ECFA WG3: Topical workshop on calorimetry, PID and photodetectors

DRD6 plans for sampling(*) calorimeters

(*) non only fibres

Gabriella Gaudio
INFN-Pavia
on behalf of the DRD6 community

Towards DRD6 - Calorimetry

- 1st Community meeting (12.1.2023)
  https://indico.cern.ch/event/1212696/
- Launch of Input proposal collection
  - mid February – April 1st
  - Scientific proposal of what need to be built and tested in the next 3 (2024-2026) - 6 (2027-2029) years
  - Description and timeline
  - Objectives:
    - Milestones
    - Deliverables
  - List of participating Institutes/Labs with short description

The Proposal Team

Track 1: Sandwich calorimeters with fully embedded Electronics – Main and forward calorimeters
Track conveners:
Adrian Irles (IFIC), **Frank Simon** (KIT), **Jim Brau** (U. of Oregon), **Wataru Ootani** (U. of Tokyo)

Track 2: Liquified Noble Gas Calorimeters
Track Conveners:
Martin Aleksa (CERN), **Nicolas Morange** (IJCLab), **Marc-André Pleier** (BNL)

Track 3: Optical calorimeters: Scintillating based sampling and homogenous calorimeters
Track Conveners:
Etiennette Auffray (CERN), **Gabriella Gaudio** (INFN-Pavia), **Macro Lucchini** (U. and INFN Milano-Bicocca), **Philipp Roloff** (CERN), **Sarah Eno** (U. of Maryland), **Hwidong Yoo** (Yonsei Univ.)

Track 4: Transversal Activities
Christophe de La Taille (Lab. Omega)

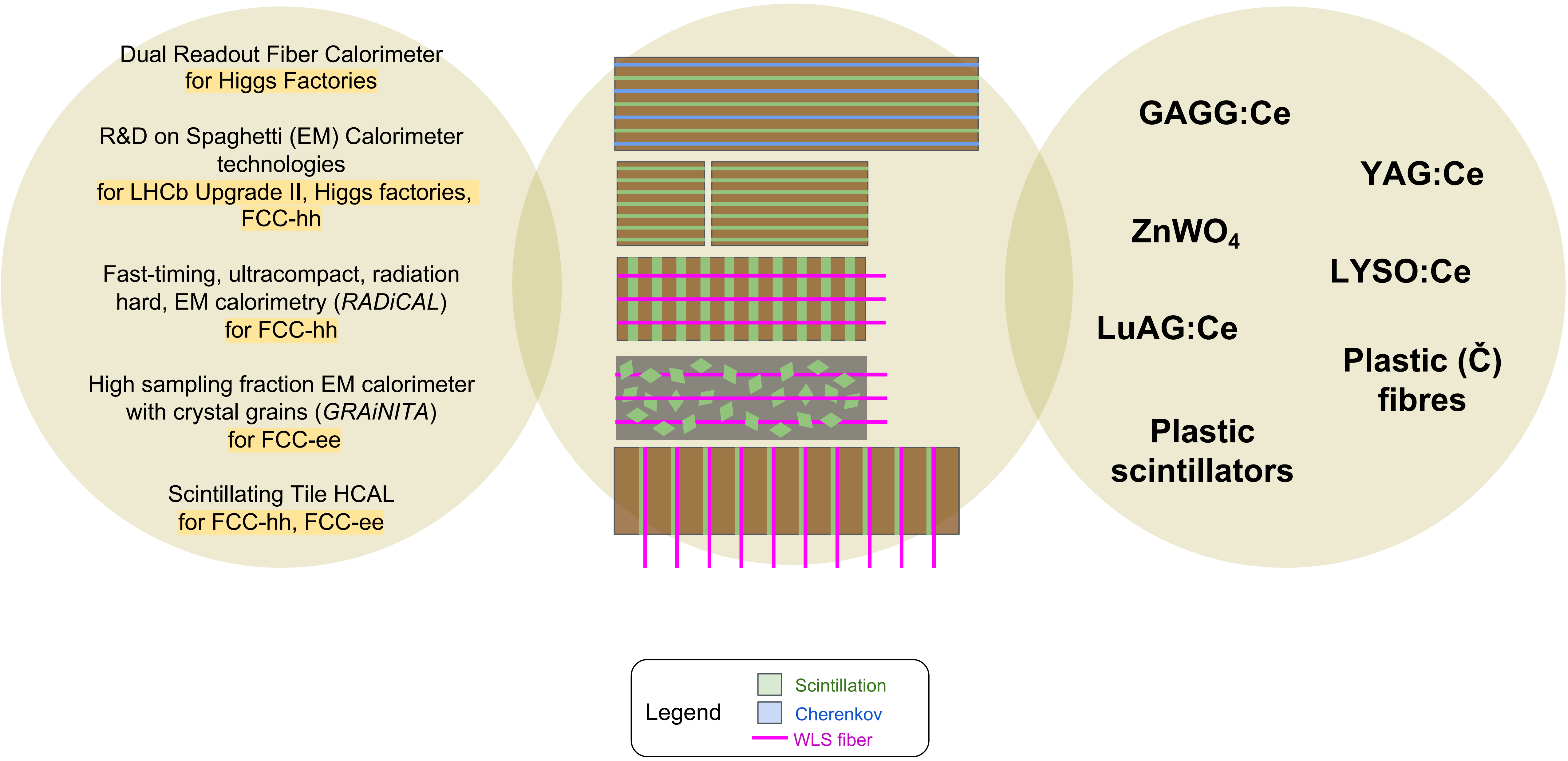
DRD6 Track 3: Optical calorimeters

Scintillator based sampling calorimeters	Homogeneous EM crystal calorimeters	Homogeneous (EM+HAD) calorimeters	Large mass cryogenic calorimeters
Dual Readout Fiber Calorimeter for Higgs Factories R&D on Spaghetti (EM) Calorimeter technologies for LHCb Upgrade II, Higgs factories, FCC-hh Fast-timing, ultracompact, radiation hard, EM calorimetry (*RADiCAL*) for FCC-hh High sampling fraction EM calorimeter with crystal grains (*GRAiNITA*) for FCC-ee Scintillating Tile HCAL for FCC-hh, FCC-ee	Maximum Information Crystal Calorimeter for Higgs Factories High Granularity Crystal Calorimeter for Higgs Factories Fast, segmented Crystal calorimeter for Muon Collider (*CRILIN*)	Triple-readout sandwich calorimeter for DM and BSM low energy physics (*ADRIANO3*) Dual-readout Sandwich Calorimeter for future colliders	Large mass cryogenic calorimeters for neutrinoless double beta decay

ScintCal: **Scintillator** material for future calorimeters

Courtesy M. Lucchini, P. Roloff
DRD6 2nd Community Meeting

Scintillator Based Sampling Calorimeters



Commonalities

- Use of SiPMs
- Particle-Flow Friendly approach
- Targeting 10-100 ps timing precision

Courtesy M. Lucchini, P. Roloff
DRD6 2nd Community Meeting

Scintillating Tile HCAL

- **Detector concept**: Hadron calorimeter with scintillating tiles and WLS fibre readout
- **Target application**: FCC-hh and FCC-ee
- **Unique challenges**: Cost-effective production of tiles, radiation hardness for FCC-hh
- **Technology**: Organic scintillating tiles, Steel (+Pb for FCC-hh) absorber, readout by WLS fibres and SiPMs
- **Next 3+ year goals**: Performance studies using simulations, R&D on PEN and PET scintillator, mechanical design and construction of test-beam modules

*CERN (**Switzerland**)*

*LIP (**Portugal**)*

*FZU (**Czech Republic**)*

*Universitetet I Bergen (**Norway**)*

*IFIC - Valencia University (**Spain**)*

*INCDTIM (**Romania**)*

*Charles University (**Czech Republic**)*

Scintillating Tile HCAL

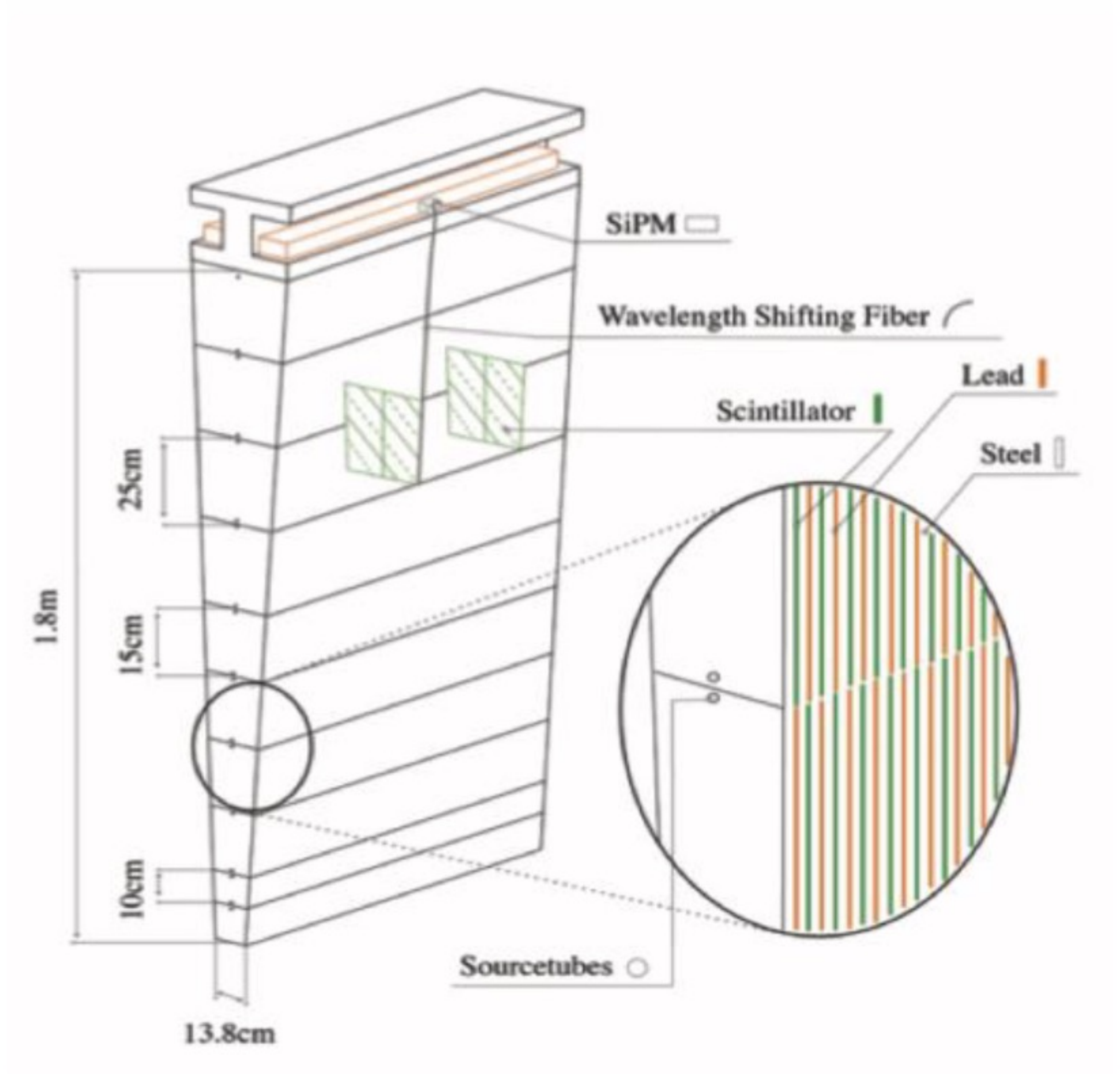


Figure 1: Sketch of the proposed layout for FCC-hh. Adding Pb absorber improves the e/h ratio.

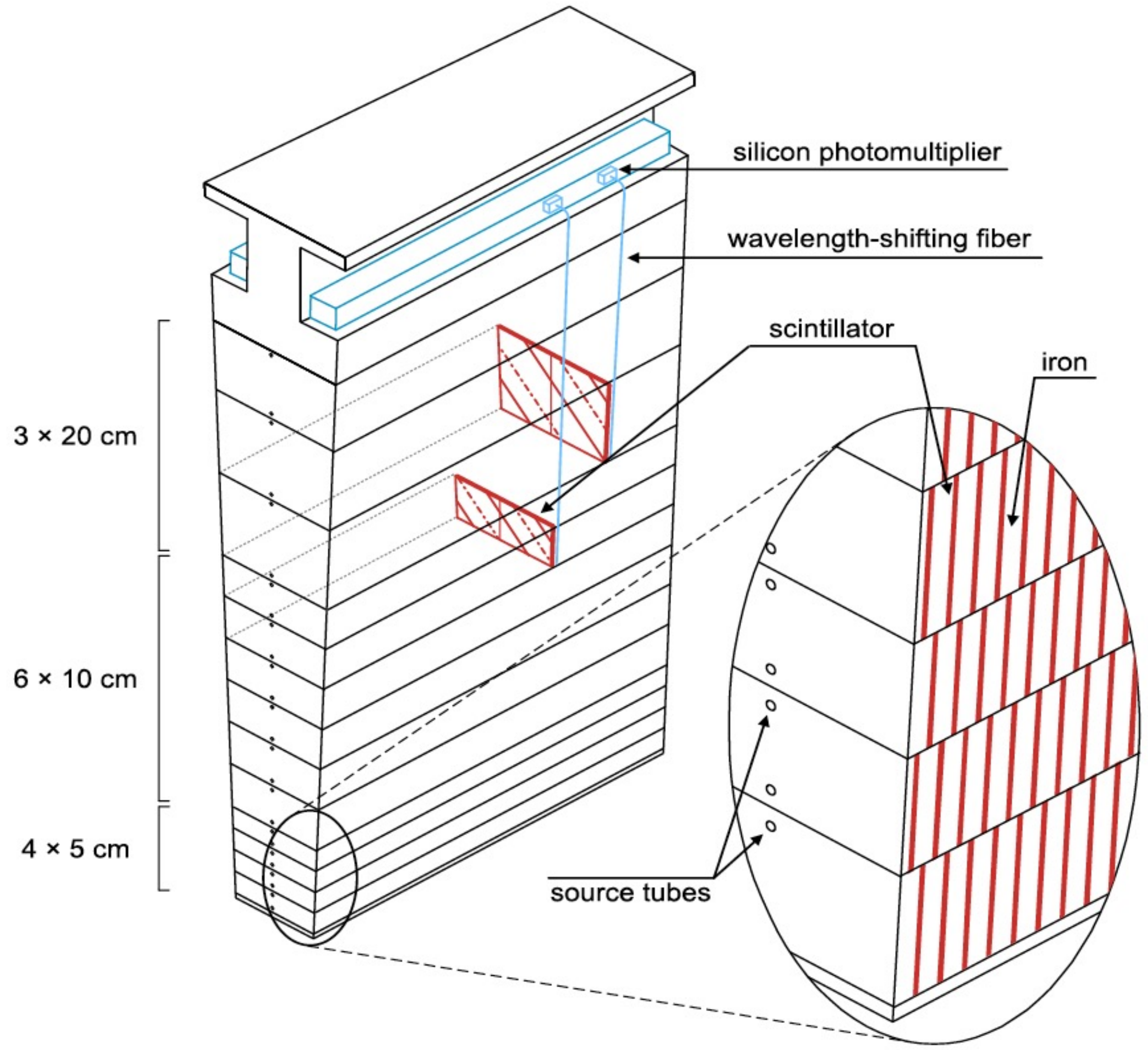
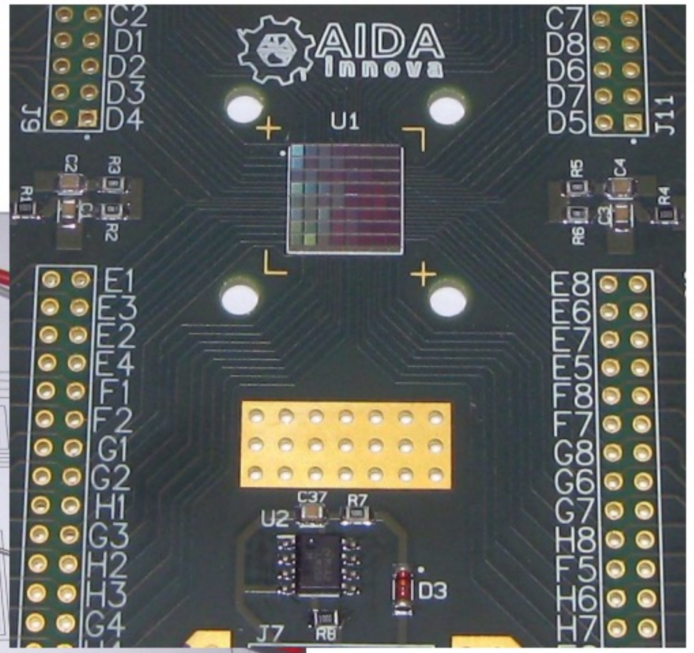


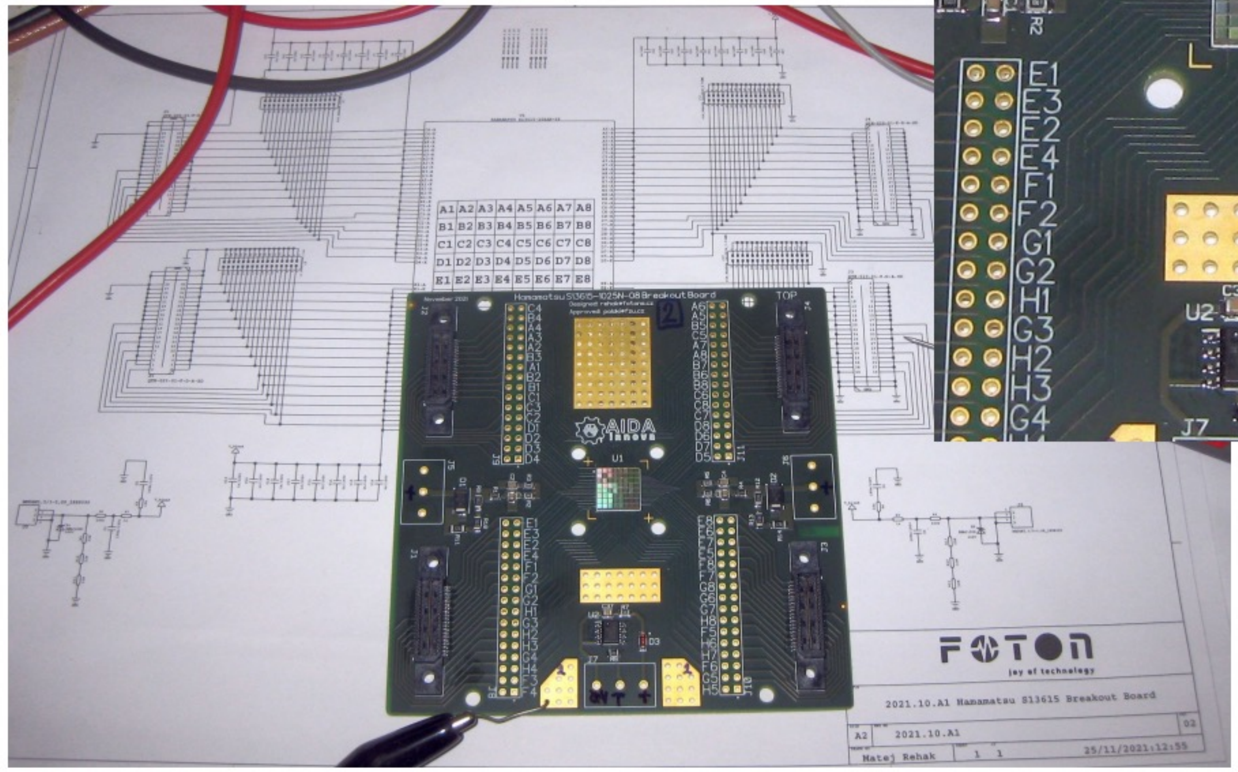
Figure 2: Sketch of the proposed layout for FCC-ee, where the absorber structure acts as return yoke for the central solenoid field.

Scintillating Tile HCAL – High granularity

Expanding PCB for SiPM array

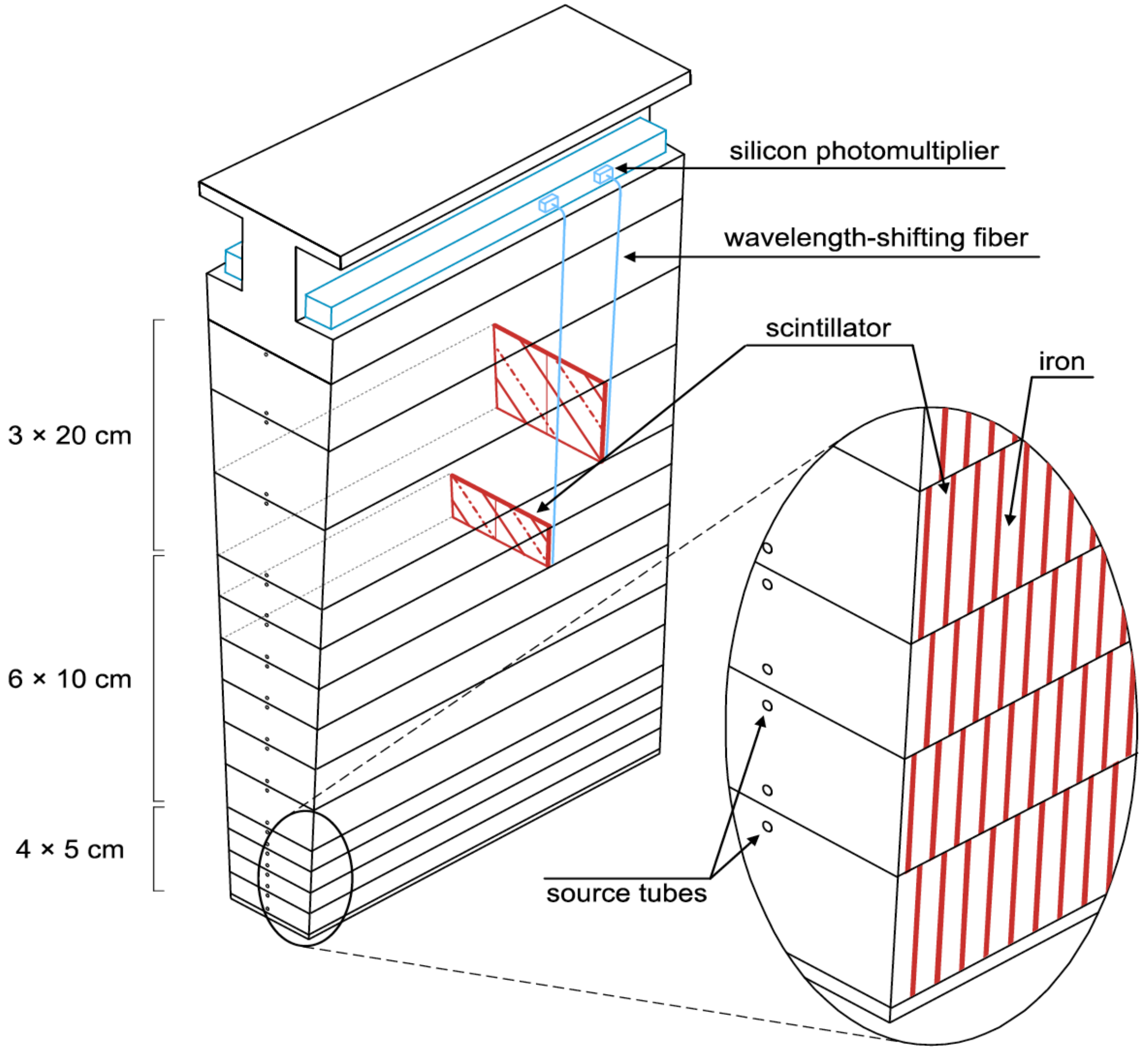
We use 64CH SiPM Hamamatsu S13615 – 1025 (U1)
- Small footprint 6 x 6 mm
- For first test we use a few channels
- Temperature sensor LM35 onboard (U2)





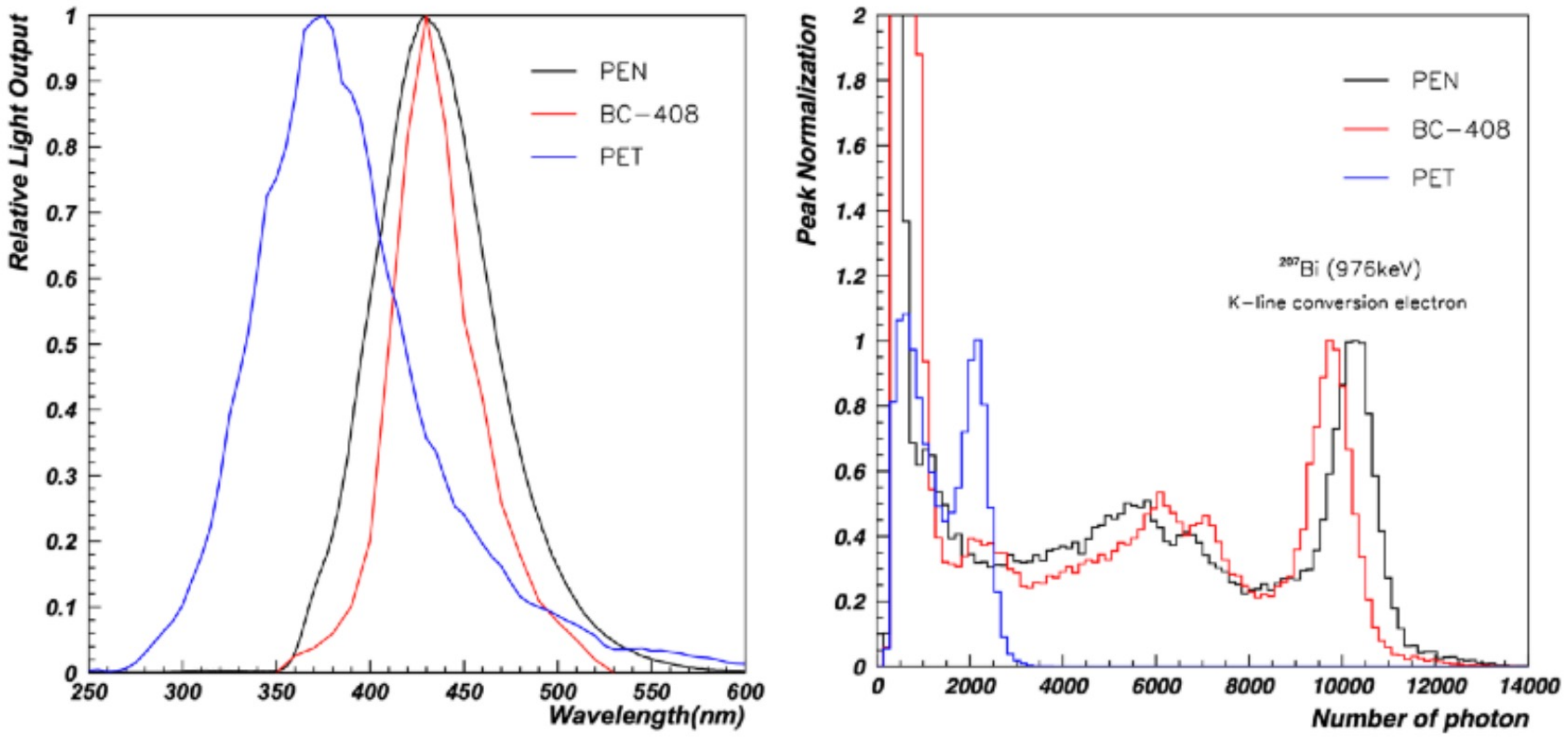
Low cost SiPM allows to consider future designs with very high granularity (Δη × Δφ = 0.007-0.025x0.025)

This opens the way for novel energy reconstruction algorithms, as particle flow or deep neural networks.



Scintillating Tile HCAL – Scintillating Material

- Polyethylene Naphthalate (PEN)
  - Intrinsic blue scintillation (425 nm)
  - Short decay time
- Polyethylene Terephthalate (PET)
  - A common type polymer
  - Plastic bottles and as a substrate in thin film solar cells.
  - Emission spectrum of PET peaks at 385 nm [Nakamura, 2013]



Emission Spectrum and Light Output of PEN, PET and commercial BC-408 scintillator. [H. Nakamura et al. 2011 EPL 95 22001]

Table 1: Properties of the three samples used in the present study.

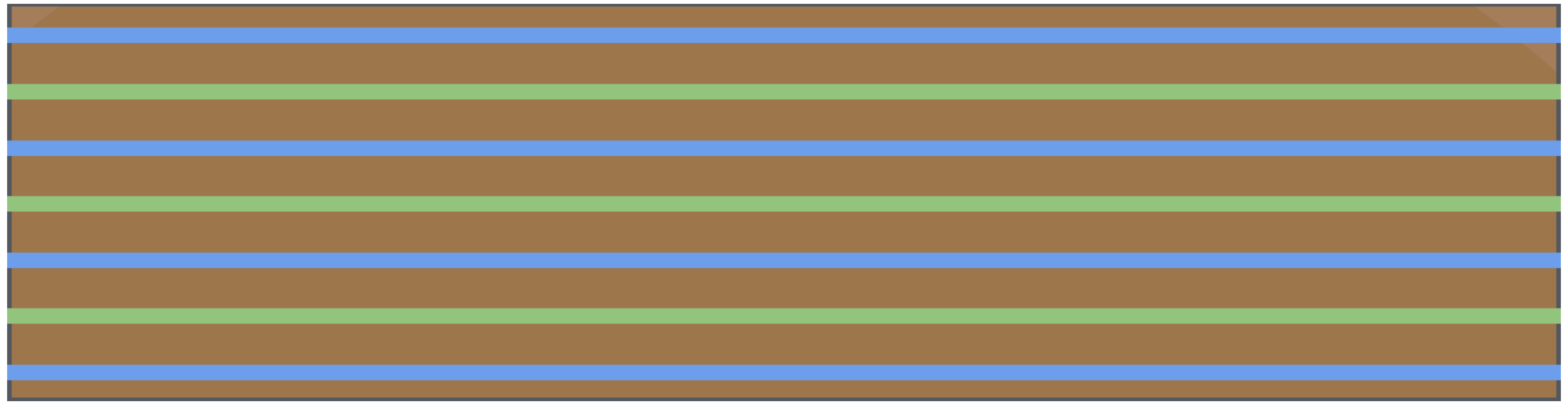
Material	Polyethylene naphthalate	Organic scintillator (ref. [14])	Plastic bottle (ref. [13])
Supplier	Teijin Chemicals	Saint-Gobain	Teijin Chemicals
Base	$(C_{14}H_{10}O_4)_n$	$(C_9H_{10})_n$	$(C_{10}H_8O_4)_n$
Density	$1.33\,g/cm^3$	$1.03\,g/cm^3$	$1.33\,g/cm^3$
Refractive index	1.65	1.58	1.64
Light output	~ 10500 photon/MeV	10000 photon/MeV	~ 2200 photon/MeV
Wavelength max. emission	425 nm	425 nm	380 nm

Fibre Dual Readout calorimeter

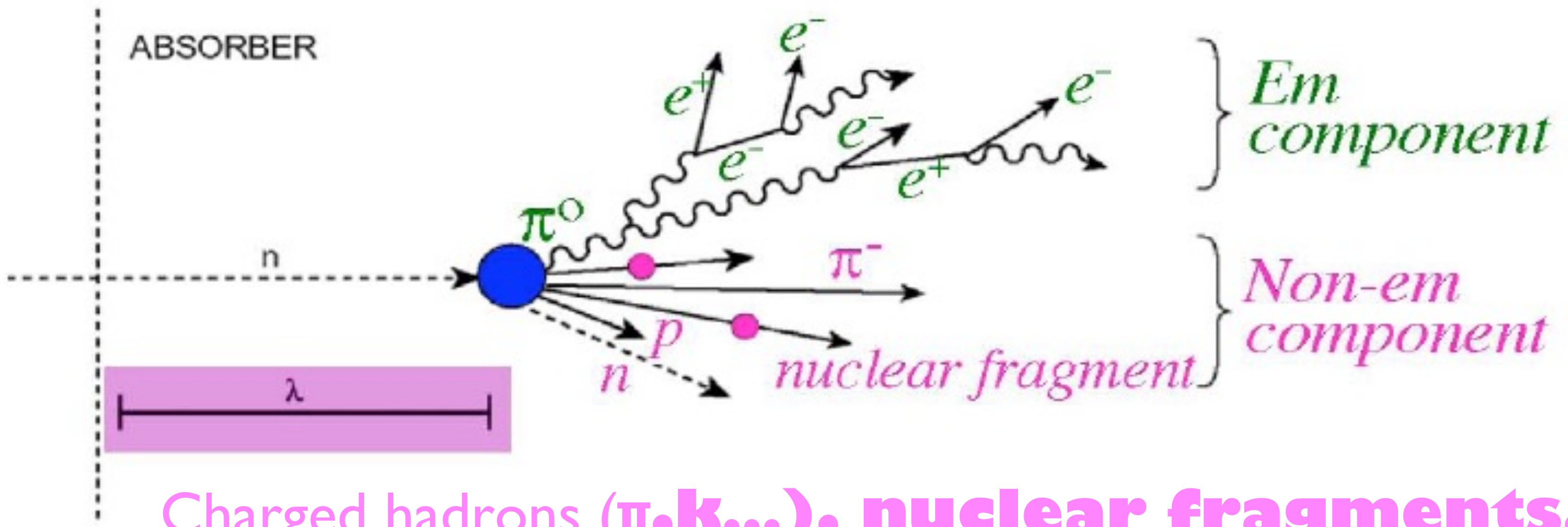
- **Detector concept**: Dual-readout calorimetry
- **Target application**: Future Higgs factory (needs excellent hadronic energy resolution, good electromagnetic energy resolution)
- **Unique challenges**: integration of a large number of SiPMs
- **Technology**: Organic scintillating fibres in brass or steel absorber, SiPM or MCP-PMT photon detectors
- **Next 3+ year goals**: test beam with full containment prototype modules, development of readout system

*University of Bologna and INFN Bologna (**Italy**)*
*University of Insubria and INFN Milano (**Italy**)*
*INFN Pavia (**Italy**)*
*INFN Pisa (**Italy**)*
*Sapienza University and INFN Roma (**Italy**)*
*University of Sussex (**UK**)*
*Texas Tech University (**USA**)*
*Korea Consortium: Yonsei University, Kyungpook National University, University of Seoul, Gangneung-Wonju National University, Pusan University, Sungkyunkwan University, Korea University, Hanyang University (**Korea**)*

Fibre Dual Readout calorimeter



electrons positrons, photons, π^0



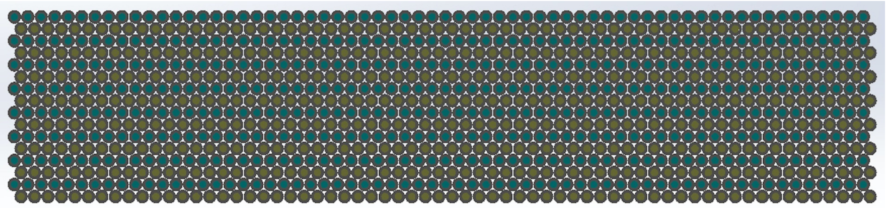
Charged hadrons (π,k…), **nuclear fragments,** neutrons, neutrinos, breakup of nuclei (invisible energy)

Target performance:

- a stand-alone hadronic resolution around 30%/√E or better, for both single hadrons and jets
- a resolution for isolated electromagnetic showers close to 10%/√E;
- a transverse resolution of O(1 mrad)/√E;
- a longitudinal resolution of a few cm (through timing);
- a constant term at ~1% level or below.

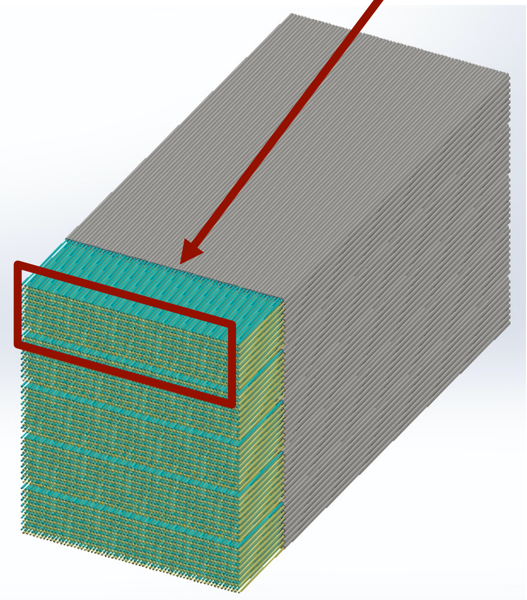
Fibre Dual Readout calorimeter - construction

The Mini-Module

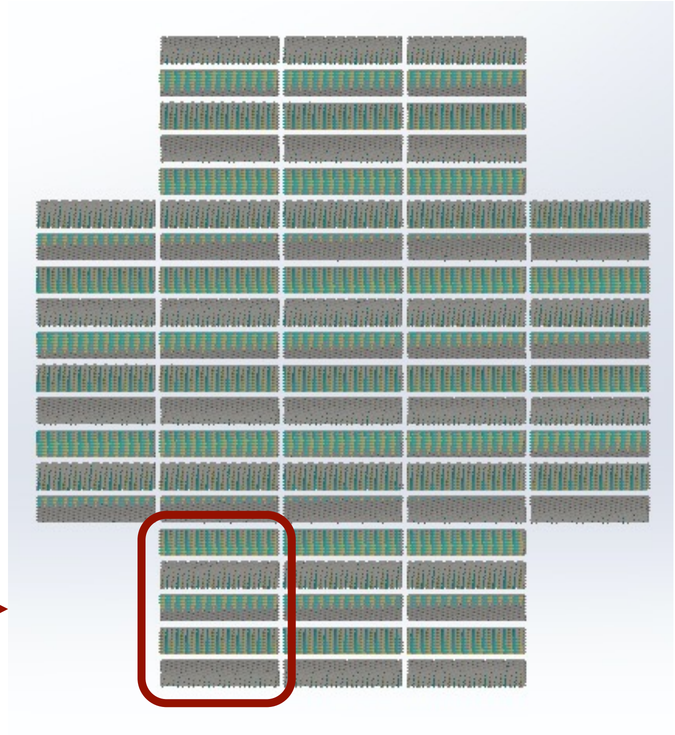


64 x 16 capillaries

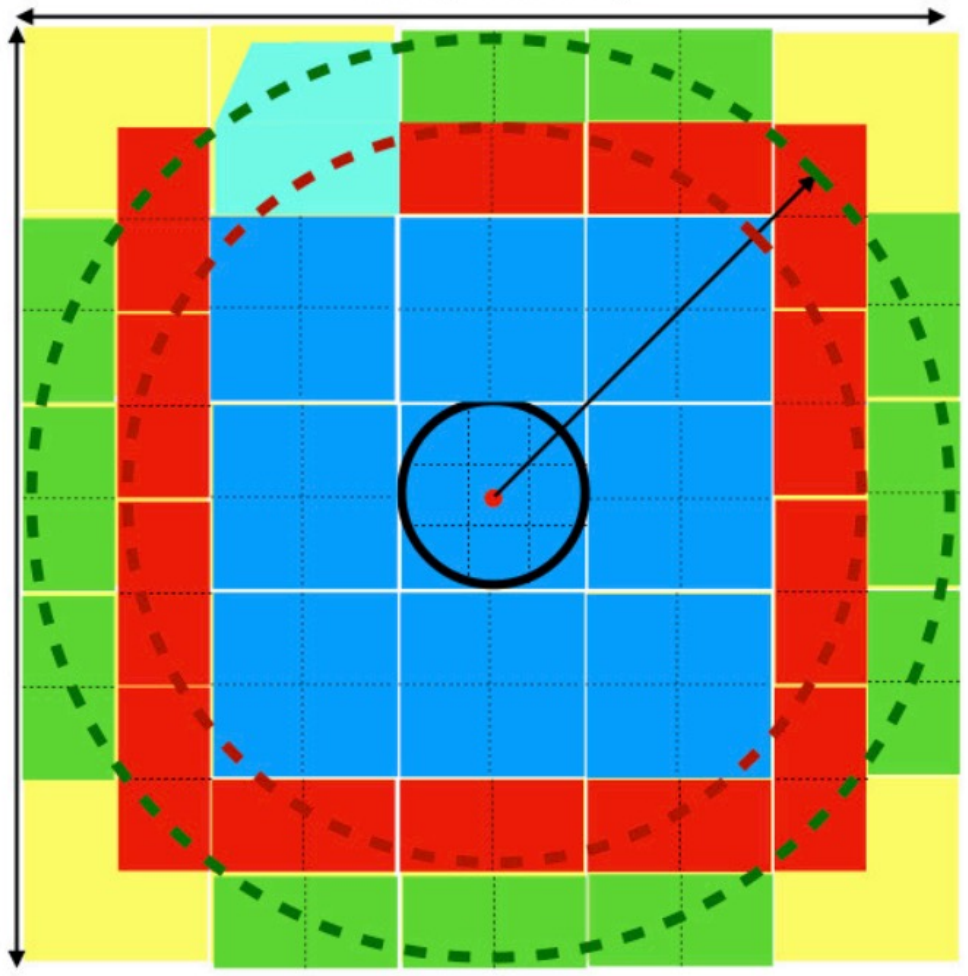
The Module



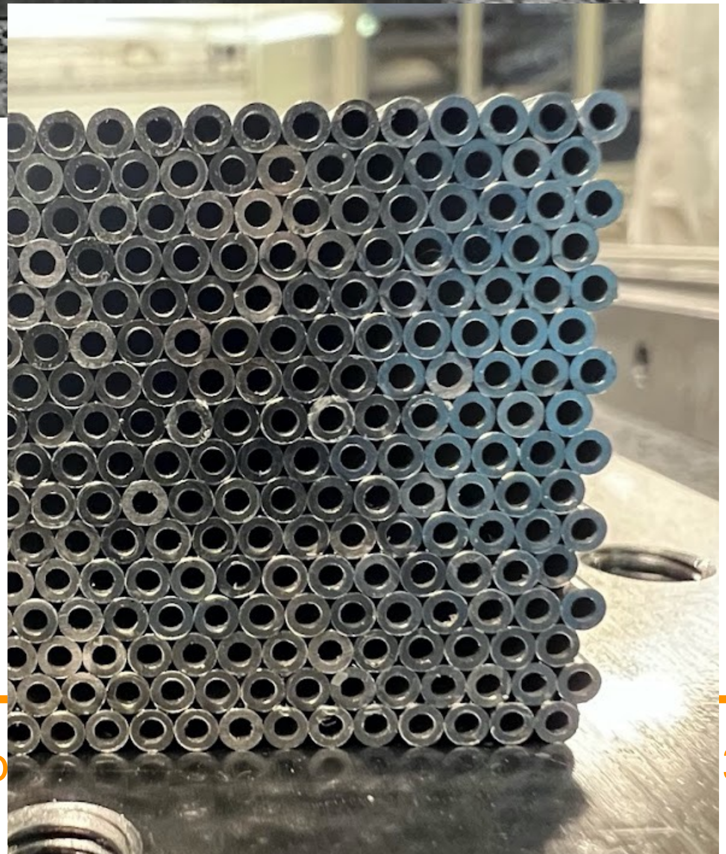
5 Mini-modules
~ 13 x 13 x 250 cm^3



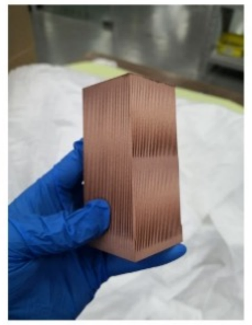
- 16 modules in total
- 2 central modules equipped with SiPMs
- 14 modules equipped with PMTs
- ~ 65 x 65 x 250 cm^3

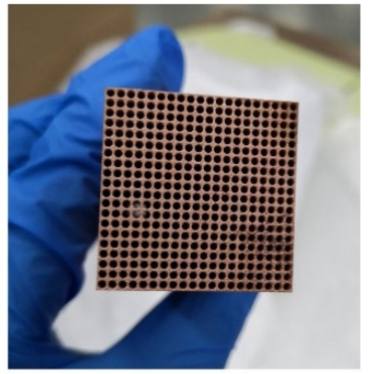


Fibre Dual Readout calorimeter - construction



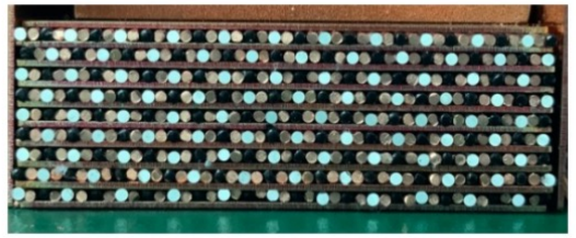
- 3D-printing

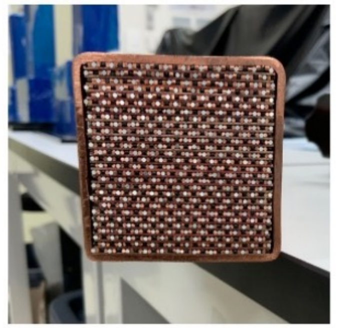




Excellent accuracy but quite expensive

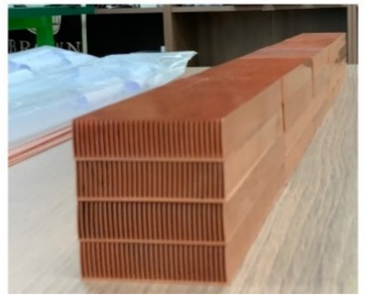
- Stacking (LEGO-like)

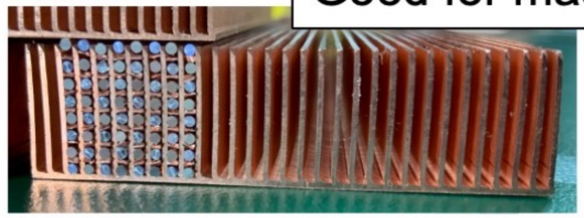




Good accuracy and quite cheap

- Skiving Fin Heatsink

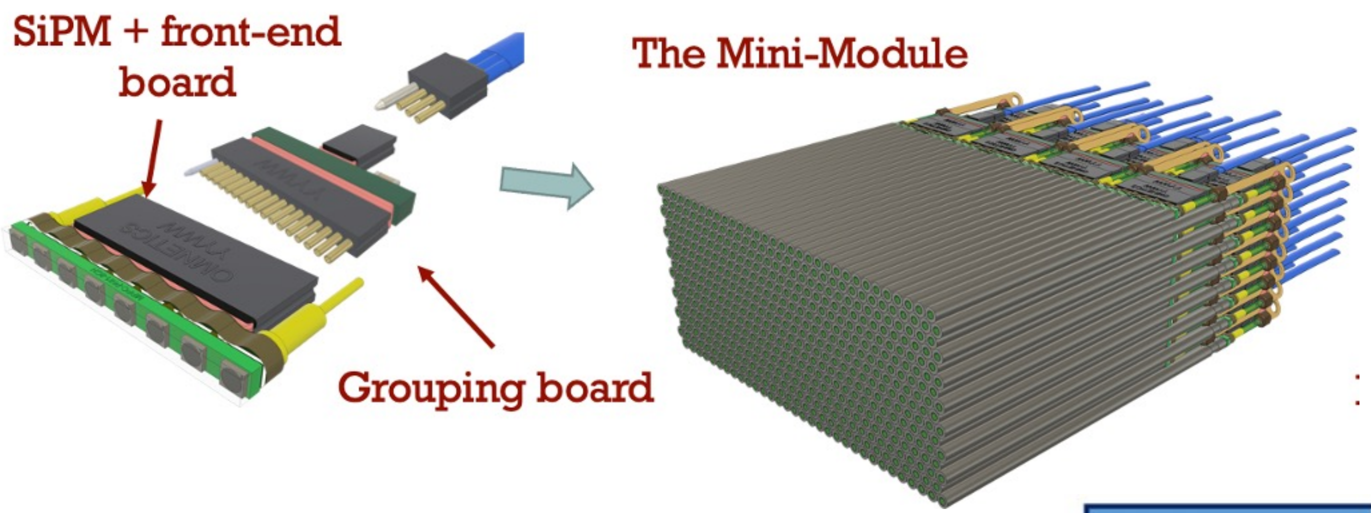




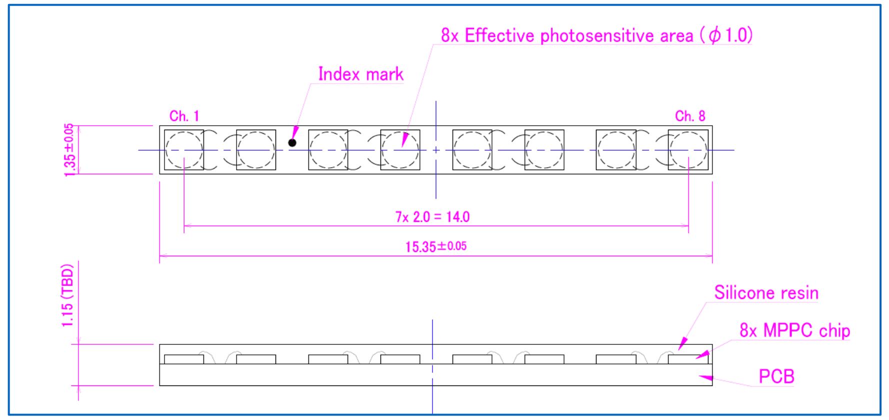
Good for mass production!

high accuracy and low cost

Fibre Dual Readout calorimeter - readout



Custom designed module with 8 SiPMs ($1x1mm^2$) from Hamamatsu
SiPM interspace: 2mm
Two SiPM: 10 and 15 μm pitch



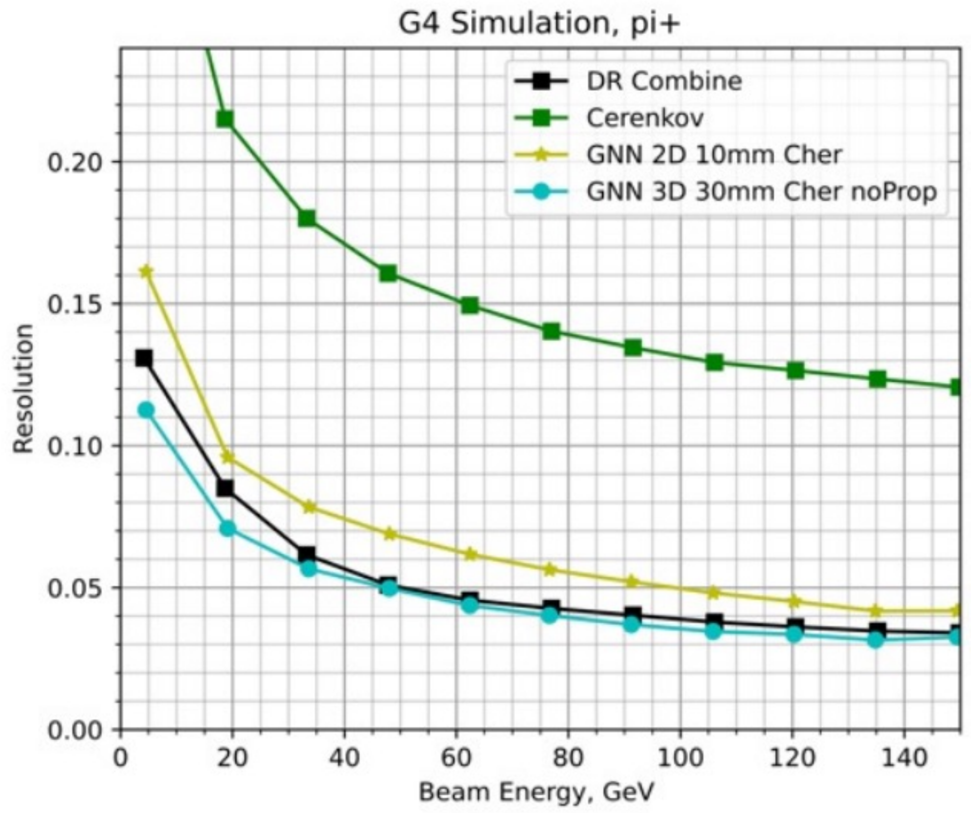
MCP-PMT	Window size	light	Quantum Efficiency (Q.E.)	max. HV (V)	Rise time (ns)	Pulse width (ns)	photo
PLANACON XP85012	$53x53 mm^2$	scintillation	~7% at 550 nm	2400	0.6	1.8	
PLANACON XP85112		Cerenkov	~21% at 400 nm	2800	0.5	0.7	

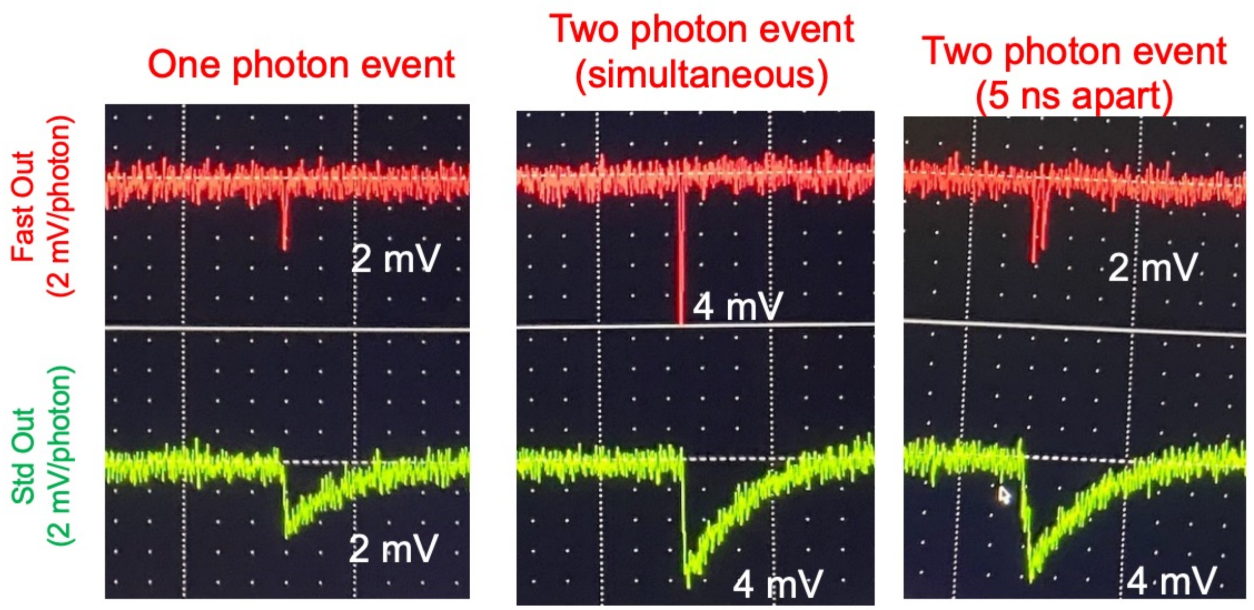
PMT	Window size	Q.E. for Ck.	Q.E. for Sc.	max. HV (V)	Time response (ns)			photo
					anode pulse rise time	electron transit time	Transit time spread (FWHM)	
R8900 series (old)	$23.5x23.5 mm^2$	35% at 420 nm	~7% at 550 nm	1000	2.2	11.9	0.75	
R11265-100 (new)	**$23x23 mm^2$**	**~35% at 400 nm**	**~7% at 550 nm**		**1.3**	**5.8**	**0.27**	

SiPM	photosensitive area	photo detection efficiency (PDE)		operating voltage	Gain at V_{BD}+5V	Linearity of Q.E.	number of pixels	geo. Fill factor
S14160-1310PS	1.3x1.3 ($1.69 mm^2$)	~15% at 400 nm	~17% at 550 nm	$V_{breaking\ Down}$ + 5 V	~$1.75x10^5$	~$2x10^{10}$/sec as incident photons	16675	31 % ($0.524 mm^2$)
fiber (Φ1 mm)	$0.785 mm^2$						~7745 (effectively)	

Fibre Dual Readout calorimeter – longitudinal (timing) segmentation

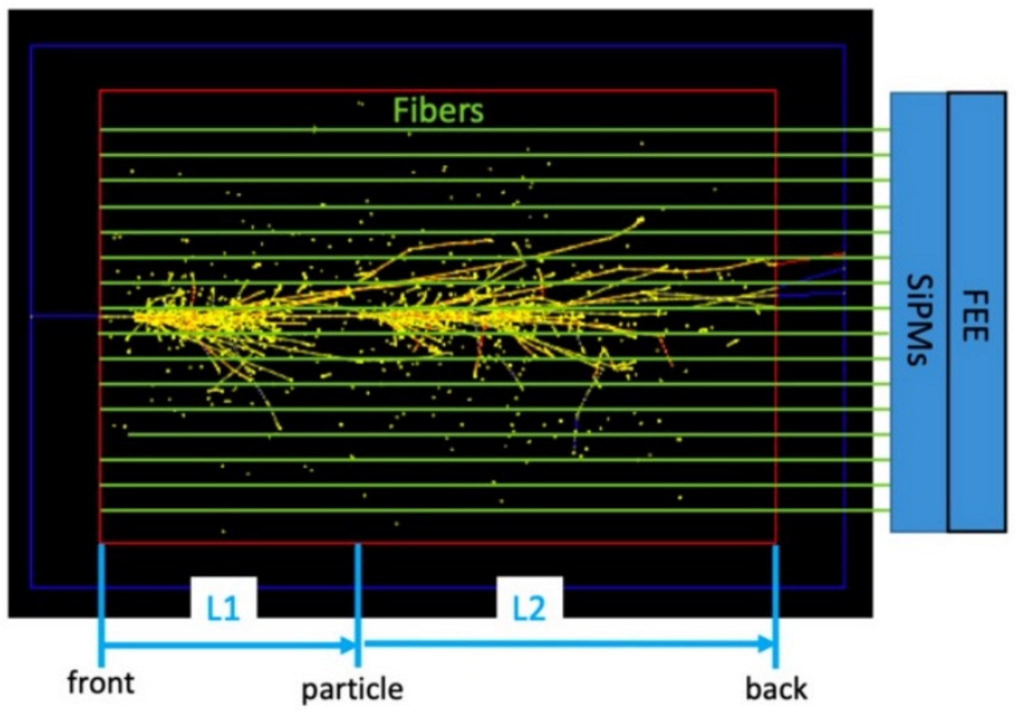
- Time information may provide longitudinal segmentation (3D-detector)
- Main advantages:
  - Less channels than a true 3D segmented detector
  - Less radiation for the readout electronics
  - No services in the calorimeter volume





high performance waveform digitizer.

NALU Scientific AARDVARC v3
- Sampling rate 10-14 GSa/s,
- 12 bits ADC,
- 4-8 ps timing resolution,
- 32 k sampling buffer,
- bandwidth 2 GHz,
- System-on-Chip (CPU)



Picosecond SpaCal Tecnology : Summary

- **Detector concept**: SpaCal (ECAL made of scintillating fibres in dense absorbers) with O(10-20) ps time resolution
- **Target application**: EM calorimetry for LHCb Upgrade II, Higgs factories, FCC-hh, fixed-target experiments at the intensity frontier
- **Unique challenges**: Radiation-hard (and radiation-tolerant) scintillating fibres
- **Technology**: Crystal or organic fibres in lead or tungsten absorber, hollow light guides, PMT/SiPM photon detectors, SPIDER ASIC for timing
- **Next 3+ year goals**: provide all individual components (e.g. absorbers, light guides, scintillating fibres, photon detectors, electronics) for module-size prototypes with lead and tungsten absorber, refinement and validation of simulation software

*CERN (**Switzerland**)*

*Institute of Physics of the Czech Academy of Sciences (**Czech Republic**)*

*University of Barcelona - IFIC Valencia (**Spain**)*

*University of Milano-Bicocca (**Italy**)*

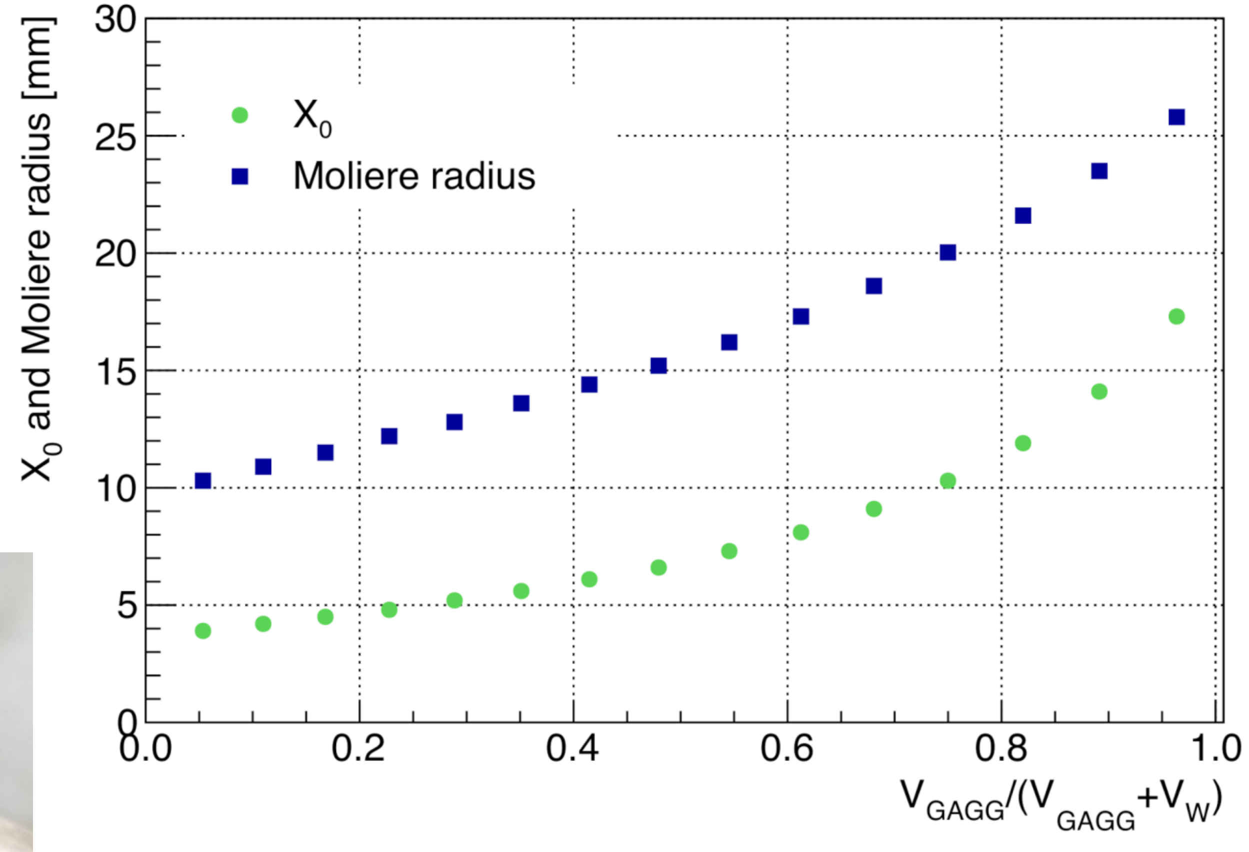
*IN2P3: IJCLab Orsay, LPC Clermont-Ferrand, LPC Caen, IP2I Lyon (**France**)*

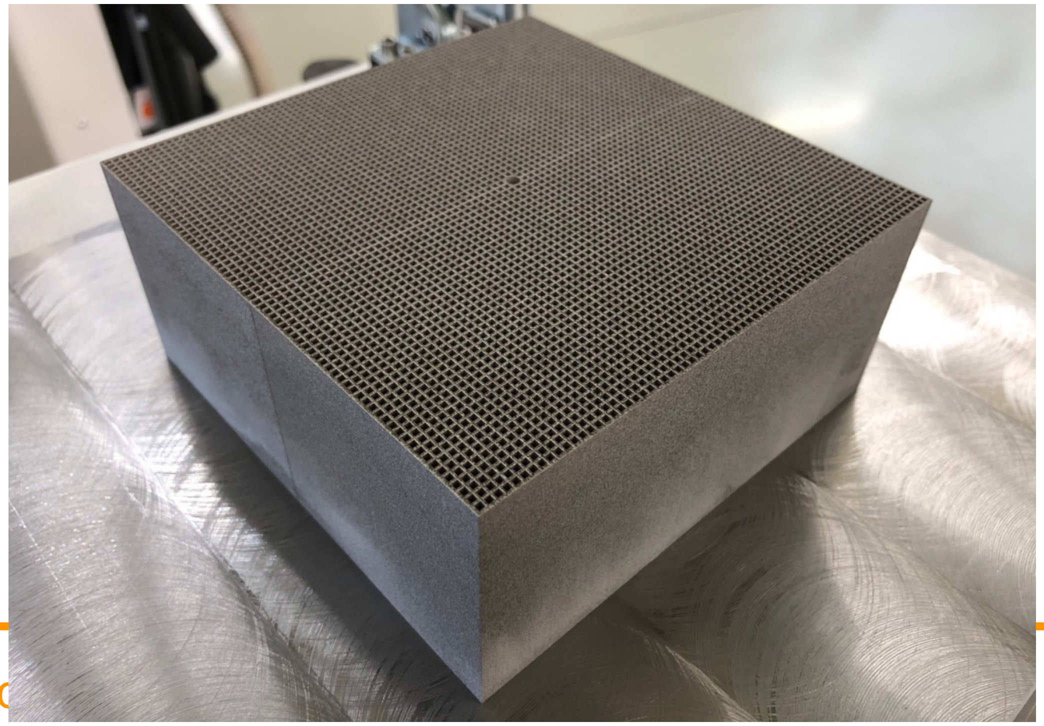
Picosecond SpaCal Tecnology: target

Target facilities: LHCb Upgrade II, Higgs factories, FCC-hh

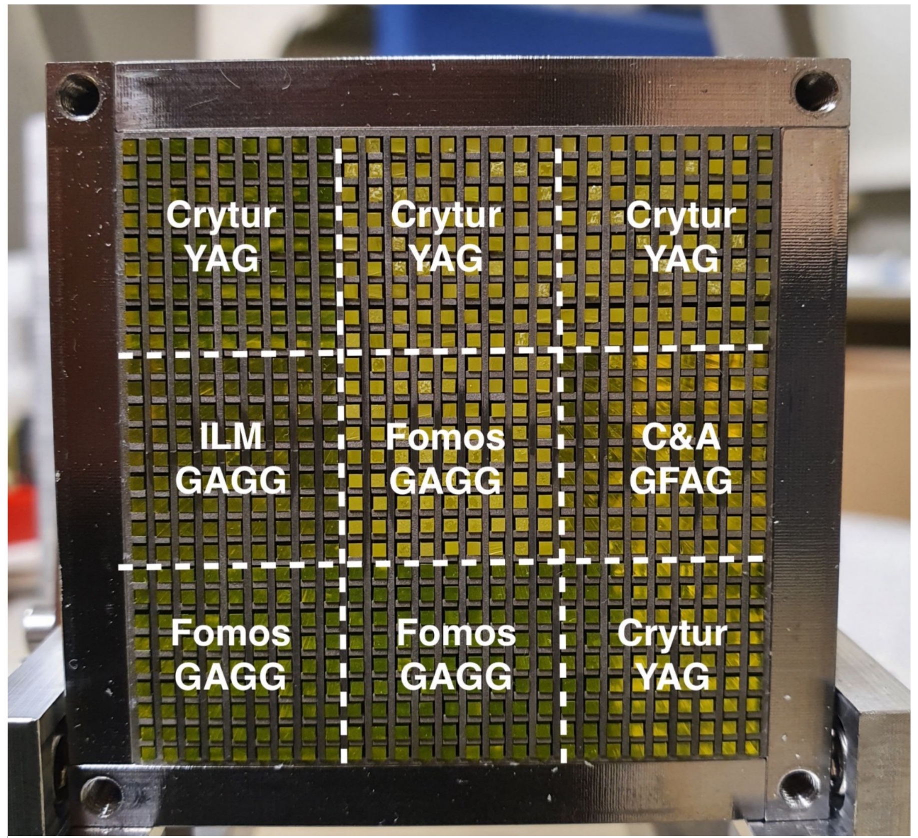
Different target performance, but scintillating sampling ECAL technology can be adapted to fulfil these requirements

- Tuneable radiation length and Moliere radius
  - different absorber (Lead or Tungsten)
  - important development with 3D printing technique in collaboration with industry

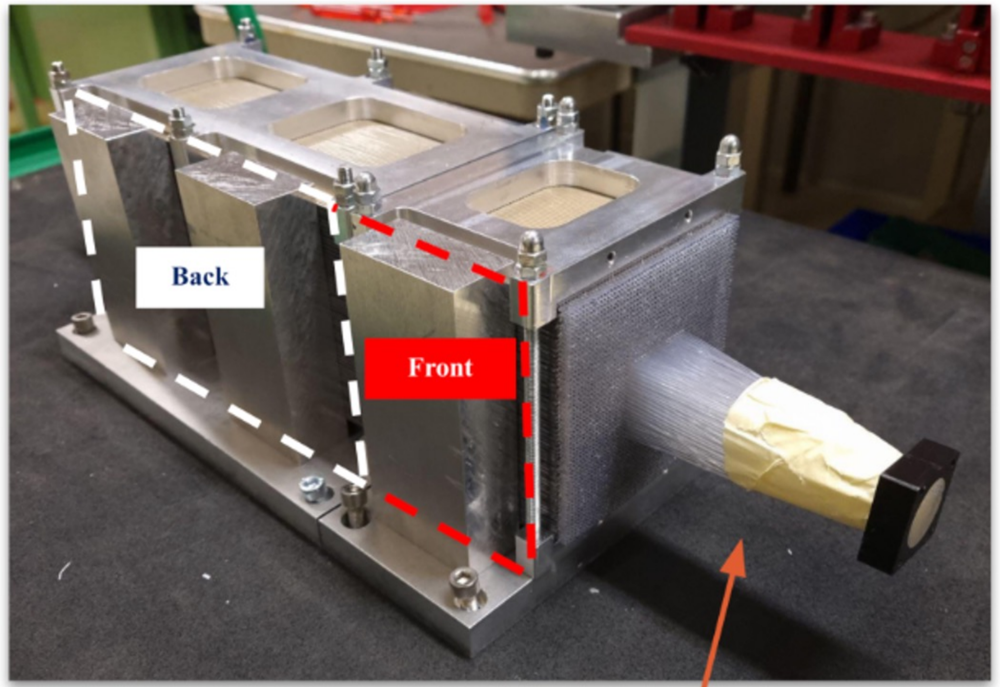




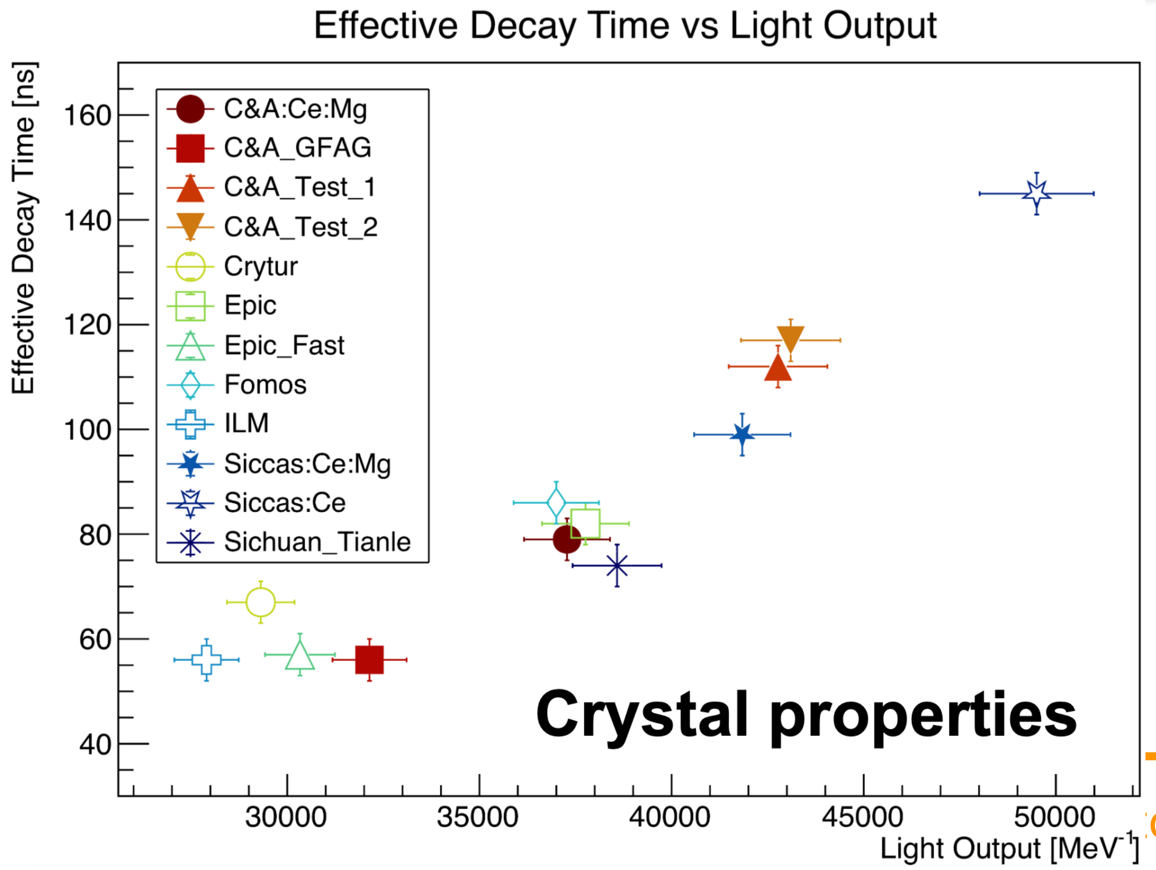
Picosecond SpaCal Tecnology: fiber R&D



Polystyrene fibres
Lead absorber



Fibres bundle (1 cell)



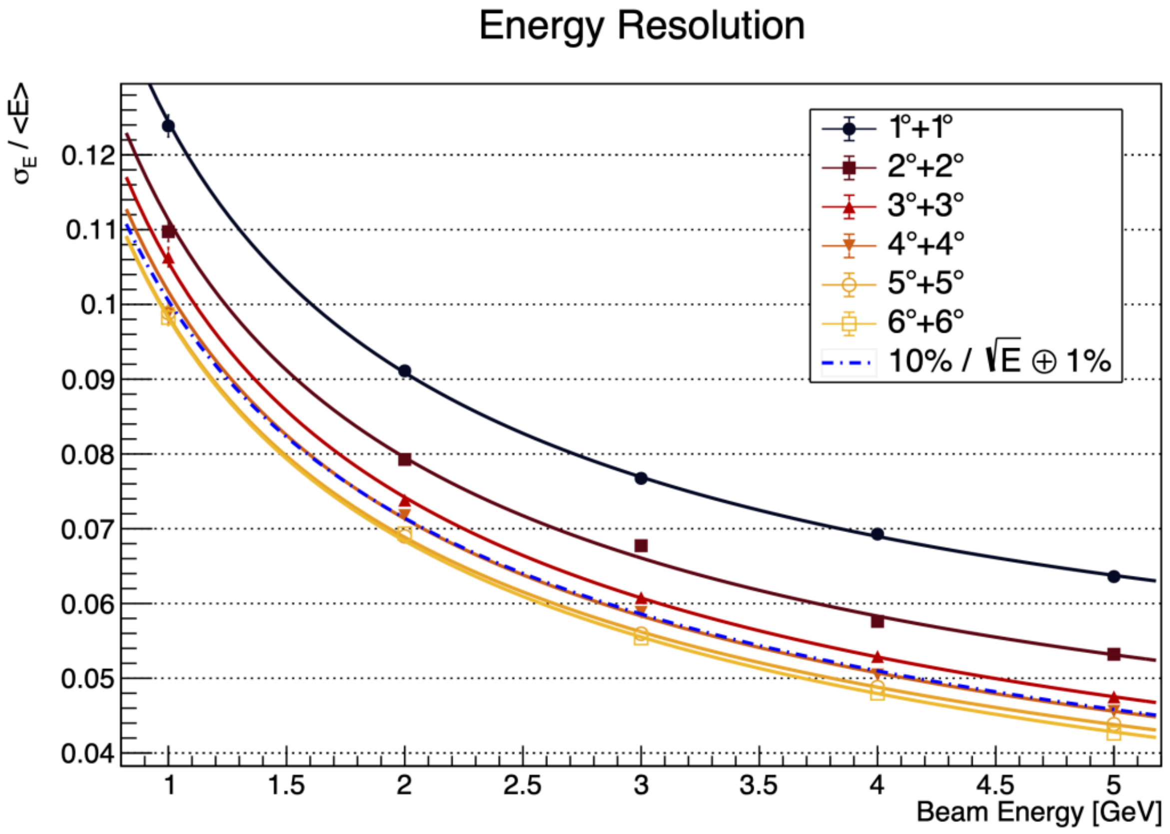
R&D on scintillating fibres:

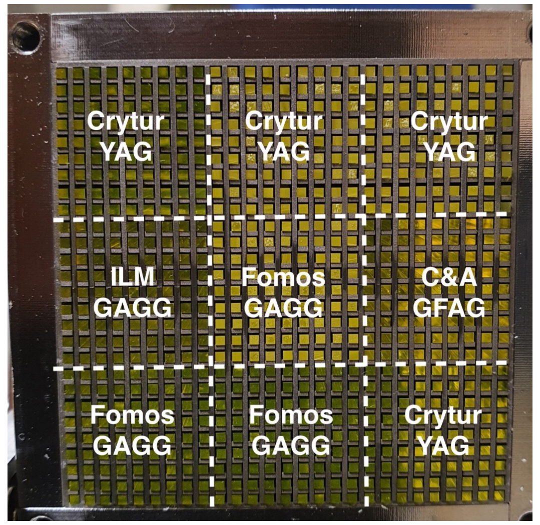
- Radiation-hard crystal scintillating fibres
- radiation-tolerant organic scintillating fibres

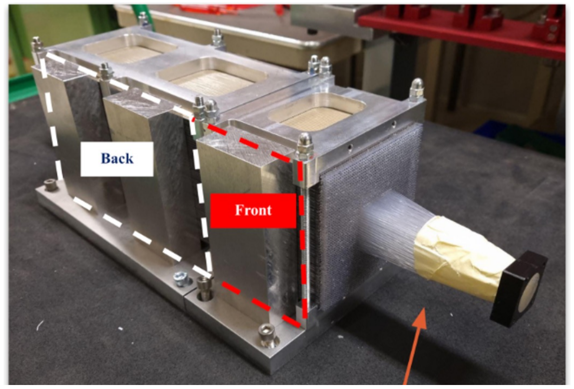
R&D on production techniques

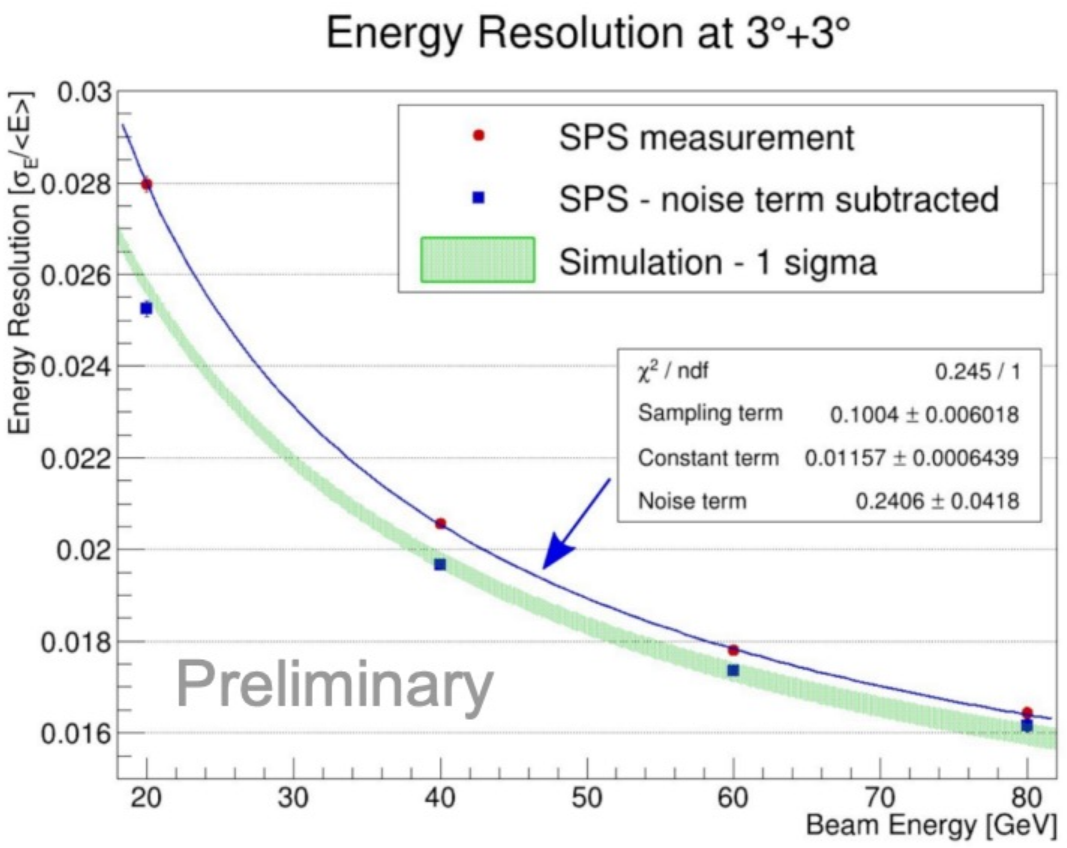
- This includes the control of the light propagation along the fibres.
- Large crystal fibre production capabilities

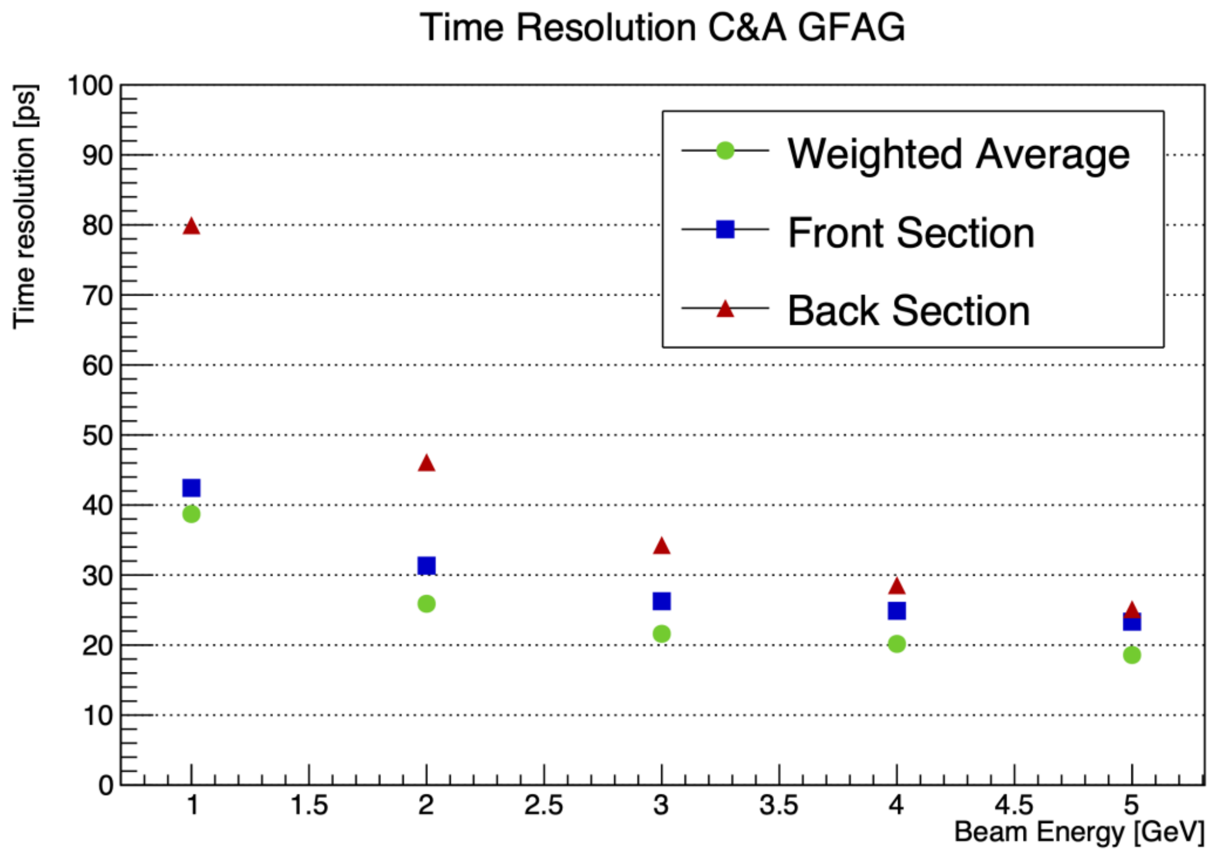
Picosecond SpaCal Tecnology: performances

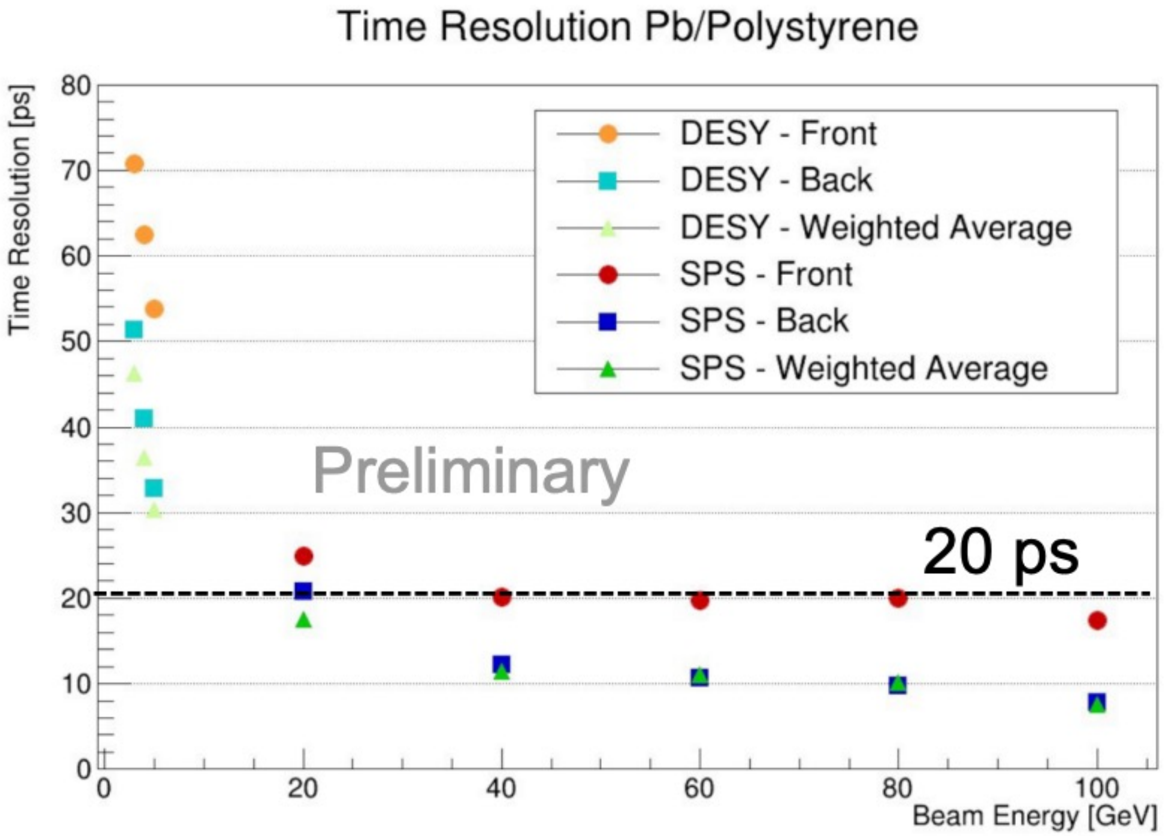










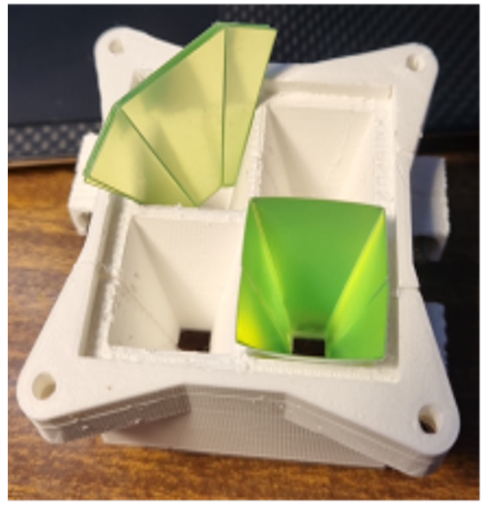


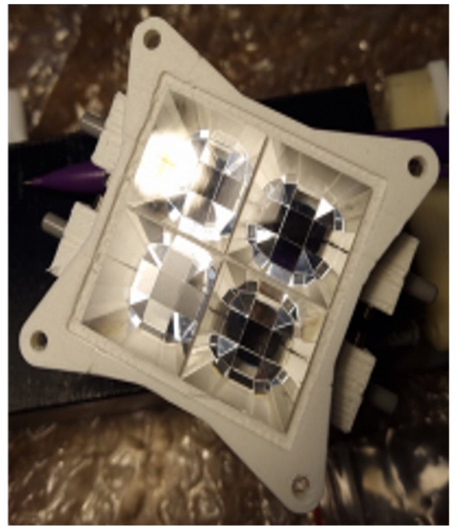
Picosecond SpaCal Tecnology: readout

Photo-sensors

- achieve linearity with PMTs in the relevant energy ranges while keeping excellent timing resolution.
- feasibility study for the usage of SiPMs for ECAL designs (space constraints are relevant)

Light Guide





- Hollow light guides provide a cost-effective and intrinsically radiation-hard option to couple a fibre calorimeter to the photon detectors

Readout

- Development of the readout chain capable of measuring precisely the time for each cell
- Fully exploiting the good timing performances.
- ASIC will be designed based on waveform sampling in analog memories,

Fast-timing, ultracompact, radiation hard EM calo (RADiCAL)

- **Detector concept**: Radiation-hard EM calorimeter with 10%/√E energy resolution and 25 ps timing resolution
- **Target application**: FCC-hh
- **Unique challenges**: Radiation-hard WLS filament and SiPM
- **Technology**: Shashlik/type ECAL modules with tungsten absorber and LYSO:Ce tiles, WLS (full-length or in shower maximum), SiPM readout
- **Next 3+ year goals**: Test beams with a 3x3 array for energy, timing and position resolution, design to serve as test bed for new materials

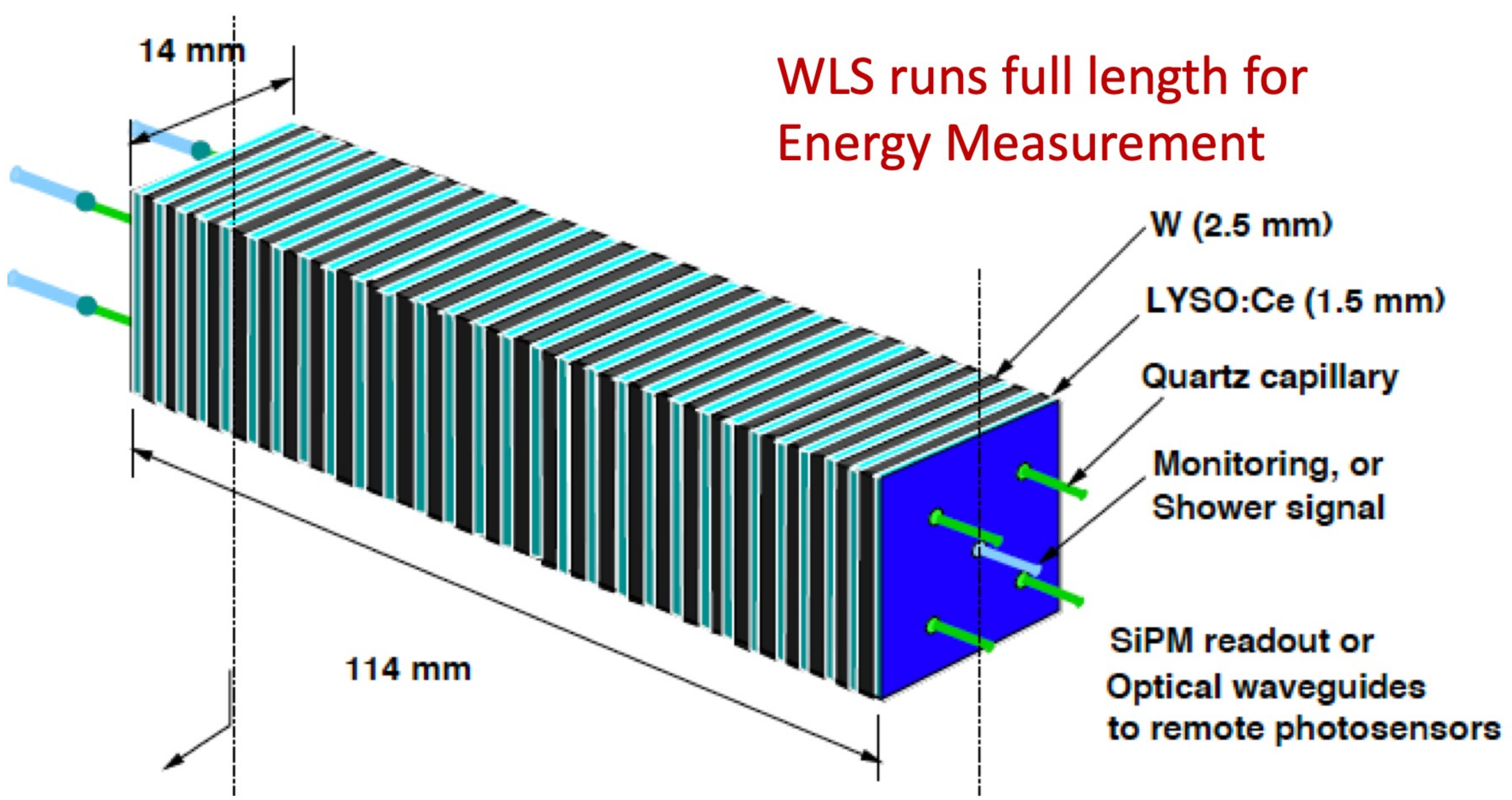
*University of Notre Dame (**USA**)*

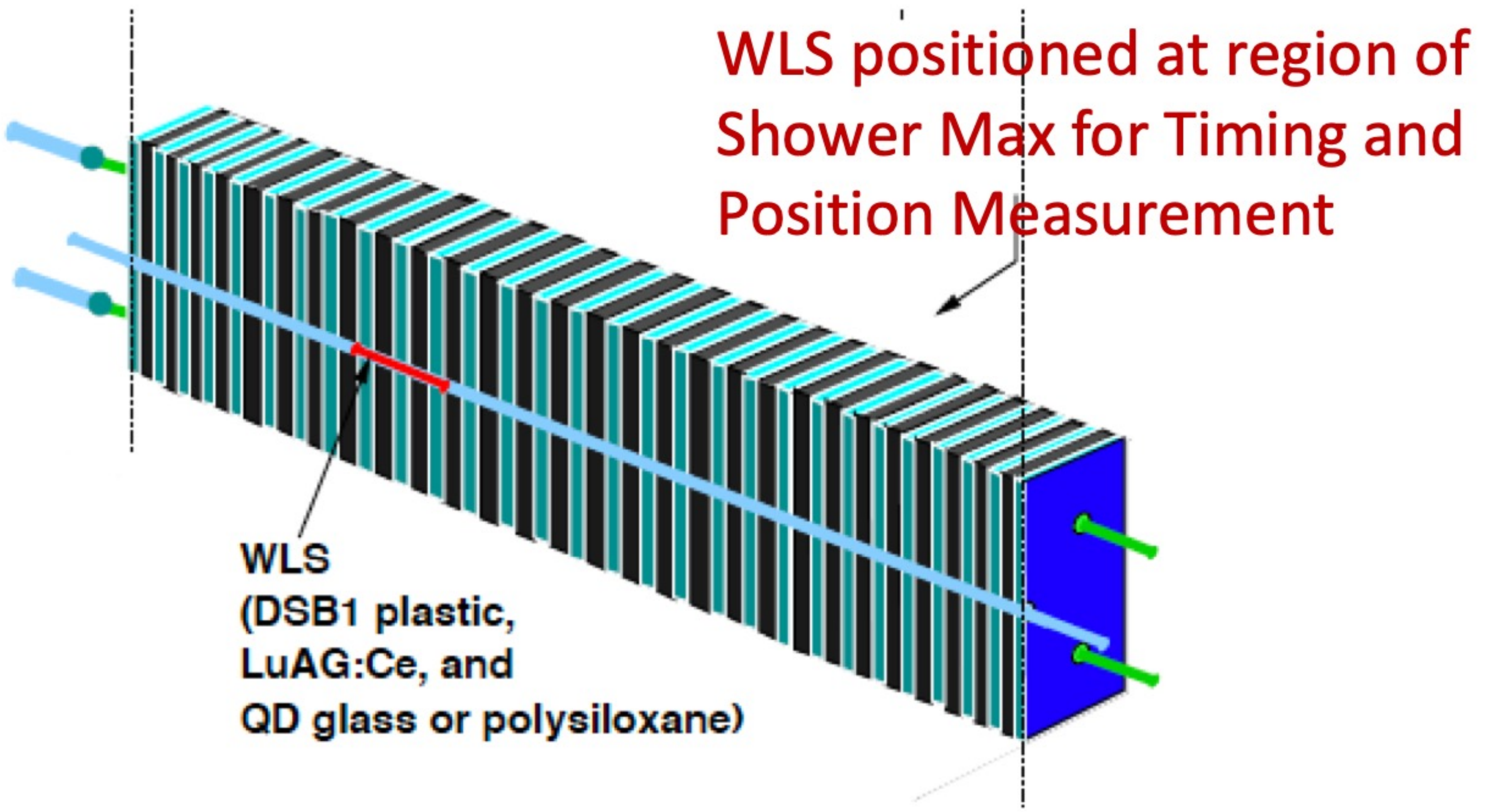
*University of Iowa (**USA**)*

*University of Virginia (**USA**)*

*Caltech (**USA**)*

ECFA Fast-timing, ultracompact, radiation hard EM calo (RADiCAL)

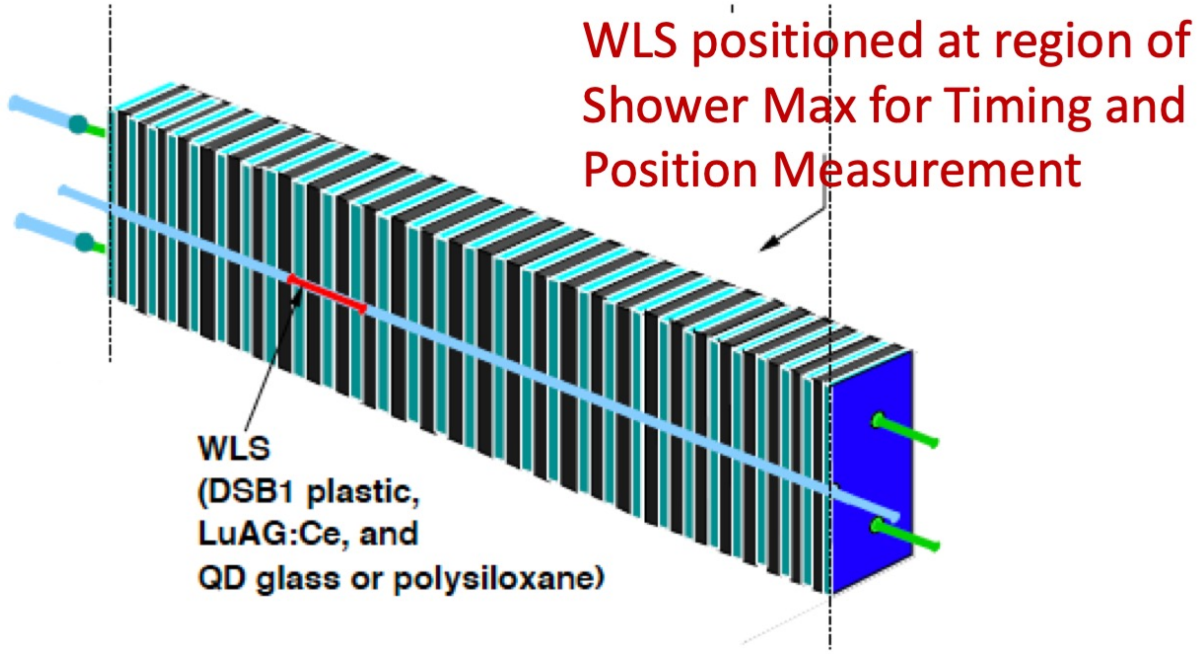


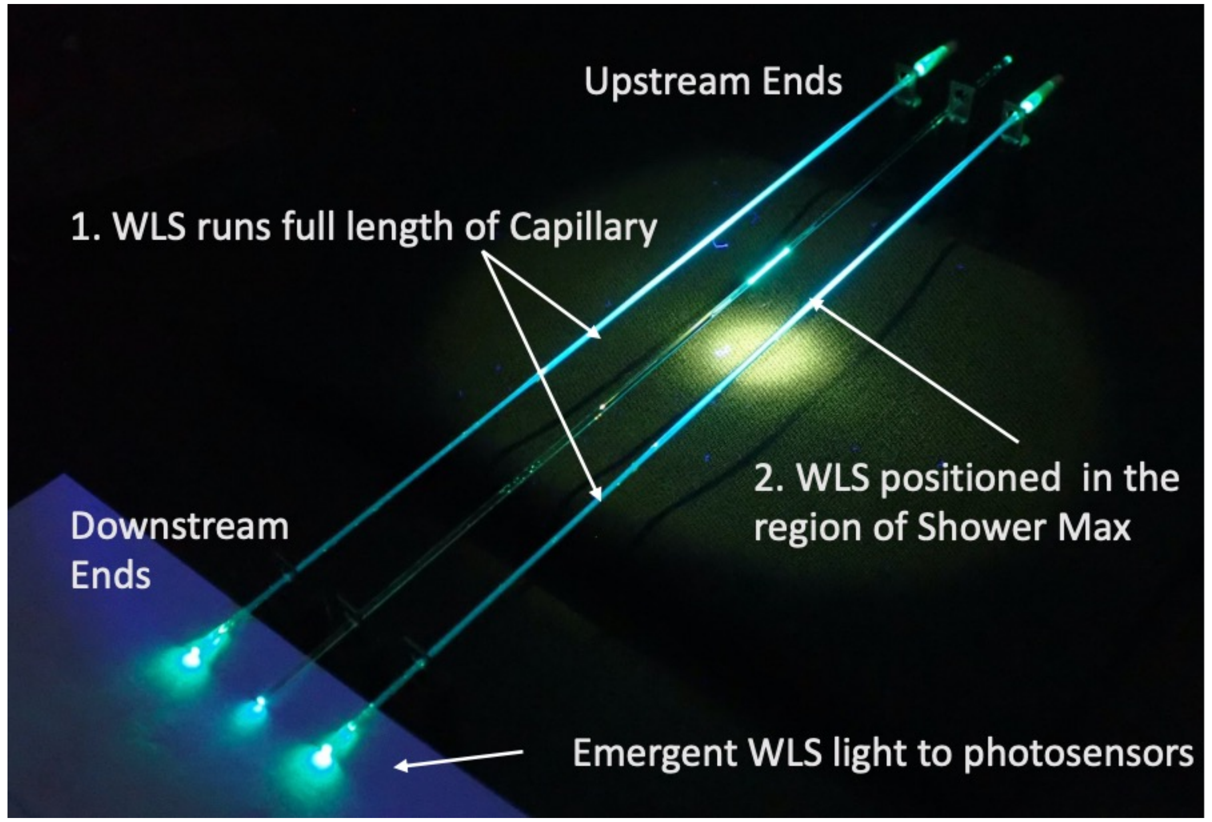


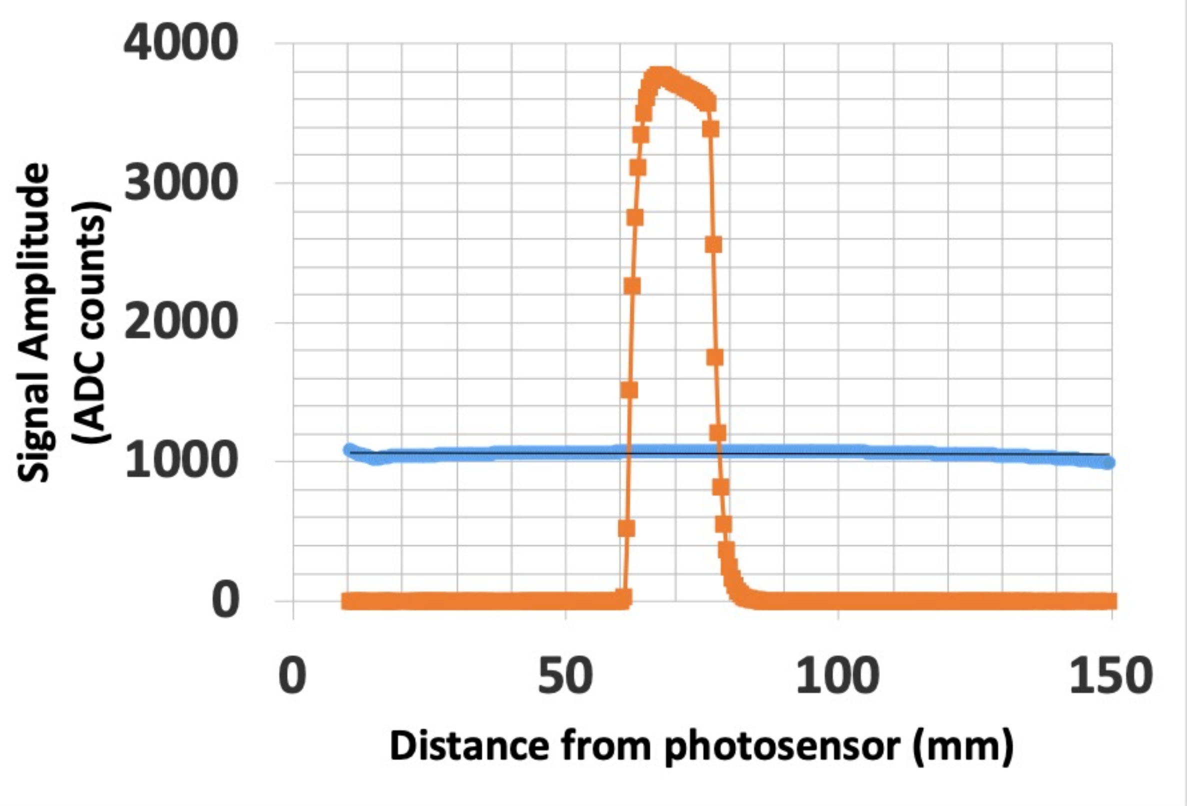
Alternating layers of W and LYSO:Ce tiles and readout with quartz capillaries containing organic DSB1 wavelength shifter filaments and radiation hard, ceramic LuAG:Ce wavelength shifter filaments

Test new scintillation and WLS materials in plate and filament/capillary form as they become available. (e.g. BaF_2:Y crystals, LuAG:Pr ceramics, flavonol organics)

Fast-timing, ultracompact, radiation hard EM calo (RADiCAL)







Detected WLS signal from a timing capillary, excited along its length by a UV LED at 420nm: strong response from the region of shower max and negligible response elsewhere

Detected liquid WLS-filled capillary for energy measurement

GRAiNITA

- **Detector concept**: Scintillating grains in transparent liquid to reach better energy resolution than in traditional Shashlik approach
- **Target application**: EM calorimetry for Higgs factories with excellent energy resolution (2%/√E)
- **Unique challenges**: Production of scintillator grains
- **Technology**: Sub-millimetric (0.5 - 1 mm) inorganic scintillator crystals in bath of high-density liquid, light collection by WLS fibres
- **Next 3+ year goals**: scintillator characterisation, MC simulation, cosmic test bench, development of a medium-size prototype (2.8 x 2.8 x 6 cm^3), full-size prototype (14 x 14 x 40 cm^3) beyond 2024 if concept proves effective

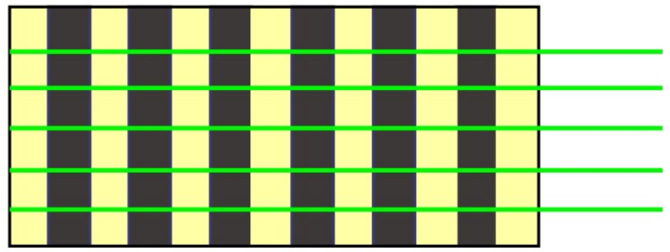
*IJCLab (**France**)*

*Laboratoire de Physique Clermont - LPC (**France**)*

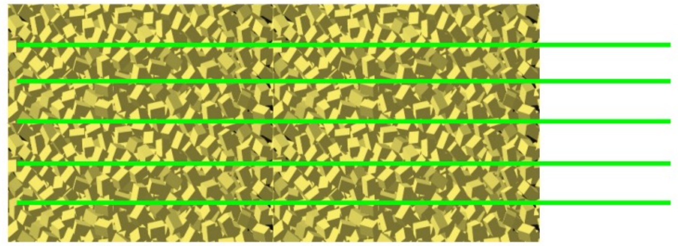
*Institute of Scintillation Materials of the National Academy of Sciences of Ukraine - ISMA (**Ukraine**)*

GRAiNITA

Shashlyk-type calorimeter

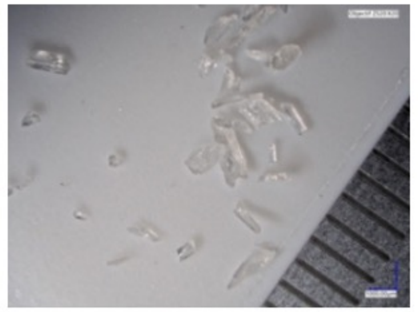


GRAiNITA

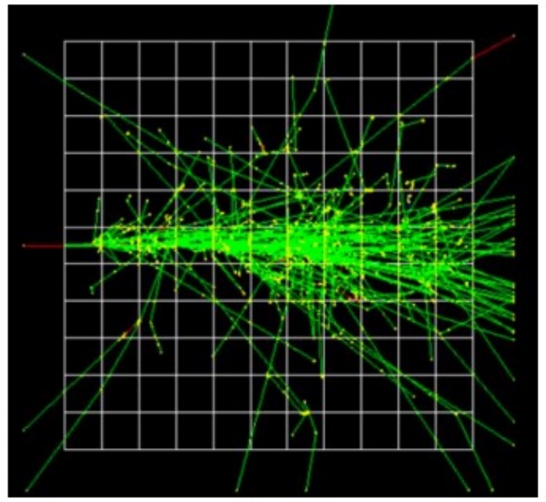


$ZnWO_4$ possible candidat:

- LY= 10kph/MeV
- Density 7.62 g/cm^3
- Index n=2.1
- τ = 20 μs
- λ_{max} = 480 nm
- grain size : 0.5 mm - 1 mm



CH_2I_2
methylene iodide
soluble in organic solvents.
refractive index of 1.741
3.325 g/cm^3



GEANT4 simulation
ZnWO4 + CH2I2 cubes
(random position)

1mm cubes $\frac{\sigma_E}{E} \sim \frac{2\%}{\sqrt{E}}$

- Innovative technique inspired by Shashlyk-type calorimeters
- Extremely fine granularity
- Scintillating candidates:
  - ZnW04 grains (spontaneous crystallization method)
  - crushed BGO crystals
  - Characterization and production capability
- WLS selection with best match
- Medium-size proto: 2.8 x 2.8 x 6 cm^3
- (If successful)

  Large-size proto: 14 x 14 x 40cm^3

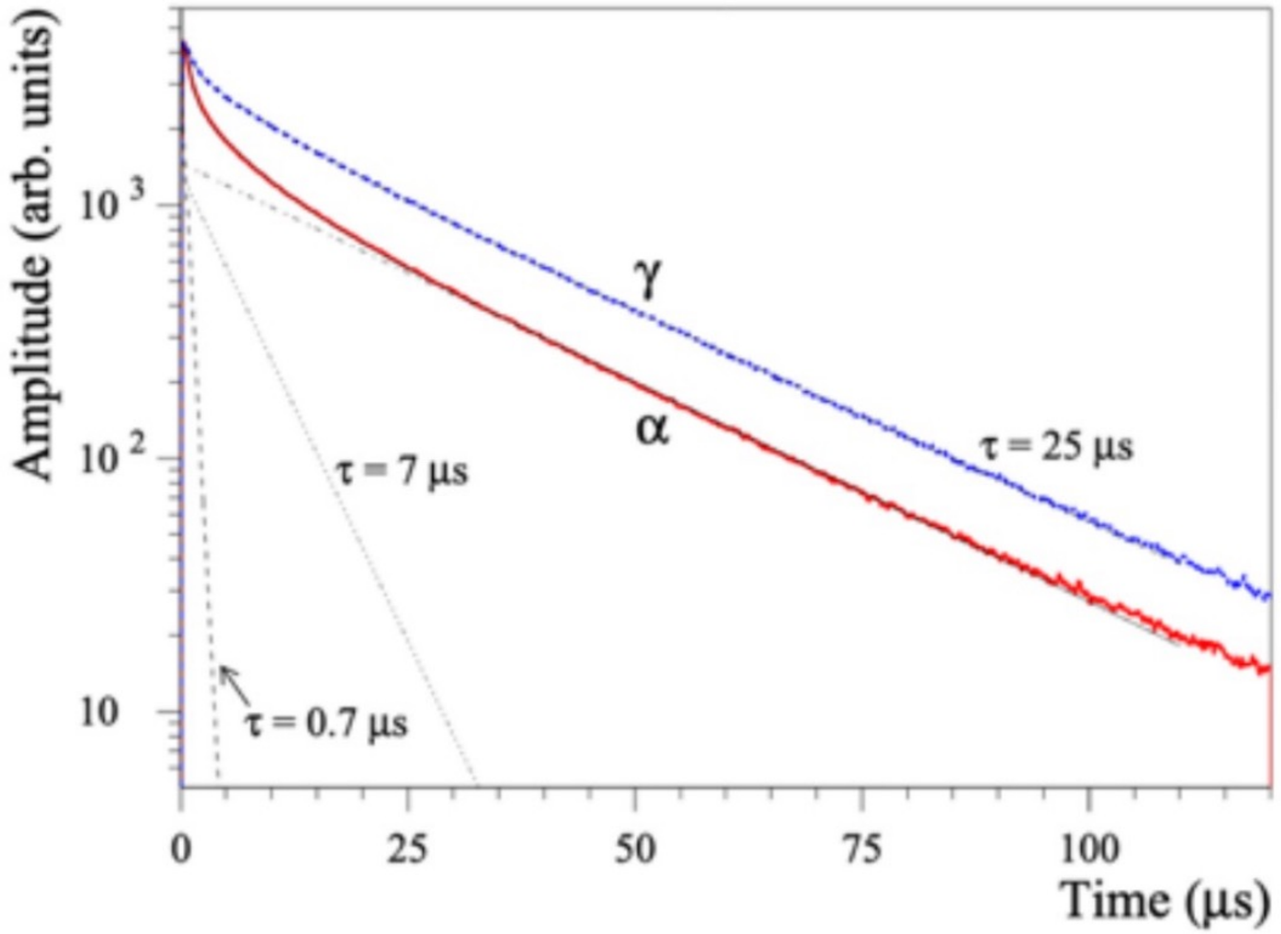
ECFA

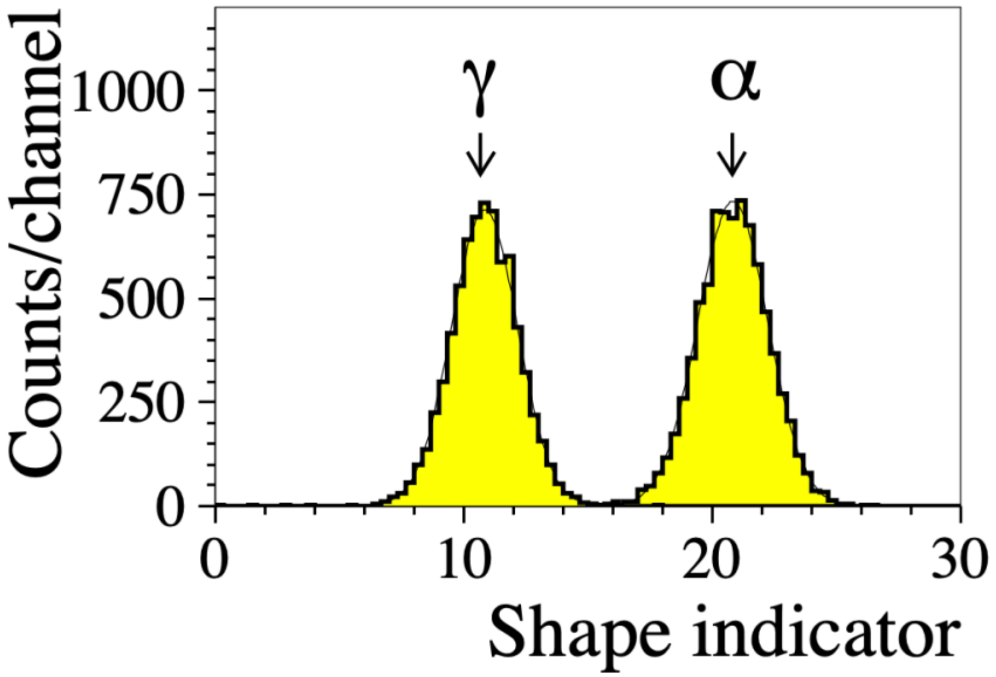
GRAiNITA: Pulse Shape Discrimination

Two components (one fast, one slow) for the scintillation decay time in inorganic crystal

Higher ionizing particles (low E proton) : higher fraction of fast component

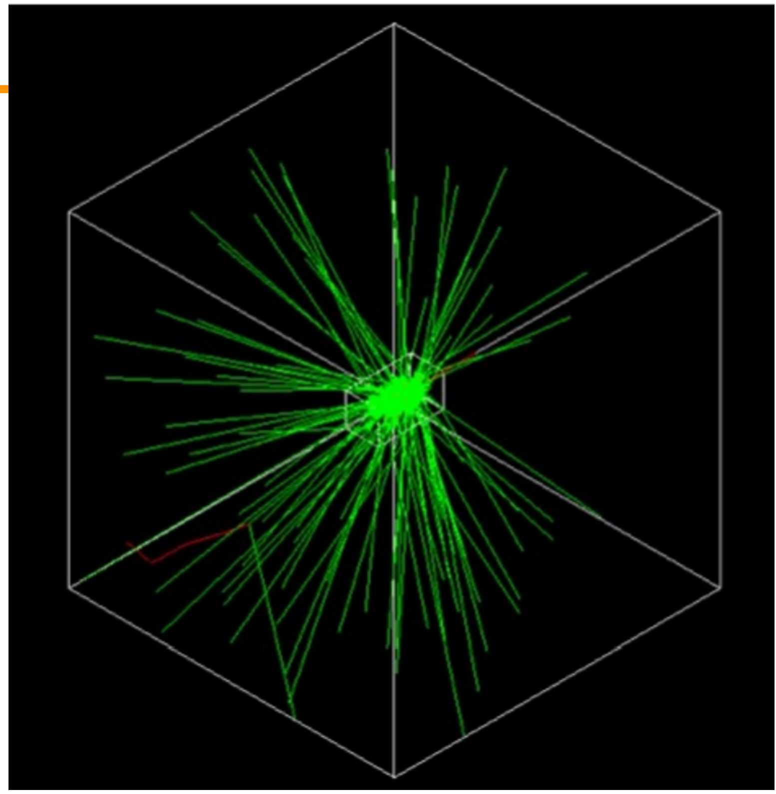
With $ZnWO_4$: clear difference between γ and α (https://arxiv.org/pdf/nucl-ex/0409014.pdf)



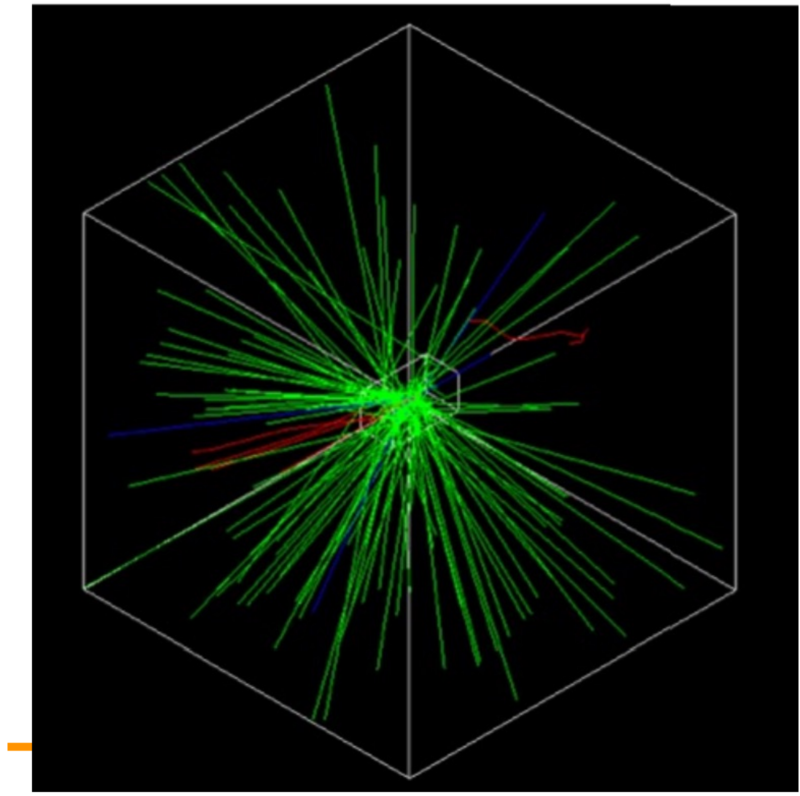


Type of irradiation	Decay constants, μs		
	τ_1 (A_1)	τ_2 (A_2)	τ_3 (A_3)
γ ray	0.7 (2%)	7.5 (9%)	25.9 (89%)
α particles	0.7 (4%)	5.6 (16%)	24.8 (80%)

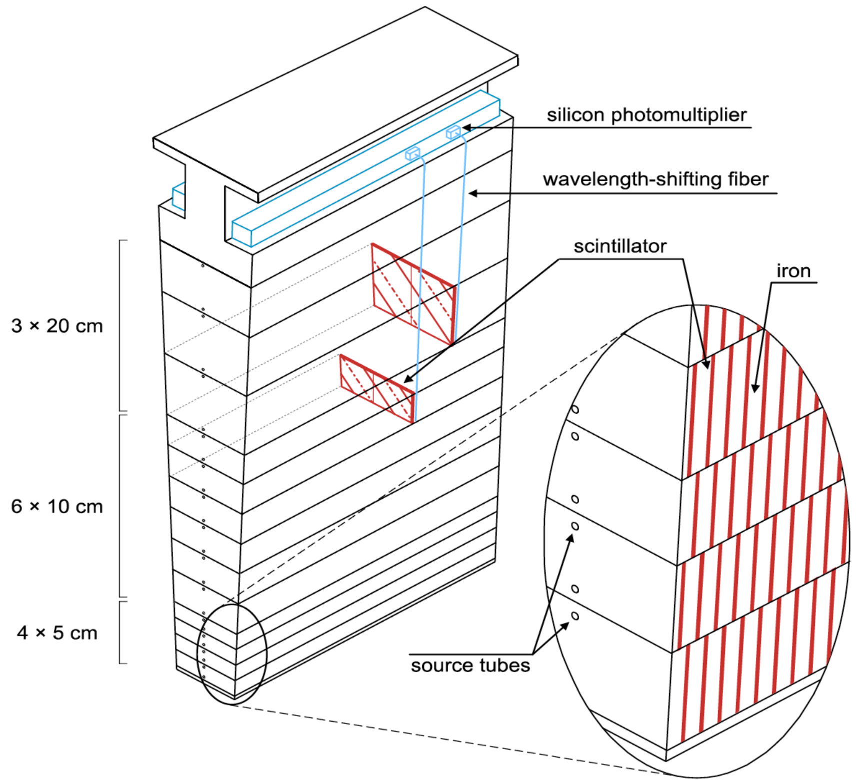
10 GeV electron

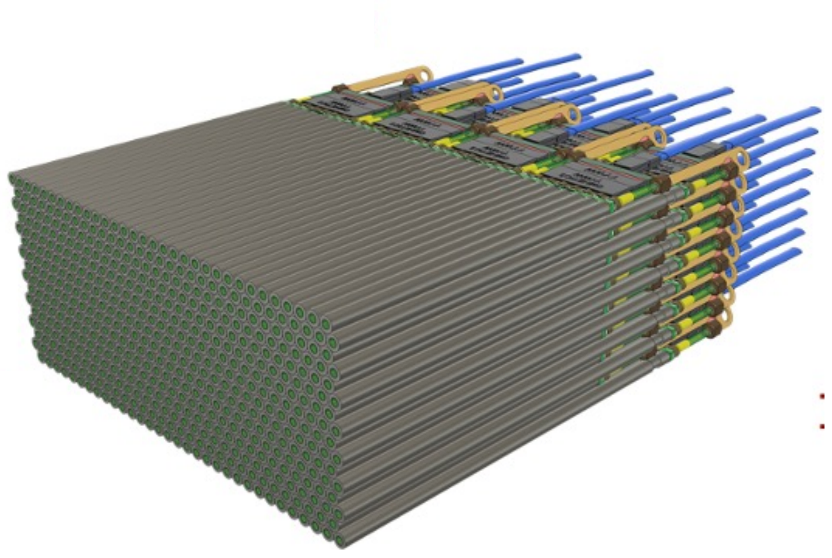


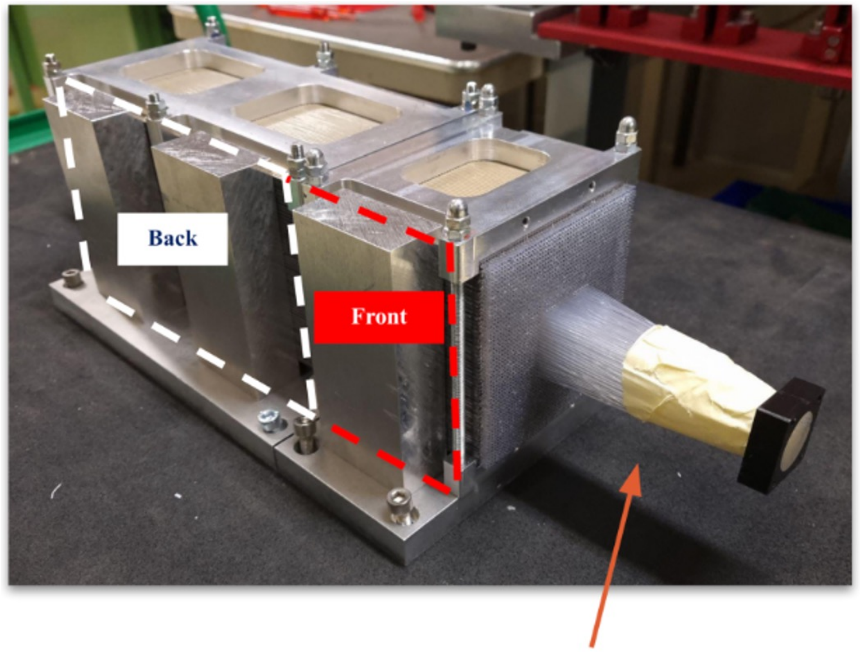
10 GeV pion



Scintillator Based Sampling Calorimeters

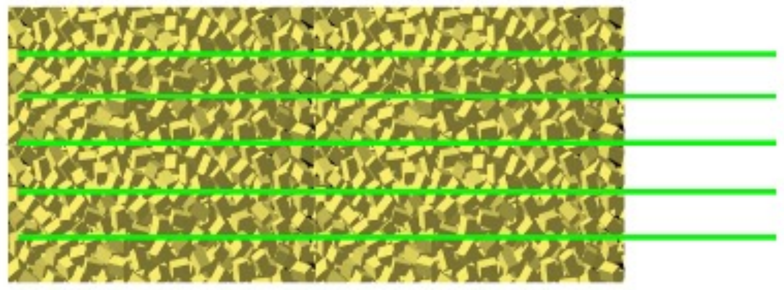




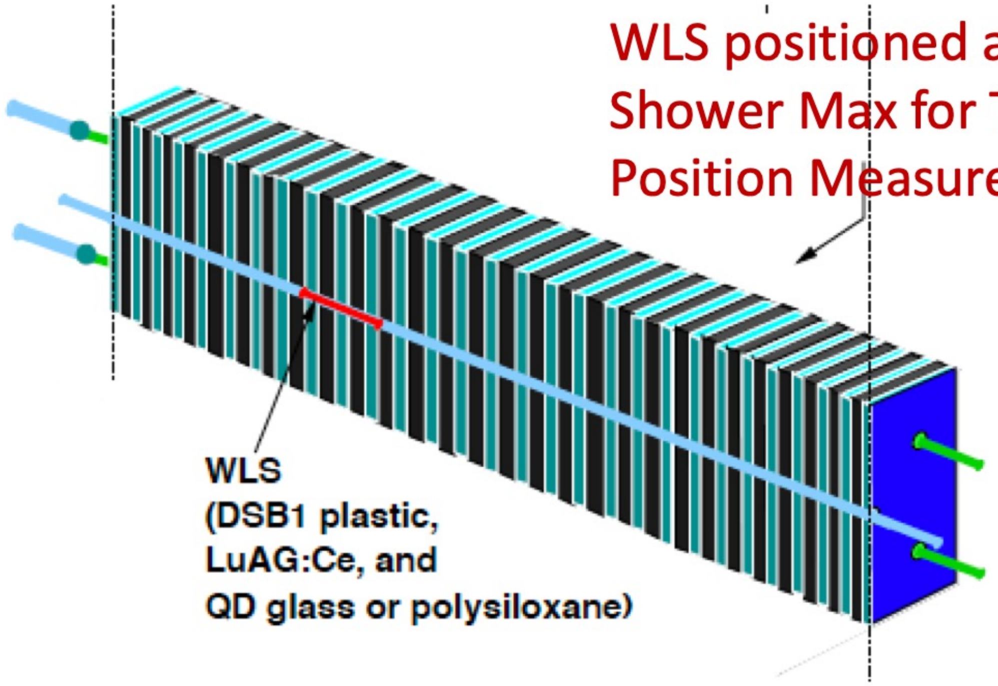


Fibres bundle (1 cell)

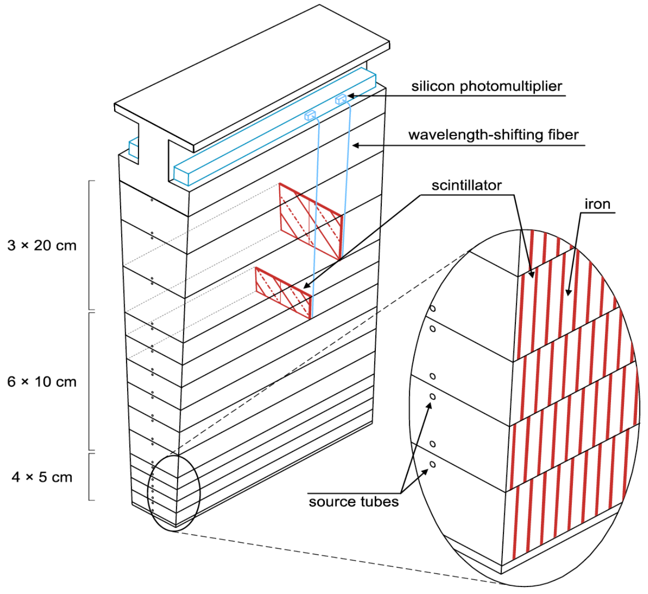
GRAiNITA

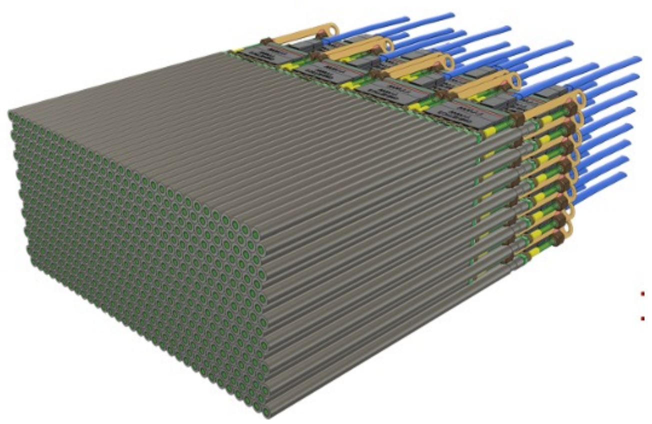


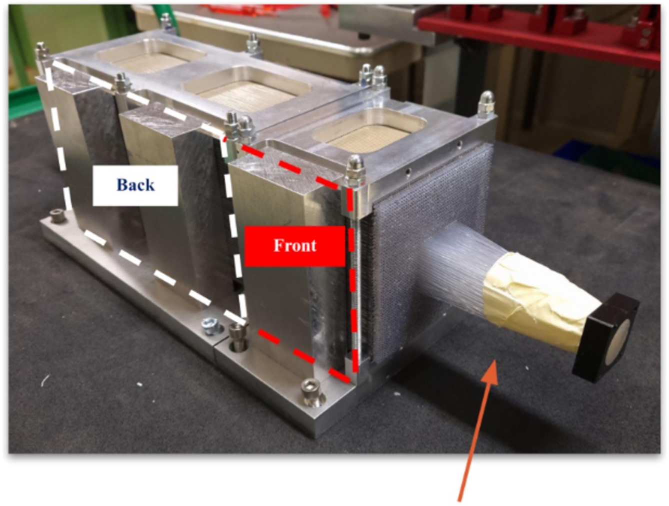
WLS positioned at region of Shower Max for Timing and Position Measurement



Scintillator Based Sampling Calorimeters







Fibres bundle (1 cell)

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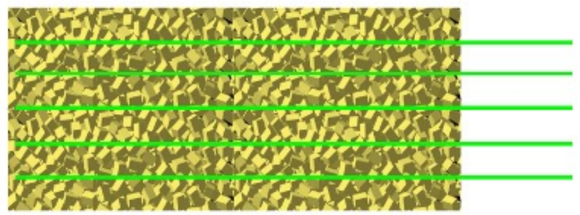

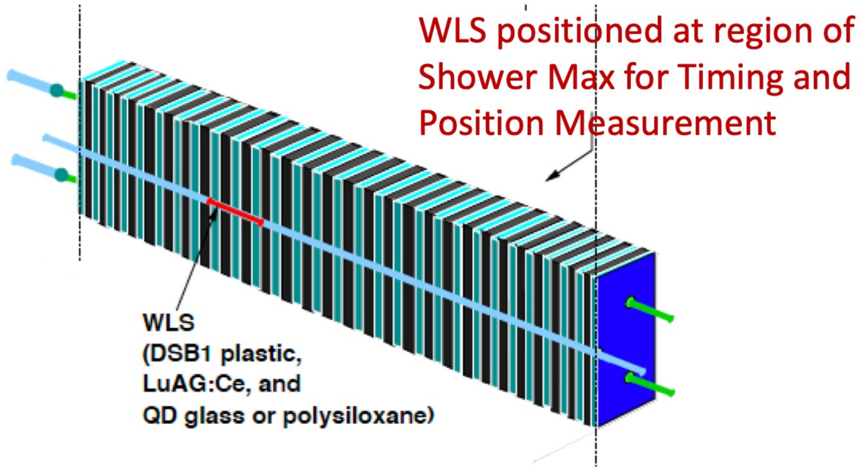

Each project has unique challenge and peculiarities
BUT
also has common issues to be addressed