Scintillating sampling ECAL technology for the LHCb PicoCal

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on behalf of the LHCb ECAL Upgrade II R&D group

LHCb in collaboration with Crystal Clear,
supported by EP R&D (WP 3.2.0 and 3.2.1)

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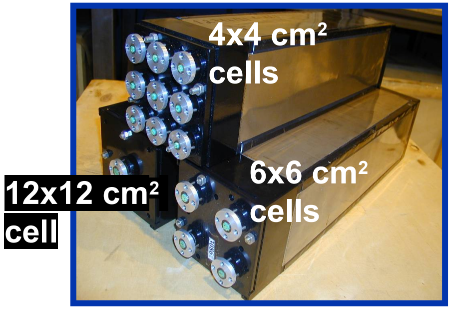
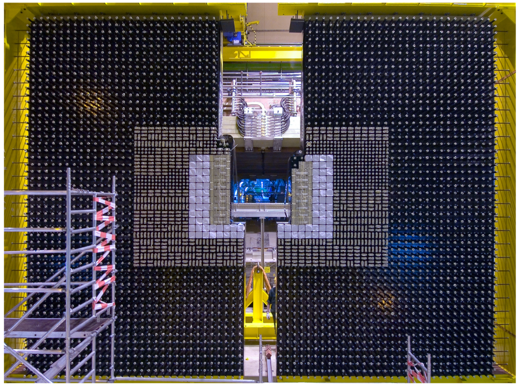
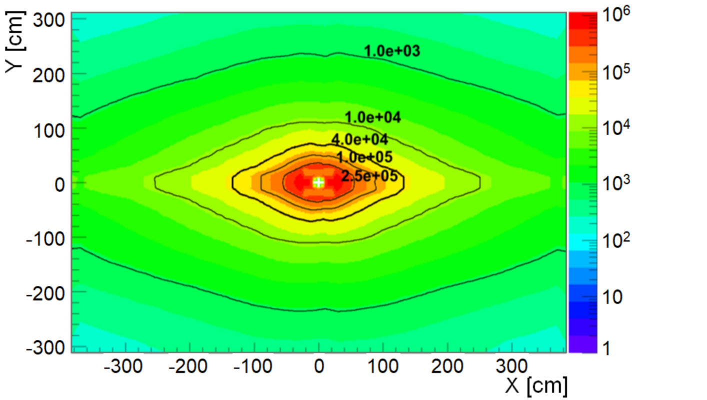
The current ECAL and motivation to upgrade

Current LHCb ECAL:
- Optimised for π^0 and γ identification in the few GeV to 100 GeV region at 2×10^{32} cm^{-2}s^{-1}
- Shashlik technology with 4x4, 6x6 and 12x12 cm^2 cell size
- Radiation hard up to 40 kGy
- Energy resolution: $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
- Large array of ≈50 m^2 with 3312 modules and 6016 channels





Accumulated radiation dose [Gy] after 300 fb^{-1}



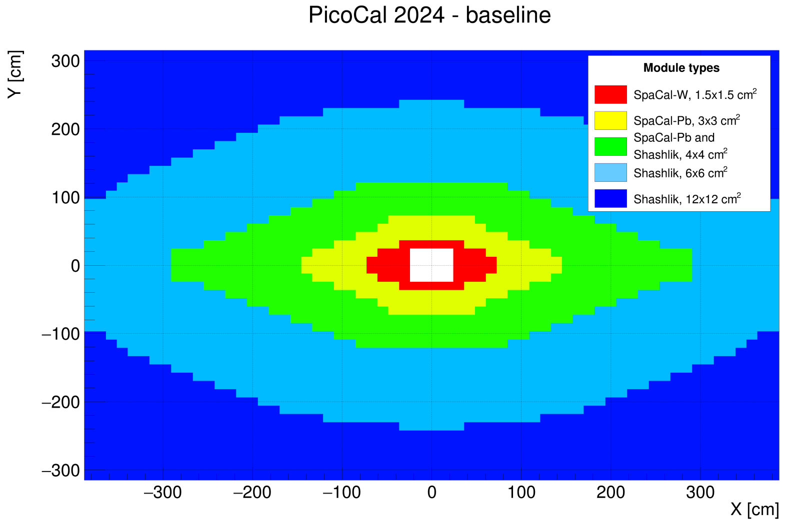
Requirements for the Upgrade II (operation at up to 1.5×10^{34} cm^{-2}s^{-1} after LS4):
- Sustain radiation doses up to 1 MGy and ≤ 6×10^{15} 1 MeV neq / cm^2 in the centre
- Keep current energy resolution of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
- Pile-up mitigation crucial

→ Timing capabilities with O(10) ps precision, preferably directly in the calorimeter modules

→ Increased granularity in the central region with denser absorber
- Better time resolution, less impact of radiation damage, more information for event reconstruction and particle identification from longitudinal segmentation

LHCb-TDR-023

Technologies for the Upgrade II



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

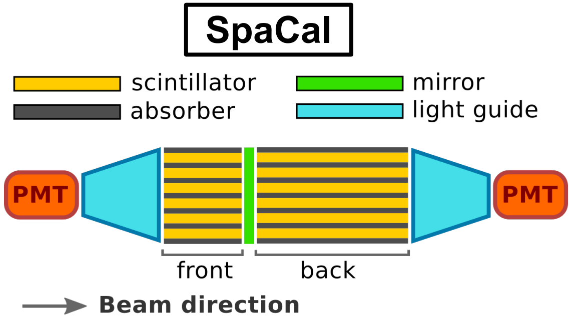
- Intermediate region with scintillating plastic fibres and Pb absorber

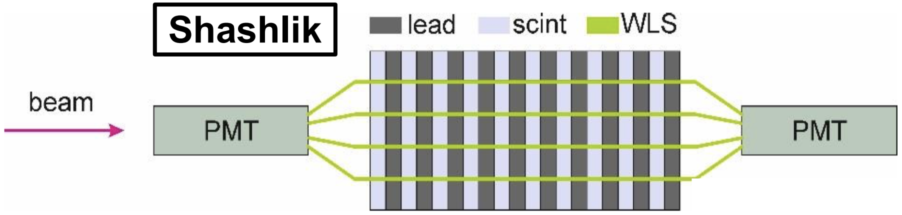
→ Need radiation-tolerant organic scintillators
→ $3x3\ cm^2$ and $4x4\ cm^2$ cell size

Shashlik technology:
- About 2900 Shashlik modules with improved timing capability and double-sided readout

→ WLS fibres replaced in all modules, about 900 modules rebuilt with smaller cell size

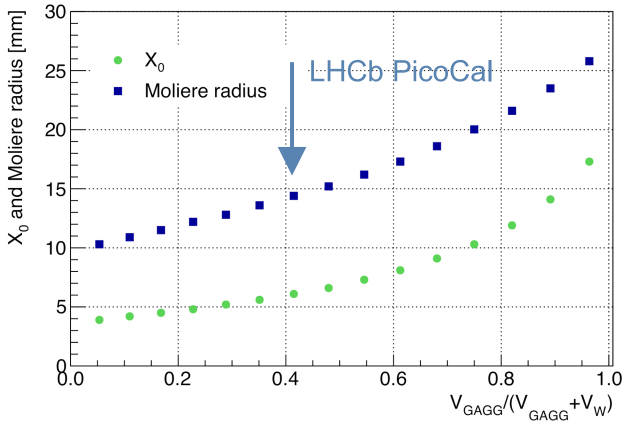
- **LS3 enhancement:** W absorber for innermost modules equipped with scintillating plastic fibres for $2x2\ cm^2$ cell size, single-sided readout
- All SpaCal modules tiled by 3°+3° → see later

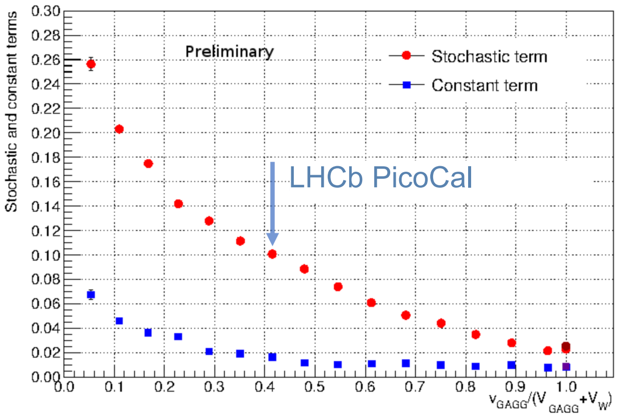


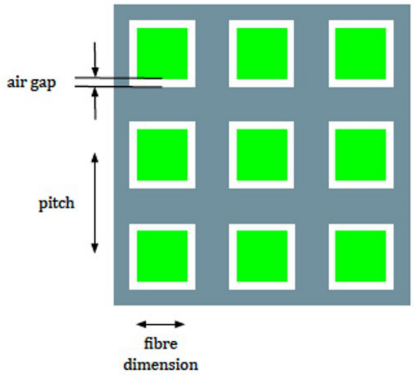


SpaCal: tuning of X_0, R_M and energy resolution

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



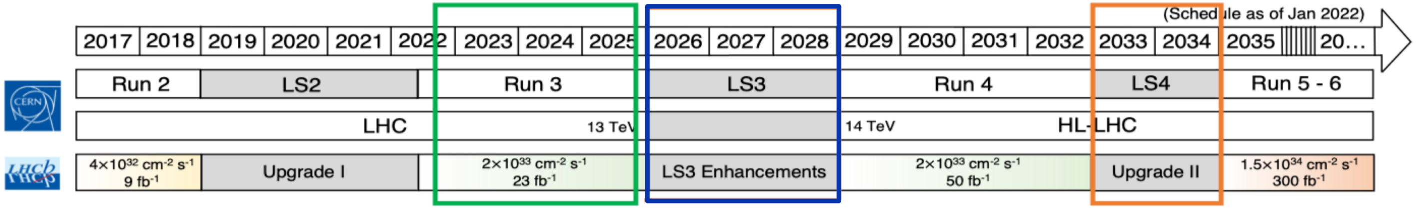


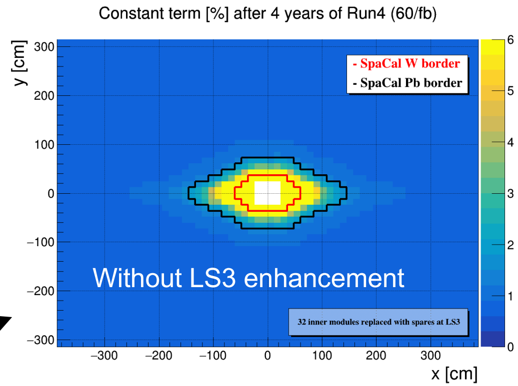


GAGG fibers/W absorber

- Similar variations also possible for polystyrene fibres or Shashlik modules!
- Very flexible technology, also relevant for Higgs factories, FCC-hh, fixed-target experiments at the intensity frontier, ...

LHCb ECAL upgrade strategy

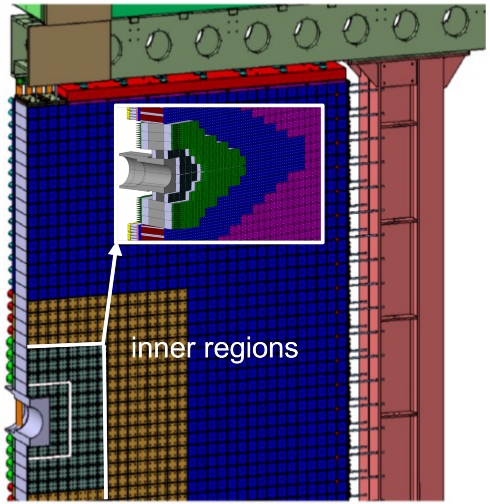




Run 3 in 2022-2025:
Run with unmodified ECAL Shashlik modules at L = 2 x 10^{33} $cm^{-2}s^{-1}$
(new 40 MHz readout)

LS3 enhancement 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
→ Option to include timing information with single-sided readout to inner regions

LS4 Upgrade II in 2033/2034:
Introduce double-section radiation hard SpaCal (1.5x1.5, 3x3 and 4x4 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

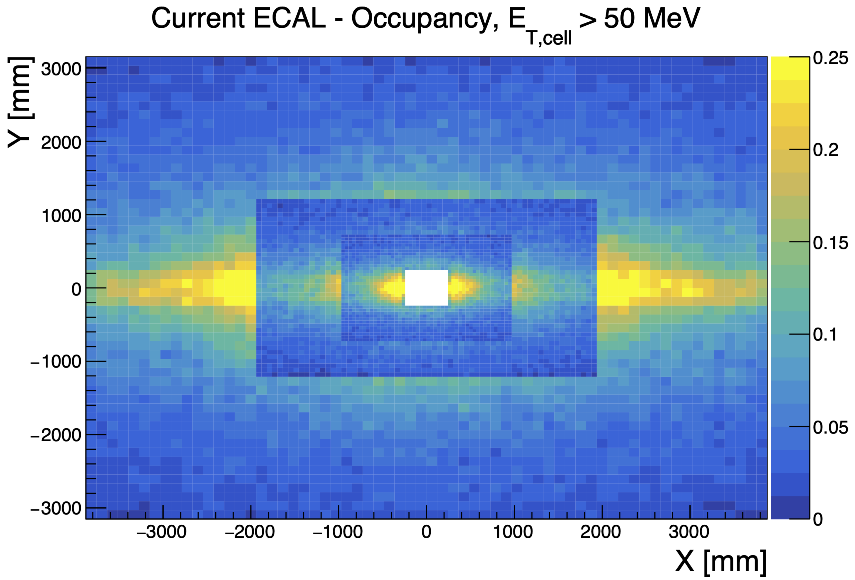


LHCb-TDR-023, LHCb-TDR-024

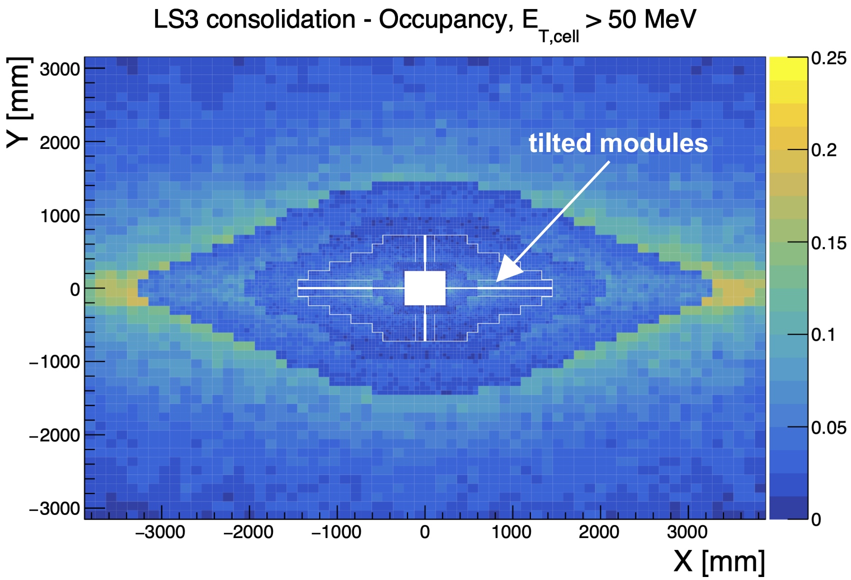
LS3: impact of improved granularity

- Occupancies from detailed simulation, also including the hadronic component!
- Assumed luminosity: $L = 2 \times 10^{33}\ cm^{-2}s^{-1}$

Current ECAL:



With LS3 enhancement:



- Sizeable occupancy in large regions before LS3 enhancement (e.g. challenge for neutral pion reconstruction)
- Occupancy map after LS3 enhancement reasonably flat

Outline: R&D and test beam results

SpaCal with tungsten absorber:

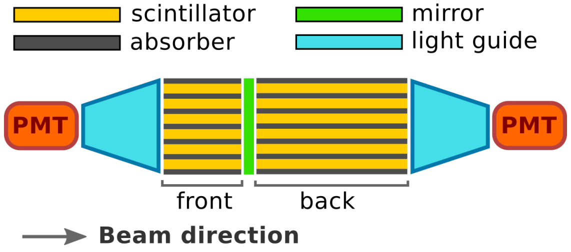
- SpaCal-W with crystal fibres for LS4
- 3D printing of absorber
- SpaCal-W with polystyrene fibres for LS3

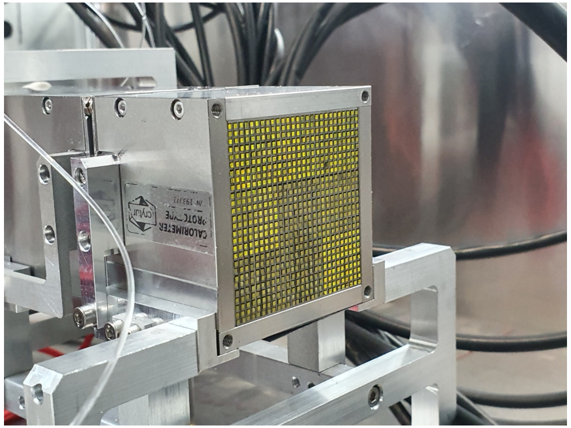
SpaCal with lead absorber

Shashlik with fast WLS fibres

SpaCal-W: prototype with garnet crystals

SpaCal prototype module with W absorber and garnet crystal fibres:
- Pure tungsten absorber with 19 g/cm^3
- 9 cells of 1.5x1.5 cm^2 ($R_M \approx 1.45$ cm)
- 4+10 cm long (7+18 X_0)
- Reflective mirror between sections

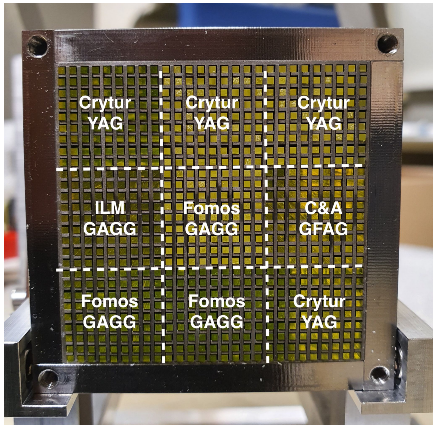




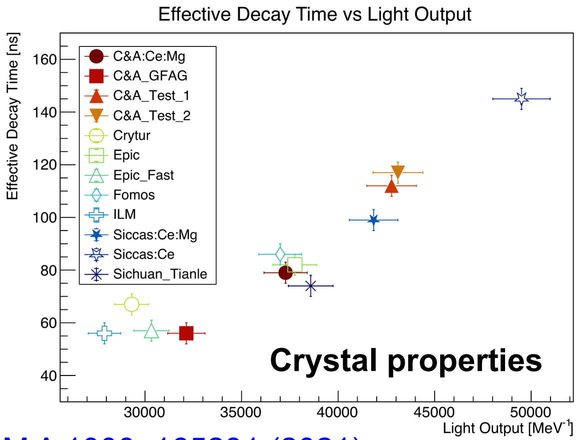
Crystal garnets from several producers:
- Crytur - YAG
- Fomos - GAGG
- ILM - GAGG
- C&A - GFAG

→ Characterised with laboratory measurements

Configuration used at DESY in 2020 and 2021



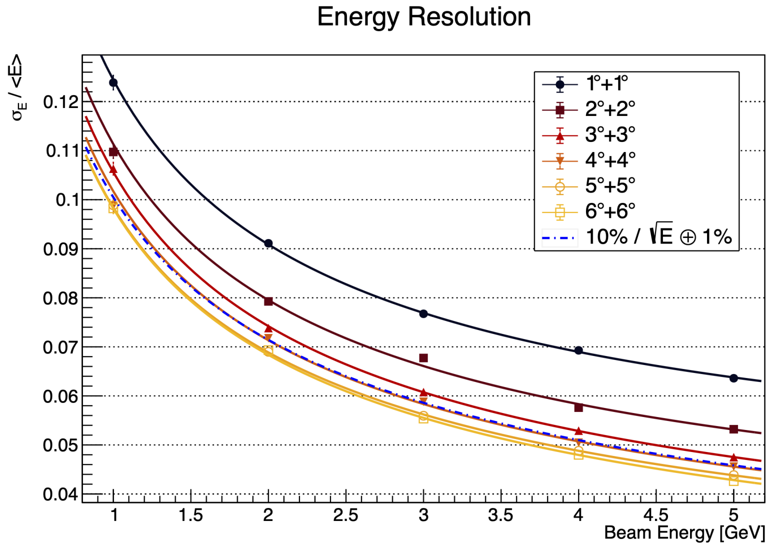
Photon detectors used:
- Hamamatsu R12421 for energy resolution
- Hamamatsu R7600U-20 metal channel dynode (MCD) PMT for timing for better time resolution



NIM A 1000, 165231 (2021)

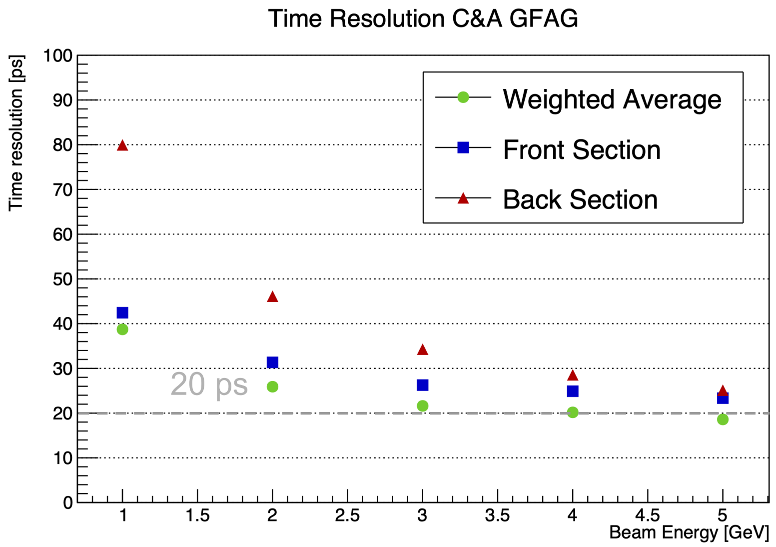
SpaCal-W with crystal fibres: test beam results

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: $\theta_X = \theta_Y = 3°$, double-sided readout
- 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)

Outline: R&D and test beam results

SpaCal with tungsten absorber:

- SpaCal-W with crystal fibres for LS4
- 3D printing of absorber and “module 0”
- SpaCal-W with polystyrene fibres for LS3

SpaCal with lead absorber

Shashlik with fast WLS fibres

Tungsten absorber: 3D printing

- 3D printing using pure tungsten powder found to be a scalable technology for absorber production
- Smooth surface mandatory to avoid damaging the fibres during insertion

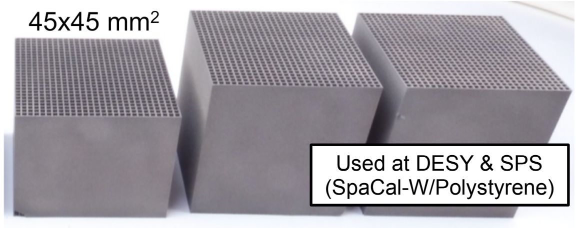
→ Very good mean roughness of R_a = 5 μm (average profile height deviations from mean) achieved

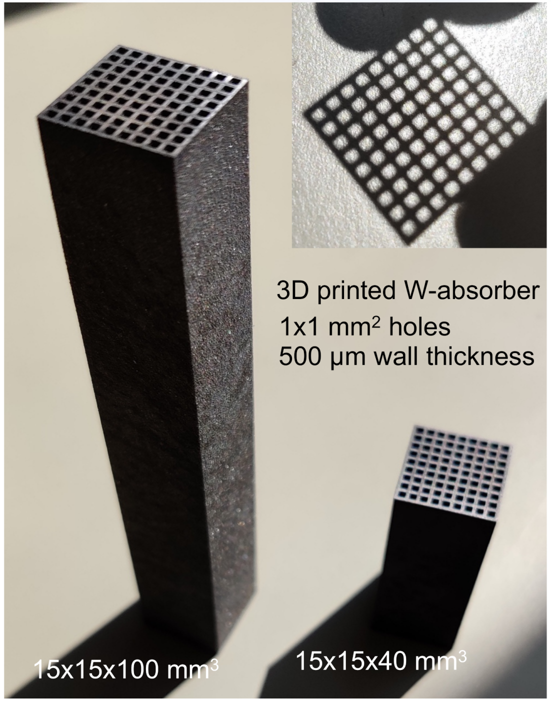
- R&D campaign with EOS (Germany):

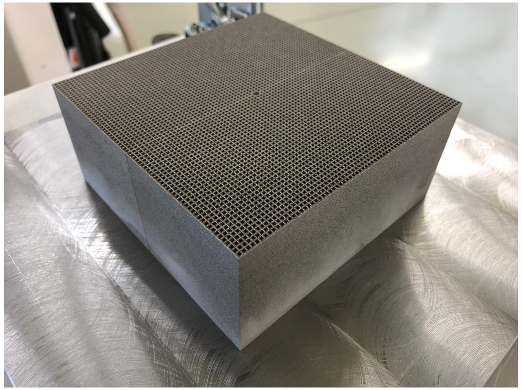
→ First 1.5x1.5 cm^2 cells with up to 10 cm length
→ Then 4.5x4.5 cm^2 pieces
→ Recently 12.1x12.1 cm^2 pieces produced and used for "module 0"

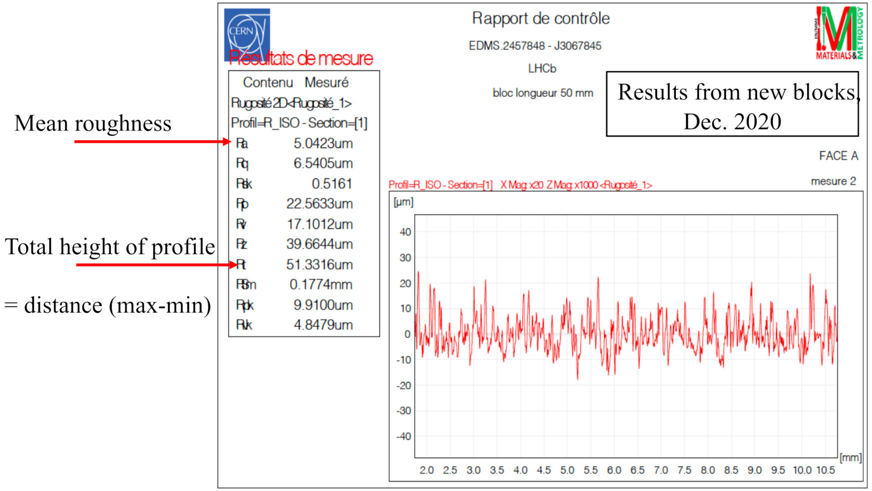
- Module-size pieces recently produced by Laser Add Technology Co. in China:

→ Two 12.1x12.1 cm^2 pieces in 2023
→ Absorber pieces for module-size prototype with crystal fibres expected very soon



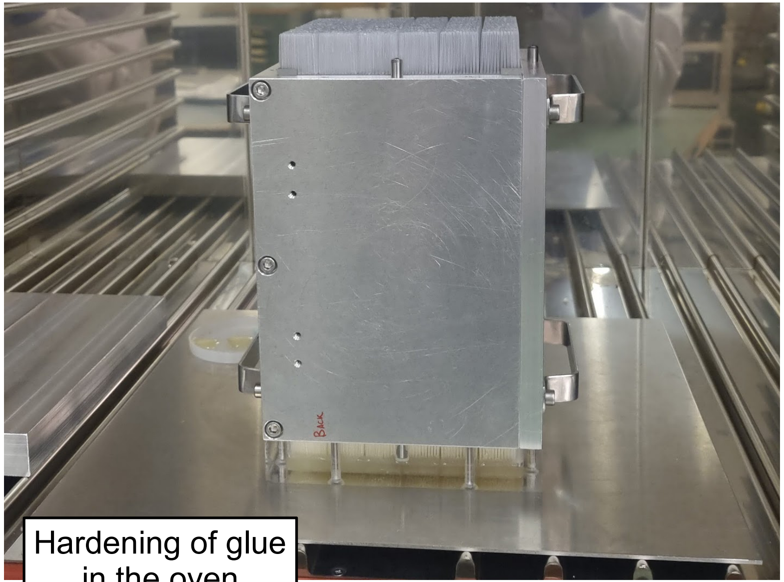




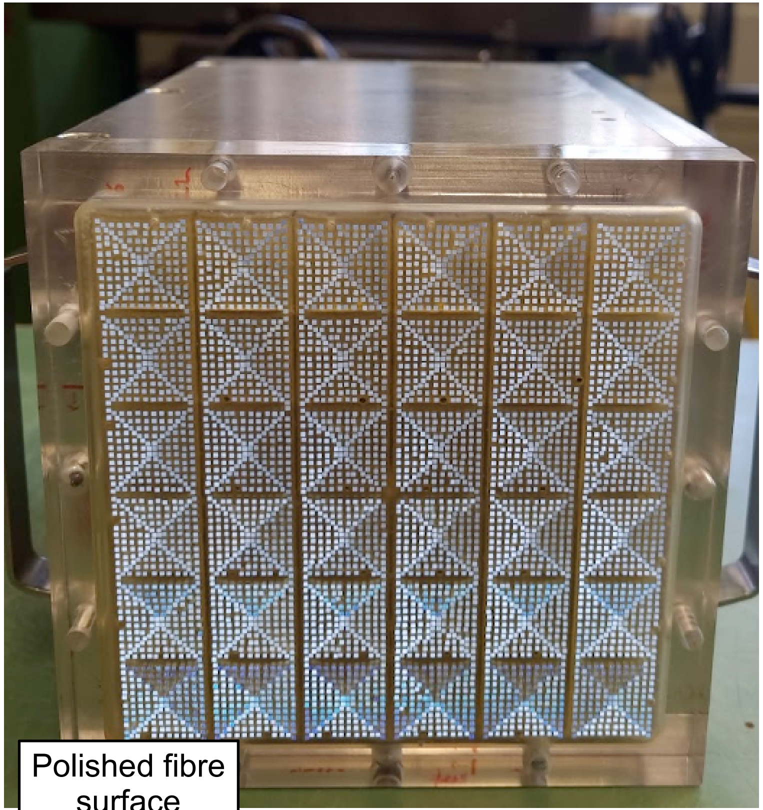


“Module 0” with tungsten absorber (1)

Full-size “module 0” with tungsten absorber assembled at CERN:
- 3D-printed tungsten absorber: 5+5+5+4 = 19 cm (LS3 configuration)
- Filled with single-cladded organic scintillating fibres (1x1 mm^2, Kuraray SCSF-78)
- Gluing and polishing procedure established
- One hole per cell removed to insert fibre for calibration



Hardening of glue in the oven

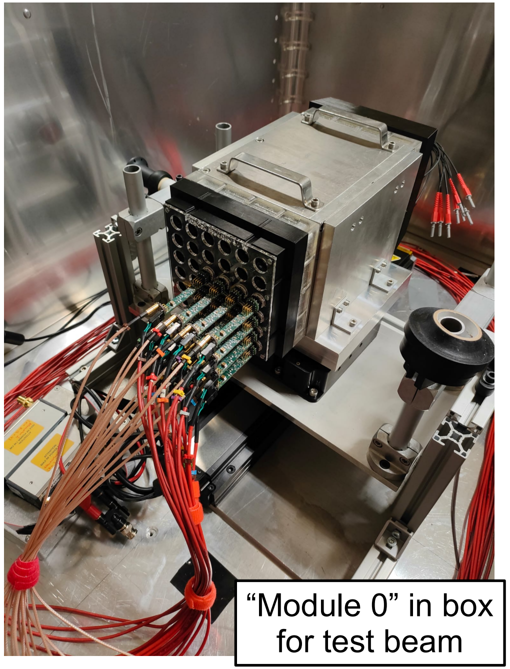


Polished fibre surface

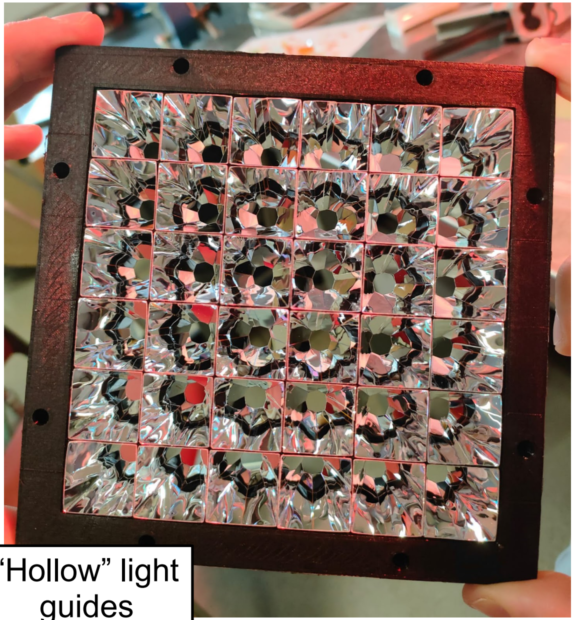
“Module 0” with tungsten absorber (2)

Full-size “module 0” with tungsten absorber assembled at CERN:
- Radiation-hard “hollow” light guides imbedded in PMT holder
- Extensive test beam characterisation performed

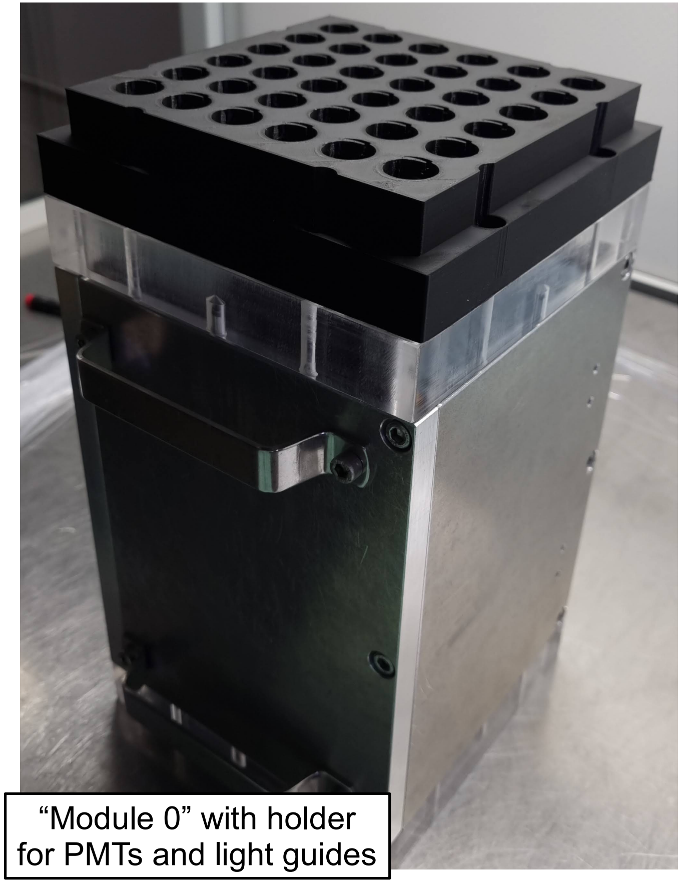
at DESY (May 2023) and CERN (June & August September 2023)



“Module 0” in box for test beam



“Hollow” light guides



“Module 0” with holder for PMTs and light guides

Outline: R&D and test beam results

SpaCal with tungsten absorber:

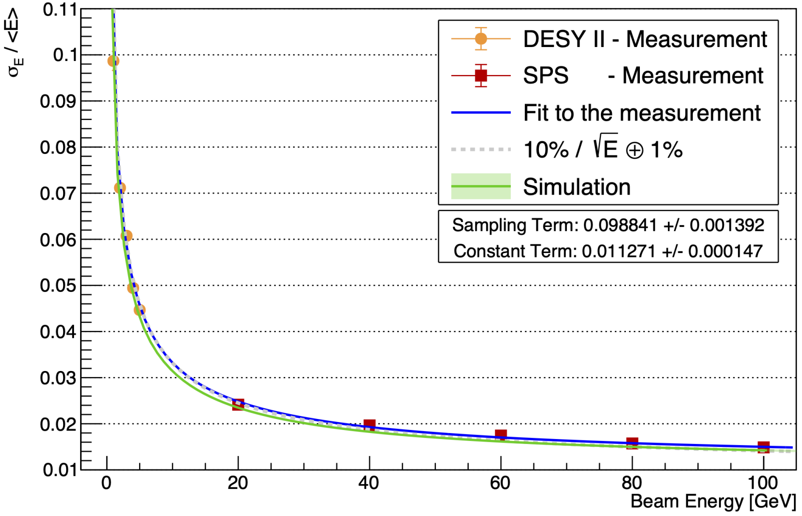
- SpaCal-W with crystal fibres for LS4
- 3D printing of absorber and “module 0”
- SpaCal-W with polystyrene fibres for LS3

SpaCal with lead absorber

Shashlik with fast WLS fibres

SpaCal-W with polystyrene fibres for LS3: test beam results

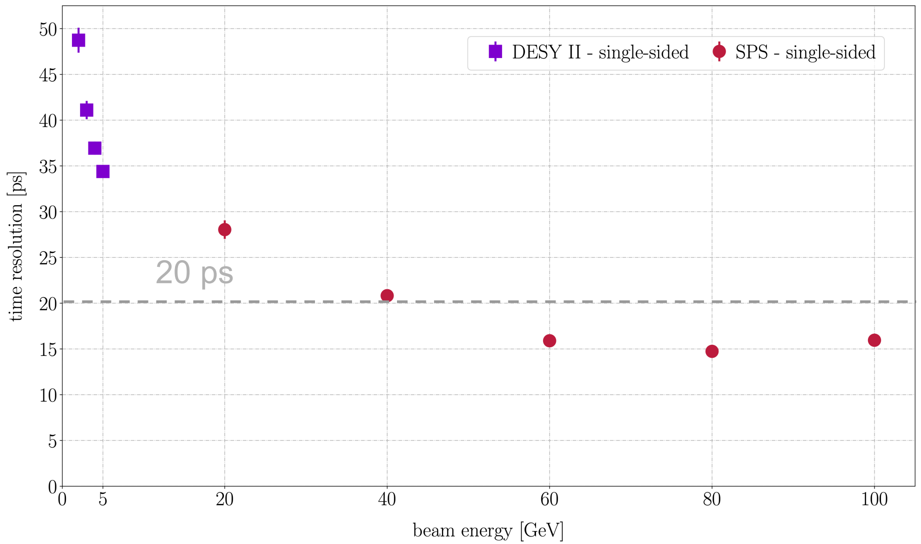
Energy resolution (DESY & SPS, R14755U-100)



- Incidence angles: $\theta_X = \theta_Y = 3°$, single-sided readout
- “Module 0” prototype
- Noise contribution subtracted
- Sampling term: 9.9%, constant term: 1.1%

→ Very good agreement with simulation

Time resolution (DESY & SPS, R7600U-M4)



- Incidence angles: $\theta_X = \theta_Y = 3°$, single-sided readout
- Prototype with 2x2 cells
- Optical coupling with “hollow” light guide
- Multi-anode PMT with 4 channels
- Time resolution above 40 GeV: better than 20 ps

LHCb-TDR-024

Outline: R&D and test beam results

SpaCal with tungsten absorber:

- SpaCal-W with crystal fibres for LS4
- 3D printing of absorber and “module 0”
- SpaCal-W with polystyrene fibres for LS3

SpaCal with lead absorber

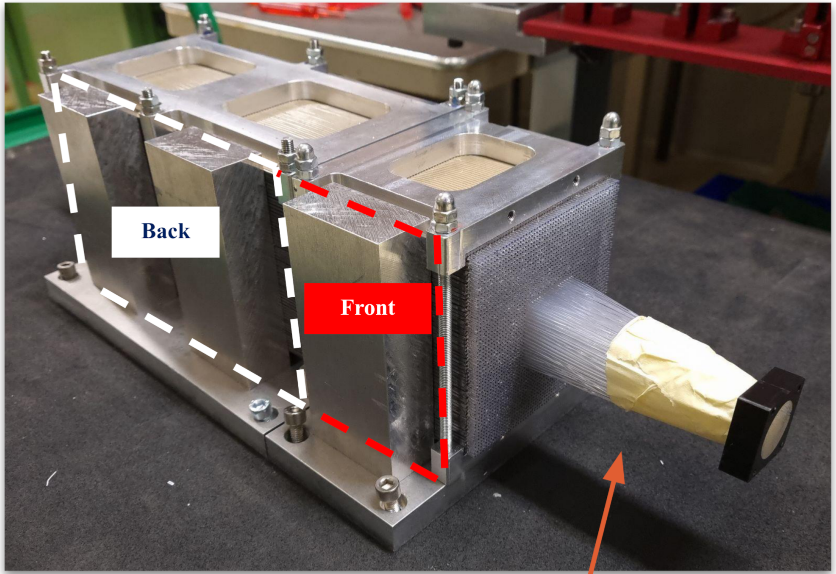
Shashlik with fast WLS fibres

SpaCal-Pb: first prototype with polystyrene fibres

- Lead absorber with polystyrene fibres (1 mm, SCSF-78M)

- 9 cells of 3x3 cm^2 ($R_M \approx 3$ cm)
- 8+21 cm long (7+18 X_0)
- Reflective mirror between sections
- Results from DESY & CERN SPS

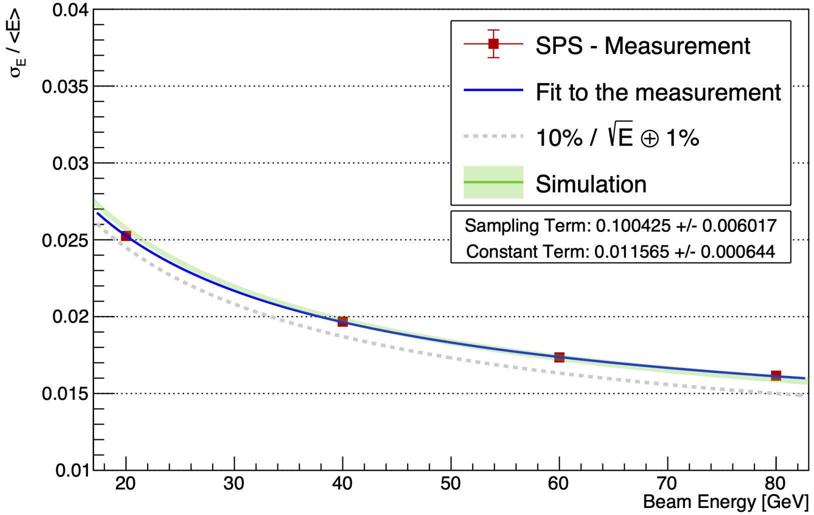
Different readout configurations compared:
- Direct contact of MCD PMT with the scintillating fibres
- PMMA light guides
- Bundle of fibres coupled directly to MCD PMT



Fibres bundle (1 cell)

SpaCal-Pb with polystyrene fibres: test beam results

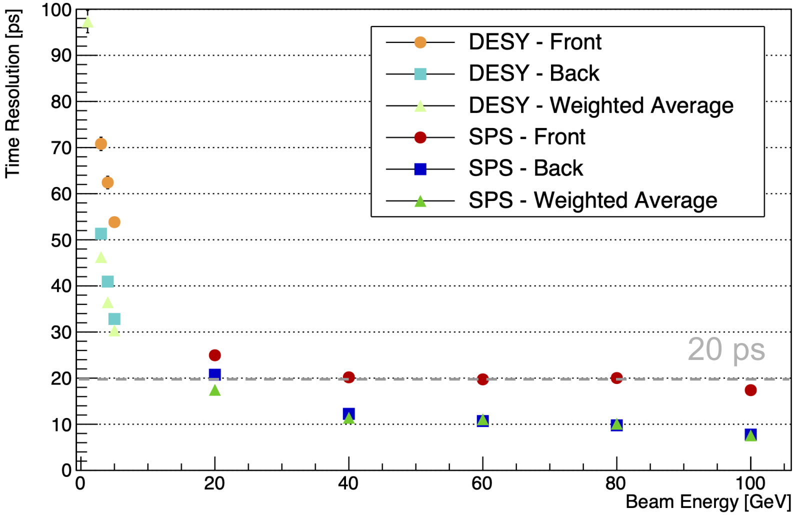
Energy resolution (CERN SPS)



- Incidence angles: $\theta_X = \theta_Y = 3°$
- Noise contribution subtracted
- Sampling term: 10.0%, constant term: 1.16%

→ Very good agreement with simulation

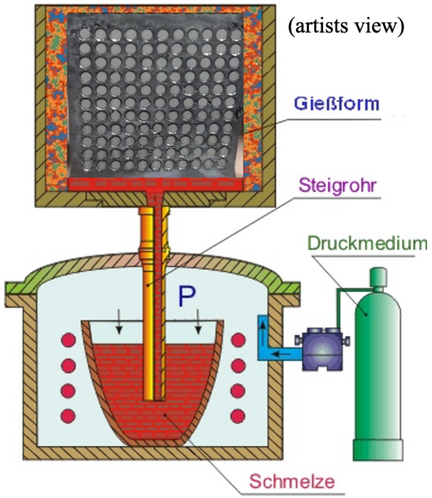
Time resolution (DESY & SPS, R11187)



- Incidence angles: $\theta_X = \theta_Y = 3°$, double-sided readout
- PMT in direct contact
- Front section more important at low energy, back section at high energy
- Time resolution above 20 GeV: better then 20 ps

LHCb-TDR-024

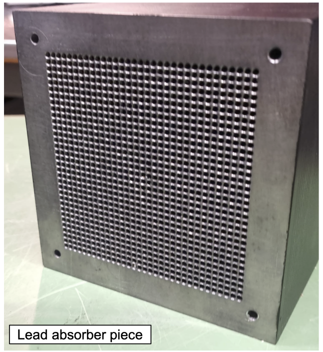
SpaCal-Pb: towards module-size prototypes

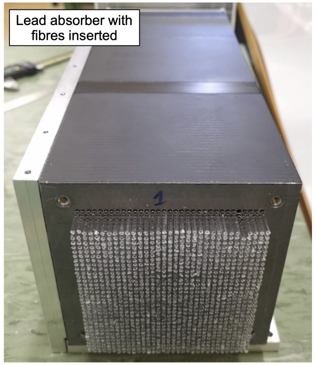


- Lead absorber produced using low-pressure casting process by MTH & ICM in Germany

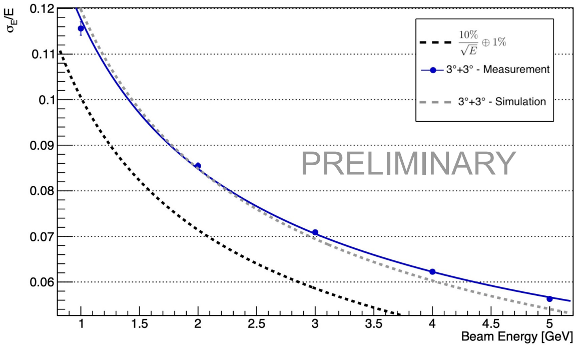
- First prototype with 9x9 cm^2 active area equipped with round SCSF-78 scintillating fibres of 2 mm diameter tested at DESY in December 2023

- Next prototype with 12x12 cm^2 active area and using SCSF-3HF scintillating fibres of 1.5 mm diameter in preparation, targeting test beam in summer 2024 at the CERN SPS



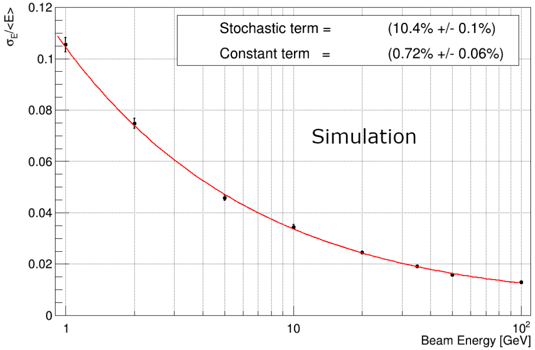


Measurement, DESY, 2 mm fibres



→ Energy resolution well described by simulation

Simulation, 1.5 mm fibres



→ Energy resolution goal achieved with 1.5 mm fibres

Outline: R&D and test beam results

SpaCal with tungsten absorber:
- SpaCal-W with crystal fibres for LS4
- 3D printing of absorber and “module 0”
- SpaCal-W with polystyrene fibres for LS3

SpaCal with lead absorber

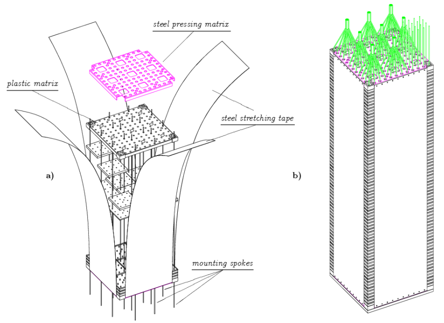
Shashlik with fast WLS fibres

Shashlik: R&D towards LS4

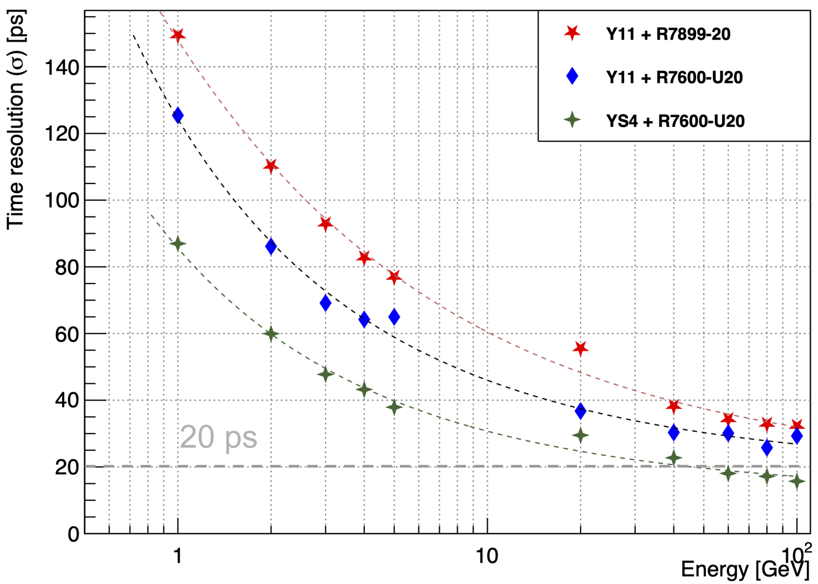
• Current LHCb Shashlik modules have good time properties, further improvement by replacing WLS fibres by faster ones:

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

• Measurements at DESY and SPS with current (R7899-20) and faster (R7600-20) PMT, single-sided readout, $\theta_X = \theta_Y = 3°$



Time resolution (DESY and SPS)



• Better than 20 ps achieved above 40 GeV (even slightly better with double-sided readout)

LHCb-TDR-024

Summary and conclusions

Summary and conclusions

• The innermost 176 modules of the LHCb ECAL need to be replaced during LS3 due to radiation damage
→ SpaCal technology with tungsten and lead absorber meets all requirements for this region
→ TDR recently approved!

• The Upgrade II in LS4 introduces picosecond-level timing capabilities and more demanding radiation hardness requirements
→ Better than 20 ps achieved with Shashlik and SpaCal technology at high energy
→ Crystal fibres in the central region

PicoCal

• Comprehensive R&D ongoing (also interesting for other future projects)
→ Test beam measurements with prototypes
→ Detailed Monte Carlo simulations
→ Study of novel absorber production techniques
→ Study of suitable PMTs and development of readout electronics
→ Investigation of new radiation-hard and fast scintillators

Thank you!