CALORIMETRY

Gabriella Gaudio

INFN Pavia



CALORIMETRY

Calorimeter:
A detector used to measure the total energy of incoming particles by completely absorbing them and generating a shower of secondary particles.

Energy

CALORIMETRY TODAY: 5D-CALORIMETER PARADIGM

Energy

Timing

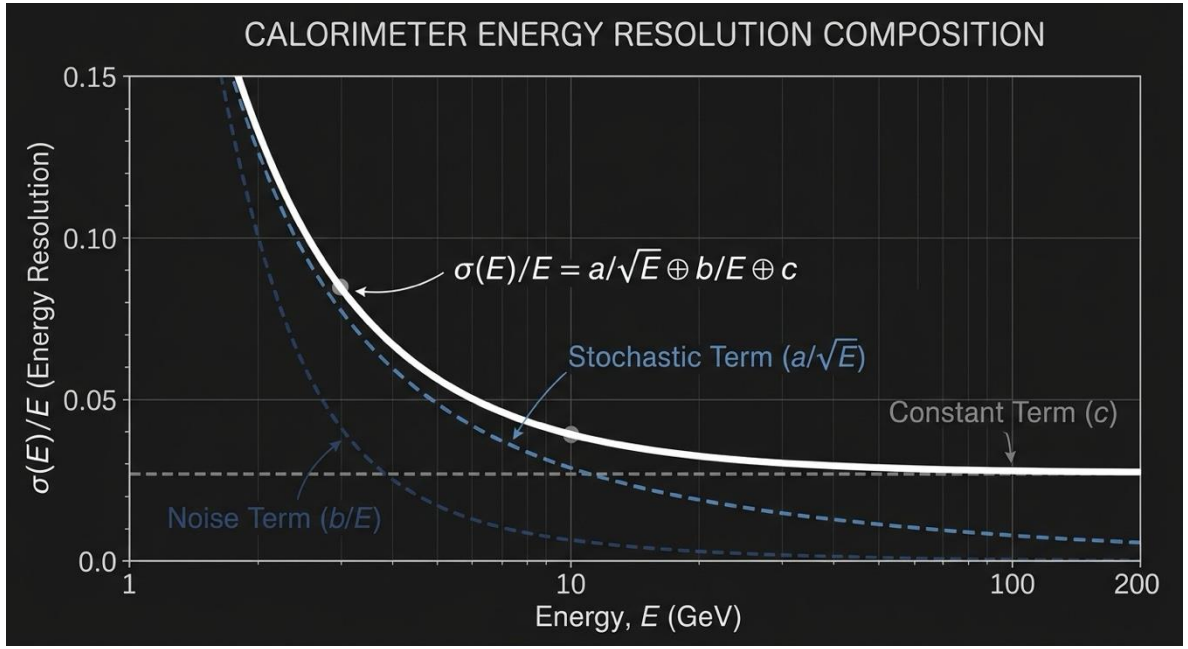
Position (3D)

5D-CALORIMETER PARADIGM: ENERGY

Energy

High Energy Resolution

- Reduce fluctuations by construction
- Improved by algorithm (e.g. Particle Flow approach) and Machine Learning approach



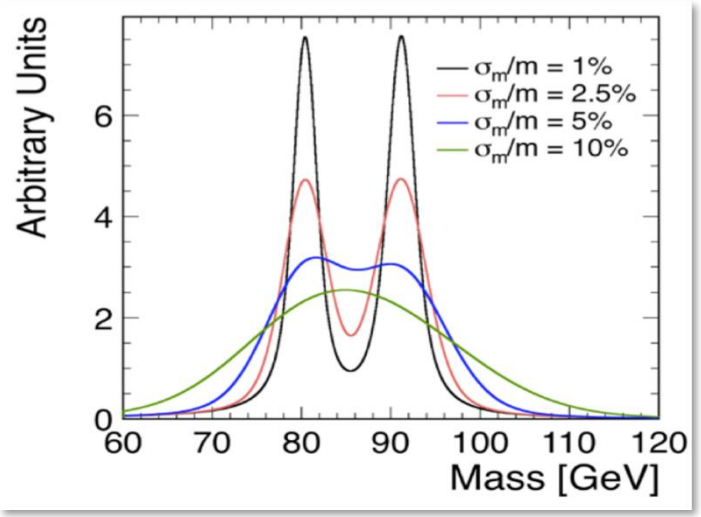
ENERGY: HEP PHYSICS DRIVERS

"Higgs Factories" are among the main drivers for current calorimeter development

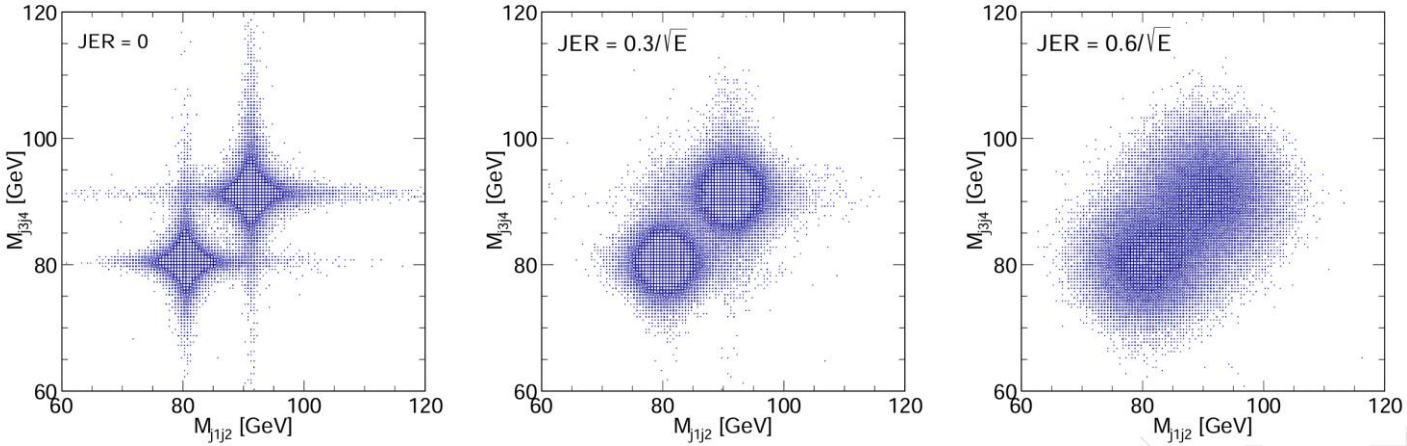
Jet final state will be dominant at the Higgs Factories

- higher branching ratio
- clean environment

Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]



Disantangling W and Z peak
e.g. Separation of VVH from WW fusion and HZ



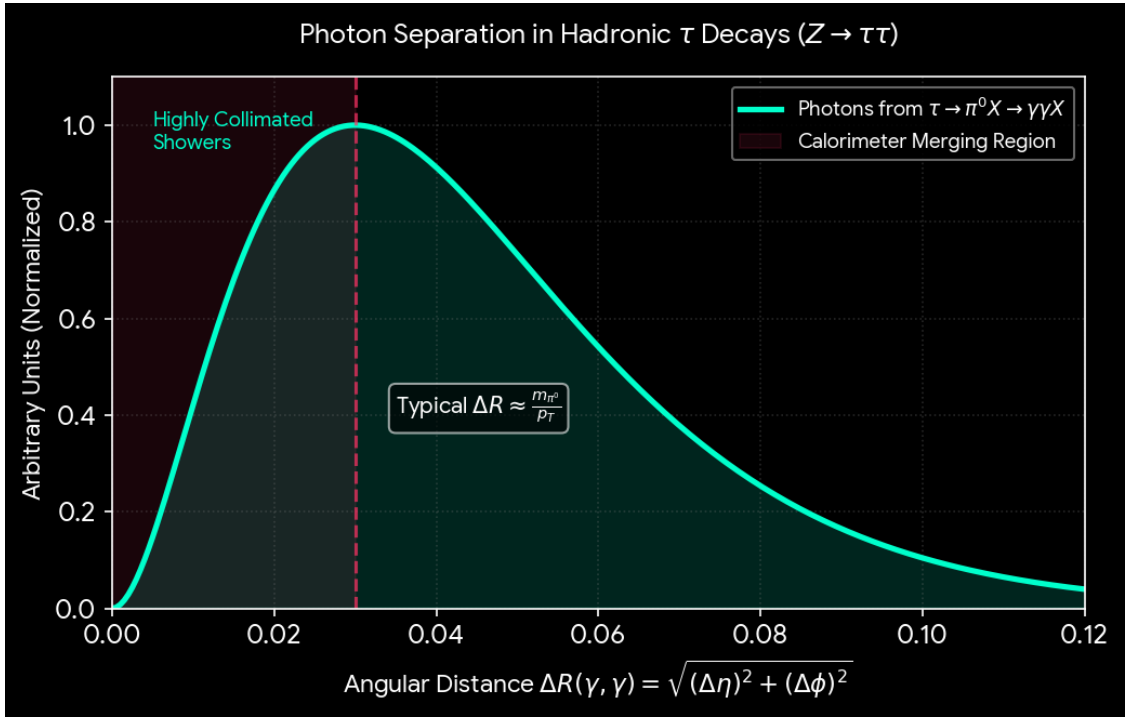
ENERGY: HEP PHYSICS DRIVERS …. AND POSITION

"Higgs Factories" are among the main drivers for current calorimeter development

e^+e^- HZ physics constraints
$H \rightarrow \gamma\gamma \Rightarrow$ ECAL resolution
As good as possible – at least $20\%/\sqrt{E} + 1\%$

For HF physics $3\%/\sqrt{E}$ is required

High granularity / Pre-shower is needed for π^0 identifications



$$Z \rightarrow \tau^+\tau^-$$
$$\tau^+ \rightarrow \rho^+\nu \rightarrow \pi^+\pi^0\nu$$

5D-CALORIMETER PARADIGM: ENERGY + POSITION

Energy

Position (3D)

High Energy Resolution

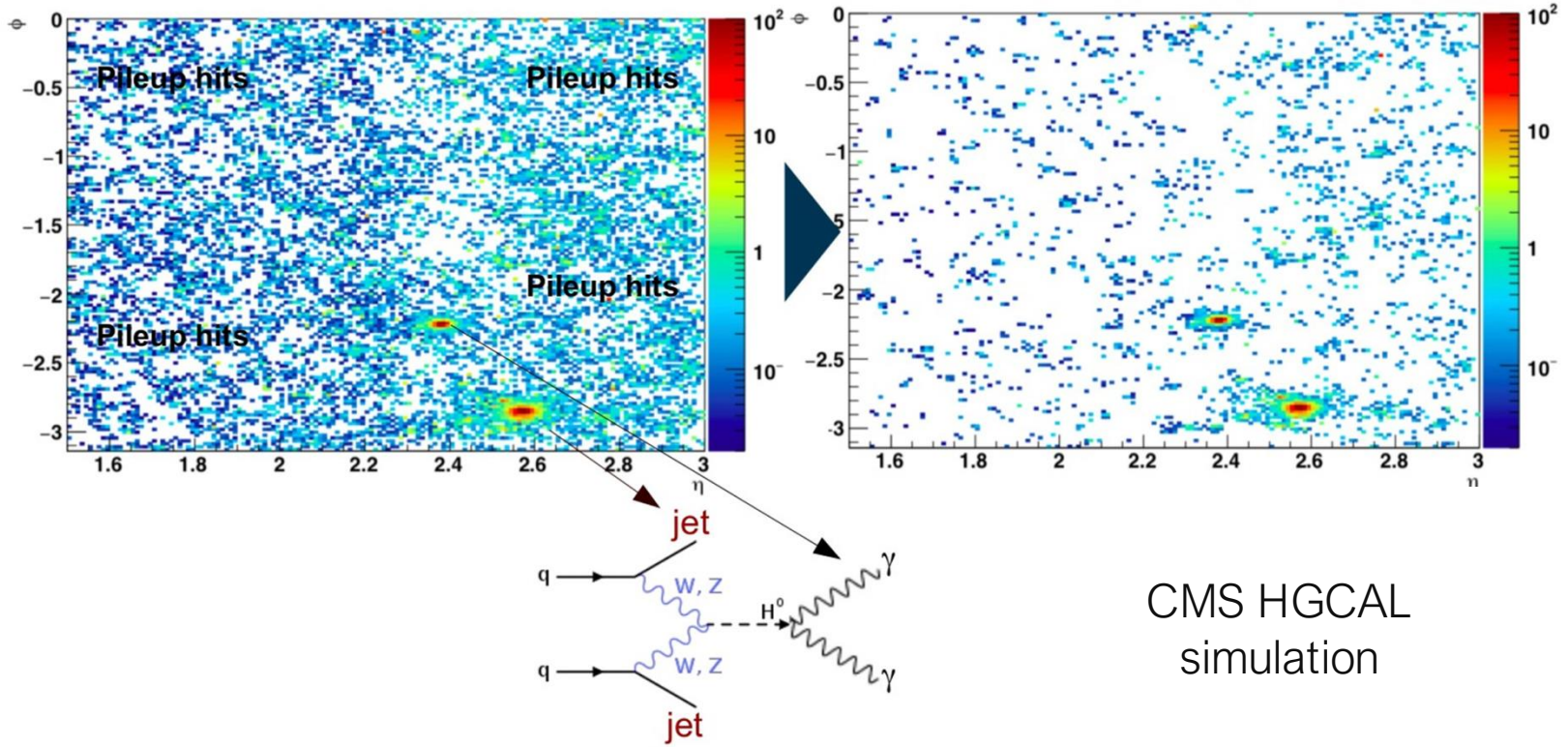
- Reduce fluctuations by construction
- Improved by algorithm (e.g. Particle Flow approach) and Machine Learning approach

High granularity

- mechanical integration
- cooling for embedded electronics
- increased number of channels

TIMING: HEP PHYSICS DRIVER

- Pile up mitigation
- Support to particle flow algorithm
- Cluster separation
- Shower time evolution (shower components identification)
- PID (charge hadron identification via TOF)
- Long lived particles
- …



CMS HGCAL simulation

5D-CALORIMETER PARADIGM

Energy

Position (3D)

Timing







High Energy Resolution

- Reduce fluctuations by construction
- Improved by algorithm (e.g. Particle Flow approach) and Machine Learning approach

High granularity

- Mechanical integration
- Cooling for embedded electronics
- Increased number of channels

Fast timing information

- Fast detector
- Fast electronics
- Larger data size

CALORIMETRY COMMUNITIES

DRDCALO (DRD6)

- Addressing three main categories of Calorimeters
  - Sandwich calorimeters with fully embedded electronics
  - Liquified Noble Gas calorimeter
  - Optical calorimeters
- Addressing transversal needs
  - Software
  - Active Materials
  - Photodetectors (no development)
  - Electronics
  - Testbeam organization

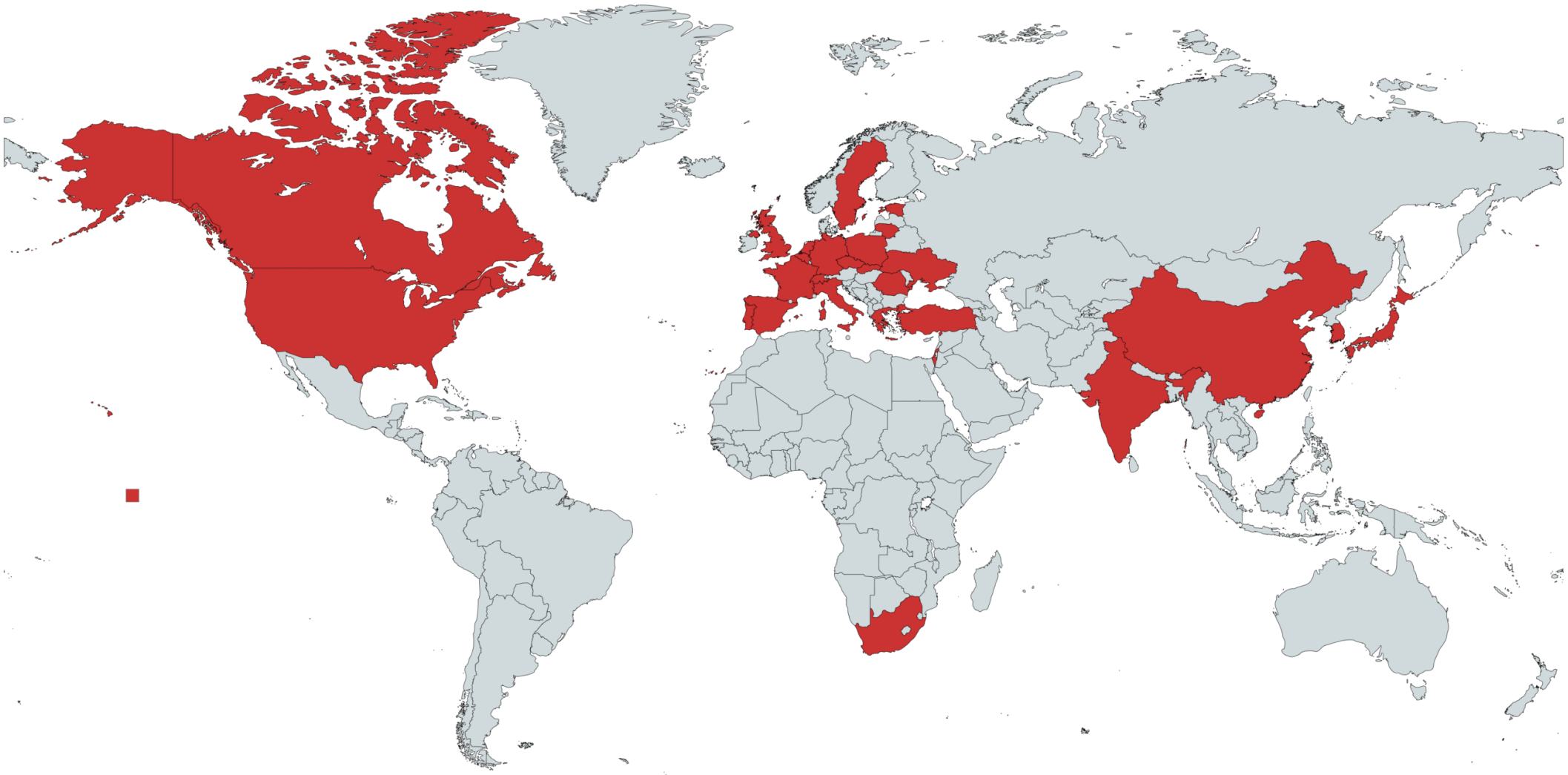
CPAD – RDC9

Areas of R&D Priorities

Topic Area	Description
RDC9-WP1	Broad R&D on new materials
RDC9-WP2	Broad R&D on calorimetry with ps timing
RDC9-WP3	Large-scale system challenge
RDC9-WP4	Scalable calorimetry optimized for large volumes and low cost
cRDCs-WP1	Intelligence in the front-end electronics
cRDCs-WP2	Timing distribution with picosecond synchronization
cRDCs-WP3	Monolithic Active Pixel Sensors
cRDCs-WP5	Readout electronics for sub-10ps timing detectors

Asian community well integrated in the DRDCalo collaboration

DRDCALO – A GLOBAL EFFORT



CPAD RDC 9: CALORIMETRY



Minfang Yeh



Marina Artuso

- Summary of RDC target area and priorities
  - New detector materials, wavelength sifters, and photon detectors
  - Fast (ps) timing calorimeters
  - Large scale system challenges (electronics, dataset); can AI/ML help?
  - Scalable calorimetry (large volume, low cost)
- A few highlight results
  - Calorimeters become imaging detectors? (fine segmentation and timing provide topology)
  - Liquid scintillator expands the detector design space
  - Simulation and reconstruction are central to detector development (GPU optical transport, AI-assisted, etc.)
  - Dual readout improves shower reconstruction (C/S separation)
- Key message for the community
  - RDC9 goals closely intertwined with several other RDCs (in particular RDC2, RDC4, RDC11)



NASA testbeam for 3D opaque Scintillators



Work on timing layers for future calorimetry



30-ton testbed for future liquid calorimetry



DESY testbeam: Multi-Institute Team

CALORIMETRY COMMUNITIES

DRDCALO (DRD6)

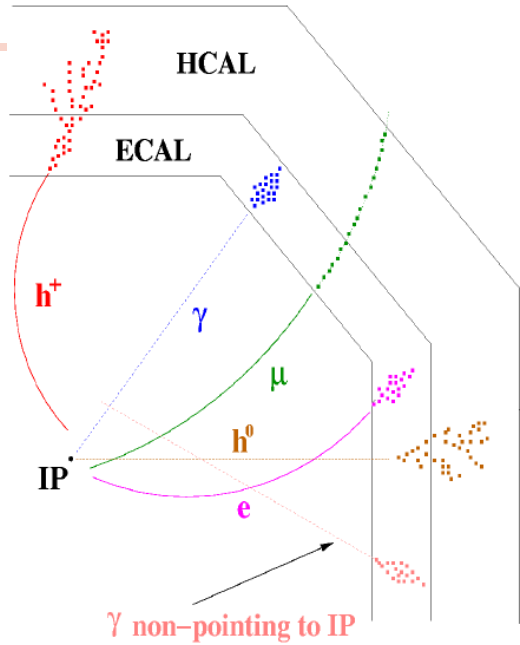
- Addressing three main categories of Calorimeters
  - Sandwich calorimeters with fully embedded electronics
  - Liquified Noble Gas calorimeter
  - Optical calorimeters
- Addressing transversal needs
  - Software
  - Active Materials
  - Photodetectors (no development)
  - Electronics
  - Testbeam organization

Added value of the collaboration

- First time different calorimeter technologies work together as a collaboration
- Leverage synergies in several common aspects
- Strenthening collaboration of calorimeter enthusiast all other the world

SANDWICH CALO WITH FULLY EMBEDDED ELECTRONICS

- Optimized for particle flow approach
  - integrated ECAL & HCAL (+ tracking)
- Sensor aspect and system aspect closely related
- Front-end electronics embedded in the calorimeter (including ASIC)



Solid State	Optical	Gaseous
Silicon or GaAs Detectors MAPS	Scintillator Strips Scintillator Tiles Glass Scintillator Tiles Lead Glass (Cherenkov)	RPC (semi-digital with Timing) MPGD

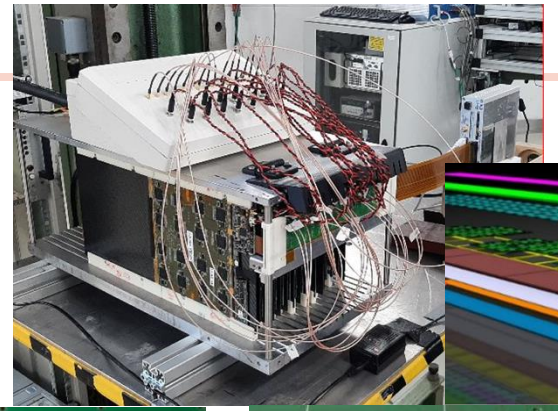
SANDWICH CALO WITH FULLY EMBEDDED ELX

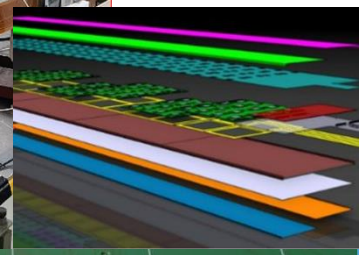
Strong connection with DRD7 (electronics)

Solid State

Silicon or GaAs Detectors
MAPS

Solid State sensors
connection with DRD3

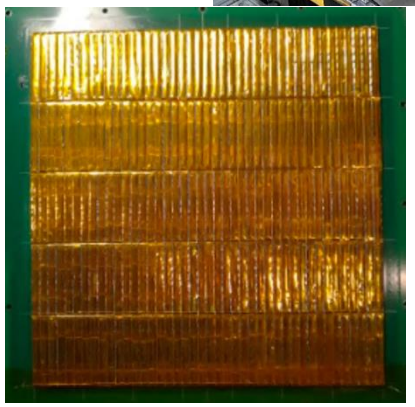


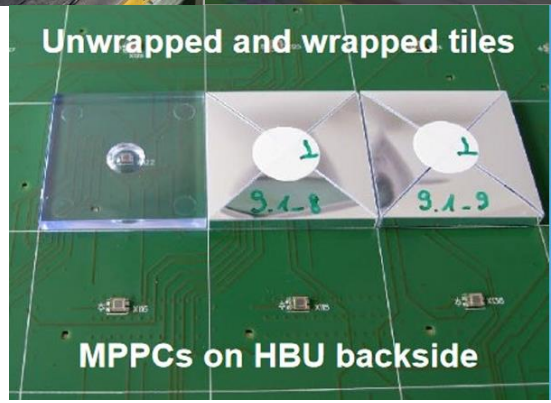


Optical

Scintillator Strips
Scintillator Tiles
Glass Scintillator Tiles
Lead Glass (Cherenkov)

R&D on optical material
Connection with DRD4
for photodetectors

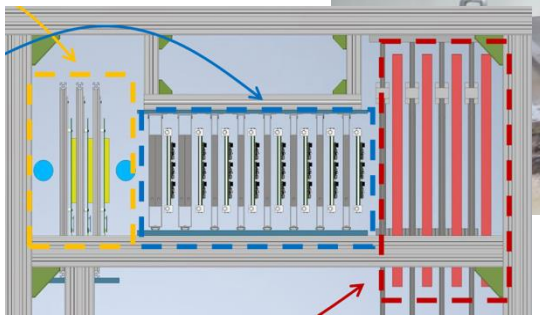




Gaseous

RPC (semi-digital with Timing)
MPGD

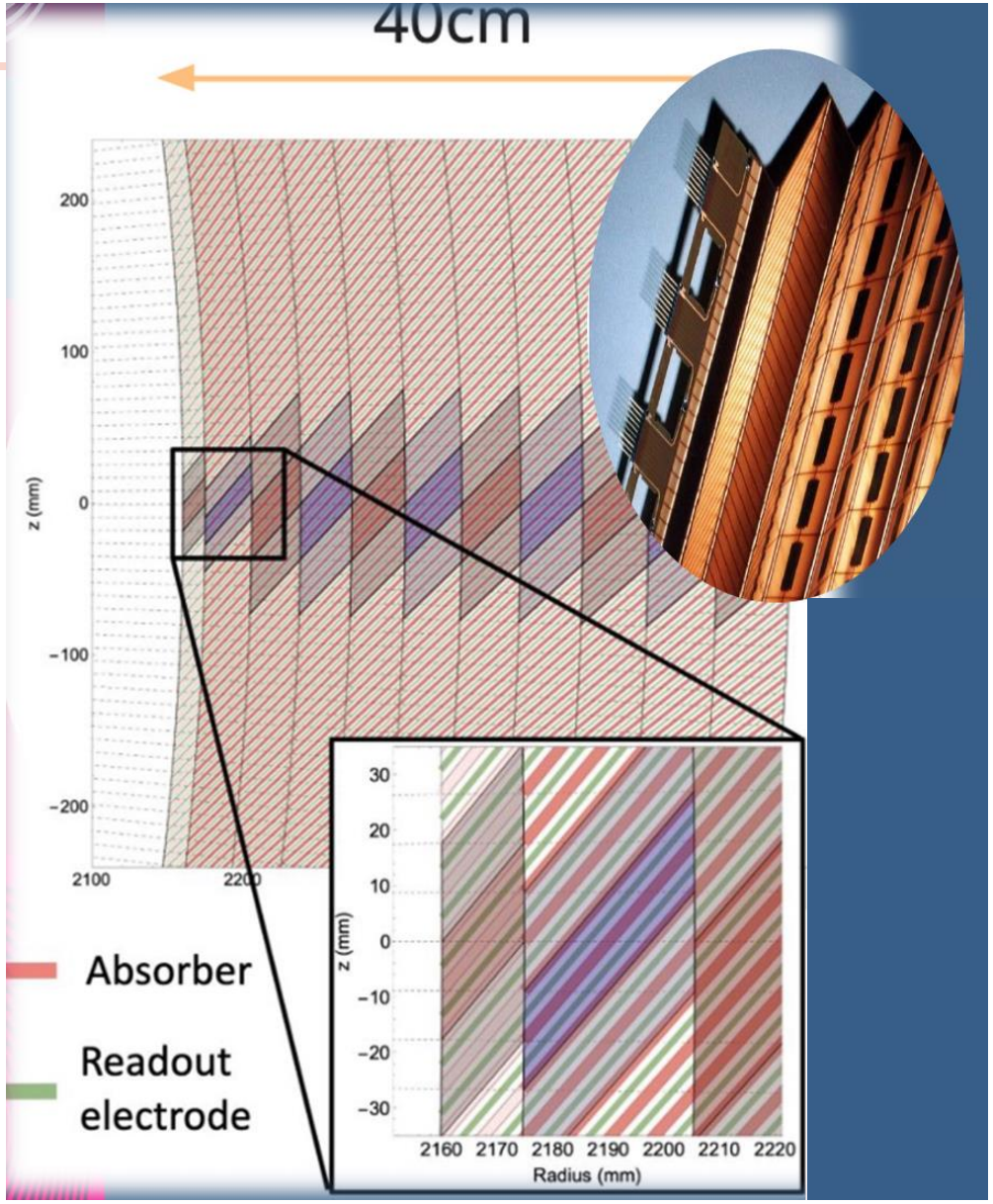
Connection with DRD1
for gaseous detector





LIQUIFIED NOBLE GAS CALORIMETERS

- Long and successful tradition in HEP
- Low systematics
- High granularity achievable => can be optimized for particle flow
- Cold electronics option under study
- Mechanical design optimization for energy resolution

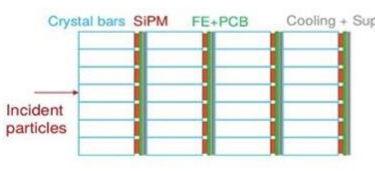


OPTICAL CALORIMETERS

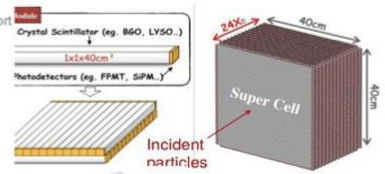
Homogeneous ECAL	Sampling ECAL	Sampling HCAL
• High granular crystal optimized for PF • Dual Readout segmented crystals • Rad-hard segmented crystals • Oriented crystals	• SpaCal with rad-hard scintillating fibres • Shashlik rad-hard with shower max measurement • Crystal grain innovative calo • 3D liquid/plastic scintillators	• Hadron tile calorimeter • Dual-Readout fibre calorimeter

Homogeneous EM

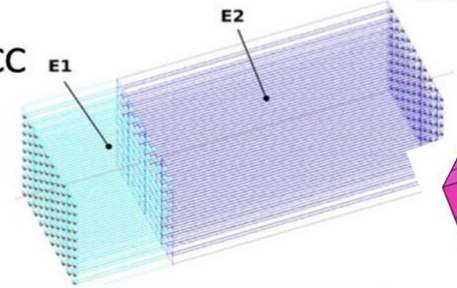
HGCCAL Design 1



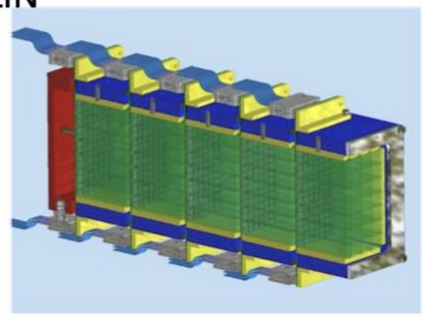
Design 2



MAXICC

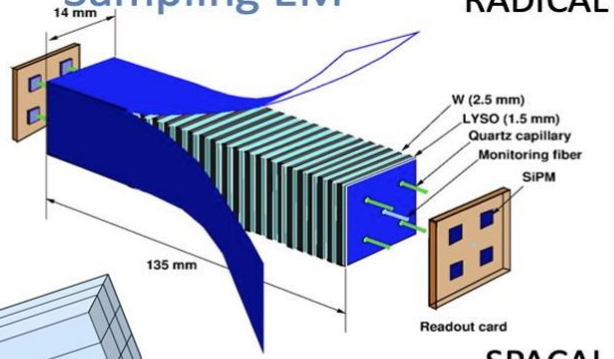


CRILIN

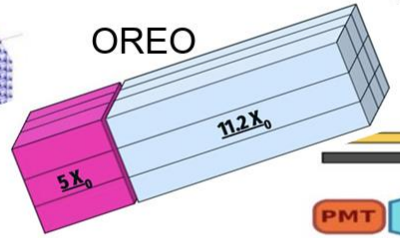


Sampling EM

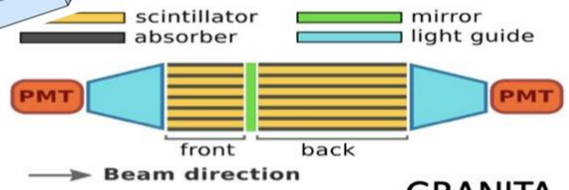
RADICAL



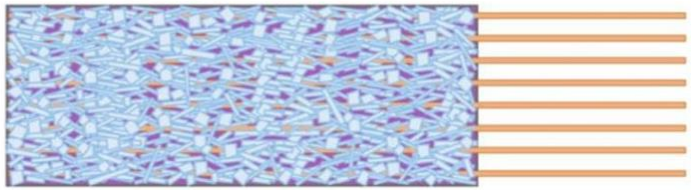
OREO



SPACAL



GRANITA

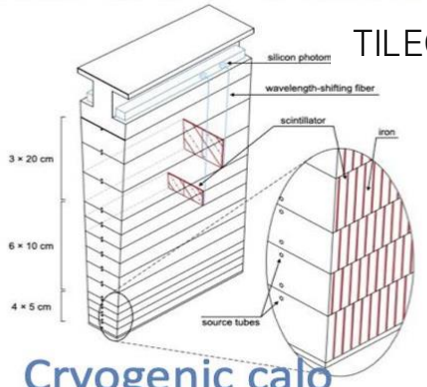


Sampling EM/HM

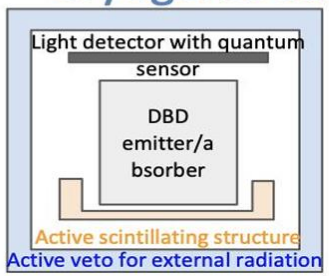
DRCAL



TILECAL



Cryogenic calo





OPTICAL CALORIMETERS

Homogeneous ECAL	Sampling ECAL	Sampling HCAL
• High granular crystal optimized for PF • Dual Readout segmented crystals • Rad-hard segmented crystals • Oriented crystals	• SpaCal with rad-hard scintillating fibres • Shashlik rad-hard with shower max measurement • Crystal grain innovative calo • 3D liquid/plastic scintillators	• Hadron tile calorimeter • Dual-Readout fibre calorimeter

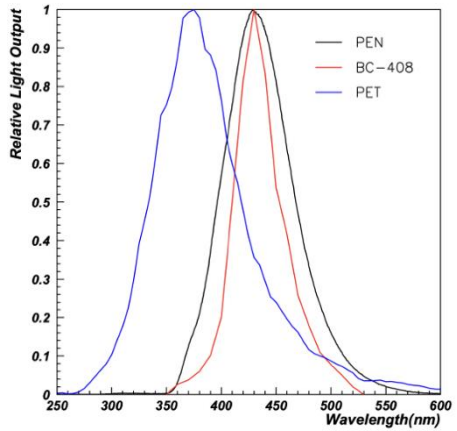
Calorimeters based on optical media

Photodetectors with large dynamic range and good linearity (mostly SiPM)

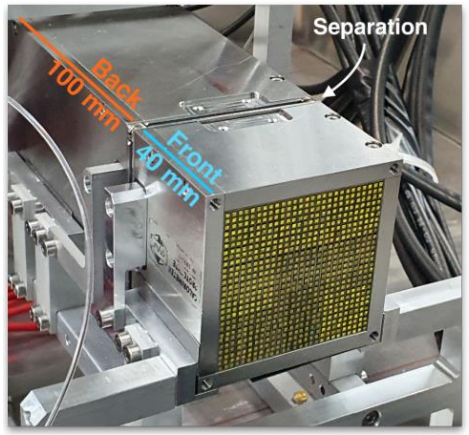
Enhanced granularity

R&D to develop faster and more rad-hard materials

OPTICAL CALORIMETERS (FEW MATERIAL EXAMPLES)

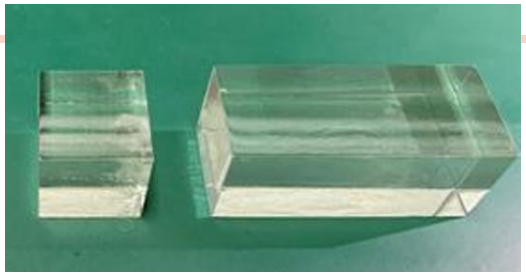


PEN/PET R&D



NIM A 1045, 167629 (2022)

W-GAGG crystal fiber R&D synergic to LHCb ECAL upgrade



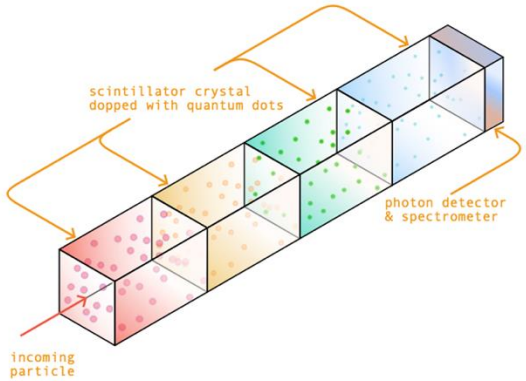
Large density	★★
High light yield	★★
Energy resolution	★★
Low cost	★★
Fast decay	★★
Large size	★★

Scintillating Glasses as a possible “cheap” alternative

$CsPbBr_3$ nanocrystals in epoxy resin



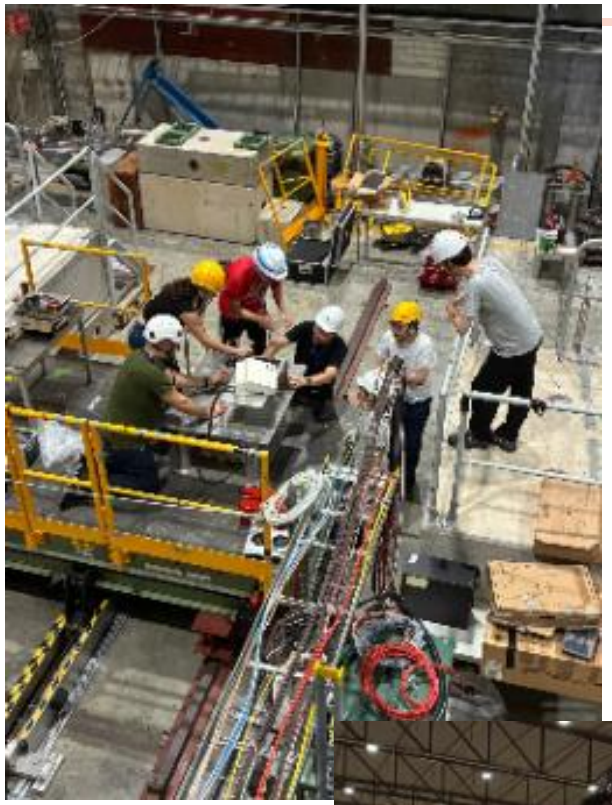
Nano-scintillators (ultrafast ~ 1ns) and rad-hard

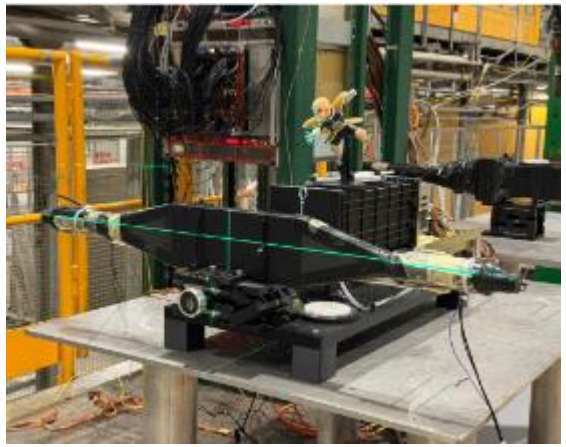


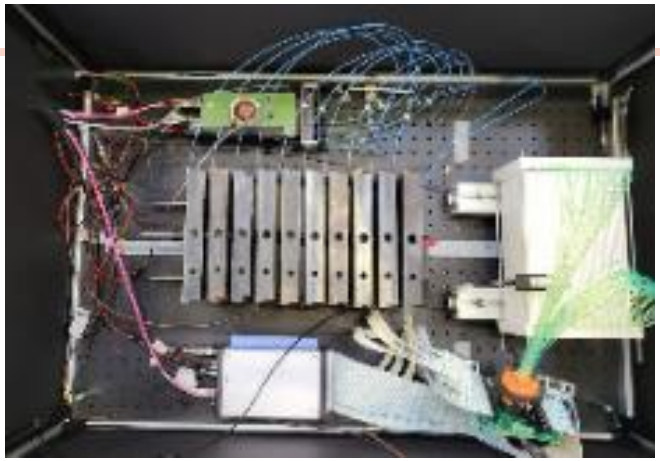
Quantum-dots for chromo calo

synergy with DRD4 and DRD5

DETECTORS PROTOTYPES … AT WORK



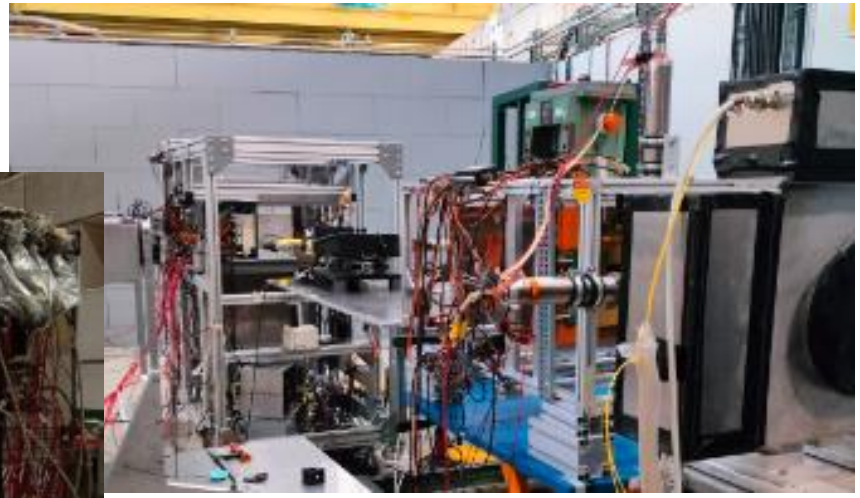


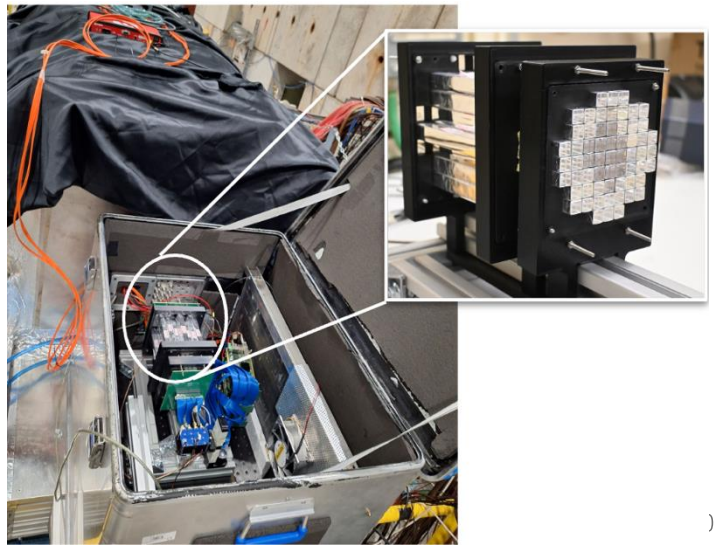


Several testbeam to prove the feasibility and the performance of the proposed technologies

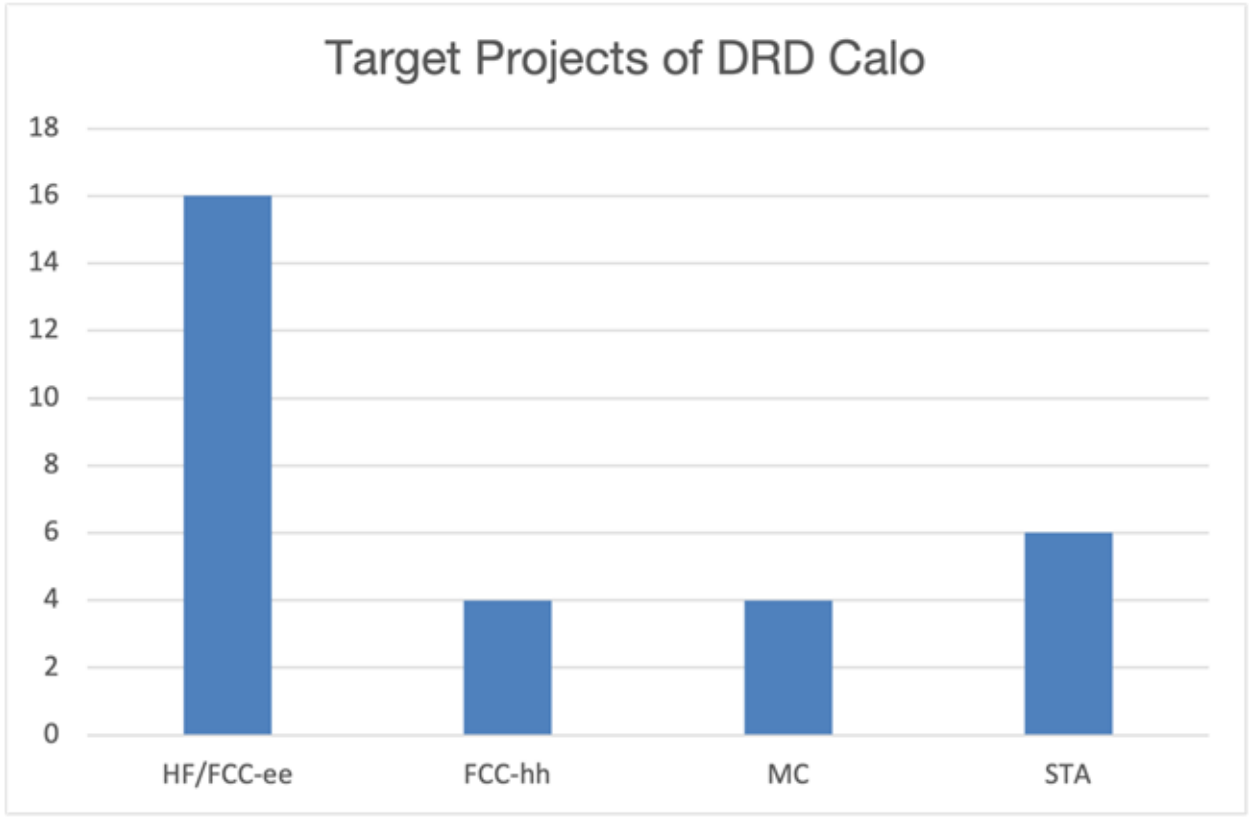






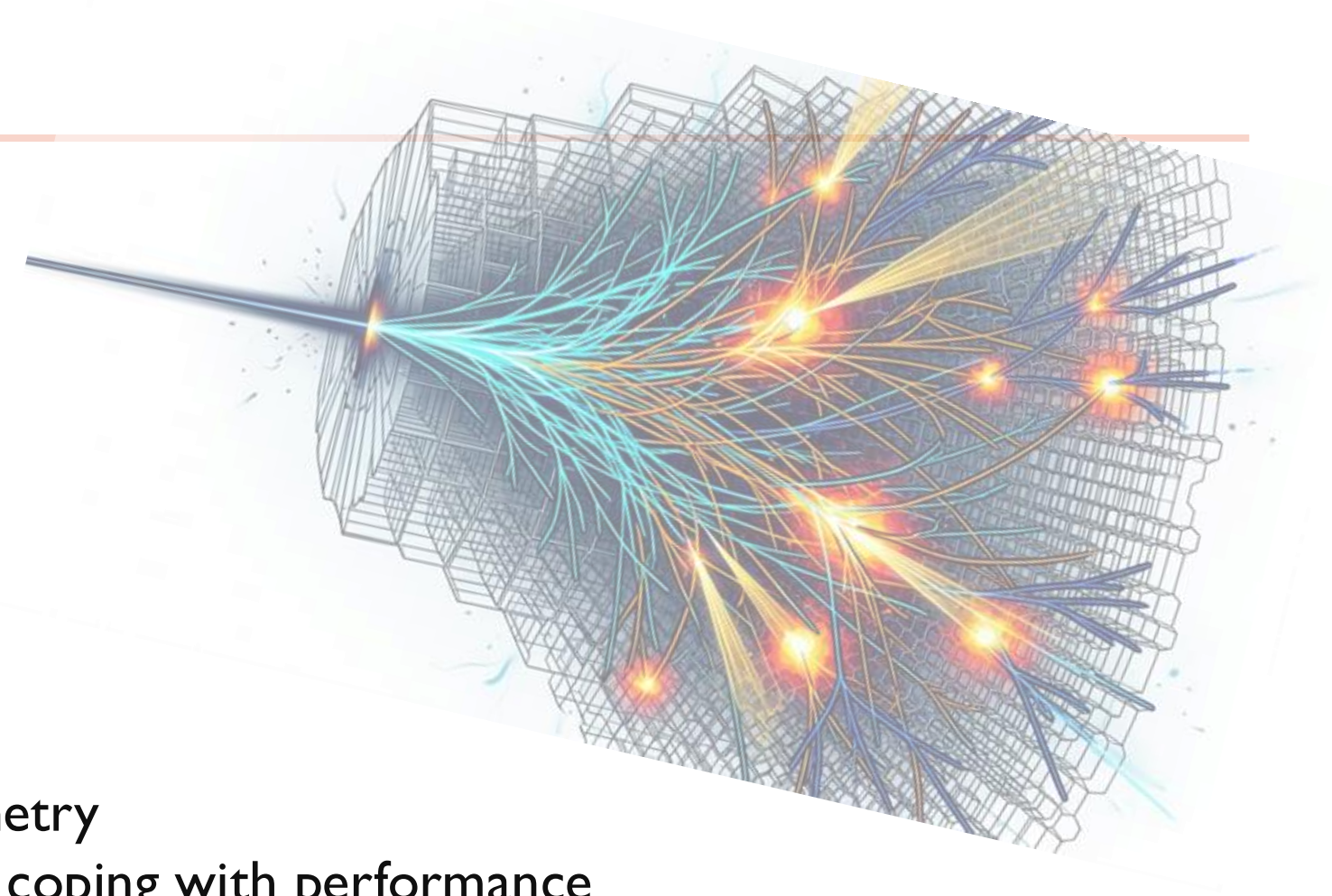


TARGETTING NEXT ACCELARATORS EXPERIMENTS



- Largely dominated by FCC-ee (w/o closing the door to alternative Higgs Facilities)
- FCC-hh already present as well as Muon Collider (MC)
- Our technologies in Short Term Applications (STA)
  - i.e. experiments that can/will happen on timescale < 10 years
  - LUXE, FASER, NA62, …

OUTLOOK



- Active R&D in the field of calorimetry
- Implementing a 5D paradigma for coping with performance needed by future experiments
- Cooperation at global level which includes all the communities

BACKUP

WP1: HIGHLY PIXELISED ELECTROMAGNETIC SECTION

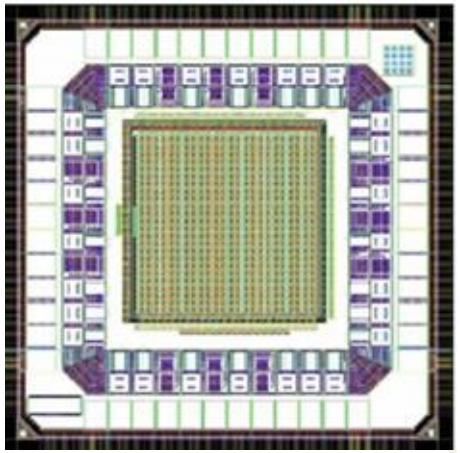


SiW ECAL

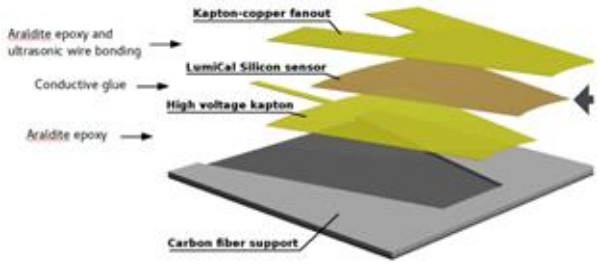
A SiW-ECAL using silicon pad sensors with analog readout

DECAL
Digital ECAL based on MAPS

A MAPS-based digital Silicon-Tungsten ECAL



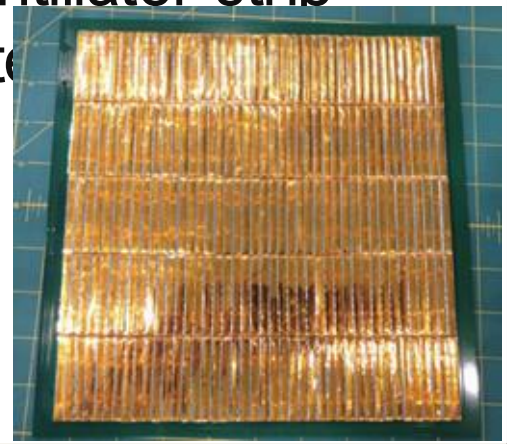
Highly compact electromagnetic calorimeter with semiconductor sensors, R&D on Si and GaAs sensors, including optimisation of readout integration



Highly Compact ECAL

Highly Granular Scintillator-strip Calorimete

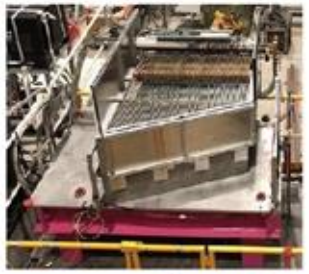
A tungsten-scintillator-strip (with SiPM readout) calorimeter



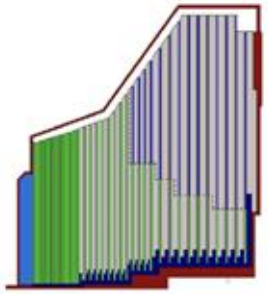
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WP1: HADRONIC SECTION WITH OPTICAL TILES

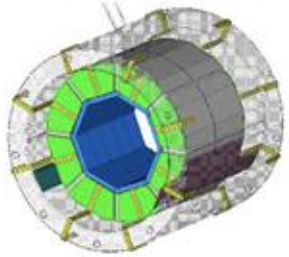
SiPM-on-Tile /Steel



2018
CALICE AHCAL
prototype
22'000 SiPMs



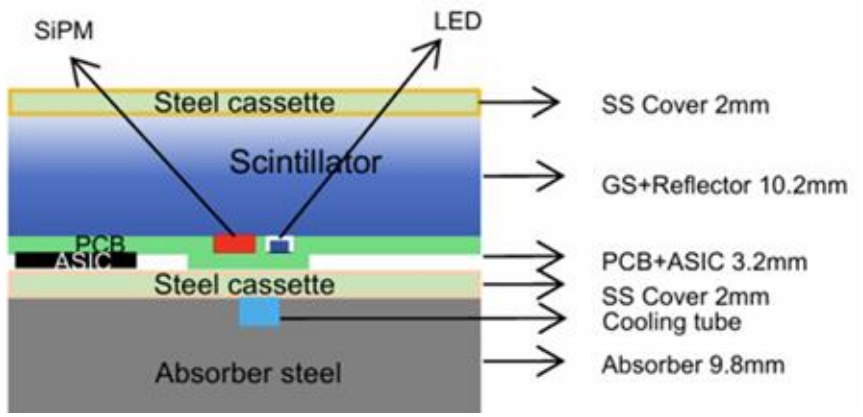
2028(?)
CMS HGCAL
(2 end-caps)
280'000 SiPMs



???
CLD / ILD HCAL
barrel only
4'000'000 SiPMs

Highly Granular HCAL with Glass Scintillator



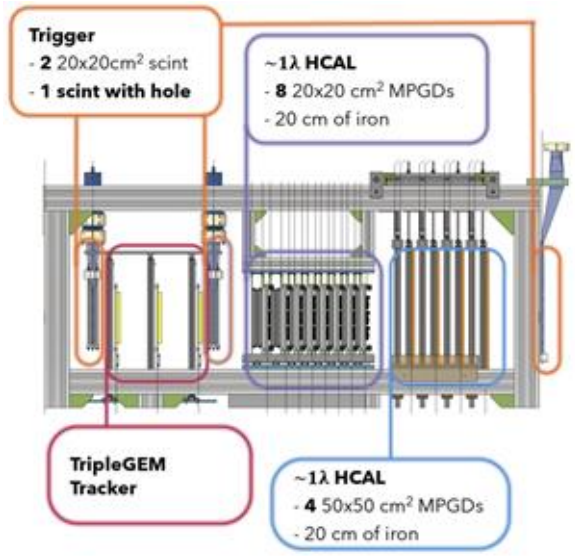


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WP1: HADRONIC SECTION WITH GASEOUS READOUT

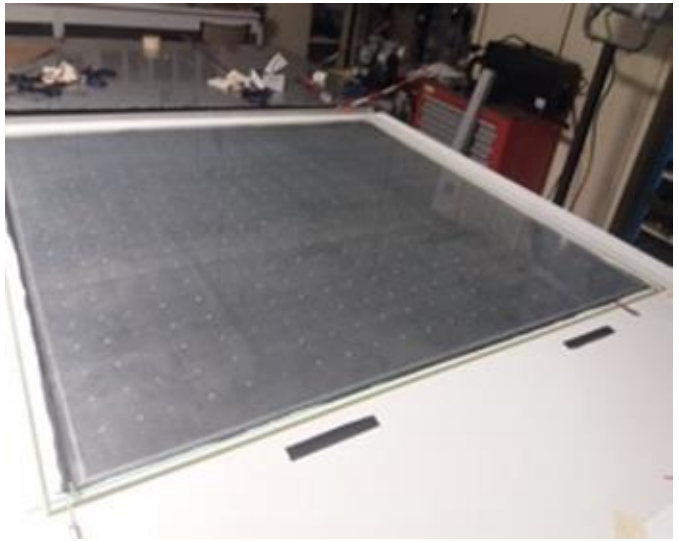
MPGD-based Hadronic Calorimeter

Using MPGDs (examples uRWELL, resistive Micromegas) for higher-rate environments



T-SDHCAL

A RPC-based semi-digital HCAL with timing capability



ADRIANO3 Triple Readout Calorimeter

Extension of ADRIANO2 (fully active granular dual readout calorimeter) to three readout modes.

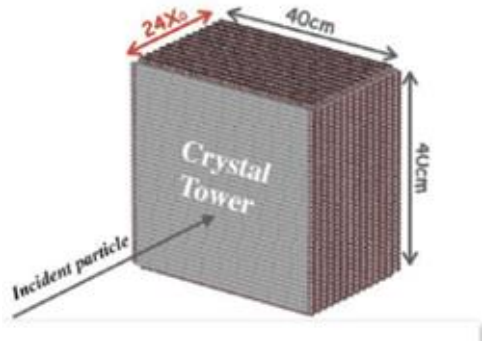
- High-density glass as Cherenkov Medium (and absorber)
- Plastic scintillator tiles
- RPCs.

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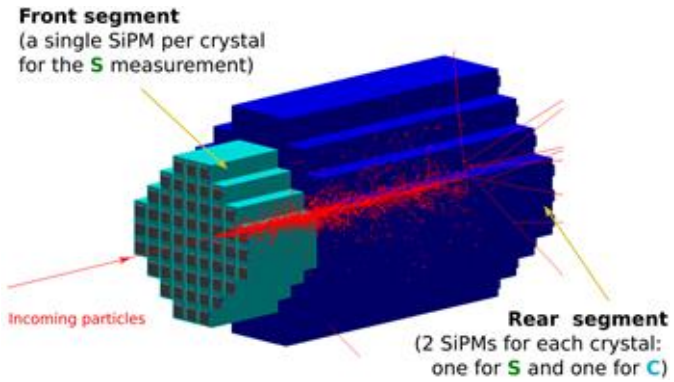
WP3: (QUASI)-HOMOGENEOUS EM CALORIMETERS

HGCCAL

Highly granular EM crystal based calorimeter to exploit maximum potential of PFA algorithms Integration



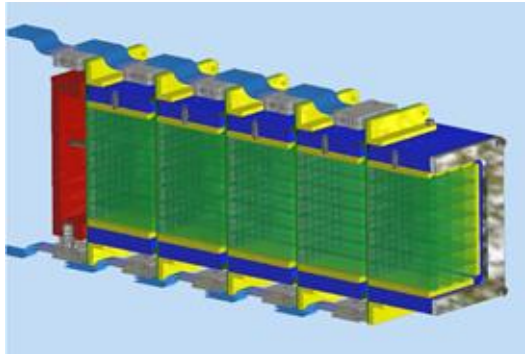
MAXICC



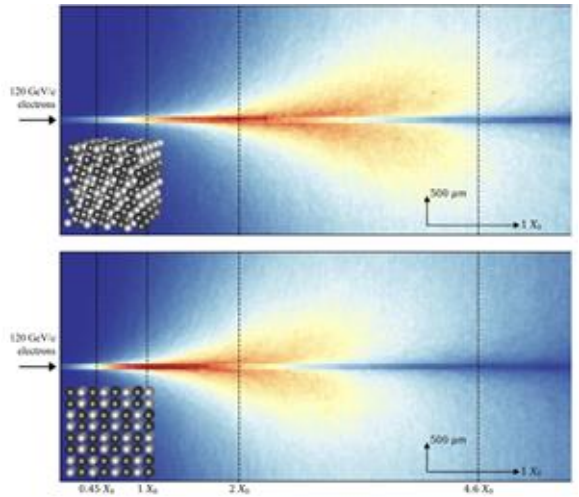
Homogeneous EM calorimeter based on segmented crystals with SIPMs readout and dual-readout capability

CRILIN

Radiation tolerant design of a longitudinally segmented crystal EM calorimeter



OREO



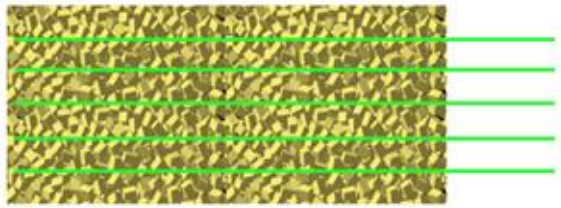
Homogeneous oriented crystals exploiting strong field (SF) regime, the shower development is accelerated

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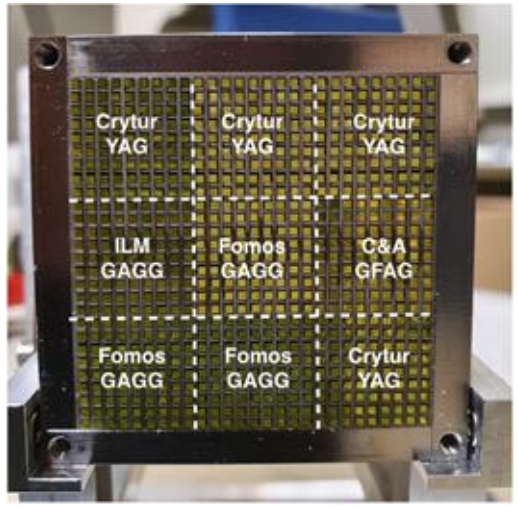
WP3: INNOVATIVE SAMPLING EM CALORIMETERS

GRAINITA

Innovative technique inspired by Shashlyk-type calorimeters. Extremely fine granularity. Grain of scintillator in dense liquid

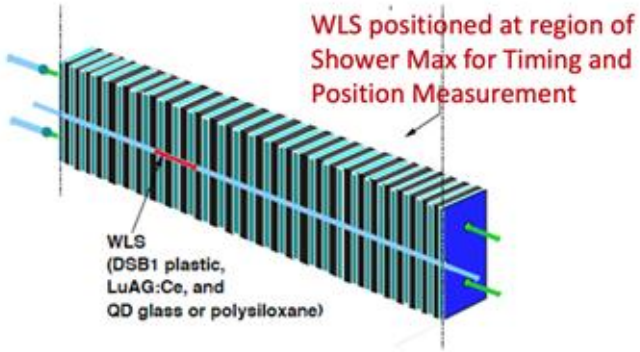


SPACAL



SpaCal (ECAL made of scintillating fibres in dense absorbers). Crystal or organic fibres in lead or tungsten absorber, hollow light guides, PMT/SiPM photon detectors

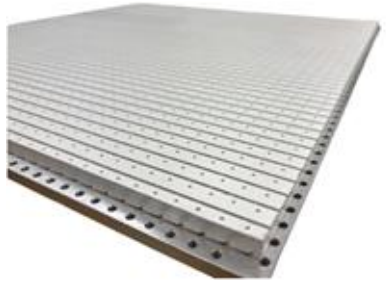
RADICAL

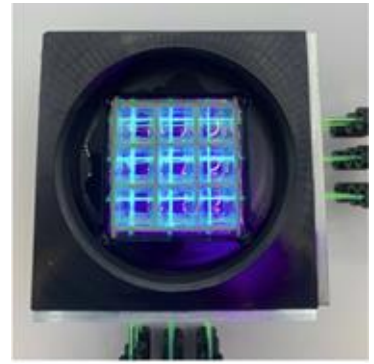


Radiation-hard WLS filament and SiPM Shashlik/type ECAL modules with tungsten absorber and LYSO:Ce tiles, WLS (full-length or in shower maximum)

3DNU

Plastic-scintillator glued cubes
3D-segmented Water-based Liquid Scintillator



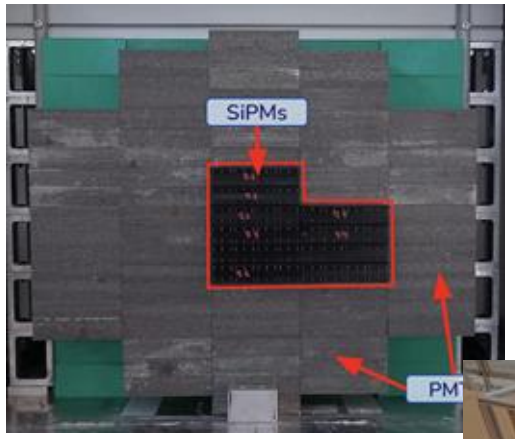


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WP3: HADRONIC CALORIMETERS

DRCAL

High resolution (Electromagnetic) and hadronic calorimeter based on dual-readout technique
Organic scintillating fibres in brass/copper/steel absorber
SiPM or MCP-PMT photon detectors

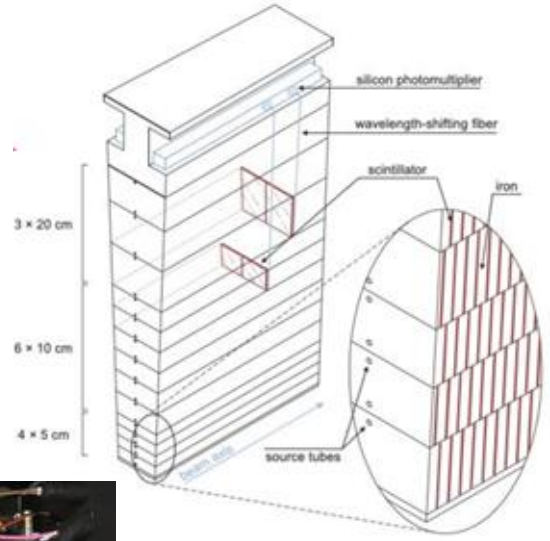


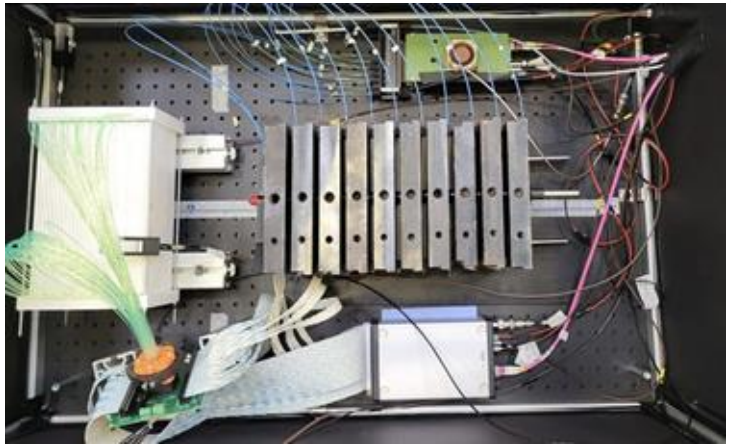




TILECAL

Hadron calorimeter with scintillating tiles and WLS fibre readout and SiPMs



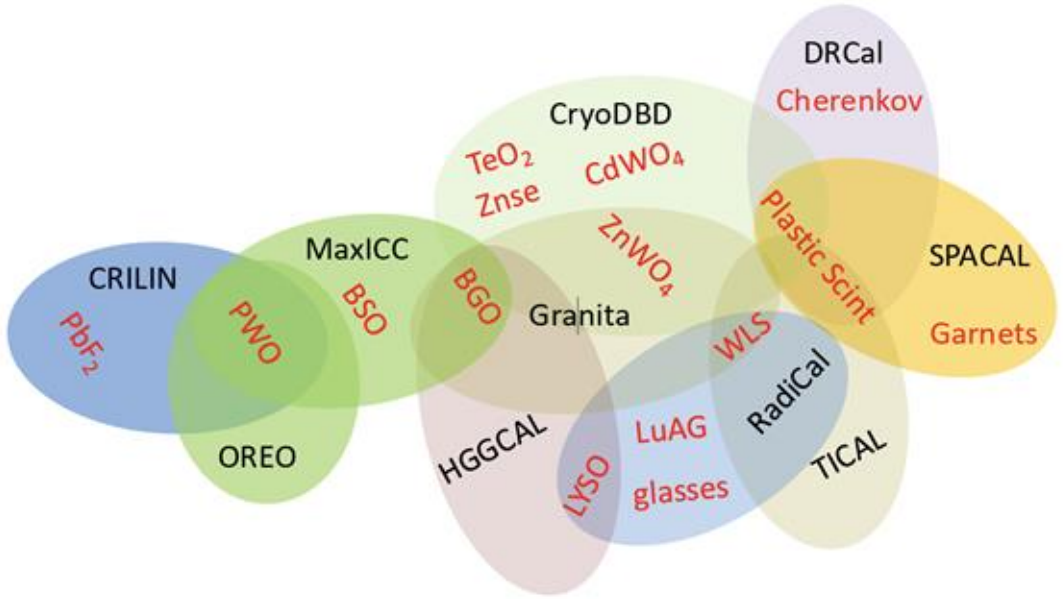


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WP3: MATERIALS

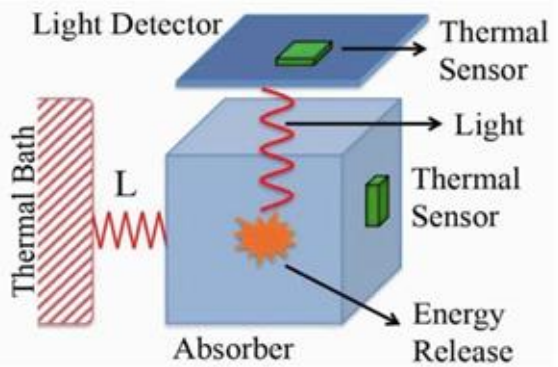
SCINTCAL (*)

Common scintillating materials between projects
Inorganic Scintillators
Scintillating glasses
Organic scintillators
Characterization method



CryoDBD Cal

Cryogenic calorimeter based on joint development of new scintillating materials to be used both as target and as active structural components of the setup



3d printed resin with the scintillating dye



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WG1: SOFTWARE, SIMULATION, AND DATA ANALYSIS

- Created to harmonise the software efforts across DRD Calo, exploiting synergies, pooling expertise, avoiding duplicate work, and ensuring long-term scalability and preservation.
- WG1 is well established with regular meetings every two months, complemented by two plenary sessions at every DRD Calo collaboration meeting.
- WG 1 steers offline activities, provides guidelines and training, discusses physics results with the broader community, and ensures members have adequate computing and storage resources.
- Identification of a common software framework, Key4hep, as the basis for all DRD Calo development
  - Already used for studies across the future-collider community, which represents the primary user community for DRD Calo projects.
  - Possibility of transfer a test-beam simulation software framework into a full 4π sub-detector simulation.
- Bridge the online and offline software worlds
  - translating data to the EDM4hep format after or during data taking
  - integrating raw data acquisition tools such as EUDAQ with Key4hep

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WG2: PHOTODETECTORS

- Supporting all calorimeter R&D activities based on light detection technologies
- Collecting and consolidating photodetector requirements from all DRD Calo work packages



photodetectors with fast response, rapid pixel recovery, large dynamic range, radiation tolerance, low crosstalk, and sensitivity from the ultraviolet to the infrared region.
achieve very small cell sizes (around 5 μm) to increase dynamic range while maintaining high photon-detection efficiency (PDE) and stable gain after irradiation

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WG5: ACTIVE MATERIALS

- All proposed detector concepts in WP 3 and some in WP 1 use (organic or inorganic) scintillating materials (link to DRD5)
  - R&D on radiation-hard fast scintillators
  - Intrinsic dense scintillators with simultaneous Cherenkov and scintillation emission
  - ultrafast inorganic scintillators for timing layers or calorimeters requiring very good timing resolutions
  - cost-effective scintillators (plastics, glasses) for large volume detectors
  - new scintillating materials using nanoscintillators
  - Look at new production technologies like e.g. 3D printing, micropulling down and low-cost crucibles.
- The objectives of the Working Group include:
  - Surveying the needs and requirements of all subtasks using scintillators;
  - Identifying synergies between requirements of the different subtasks to maximise a common and transversal R&D between subtasks to limit the duplication
  - Helping subtasks in the choice of the best scintillators or in the development of new materials by making the link between subtasks and experts in scintillator development and characterisation (crystal growers, chemists and physicists, etc.);
  - Giving access to dedicated characterisation setups;
  - Making the link between the HEP and scintillator communities to:
    - in one way, by informing DRD Calo members about new scintillator developments,
    - in the other way, by informing the scintillator community of the needs in HEP
  - promote innovative and blue-sky developments for long-term future detectors

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WP4: ELECTRONICS AND DAQ

- Goal
  - Optimize commonalities between readout chips or DAQs, enable common test beams
  - Foster exchanges on designs and architectures between WPs
  - Share engineering runs whenever possible to get large quantities at affordable price

- Recent evolution of technologies
  - TSMC is phasing out 130nm fab12&14 in 2026, possibly keeping access to fab6 for a few years
  - TSMC is discouraging new projects in 65nm (and 28) in the next few years
  - TSMC policy is evolving rapidly (towards 2nm AI chips) and becomes more unpredictable
  - Reminder : TSMC produces 17M wafers/year, particle physics buys at most 1k (DRD6 bought 6)

- Need to find alternative manufacturers
  - But long time needed for development and qualification for radiation
  - Perenity is the leading factor for us

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