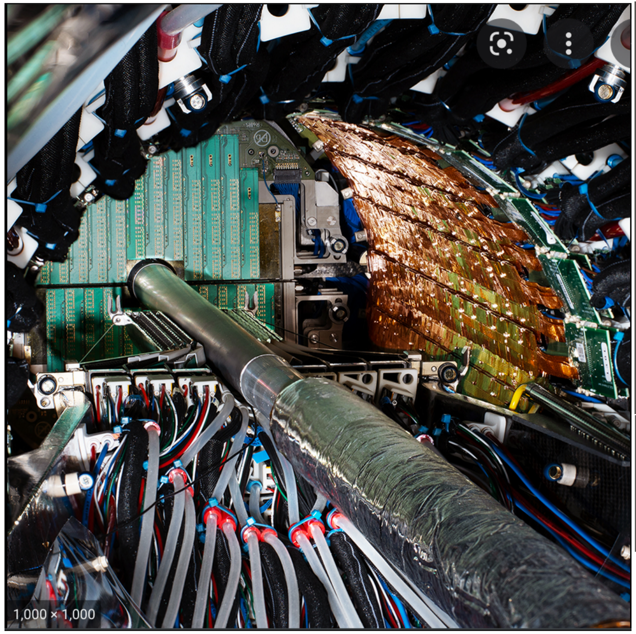
TRACKING & VERTEXING

Tracking down particles

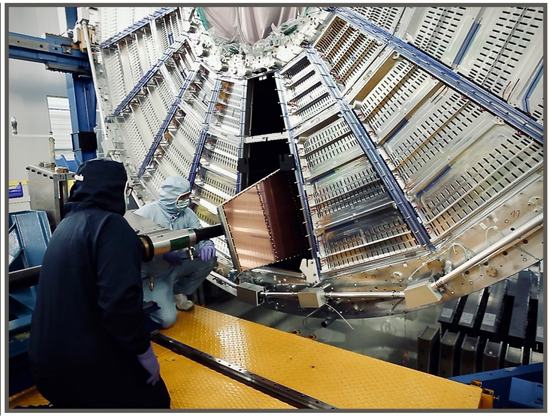


TRACKING & VERTEXING

- Measuring Vertex & Particle Tracks parameters (Tracker can also be used to identify particles). Measure precisely particle origin O(1) µm (radius and material or first layer is crucial, retractable VD)
- Challenge: hit position precision, while keeping X/Xo small.
- Both Tracker & Vertex detector are very precise multilayer detector

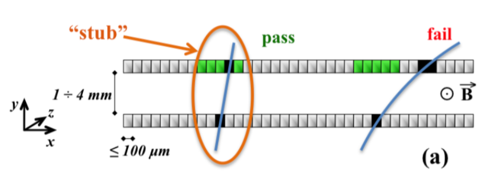


ALICE ITS2 SSD w/10 layers, best accuracy < 10 µm X/Xo = 0.36%



Meg II (Drift Chamber), ALICE TPC O(100) points at O(100) µm, lowest X/Xo

FCC-hh tracking ~ 1000 TB/s @ 40 MHz
Need on detector processing for data reduction (CMS Phase-2)



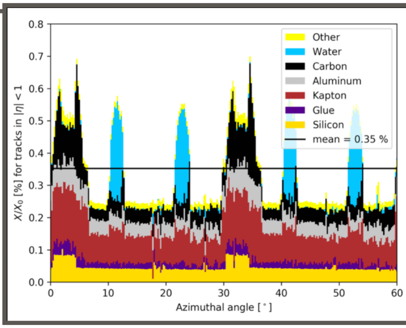
Increasing demands on particle rates, time and spacial resolutions, and radiation tolerance.

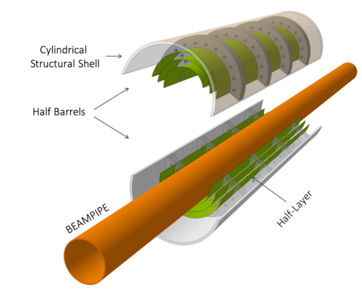
Expected particle rate: FCC-ee O(100) MHz/cm^2, CLIC up to 6 GHz/cm^2, FCC-hh up to 30 GHz/cm^2

TRACKING & VERTEXING

Innovating with ALICE ITS3 (Inner Tracking System)

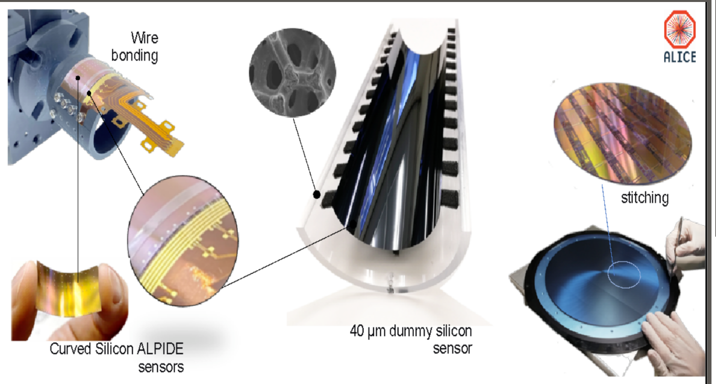
Large R&D by ALICE benefiting from CMOS imaging sensor technologies leading to large size MAPS (**M**onolithic **A**ctive **P**ixel **S**ensor w/ reduced thickness ~ 20-40 µm) using stitching techniques→ ultra-thin silicon sensors arranged in perfectly cylindrical layers. Material budget reduced by a factor 6 → better tracking precision and efficiency at low pT. Radiation load 10^{15}neq/cm^2. More info here.

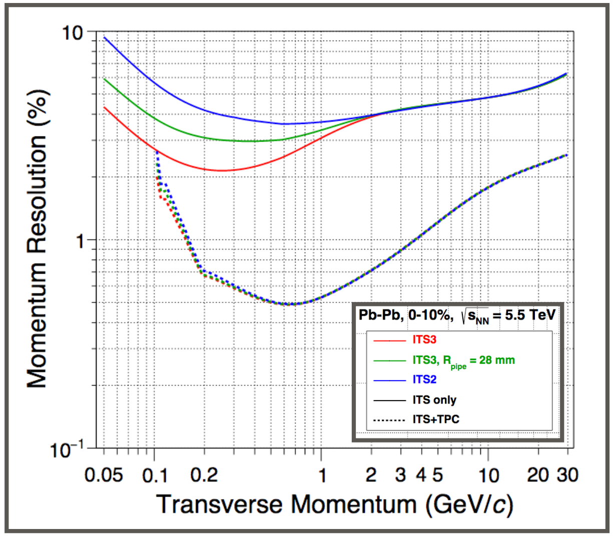




Parameters:

- 0.05% Xo/layer
- 18 mm from IP
- 7 layers of MAPS
- Readout in single chip APLIDE 12m^2 = 12.5 billion pixels
- 20mW/cm^2
- Timing < 100 ps

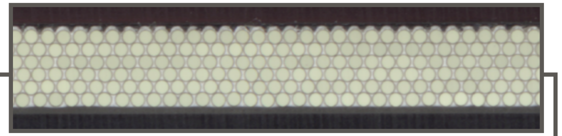




ALICE paving the way toward FCC-ee

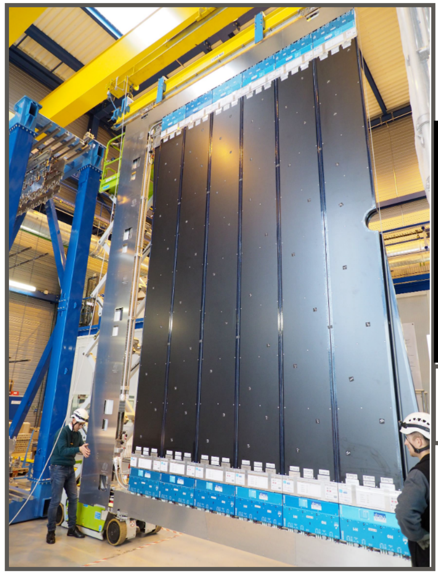
Expected particle rate O(100) MHz/cm^2

TRACKING & VERTEXING



Scalable solution with LHCb Mighty Tracker (info)

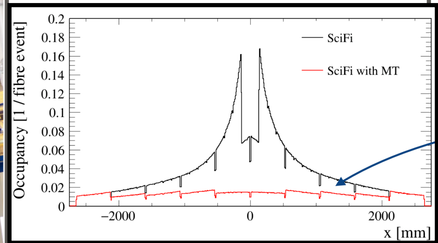
- **Run-3**: densely packed 250µm Scintillating Fibers (SciFi) = 10000 km + SiPM (524k readout channels). Radiation load of 6×10^{11} neq/cm^2
- **HL-LHC (Run-5): MightyTracker SciFi(outter)+Pixels(Inner)** equipped with HV-MAPS (100 µm x 300 µm) time resolution < 8ns , 150mW/cm^2, X/Xo~1%



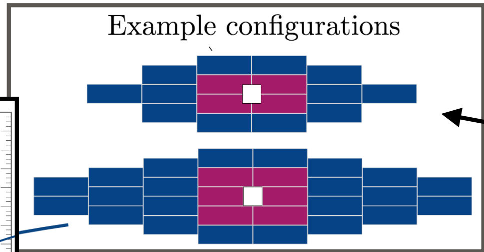
Parameters: SciFi Trk

Run-3 detector

- 3 stations 6mx5m
- Fiber array
- 100 µm resolution

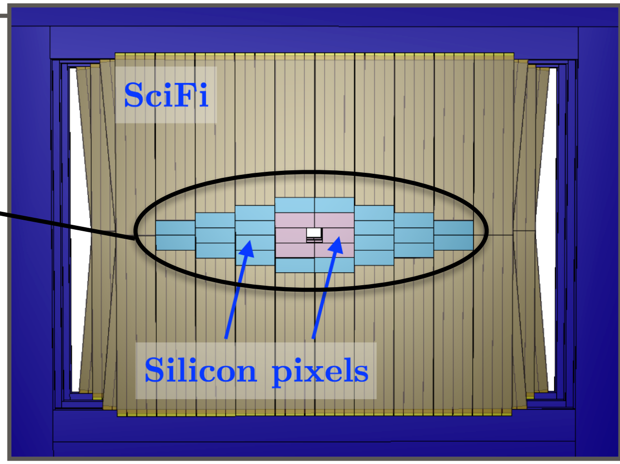


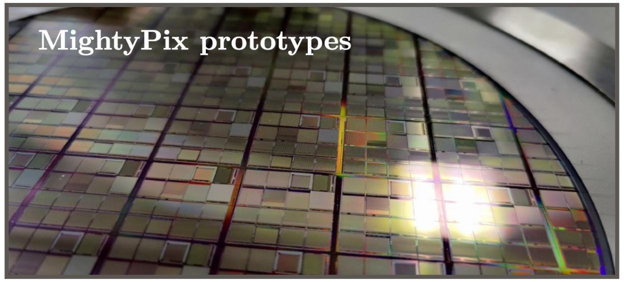
Material budget



Parameters: SciFi Trk + Pixels

- Monolithic 2x2cm sensors
- 20x54cm modules



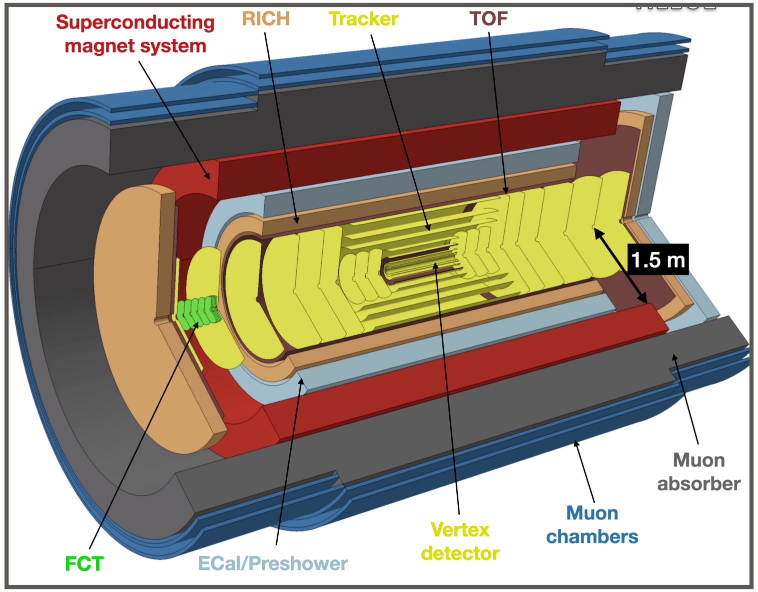


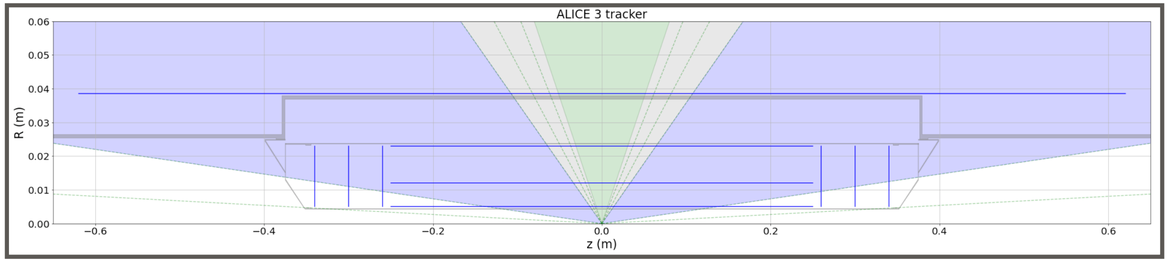
MightyPix (MuPix & ATLASPix) Continuous readout

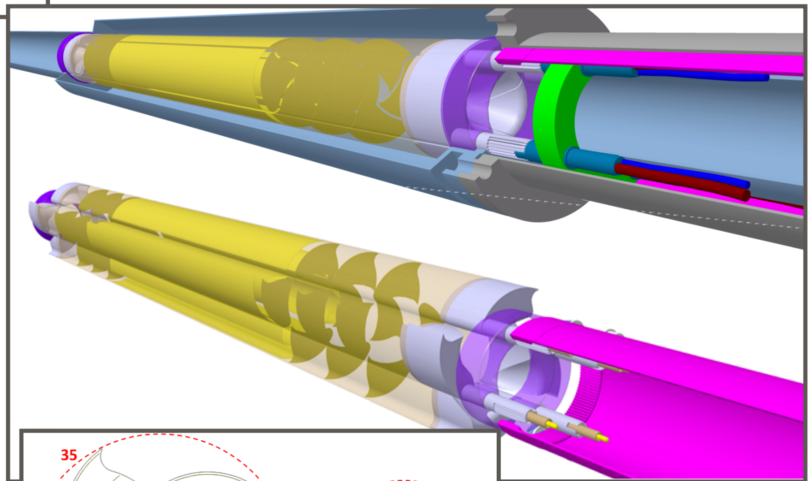
TRACKING & VERTEXING

ALICE-3 detector concept for LHC Run-5 → capitalising on MAPS

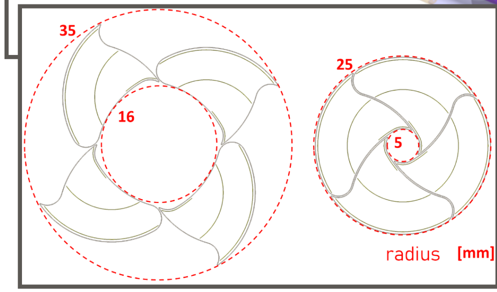
- Vertex detector: bent MAPS
  - 3 layers, 10μm pitch, 0.1X/Xo
  - R~5mm, R~15mm @ injection (retractable device)
  - Pointing resolution 10 μm







- Tracker: MAPS
  - 11 layers, 50μm pitch, 1 X/Xo
  - Timing resolution 100 ns
  - pT resolution 1% up to η=4
  - Outer tracker = 60m^2 silicon

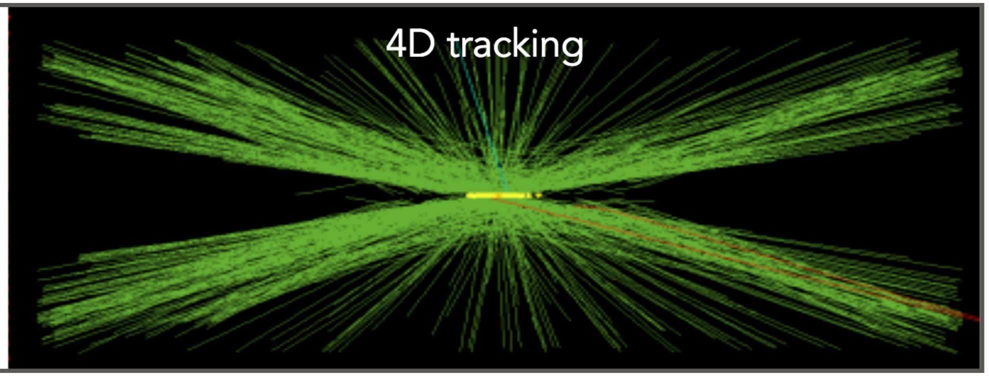


N. Poljak "performance and upgrade of ALICE (Tuesday session)

TRACKING & VERTEXING

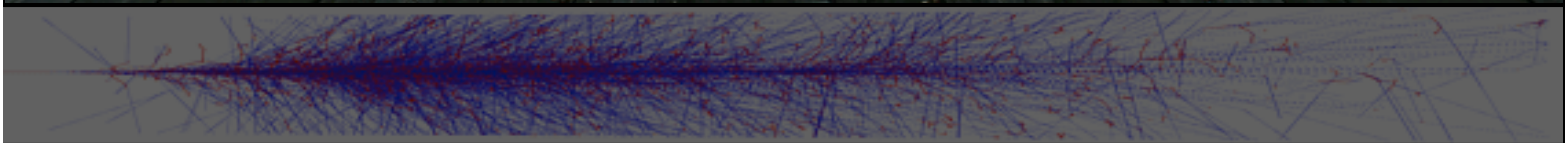
The next level: FCC-hh <1000>/bunch and 30 GHz/cm^2 (multiplicity)

- 4D tracking: assigning space and time coordinate to a hit (w/ precision of <10 ps), using combination of Sensor(pulse) + ASICS(measure ToA & ToT) → new range of transfer bandwidth requires on-detector processing for data reduction (CMS HL-LHC tracker 2GeV tracks + timing layer MTD).
- Principle: Hit & track-vertex time association can reduce significantly Beam induced background and PU at ee/hh colliders
- Tech options:
  - **Low-Gain-Avalanche-Diode** (SSD, w/ amplification) 30ps but not so good spatial resolution (pixel/sqrt(12))
  - **Resistive readout** better for both spacial (5 μm) and time resolution (30 ps)
  - **MAPS 3D** (w/o amplification, ALICE-3)



CALORIMETRY

More than just measuring energy



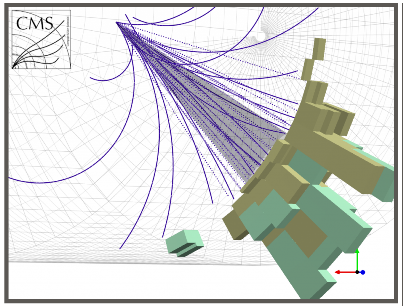
CALORIMETRY

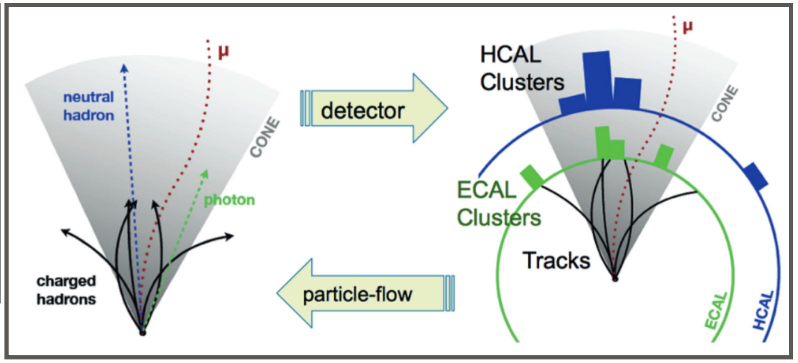
- **Entering a new realm of calorimetry: imaging calorimetry**

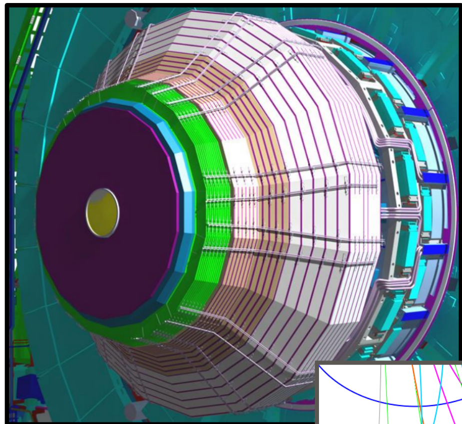
We ask much more of calorimeters today than just measuring energy. Given the intense environment: shower separation and containment to minimise overlap, optimise matching with tracks, mitigate the impact of pile-up, etc.

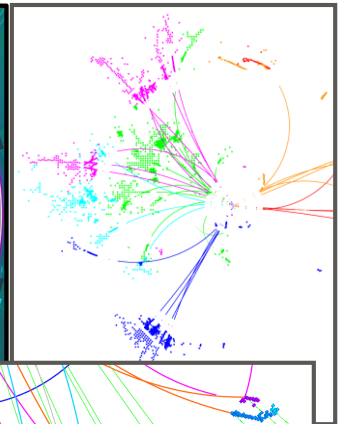
→High granularity (transverse & long segmentation): **Particle-Flow calorimetry**

→Inclusion of timing measurement: **5D Calorimetry**









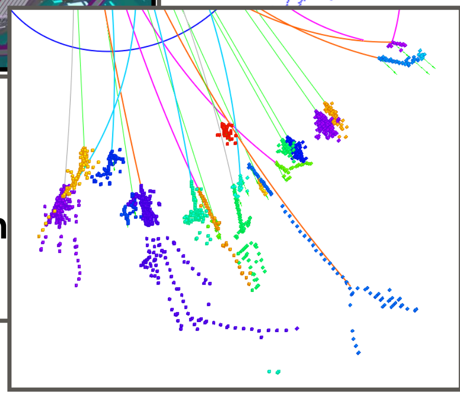
Improving jet resolution:

- Mitigate the inherent fluctuations (shower, fEM)
- Compensation of e/h response compensation
- Reduction fluctuations from invisible energy

Main limitation of jet resolution coming from confusion between hadron & neutral deposited energy not intrinsic calorimeter performance

@Higgs Factory = good separation of W/Z/H

CMS HGCAL for HL-LHC
Forward region
1.5< eta < 3



Pioneer studies conducted by CALICE Collaboration (ILC)
Tested @ 200 PU at the HL-LHC

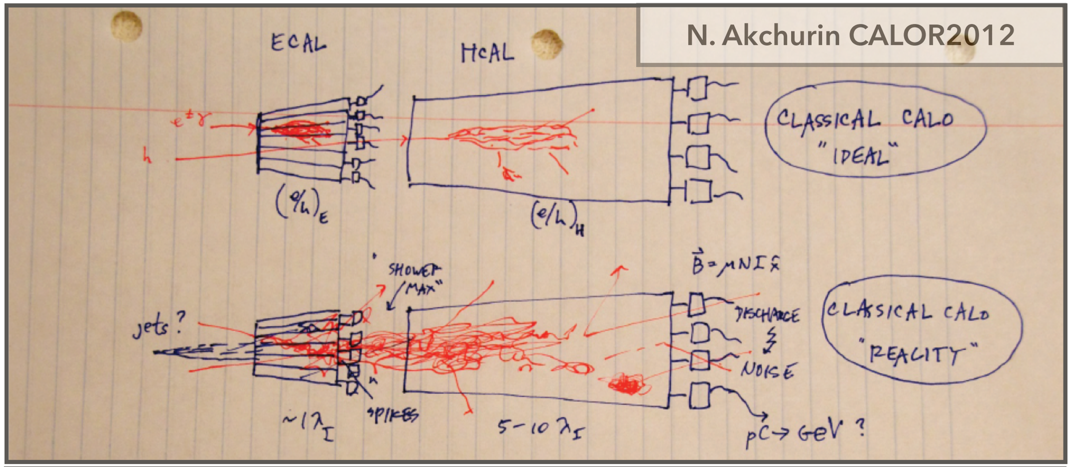
CALORIMETRY

- **New calorimeter concepts:**

→Dual EM & HAD: shower component measurement for e/γ - π ID and energy compensation
→Heterogenous Novel design
→Digital high granularity calorimeter

- **Still around:**

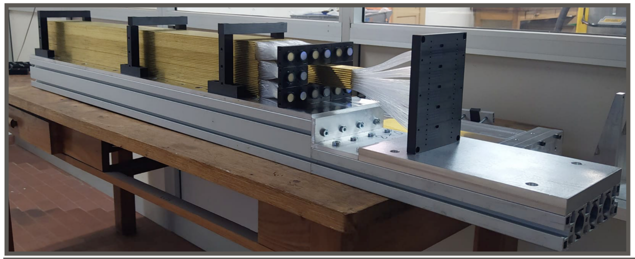
→Homogenous calorimeters still provide best E-resolution, but limited to specific use and environment
→Sampling calorimeters offer many possibilities (structure etc.) reach similar ball park performance

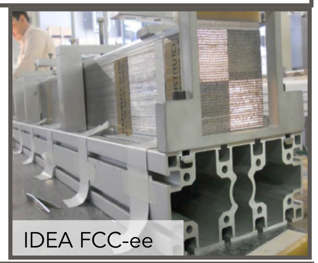


N. Akchurin CALOR2012

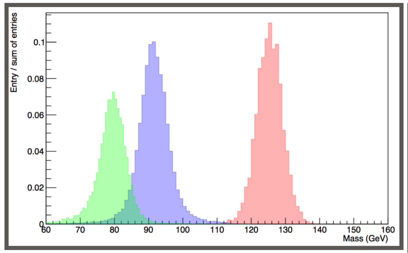
Principle of Dual Readout Calorimeter: Using simultaneous measurements of scintillation light and Cherenkov light produced by the shower →measure the em fraction event-by-event (eliminate fluctuations).
→**Scintillating & Cherenkov fibers in absorber**

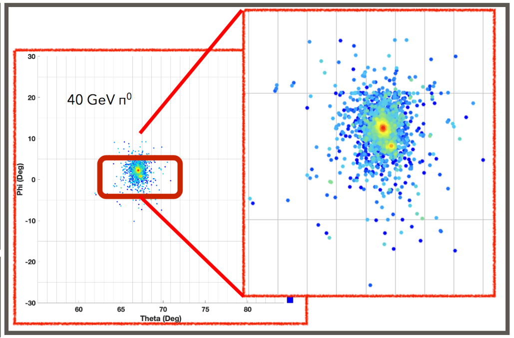
Pioneer studies by DREAM / RD52





Prototype for **IDEAL @ FCC-ee** (130 M channels, 1 module = 13x13x200 cm, fibers in brass capillaries absorber + SiPMs). Longitudinal segmentation + all electronics in the back.

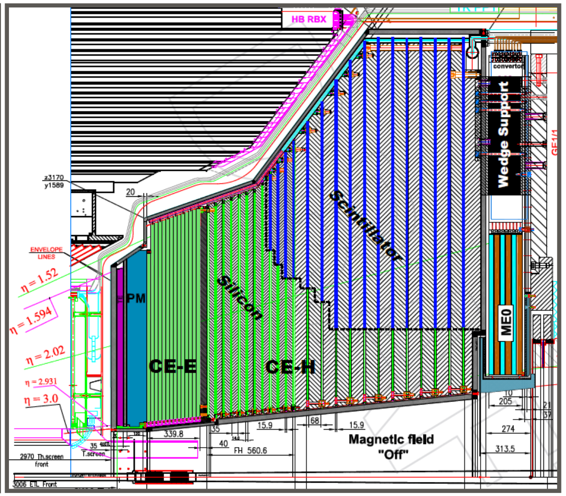




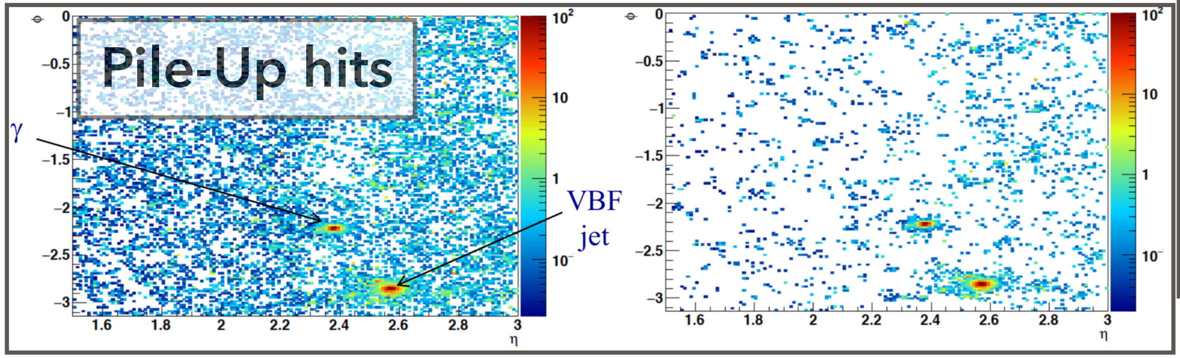
DR performance

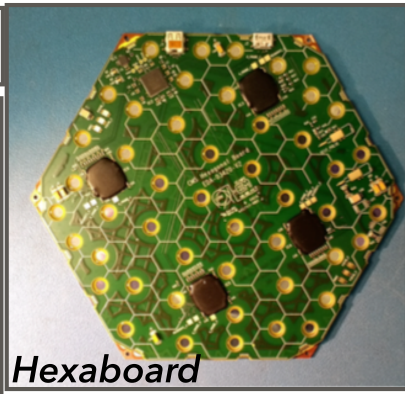
CALORIMETRY

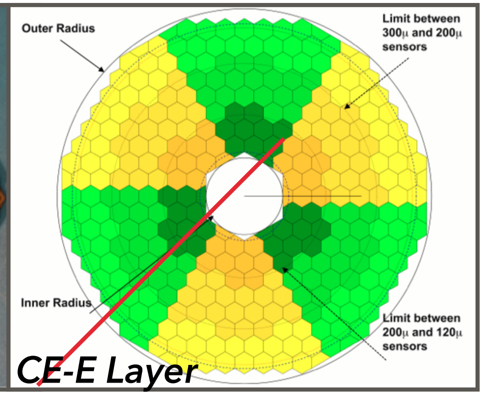
- **High granularity calorimeters: first occurrence in HEP with CMS HGCAL @ HL-LHC (Rad. hard. Si/Scint Tiles, 47 layers-6M channels)**
- Porting tracking technology into calorimeter for ultimate shower separation and matching with tracks.
- Timing resolution ~ 30 ps

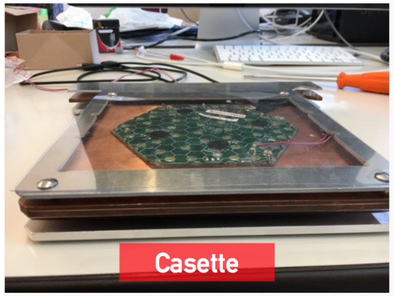


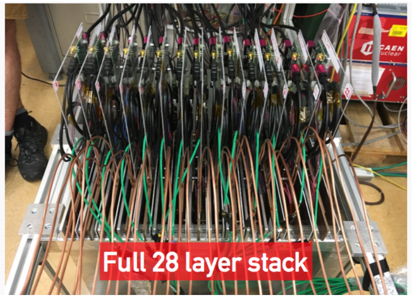
Layers projected no timing cut (left), within 90ps (right)

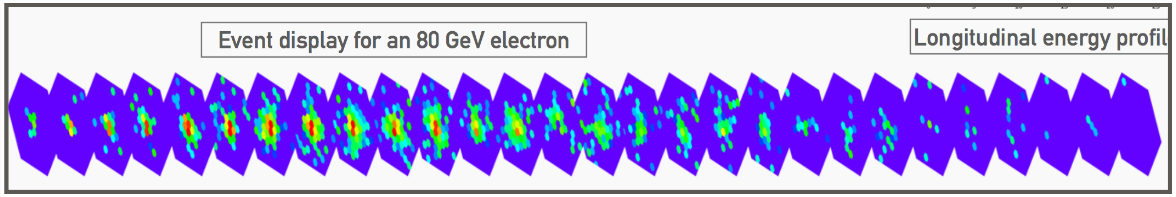












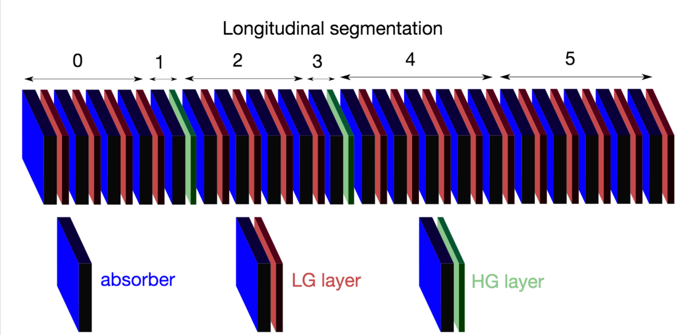
Proof of principle demonstrated with dedicated test beam

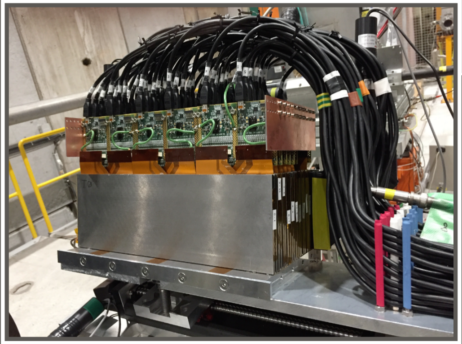
*Talk by M. Mannelli (monday session)

CALORIMETRY

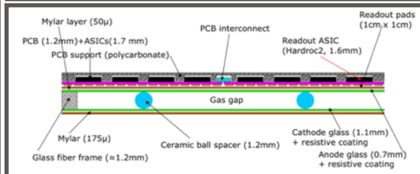
Digital high granularity calorimetry

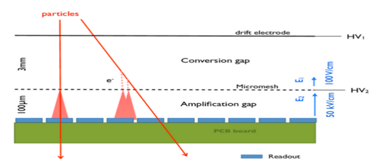
Principle is to mesure the energy by counting hits: E proportional to N secondary particles in the shower. Highly granular calorimeters, compact, low power dissipation, sampling fractions, etc.

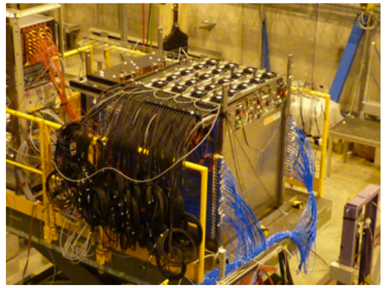




Scintillating Tiles, RPCs, MPGDs





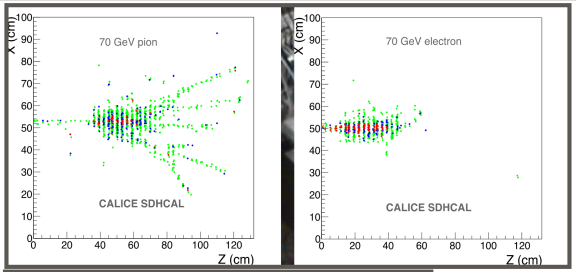


ALICE-3 <u>FOCAL</u> Forward Calorimeter (HL-LHC)

3.2 <η <5.8

- Highly granular & compact EM (Si+W) + Sampling Calorimeter HAD (Cu + Scint)
- **EM CALO:** Pixel Layer (equipped with MAPS) →Digital pixel readout layers w/ granularity 30 x 30 μm^2 → Reduce dead material = better resolution

<u>DHCAL</u> Digital Calo



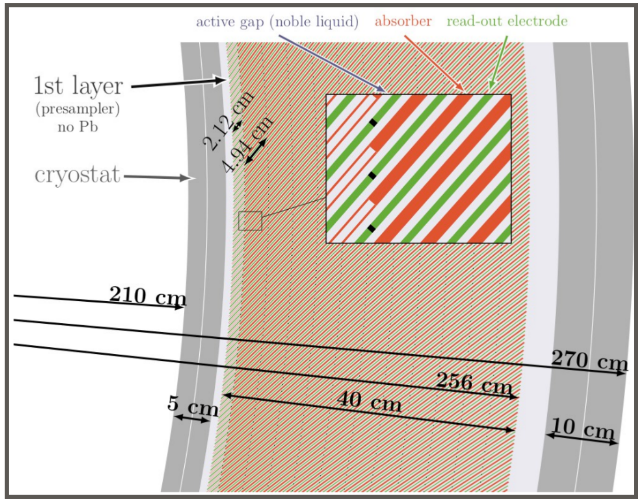
Pioneer project CALICE ILC

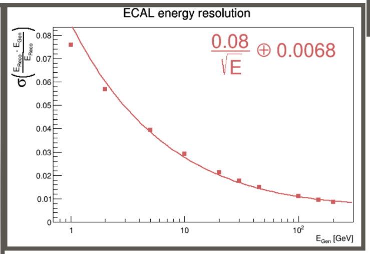
CALORIMETRY

‣ Heterogeneous concepts

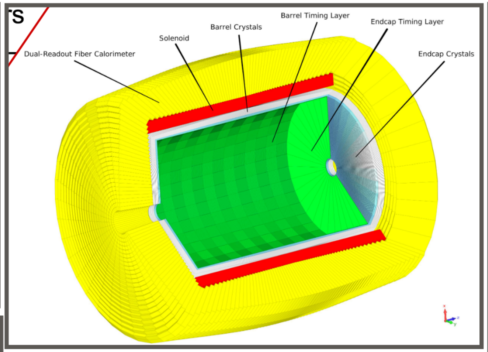
Best performance for all objects is not achieved by a single calorimeter concept yet. Combine different and complementary technologies for EM & HAD calorimeters. 2 examples for FCC-ee:

EM: Noble Liquid Gas (Ar/Kr/Xe)
HAD: scintillating tiles
Radiation hardness: could also be an option for FCC-hh (inspired form ATLAS)



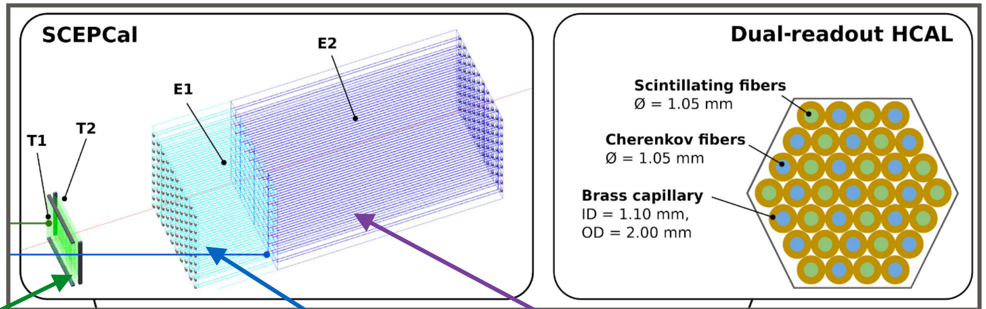


12 longitudinal layers (LAr + Pb/Stell + PCB)
2 Million channels



IDEA @ FCC

Ongoing proposal
EM: Homogenous xtal (best e/ɣ reso)
HAD: Dual Readout or Scintillating tiles



Timing layers — $\sigma_t \sim 20$ ps
- LYSO:Ce crystals ($\sim 1X_0$)
- 3x3x60 mm³ active cell
- 3x3 mm² SiPMs (15-20 um)

ECAL layers — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
- PWO crystals
- Front segment ($\sim 6X_0$)
- Rear segment ($\sim 16X_0$)
- 10x10x200 mm³ crystal
- 5x5 mm² SiPMs (10-15 um)

HCAL layer — $\sigma^{HAD}_E/E \sim 27\%/\sqrt{E}$
- Scintillating and quartz fibers inserted in brass capillaries

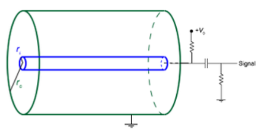
MUONS

Even larger muon spectrometers

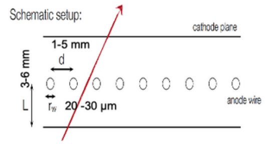
MUONS

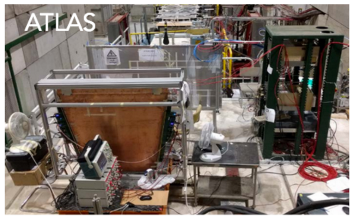
- **<u>Large muon spectrometers</u>: Further away from IP imposes less stringent constraints on radiation tolerance.**
- Existing Gas Detectors achieve performance needs: Several configurations of signal collection can be tailored to requirements
- <u>Note</u>: simplified devices for easier production assembly possible
- <u>Note</u>: @FCC-hh, standalone momentum measurement relies on a forward dipole (ATLAS, ALICE)

Straw Tube

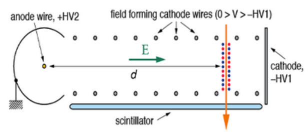


Cathode Strip Cham.

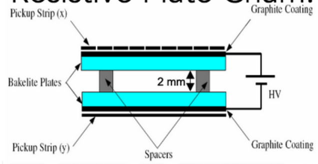


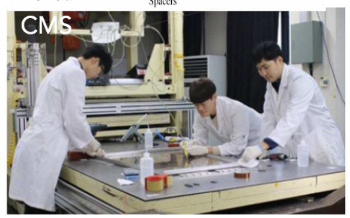


Drift Tubes (x = vt)



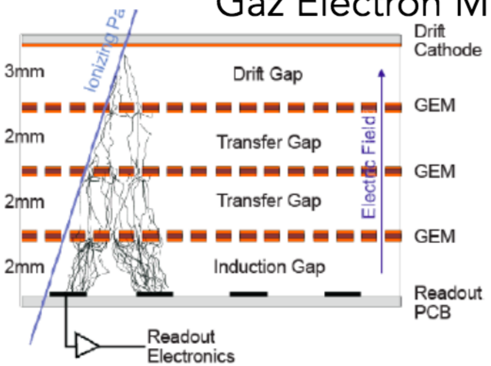
Resistive Plate Cham.

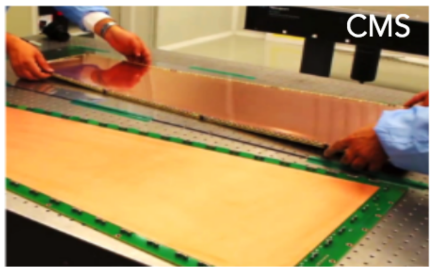




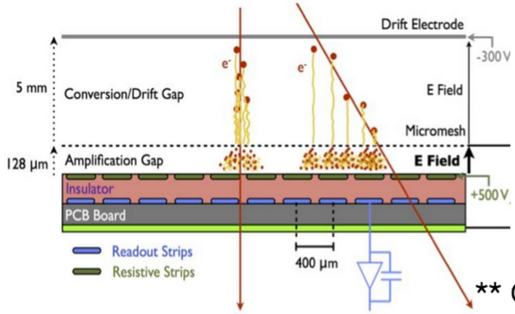
MicroPattern Gas Detectors precision O(0.05) mm and rates O(1) MHz/cm^2

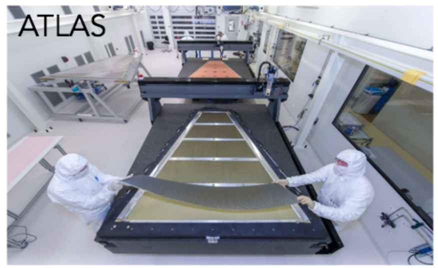
Gaz Electron Multiplier (GEM)





MicroMegas** (MM)





** CEA/IRFU flagship development

PARTICLE IDENTIFICATIONS

more identification techniques

PARTICLE IDENTIFICATION

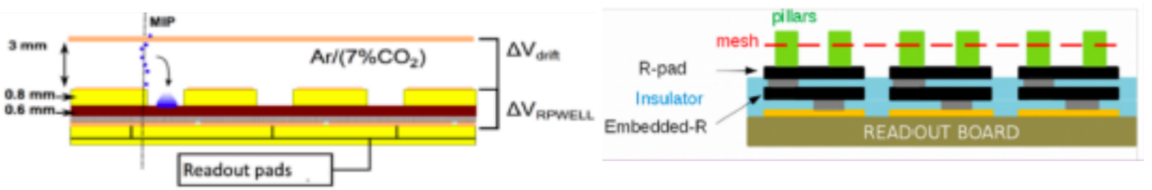
- Techniques in particle identification have also made progress with the technology available. **note: not yet achieved by a single system**
- **Reminder of the common techniques:**
  - Time Projection Chamber (TPC) using dE/dx
  - Ring Imaging Cherenkov (RICH) using photon emission cone angle
  - Time of Flight (ToF) using particle β

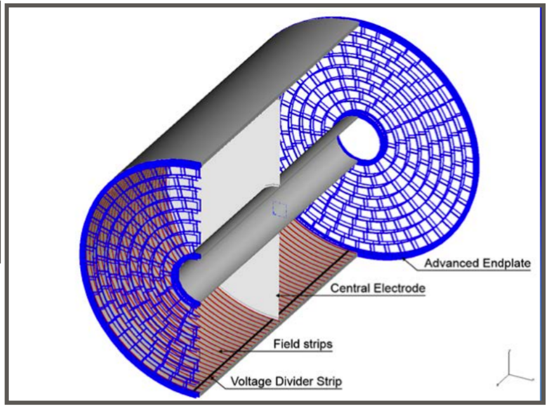
TPC & Drift Chambers (could combine) provide O(100) x $\sigma_{hit} \simeq 100$ μm & low X/X0

TPC @ILC (50μm pixel pitch) Even if concept known since a long time (ex ALEPH TPC), new assembly techniques & material (Carbon wires). High-granularity obtained with MPGD readout (Micromegas / GEM).

DC @FCC-ee IDEA: 1.6(5)% X/Xo (barrel/endcap) σ(pT) / pT ≃ 3 x10^{-3}

GEM and MicroMegas new RO designs



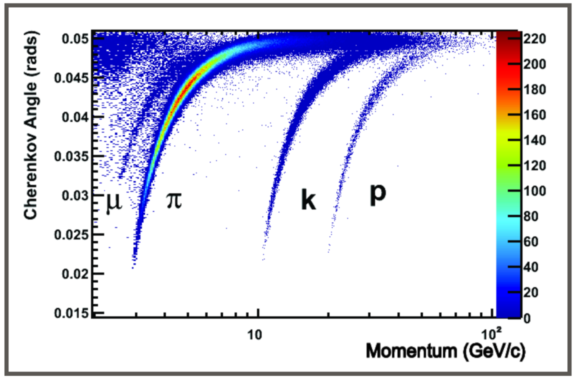


PARTICLE IDENTIFICATION

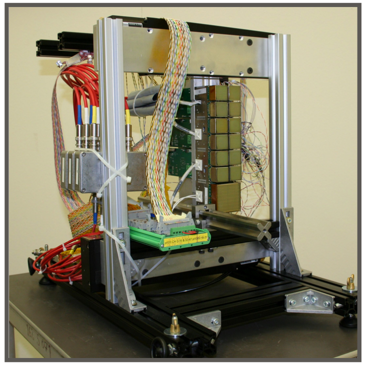
RICH (Ring Imaging Cherenkov)

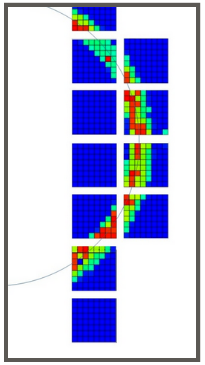
Concept also known but implementing differently to cover different p-range, combined with fast-timing electronics to exploit same **γ**-Cherenkov arrival time for background rejection (SiPM/LAPPD σ_t <50ps)

LHCb RICH Upgrade
Multianode PMT (MaPMT Hamamatsu)

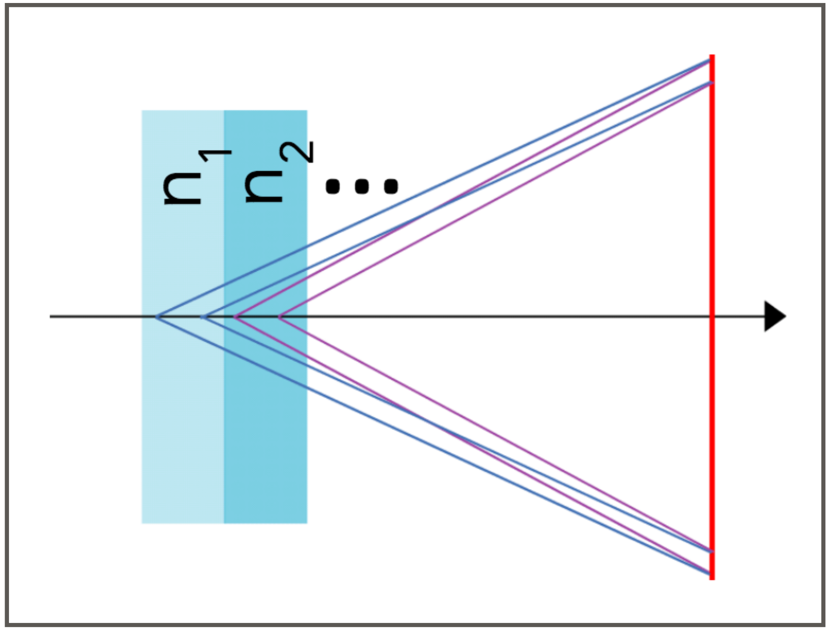


LHCb RICH 2 C_4F_{10}/CF_4
up to p ≃ 100 GeV, σΘ ≃ 0.2 mrad





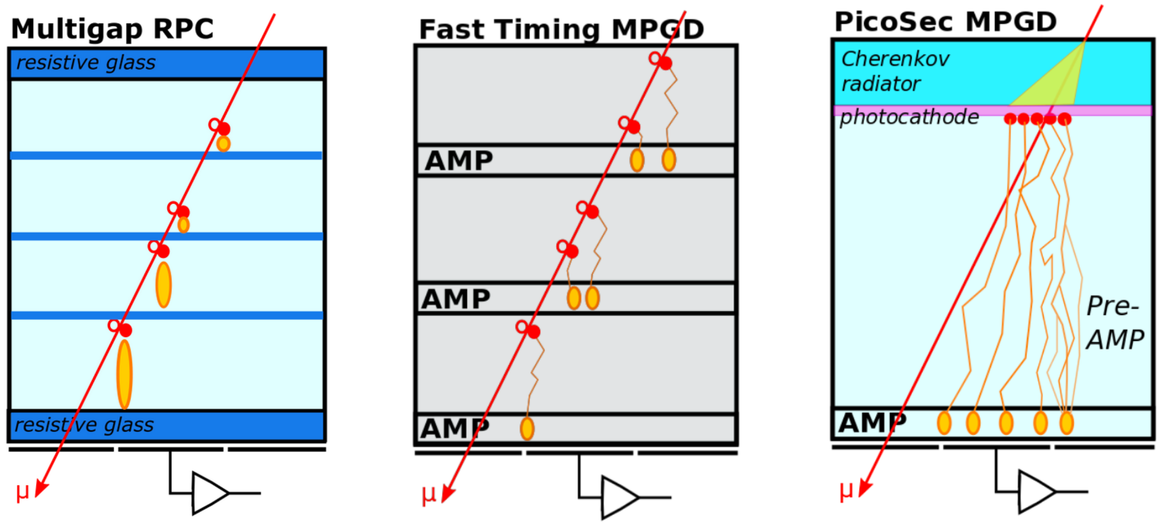
ALICE-3 RICH
multiple refractive index
down to p ≃ 10 MeV/c
Double or multiple aerogel

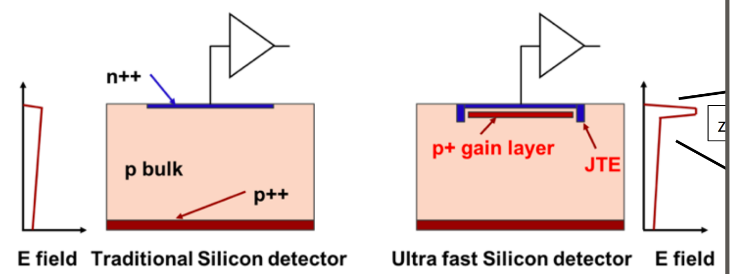


PARTICLE IDENTIFICATION

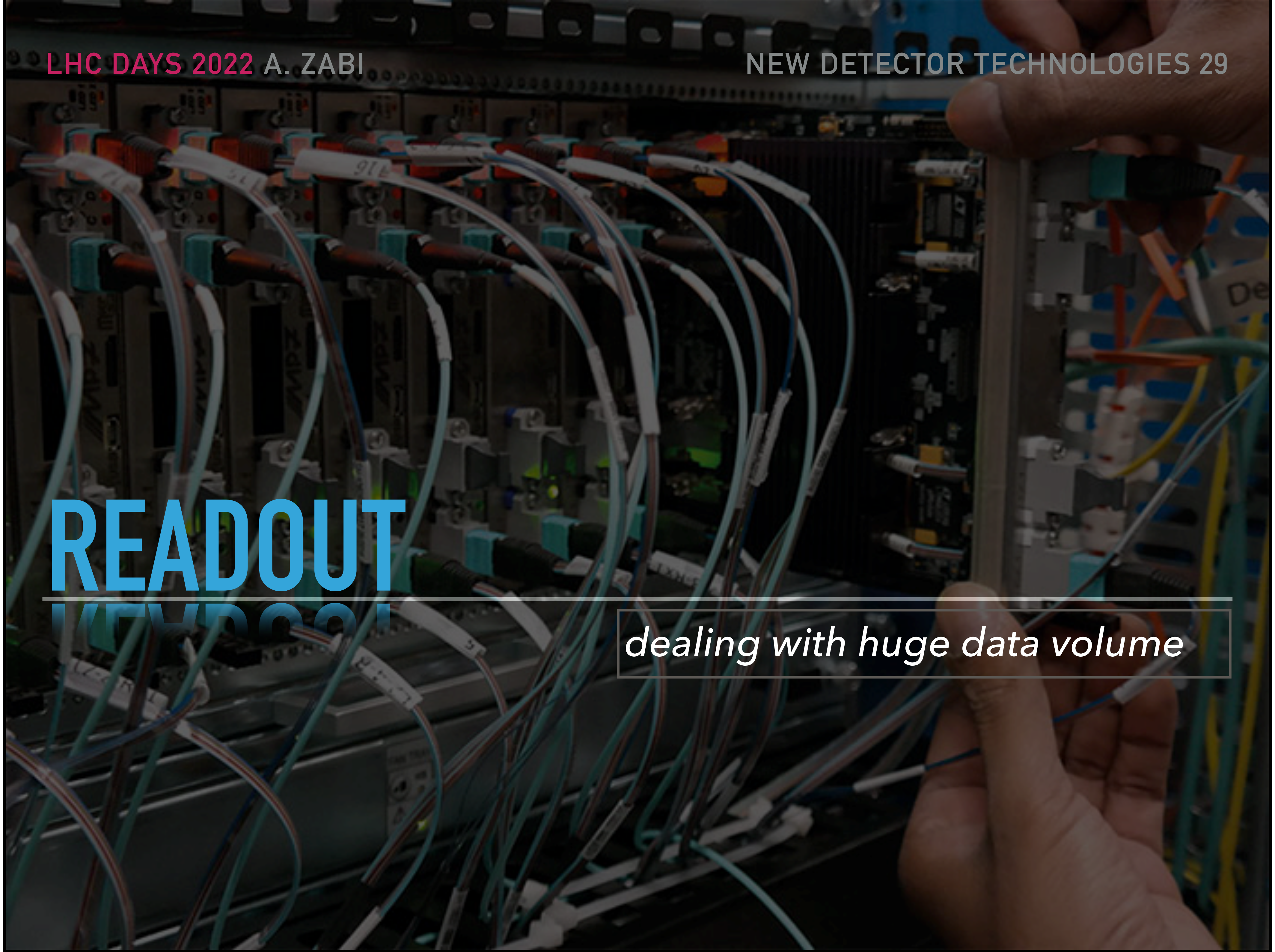
- Time-Of-Flight Ultrafast timing with gas detectors
- Ultrafast timing layers
  - Multigap RPCs, 24 x 160 μm gaps for $\sigma_t \simeq$ 10-20 ps in O(5) mm
- Fast Timing MPGD
  - Multiple thin amplification gaps
- Micromegas with Cherenkov radiator and photocathode (~24 ps)
  - New materials for photocathode, ex Diamond Like Carbon coating for rad. tol.

Intrinsic multilayer concept





- Time-Of-Flight SSD
- LGADs or hybrid Si 3D (30 ps timing) covering blind dE/dX region @ a few GeV

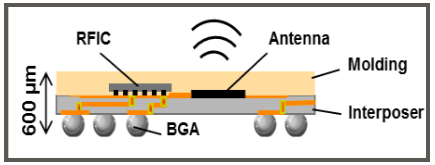


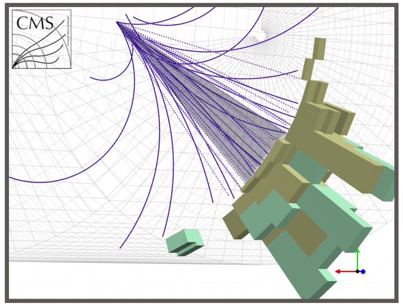
READOUT

dealing with huge data volume

DATA ACQUISITION & TRIGGER

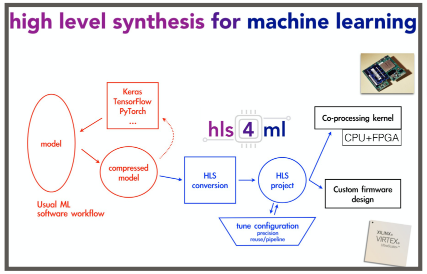
- Readout challenge @ every level (FCC-hh ~ O(3)PB/s)
- **Front-End ASICS (25nm nodes, data reduction)**
- **Back-End (off-detector electronics)**
  - Data transfert high-speed optical links & commercial network
  - Trigger with generic processing engine (porting AI into FPGA, progress at LHC & for HL-LHC) 10μs latency @L1 & 100ms @ HLT w/ 500kHz output
- **Event building & data selection:** custom FPGA boards, GPU & CPU. HCb demonstrated GPUs data selection at 5TB/s, ALICE performs full reconstruction on-line with GPUs, CMS achieved 25% off-loaded of selection to GPUs

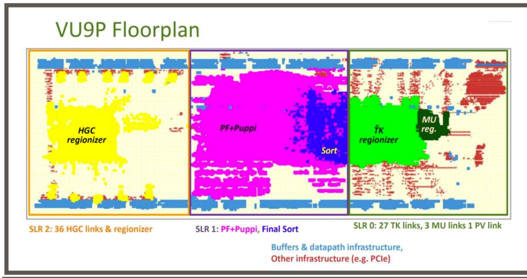




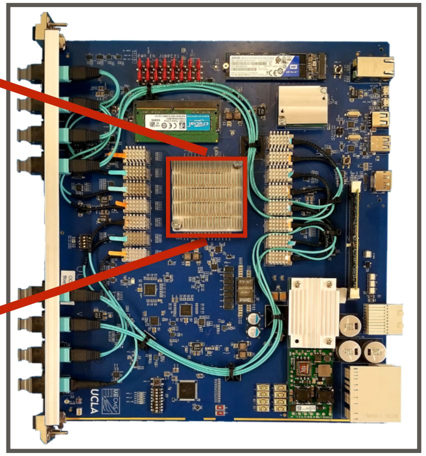
Particle Flow reconstruction
Pile-Up Per Particle Identification

Implementation of the algorithm in VHDL





Implementation of the algorithm in firmware and placement in hardware



Triggering on the unknown with advanced machine learning techniques (including anomaly detection)
Introducing Trigger-Less approaches, 40 MHz Scouting techniques to scrutinise the data further.

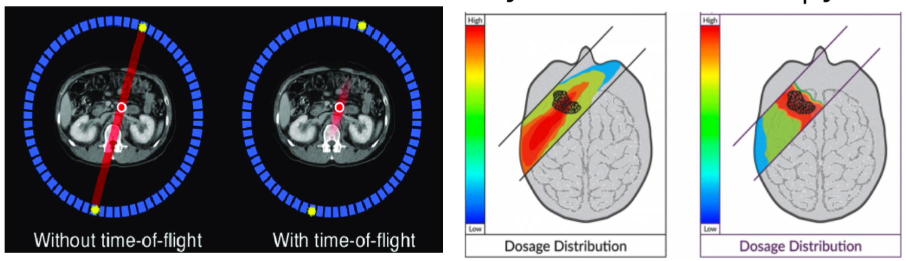
SUMMARY

FUTURE OF DETECTORS AND BEYOND

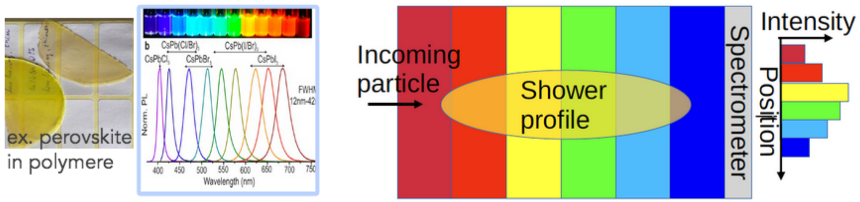
BEYOND HEP

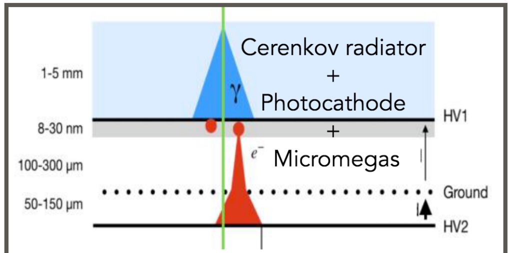
- Many of this work is conducted within collaborations beyond HEP
- **Solid State Devices (SSD)** for time precision w/ ~10ps target requires new designs and electronics (reconcile small pixel pitch & low power)
- **CMOS imaging technology** → lower nodes and 3D integration of electronics functions brings ultimate hit & time precision, at low power & high rad tolerance
- **Cross-application**: introducing nano material for calorimetry

Strong interest in health care for Time of Flight PET and dose distribution in X-ray and hadron therapy



ex. Quantum dots allow tuning of wavelength, opening new idea for // segmentation

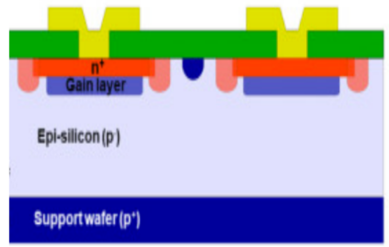


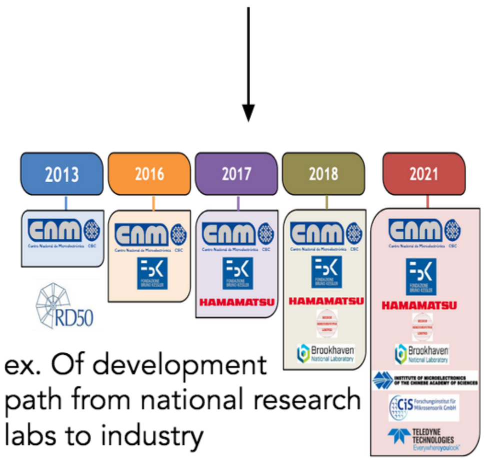


Picosec: 24 ps precision

Gas detector approaching SSD performance
→ *Versatile, easy system to use and scale, etc. Many applications*

Low Gain Avalanche Diode
O(30) ps today





ex. Of development path from national research labs to industry

SUMMARY

- Future physics program is a unique opportunity to unveil the mysteries of the universe. **Many innovative ongoing developments within CERN scientific collaborations and beyond. Physics detector specifications are pushing the limits with the introduction of precise timing and position combined with advanced reconstruction techniques.**

- Greater challenges ahead: **Exciting times of detector designs and instrumentation inspiring for younger collaborators and projects. Required instrumentation and data treatment are multi-disciplinary, well in line with society needs.**

- ***Design of these detectors represent unprecedented opportunities to push the technologies for the benefit of fundamental science.***