Scintillating sampling ECAL technology for the Upgrade II of LHCb

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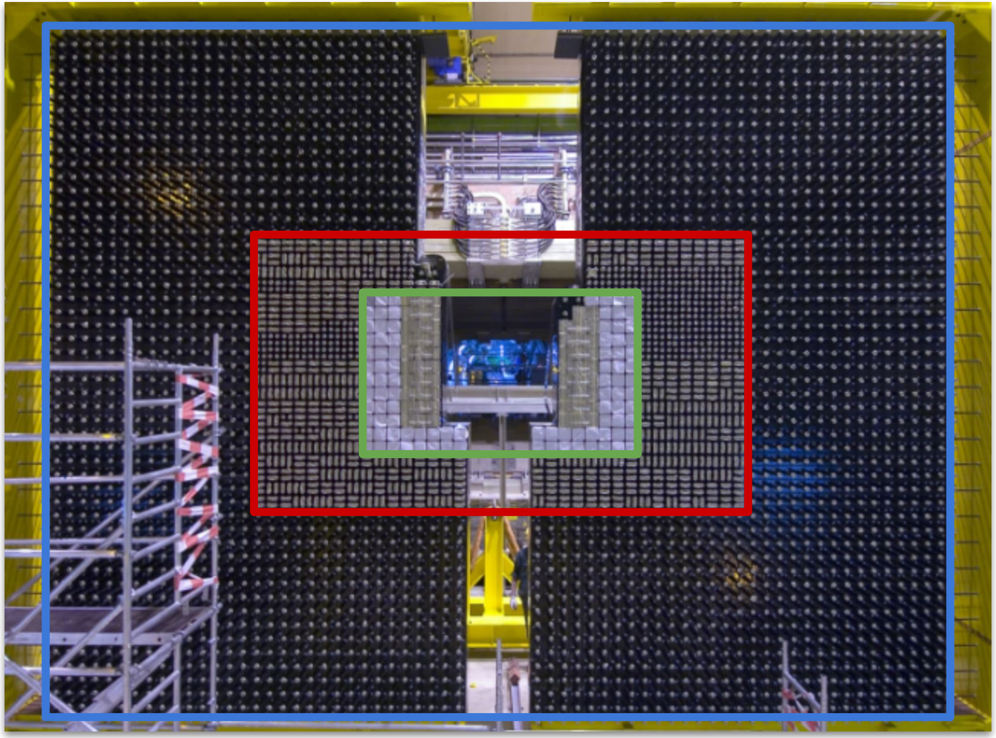
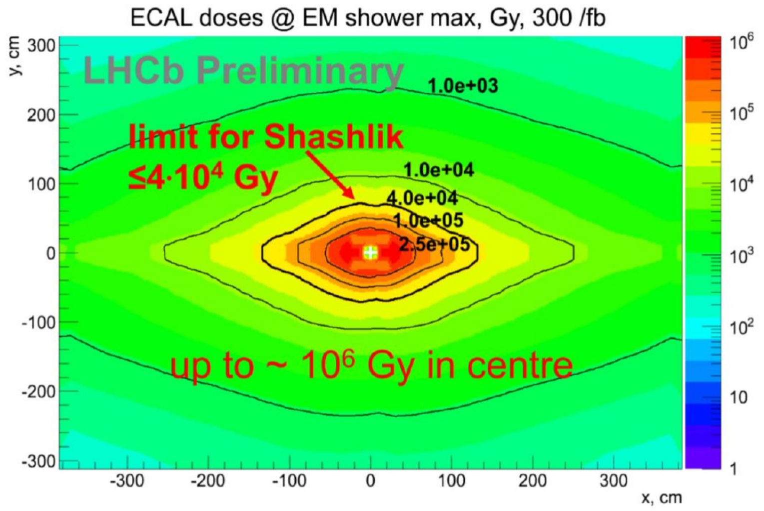
Current LHCb ECAL configuration

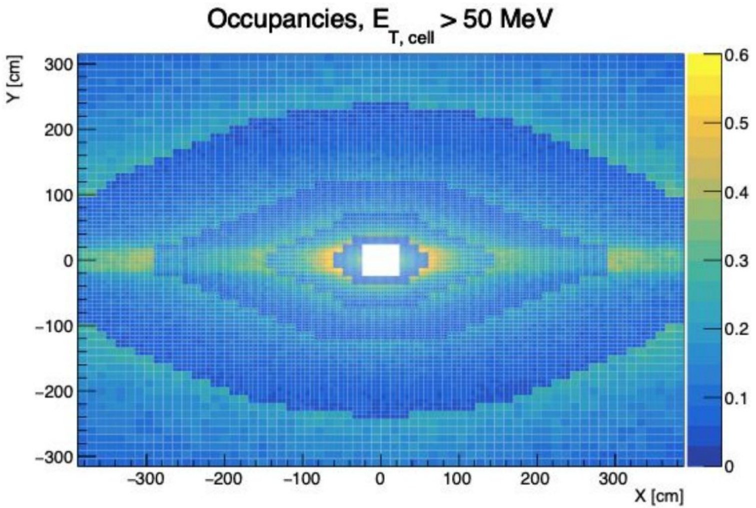


- Large **Shashlik** array (about 50 m^2), with 3312 modules and 6016 channels:
  - ➢ **176** modules 4 x 4 cm^2 cell size
  - ➢ **448** modules 6 x 6 cm^2 cell size
  - ➢ **2688** modules 12 x 12 cm^2 cell size
- Optimized for π^0, e^- and γ identification in the few GeV to 100 GeV region at 2 x 10^{32} cm^{-2} s^{-1}
- Radiation hard up to **40 kGy**
- Energy resolution: $\boldsymbol{\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%}$

Requirements for ECAL Upgrade II

Upgrade II (to be installed at LS4): operation at **$1\text{-}2 \times 10^{34}$ cm^{-2} s^{-1}**





Radiation doses up to 1 MGy and 1 MeV neq/cm^2 in the center for 300 fb^{-1}:

- New technologies required for the center

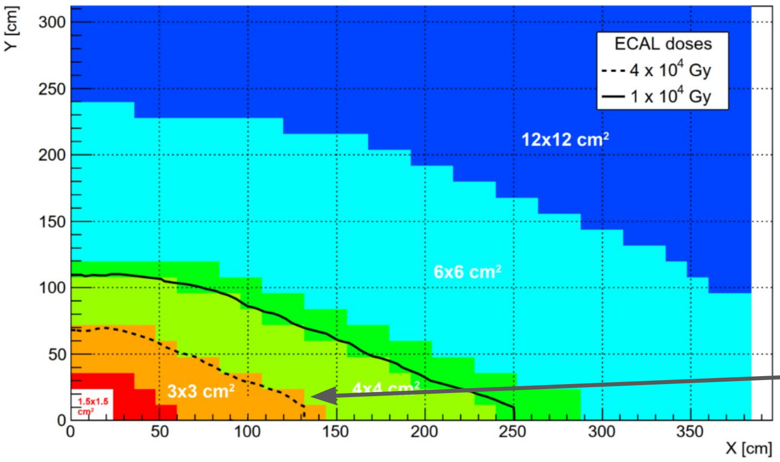
Increased **occupancy** and **pile-up**, requiring:

- Timing O(10ps)
- Increased granularity
- Longitudinal segmentation

Keep the **current energy resolution** of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$

R&D strategy for the ECAL upgrade II

New configuration of modules optimized for radiation dose level



SPACAL-W	1.5 x 1.5 cm^2	32 new modules, rad-hard up to 1 MGy
SPACAL-Pb	3 x 3 cm^2	144 new modules, rad-hard up to 200 kGy
Shashlik	4 x 4 cm^2	272 new + 176 refurbished modules
	6 x 6 cm^2	896 rebuilt + 448 refurbished modules
	12 x 12 cm^2	1344 refurbished modules

Radiation limit of current Shashlik technology

Goals and challenges

- Introduce new Spaghetti Calorimeter (SPACAL) technology in the LHCb ECAL
- Develop radiation hard scintillating crystals
- Need for radiation tolerant organic scintillators
- Add timing to Shashlik modules with new WLS fibres
- Add longitudinal segmentation
- R&D on possible timing layer, based on MCP-PMTs (LAPPD) -> See talk from S. Perazzini (https://indi.to/Y97mz)

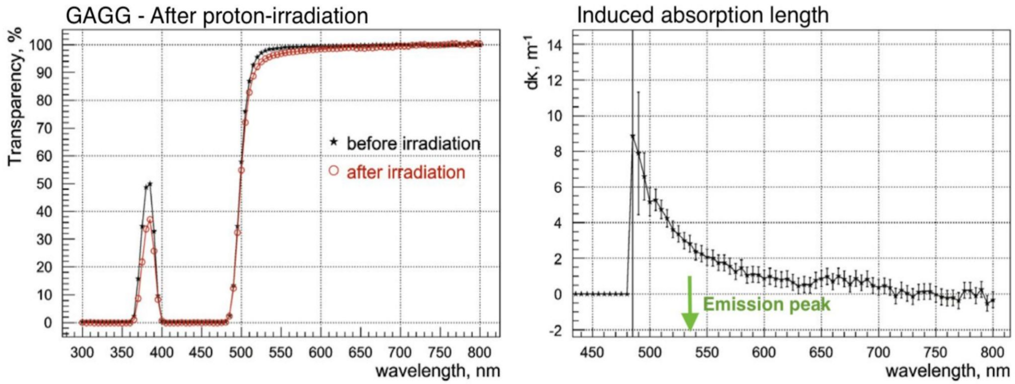
R&D on GAGG crystals

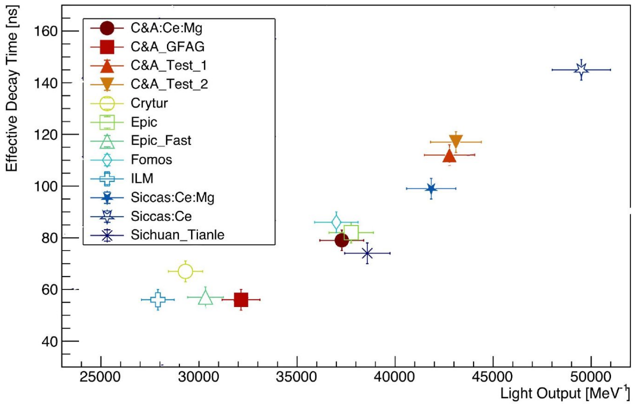
Gadolinium Gallium Aluminium Garnet (GAGG) has **high light yield** and relatively **fast scintillation**

Garnet crystals are **radiation hard**. GAGG irradiated with protons of 24 GeV/c:

- Fluence of 3.1×10^{15} cm^{-2}
- 910 kGy dose
- Induced absorption below 4 m^{-1} at the emission peak

See: V. Alenkov et al., NIM A 916 (2019) 226-229



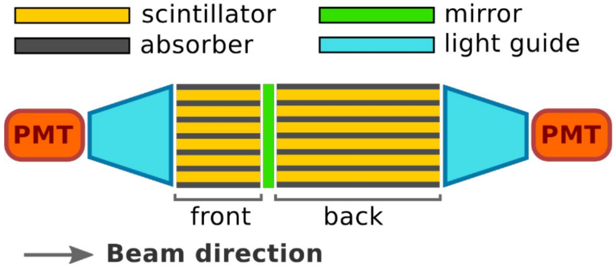


Scintillation properties of GAGG **can be tuned** with different levels of dopants (Ce,Mg) and growth conditions:

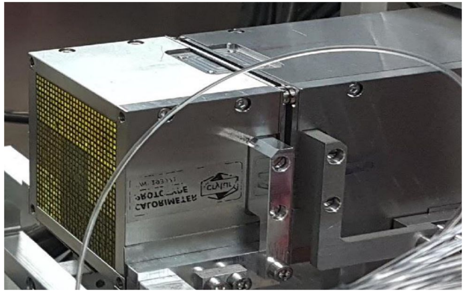
- Sample tested over a factor 2 in light output and 3 in decay time
- High light yield -> slow decay time
- Scintillation is sped up at the expense on light output with Mg codoping
- Further R&D ongoing to reduce decay time below 20 ns

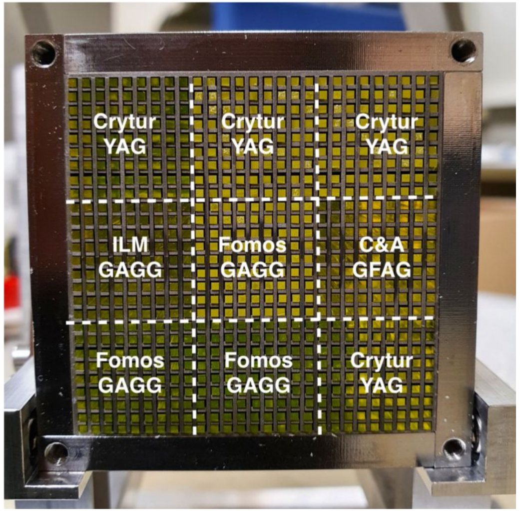
See: L. Martinazzoli et al., NIM A 1000 (2021) 165231
L. Martinazzoli et al., submitted to Light: Science & Applications

SPACAL-W prototype with garnet crystal fibres



- **Pure tungsten** absorber with 19 g/cm^3
- **Crystal garnet scintillators**
- 9 cells, each 1.5 x 1.5 cm^2 (R_M ≈ 1.45 cm)
- 4 + 10 cm long split (7+18 X_0)
- Reflective mirror between sections

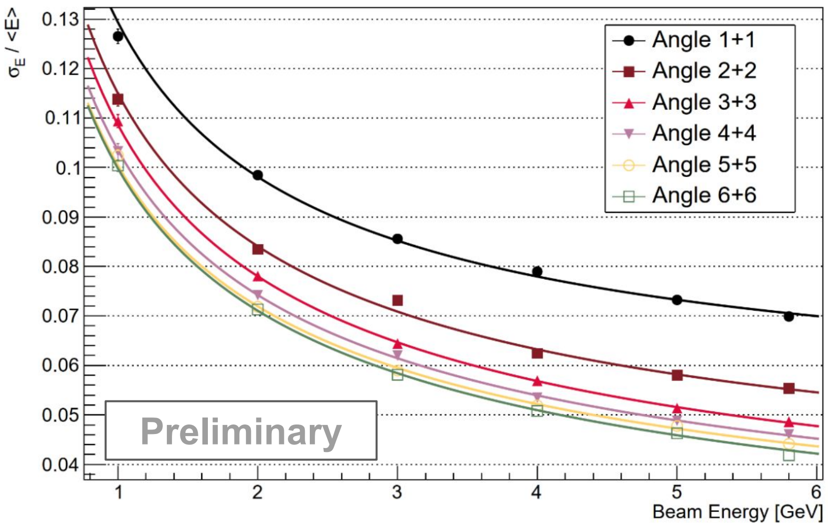




- Crystal garnets from several producers tested:
  - ➢ Crytur - YAG
  - ➢ Fomos - GAGG
  - ➢ ILM - GAGG
  - ➢ C&A - GAGG
- Different photo-detectors tested:
  - ➢ Hamamatsu R12421 for energy resolution (coupled with light guides)
  - ➢ Hamamatsu R7600U-20 metal channel dynode (MCD) PMT for timing (direct coupling)
- Further tests performed (not discussed in this presentation):
  - ➢ Optical coupling with 3M foil instead of air
  - ➢ 12 m long (instead of 3 m) analog cables between sensors and front-end electronics

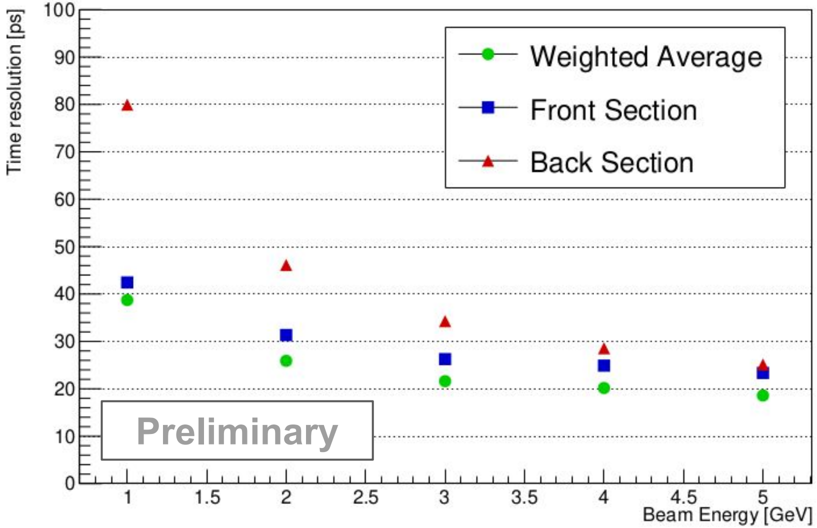
SPACAL-W with crystals: test beam results

Energy resolution (DESY 2020, R12421)



- Energy resolution **improves** at larger incidence angles
- Energy resolution at 3°+3°:
  - ➢ sampling term: **10.6%**
  - ➢ constant term: **1.9%**

Time resolution (DESY 2021, R7600-20)



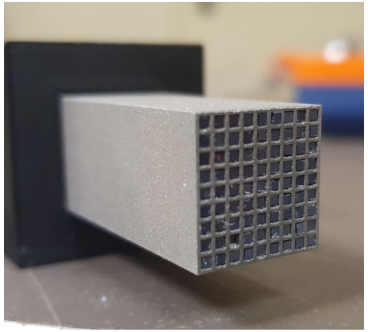
- Timing resolution measured at 3°+3° incidence angle
- Time stamps from front and back sections obtained with constant fraction discrimination (CFD)
- Time resolution (C&A GAGG): **18 ps** @ 5 GeV

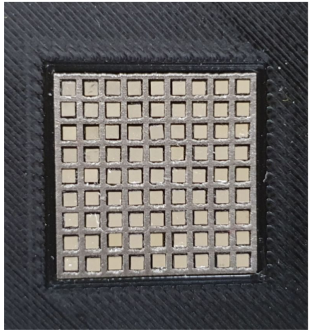
Analysis of SPS 2021 data (higher energy) ongoing

SPACAL-W with organic scintillating fibres

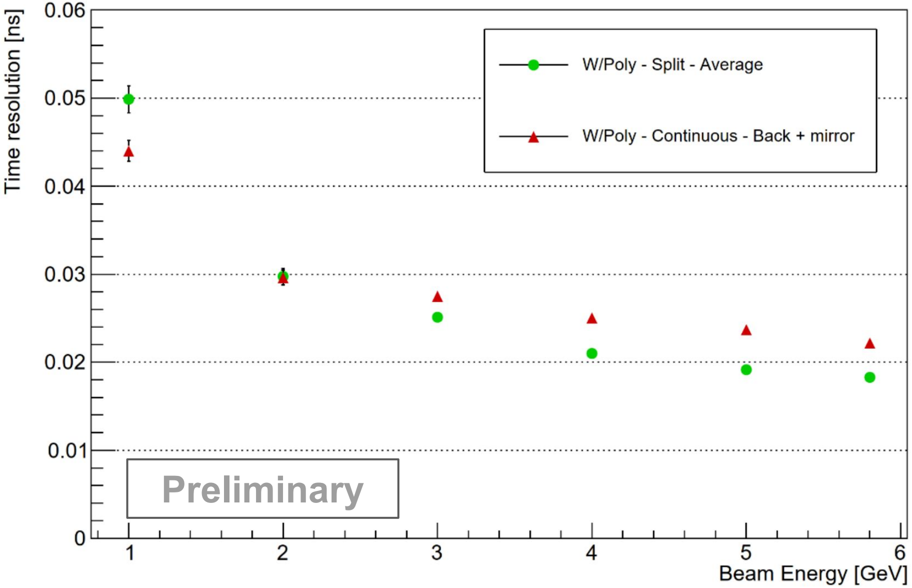
- Candidate for consolidation of inner region during LS3
- 3D printed **pure tungsten** absorber
- **Polystyrene** squared scintillating fibres
- 1 cell produced, 1.5 x 1.5 cm^2 (with $R_M \approx 1.8$ cm)

- Two configurations tested:
  - ➢ 5+14 cm long split cell (7+18 X_0), double readout
  - ➢ 19 cm long continuous cell, single readout at back
- Reflective mirror between sections, or continuous fibres with mirror at front



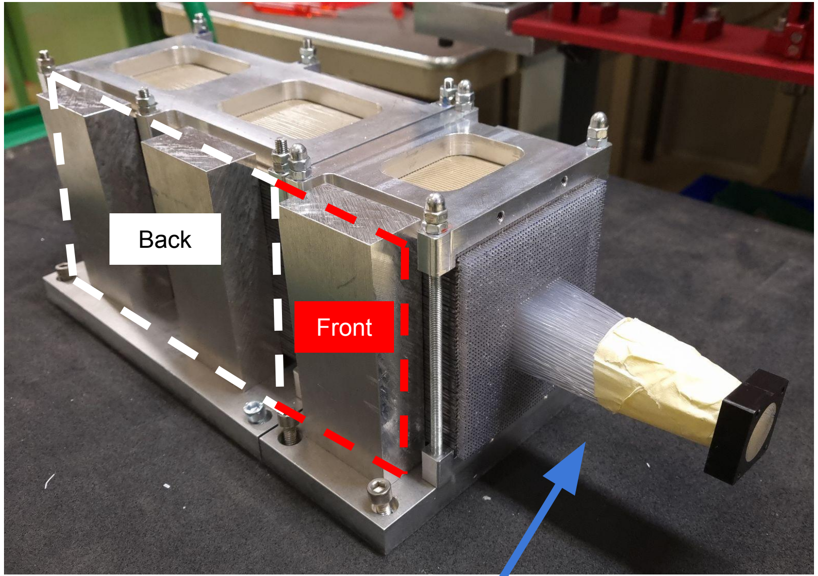


Time resolution (DESY 2021, R7600-20)



- Time resolution measured at 3°+3° incidence angle
- Split cell: **19 ps** @ 5 GeV
- Continuous cell: **24 ps** @ 5 GeV

SPACAL-Pb with organic scintillator fibres



Fibres bundle, 1 cell

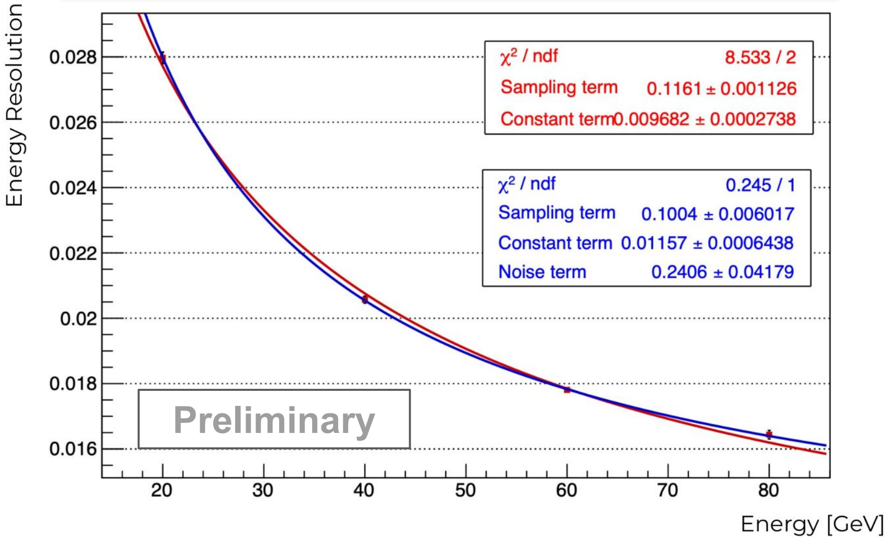
- **Lead** absorber with **polystyrene** fibres
- 9 cells, each 3 x 3 cm^2 ($R_M \approx 3$ cm)
- 8 + 21 cm long (7+18 X_0)
- Reflective mirror between sections

- Hamamatsu R7899 for energy resolution
- Hamamatsu R7600U-20 metal channel dynode (MCD) PMT for timing

- Different readout configurations:
  - ➢ Direct contact
  - ➢ 10 cm long PMMA light guide
  - ➢ Bundle of fibres coupled directly to MCD PMT

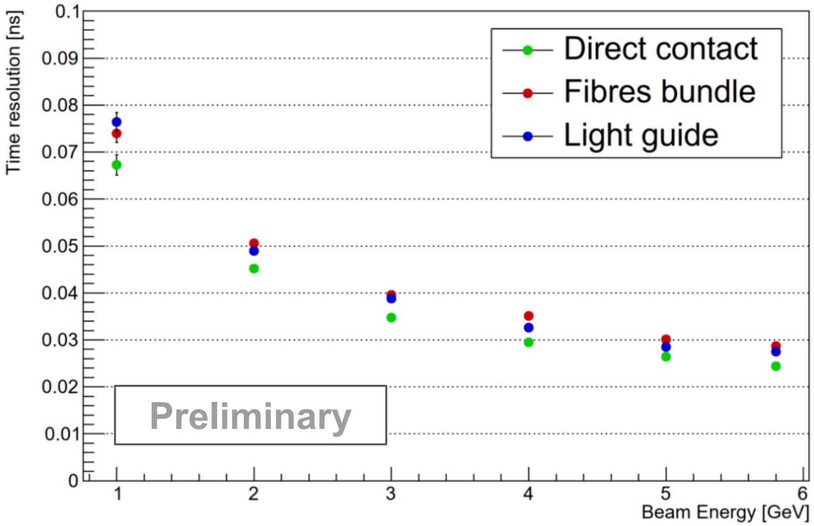
SPACAL-Pb: test beam results

Energy resolution (SPS 2021, R12421)



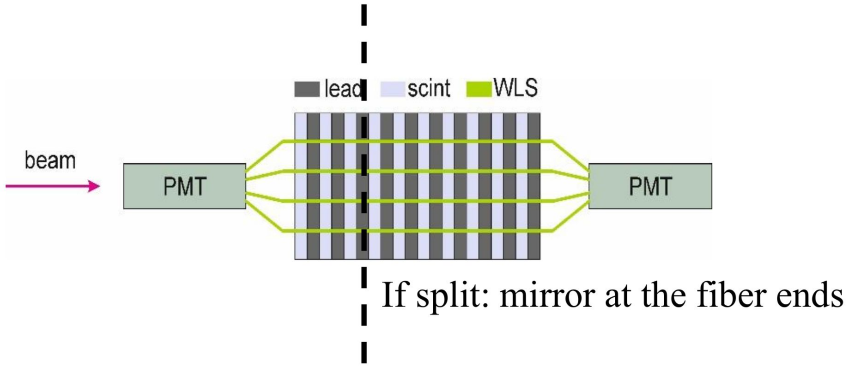
- Measured at high energy at SPS CERN
- At 3°+3° incidence angle
- Best fit to data adding noise term
- Sampling term: **10.0%**
- Constant term: **1.16%**

Time resolution (DESY 2021, R7600-20)



- Timing resolution measured at 3°+3° incidence angle
- Time stamps from front/back sections with CFD
- Only part of cell readout in direct contact due to smaller active area of the PMT (1.8 x 1.8 cm^2)
- Analysis of higher energy SPS 2021 data ongoing
- Time resolution: **26 ps** @5 GeV

Shashlik: towards Upgrade II



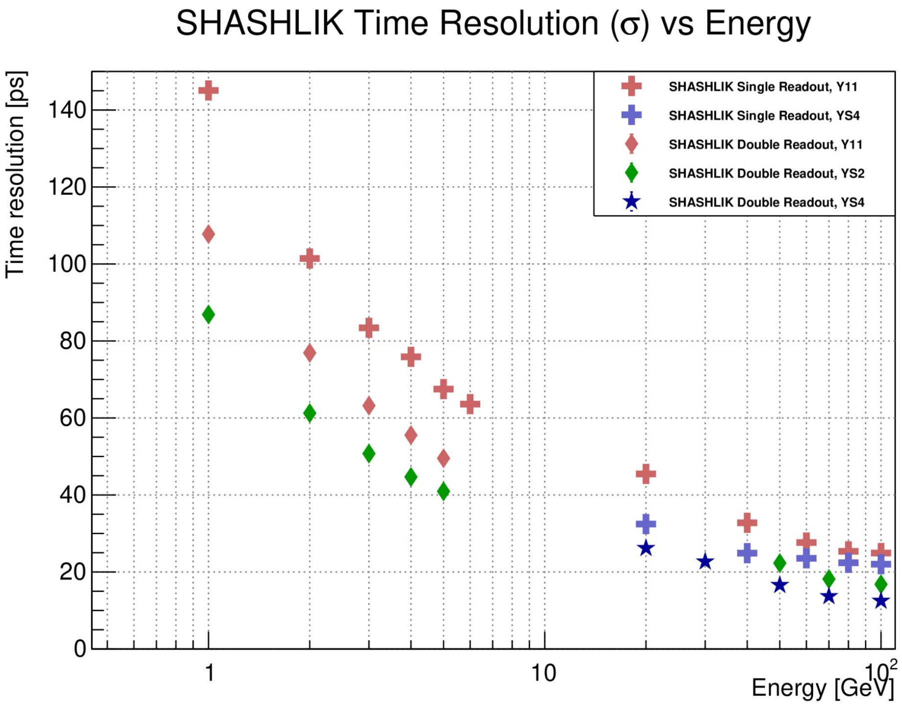
- 4 mm thick **scintillating tiles** and 2 mm thick **lead tiles** with **wavelength shifting** (WLS) fibres
- **Radiation hardness limit** at 40-50 kGy -> suitable for non-central part of ECAL
- R&D to **improve intrinsic time resolution**

- Main focus on **double-sided readout** to mitigate the effect of longitudinal shower fluctuations
  - ➢ With continuous WLS fibers
  - ➢ With split fibres at shower maximum (≈ $7X_0$)
- **PMTs** allowing better timing performance (R7600U-20)
- WLS (from KURARAY*) with **shorter decay time**
  - ➢ Y11 (current LHCb) = 7 ns decay time
  - ➢ YS2 = 3 ns decay time
  - ➢ YS4 = 1.1 ns decay time

*Many thanks to KURARAY for providing pre-production YS2 and YS4 samples

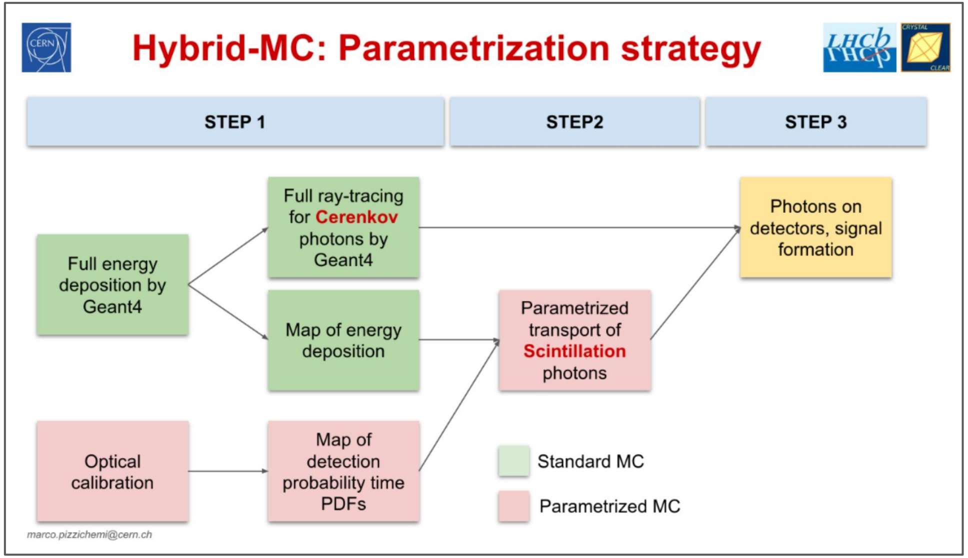
Shashlik: test beam results

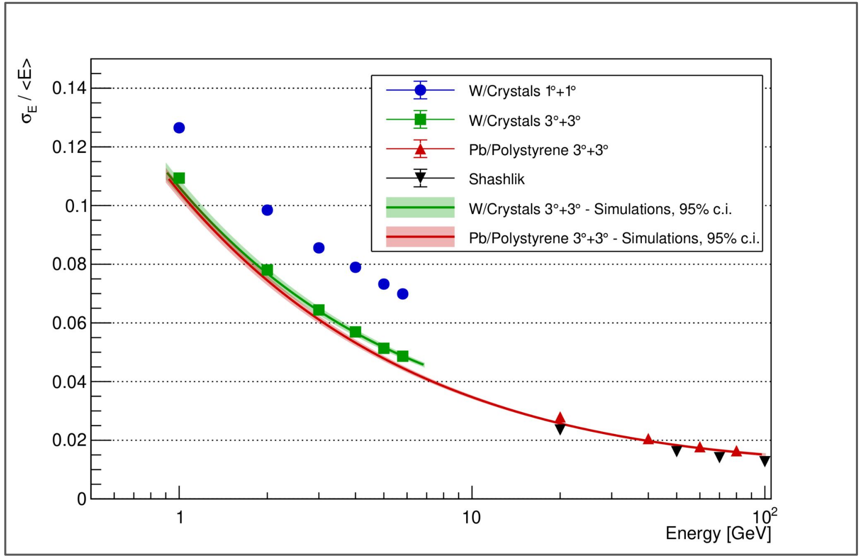
Time resolution (DESY & SPS 2021)



- Time resolution **improved with faster WLS fibres**
- **Double-sided readout** shows improved timing performance over single side readout
- Similar time resolution with **continuous and split** WLS fibers and double-sided readout
- Time resolution **better than 40 ps > 5 GeV**

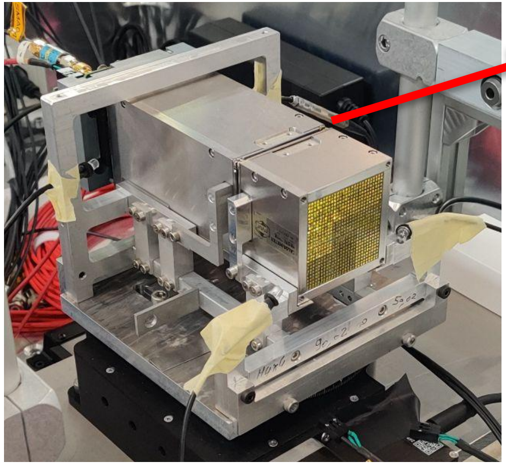
Detailed Monte Carlo simulations





- Geant4 simulation of energy deposit and parametrized transport of scintillation photons
- Allows a gain in computation time by a **factor x100**
- Particle flux from full LHCb simulation can be included
- Different module types (SPACAL-W, SPACAL-Pb, Shashlik)
- Parametrised response of photo-detectors
- **Good agreement with test beam** data over the 1-100 GeV range

Energy resolution and longitudinal separation

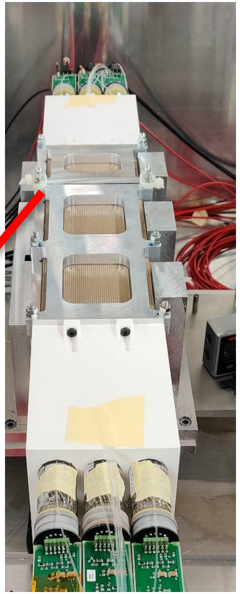


WGAGG

0.065 mm	ESR
0.3 mm	Alu
1.5 mm	**Stainless**
2.37 mm	Air
1.05 mm	**Stainless**
0.3 mm	Alu
0.065 mm	ESR

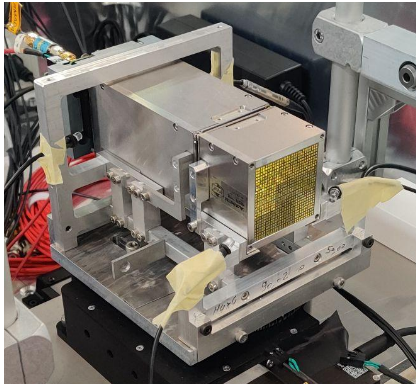
PbPoly

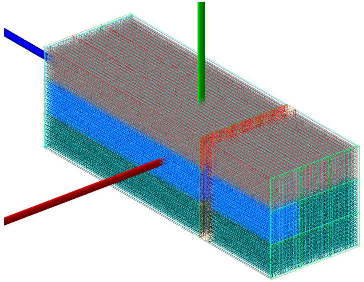
0.065 mm	ESR
2.0 mm	**Stainless**
1.0 mm	Air
2.0 mm	**Stainless**
0.065 mm	ESR



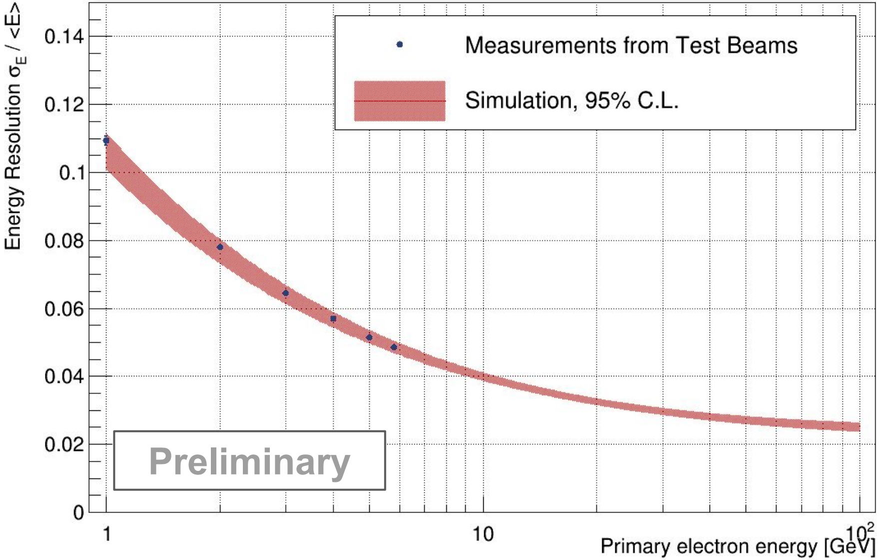
- In SPACAL prototypes produced for Test Beam the **longitudinal separation** (front/back sections) is **not optimized**
- This is due to the need for flexibility to perform several tests
- Material budget between SPACAL sections is not negligible -> **energy resolution is degraded**

Energy resolution and longitudinal separation





Energy resolution WGAGG @ 3°+3°



- The **MC framework reproduces well the Test Beam measurements**, when the material between front and back sections is properly taken into account
- In SPACAL modules designed for usage in the LHCb ECAL the front/back separation will be optimized (e.g. thin reflector foil)
- The MC framework allows to predict the energy resolution expected in these **optimized modules**

SPACAL front-back separation

		Measurements on TB modules [%]	MC simulations on TB modules [%]	MC simulations on optimized modules [%]
SPACAL-W	*Sampling term*	10.6 ± 0.1	10.4 ± 0.1	9.1 ± 0.1
	Constant term	1.9 ± 0.5	2.27 ± 0.04	1.38 ± 0.03
SPACAL-Pb	*Sampling term*	10.0 ± 0.6	10.4 ± 0.1	10.4 ± 0.1
	Constant term	1.16 ± 0.06	1.09 ± 0.04	0.62 ± 0.06

Energy resolution expected in optimized modules in line with requirements

Summary and Outlook

- SPACAL and Shashlik technologies provide an **attractive option** for the Upgrade II of LHCb ECAL
- Several prototypes produced and tested at DESY and SPS-CERN
- **Time resolution** above 5 GeV
  - ➢ SPACAL W+GAGG < 20 ps
  - ➢ SPACAL W+Polystyrene < 20 ps
  - ➢ SPACAL Pb+Polystyrene < 25 ps
  - ➢ SHASHLIK < 40 ps
- **Energy resolution** in line with requirements when final, optimized configuration is considered
- Comprehensive **R&D studies ongoing**:
  - ➢ Production and Test Beam measurements of new prototypes
  - ➢ Detailed Monte Carlo simulations
  - ➢ Investigation on new radiation-hard and fast scintillators
  - ➢ Study of more realistic PMTs and electronics readout
  - ➢ Study of new absorber production techniques