Picosecond scintillating sampling electromagnetic calorimeters

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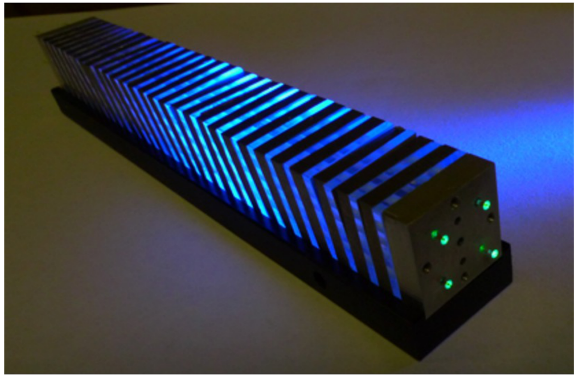
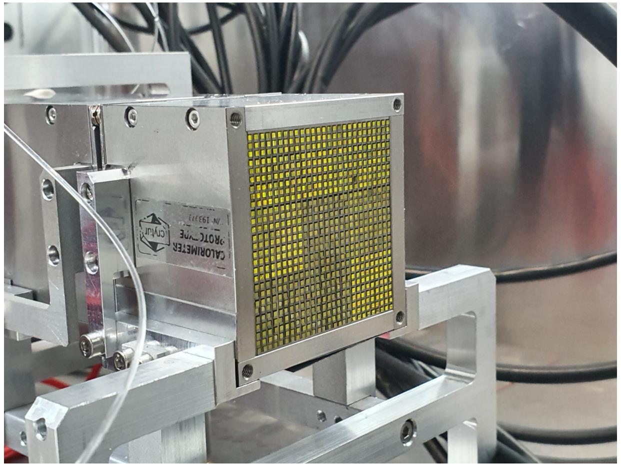
ECFA Detector R&D Roadmap
Task Force 6: Calorimetry
Community Meeting
CERN, 12/01/2023

Content of the presentation

- Introduction
- Status of R&D
- Input for DRD discussion

Introduction: picosecond scintillating sampling ECALs





Most common approaches:

• Shashlik
• SpaCal
→ Molière radius tunable in both cases
→ Lower cost than homogenous crystal

Key R&D challenges for future experiments:

• Radiation hardness:
→ Crystal scintillators suitable for future experiments at hadron colliders
→ No radiation-hard WLS fibres available (yet)

• Small cell sizes: dense absorber, e.g. tungsten

• Picosecond time resolutions:
→ Fast photon detectors (e.g. MCD PMTs, SiPM, …) needed for O(10-20) ps time resolutions

Typical ECAL physics requirements

LHCb Upgrade II:
- Sustain radiation doses up to 1 MGy and ≤ 6 x 10^{15} 1 MeV neq / cm^2 in the centre
- Keep current energy resolution of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
- Pile-up mitigation crucial

→ Timing capabilities with O(10-20) ps precision for electromagnetic particles, preferably directly in the calorimeter modules
→ Increased granularity in the central region with denser absorber

Future e^+e^- Higgs/top/EW factory:
- Stochastic term of 15-20% good enough for ≈3% jet energy resolution at 50 GeV using particle flow analysis

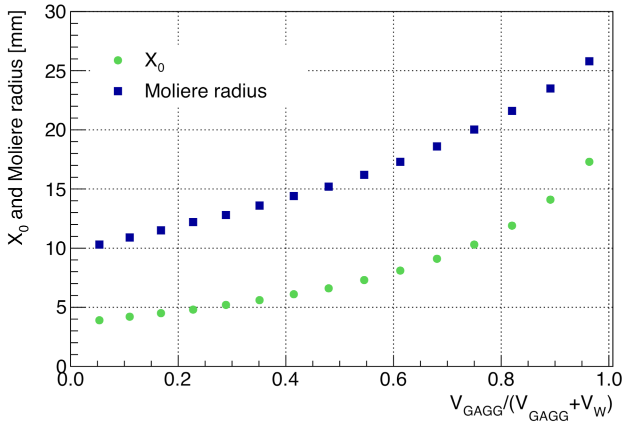
→ However, $5\% / \sqrt{E}$ or better desirable for flavour physics
- Timing for hadronic particles can help with PID (e.g. cover region where gaseous tracking not sensitive for K/π separation)
- Small Molière radius with tungsten absorber → preferred for particle flow analysis
- Tight requirements on cell size from high-energy $\pi^0 \rightarrow \gamma\gamma$, e.g. for τ-lepton polarisation measurement, or low-mass ALPs

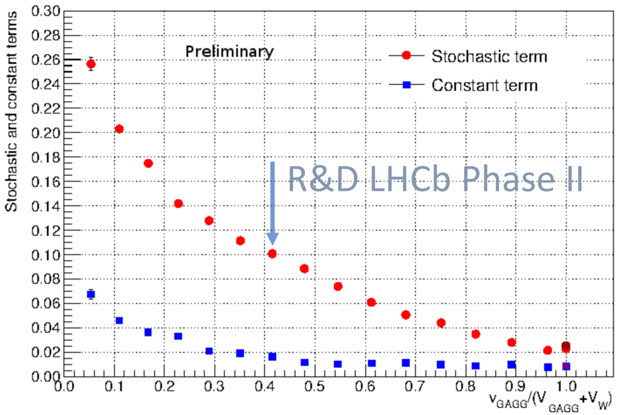
FCC-hh:
- Radiation doses of O(1) MGy and 1 MeV neq fluence of O(10^{16}) cm^{-2}
- Energy resolution target of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
- O(30) ps timing for pile-up mitigation

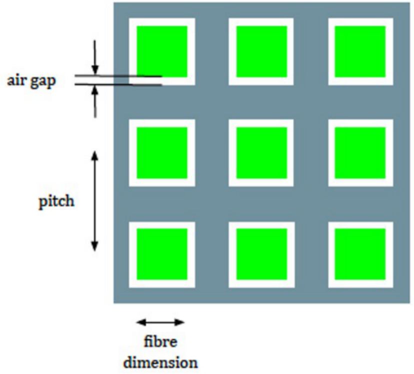
→ Scintillating sampling ECAL technology can be adapted to fulfil these requirements

SpaCal: tuning of X_0, R_M and energy resolution

Example: Variation of fibre size with constant pitch in SpaCal-W/GAGG







GAGG fibers/W absorber

→ Similar variations also possible for polystyrene fibres or Shashlik modules!

Overview of ongoing activities

Future LHCb Upgrades:
- SpaCal with polystyrene (LS3) and GAGG crystal (LS4) fibres in W absorber, polystyrene fibres in Pb absorber (LS3 / LS4)
- Shashlik with fast WLS fibres

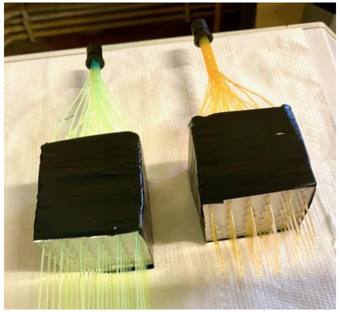
→ examples on the following few slides

RADiCAL:
- R&D in view of FCC-hh ECAL, based on work for CMS phase 2 upgrade, focus on radiation hardness
- Initially, Shashlik-like approach with LYSO:Ce crystal, W absorber and SiPM readout

GRAiNITA:
- Novel approach: small grains of heavy scintillator in heavy liquid, light collected by WLS fibres

NanoCal:
- Shashlik using scintillating nanocrystals

→ see presentation by Etiennette Auffray



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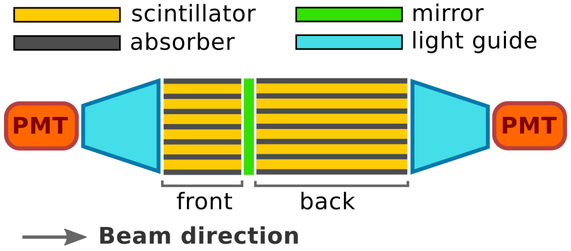
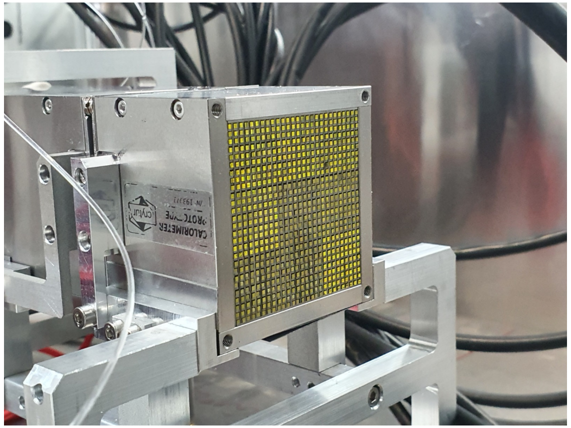
SpaCal-W: prototype with garnet crystals

SpaCal prototype module with W absorber and garnet crystal fibres:
- Pure tungsten absorber with 19 g/cm³
- 9 cells of 1.5x1.5 cm² ($R_M \approx 1.45$ cm)
- 4+10 cm long (7+18 X_0)
- Reflective mirror between sections

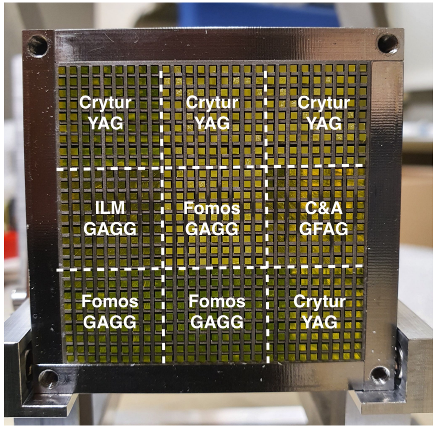




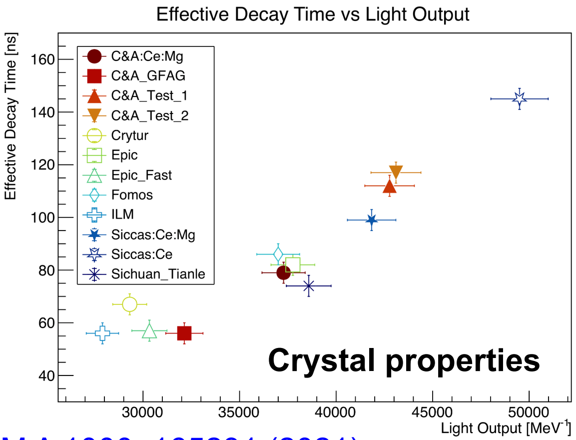
Crystal garnets from several producers:
- Crytur - YAG
- Fomos - GAGG
- ILM - GAGG
- C&A - GFAG

→ Characterised with laboratory measurements

Configuration used at DESY in 2020 and 2021



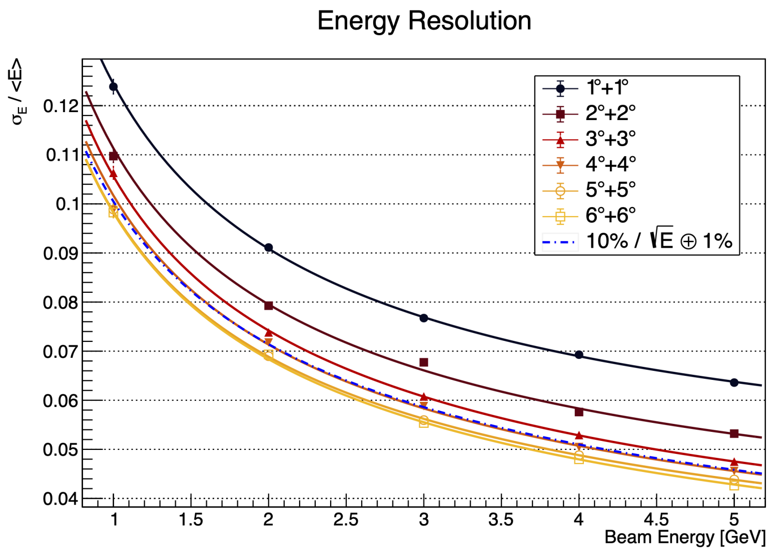
Photon detectors used:
- Hamamatsu R12421 for energy resolution
- Hamamatsu R7600U-20 metal channel dynode (MCD) PMT for timing due to better time resolution



NIM A 1000, 165231 (2021)

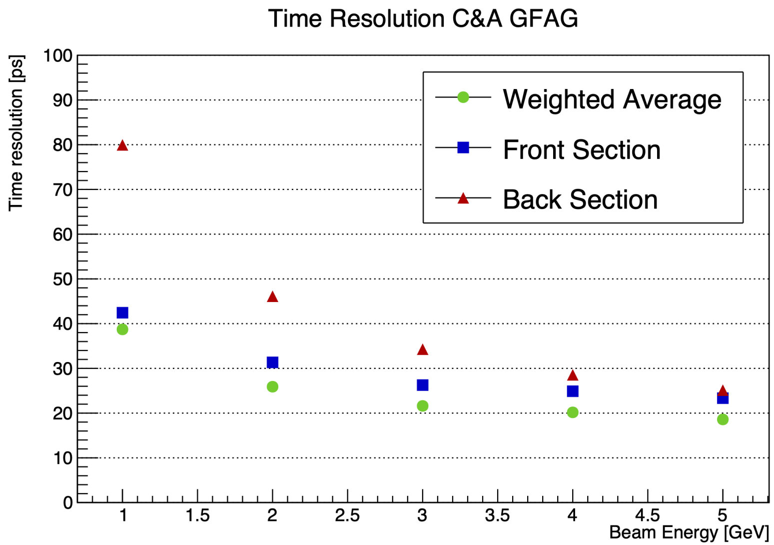
SpaCal-W with crystal fibres: test beam results

Energy resolution (DESY 2020, R12421)



- Better energy resolution with larger incidence angles
- Data up to 5 GeV give (10.2 ± 0.1)% sampling term and 1-2% constant term for $\theta_X = \theta_Y = 3°$

Time resolution (DESY 2021, R7600U-20)



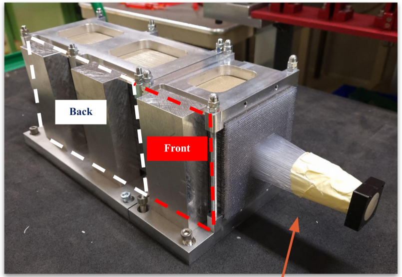
- Incidence angles: $\theta_X = \theta_Y = 3°$
- Time stamps in front and back obtained using constant fraction discrimination (CFD)
- Time resolution at 5 GeV for GFAG: better than 20 ps

NIM A 1045, 167629 (2022)

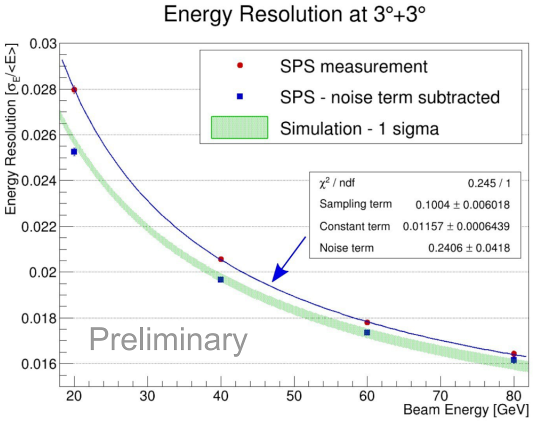
SpaCal with organic scintillator fibres

With lead absorber:

- 9 cells of 3x3 cm² ($R_M \approx 3$ cm)
- 8+21 cm long (7+18 X_0)
- Split fibres (Kuraray SCSF-78, round, 1 mm diameter)
- Reflective mirror between sections

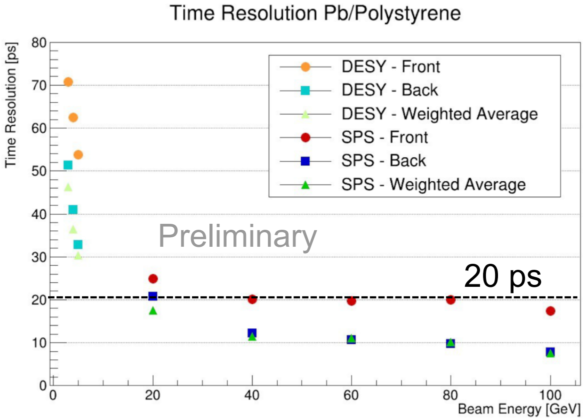


Fibres bundle



Sampling term: (10.0 ± 0.6)%

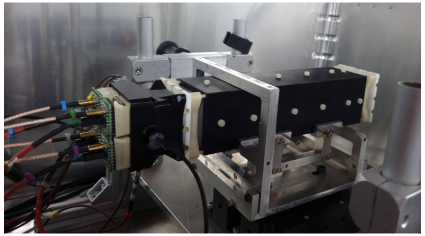
Constant term: (1.2 ± 0.1)%

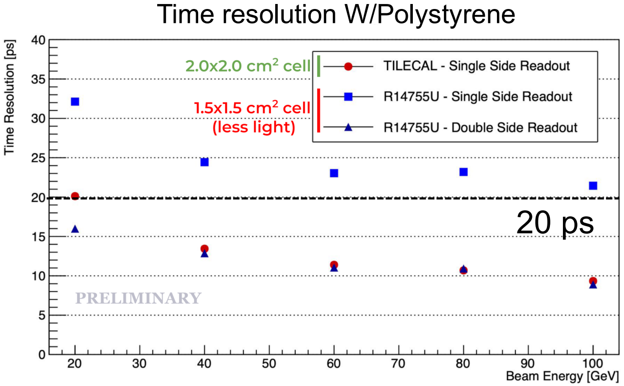


Time resolution below 30 ps for energies above 10 GeV

With tungsten absorber:

- 4 cells of 2x2 cm²
- 19 cm long
- Continuous fibres (Kuraray SCSF-78, square, 1 mm)





→ comparison of different photon detectors

Shashlik: Test beam results and R&D plans

• Current LHCb Shashlik modules have good time properties, further improvement by replacing WLS fibres by faster ones:

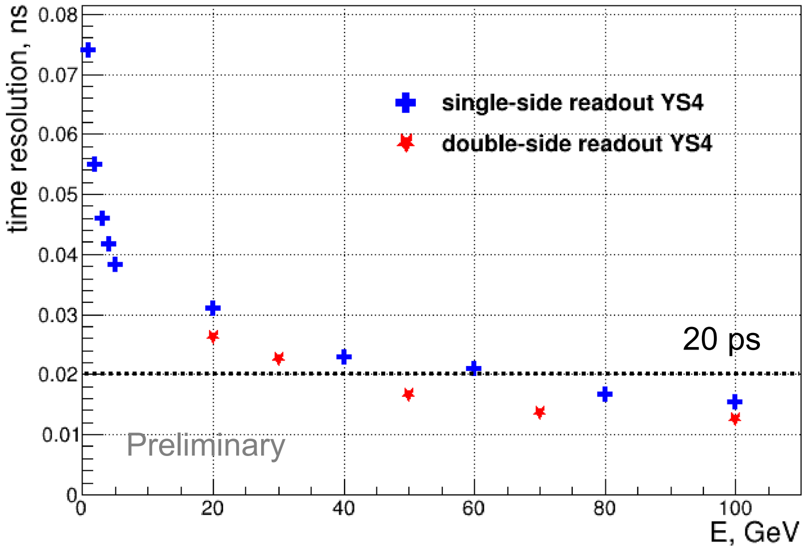
- Y11 (7 ns decay time) → current LHCb
- YS2 (3 ns decay time)
- YS4 (1.1 ns decay time)

• Measurements at DESY and SPS with R7600-20 PMT, $\theta_X = \theta_Y = 3°$

• Better than 20 ps achieved above 30 GeV with double-sided readout

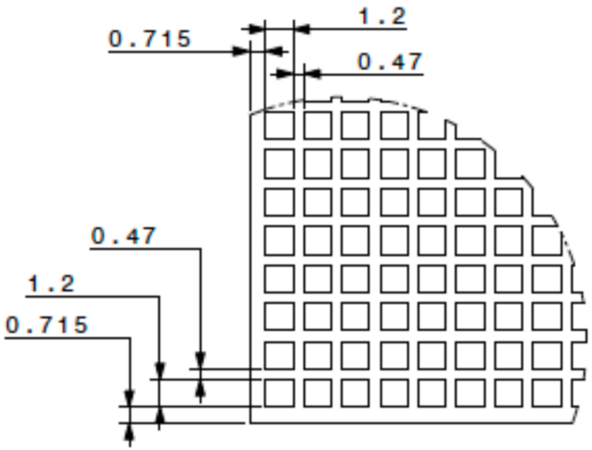
• Somewhat worse performance with single-sided readout

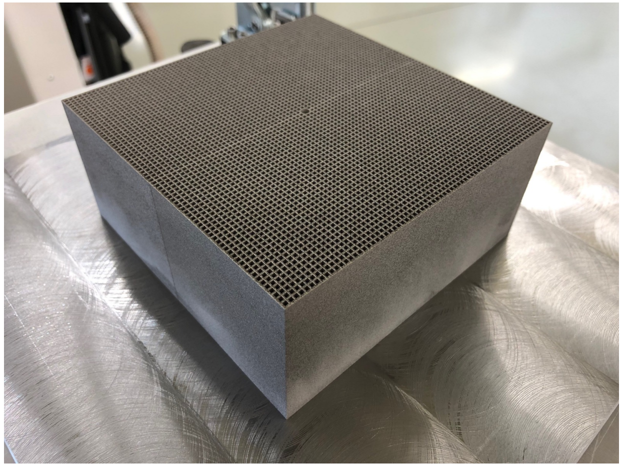
Time resolution: DESY and SPS

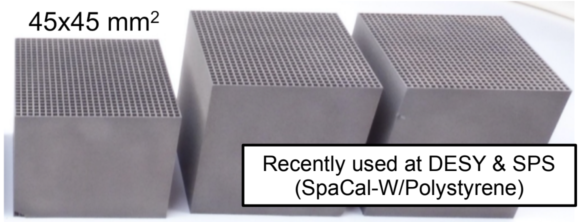


Tungsten absorber: R&D on 3D printing

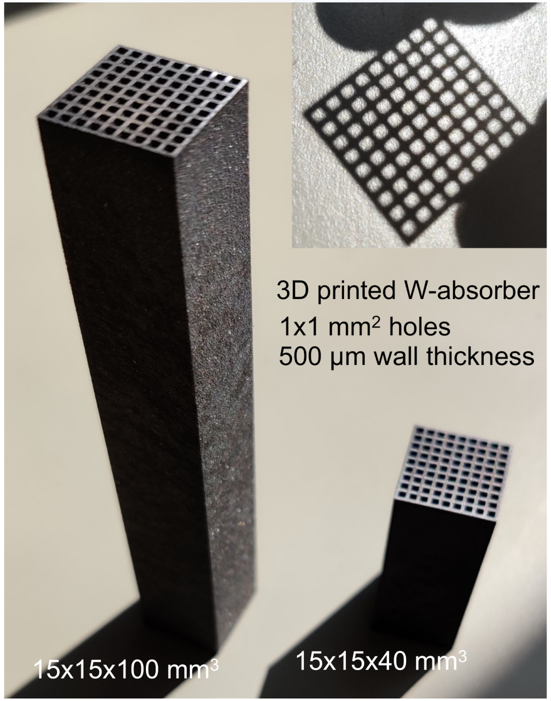
- R&D on 3D printed tungsten prototype
→ produced 1.5x1.5 cm^2 cells with up to 10 cm length (and 4.5x4.5 cm^2 pieces) used in test beams
- Smooth surface mandatory to avoid damaging the fibres during insertion
→ Very good mean roughness of Ra = 5 μm achieved
- Pieces for full-size prototype (up to 12 x 12 x 5 cm^3) to arrive at CERN soon







Recently used at DESY & SPS (SpaCal-W/Polystyrene)



R&D with EOS (Germany)

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Ideas for the next 5 years

Continuation of the technology R&D, e.g.:
- Faster scintillating crystals and WLS fibres
- Photon detectors
- Irradiation tests

Optimisation of ECAL modules:
- Simulations are a key tool
- Optical coupling between between SpaCal fibres and photon detector
- Mechanical integration issues

Performance validation in test beams:
- Move from small prototypes to ECAL modules
- Calibration is a particular topic of importance

Potential synergies within DRD

R&D topics:

• Photon detectors with good energy resolution, time resolution and linearity over large dynamic range (+ radiation tolerance where relevant)
→ also relevant for other light-based calorimeters (homogenous crystals , CALICE ScECAL, …)
• Absorber production (e.g. 3D-printed tungsten)
→ also interesting for dual readout calorimetry (IDEA), CALICE SiW-ECAL, …
• R&D on scintillating crystals, organic scintillating fibres and WLS fibres
• Generic simulation software
→ e.g. faster transport of optical photons in Geant4, local reconstruction based on machine learning

Test beams:

• Test beam infrastructure:
→ Shared hodoscopes, reference time detectors where requirements are in line
→ For discussion: read-out electronics, DAQ system?
• Common test beam requests
→ Seem beneficial in case joint activities like ECAL+HCAL test are relevant

Summary and conclusions

- The flexibility of picosecond scintillating sampling ECALs allows to meet the requirements for a variety of future experiments

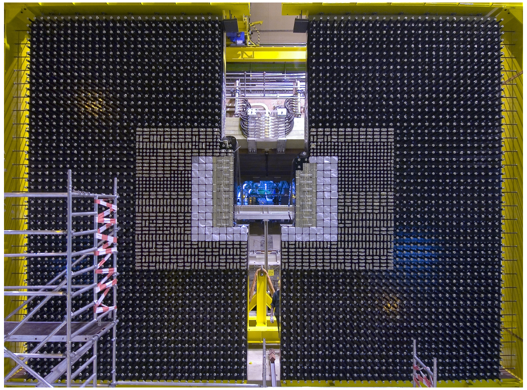
- Better than 20 ps time resolution achieved for SpaCal and Shashlik technology with high-energy electron beams

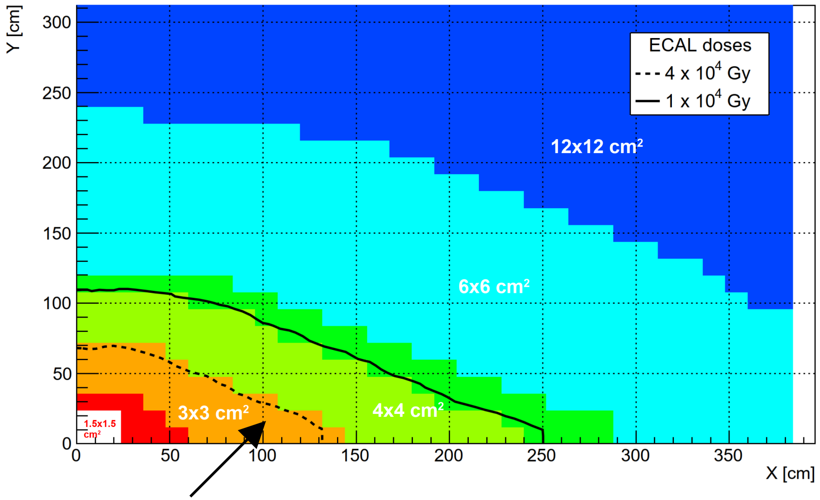
- Many potential synergies with other DRD activities in the next 5 years identified
→ Looking forward to the following discussions and exchange of experience!

Thank you!

Backup slides

Reminder: SpaCal/Shashlik ECAL for Upgrade II





Radiation limit of current Shashlik technology

Requirements for the Upgrade II:
- Sustain radiation doses up to 1 MGy and ≤ 6 x 10^{15} 1 MeV neq / cm^2 in the centre
- Keep current energy resolution of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
- Pile-up mitigation crucial

→ Timing capabilities with O(10) ps precision, preferably directly in the calorimeter modules
→ Increased granularity in the central region with denser absorber

SpaCal technology for inner region:
- Innermost modules with scintillating crystal fibres and W absorber

→ Development of radiation-hard scintillating crystals
→ 1.5x1.5 cm^2 cell size
- 40-200 kGy region with scintillating plastic fibres and Pb absorber

→ Need radiation-tolerant organic scintillators
→ 3x3 cm^2 cell size

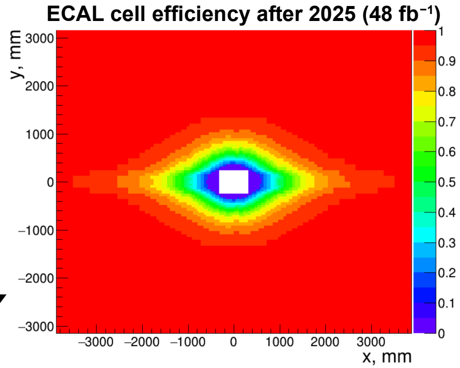
Shashlik technology:
- Timing with new WLS fibres, long. segmentation (double-sided readout)

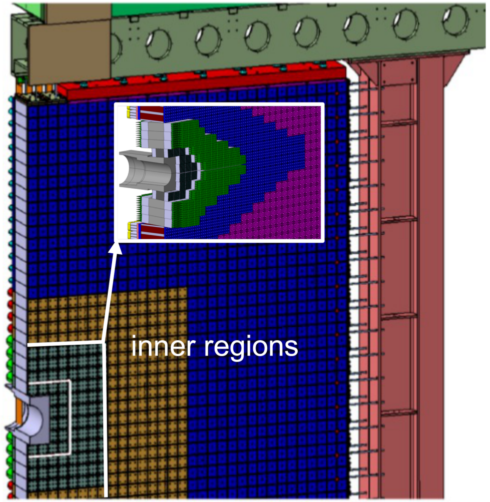
→ Cost optimisation by refurbishing ≈2000 existing modules for timing
→ Adapt to the required cell sizes by adding ≈1300 new modules

LS3 consolidation: W absorber for innermost modules equipped with scintillating plastic fibre for 2x2 cm^2 cell size

CERN/LHCC 2021-012

LHCb ECAL upgrade strategy



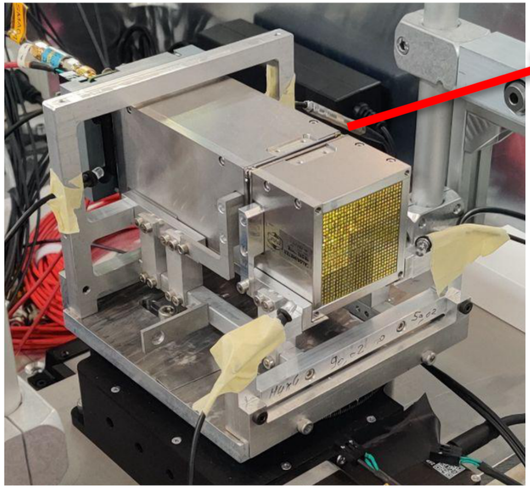


Run 3 in 2022-2025:
Run with unmodified ECAL Shashlik modules at L = 2 x 10^{33} $cm^{-2}s^{-1}$

LS3 consolidation in 2026-2028:
Introduce single-section rad. tolerant SpaCal (2x2 and 3x3 cm^2 cells) in inner regions and rebuilt ECAL in rhombic shape to improve performance at L = 2(4) x 10^{33} $cm^{-2}s^{-1}$
→ 32 SpaCal-W & 144 SpaCal-Pb modules with plastic fibres compliant with Upgrade II conditions
→ Could include timing information with single-sided readout to inner regions

LS4 Upgrade II in ≥2035:
Introduce double-section rad. hard SpaCal (1.5x1.5 & 3x3 cm^2 cells) and improve timing of Shashlik modules for a luminosity of up to L = 1.5 x 10^{34} $cm^{-2}s^{-1}$
→ Innermost SpaCal-W modules equipped with crystal fibres
→ Include timing information and double-sided readout to full ECAL for pile-up mitigation

Energy resolution and longitudinal separation

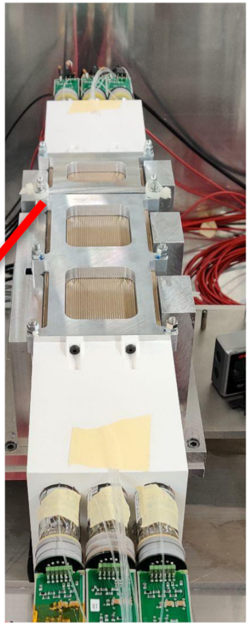


WGAGG

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

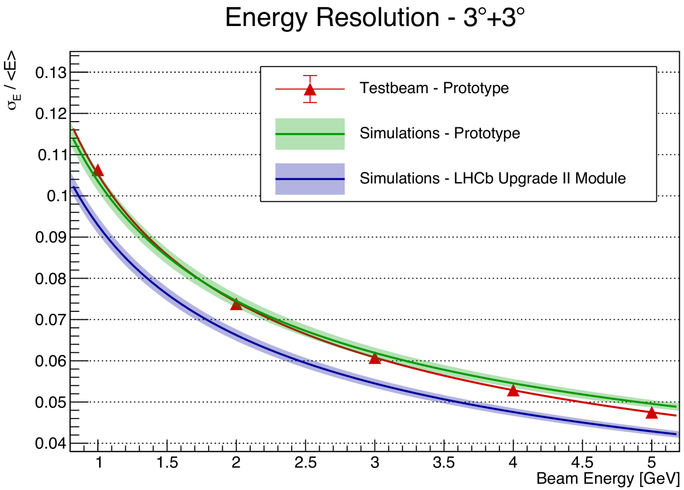
0.065 mm	ESR
2.0 mm	**Stainless**
1.0 mm	Air
2.0 mm	**Stainless**
0.065 mm	ESR



- In SpaCal prototypes produced for test beams, the longitudinal separation (front/back sections) is not optimised
- This is due to the need for flexibility to perform several tests (calibration, additional timing layer, …)
- Material budget between SpaCal sections not negligible → energy resolution is degraded

SpaCal energy resolution of optimised modules

SpaCal-W



SpaCal-Pb

	Measured with TB module [%]	MC simulation of TB module [%]	MC simulation of optimised module [%]
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

• Hybrid-MC framework reproduces well the test beam measurements (if material between front and back is taken into account)
• In SpaCal modules designed for the LHCb ECAL, front/back separation will be optimised (e.g. thin reflector foil)
→ The MC allows to predict the energy resolution of these optimised modules

→ Expected energy resolution in optimised modules well in line with the requirements

arXiv:2205.02500