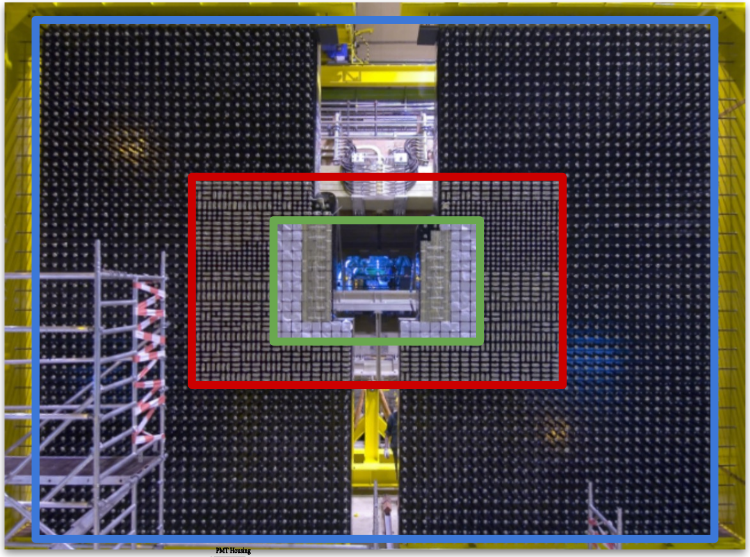
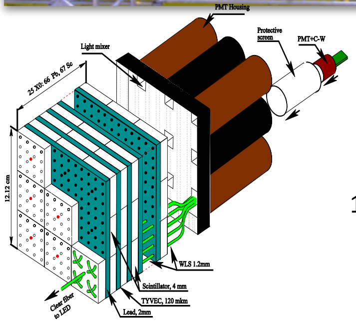
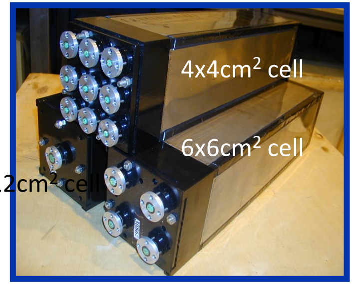
SCINTILLATING SAMPLING ECAL TECHNOLOGY FOR THE UPGRADE II OF LHCb

E. Auffray, *CERN*
on behalf of SPACAL EP-R&D and the LHCb ECAL Upgrade R&D Groups

Current LHCb ECAL configuration





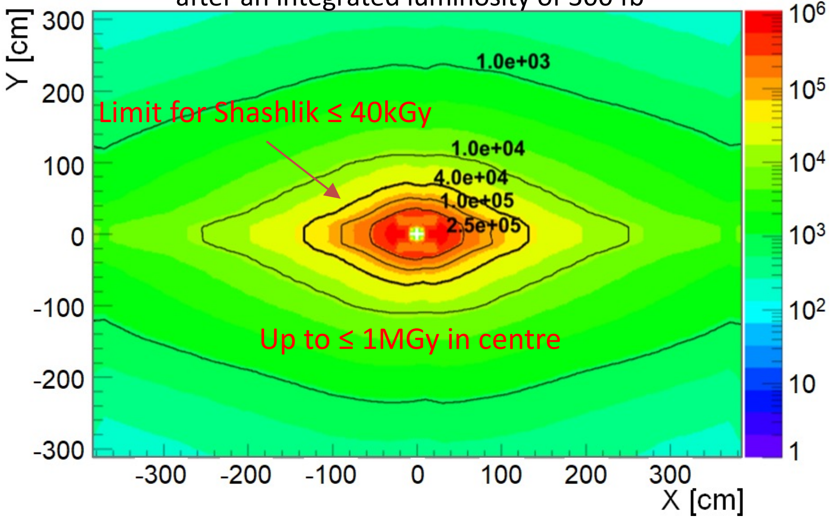


- Large Shashlik array (about 50 m^2), with 3312 modules and 6016 channels:
  - 176 modules — 4 x 4 cm^2 cell size (center)
  - 448 modules — 6 x 6 cm^2 cell size
  - 2688 modules — 12 x 12 cm^2 cell size (outer)
- Optimized for π^0, e^- and γ identification in the few GeV to 100 GeV region at 2 x 10^{32}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

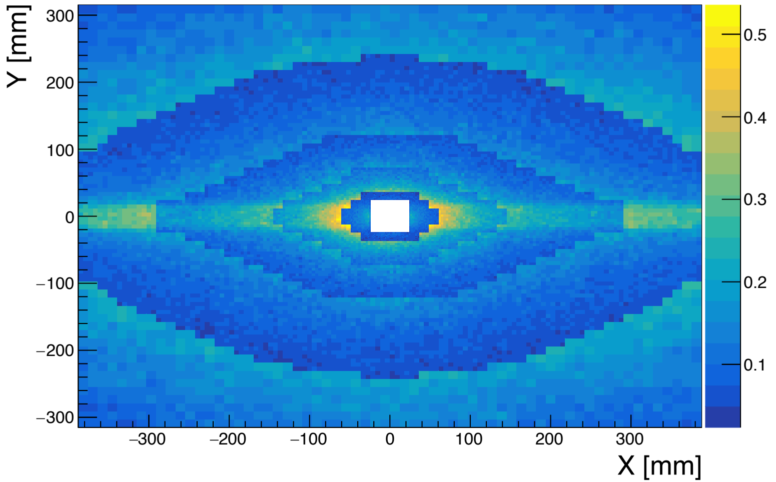
Requirements for ECAL Upgrade II @LS4

Keep the current energy resolution of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
with the new operating conditions up to $L = 1.5 \times 10^{34}\ cm^{-2}s^{-1}$:

Expected accumulated radiation dose (Gy) on the ECAL
after an integrated luminosity of 300 fb^{-1}



Occupancy, front section, $E_{T,cell}$ > 25 MeV



Radiation doses:

up to 1 MGy and 6×10^{15} 1 MeV neq/cm^2 in the center for 300 fb^{-1}:

=> **New technologies more radiation hard than shashlik required in the centre**

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

- Timing O(10ps)
- Increased granularity
- Denser absorber in inner region => tungsten
- Longitudinal segmentation

See FTDR LHCb upgrade phase II : https://cds.cern.ch/record/2776420

R&D strategy for the ECAL upgrade II

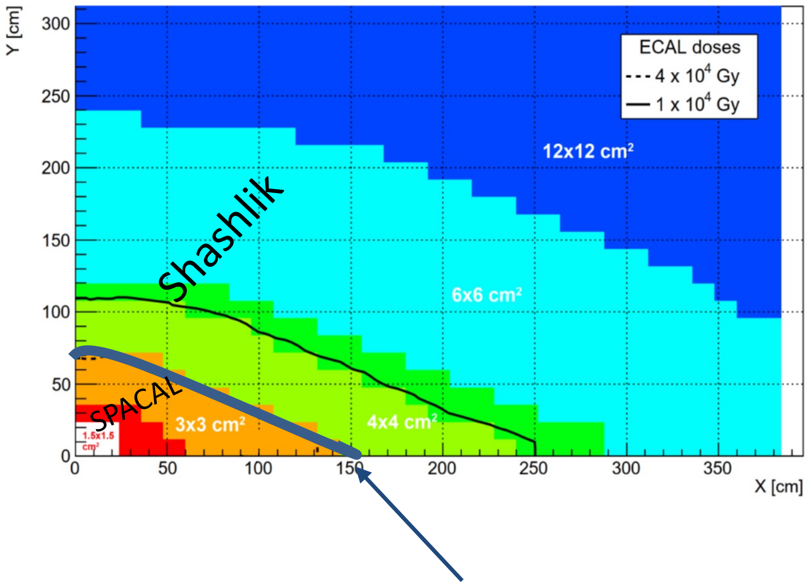
Detector technology optimization
for different regions according radiation dose levels

New configurations of Shashlik modules in outer part (< 40kGy)

12 x 12 cm^2 1344 refurbished modules
6 x 6 cm^2 896 rebuilt + 448 refurbished modules
4 x 4 cm^2 272 new + 176 refurbished modules

SPACAL technology in the inner region (> 40kGy) :

SPACAL-Pb:
3 x 3 cm^2 144 modules, rad-hard up to 200 kGy=> **plastic fibres**
SPACAL-W:
1.5 x 1.5 cm^2 32 modules, rad-hard up to 1 MGy => **crystal fibres**

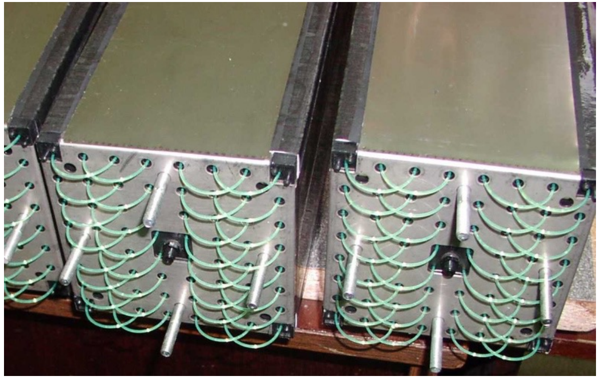


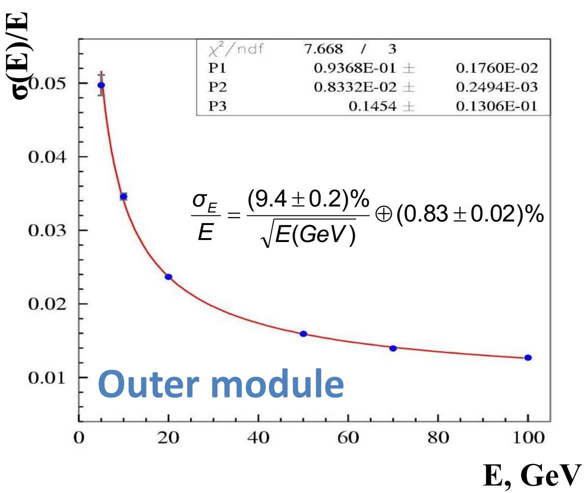
Radiation limit of current Shashlik technology

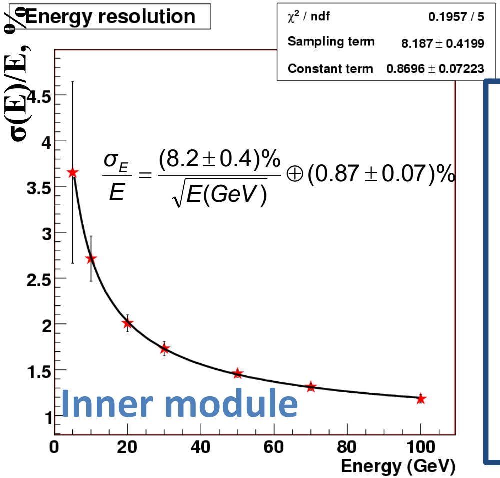
Shashlik: towards Upgrade II

Current Shaslik

- 4 mm thick **scintillating tiles** and 2 mm thick **lead tiles** with **wavelength shifting** fibres (Kuraray YS11 (7ns))
- Energy resolution: $\frac{\sigma_E}{E} = \frac{(8 \div 10)\%}{\sqrt{E(GeV)}} \oplus (0.8 \div 0.9)\%$
- Photoelectron yield: ≈ 3000 ph.el. / GeV (with HAMAMATSU R7899-20)







For Upgrade II:

Current performance suitable for non central part

- Good Energy resolution
- Radiation hardness limit at 40-50 kGy

=> need R&D to exploit intrinsic time resolution from Shashlik

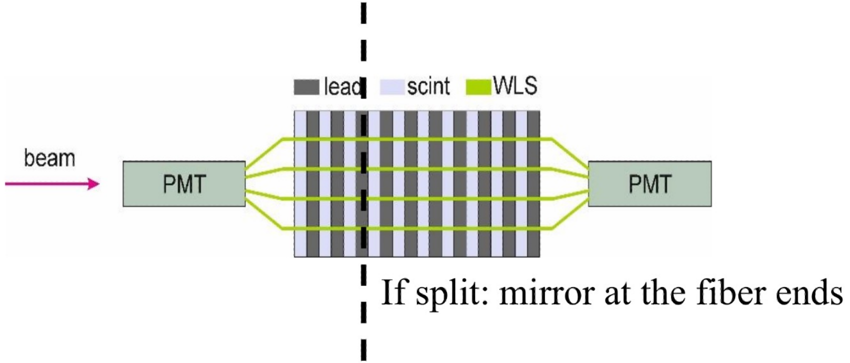
The performance obtained from test beams in 2003 – 2006:

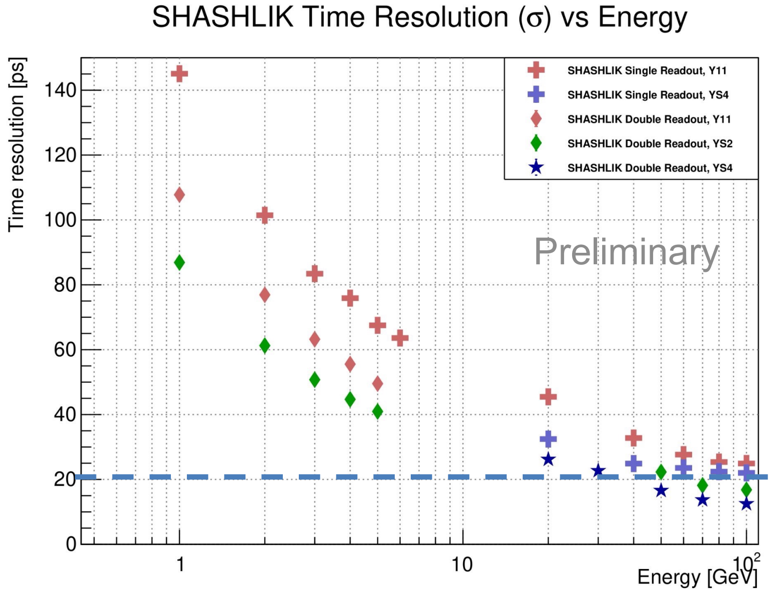
See S. Barsuk, IEEE Trans. Nucl. Sci. 57 1447/ A. Arefiev et al, LHCb-2007-149

Shashlik: towards Upgrade II

Improve time resolution

- New Kuraray **faster wavelength shifter** (WLS)
  - YS2: 3 ns decay time
  - YS4: 1.1 ns decay time
- PMT with **better timing performance** (R7600U-20)
- **Double-sided readout** to mitigate the effect of longitudinal shower fluctuations
  - With continuous WLS fibers
  - With split fibres at shower maximum (≈ 7Xo)





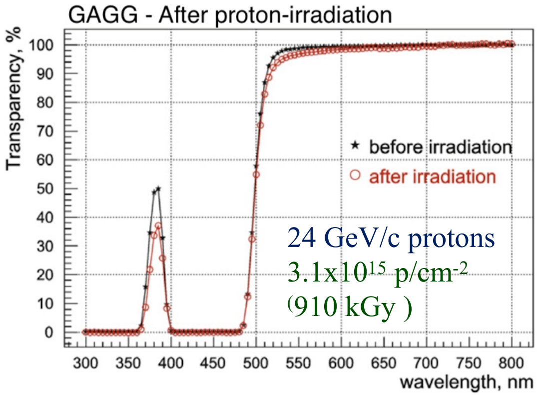
Better than **20ps achieved at E > 30GeV** with double-sided readout
Expected to further improve at higher energies

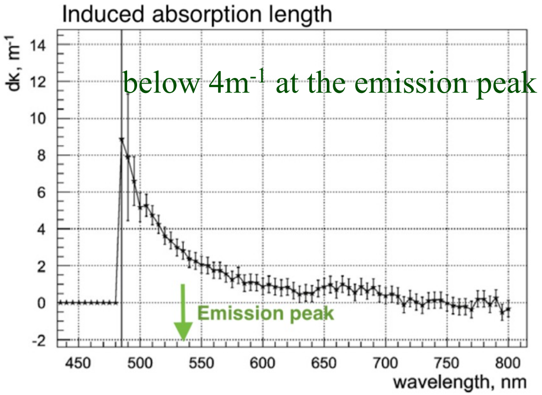
*Many thanks to KURARAY for providing pre-production YS2 and YS4 samples

SPACAL-W R&D for inner part

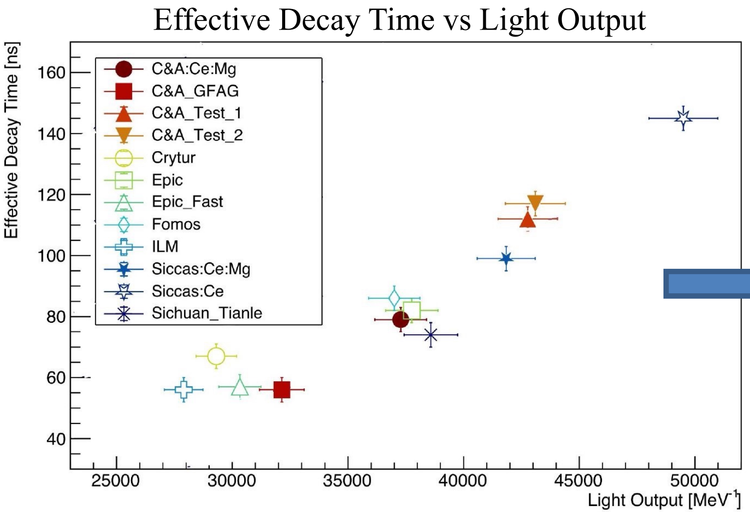
Search for radiation hard and fast scintillators: garnet crystals

Garnet crystals are **radiation hard**
Scintillation properties can be tuned with different levels of dopants (Ce,Mg) and growth conditions





See: *V. Alenkov et al., NIM A 816 (2016) 176*



- Variation of a factor 2 in light output and 3 in decay time
- High light yield → slow decay time
- Scintillation speed increases with Mg-codoping at expense of light output
- Further R&D ongoing to reduce decay time below 20 ns

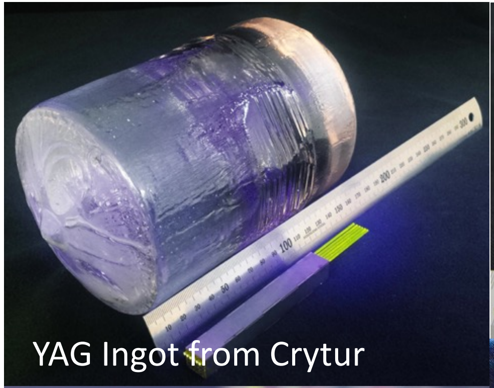
See: L. Martinazzoli et al., NIM A 1000 (2021) 165231
L. Martinazzoli et al., submitted to Materials Advances and J. Mater. Chem. C

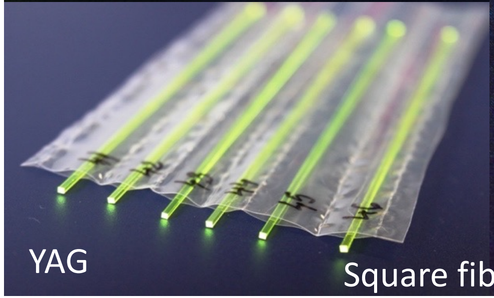
SPACAL-W R&D for inner part

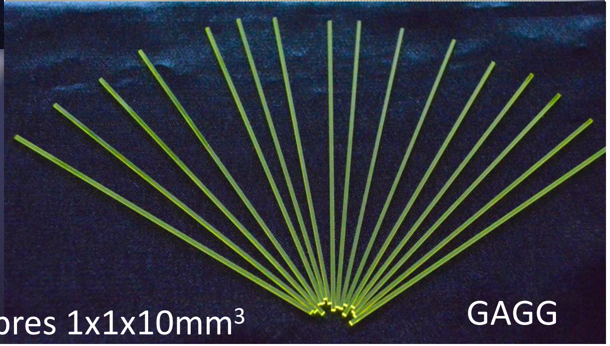
Optimize Garnet fibre crystal production

Garnet crystal fibres can be obtained from:

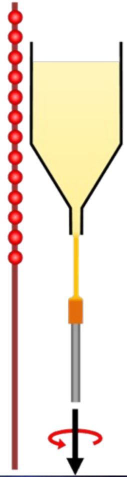
Large ingot grown by Czochralski method

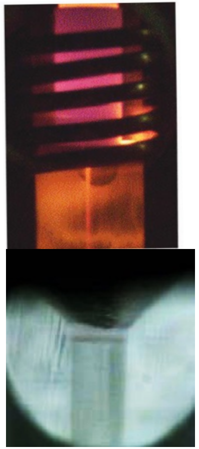


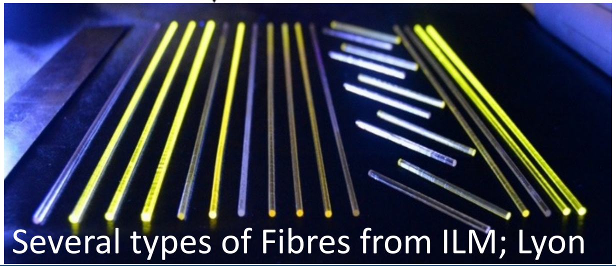




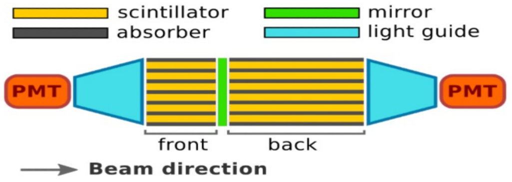
Micropulling down technique





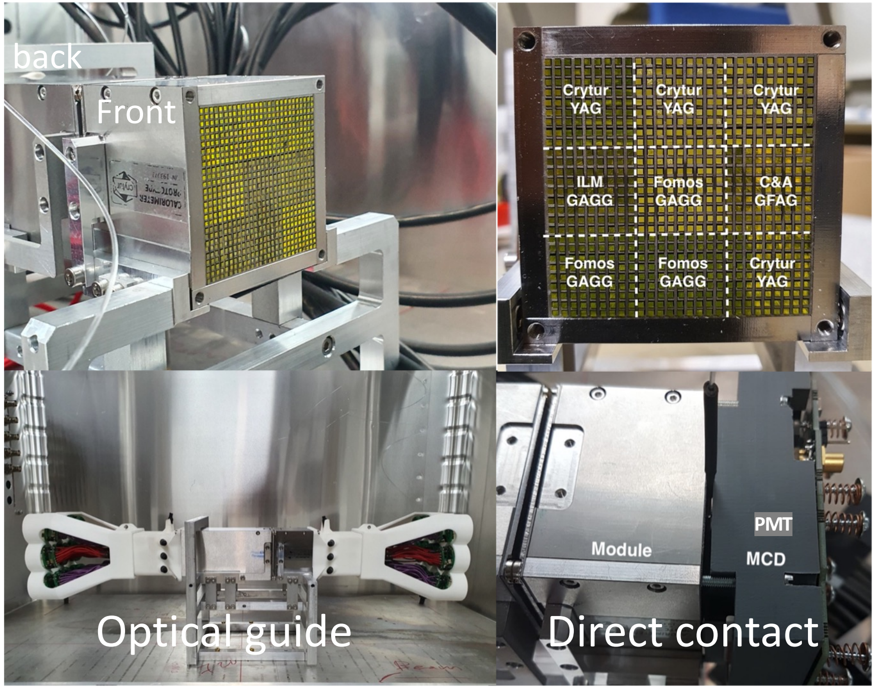


SPACAL-W prototype with garnet crystal fibres



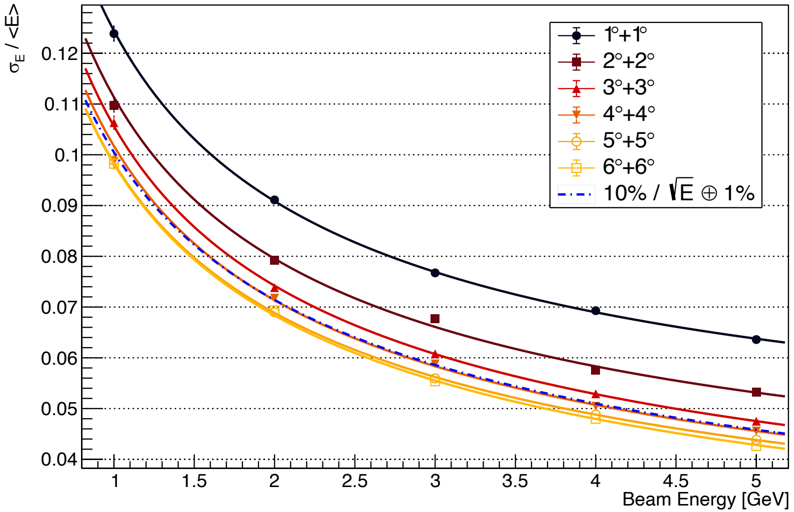
- **Pure tungsten** absorber with 19 g/cm^3
- **Crystal garnet scintillating fibres** (1x1cm^2, cut from ingot)
- 9 cells, each 1.5 x 1.5 cm^2 ($R_M \approx 1.45$ cm)
- Longitudinal segmentation at the shower maximum:
  - 4 + 10 cm long split (7+18 X_0), pitch 1.7mm
  - Reflective mirror between sections

- 4 garnet types tested:
  - Crytur - YAG
  - Fomos - GAGG
  - ILM - GAGG
  - C&A – GFAG
- Two photodetection readouts:
  - Energy resolution: Hamamatsu R12421 PMT and PMMA light guides between fibres and PMT
  - Timing resolution: Hamamatsu R7600U-20 metal channel dynodes (MCD) PMTs in direct contact with fibres



SPACAL-W with garnet crystals: test beam results

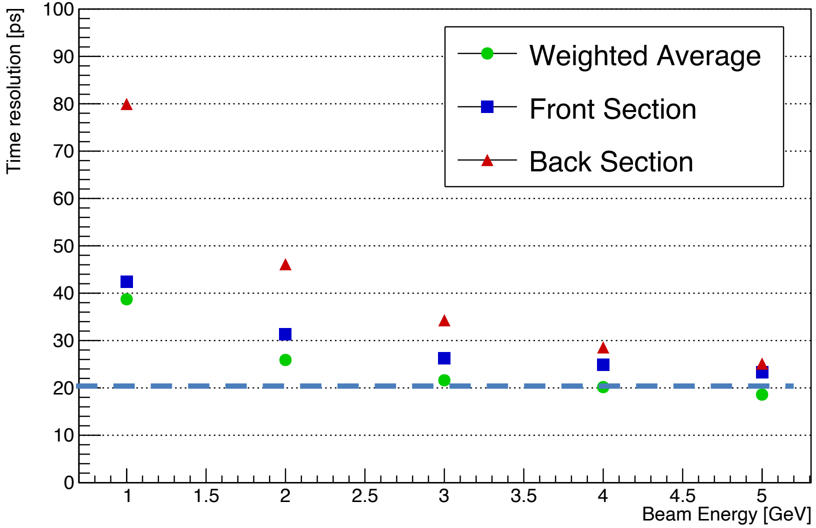
Energy resolution versus incident angles (DESY 2020 , R12421)



Energy resolution **improves** for larger incident angles

Energy resolution at 3° + 3°
Sampling term: 10.2% ± 0.1
Constant term: 1.2% ± 0.3

Time resolution GFAG cell @ incident angle of 3° + 3° (DESY 2020 , R7600-20)

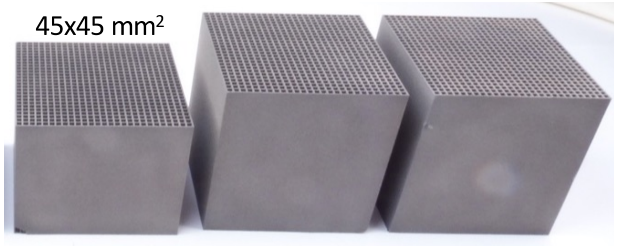


18 ps @ 5 GeV

Analysis of SPS 2021 data (higher energy) ongoing

L. Ann, et al. , arXiv:2205.02500 , submitted to NIMA

SPACAL-W: R&D on absorber 3D



R&D on single cell 3D printed tungsten prototype

=> Produced 1.5x1.5 cm² cells with up to 10 cm length (4.5x4.5 cm² section)

Smooth surface mandatory not to damage scintillating fiber crystals

=>Very good roughness of Ra= 5 µm achieved

Metrology report for 1cell

Résultats de mesure

LHCb

bloc longueur 50 mm

Contenu	Mesuré
Rugosité 2D<Rugosité_1>	
Profil=R_ISO - Section=[1]	
Ra	5.0423um
Rq	6.5405um
Rsk	0.5161
Rp	22.5633um
Rv	17.1012um
Rz	39.6644um
Rt	51.3316um
RSm	0.1774mm
Rpk	9.9100um
Rvk	4.8479um

Mean roughness → Ra

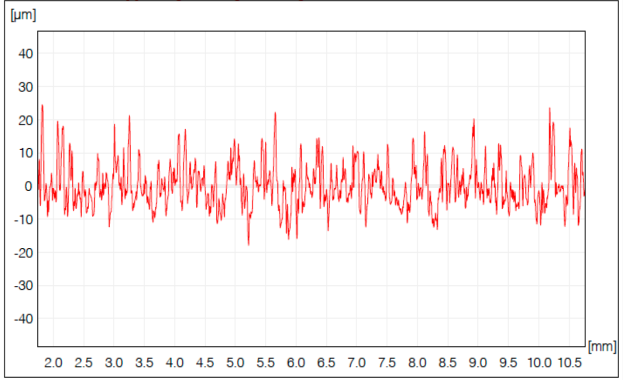
Total height of profile → Rt

= distance (max-min)

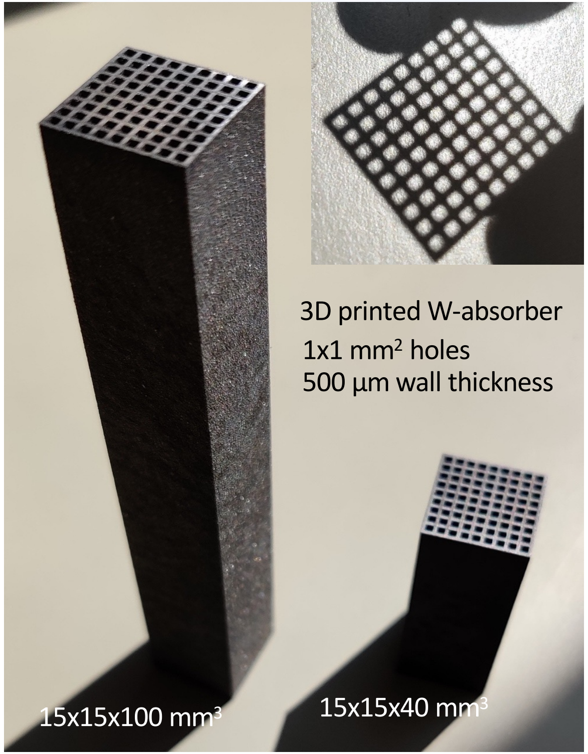
FACE A

mesure 2

Profil=R_ISO - Section=[1] X Mag x20 Z Mag x1000 <Rugosité_1>



Dec. 2020

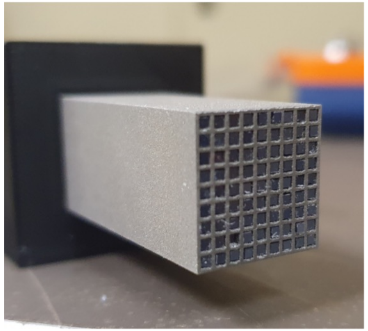


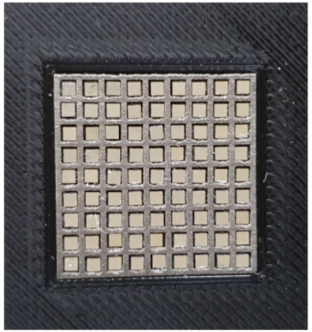
Developed by EOS, Germany

SPACAL-W prototype with organic scintillating fibres

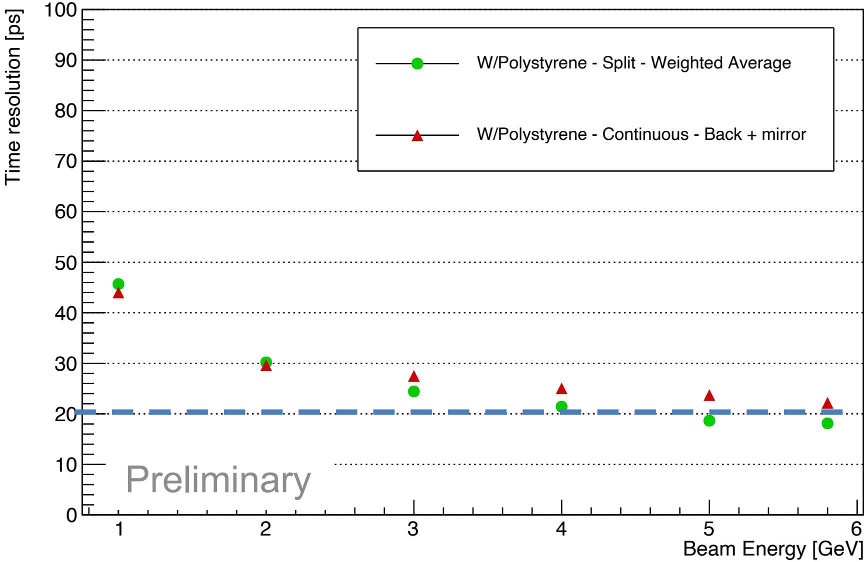
- Candidate for consolidation of inner region during LS3
- 3D printed **pure tungsten** absorber
- **Polystyrene** squared scintillating fibres (1x1mm², SCSF-78M)
- 1 cell produced, 1.5 x 1.5 cm² (with $R_M \approx 1.8$ cm)

- 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



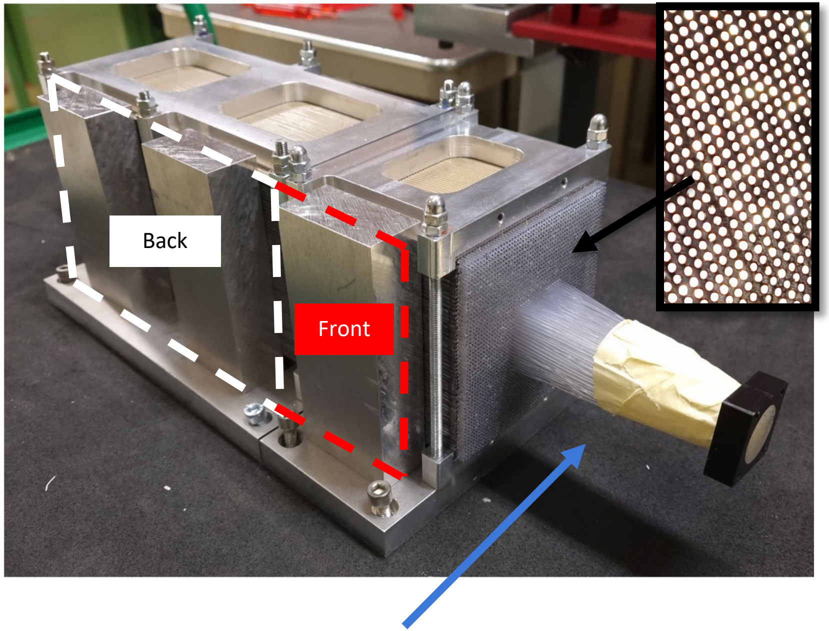


Time resolution @ 3°+3° incidence angle (DESY 2021, R7600-20)



Split cell: 19 ps @ 5 GeV
Continuous cell: 24 ps @ 5 GeV

SPACAL-Pb prototype with organic scintillator fibres

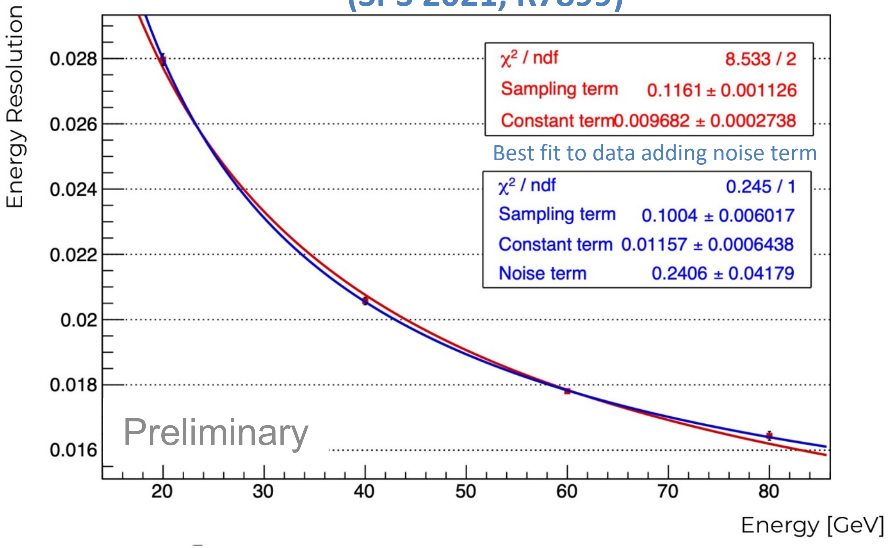


Fibres bundle, 1 cell

- **Lead** absorber with **polystyrene** fibres (1x1mm^2 SCSF-78M)
- 9 cells, each 3 x 3 cm^2 ($R_M \approx 3$ cm)
- Longitudinal segmentation at shower maximum
  - 8 + 21 cm long (7+18 X_0)
  - Reflective mirror between sections
- Two photodetectors employed
  - Energy resolution: Hamamatsu R7899 with light guide
  - Timing resolution: Hamamatsu R7600U-20 metal channel dynodes (MCD) PMTs in direct contact
- Different readout configurations:
  - Direct contact (timing)
  - 10 cm long PMMA light guide
  - Bundle of fibres coupled directly to MCD PMT

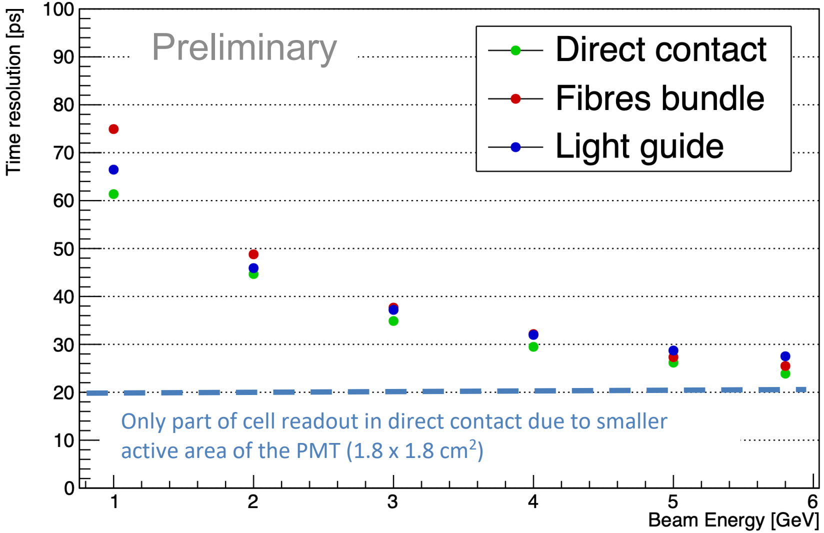
SPACAL-Pb with organic scintillator fibres: test beam results

Energy resolution @ 3°+3° incidence angle (SPS 2021, R7899)



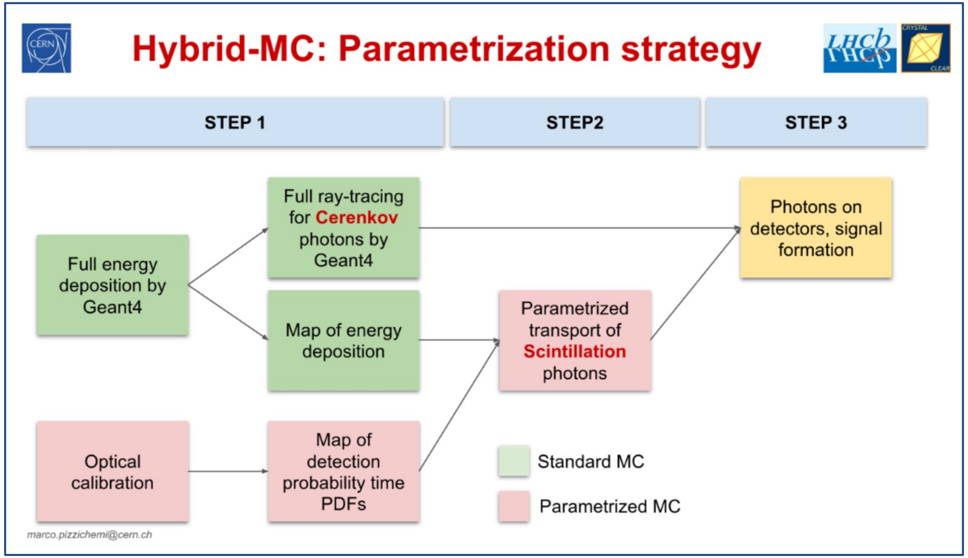
Sampling term: 10.0%
Constant term: 1.2%

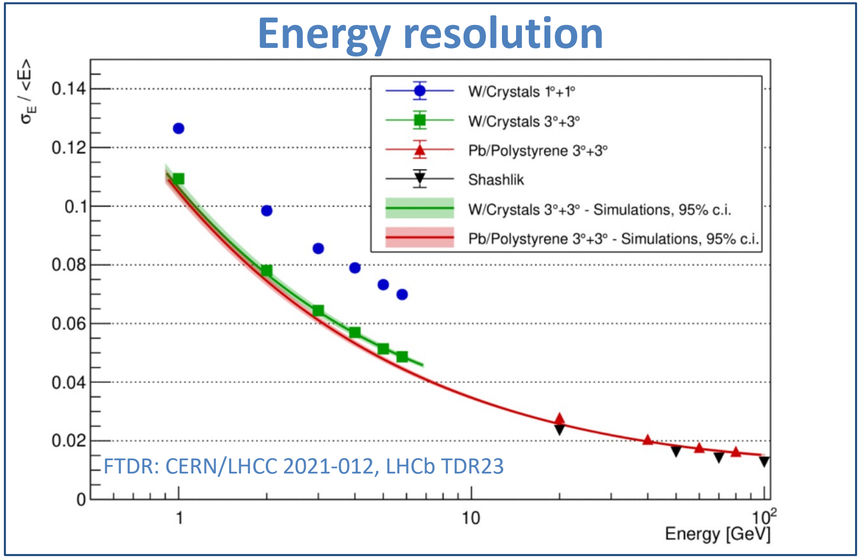
Time resolution @ 3°+3° incidence angle (DESY 2021, R7600-20)



26 ps @5 GeV

Detailed Monte Carlo simulations



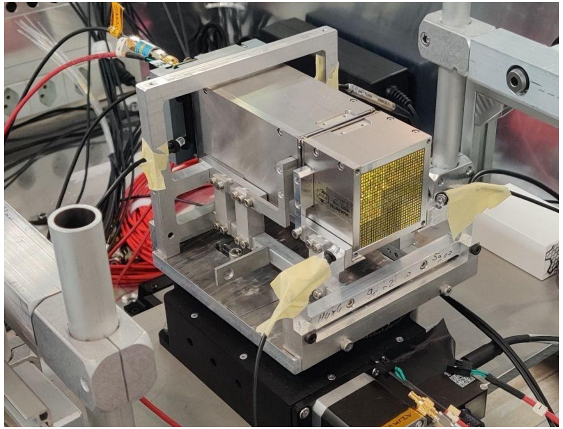


- Geant4 simulation of energy deposit and parametrized transport of scintillation photons
- Allows a gain in computation time by a **factor x100**
- Particle flux from full LHCb simulation can be included
- Different module types (SPACAL-W, SPACAL-Pb, Shashlik)
- Parametrised response of photo-detectors

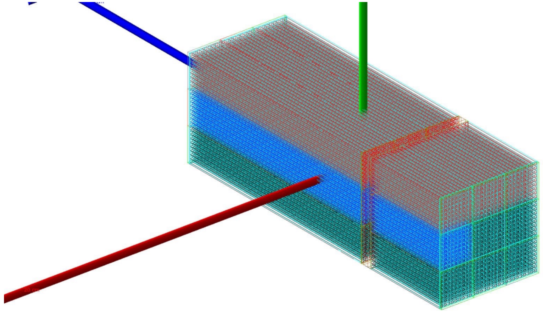
Good agreement with test beam data over the 1-100 GeV range

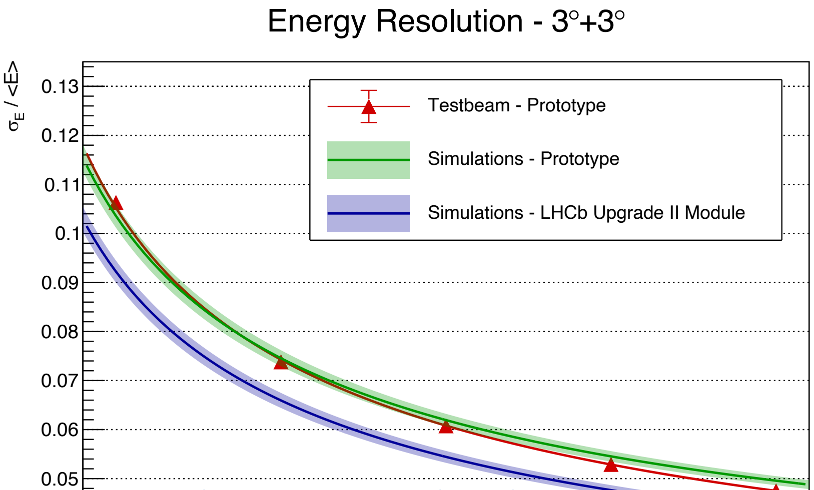
SPACAL W with garnet crystal fibres:

Test beam set-up



Simulation





L. Ann, et al. , arXiv:2205.02500 , submitted to NIMA

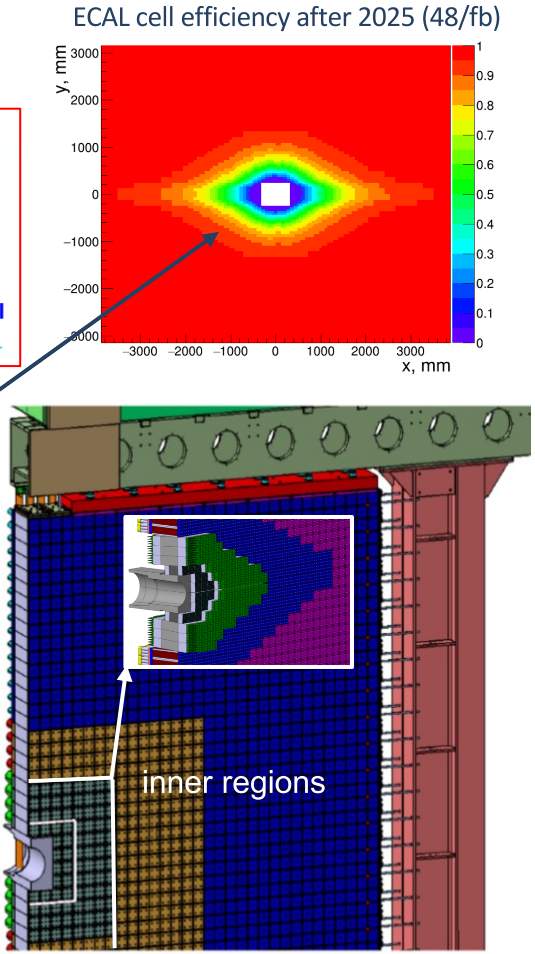
- The **MC framework reproduces well the testbeam measurements**, when the material between front and back sections is properly taken into account
- In SPACAL modules designed for usage in the LHCb ECAL, the front/back separation will be optimized (e.g. thin reflector foil)
- The **MC framework allows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

SPACAL: Energy resolution performance

		Measurements on TB modules [%]	MC simulations on TB modules [%]	MC simulations on optimized modules [%]
SPACAL-W	*Sampling term*	10.6 ± 0.1	10.2 ± 0.1	9.2 ± 0.1
	Constant term	1.9 ± 0.5	1.98 ± 0.04	1.18 ± 0.03
SPACAL-Pb	*Sampling term*	10.0 ± 0.6	10.3 ± 0.1	9.7 ± 0.1
	Constant term	1.16 ± 0.06	0.94 ± 0.04	0.62 ± 0.06

Energy resolution expected in optimized modules in line with requirements

LHCb ECAL upgrade strategy



Run3 in 2022-2025:

Run with unmodified ECAL shashlik modules at L=2x10^{33} cm^{-2}s^{-1}

LS3 consolidation in 2026-2028:

Introduce **single section rad. tolerant** SPACAL (2x2 & 3x3 cm^2 cells) in **inner regions** and rebuilt ECAL in **rhombic shape** to improve performance at L=2(4)x10^{33} cm^{-2}s^{-1}

=> 32 SPACAL-W & 144 SPACAL-Pb modules with plastic fibres **compliant with Upgrade II** conditions

=> Include **timing information with single sided R/O to inner regions**

LS4 Upgrade II in ≥ 2035:

Introduce **double section rad. hard** SPACAL in inner regions

⇒ 1.5x1.5cm^2 cells with crystal fibres and 3x3 cm^2 cells with plastic fibres

Improve **timing of Shashlik modules** for a luminosity of up to L=1.5x10^{34} cm^{-2}s^{-1}

Include **timing information with double sided R/O to full ECAL** to mitigate pile-up

Summary and Outlook

- SPACAL and Shashlik technologies provide the required performance for the LHCb ECAL upgrades
- 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 of order $\sigma(E) / E \approx 10\% / \sqrt{E} \oplus 1\%$ expected for final, optimized configurations
- 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 (both garnet and organic fibres)
  - Study of more realistic PMTs and electronics readout
  - Study of new absorber production techniques