New scintillators for FCC

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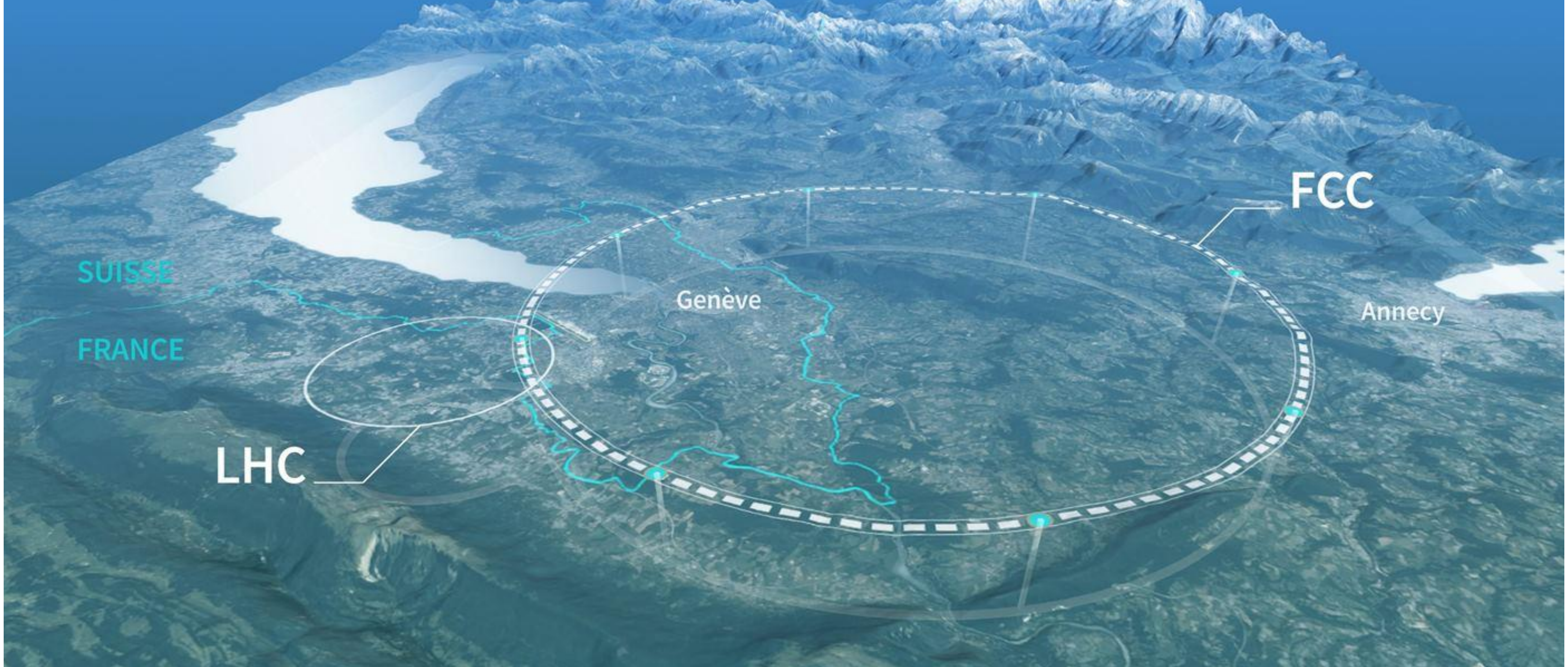
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

IDTM Workshop - Innovative Detector Technologies and Methods
Lisbon, 12-14 Sept 2023

Future Circular Collider

The goal of the FCC is to push the energy and intensity frontiers of particle colliders, with the aim of reaching collision energies of 100 TeV, in the search for new physics.



Possible location for the Future Circular Collider, ~91 km long particle collider

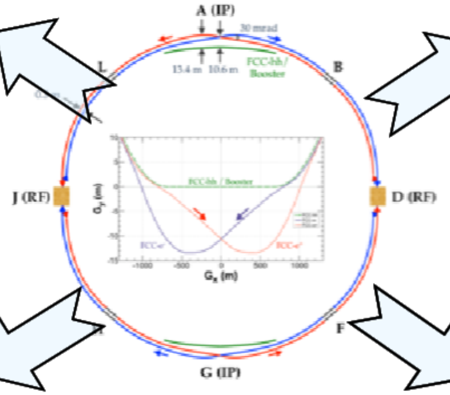
FCC-ee detector requirements summary

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
    - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

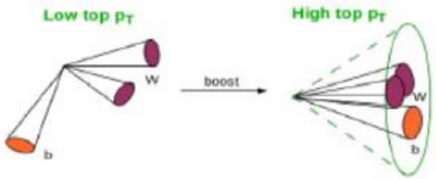
- Sensitivity to far detached vertices (mm → m)
    - Tracking: more layers, continous tracking
    - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

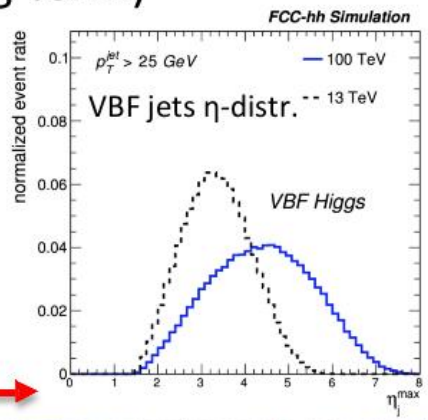
Mogens Dam, ECFA Detector R&D Roadmap Input Session 19 Feb, 2021

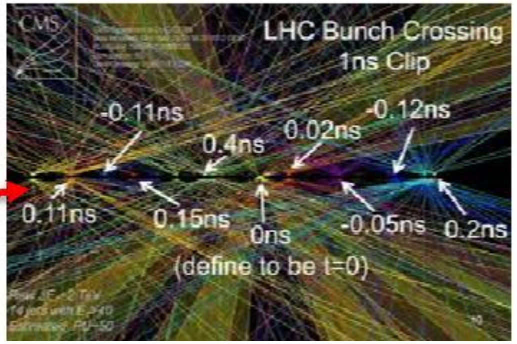
FCC-hh detector requirements summary

Used in Delphes physics simulations

- **ID tracking target**: achieve σ_{p_T} / p_T = 10-20% @ 10 TeV
- **Muon target**: σ_{p_T} / p_T = 5% @ 10 TeV
- Keep **calorimeter constant** term as small as possible (and good sampling term)
  - Constant term of <1% for the EM calorimeter and <2-3% for the HCAL
- **High efficiency vertex reconstruction, b-tagging, τ-tagging, particle ID**!
  - Pile-up of <μ>=1000 → 120μm mean vertex separation
- **High granularity** in tracker and calos (boosted obj.)
- **Pseudorapidity (η) coverage**:
  - Precision muon measurement up to |η|<4
  - Precision calorimetry up to |η|<6
- **→ Achieve all that at a pile-up of 1000! → Granularity & Timing!**
- **On top of that radiation hardness and stability!**

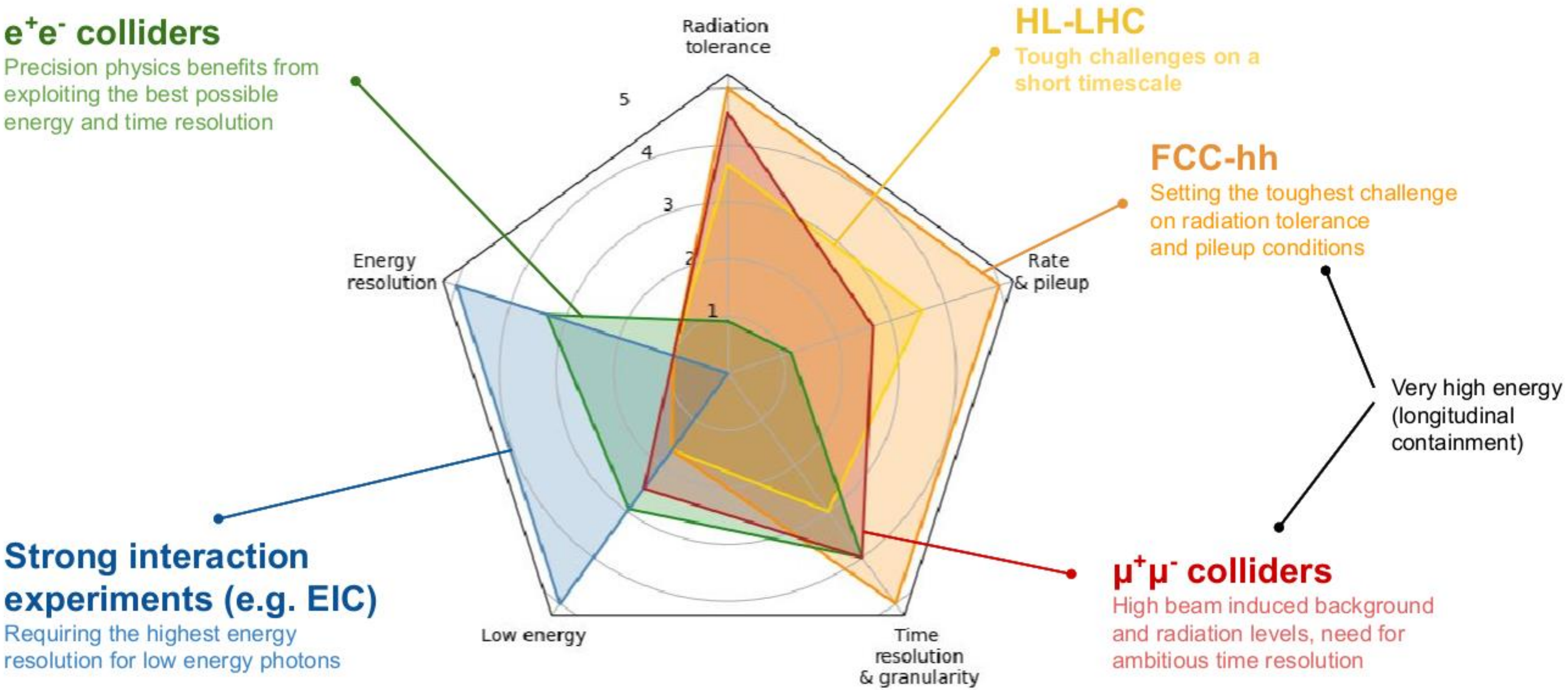






Martin Aleksa, ECFA Detector R&D Roadmap Input Session 19 Feb, 2021

Qualitative representation of **requirements** for calorimetry **at future colliders**



M. T. Lucchini ECFA Detector R&D Roadmap TF 6: Calorimetry Community Meeting, 12 Jan 2023

Inspired from https://indico.cern.ch/event/994685/

R&D on new scintillators

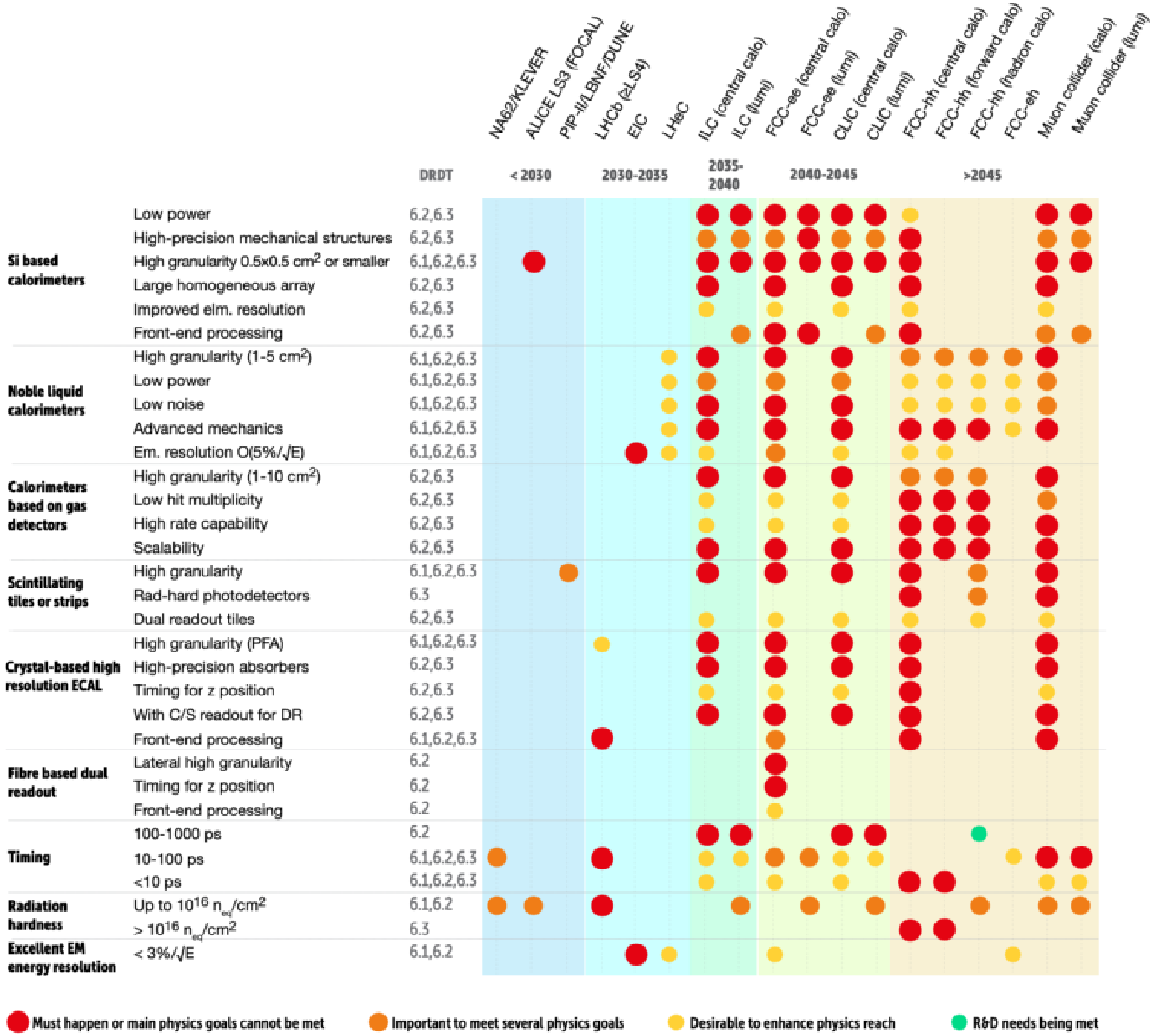
A few key factors on the roadmap for future particle detectors:

- Large light yield
- Fast signals
- Dual readout
- High granularity
- Radiation hardness

Towards DRD6 several pertinent R&Ds were identified as well as possible detector concepts

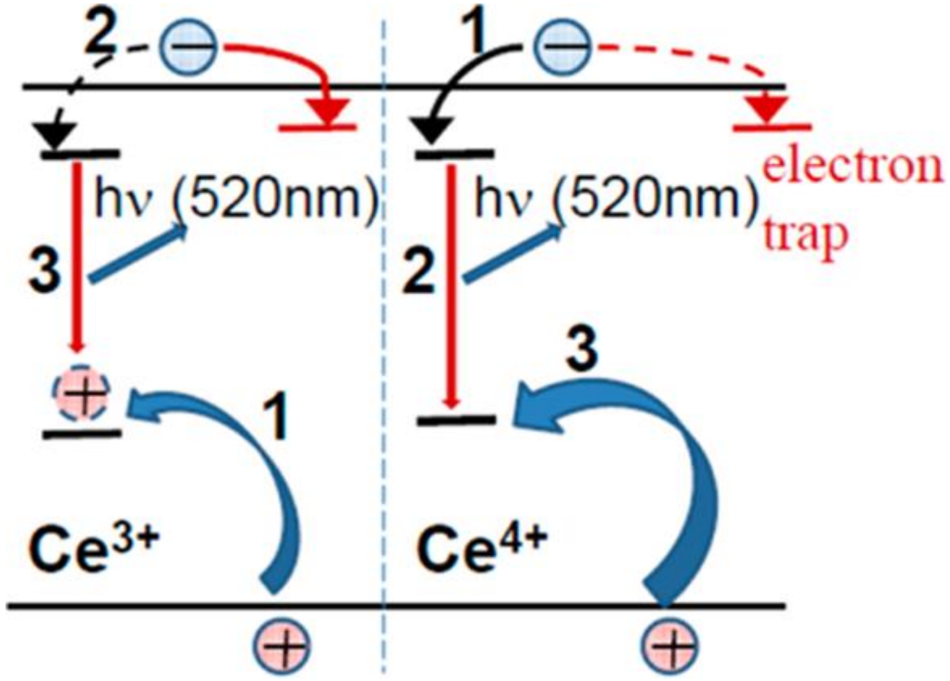
Table 2: Overview of R&D activities on optical calorimeter concepts.

Name	Calorimeter type	Application	Scintillator/WLS	Photodetector
HGCCAL	EM / Homogeneous	e^+e^- collider	BGO, LYSO	SiPMs
MAXICC	EM / Homogeneous	e^+e^- collider	PWO, BGO, BSO	SiPMs
CRILIN	EM / Quasi-Homog.	$\mu^+\mu^-$ collider	PbF_2, PWO-UF	SiPMs
GRAINITA	EM / Quasi-Homog.	e^+e^- collider	$ZnWO_4$, BGO	SiPMs
SPACAL	EM / Sampling	e^+e^-/hh collider	GAGG, organic	MCD-PMTs, SiPMs
RADICAL	EM / Sampling	hh collider	LYSO, LuAG	SiPMs
DRCAL	EM+HAD / Sampling	e^+e^- collider	PMMA, plastic	SiPMs, MCP
TILECAL	HAD / Sampling	e^+e^-/hh collider	PEN, PET	SiPMs



Technological needs for calorimetry
2021 ECFA Detector R&D Roadmap

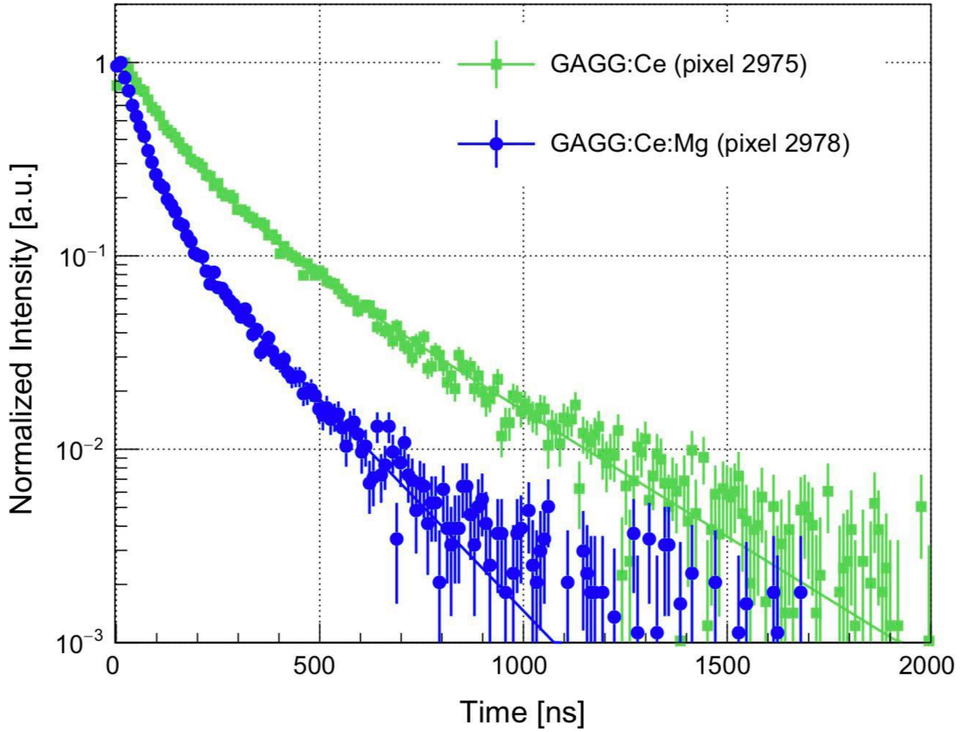
Crystals: playing with the time
Accelerating the emission, co-doping Ce, Mg in garnet



M. Nikl et al. Cryst. Growth Des. 2014 , 14 , 4827

The competitive processes in the case of the Ce^{4+} allow the faster arrival (in step 1) to the excited state that will generate the photon, while in Ce^{3+} it only happens in step 2 since it needs to capture the hole first

Presence of Mg^{2+} increases number of Ce^{4+} centers, compete with electron traps for electron capture in the initial instants of scintillator mechanism -> faster decay

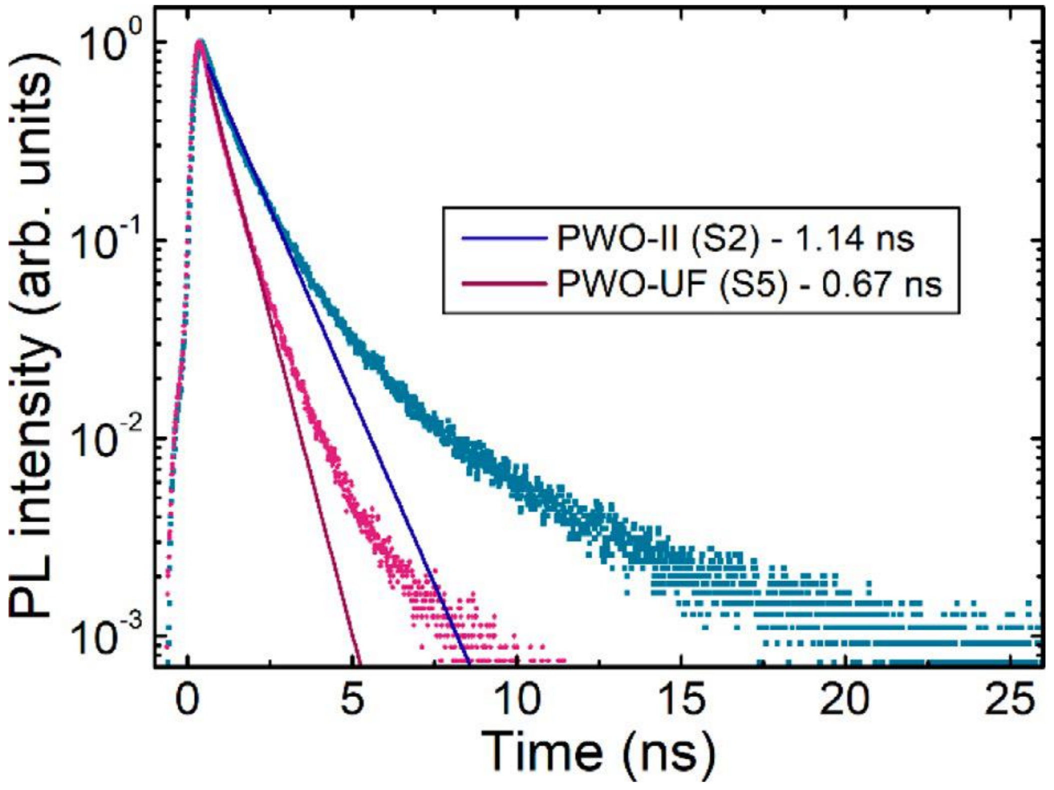


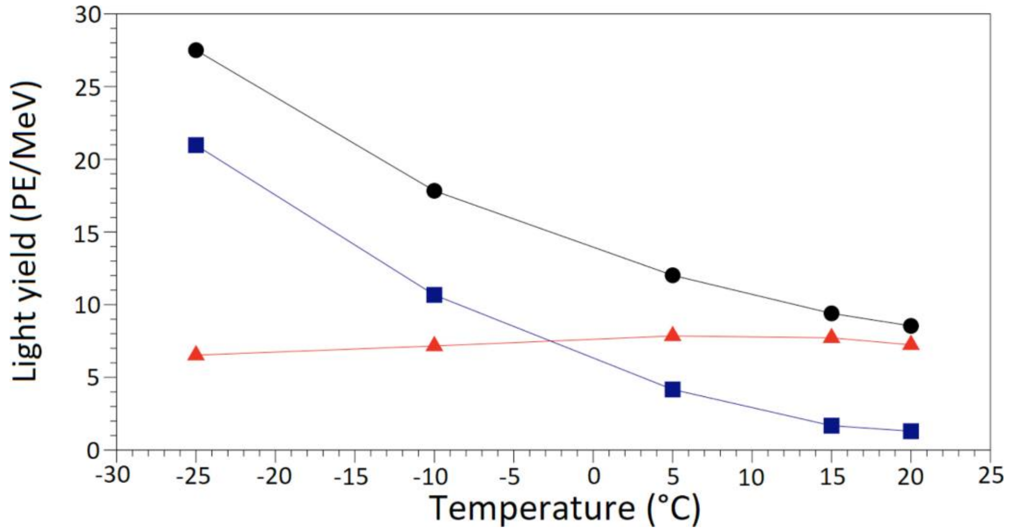
Faster decay time with co-doping Ce^{3+} /Mg^{2+} in $Gd_3Al_2Ga_3O_{12}$ garnet

M. T. Lucchini et al., NIM A, 816 (2016) 176

Ultra fast PWO

PWO now is the most extensively used scintillator in HEP experiments
Doping of PWO by La and Y at the level above 1000 ppm (~10x standard)
Fast component improved, but less light than 2nd generation PWO





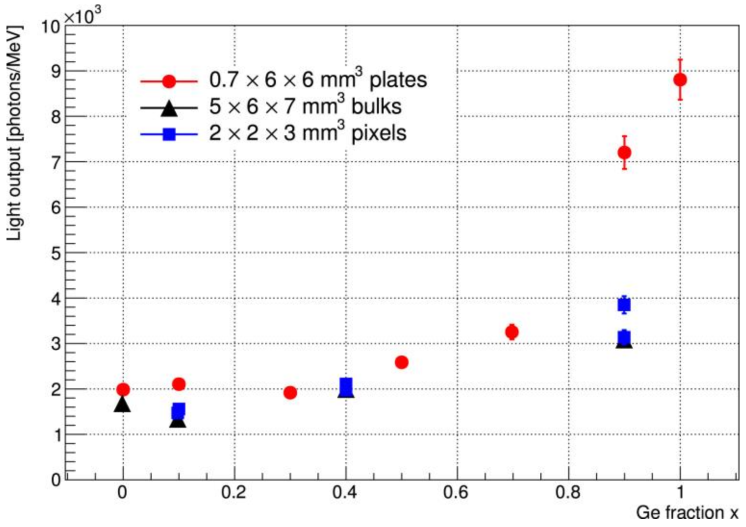
Triangles – ultra fast component
Squares – slow component
Circles - total

M. Korzhik et al, Nucl. Instr. Meth. in Phys. Res. A 1034 (2022) 166781

Mixed Material BGO-BSO

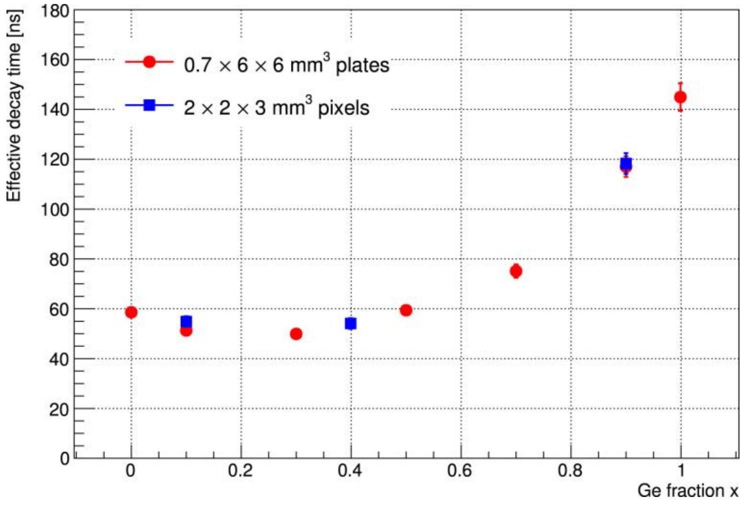
Tune timing changing the fraction Ge/Si in the material

Light output and decay time depend on the Ge fraction in the material

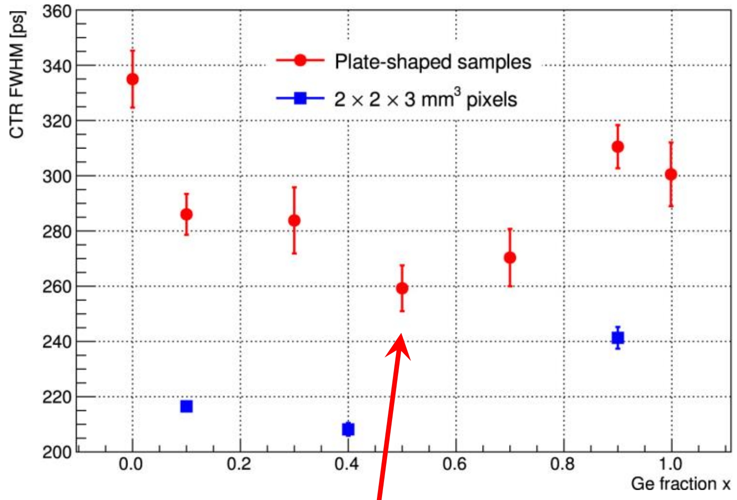


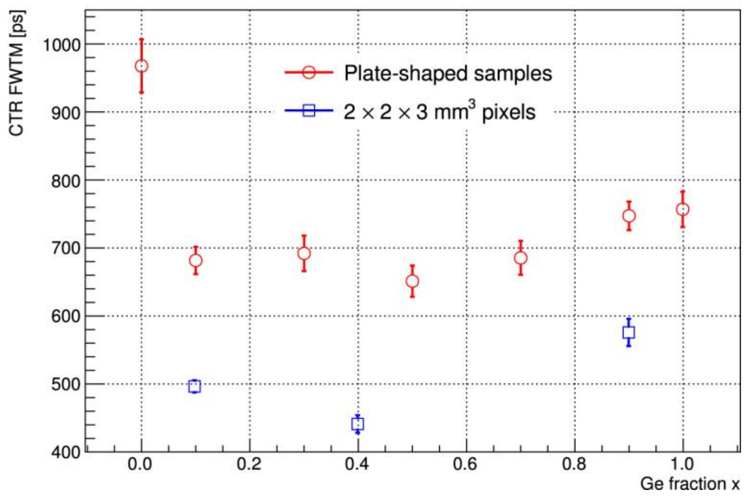
BSO

BGO



R. Cala et al, NIMA, A 1032 (2022) 166527

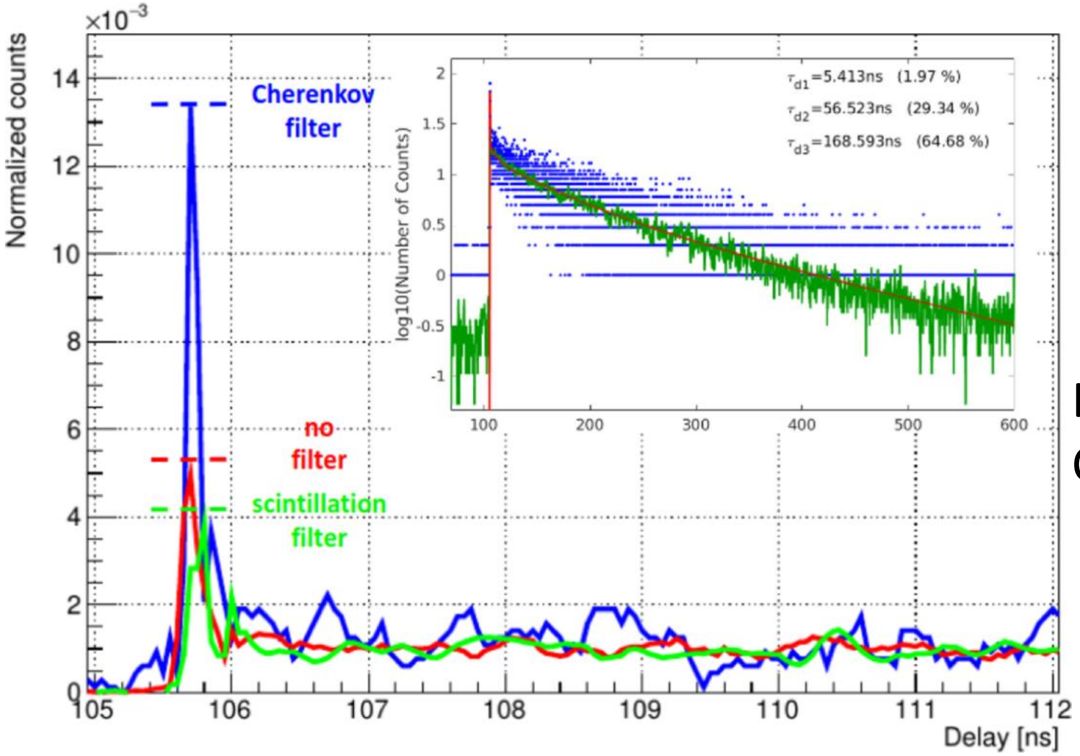




Coincidence time resolution @511Kev versus Ge fraction.
It is optimal at 50% Ge fraction for plate shaped samples.

Improving time resolution with Cerenkov

In BSO, Cerenkov light spectrum mostly in the UV, and scintillation light peaks in the blue filters can be used to separate the 2 components



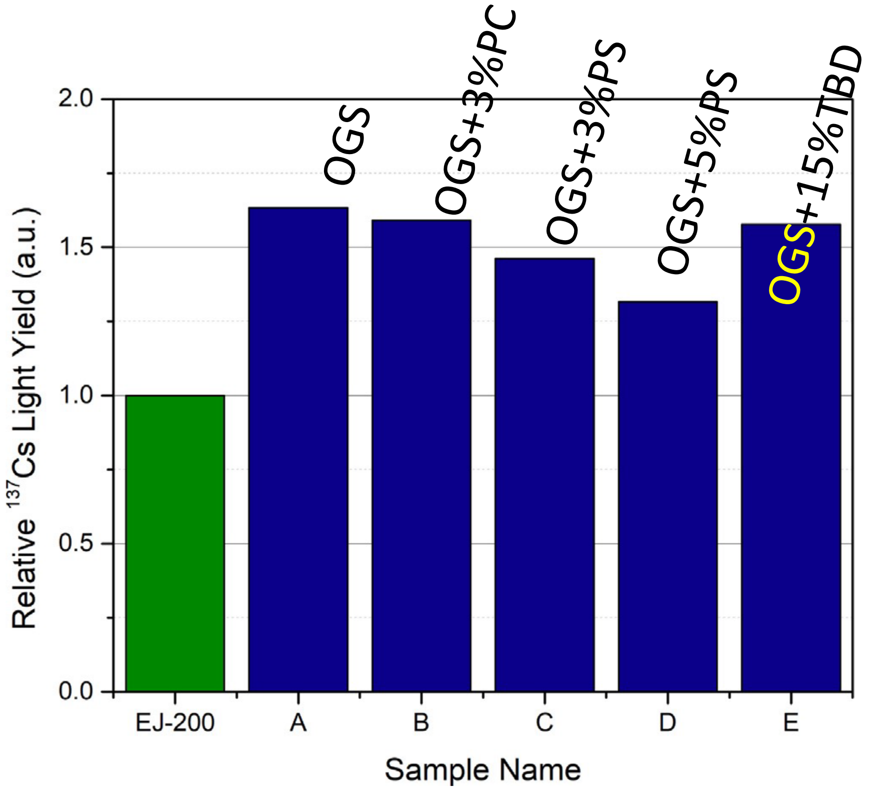
Distributions normalized to the region without Cerenkov influence (106.5 to 200 ns)

R. Cala et al, NIMA, A 1032 (2022) 166527

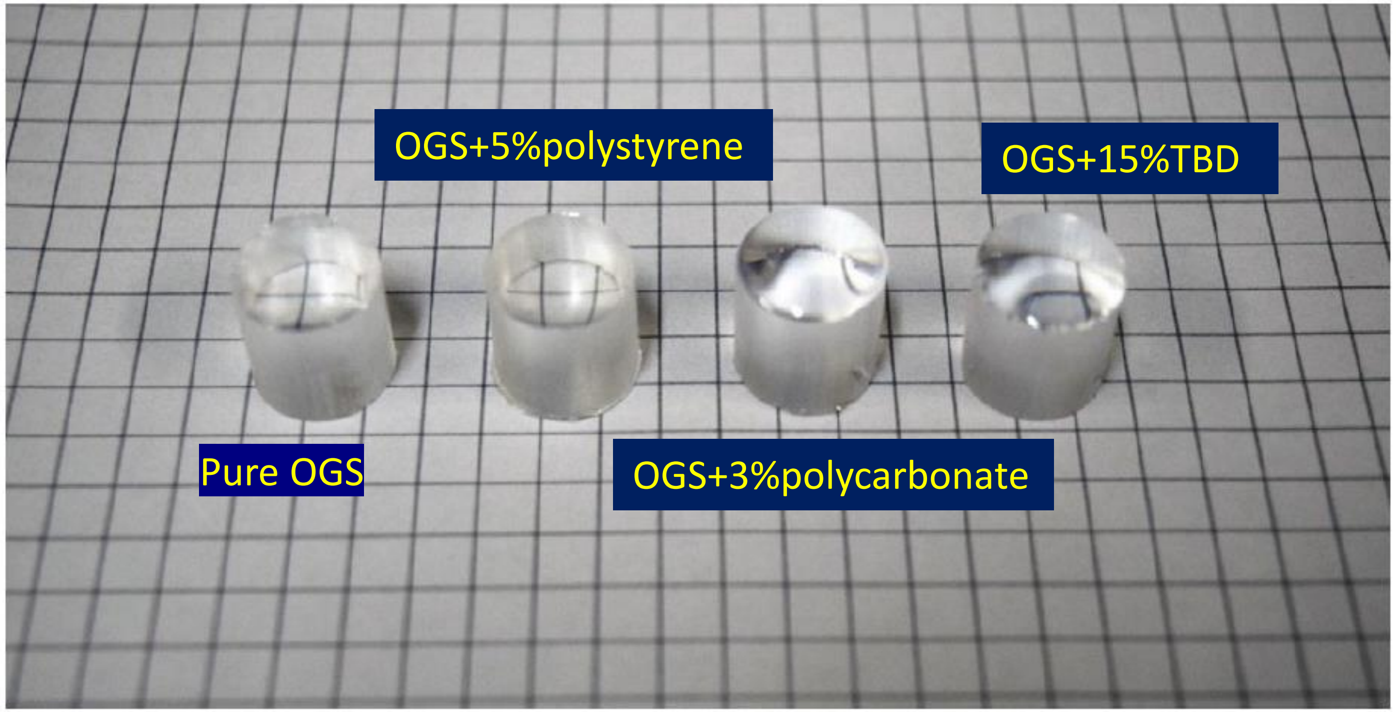
Using different SiPMs with adequate spectral sensitivity will allow the collection of Cerenkov and the scintillator components separately in a crystal based dual-readout calorimeter

Organic glass scintillator

Organic glasses developed by Sandia National Lab are better in terms of light yield compared with an industry standard plastic scintillator (EJ-200 from Eljen)



L. Q Nguyen et al., NIMA 1036 (2022) 166835



1 cm cylinders of OGS with additives

Plastic scintillators

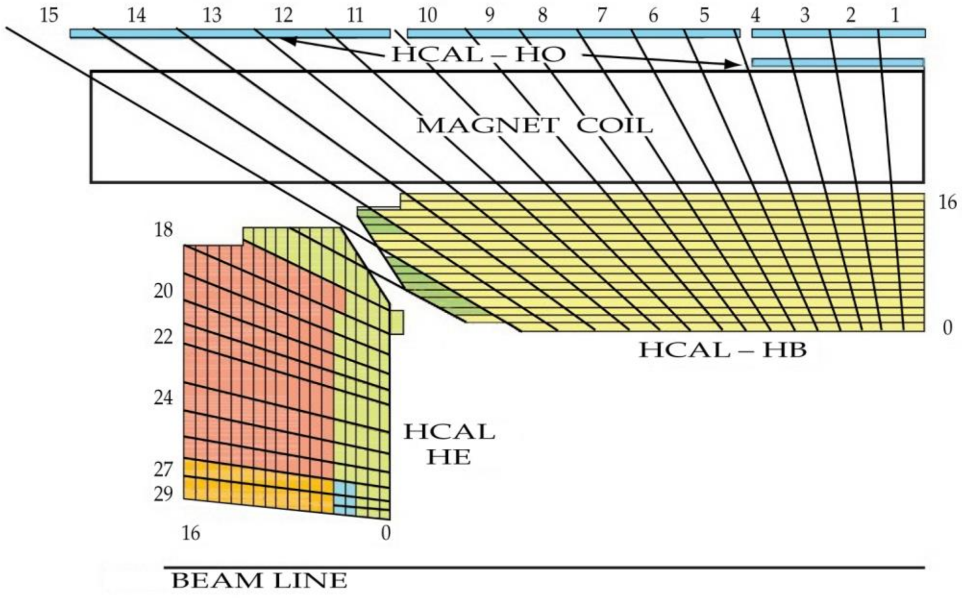
Plastic scintillators have been widely used in calorimeters at the LHC with a remarkable success

A few examples (combined with Y11 WLS fibres):

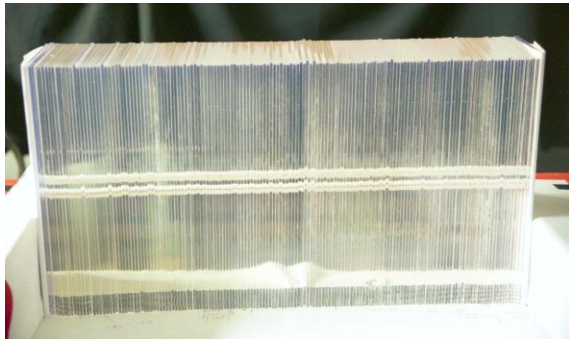
CMS HCAL, SCSN81 and BC408 plate scintillators

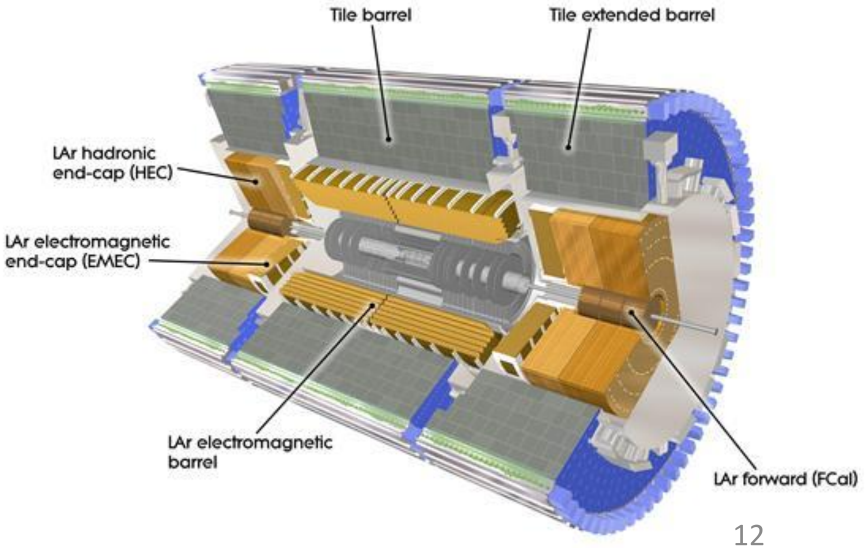
LHCb HCAL, Protvino PS+pTp+POPOP scintillator

ATLAS TileCal, Protvino PS+pTp+POPOP scintillator



Protvino PS + pTp + POPOP scintillator produced in large quantities by cheap injection moulding technology

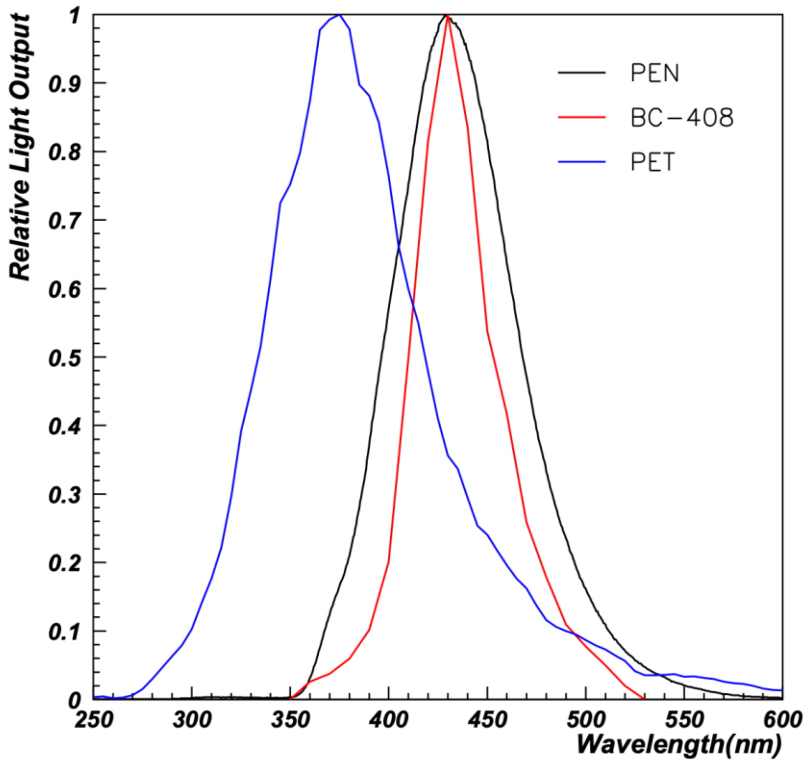


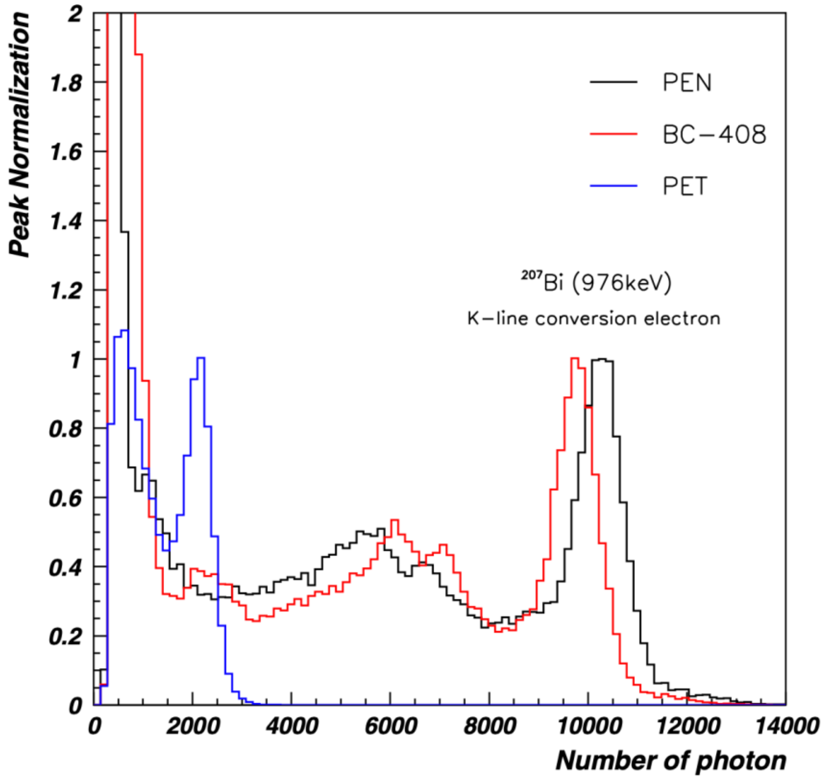


PET/PEN scintillators

PEN (Polyethylene Naphthalate) and PET (Polyethylene Terephthalate) are promising plastic scintillators

- Adequate emission spectra
- Competitive Light yield
- Relatively radiation hard





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

PET/PEN scintillators - DLight

R&D project of LIP with Institute for Polymers and Composites (Univ. Minho), Portugal

Started production of small samples of PEN and PET scintillators by injection moulding

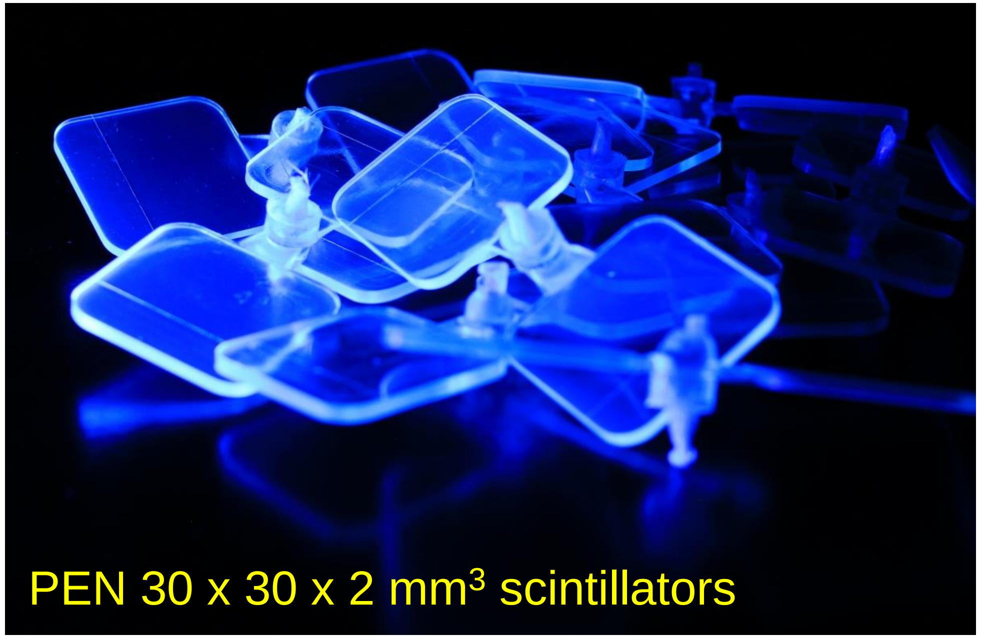
Process PET/PEN granulate

- Extrusion/injection-moulding
- Tuning parameters for better transparency and homogeneity
- Set up a scalable manufacturing technique

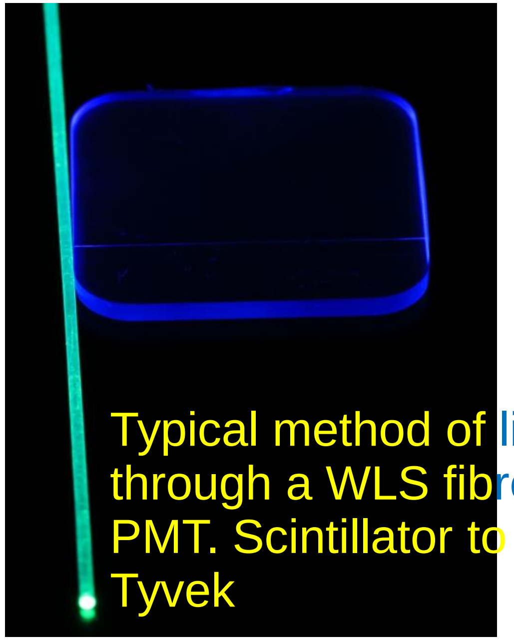
Production of $30x30x2mm^3$ PEN and PET samples by injection moulding.

PET/PEN scintillators - DLight

Samples produced and started to be tested



PEN 30 x 30 x 2 mm^3 scintillators

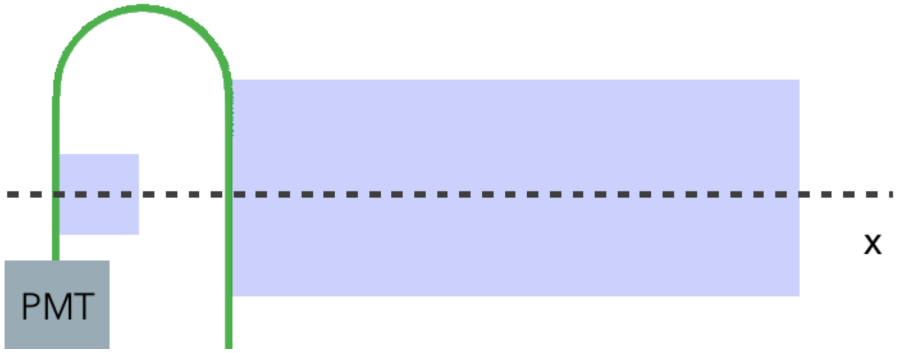


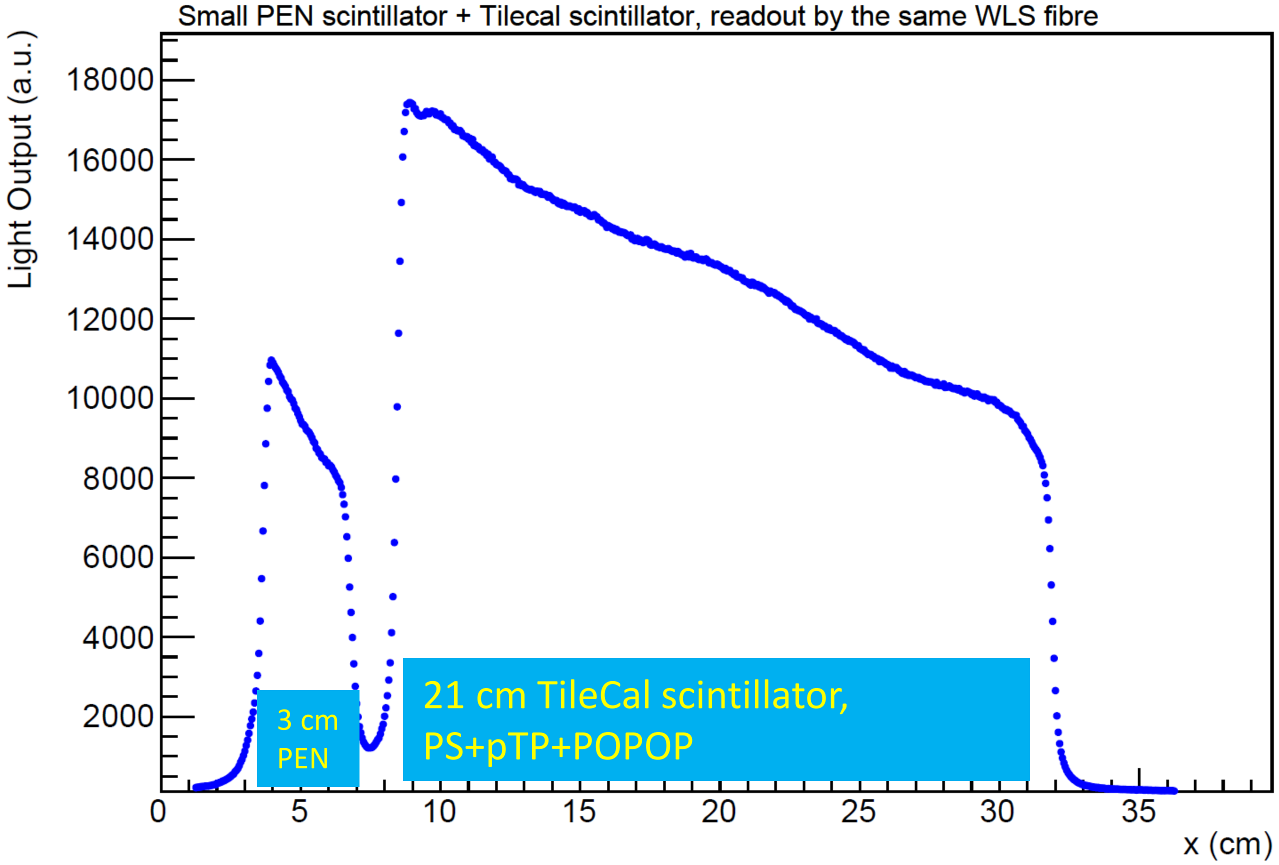
Typical method of light collection through a WLS fibre and a SiPM or PMT. Scintillator to be wrapped in Tyvek

Goal of the project is to produce relatively cheap PET and PEN based scintillators and study the respective properties includding radiation hardness

To operate as barrel hadron calorimeter at FCC-hh need to survive in high radiation environment

PET/PEN scintillators - DLight

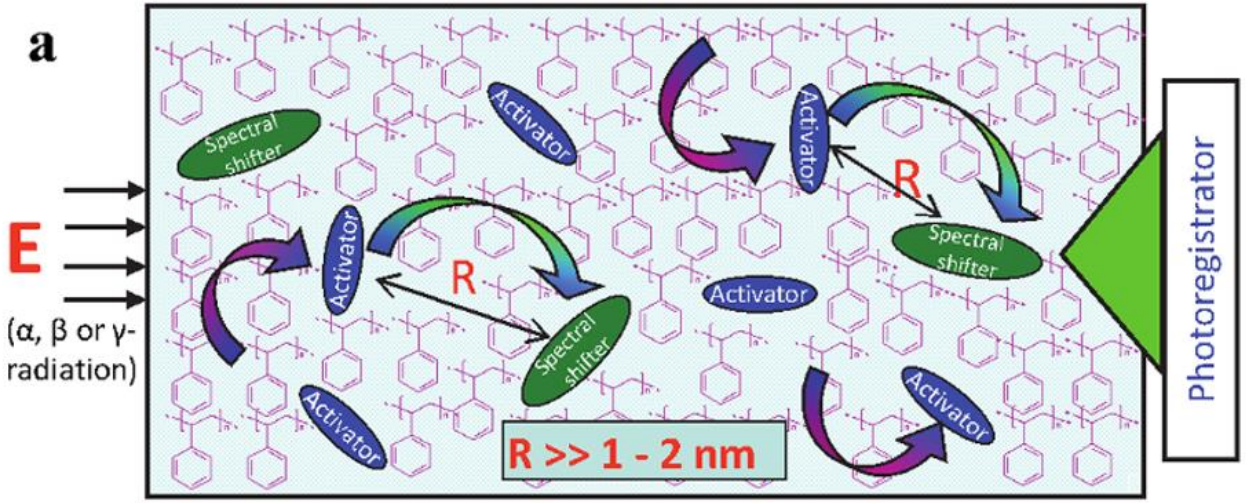


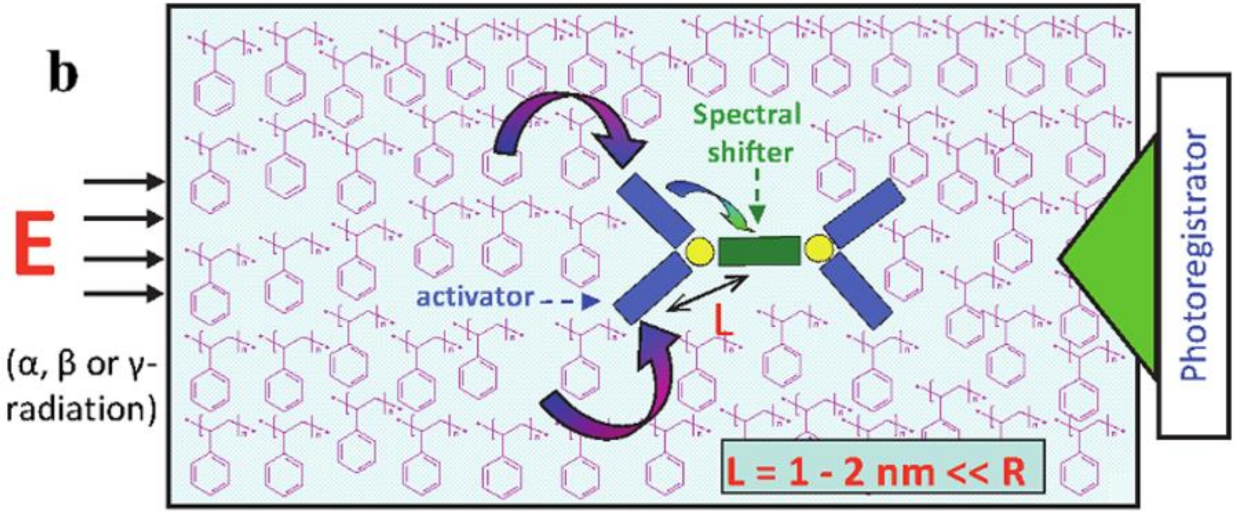


Scan using ^{90}Sr source to excite the scintillators across the dashed line in the left figure.
Y11(200) WLS fibre used.
Tilecal scintillator used as reference (3mm thick, wrapped in Tyvek)
PEN scintillator (2mm thick, wrapped in white paper)
Need to increase dimensions, improve mould and injection conditions

Nanostructured organosilicon luminophores

Space distribution of activators and spectral shifthers in a plastic scintillator not very efficient due to distances between activator and spectral shifter molecules



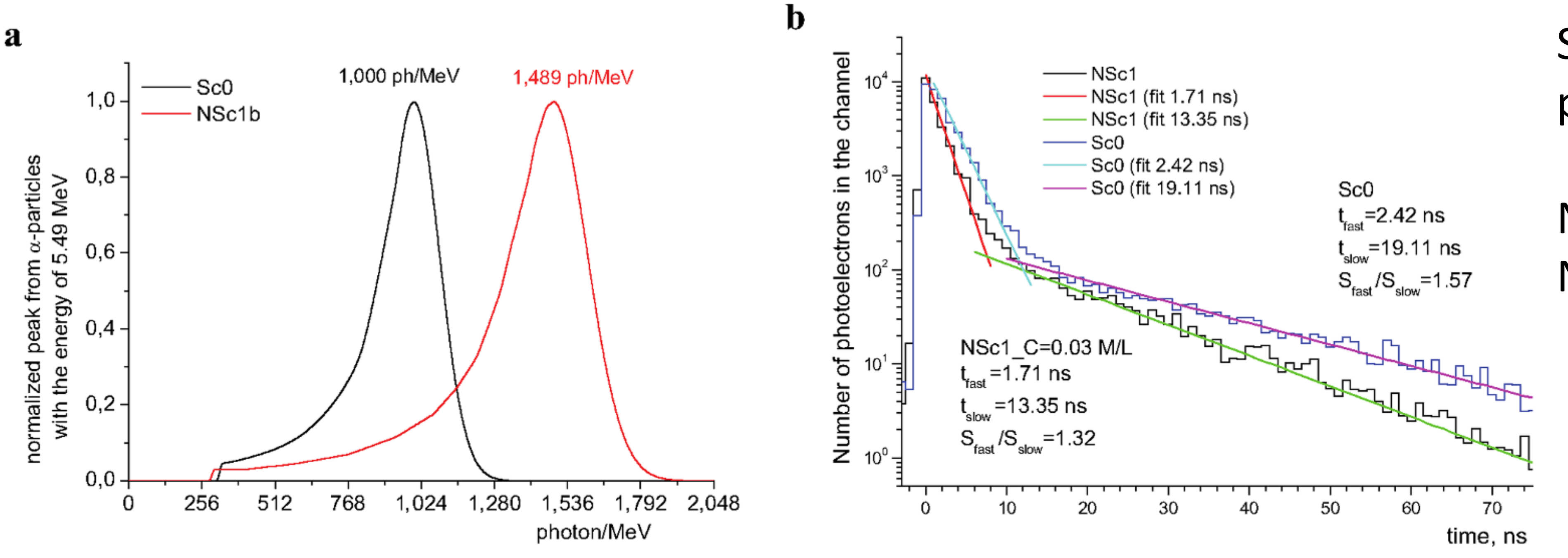


Typical organic scintillator, e.g., PS + pTp as activator and POPOP as spectral shifter to avoid light absorption by base and activator materials

Engineer a spectral shifter that can be inserted in an activator molecule. Distance of order of nm ensures very good efficiency in the production of light by the spectral shifter for which the material is transparent

S. A. Ponomarenko et al, Sci Rep 4, 6549 (2014)

Nanostructured organosilicon luminophores



Sc0 – PS scintillator with pTp and POPOP

NSc1 – PS scintillator with a NOL

NOL improves light yield and decay time

Different NOLs can provide a wide range of wavelengths that are suitable to the SiPMs

3D printed plastic scintillator

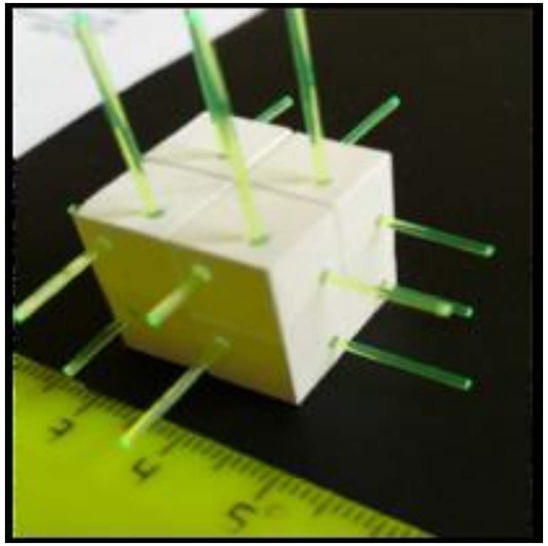
There is a tendency to develop large plastic scintillator detectors with complex and fine granularity geometries

Example: 2 million scintillator cubes needed in T2K experiment

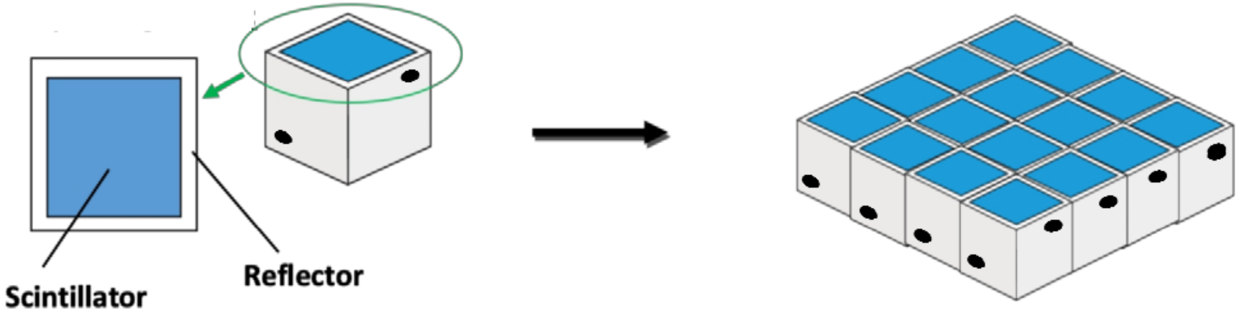
These small cubes need holes to pass WLS fibres to collect the light

Even using mould injection for scintillator production would require lots of holes drilling

Additive manufacturing seems to be a viable solution

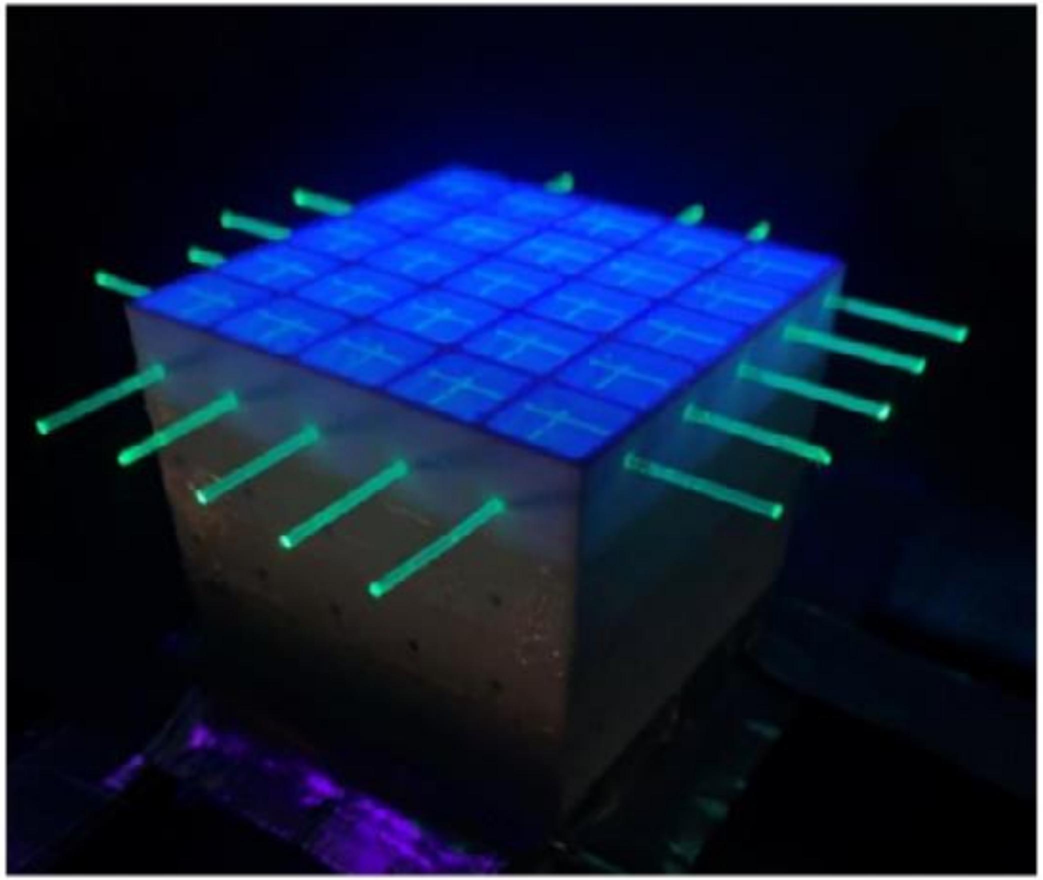


3DET Collaboration

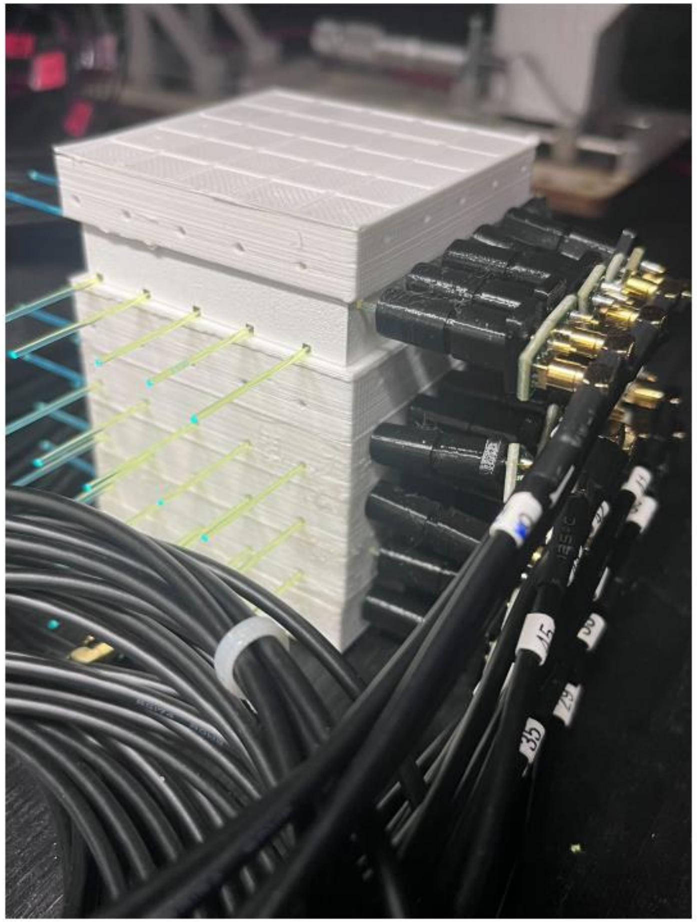


Simultaneous printing of scintillator and reflector with the holes in a single step is an efficient way of production

3D printed plastic scintillator



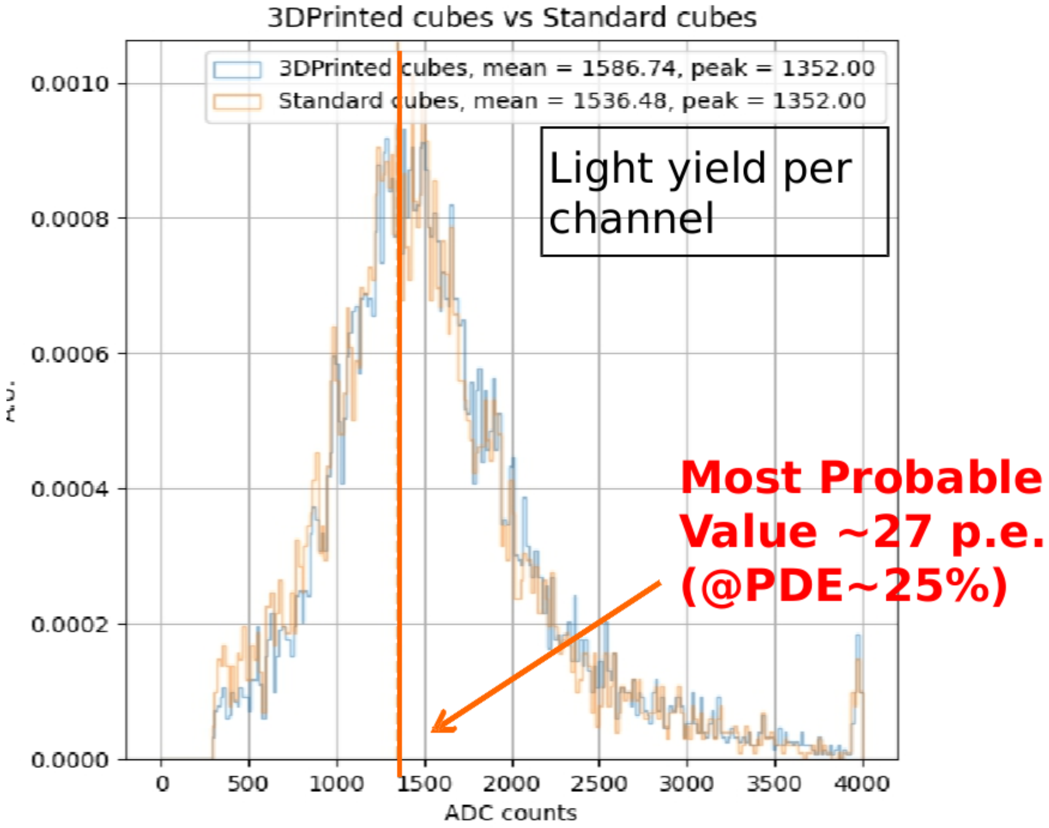
3D printed SuperCube, filled with WLS fibres (iluminated with UV light)



Detector ready for testing. Readout by SiPM.

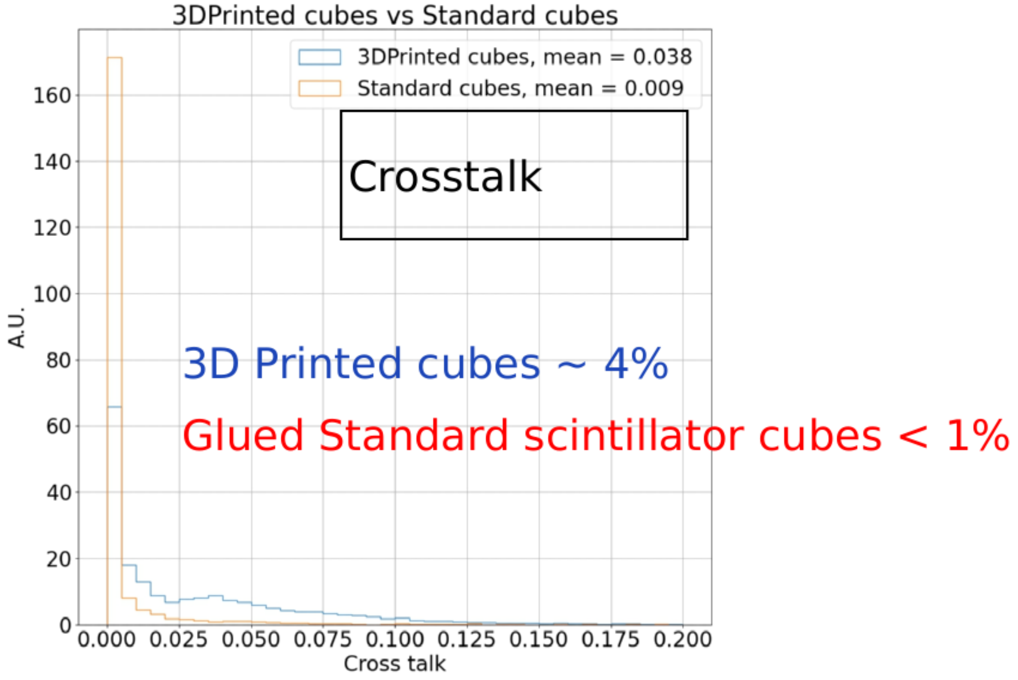
3DET Collaboration

3D printed plastic scintillator



Tested with cosmic, light yield ~ 27p.e./channel/cosmic

Botao Li, 3DET Collaboration, presentation at EPS-HEP2023



Successfully tested for the first time a totally 3D printed "final" plastic scintillator detector (no post-processing) with performance acceptable for a particle physics experiment

Summary

Scintillators are excellent candidates to be the active components of FCC calorimeters

Huge amount of R&D ongoing to develop scintillators with adequate properties

- Fast
- Large light yield
- High granular
- Radiation tolerant

New technologies being explored and developed

Old and new production methodologies being used to produce practical detectors

LIP and IPC developing PEN and PET scintillators by injection moulding

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