ECFA Detector R&D Roadmap Summary - TF6 Symposium

TF6 Task Force

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Disclaimer: No conclusions or recommendations today, Drafting of roadmap ongoing

FCC France Conveners Meeting
June 2021

ECFA Detector R&D Roadmap - Mission

ECFA
European Committee for Future Accelerators

Detector R&D Roadmap

European Particle Physics Strategy Update

"Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields."

"The roadmap should identify and describe a diversified detector R&D portfolio that has the largest potential to enhance the performance of the particle physics programme in the near and long term."

"Detector R&D activities require specialised infrastructures, tools and access to test facilities."

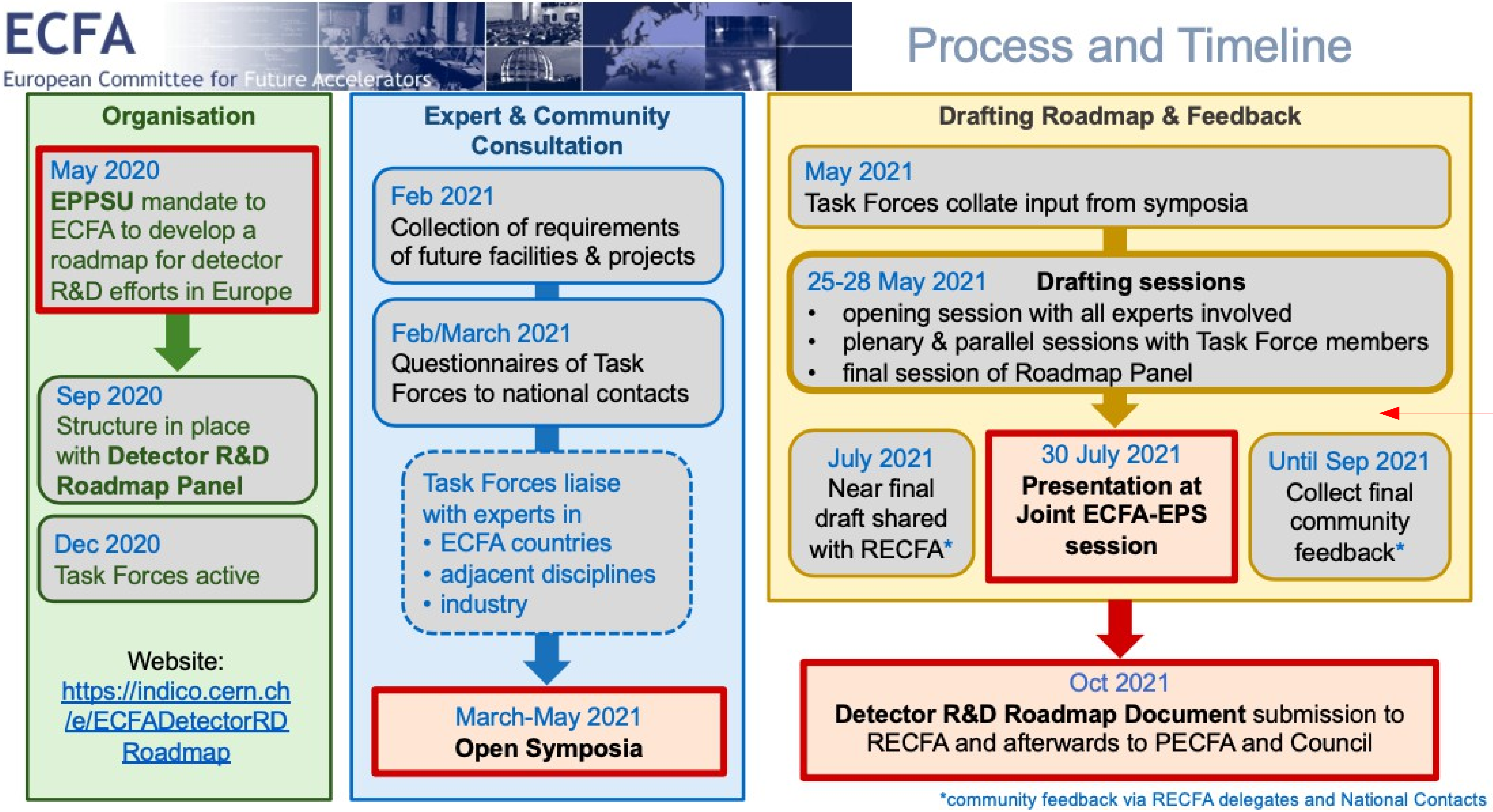
"The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels."

Extracted from the documents of 2020 EPPSU, https://europeanstrategyupdate.web.cern.ch/

For previous presentations on the Detector R&D Roadmap see Plenary ECFA: Jorgen D'Hondt (13/7/20) & Susanne Kuehn (20/11/20) (https://indico.cern.ch/event/933318/ & https://indico.cern.ch/event/966397/)

More roadmap process details at: https://indico.cern.ch/e/ECFADetectorRDRoadmap

ECFA Detector R&D Roadmap - Timeline



We are here

TF6 Symposium

- TF6 Symposium 7/5/21

https://indico.cern.ch/event/999820/

08:59 → 09:00 **Answers to TF6 Questionnaire** 1m
Answers-DidierCon... | Answers-Gerald-Eig... | ECFA TF6 Question... | Questions of TF6 C... | TF6_UK_responses...

09:00 → 09:25 **Introduction** 25m
Speakers: Philip Patrick Allport (University of Birmingham (UK)), TF6 Taskforce
talk070521-final.pdf

09:30 → 09:55 **Lessons learned: calorimeter upgrade R&D for HL-LHC & by Calice** 25m
Screenshot
Speaker: David Barney (CERN)
ECFA_TF6_Lesson... | ECFA_TF6_Lesson...

10:10 → 10:30 **Precision timing and their applications in calorimetry** 20m
Speaker: Nural Akchurin (Texas Tech University (US))
ECFA_PrecisionTim... | ECFA_PrecisionTim...

10:45 → 11:00 **Coffee break** 15m

11:00 → 11:20 **Si based highly and ultra-highly granular calorimeters** 20m
Speaker: Vincent Boudry (LLR – CNRS, École polytechnique, Institut Polytechnique de Paris)
ECFA_TF6_SiHGCal... | ECFA_TF6_SiHGCal... | ECFA_TF6_SiHGCal...

11:35 → 11:55 **Future Noble Liquid Systems** 20m
Speaker: Brieuc Francois (CERN)
ECFA_TF6_NobleLi...

12:10 → 12:25 **Gaseous calorimeters** 15m
Speaker: Maria Fouz Iglesias (Centro de Investigaciones Energéti cas Medioambientales y Tecno)
ECFATF6_Gaseous...

13:55 → 14:15 **Tile and strip calorimeters** 20m
Speaker: Katja Kruger (Deutsches Elektronen-Synchrotron (DE))
TF6_Tiles_strips_v...

14:30 → 14:50 **Crystal calorimetry** 20m
Screenshot
Speaker: Marco Toliman Lucchini (Princeton University (US))
2021_05_07_ECFA_...

15:05 → 15:25 **R&D for Dual-Readout fibre-sampling calorimetry** 20m
Speakers: Gabriella Gaudio (INFN-Pavia), Gabriella Gaudio (Dipartimento di Fisica Nucleare e Teorica)
20210407_DualRea...

15:40 → 15:55 **Coffee break** 15m

15:55 → 16:15 **Compact and high performant readout systems** 20m
Speaker: André David (CERN)
20210507 ECFA TF...

16:30 → 18:00 **Wrap up and discussion** 1h 30m
Speaker: TF6 Taskforce
tf6-symposium-dis... | tf6-symposium-dis...

- Nine task forces on different topics to prepare formulation of roadmap with community

- One task force on calorimetry

- Central events were symposia organised between March and May 2021

ECFA

Review Input Sessions – Overview Table

European Strategy Update

Project	~Earliest start of data taking	Current Calorimeter options					
		Solid state	Scintilling tiles/strips	Crystals	Fibre based r/o (including DR)	Gaseous	Liquid Noble Gas
HL-LHC (>LS4)	2030			✔	✔		
SuperKEKb (>2030)	2030			✔			
ILC	2035	✔	✔			✔	
CLIC	2040	✔	✔				
CEPC	2035	✔	✔	✔	✔	✔	✔
FCC-ee	2040	✔	✔	✔	✔	✔	✔
EiC	2030		✔	✔	✔		
FCC-hh (eh)	>2050	✔	✔				✔
Muon Collider	> 2050	✔	✔	✔	✔	✔	
Fixed target	"continous"		✔	✔	✔		✔
Neutrino Exp.	2030		✔				(✔)

In most of the cases final choices have still to be made

Paradigm change and R&D Topics

- Paradigm change
  - Calorimeters are moving from pure energy measurement to more differential measurements
  - Recording and combination of several type of signals
  - Tightened interplay with other sub-detectors in a detector system

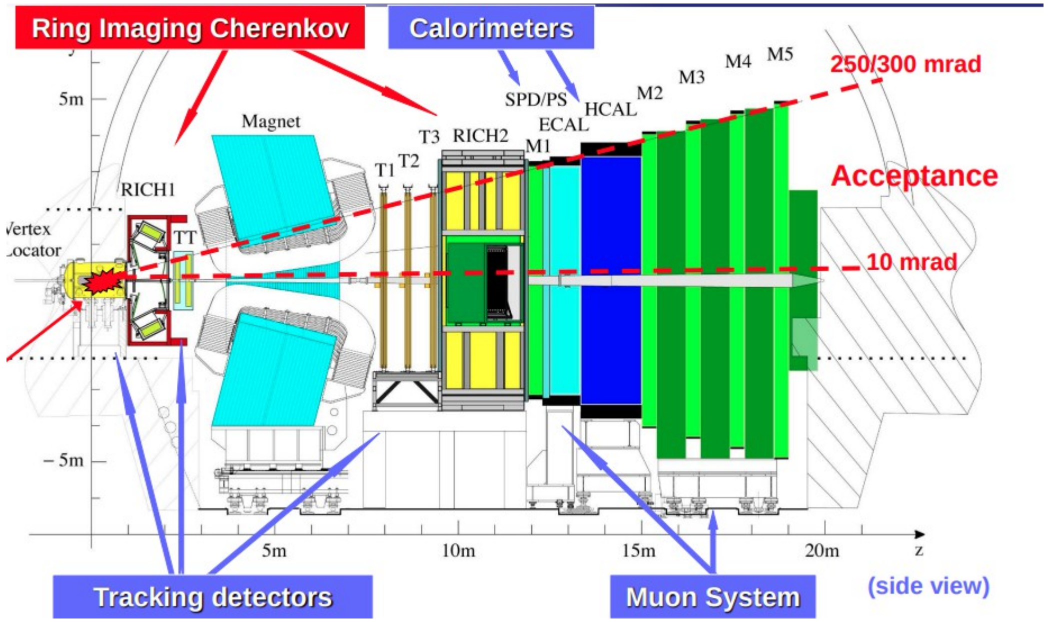
This leads to a broad set of R&D topics:

1. improve granularity
2. exploit timing
3. exploit tracking information (PFA)
4. exploit dual-readout (DR) compensation
5. develop fast, rad hard materials/solutions

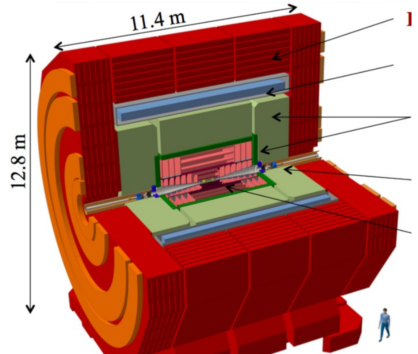
New paradigm: integral → differential (5D) detectors

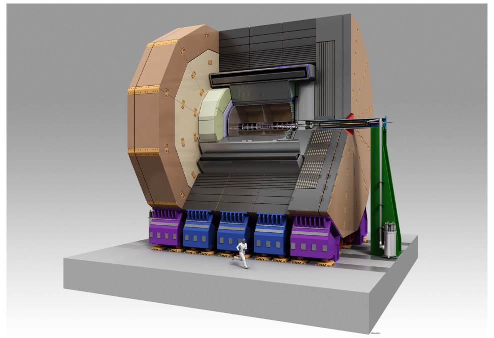
TF6 (Main) Target Projects

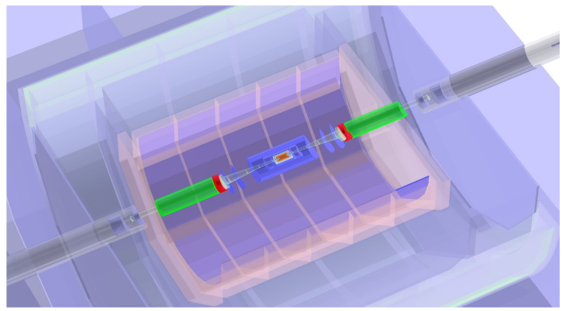
HL-LHC (mainly) after LS4

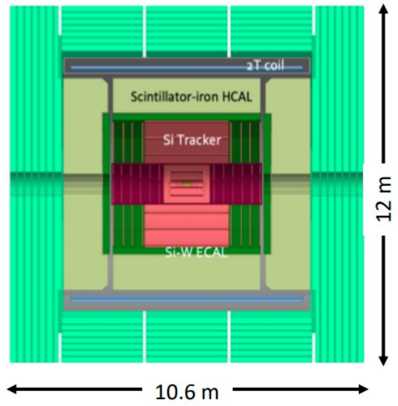


Higgs Factories

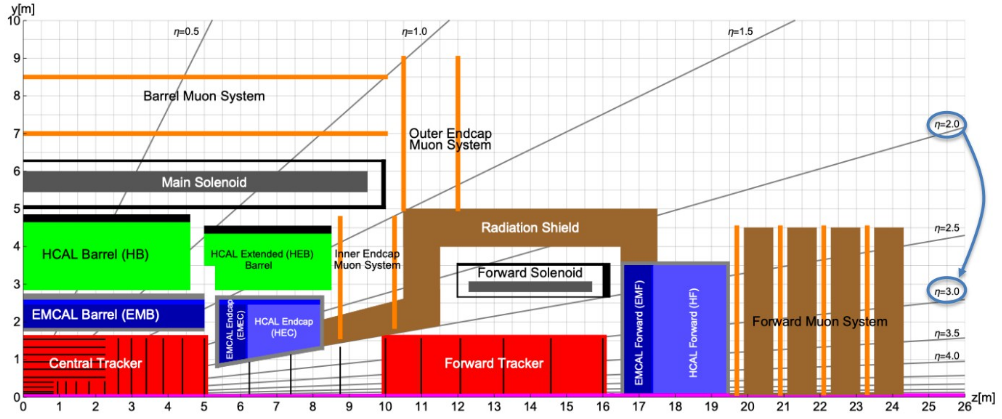




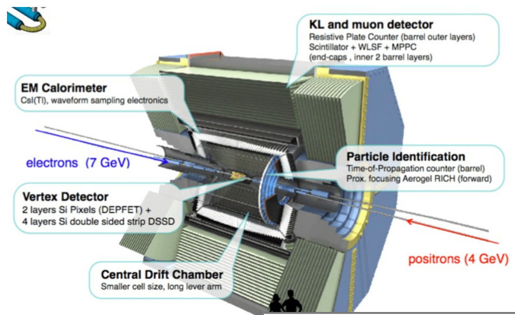


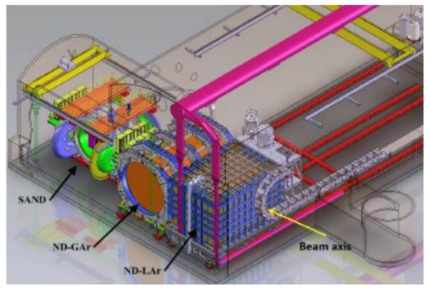


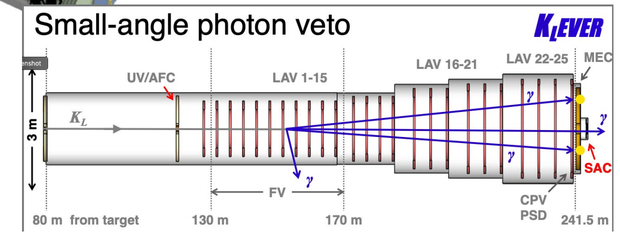
Future hadron colliders (including eh colliders)



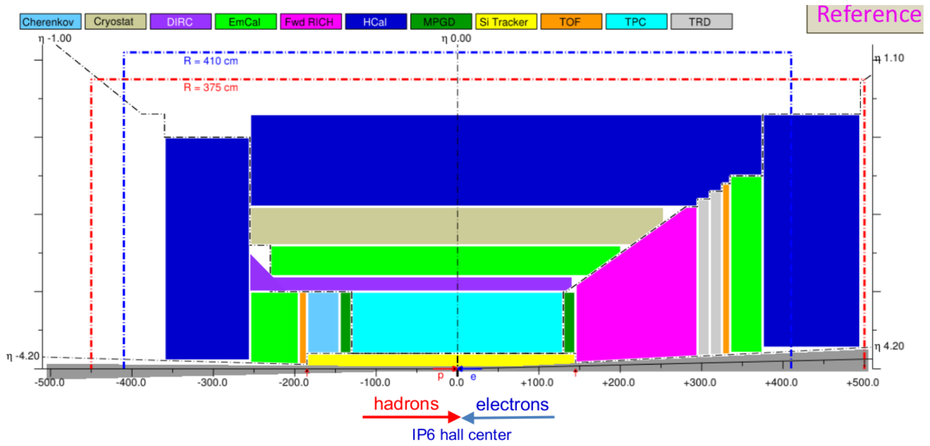
SuperKEKB, DUNE ND and Fixed Target



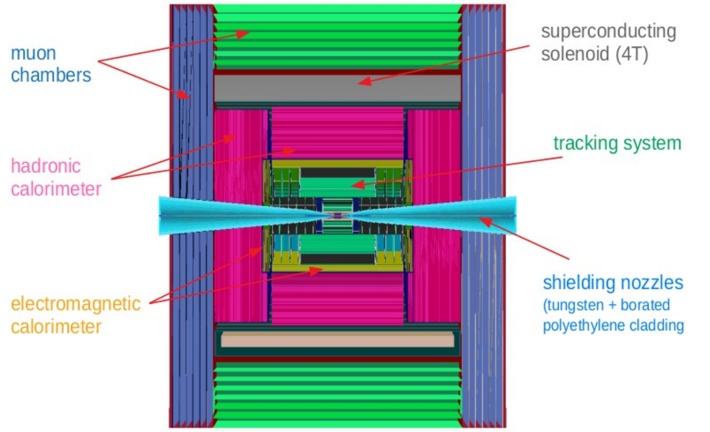




EiC



Muon Collider



Future projects – Some general considerations

- Detectors at future high energy e+e- colliders
  - Relative benign environment in terms of radiation (well, maybe less true for Muon Collider)
  - Physics program span between Z-pole and few TeV
    - At same machine in case of LC
  - Consequences for detector design?
  - This is particularly important for calorimeters since calorimeters require significant human resources and material during construction and during maintenance

- Detectors at future hadron colliders
  - No strong change in centre-of-mass energy within one project
  - However,
    - Harsh radiation environments from the beginning
    - ... amplified by potential luminosity upgrades
  - Requires calorimeters that can stand severe conditions w/o degradation (or upgrades are priced in from the beginning)
  - Again calorimeters are huge and require sustained long term support

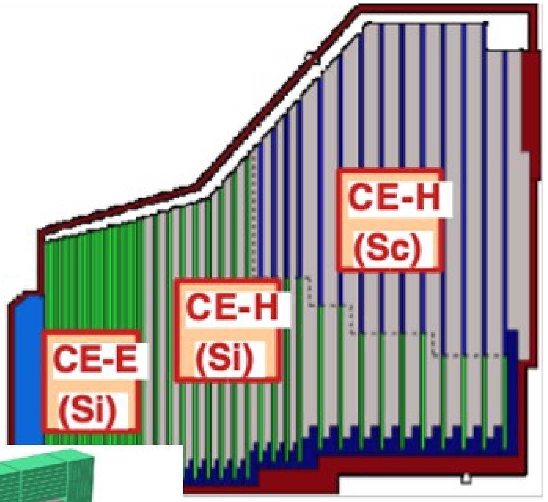
- Most other projects have constraints that are subsets of the above but in different combinations and on different time scales

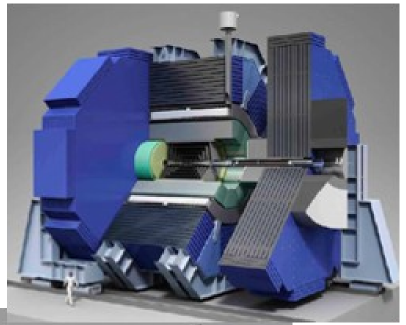
Si Based Calorimeters in Current and Future Experiments

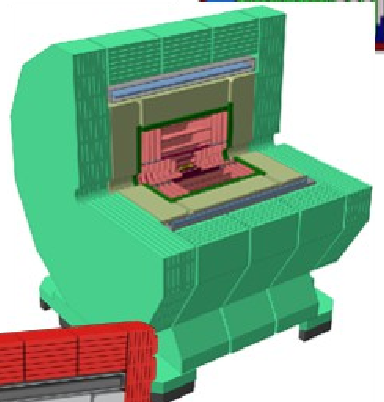
- Grouped into two categories:

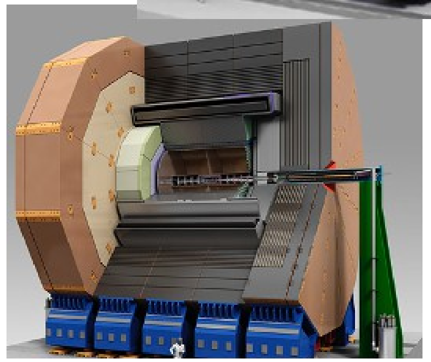
Main calorimeters of collider experiments
(barrel and / or endcap)

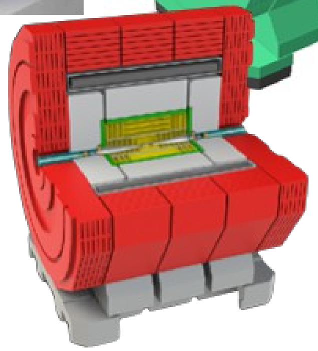
CMS HGCAL
(ECAL, part of HCAL)







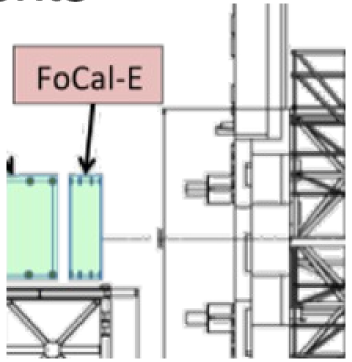


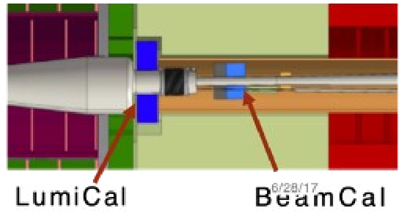


ECALs of Higgs Factory detectors
(linear and circular colliders);
Muon colliders

Smaller, specialized calorimeter systems
in collider and non-collider experiments

Very forward calorimeters: ALICE





Luminosity
measurement at e^+e^-

Non-collider experiments: LUXE, Satellites, …

Main arguments for adopting silicon:
- Finely segmentable: High granularity
- Robust and stable performance
- Compact design, high density
  - typically combined with W absorbers for maximum compactness, small ρ_M

Main challenge: Cost

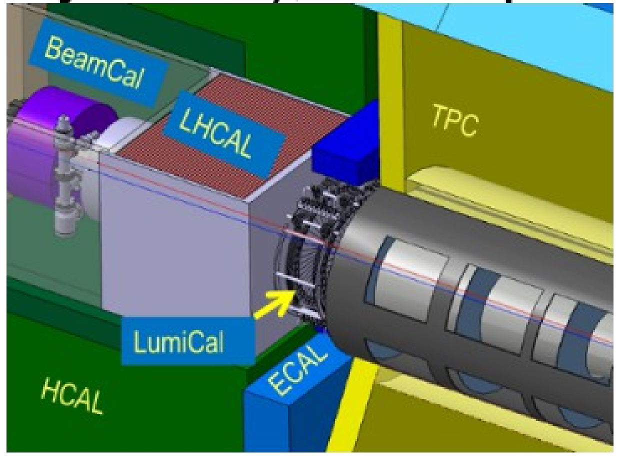
Symposium talk: V. Boudry

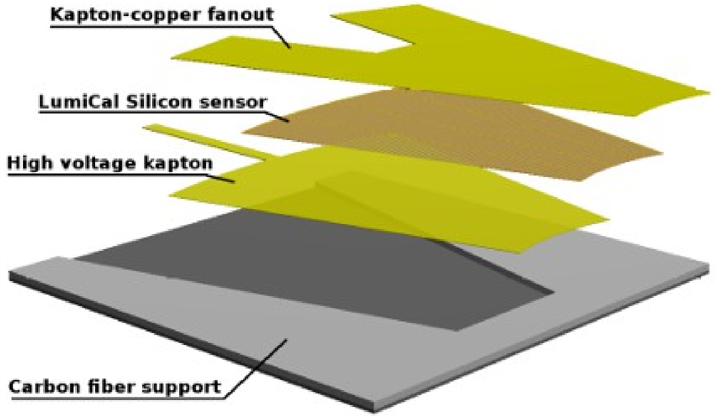
Key Challenges for Main Calorimeters

- *Design*:
  - Embedded electronics: low noise (small cells, large dynamics: ½ –3000 mips)
  - Connectivity to PCBs for compact detectors, edge effects in particular in endcaps
  - System aspects crucial: Integrated approach needed for mechanics, electronics, cooling & services
  - Figure of merit for detector optimisation needs to be re-thought - Complex system performance question, not just energy resolution
- *Construction*:
  - Scalable designs crucial - increased industrialisation required in future, likely going beyond individual components and extending to larger units
  - Automatisation in assembly, book-keeping / documentation of data / parameters
- *Operation*:
  - Calibration of highly granular calorimeters with ~10^8 (or more) channels - handling, and possibly compressing of large calibration databases
  - Redundancy in detector design, complex monitoring

Si based Calorimeters – Forward Calorimeters

- Very forward systems at lepton colliders for luminosity measurement (integrated, bunch-by-bunch), developed in **FCAL** collaboration

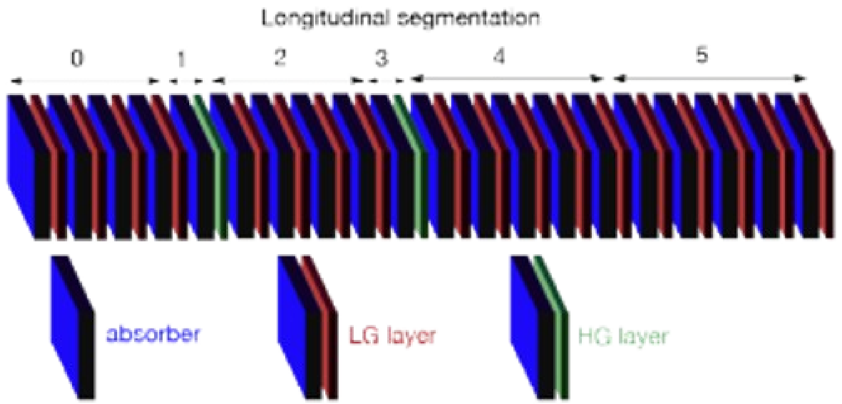




Key challenges

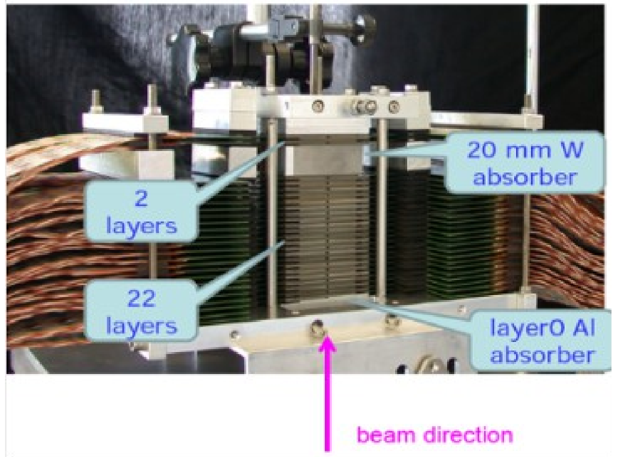
- Ultimate compactness: smallest possible ρ_M in high-density shower environment, constrained space
- Occupancy close to 100% in some regions
- Extreme mechanical precision to achieve required lumi precision: 50 μm at linear colliders, ~ 1 μm for Z-pole running at circular colliders

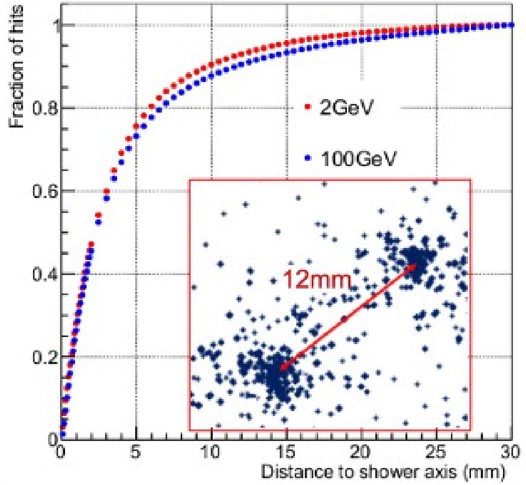
- A forward calorimeter for ALICE, to tag forward photons and π^0
- A combination of pad and extremely granular pixel layers



total:
14.5 m^2 Si pads
1.5 m^2 CMOS pixels

Full CMOS prototype of a digital ECAL





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Si based Calorimeters – Sensor R&D Challenges

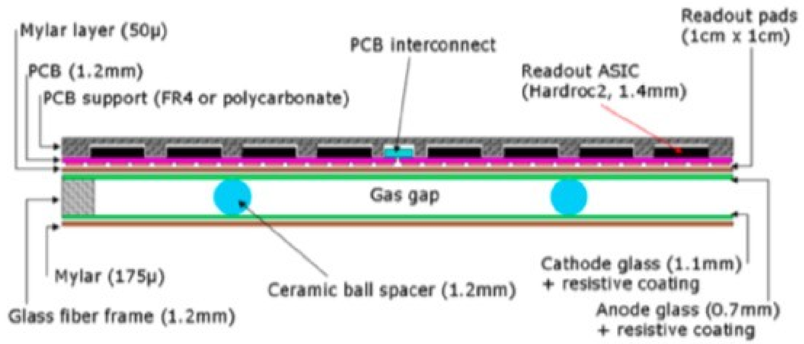
European Strategy Update

- *Reducing dead spaces*: Larger sensors to reduce impact of inter-wafer gaps - adoption of larger wafers can have unexpected pitfalls, close collaboration with producer(s) mandatory
- *Reducing dead spaces*: Guard rings as a complex issue - increases with sensor thickness, electrical properties require careful study to avoid noise issues
- *Increasing signal*: Thicker sensors provide improved em-resolution (higher sampling fraction), physical gain (LGADs et al.) boost S/N and thus timing
- *New technology:* Using CMOS MAPS for large area digital ECALs - with possible significant cost benefits
- *Improved intelligence*: Additional capabilities in CMOS sensors - power a key challenge. Fully digital approaches inspired by digital SiPMs - "SMAD" - Single MIP Avalanche Diode?
- *Reduced channel count*: Position-sensitive Si pad sensors for low-occupancy applications: lower power?
- *New materials*: GaAs and beyond - higher density, "right" band gap, processing, price, …
- *Radiation hardness*: For future hadron colliders no magic expected - need to develop suitable system designs that allow replacement of elements in most exposed regions without excessive mechanical complications

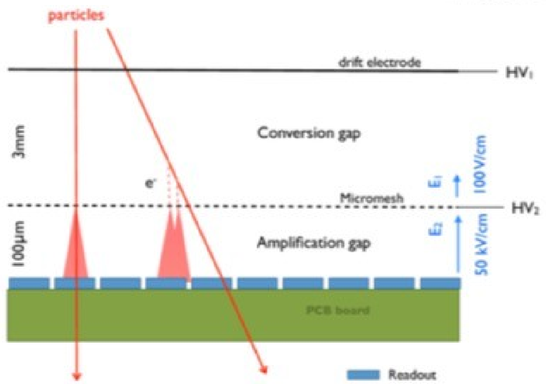
Calorimetry based on Gase Detectors

- **Resistive Plate Chambers (RPC) and Micro Pattern Gas Detectors (MPGD)** are good candidates as active medium for high granularity sampling calorimeters
  - RPC, Resistive Anode MPGD (SCREAM project), Micromegas, GEM
  - Digital (0, 1) or semi-digital read-out (0,1, few, many)
- **General properties** (depend on each detector type)
  - Robust and less expensive than others (as solid state detectors)
  - Coverage of large areas
  - Segmentation in different size pads, being capable achieve 50-100 microns space resolution (→ can easily be designed for required granularity)
  - Radiation hardness
  - High-Rate capability (→ mainly suited for e+e- colliders)
  - Good time resolution (5-10 ns, that in some cases can/could be decreased to the ps level)
- **R&D and Engineering Challenges**
  - Uniformity of the response (particular for application as calorimeter)
  - Gas homogeneity & time stability:
  - PCB and chamber size: The industrial manufacturing of PCB boards is limited to 60 cm wide (→ dead zones, connectors, inhomogeneities)
  - Planarity of PCB
  - Low sampling fraction → large sampling fluctuations

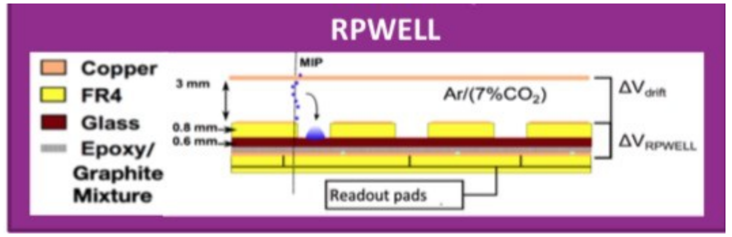
RPC



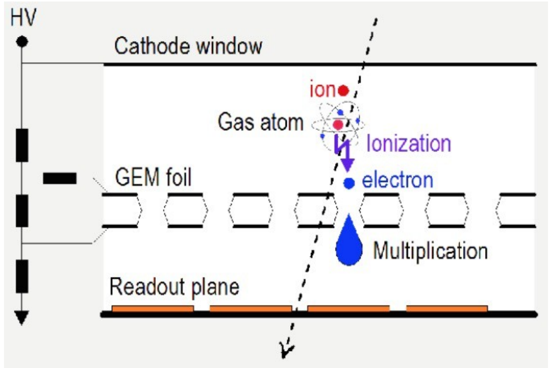
Micromegas



Resistive Anode MPGD (RPWELL)



GEM



Symposium talk: M.C. Fouz

Calorimetry based on Liquified Noble Gases

Noble Liquid calorimetry is a well proven technology

- Successfully operated/operating in SLD, D0, H1, NA48/62, ATLAS, ...

Key features

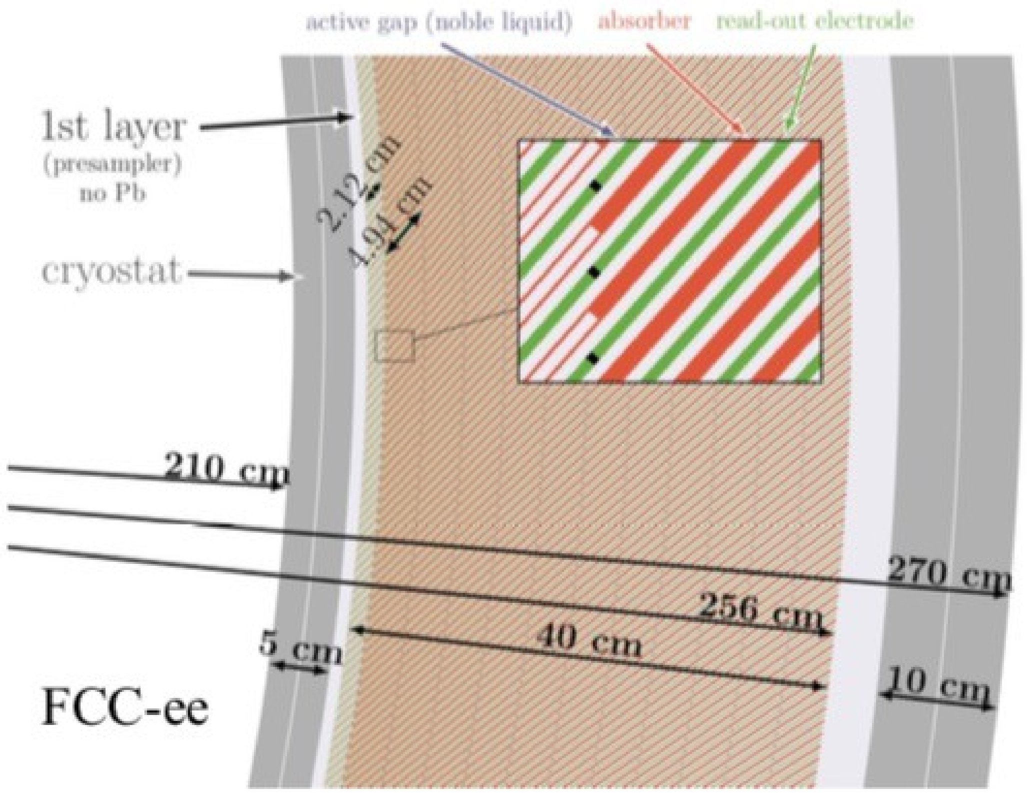
- Radiation hardness, long term stability
- Linear response, uniformity, high control over systematics
- Very good energy/timing resolution (10%/E1/2, 100 ps easily achievable)
- Electrodes can be easily adjusted to required granularity → cells sizes down to θ x ῶ x t of 5mm x 10mm x 20mm achievable

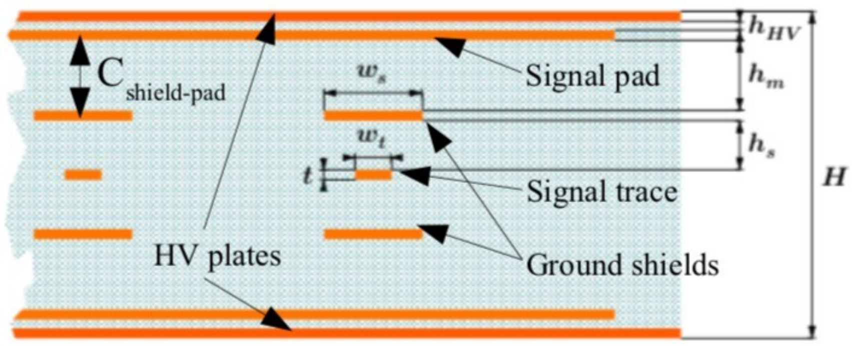
Very promising candidate to meet future experiment's requirements

- Proposed as the baseline for FCC-hh ECAL + Hadronic Endcap/Forward and LHeC ECAL (see backup)
- Adapted to an e+e- experiment (FCC-ee), leading to a very interesting option

R&D and engineering challenges:

- **Read-out electrodes with high granularity:**
  - *Higher granularity* can be achieved thanks to multilayer PCB read-out electrodes → traces can run beneath other cells, inside the PCB
  - Prevent cross talk with ground shields, ground shields increase the capacitance → impact on noise → needs careful optimisation and
- **Engineering:**
  - *Large cryostats, low material budget* → aluminum (ATLAS), Al honeycomb structures, carbon fibre
  - *Heavy calorimeters* (100s of tons) need to be *supported by cryostat*
- **Cryogenic feedthroughs:**
  - The *large granularity* of future calorimeters will require an *increased signal density* at the feedthroughs (FT) of up to 20-50 signals/cm2 which is a factor ~5-10 more than in ATLAS (ATLAS used gold pin carriers sealed in glass).
- **Large-size read-out electrodes** O(1m x 3m), might be realised in several smaller pieces
  - PCBs or copper/kapton/glue with resistors made of resistive ink (ATLAS)).
  - Optimisation of capacitance to ground (noise) while keeping cross-talk at a reasonable level O(1%).
- **Preamplification and optical transmission of signals:**
  - *Warm electronics:* no active elements inside the cryostat (upgradeability!), very small signals, long transmission lines → Noise!
  - *Cold electronics:* active elements inside the cryostat, potentially lower noise
    - Cryogenic feedthroughs for optical fibres – one fibre carries signal of many channels → advantage for cryogenic feedthroughs
    - Cold electronics heat dissipation inside the noble-liquid bath → needs to be taken into account for the cooling of the noble liquid



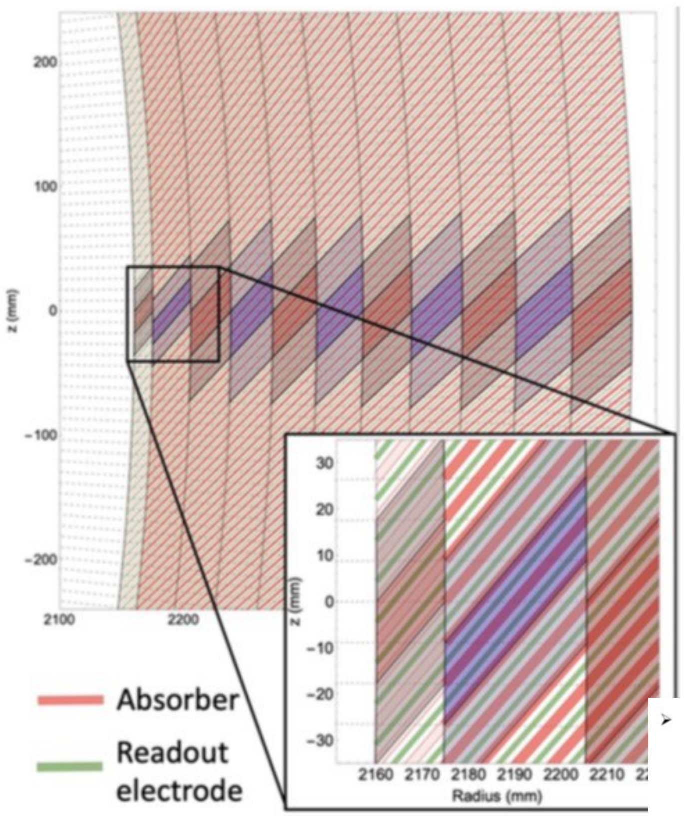


Cross section of read-out electrode

Symposium talk: B. Francois

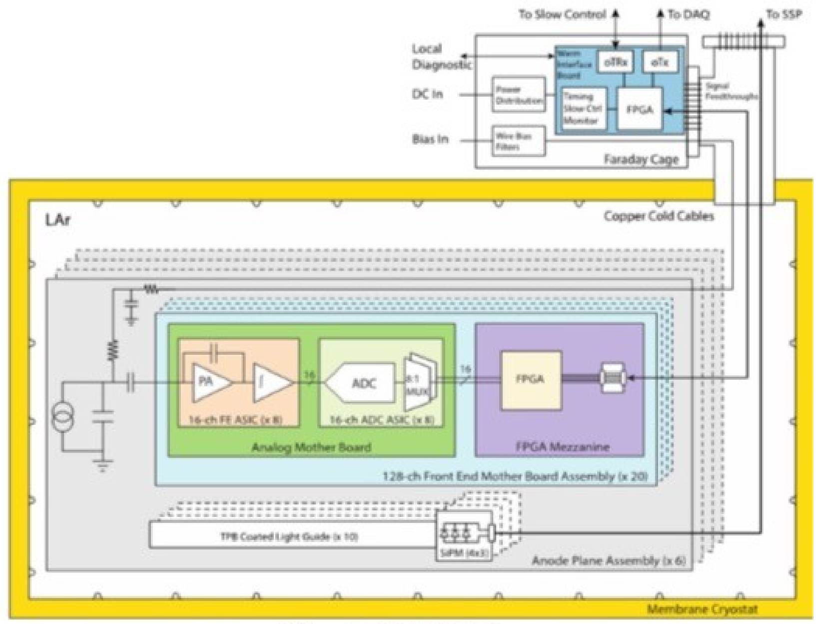
Example: Electromagnetic Calorimeter for FCCee

- **All the 'free' parameters of the detector have to be optimized**
  - Absorber material (considering Pb and W), Noble Liquid (LAr, LKr, LXe)
    - Energy resolution, radial compactness/Moliere radius, signal over noise, dead material, cost and availability
  - Absorber and sensitive gap thickness
    - Machining capability, energy resolution, compactness
    - Absorber with increasing thickness towards large radius
      - Reduce the radial thickness, approach a constant sampling fraction
      - More complex manufacturing → may introduce more non-uniformities
  - Plate inclination, layer depths, cell merging…
- **Complicated exercise** given the number of figure of merits, the number of free parameters and their interdependence
  - High dimensional manifold with many local minima's and forbidden regions



FCC-hh, see backup

Cold read-out electronics used in ProtoDUNE



ProtoDUNE

Warm or cold read-out electronics?

- **Advantages** of placing the front-end inside the cryostat (**cold electronics,** choice for Dune experiment)
  - **Lower noise:** electronics at lower temperature, PA directly connected to the sensor wire (no cable), longer shaping time envisaged
    - Can **easily achieve MIP S/N > 5 per cell**
  - **Eases** the **feedthrough design** (possibility to use optical fibers)
- **Drawbacks**/technical challenges
  - Very **difficult maintenance or upgrade** (cryostat opening) → robust electronics + redundancy
  - Minimize **heat dissipation** inside Noble Liquid (low power electronics)
    - Avoid bubbles (electrical breakdown, local change of sampling fraction)

ECFA

Optical readout calorimeters: Summary Table

European Strategy Update

<table>
<tr><th></th><th>Examples</th><th>2030</th><th>2035 - 2040</th><th>2045</th><th>2050</th></tr>
<tr><td>Crystals</td><td>· CMS ECAL
· ALICE PHOS
· L3 ECAL
· BELLE
· …</td><td>LHCb – ECAL
· 10%/√E
· Shower timing 10 ps (pileup rejection)</td><td rowspan="3">Detectors for ILC/CLIC, FCC-ee, CepC

Higgs boson, top factories: jet energy resolution <30%/√E
• Segmentation, multiple-information, shower ”imaging” (Cherenkov, scintillation, space, time, …)
  • Particle flow and/or dual-readout concepts
  • Time information within the shower

EM resolution for exclusive states (low energy) flavour physics
• High resolution front EM compartment (crystals)
• Possibly integrated in the dual-readout concepts with dual readout (Cherenkov and scintillation)</td><td rowspan="3">FCC-hh

Additional specs:
• Radiation tolerance
• Fast response
• Combat pileup (1000 evts/BX) with segmentation and timing</td><td rowspan="3">Muon collider

Additional specs:
· Combat beam induced background with segmentation and timing</td></tr>
<tr><td>Tiles or Strips</td><td>· ATLAS HCAL
· CMS HCAL
· …
· CMS HGC (HL-LHC)</td><td>DUNE Near Detector
· High granularity; large area; thin absorber;
• <10%/√E; π0 ID
• Moderate timing for neutron ID (sub-ns)</td></tr>
<tr><td>Dual Readout</td><td></td><td></td></tr>
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Input talks:

[1] *Tile and strip calorimeters*, **Katja Krüger (DESY)**

[2] *Crystal calorimetry*, **Marco T. Lucchini (Milano-Bicocca)**

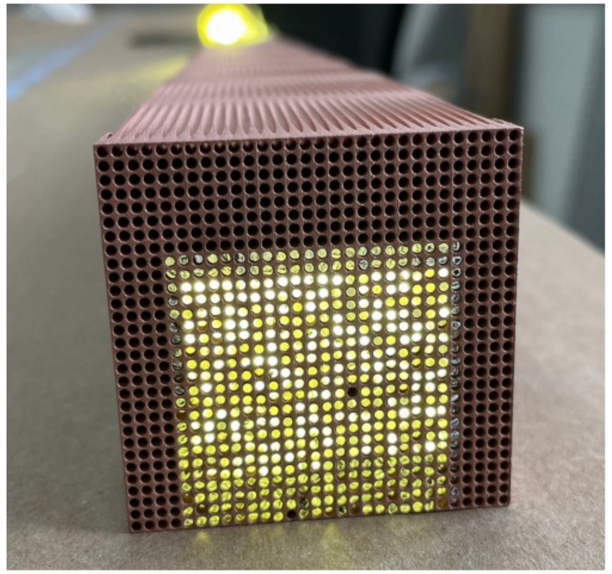
[3] *R&D for Dual Readout fibre-sampling calorimetry*, **Gabriella Gaudio (Pavia)**

Optical readout calorimeters: Common R&D Challenges

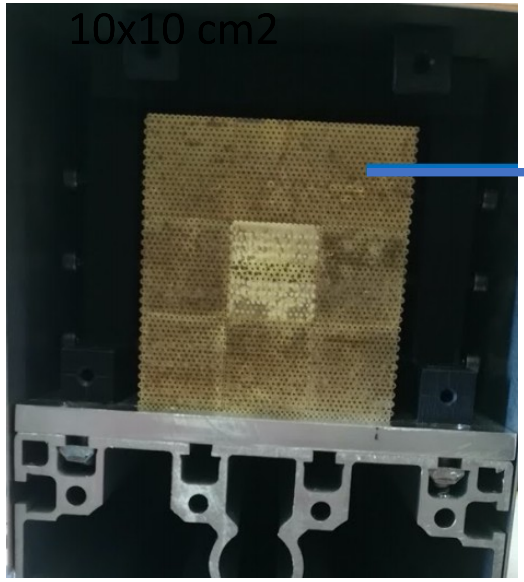
- Improved photodetectors: Spectral response matched to scintillation/Cherenkov emission (also for new media); field immunity (chiefly for vacuum devices); improved radiation tolerance (chiefly for FCC-hh); low power consumption (for integrated designs); digital SiPMs
- Integration: Thermal management (global or local cooling, options for in-situ annealing); complex integration (signal routing) for highly segmented calorimeters (chiefly crystals or tiles with longitudinal segmentation)
- 3D-printing: Explore 3D-printing of absorbers or even active materials
- Prototyping: Proof-of-principle with prototypes with full containment of hadron showers

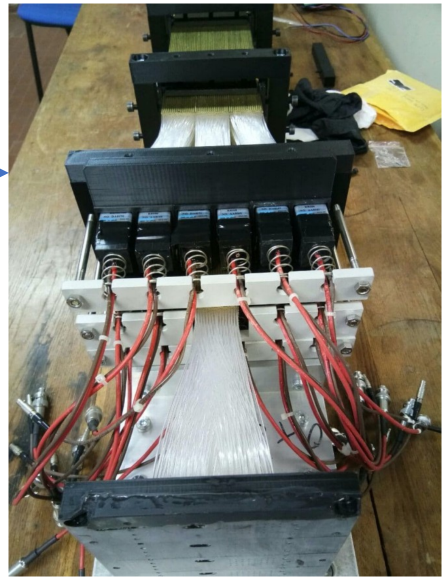
Magatile prototype integration

3D printing of crystals and absorber



Dual Readout EM size prototye

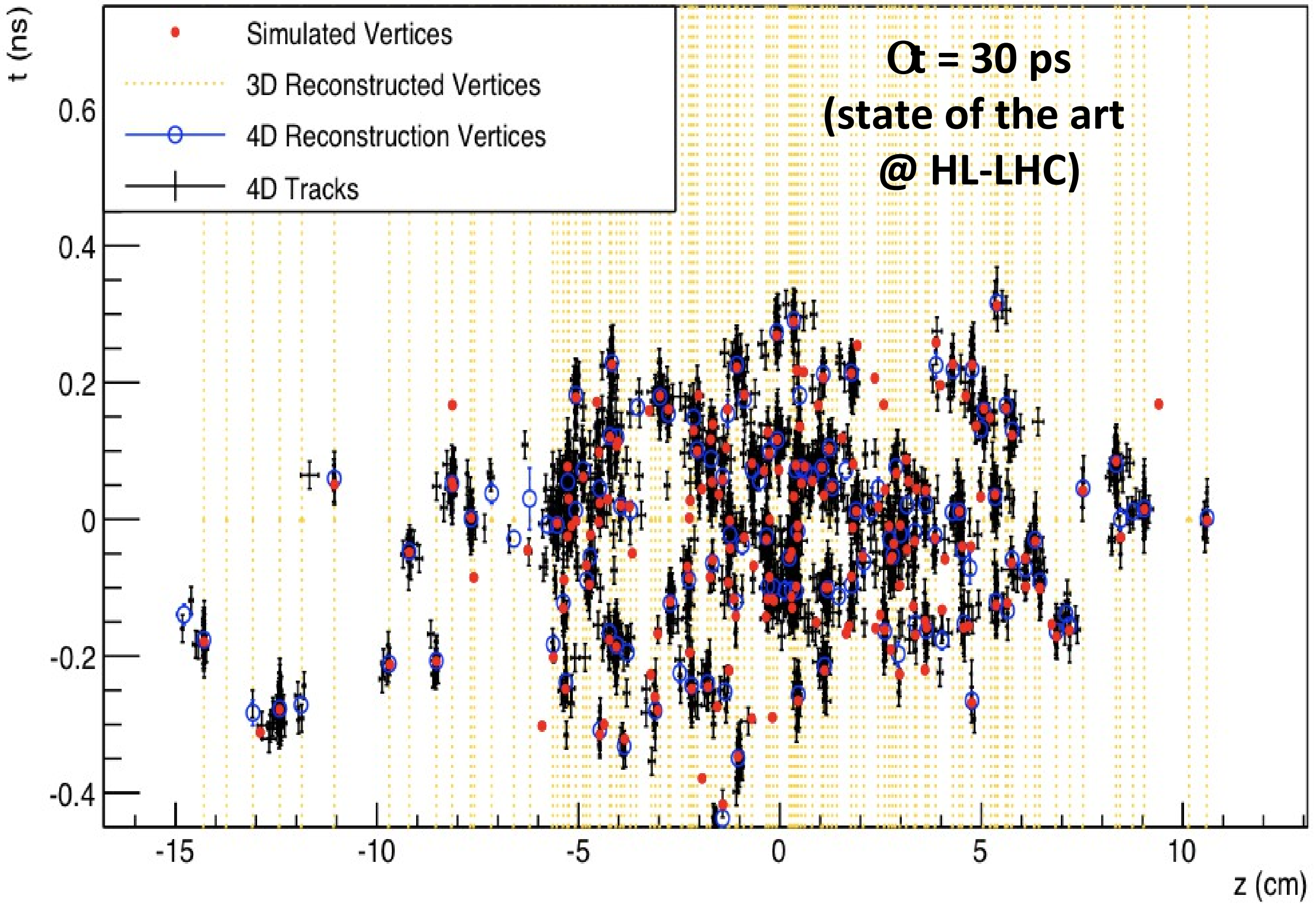


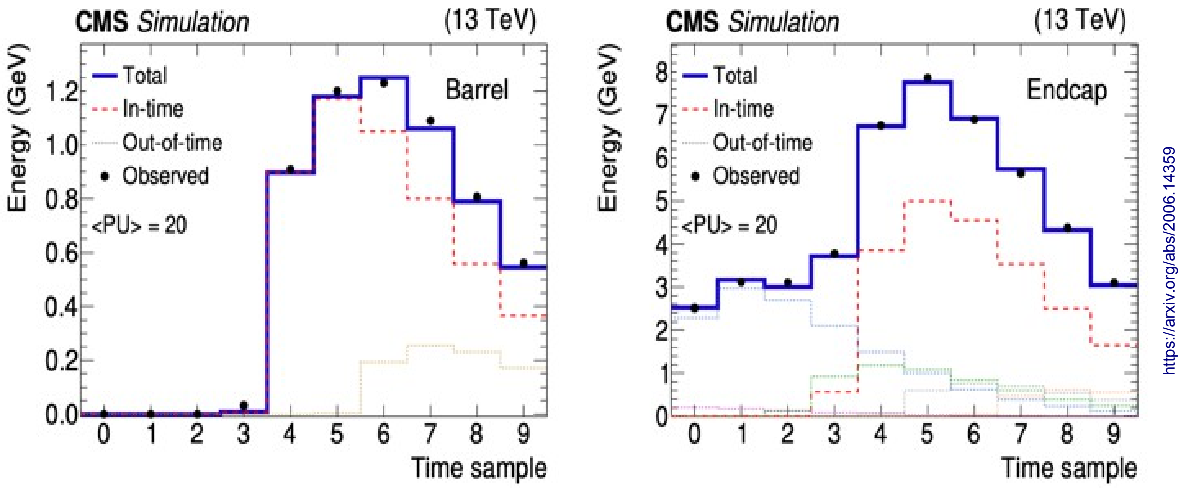


Optical readout calorimeters: Specific R&D Challenges

- Tiles and Strips:
  - Segmentation for cost-effective ultimate granularity (complex integration);
  - Radiation hardness of plastic scintillators (where needed) and new materials (*)
  - Timing with plastic scintillators (light output vs scintillation time balance, time spread from cell size, …)
  - Dual readout options for tiles
- Crystals:
  - New materials fast, bright, and cost-effective (low-cost materials vs sampling calorimeters)
  - Combined EM calorimetry with dual-readout concepts without spoiling hadron resolution (e/h ratio, etc.)
  - Crystal radiation hardness (where needed)
  - Embedded timing
- Dual readout fiber-sampling calorimeter:
  - Further understanding the C/S calibration and energy components
  - Exploring novel methods for absorber production (3D-printing) and new materials (crystals) for fibers
  - Integration aspects (full size detector never built)
  - Potential for integration with other approaches (particle flow, front EM compartment, timing from fibers)

"Passive" and "Active" Usage of Timing

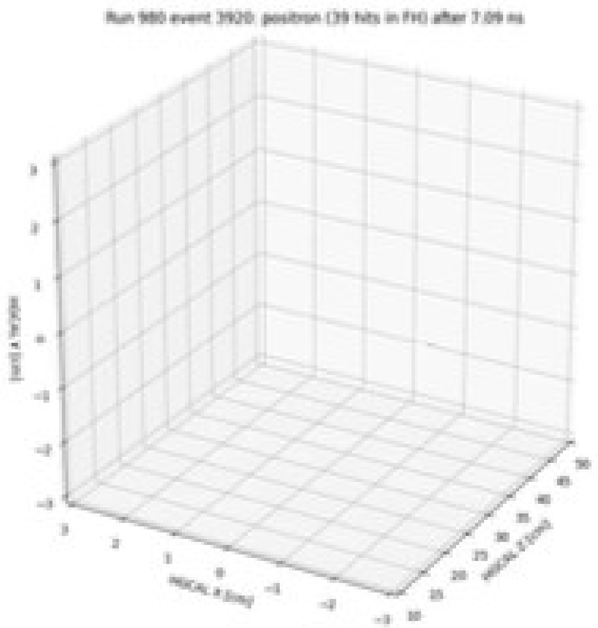




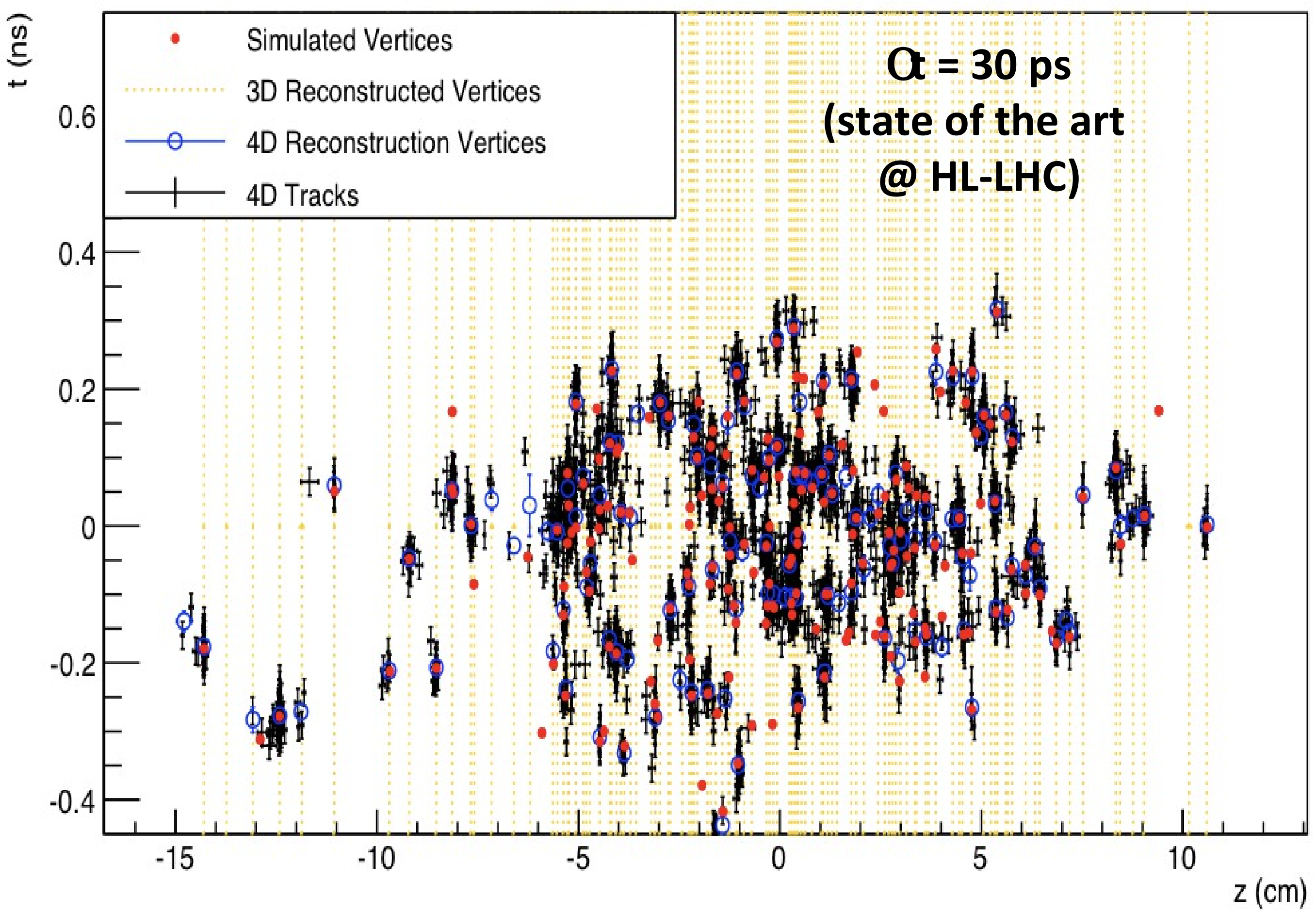
CMS ECAL uses template fits to in-time signal plus out-of-time signals to extract the best energy measurement

Red dots: 200 simulated vertices
Vertical yellow lines: 3D-reconstructed vertices (*i.e.* no timing info.) **Black crosses** and **blue open circles: 4D-reco inc. time information**

Many vertices that appear to be merged in the spatial dimension are clearly separated when time information (~30ps accuracy) is available



CMS HGCAL has measured **evolution of hadronic showers in the time domain** with ~80ps accuracy (50ps TDC binning)



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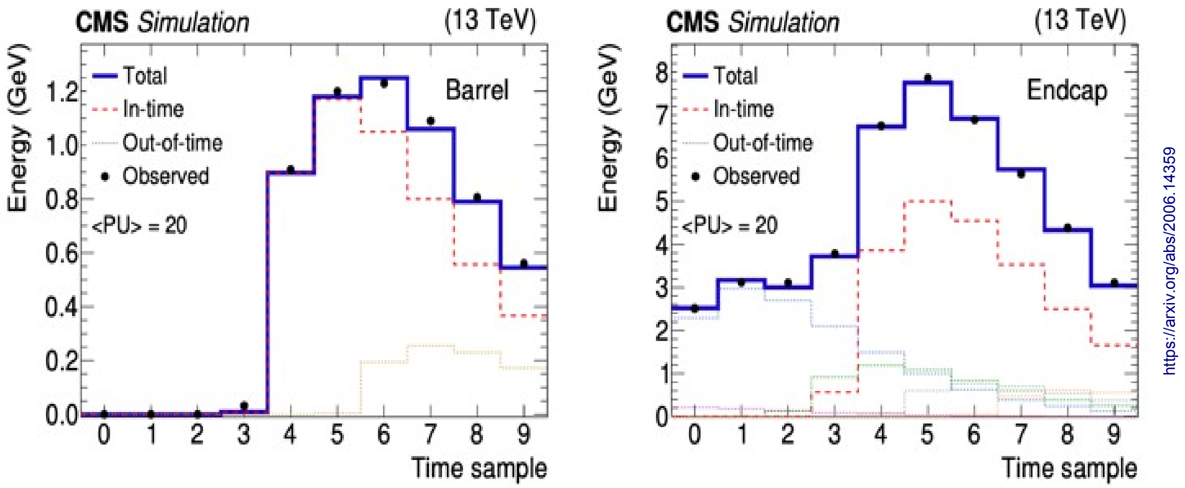

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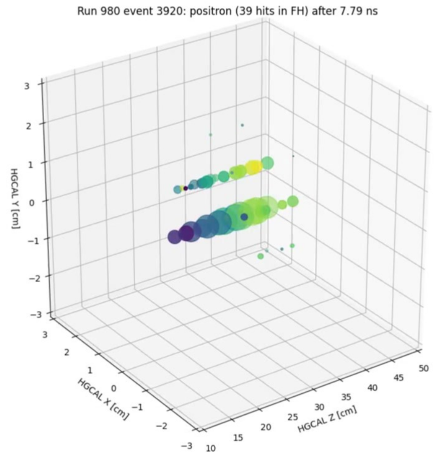
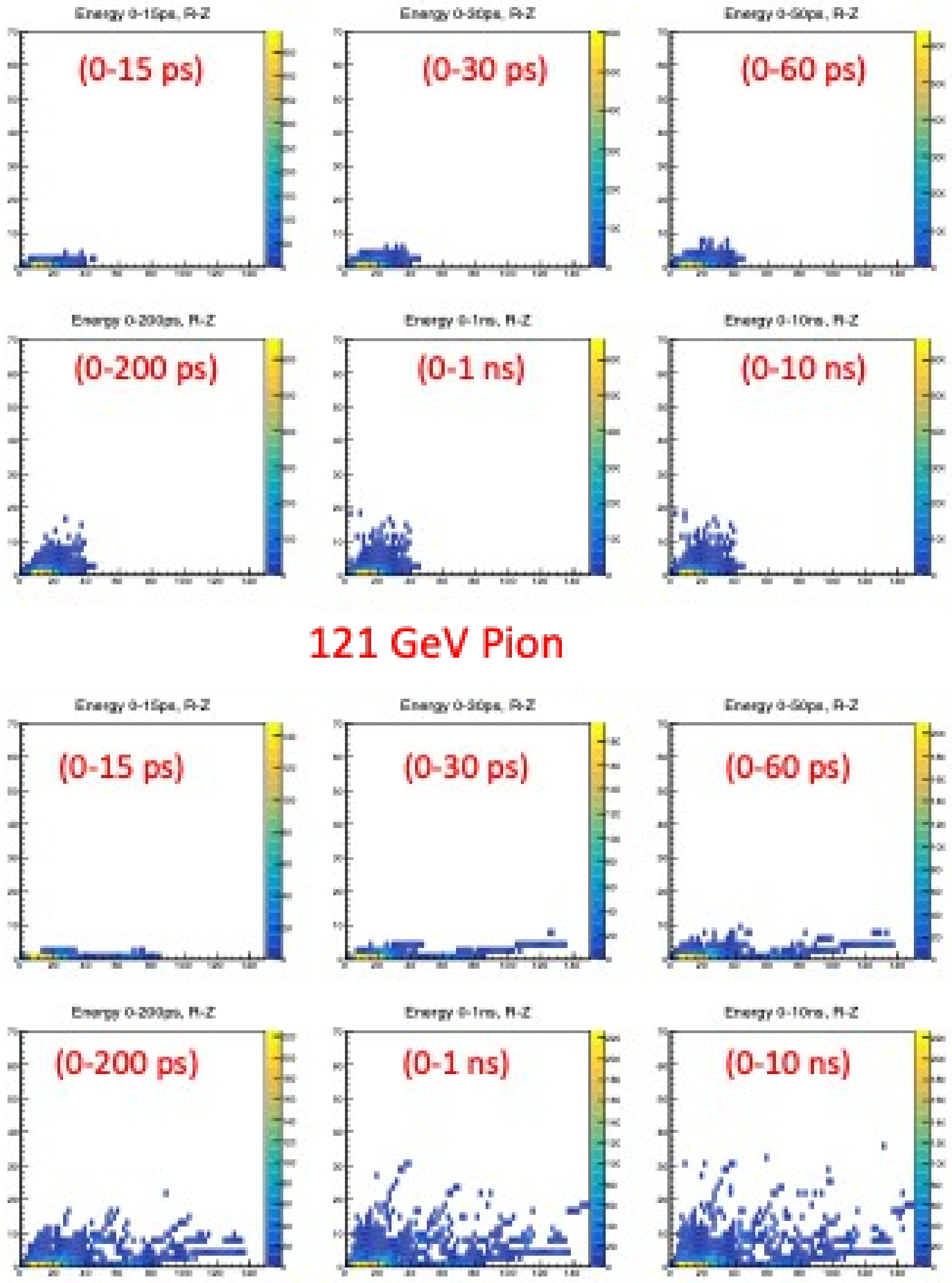
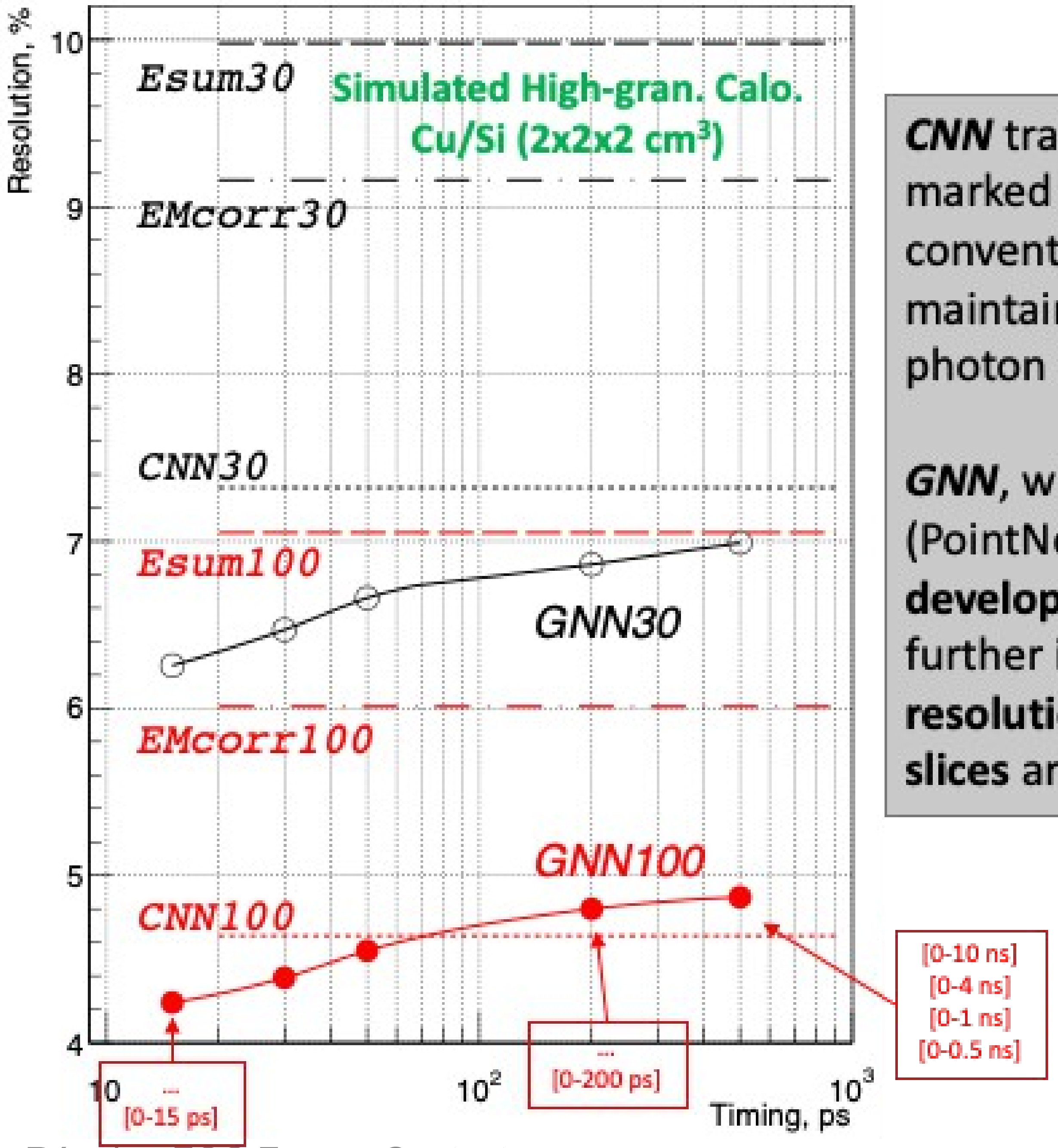


CMS HGCAL has measured **evolution of hadronic showers in the time domain** with ~80ps accuracy (50ps TDC binning)

Exploiting features in the time domain

Features that emerge in the time domain can help distinguish particle types and, with GNNs, enhance $\sigma(E)/E$

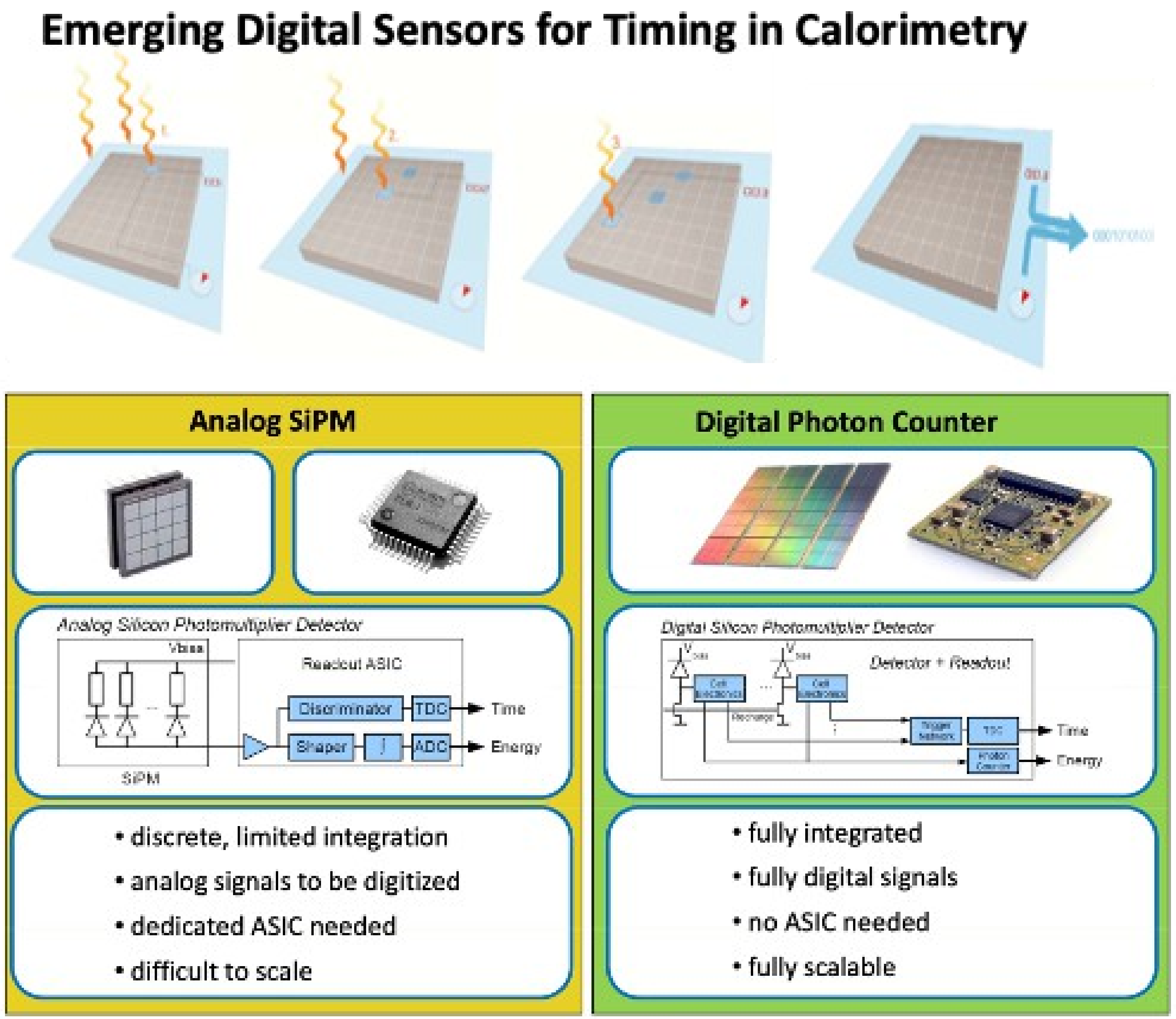




CNN trained on pions achieves marked improvement over the conventional approache while maintaining performance for photon reconstruction

GNN, with edge convolution (PointNet), **with shower development timing information** further **improves energy resolution** when **shorter time slices** are included

R&D Needs for Precision timing in calorimetry



Signal-producing materials
- Optimization of properties e.g. fast rise/fall times; suppression (through doping) of slower components
- Industrialization of cost-effective mass production

Electronics
- Low-power high-precision TDCs & PLLs in ASICs
- Highly-performant low-power on-detector digitizers

Light-detection devices
- Ultra-fast light detectors (e.g. SiPMs) inc. digital varieties

Detectors
- High-precision timing over very large areas
- Use of dedicated embedded timing layers e.g. shower-max timing with RADiCAL, or LGAD layers etc.

Software/firmware
- Use of RNN, GNN etc. for single-photon detection, pileup mitigation, energy measurements, particle ID

General
- Prototyping & beam tests – critical for progress & training
- Close partnerships with industry for materials, sensors, electronics etc.

Readout (processing) systems – Some general considerations

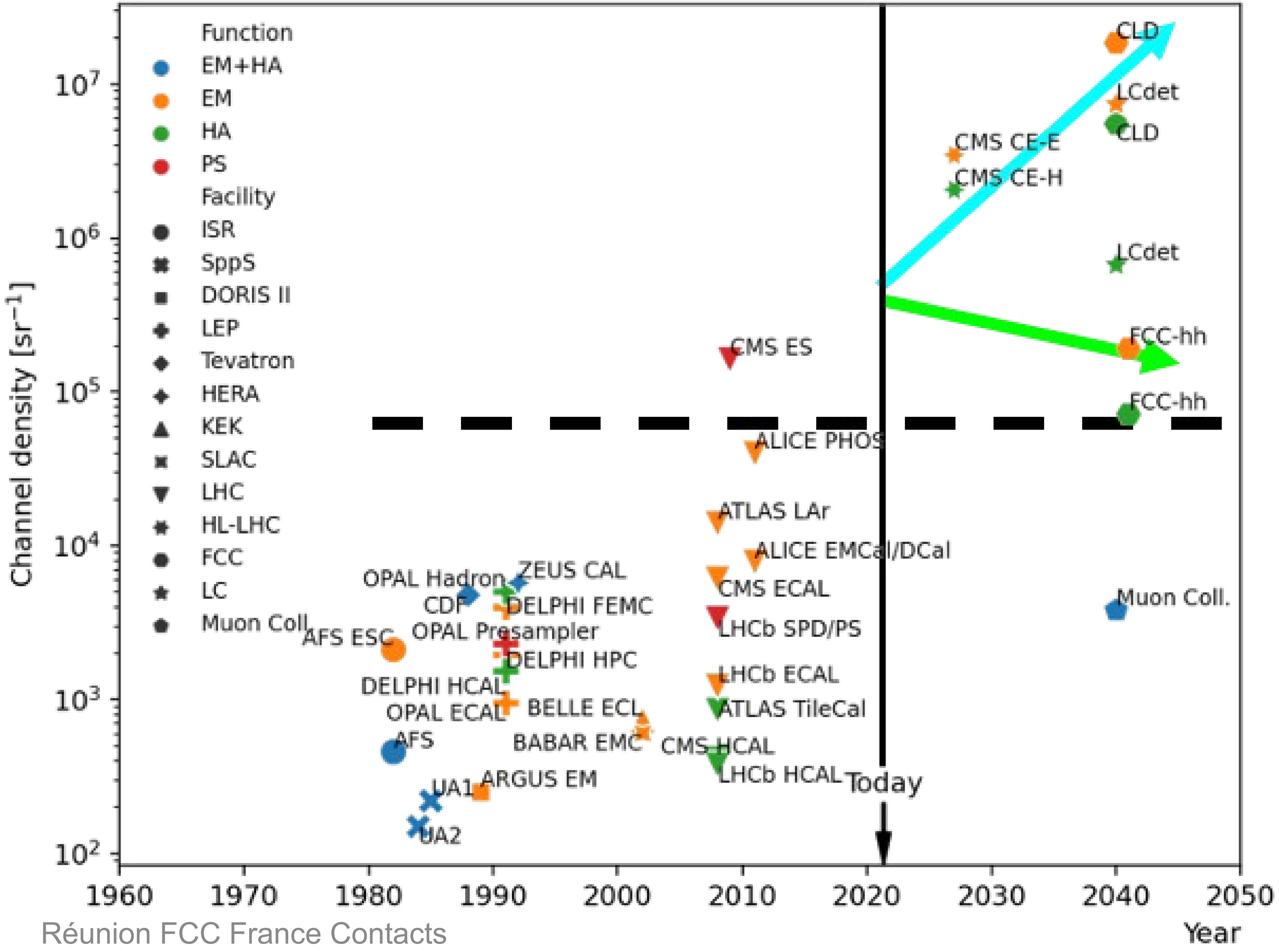
HEP is not a "development driver" → we need to keep-up with the commercial world, work with them & exploit their developments

In the last 40 years calorimeters **grew in size.**

In the next 20 years **they will grow in:**
- **spatial density** and/or
- **timing resolution**

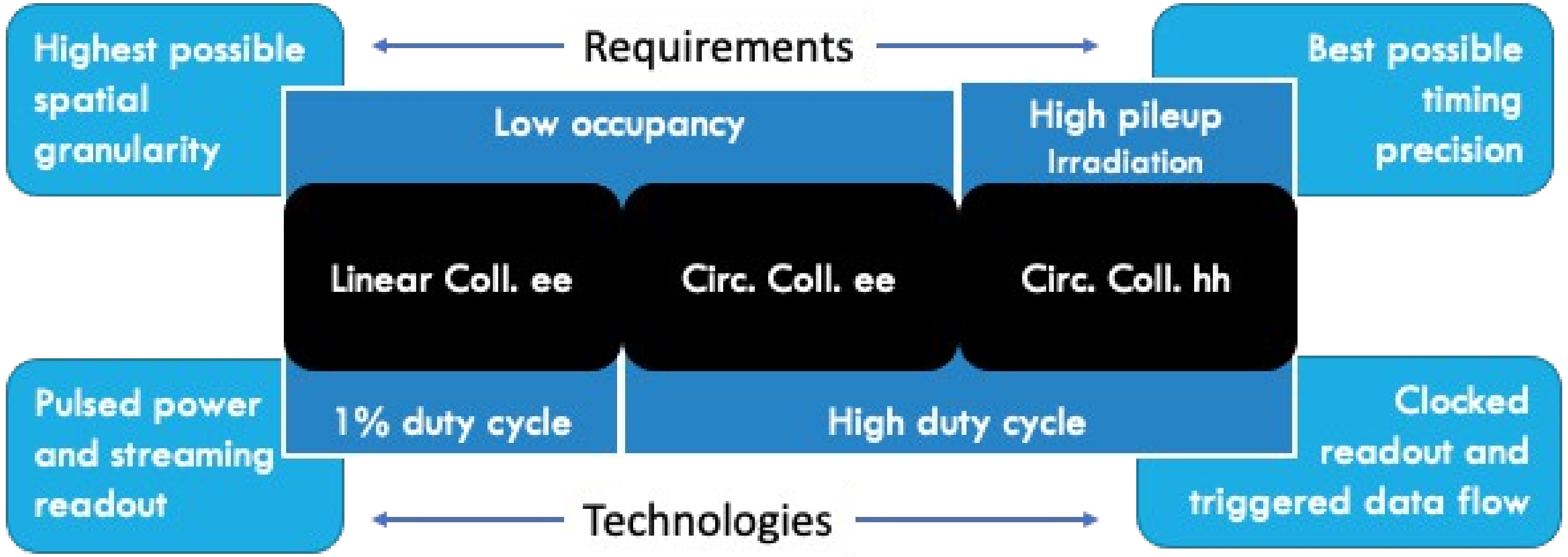
Needed for **next-generation particle-flow 5D-reconstruction** in space, energy, and time

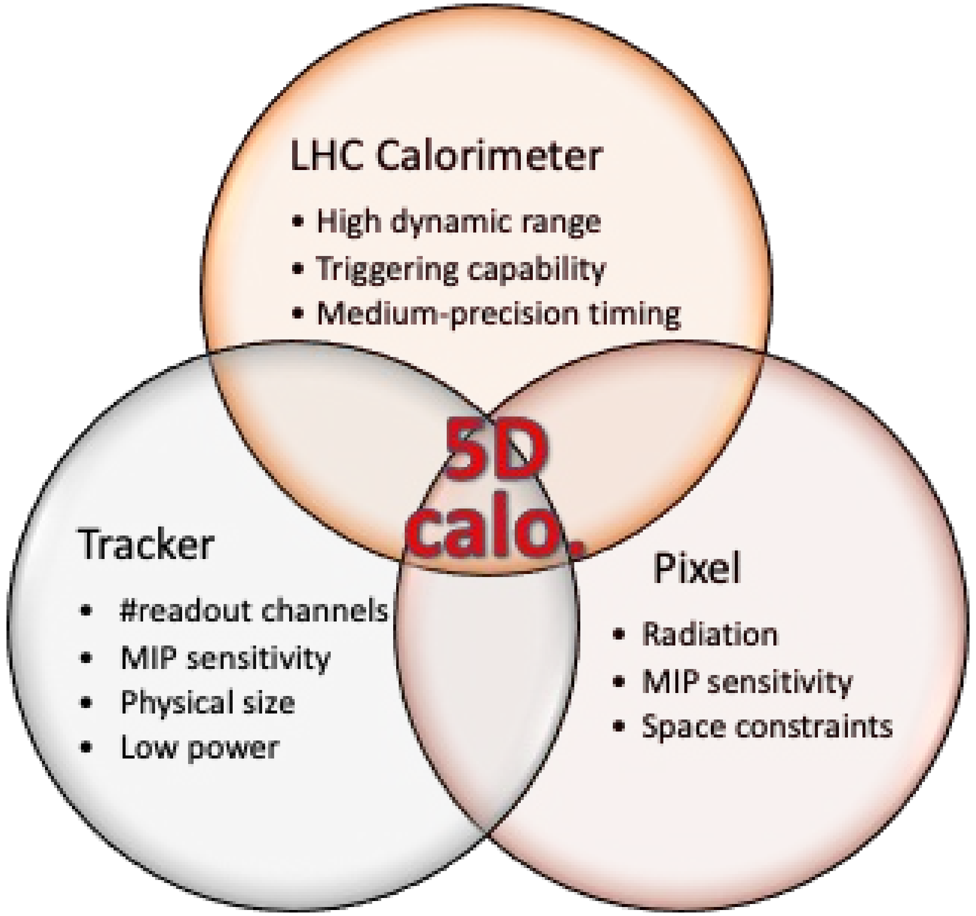
Move to **processing at all levels**, from front-end to back-end, including **data compression, encoding/decoding, embedded neural networks**

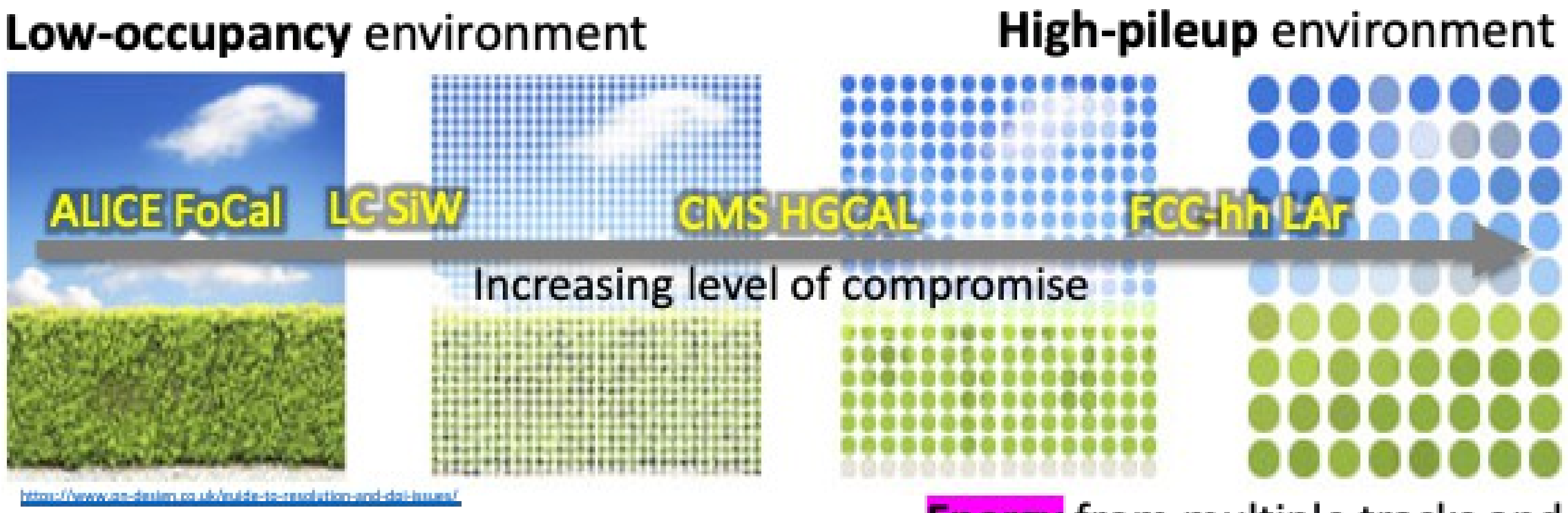


Requirements on future readout systems

Future calorimeters really require readout that can do it all, but there is a need to compromise and adapt to the physics







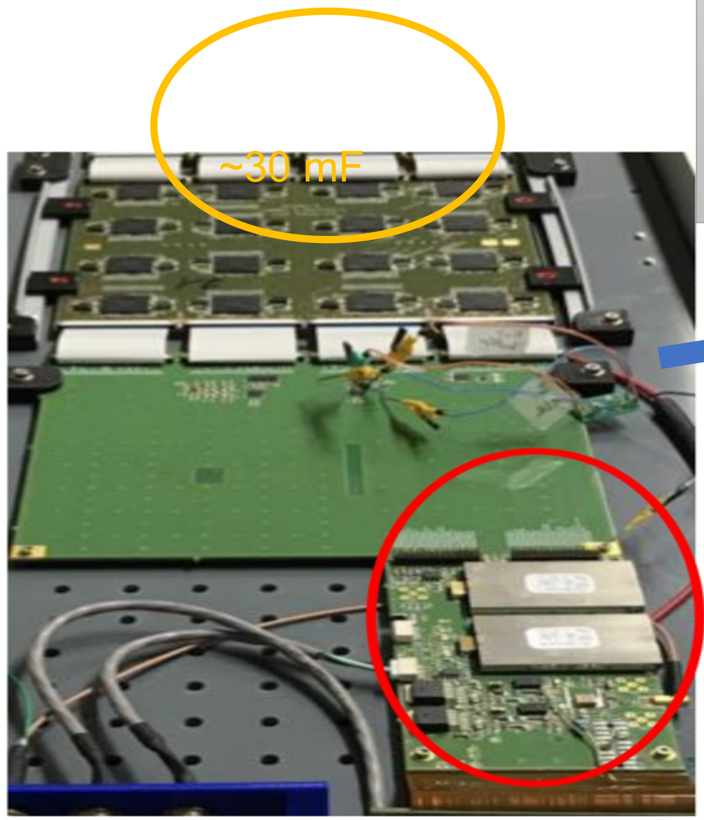
Energy from multiple tracks and mandatory precise **timing**.

Choices need to be made for any particular calorimeter. Features come at a price – **power!**

Having a **set of IP blocks & libraries** (ADCs, TDCs, PLLs, DLLs, memories, SER/DES) to construct front-end electronics **is mandatory**

Limits of ASIC Integration

https://indico.cern.ch/event/818783/contributions/3598490/attachments/1952892/3242642/CHEF_Novembre_2019.pdf

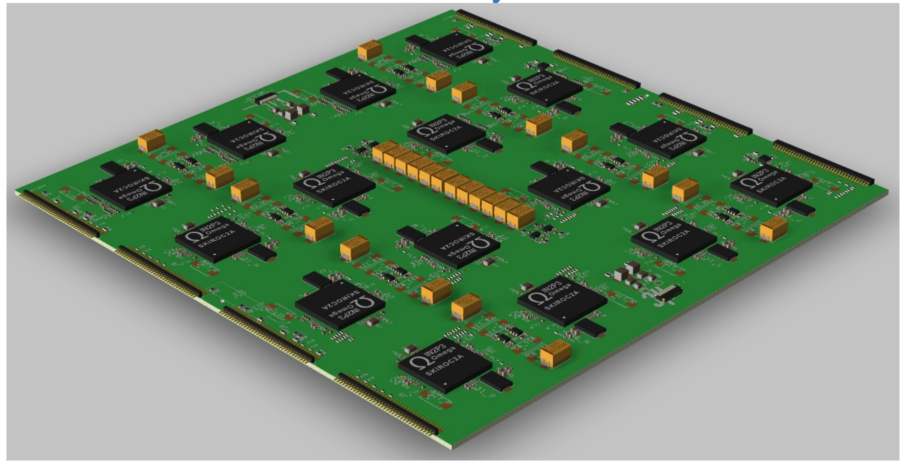


Power-pulsing for linear colliders requires large discrete capacitors

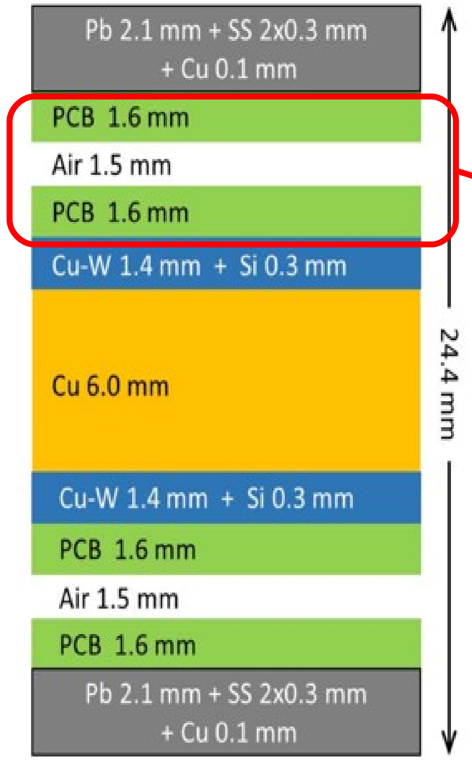
Passive material takes space

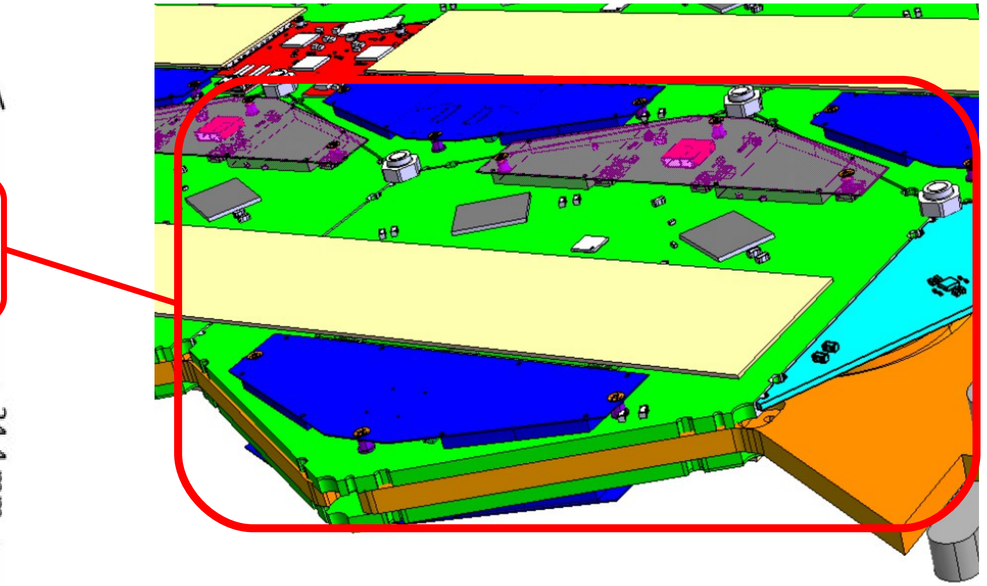
Capacitor type and location impact ASIC performance

~400 mF

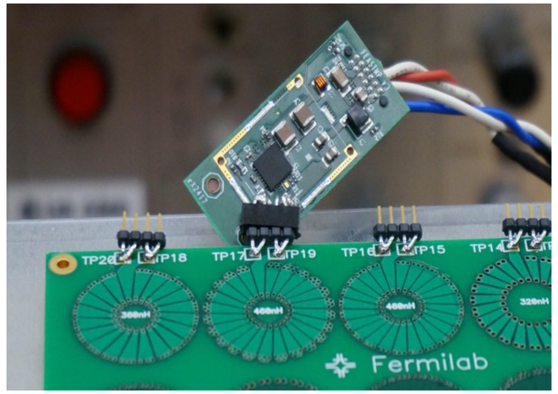


CMS HGCAL double-sided layer





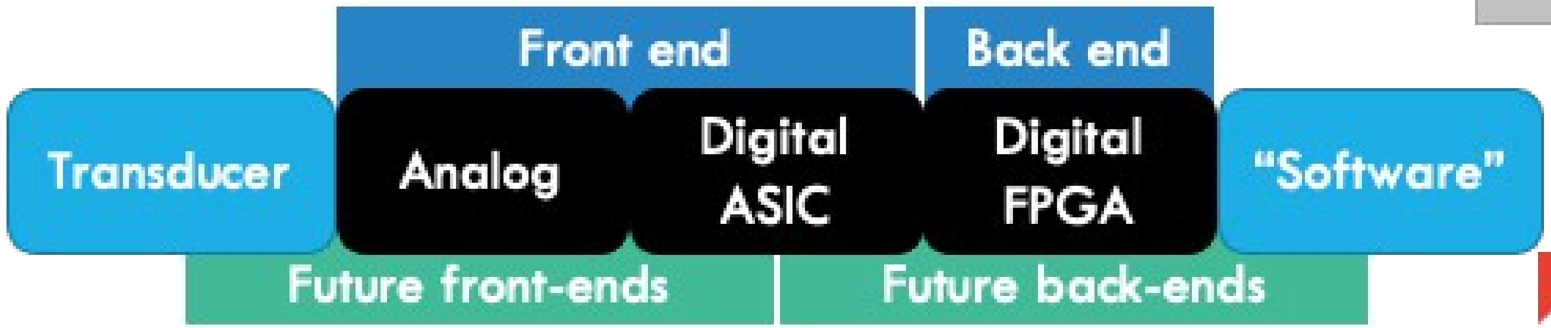
Space limitations in compact calorimeters requires **development of compact discrete components** e.g. coils, and use of compact capacitors, connectors etc.
→ **mobile-phone tech. on a grand scale**

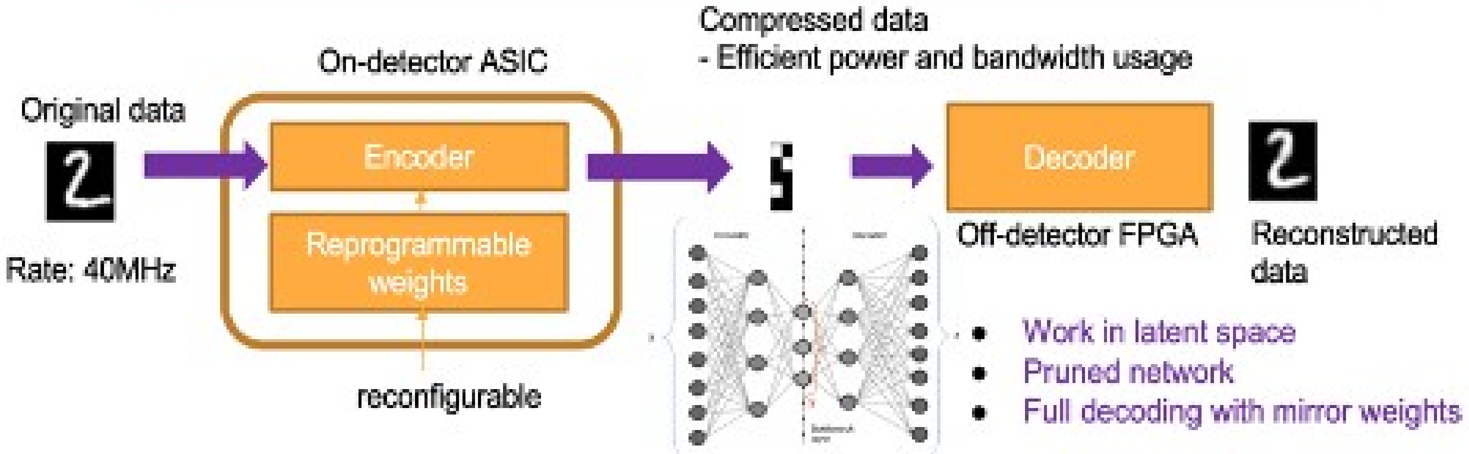


e.g. development of low-profile in-PCB and discrete toroids

Back end and off detector processing is changing ...

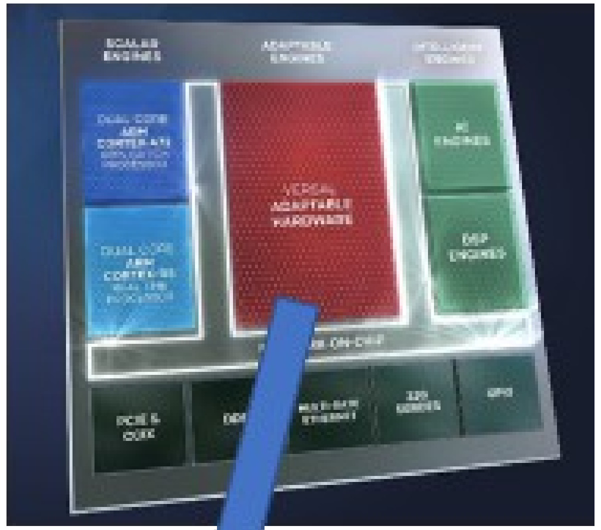
Previously: ASIC → FPGA → CPU
Now also:
CPU = GPU, TPU (matrices), DPU (network)
"Software" migrating now from CPU to GPU!

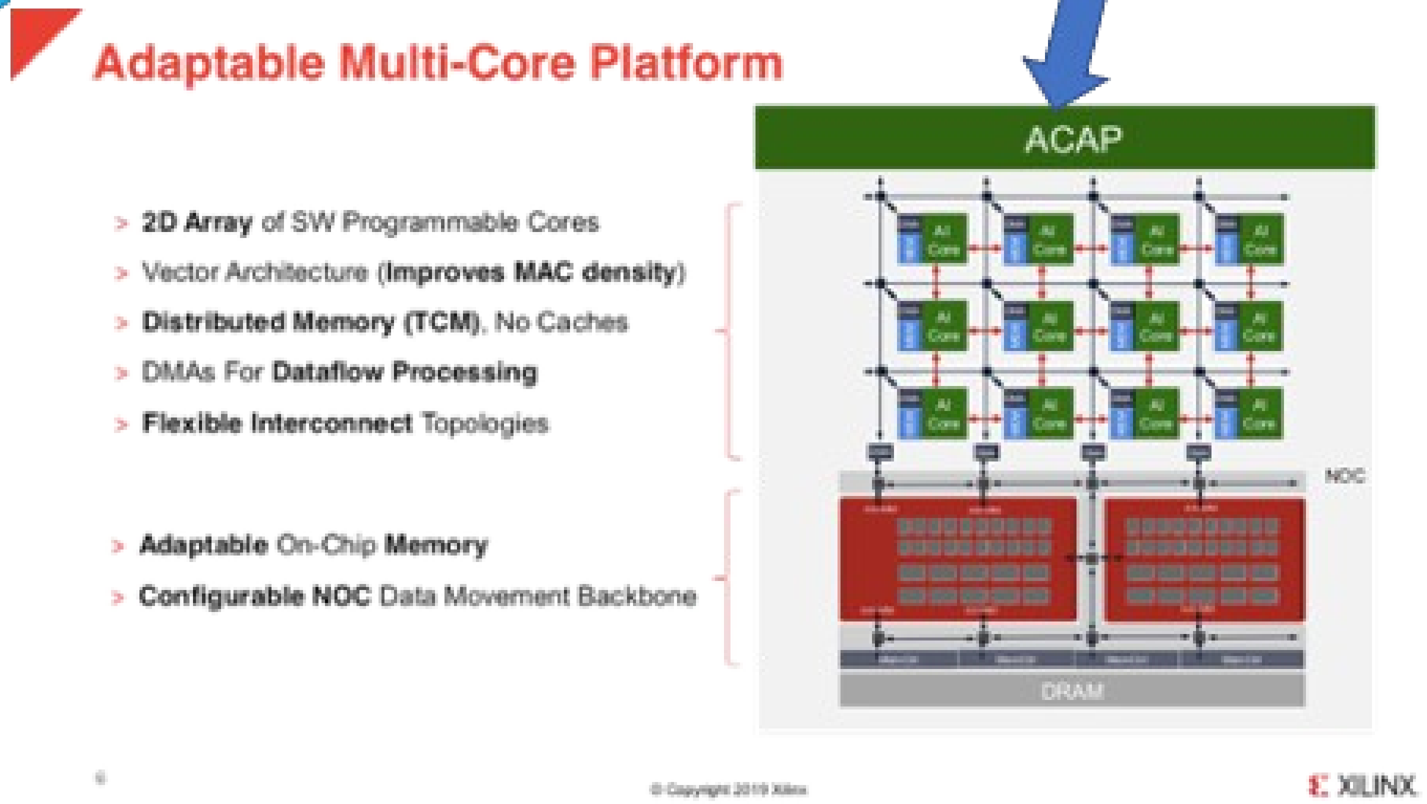




Blurring the edges: implementing advanced processing e.g. neural networks, compression etc. in the front-end
→ **a lot of R&D needed in front-end and back-end**

New generation of FPGAs
are reflecting the AI-driven market:
- Fewer programmable logic gates
- Multiple "AI cores"





ECFA

R&D Needs for readout systems for calorimetry

European Strategy Update

Most future calorimeters will use HEP-standard building blocks:

- e.g. ASIC IP blocks & libraries, DCDC converters, optical links etc.

But calorimetry has some additional needs:

Discrete on-detector passive components

- e.g. coils for compact DCDC converters, connectors

Connectivity

- e.g. between silicon & PCB: anisotropic conductive films; PCBs with same CTE as silicon
- e.g. between layers: distributed in-detector across-layer data processing

Processing at all levels (ASICs, FPGAs) to include features without exploding the power budget

- e.g. precision timing, neural networks in ASICs, lossy/lossless compression
- Mandatory to work closely with industry from the beginning (inc. training etc.)

Summary

- TF6 Symposium allowed for paving the way for defining the roadmap for future calorimeter R&D
- Broadly three time scales
  - Short term: HL-LHC after LS4 and partially also LS3
  - Medium term: electron-positron colliders
    - Linear and circular machines have commonalities but also significant differences
  - Long term: hadron collider and/or Muon Colliders
    - Extreme environment at future hadron colliders requires strategic approach now
    - High rates and radiation, particle and jet energies >> HL-LHC

- Important message I: Calorimeters require system approach from day one on
  - Tight collaboration between physicists, engineers and industry

- Important message II: In future calorimeters energy resolution may not be the key metric
  - Although there are of course still a number of applications that require extremely good energy resolution

- Integration of timing into calorimeters is one of the big tasks in future R&D
  - This requires as Step 0 to understand what level of precision is needed for which application

- Changes in readout architectures need to be followed up and integrated into our planning

Collaborations and Networks

- European projects such as AIDAinnova (start 4/2021)
- CERN EP-Programme
- Existing collaborations (LHC Experiments, Belle II, DUNE, NA62, KLEVER, ...)
- R&D Collaborations (CALICE, FCAL, CrystalClear, ...)
- Proto collaborations (ILD, SiD, CLICdp, FCC, IDEA, EiC)

Backup

Bulleted list of contents: Timing and readout systems

Timing

Main messages:

"moving to dynamic measurements of showers"
"features that emerge in the time domain can help push calorimetry further"
"timing doesn't come for free" → highly-performant electronics (digitizers, processors, synchronization etc.) & increased power consumption

- Uses of timing in calorimetry inc. aims for the future
  - "passive": Pileup mitigation (esp. in hh colliders)
  - "active": improvements in energy resolution (esp. for hadrons), linearity & particle ID
    - CMS ECAL template fits; animation from HGCAL (static for paper); plots from sim. of Cu/Si calorimeter
- Contributions to timing performance
  - Equation showing terms etc.
- State of the art
  - Materials & full detectors
- R&D needs
  - To meet ~10ps by 2030; 5ps by 2045; 1ps very long term
  - Materials on large scale – esp. crystals
  - Electronics – e.g. low-power ASICs & processors
  - Devices esp. digital SiPM
  - Software inc. AI, neural networks, machine learning etc.

Readout Systems

Main messages:

"HEP is not at all a 'development driver' → we need to keep up and adapt to commercial developments and exploit them for our needs"
"firmware is the new software"
"FPGAs, as we know them, may cease to exist"
"A lot of the need is research and adaptation of upcoming technologies, to ensure the ability to engineer our own solutions"

- Breadth of challenges for future & where things are heading
  - Move to "processing" at all levels (inc. compression, encoding, processing)
- Many suitable technologies exist (e.g. ADCs, TDCs, PLLs, power converters) but compromises have to be made
  - Cannot have it all → choice depends on application
- Integration is a major challenge
  - On-sensor component developments (pre/amps, memories etc.) can only go so far
  - Need for bulky discrete passive components esp. capacitors, connectors
- Lines between functions at front-end and back-end are blurred
  - Putting "software" into front-end e.g. lossy NN, lossless compression
- R&D needed on new FPGAs that are more "AI-oriented"
  - A common need with all HEP

Symposium talks: N. Achurin and A. David

Introduction – (Traditional) role of Calorimeters

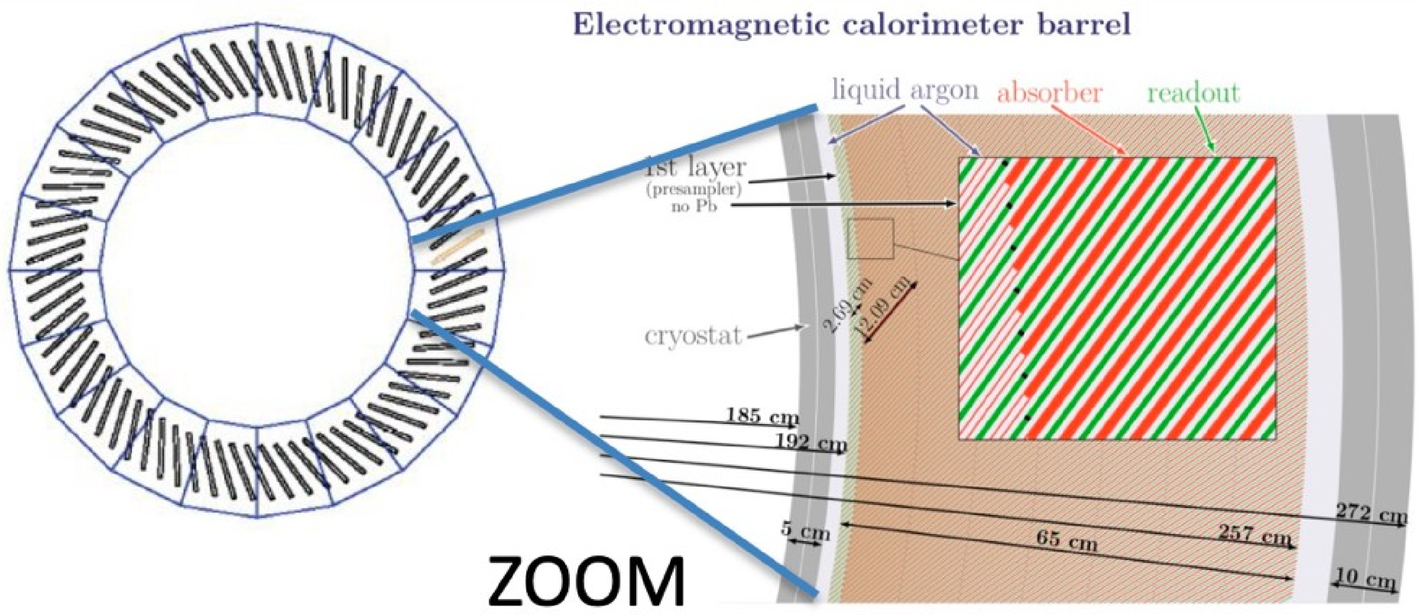
Recap of calorimeter role in HEP detectors:

1. energy measurement → resolution
2. triggering → speed/ rate
3. basic particle ID (em/had separation) → segmentation

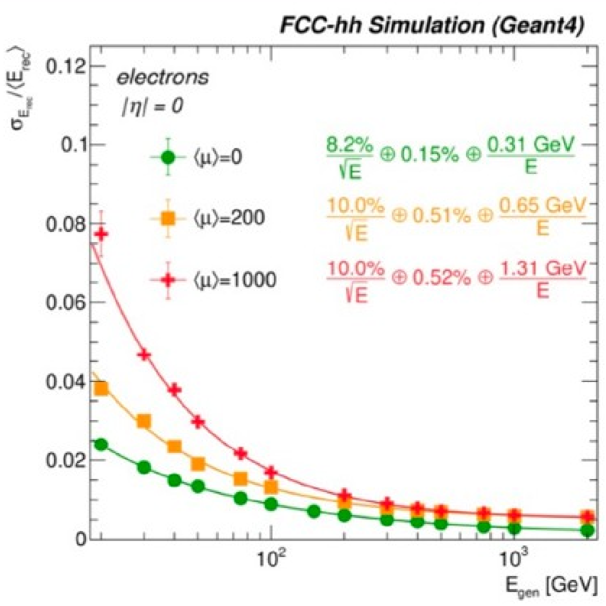
Recap of past/present implementations:

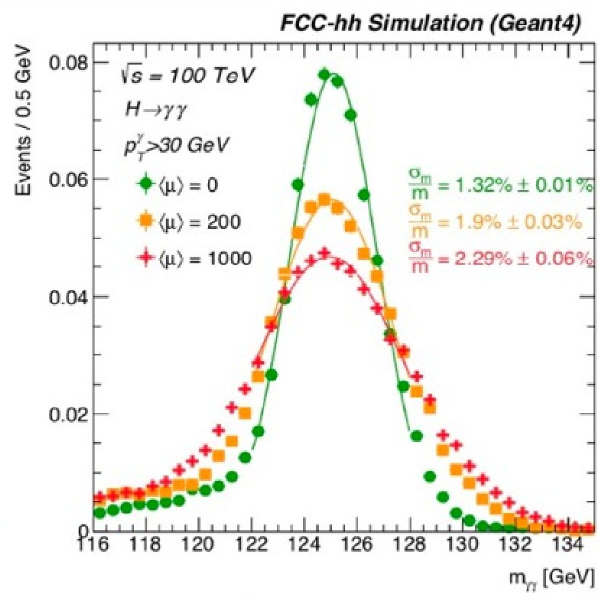
1. electromagnetic:
    a. sampling (Pb/W absorber) → granularity ↑
    b. homogeneous (crystals) → resolution ↑
2. hadronic:
    a. non compensating → design/construction ↑
    b. compensating (bounded f_{samp}) → resolution ↑

Example: Electromagnetic Calorimeter for FCChh

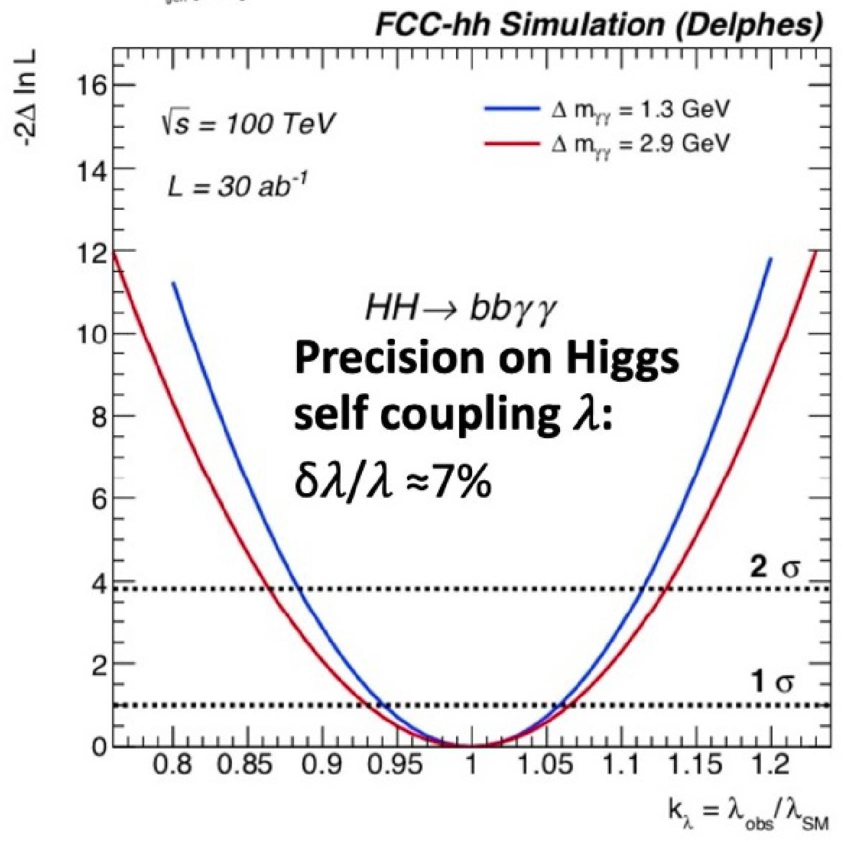


- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;





- **CDR Reference Detector: Performance & radiation considerations → LAr ECAL, Pb absorbers**
  - Options: LKr as active material, absorbers: W, Cu (for endcap HCAL and forward calorimeter)
- **Optimized for particle flow: larger longitudinal and transversal granularity** compared to ATLAS
  - 8-10 longitudinal layers, fine lateral granularity ($\Delta\eta$ x $\Delta\phi$ = 0.01 x 0.01, first layer $\Delta\eta$=0.0025),
  - → ~2.5M read-out channels
- Possible only with **straight multilayer electrodes**
  - Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
  - Baseline: warm electronics sitting outside the cryostat (radiation, maintainability, upgradeability),
    - Radiation hard cold electronics could be an alternative option
- **Required energy resolution achieved**
  - Sampling term ≤ 10%/$\sqrt{E}$, only ≈300 MeV electronics noise despite multilayer electrodes
  - Impact of in-time pile-up at <μ> = 1000 of ≈ 1.3GeV pile-up noise (no in-time pile-up suppression)
  - →Efficient in-time pile-up suppression will be crucial (using the tracker and timing information)



Optical readout calorimeters: Introduction

- **Input talks:**
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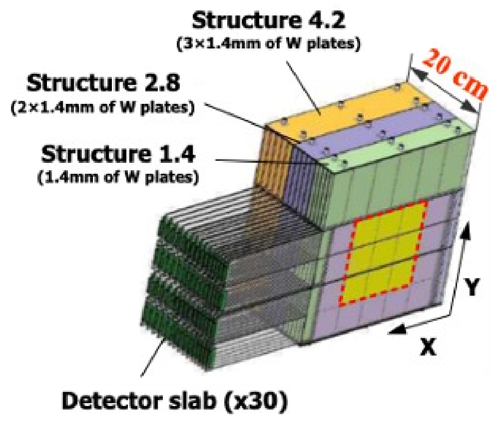
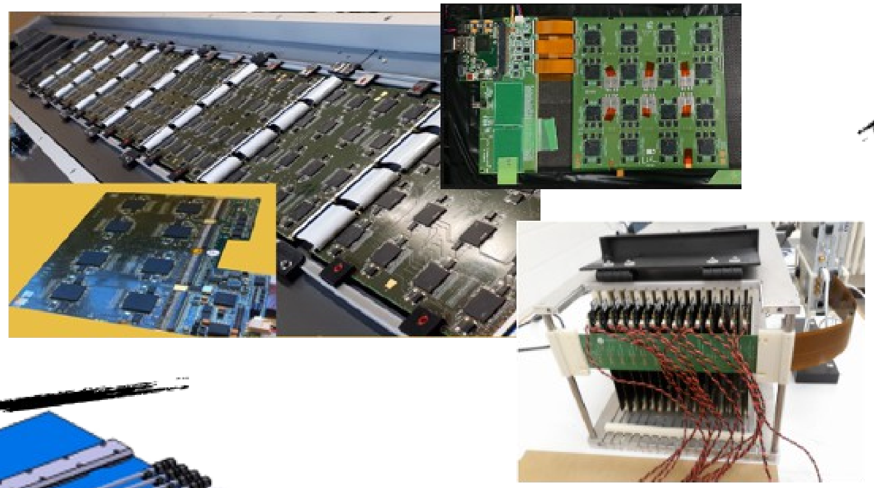
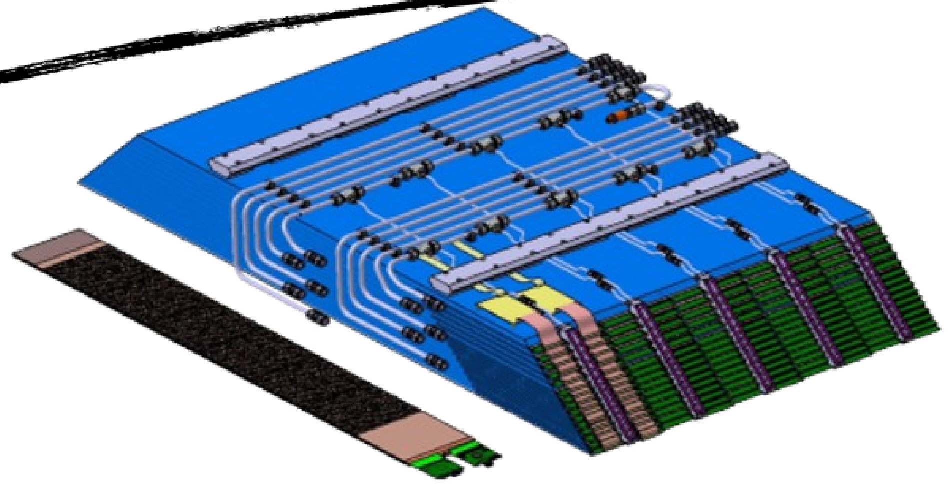
  - [2] *Crystal calorimetry*, **Marco T. Lucchini (Milano-Bicocca)**
  - [3] *R&D for Dual Readout fibre-sampling calorimetry*, **Gabriella Gaudio (Pavia)**
- **Background:**
  - [1, 2]: Consolidated technologies employed in past, current, and imminent experiments
    - Focus of [1]: hadron calorimetry (cost-effective performance optimization over wide areas)
    - Focus of [2]: electromagnetic calorimetry (superior resolution at low energies)
  - [3]: Mature R&D for ultimate hadron energy resolution never implemented in a full scale experiment
- **Prospects:**
  - Excellent candidates for calorimeters at future collider and non-collider experiments either in classical implementation (with "boosted" materials/sensors/layouts) or in new combinations exploring new paradigms in energy reconstruction:
    - Multiple-readout high-granularity total absorption calorimetry for shower "imaging" (Č, S, space, time, …)
    - Front EM compartment integrated in the dual-readout concept combining low energy EM resolution with the ultimate hadron resolution
  - Specific implementations depend on the experiment's goals, but there are common R&D objectives

Si Based Calorimeters – Main Calorimeters for Collider Detectors

- Active development by **CALICE** collaboration since 2005
  - ~1 m^2 sensor area prototypes (physics, technological - with integrated electronics)

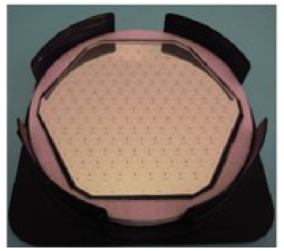






inspired the **CMS HGCAL**

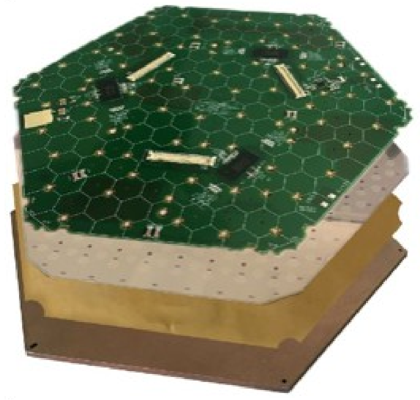
- 600 m^2 of silicon sensors, 6 M channels, 30 ps timing, continuous readout, highly challenging radiation environment



hexagonal sensors, 8'' wafers

integrated electronics

complex mechanics



- Full system (~ 2035): 2500 m^2 sensor area, ~ 70 M channels for pad detectors
  - Possible CMOS digital ECAL solutions - channel density increase x ~10^4, requiring substantial R&D on technology & integration

3

State of the Art – Example: SDHCAL with GRPC

Detector: **GRPC (Glass Resistive Plate Chambers)** operating in **avalanche mode**

1x1 cm² pads. Semi-Digital Readout, 2bits - **3 thresholds**

➔ It counts **how many** and **which pads** have a **signal larger than one of the 3 thresholds**

Embedded electronics:

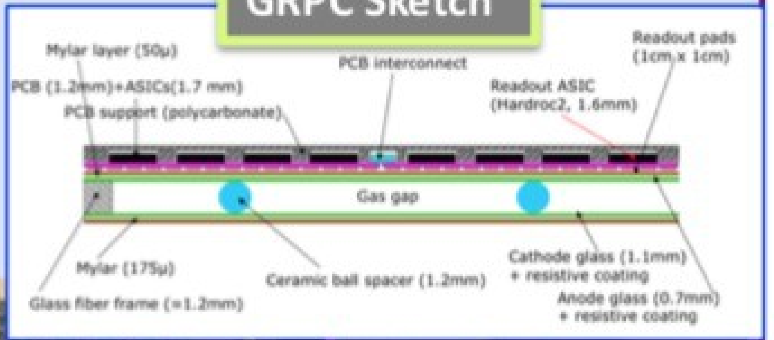
PCB separated from the GRPC by a mylar layer (50µm).

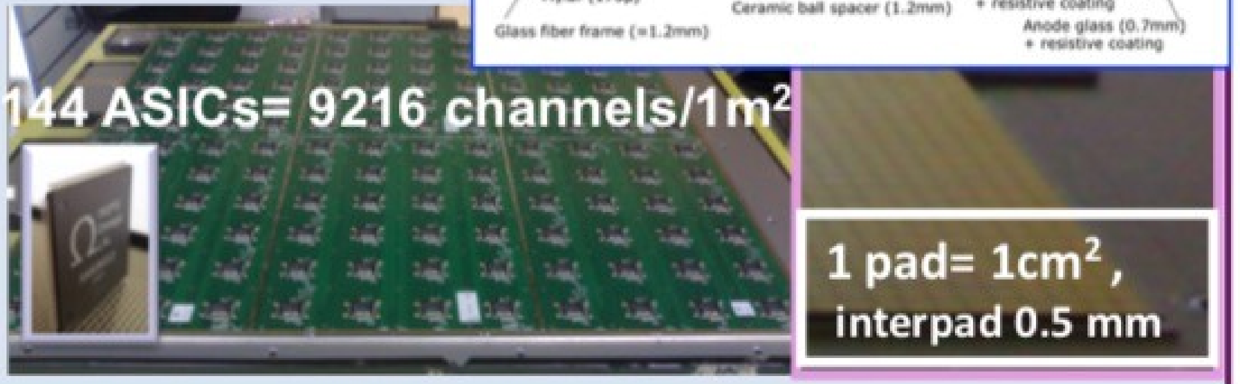
➔ Bottom: **1x1cm2 pads**

➔ Top: **HARDROC** (**HA**dronic **R**pc **R**ead**O**ut **C**hip) & related connections

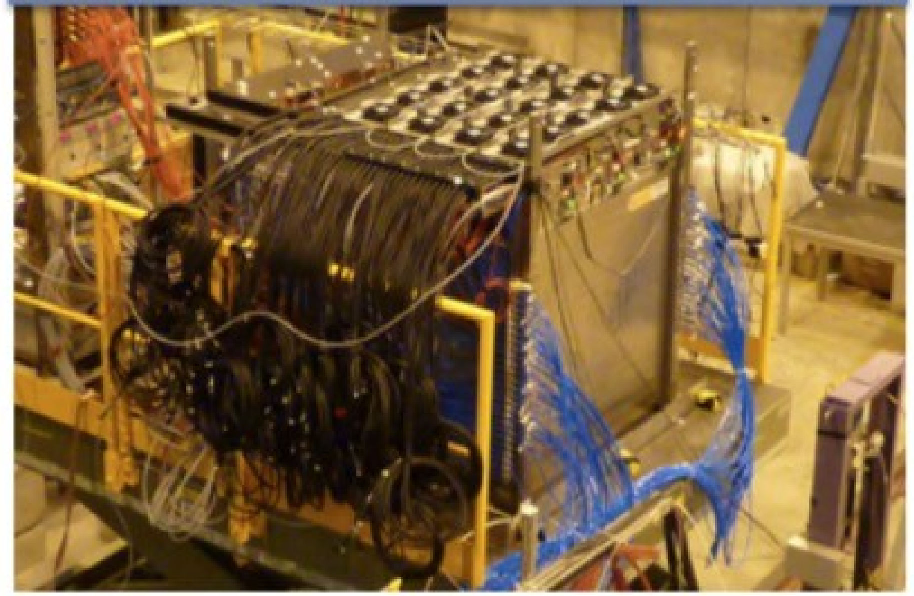
Power-pulsed electronics: In **stand-by during dead time** in between ILC Collisions or spills in beam tests

GRPC Sketch

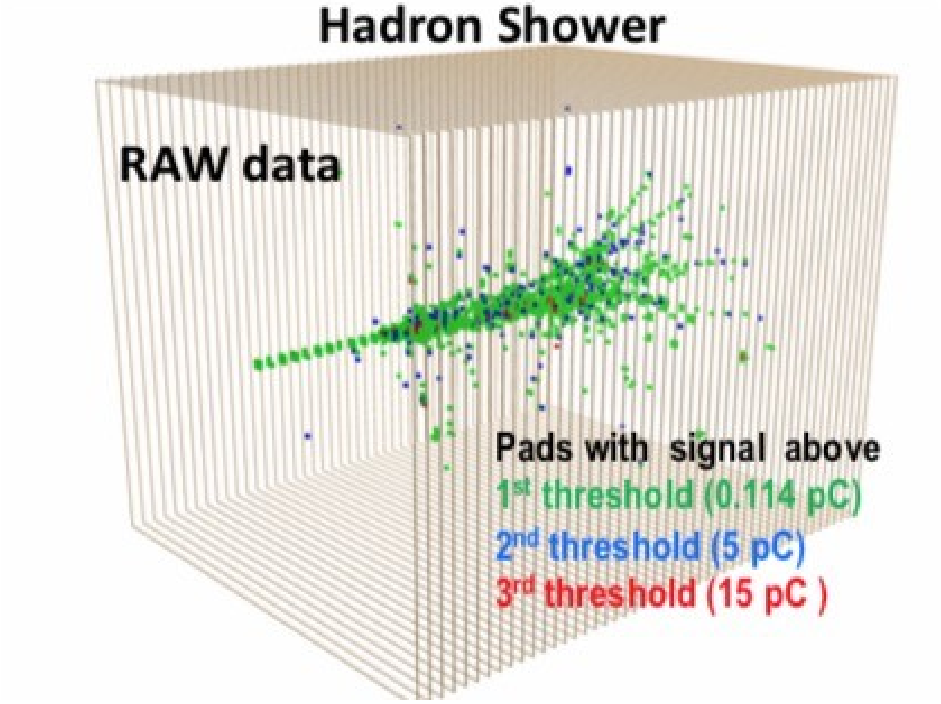


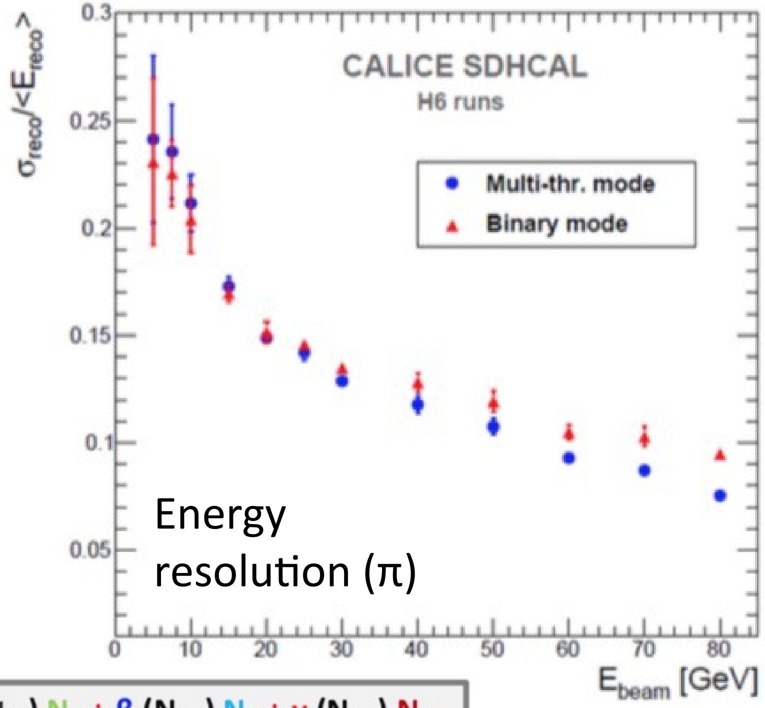


~1.3m³ prototype at CERN Test Beam



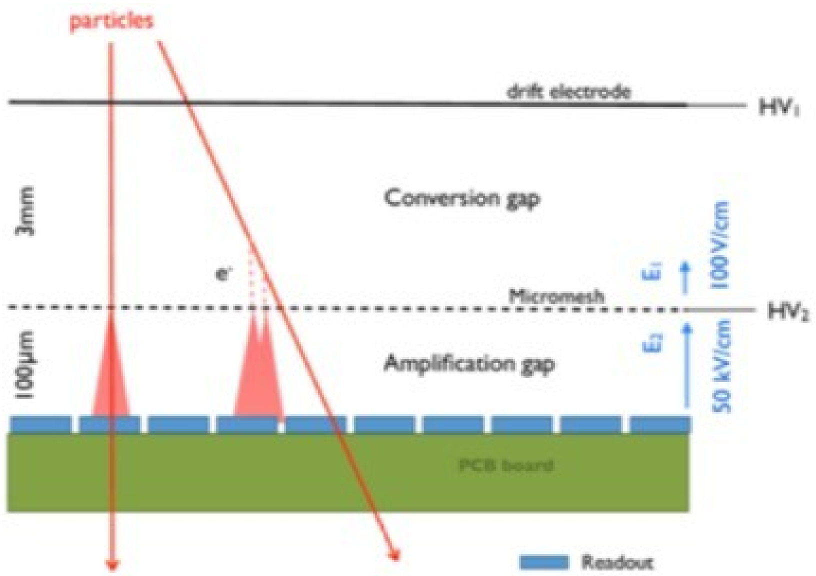
~ half million channels!!





$E_{rec} = \alpha(N_{tot})\,N_1 + \beta(N_{tot})\,N_2 + \gamma(N_{tot})\,N_3$

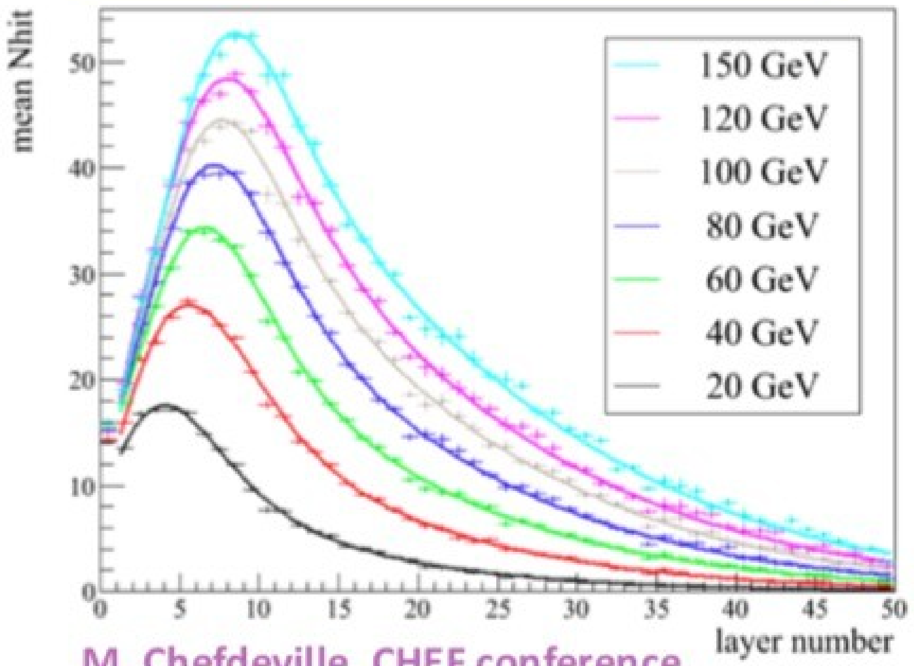
State of the Art – Example: SDHCAL with MICROMEGAS



Micromegas prototype of 1x1m2 consisting of six independent Micromegas boards

Tested together with the RCP at the SDHCAL 1m3 prototype at CERN/SPS
By substituting RPC layers 10, 20, 35 and 50 by Micromegas

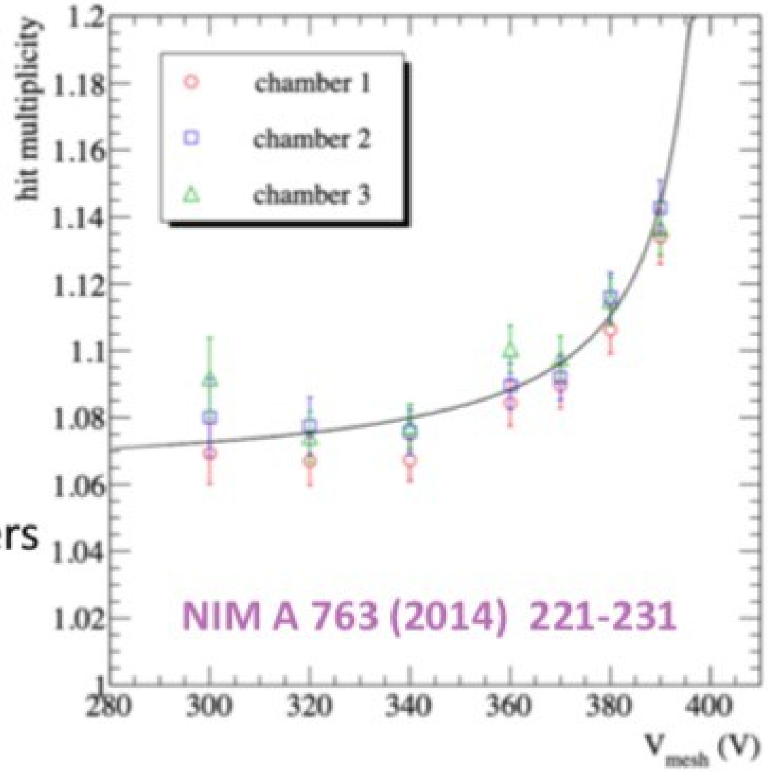
Longitudinal profile of pions showers (low thr.)



M. Chefdeville, CHEF conference, Paris, 22nd-25th of April 2013

Profile was computed despite of having only 4 chambers available, thanks to the fluctuations on the shower starting layer

Similar performance for all chambers
Hit multiplicity ~1.1



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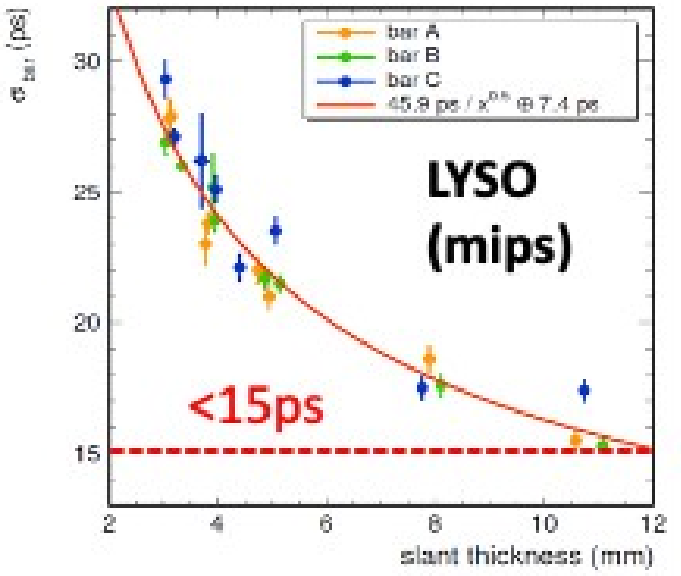
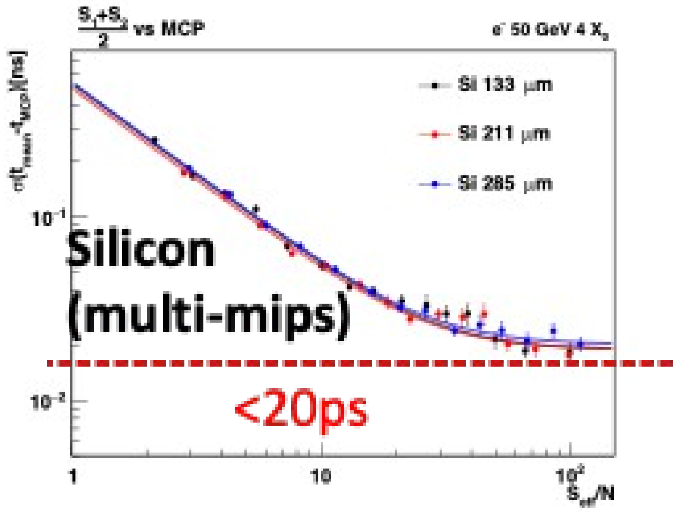
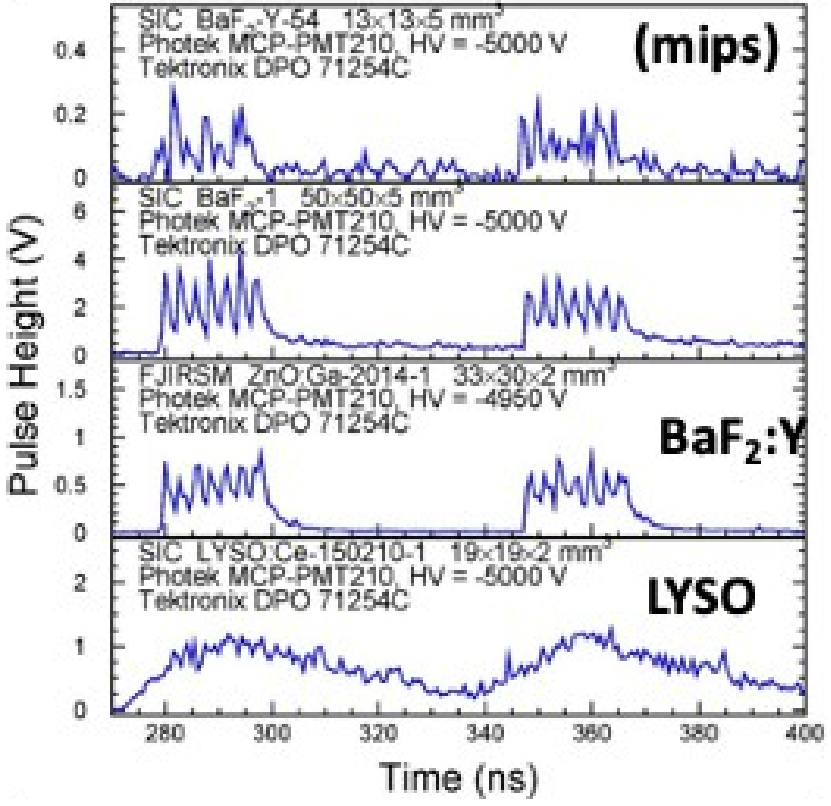
State of the Art – Materials and full detector





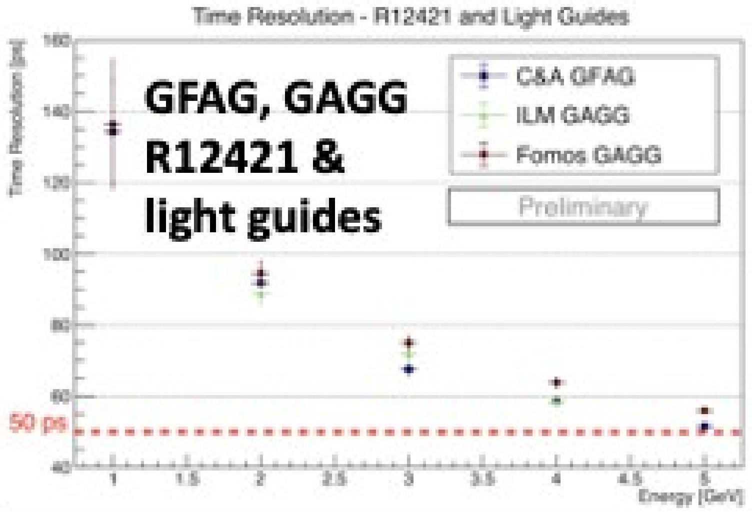


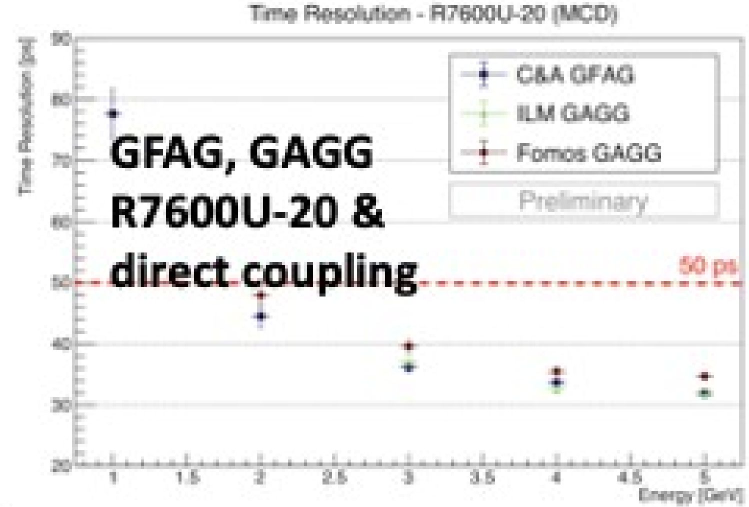
Several materials (crystals & semiconductors) show fast signal production & quite fast decay times

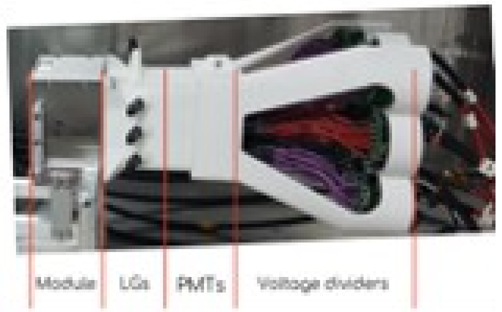
BaF_2 known for decades. ~0.5ns decay time when doped with Y
→ ultrafast calorimetry for fast-repetition-rate colliders

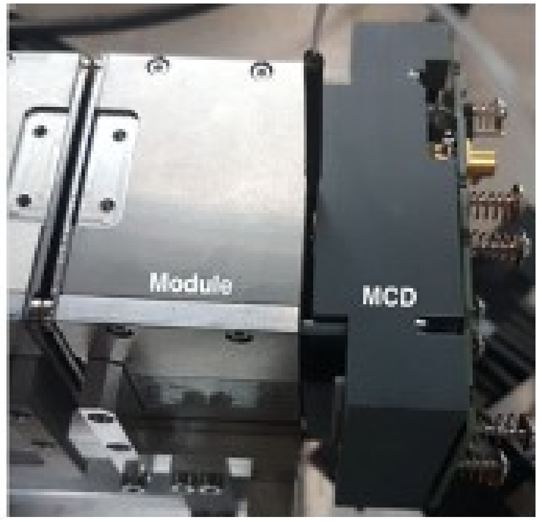
LHC SPACAL R&D

DESY 2020, 5 GeV e^-



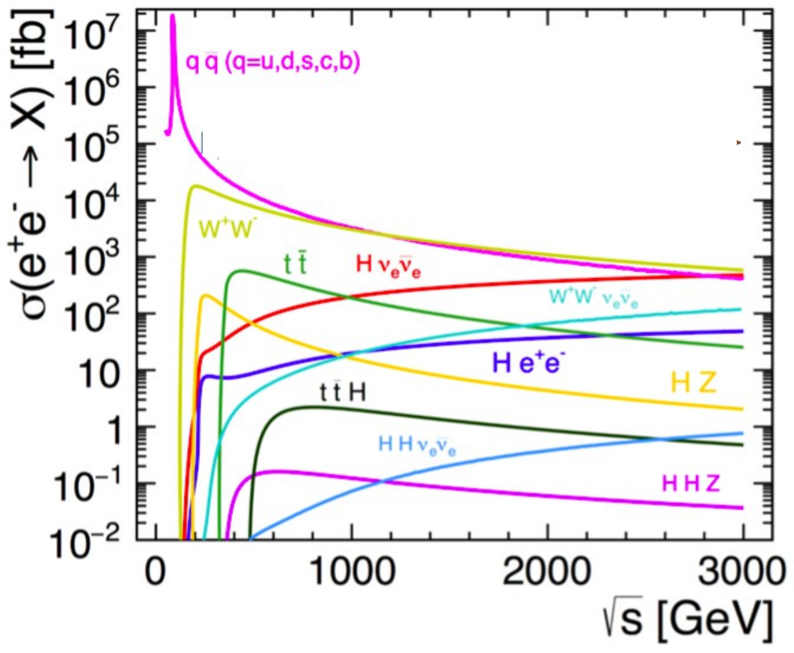


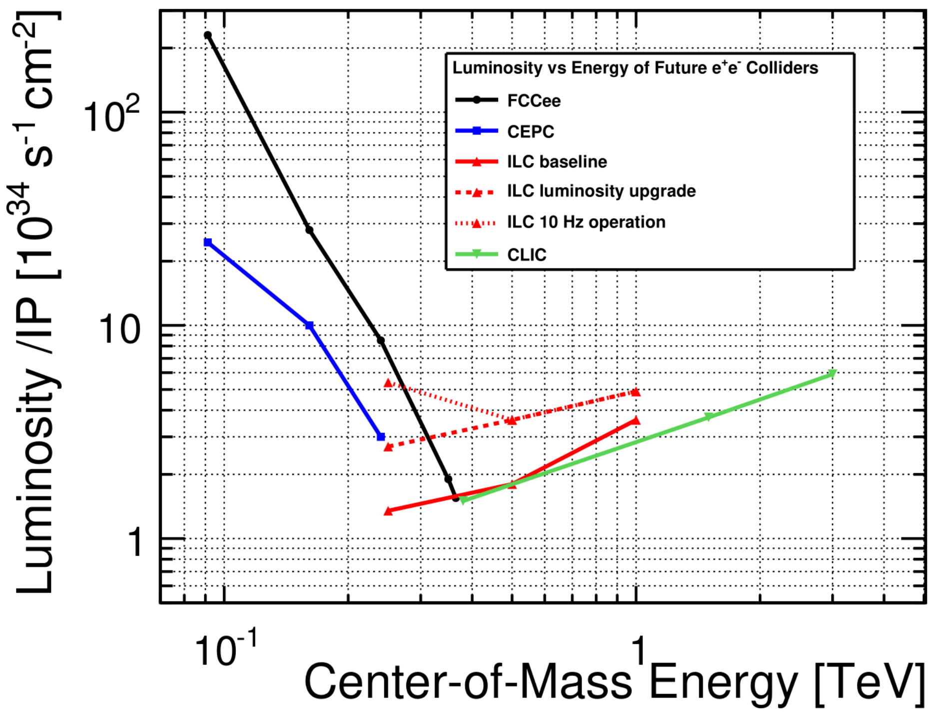




Improvement due to **higher light-detection efficiency** and **better time-transit-spread** homogeneity
Expected time resolution of **order 10ps at 100 GeV**

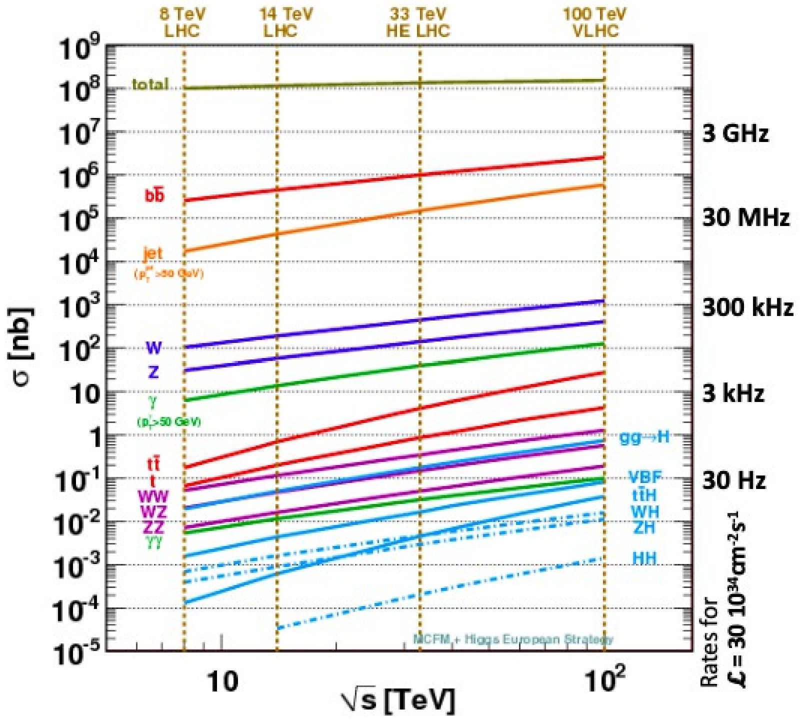
Impact of rates





High energy e+e- colliders:

- Physics rate is governed by strong variation of cross section and instantaneous luminosity
- Ranges from 100 kHz at Z-Pole (FCC-ee) to few Hz above Z-Pole
- (Extreme) rates at pole may require other solutions than rates above pole
  - strong active cooling, calo trigger and feature extraction in front-end elx.
- Rates in Beam Calorimeters comparable to Z-Pole rate



Hadron collisions/colliders

- Interesting physics processes are only small fraction of total cross section
- Event filtering motivates implementation of sophisticated algorithms (PFA) in or close to front-end electronics
- Pioneering work by current LHC experiments and fixed target experiments
  - ... in particular LHCb

See also talk by Andre David