Development of Sampling Modules for the Upgrade II of the LHCb ECAL

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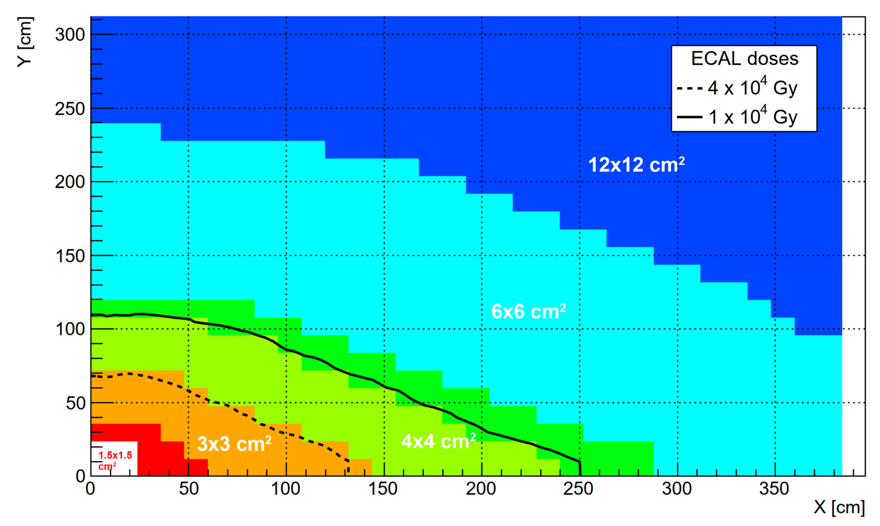
Motivations

The LHCb experiment will run at increased luminosity up to $2{\times}10^{34}$ cm^{-2}s^{-1}.
New requirements will be posed on the electromagnetic calorimeter (ECAL) in terms of **radiation hardness** and **occupancy**.



Upgrade II ECAL configuration with cells sizes, top-right quadrant. All the modules have 12x12 cm^2 dimensions, but different cells size.

Shashliks used now are radiation-hard up to 40 kGy. A new technology is needed for:

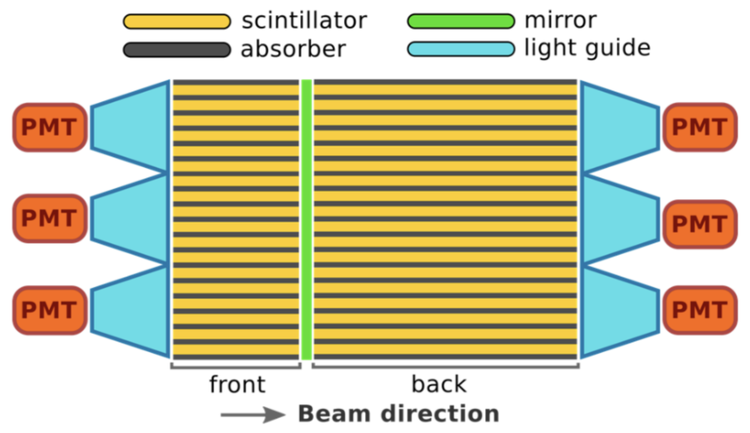
- the 32 innermost modules up to 1 MGy
- 144 inner modules up to 200 kGy

Detector Requirements	
Radiation Hardness	up to 1 MGy
Cell lateral size	~ 2 cm
Time resolution	O(10) ps
Energy resolution	10%/√E + 1%

Spaghetti Calorimeter (SPACAL)

Scintillating fibres embedded in dense absorber:

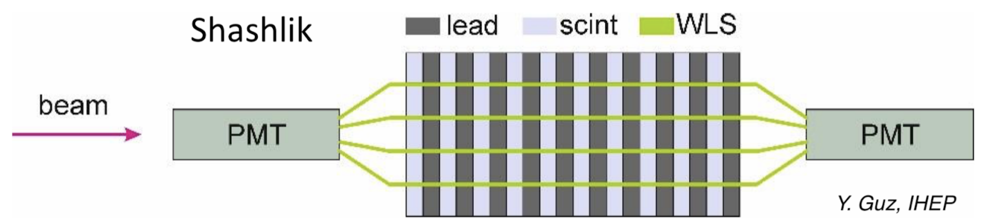
- **Garnet crystals** and **Tungsten** for the 1 MGy area
- **Polystyrene** and **Lead** for the 200 kGy area
- Longitudinal segmentation and double readout front and back to **increase radiation tolerance**, **improve reconstruction**, and to allow for an optional **timing layer in the shower maximum**



Shashlik

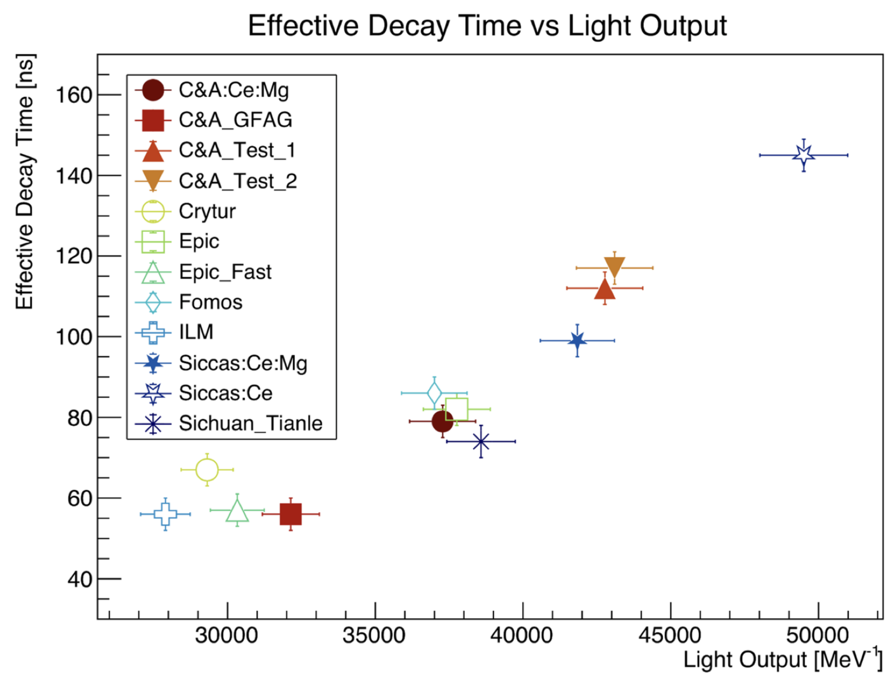
Lead and plastic scintillators tiles, with wavelength-shifting (WLS) fibres:

- Employed in the current ECAL
- Old modules will be refurbished and upgraded with **double readout** and **faster WLS fibres** (e.g. Kuraray YS-4)



R&D on Scintillating Crystal Garnets

Crystal garnets are radiation hard.
$Gd_3Al_2Ga_3O_{12}$:Ce (**GAGG**) is a candidate for the innermost region.

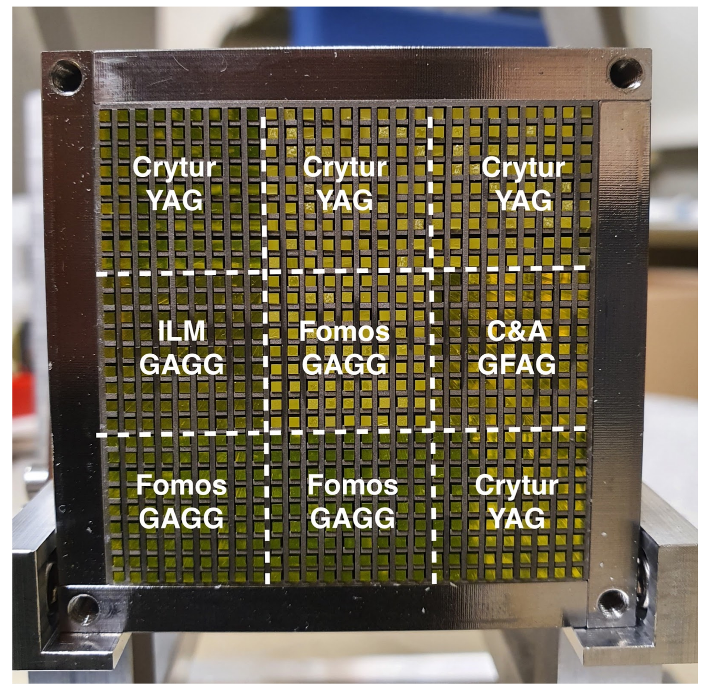


L. Martinazzoli et al., NIM A 1000 (2021), 165231

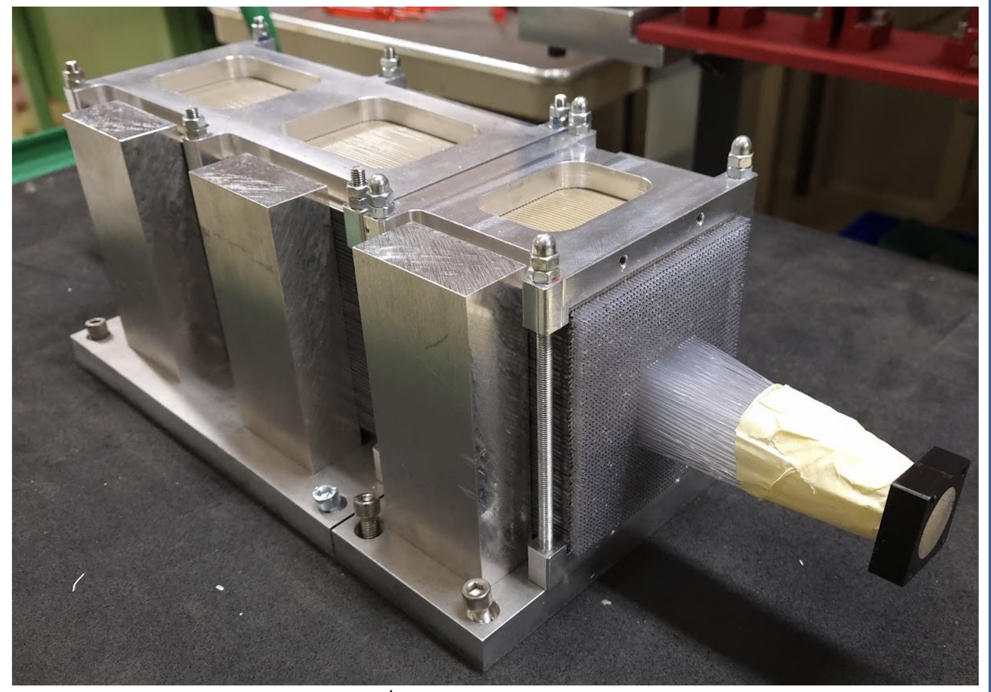
Tuning growth parameters, it is possible to produce GAGG with **high light output**, **fast scintillation** and **excellent time resolution**.

- Different samples explored from various producers
- Samples spanning a factor 2 in light output and 3 in decay time
- Mg^{2+} co-doping stabilises Ce^{4+} speeding up scintillation and improving time resolution
- R&D ongoing in the Crystal Clear collaboration to shorten the decay time and reduce spill-over

SPACAL Prototypes



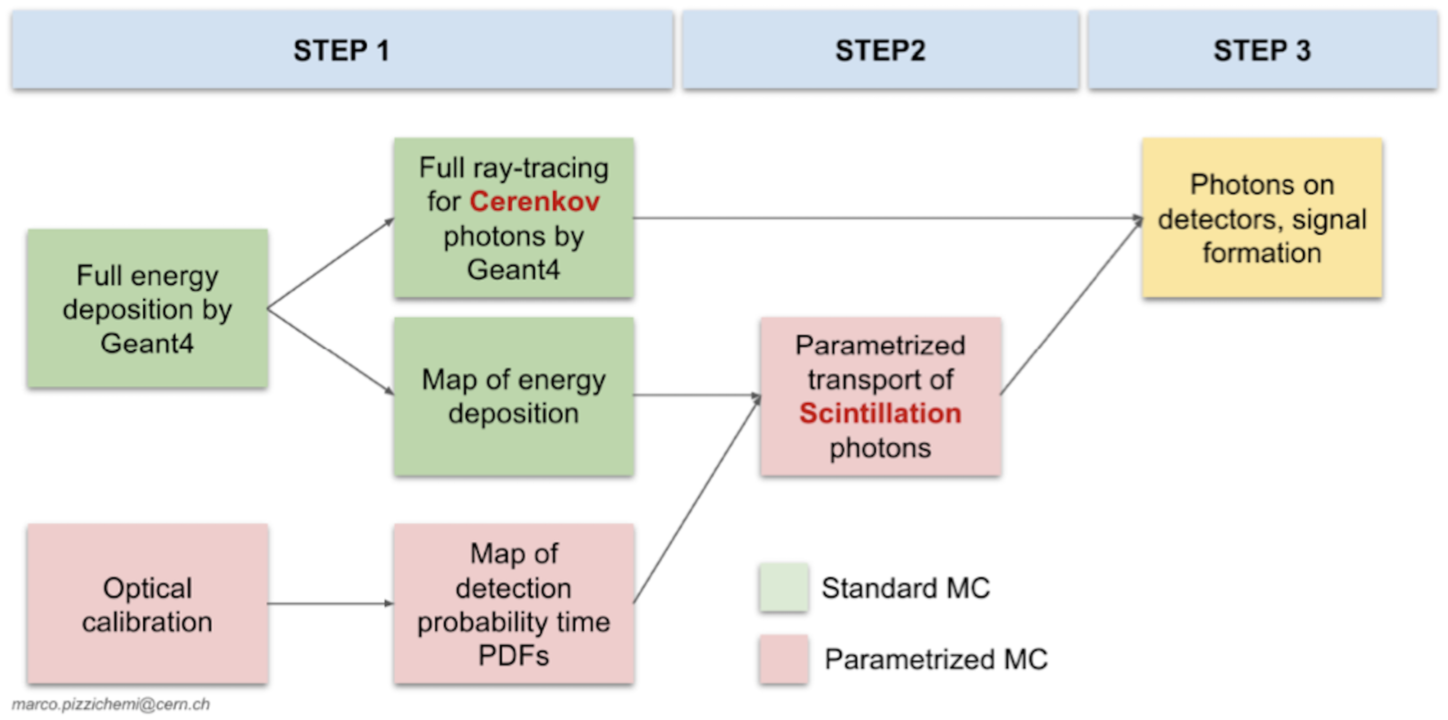
W/GAGG



Pb/Polystyrene

	W-GAGG	Pb-Polystyrene
Absorber Material	Tungsten	Lead
Absorber Density [g/cm³]	19	11
Length [cm] (X_0)	14 (24)	29 (25)
Sections length [cm]	4 + 10	8 + 21
Molière radius [cm]	1.5	2.9
Cell size [cm²]	1.5x1.5	3x3
Pitch [mm]	1.7	1.7
Active Material	GAGG	Polystyrene
Fibre section [mm]	1x1	1 ⌀

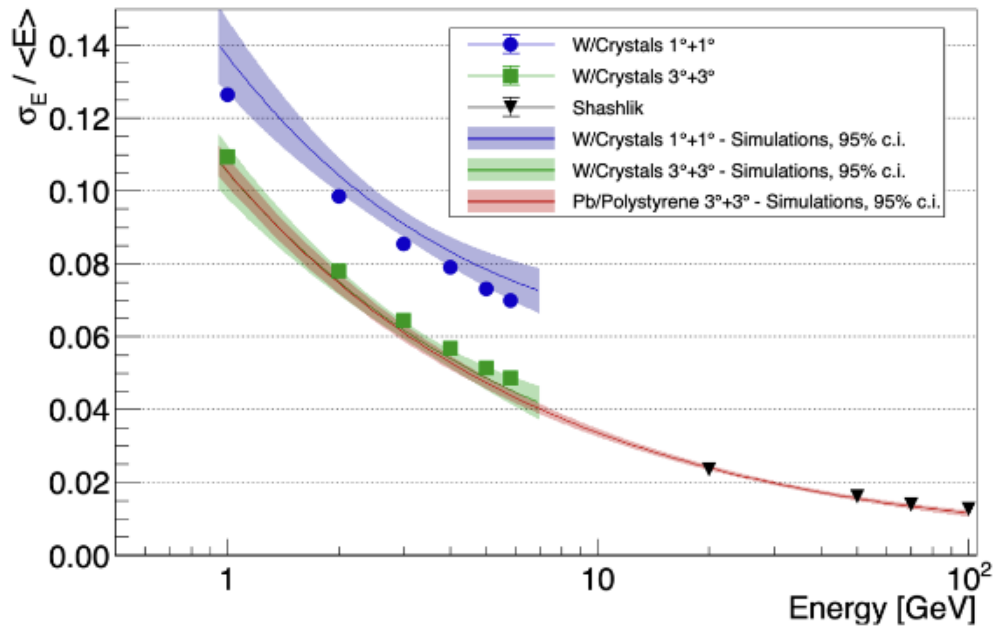
Simulations



- Geant 4 Monte Carlo simulation of energy deposit and parameterised ray-tracing transport of scintillation photons. **Gain in computation time by factor 1000x**
- Particle flux from the LHCb simulation and Upgrade II ECAL geometry available for physics studies

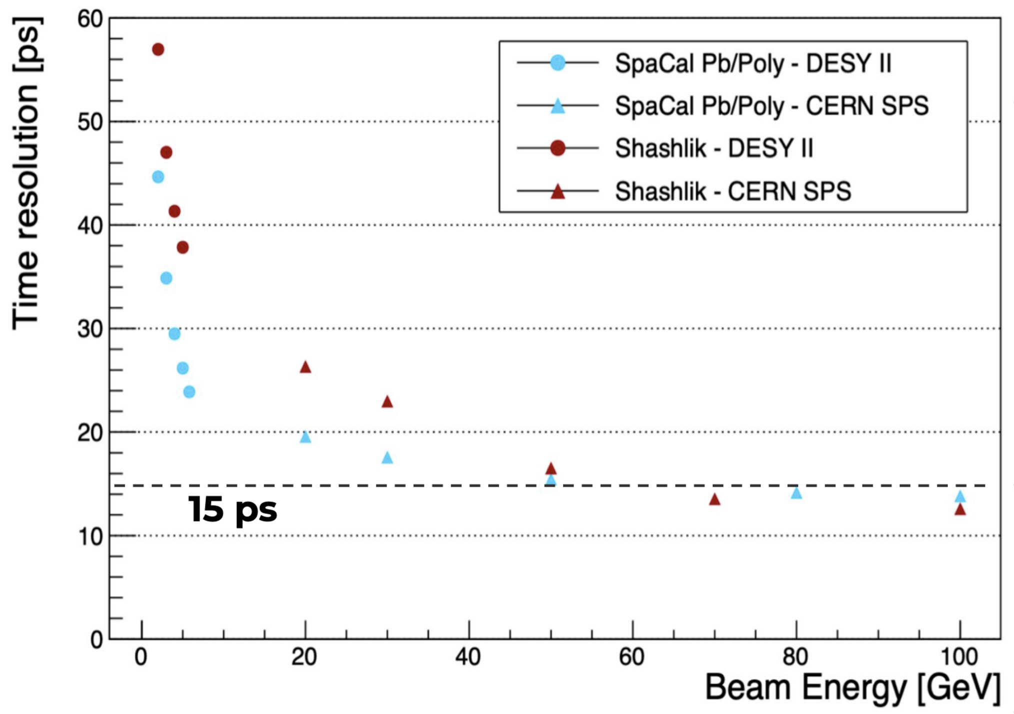
Testbeam Campaigns 2020-2021

Several prototypes tested with electron beams at DESY II and CERN SPS



Energy Resolution

- SPACAL prototypes require an incidence angle different from 0° due to their pointing geometry
- Energy resolution close to $\frac{10\%}{\sqrt{E}} \oplus 1\%$ with a small tilt of $3° \oplus 3°$ (vertical $\oplus$ horizontal)
- Good agreement between testbeam results and Monte Carlo simulations



Time Resolution

- Time resolution dominated by:
  - Scintillation of the active materials
  - Photodetectors properties, e.g. time transit spread (TTS) and single photoelectron response
  - Electronics
- SPACAL modules have better time resolution at low energy (no wavelength-shifting fibres, higher light output)
- **All the prototypes reach time resolution of order 15 ps at high energy**

Readout

The baseline approach for the calorimeter architecture is to move the Front-End board to the ECAL platforms, an area with lower radiation dose. Tested the current 12 m long cables:

- No major degradation of time resolution observed with current cables
- Low-attenuation cables are under study