PicoCal

Scintillating sampling ECAL technology for the LHCb PicoCal

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

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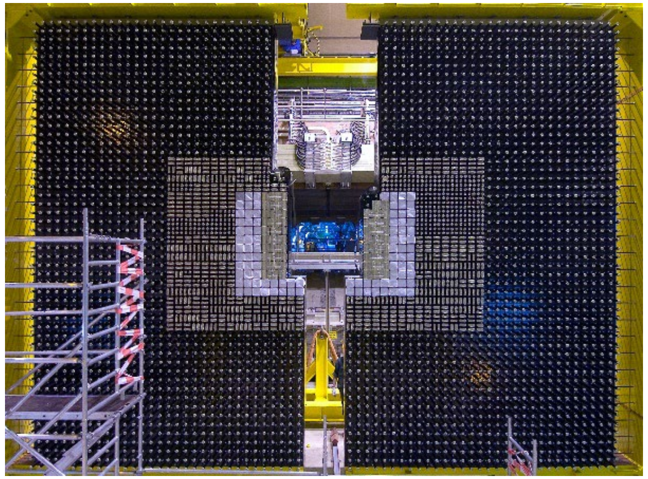
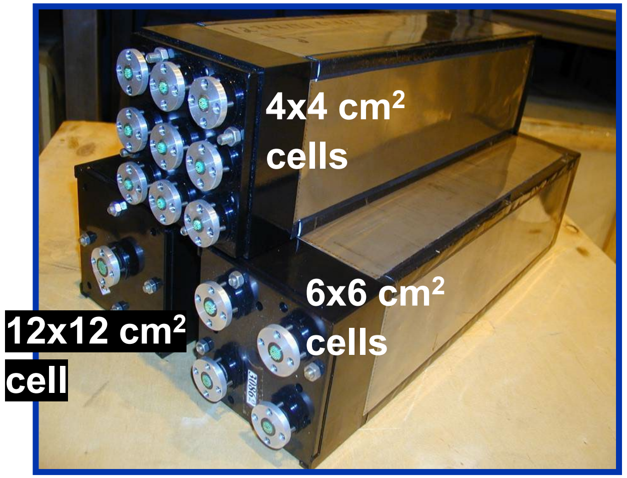
ICCUB

Universitat de Barcelona

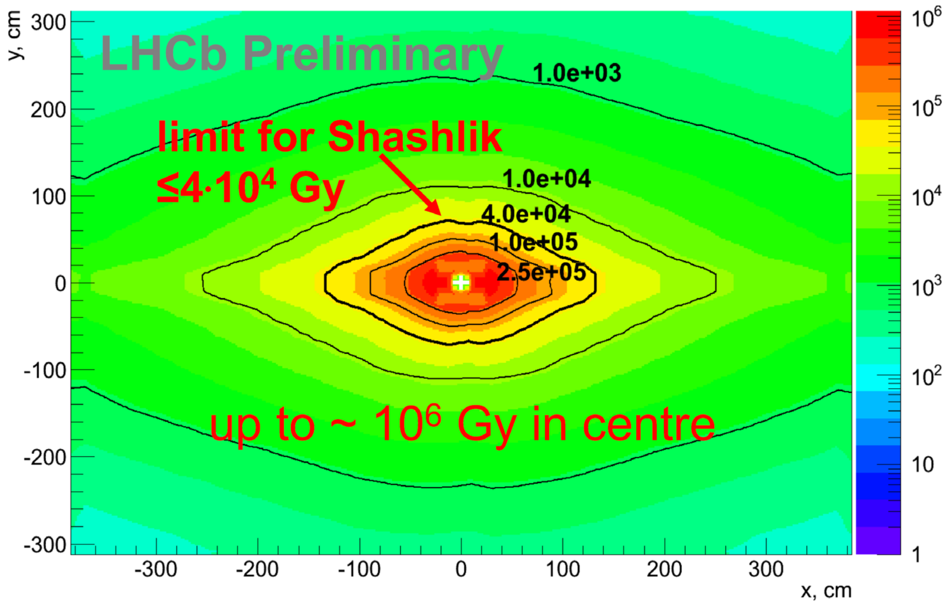
The current ECAL and motivation to upgrade

Current LHCb ECAL:

- Optimised for π^0 and γ reconstruction in the few GeV to 100 GeV region at 2×10^{32} $cm^{-2}s^{-1}$
- Shashlik technology: 4x4 / 6x6 / 12x12 cm^2 cell size
- Radiation hard up to 40 kGy
- Energy resolution: $\sigma(E) / E \approx 10\% / \sqrt{E} \oplus 1\%$
- Large array (8 x 7 m^2) with 3312 modules and 6016 channels

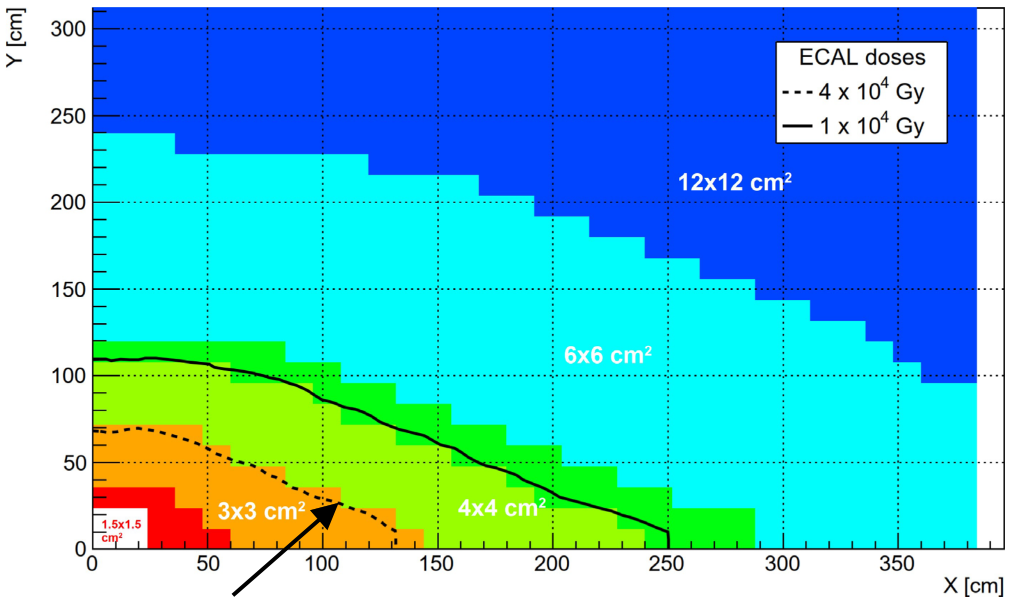
Accumulated radiation dose [Gy] after 300 fb^{-1}



Requirements for the Upgrade II: operation at L = 1-2 x 10^{34} $cm^{-2}s^{-1}$

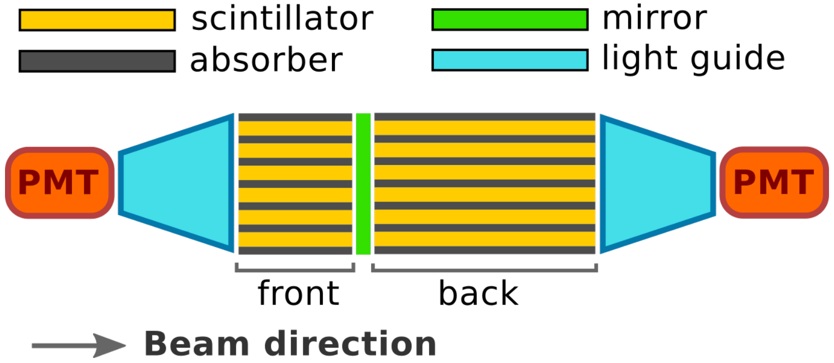
- Sustain radiation doses up to **1 MGy** and ≤ $6 \cdot 10^{15} cm^{-2}$ for 1MeV neq/cm^2 at 300 fb^{-1}
- Keep at least current energy resolution
- Pile-up mitigation crucial
  - → Timing capabilities with O(10) ps precision, preferably directly in the calorimeter modules
  - → Increased granularity in the central region with denser absorber
- Respect outer dimensions of the current modules: 12x12 cm^2

Technologies for the Upgrade II



Radiation limit of current Shashlik technology

SpaCal



SpaCal technology for inner region:

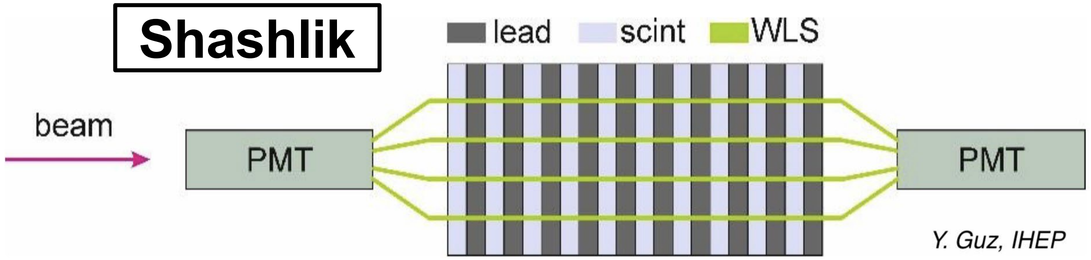
- Innermost modules with scintillating crystal fibres and W absorber
  - → Development of radiation-hard scintillating crystals
  - → 1.5x1.5 cm^2 cell size
- 40-200 kGy region with scintillating plastic fibres and Pb absorber
  - → Need radiation-tolerant organic scintillators
  - → 3x3 cm^2 cell size

Shashlik technology:

- About 3300 new Shashlik modules with improved timing capability and double-sided readout
  - → Possible cost optimization by refurbishing ≈2000 existing modules with fast new WLS fibres, adding ≈1300 new modules with required cell sizes

LS3 enhancement:

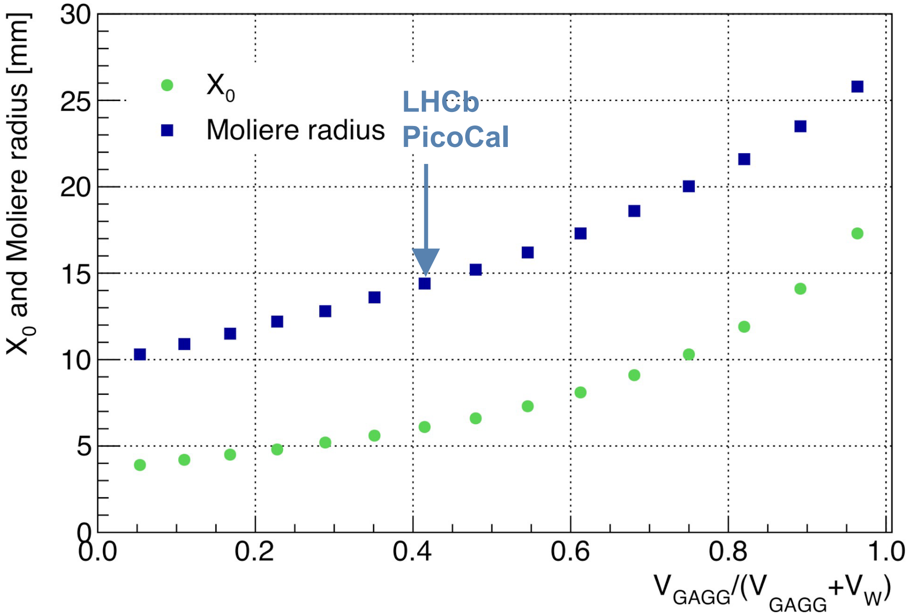
- SpaCal with W absorber for innermost modules equipped with scintillating plastic fibres for 2x2 cm^2 cell size, single-sided readout
- All SpaCal modules titled by 3°+3°

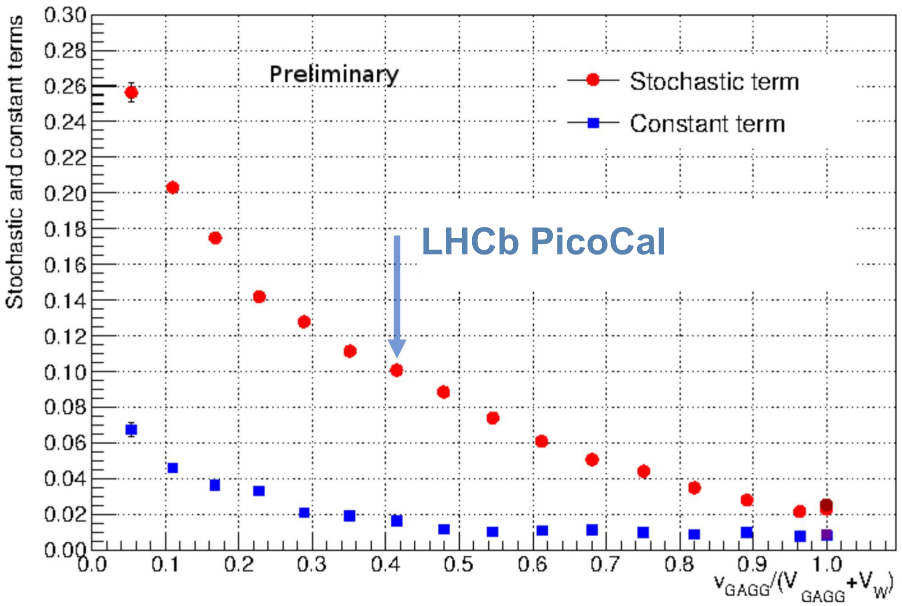


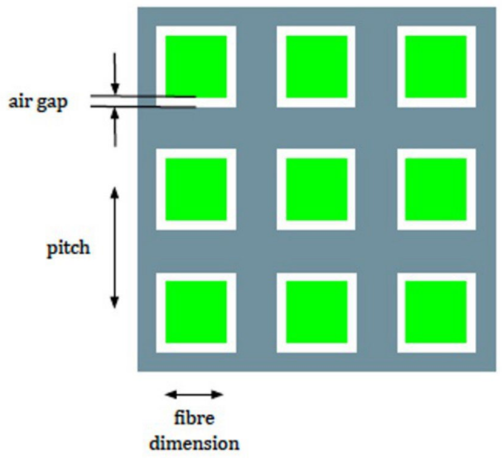
LHCb-TDR-023

SpaCal: tuning of X_0, R_M and energy resolution

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







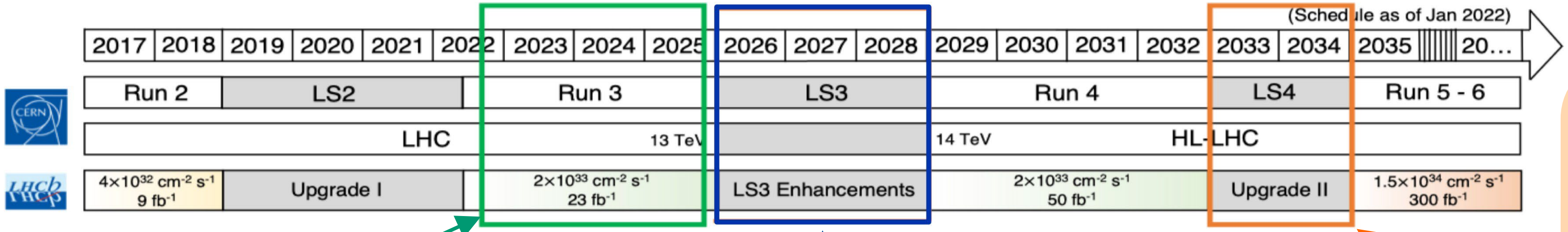
GAGG fibers/W absorber

- 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, ...

Talk by Loris Martinazzoli:
R&D of GAGG single crystals for fast timing detectors in high rate and radiation environments

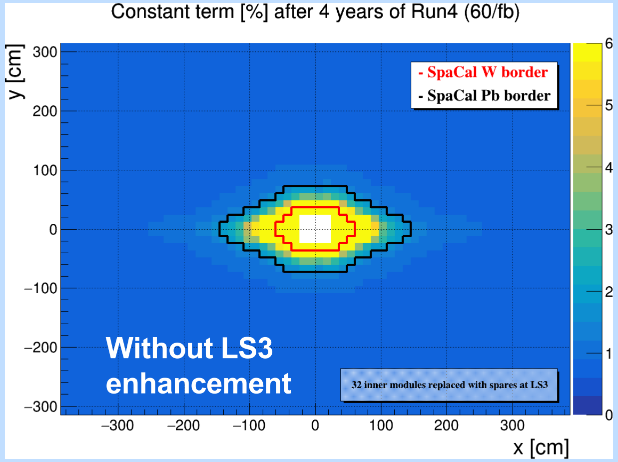
LHCb ECAL upgrade strategy

LHCb-TDR-023, LHCb-TDR-024



Run 3 in 2022-2025:

- Run with unmodified ECAL Shashlik modules at $L = 2 \times 10^{33}\ cm^{-2}s^{-1}$ (new 40 MHz readout)

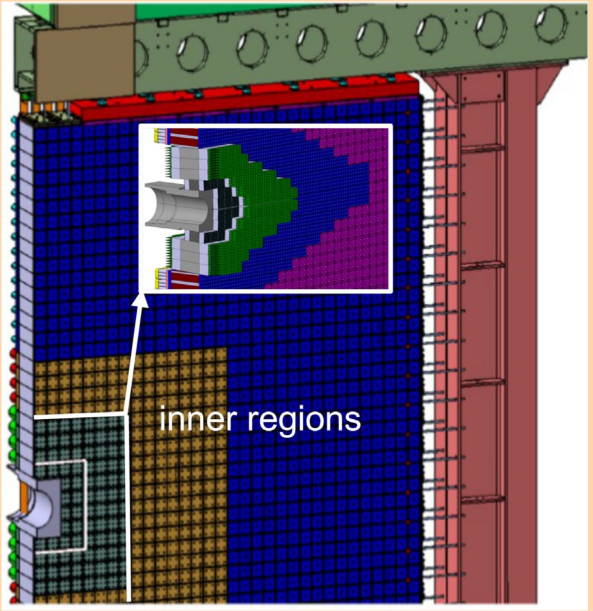


LS3 enhancement in 2026-2028:

- 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 $L = 2(4) \times 10^{33}\ cm^{-2}s^{-1}$
  - → **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:

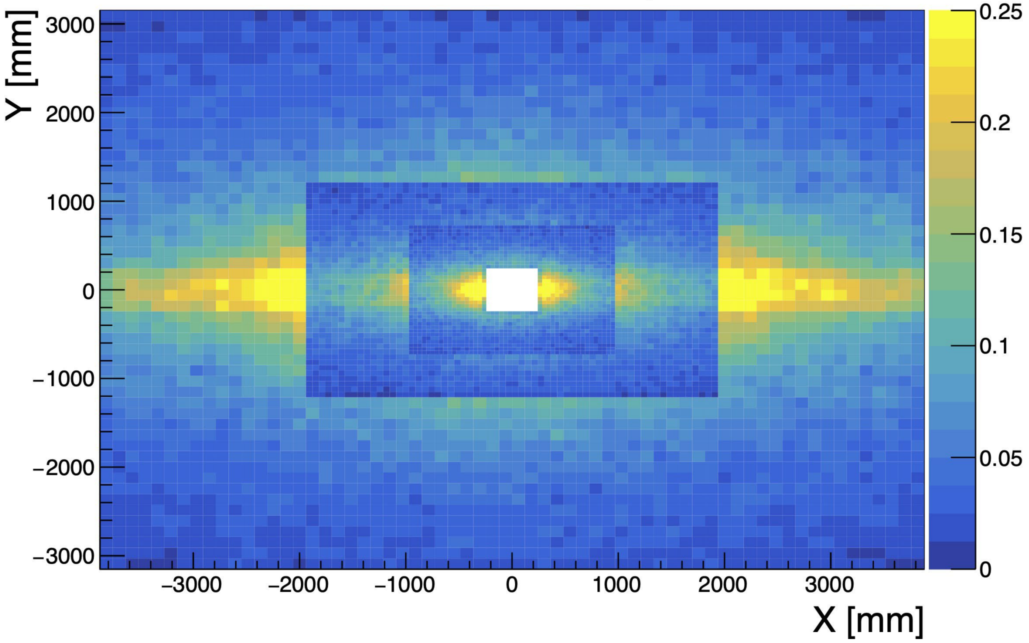
- Introduce double-section radiation hard SpaCal (1.5x1.5 & 3x3 cm^2 cells) and improve timing of Shashlik modules for a luminosity of up to $L = 1.5 \times 10^{34}\ cm^{-2}s^{-1}$
  - → Innermost SpaCal-W modules equipped with **crystal fibres**
  - → Include **timing** information and double-sided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



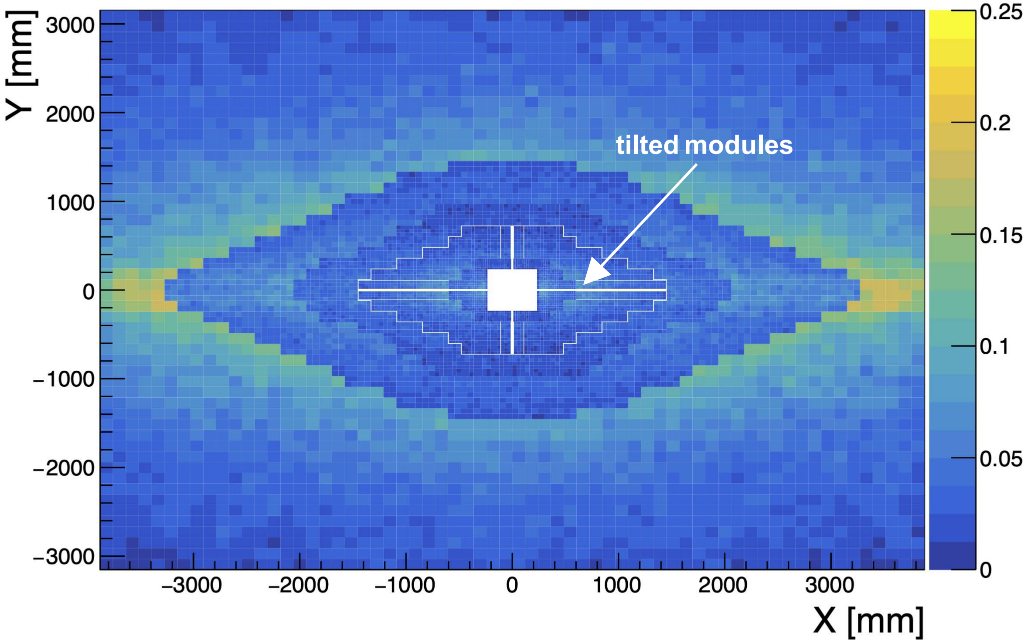
LS3: impact of improved granularity

- 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 and “module 0”
- SpaCal-W with polystyrene fibres for LS3

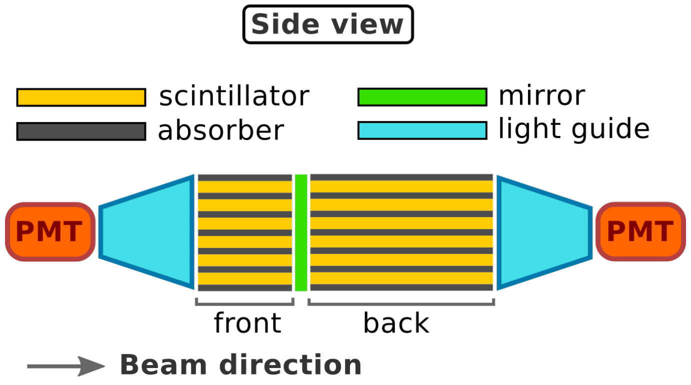
SpaCal with lead absorber

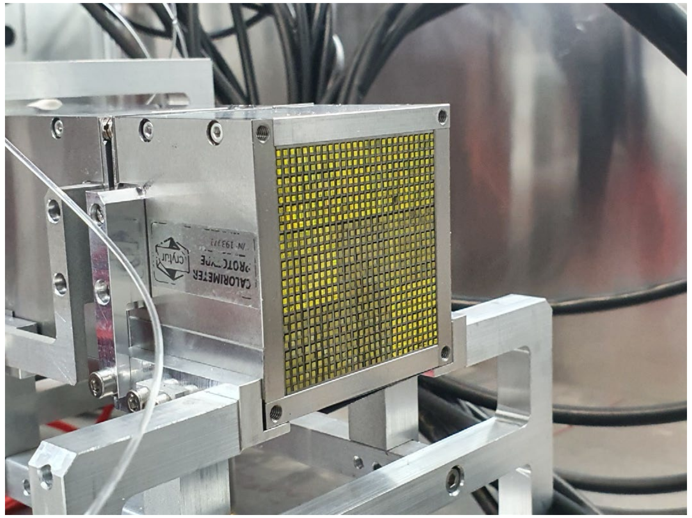
Shashlik with fast WLS fibres

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



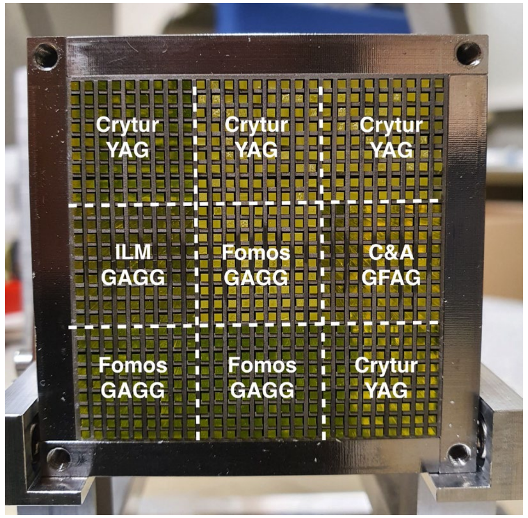


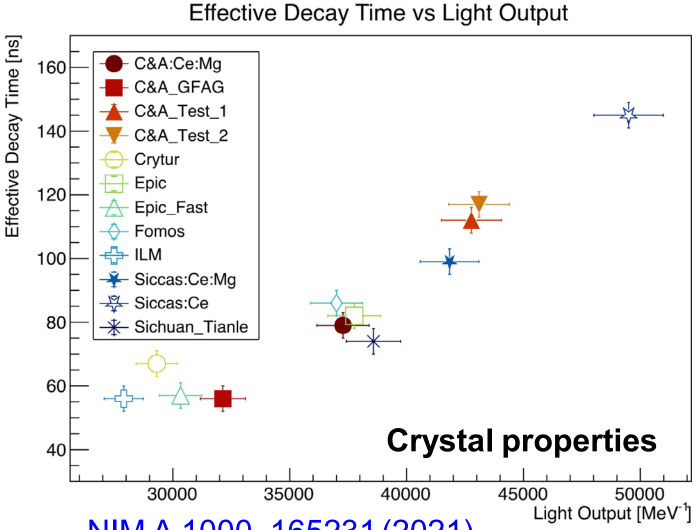
Crystal garnets from several producers:

- Crytur - YAG
- Fomos - GAGG
- ILM - GAGG
- C&A - GFAG

→ Characterised with laboratory measurements

Configuration used at DESY in 2020 and 2021





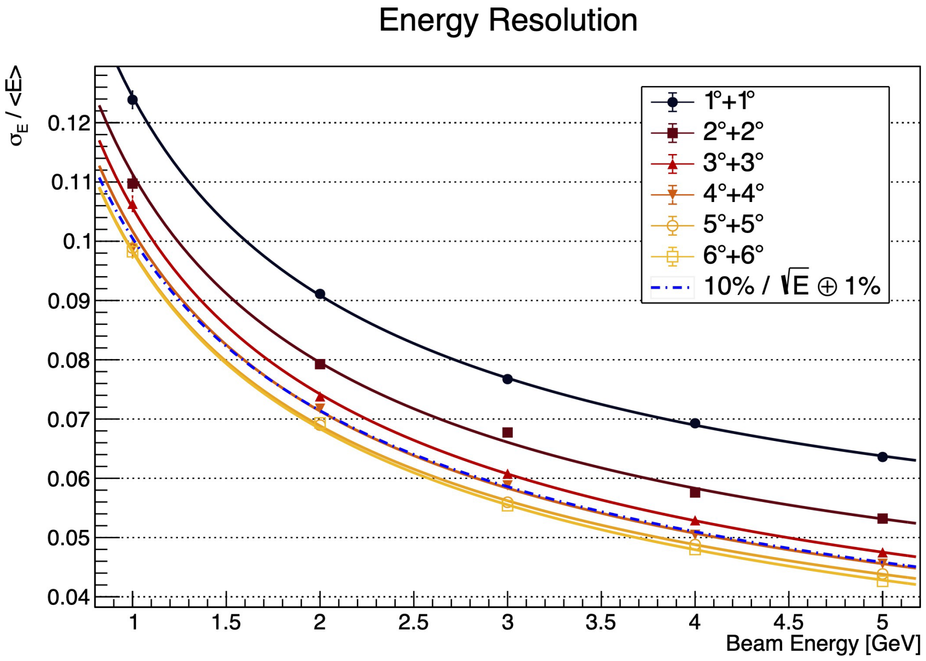
NIM A 1000, 165231 (2021)

Photon detectors used:

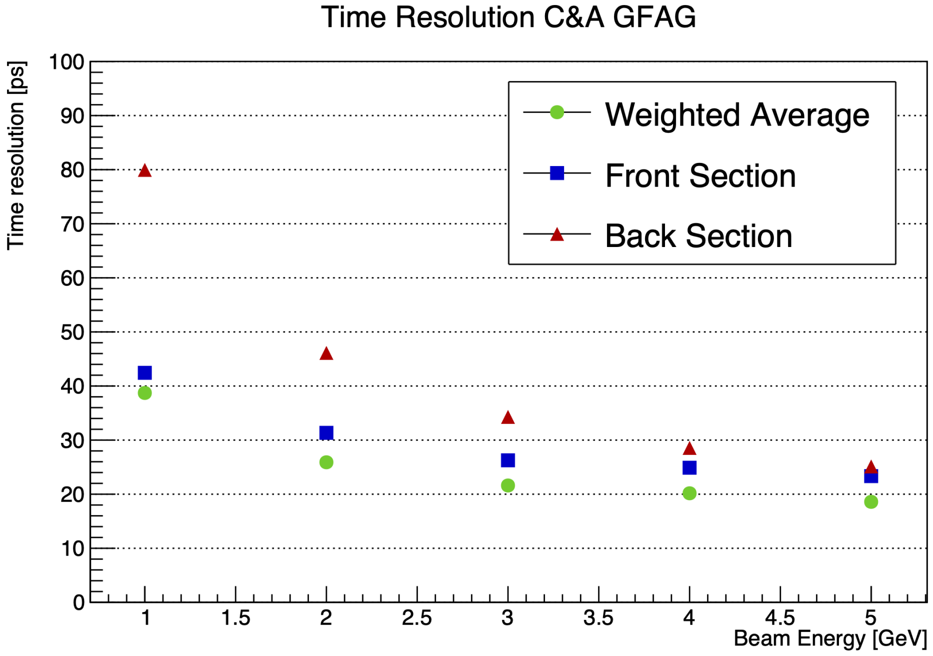
- Hamamatsu R12421 for energy resolution
- Hamamatsu R7600U-20 metal channel dynode (MCD) PMT for better time resolution

SpaCal-W with crystal fibres: test beam results

Energy resolution (DESY 2020, R12421)



Time resolution (DESY 2021, R7600U-20)



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

- 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):

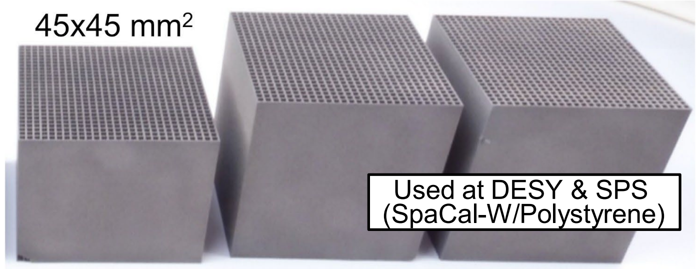
→ First 1.5x1.5 cm^2 cells with up to 10 cm length

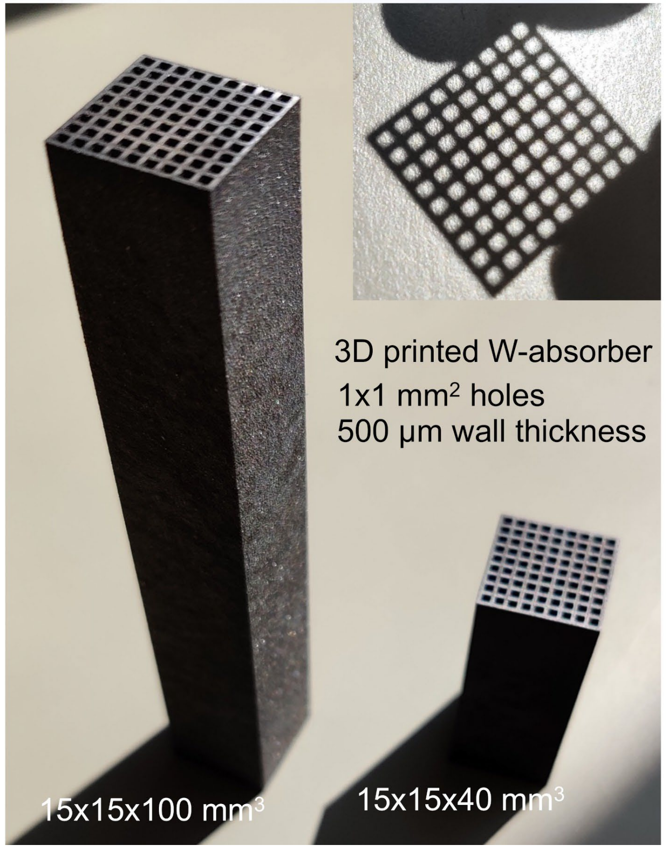
→ Then 4.5x4.5 cm^2 pieces

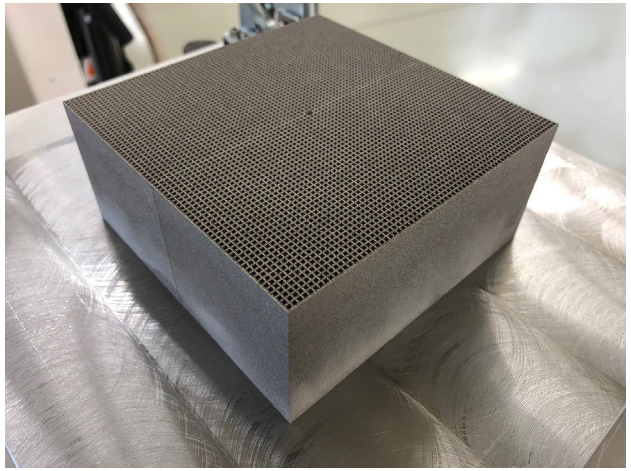
→ Recently 12.1x12.1 cm^2 pieces produced and used for "module 0"

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

→ Two 12.1x12.1 cm^2 pieces in 2023



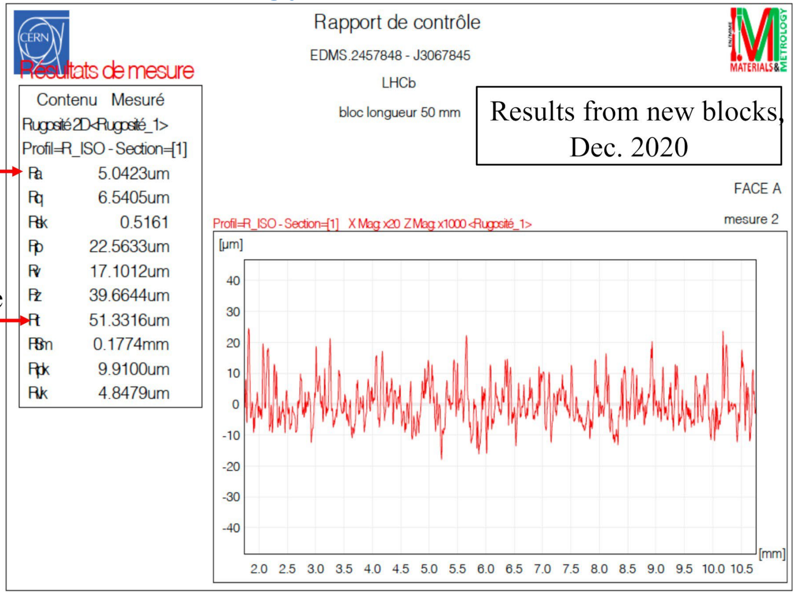




Mean roughness

Total height of profile

= distance (max-min)


Rapport de contrôle
Résultats de mesure
EDMS 2457848 - J3067845
LHCb
bloc longueur 50 mm

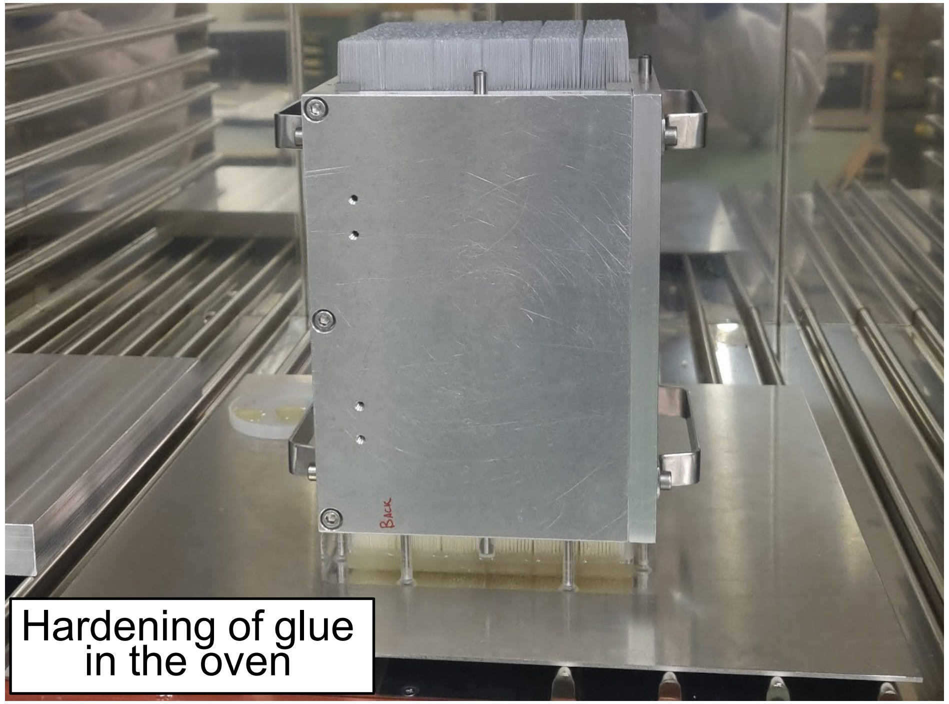
Contenu	Mesuré
Rugosité 2D<Rugosité_1>	
Profil=R_ISO - Section=[1]	
Ra	5.0423um
Rq	6.5405um
Rsk	0.5161
Rp	22.5633um
Rv	17.1012um
Rz	39.6644um
Rt	51.3316um
RSm	0.1774mm
Rpk	9.9100um
Rvk	4.8479um

Results from new blocks, Dec. 2020

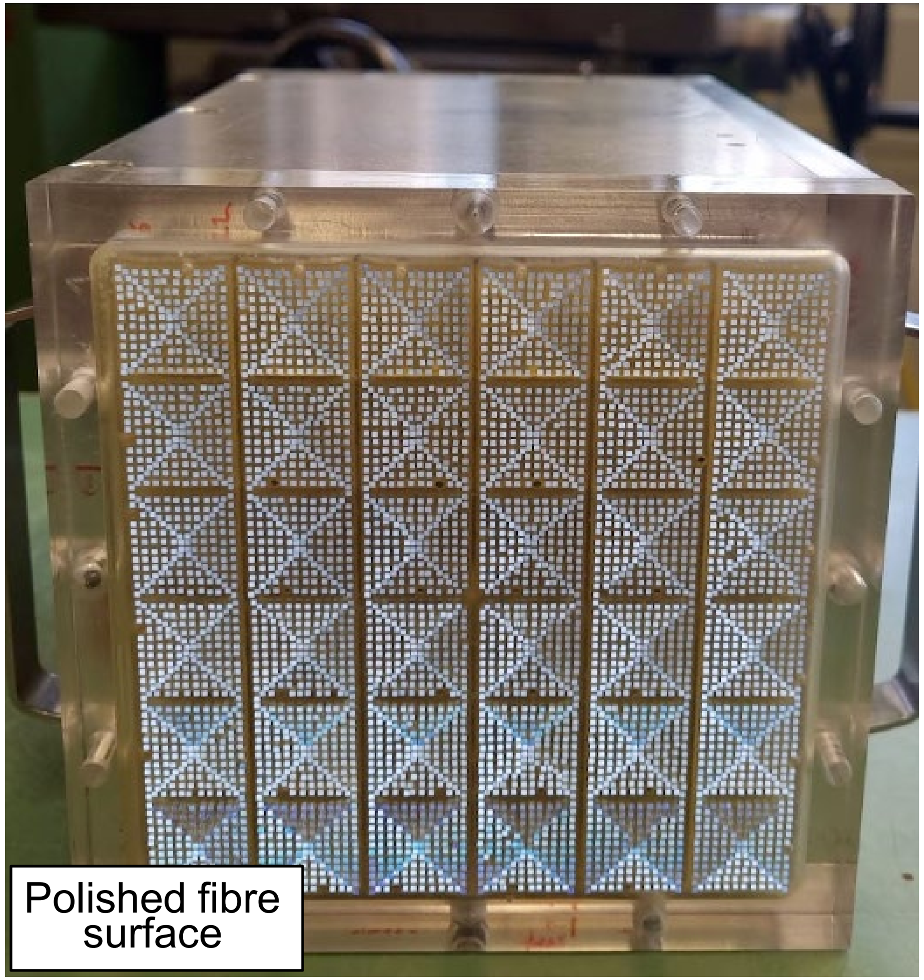
"Module 0" with tungsten absorber (1)

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 quartz fibre for calibration



Hardening of glue in the oven

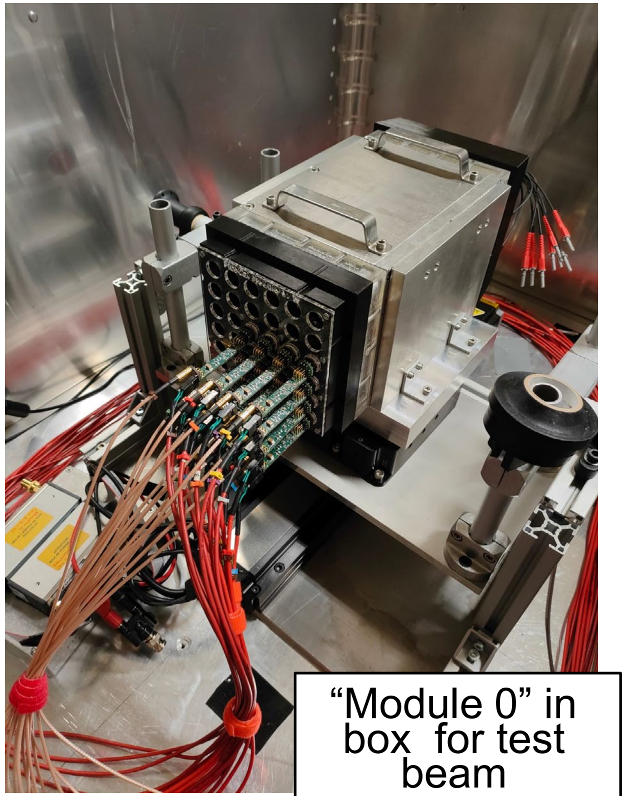


Polished fibre surface

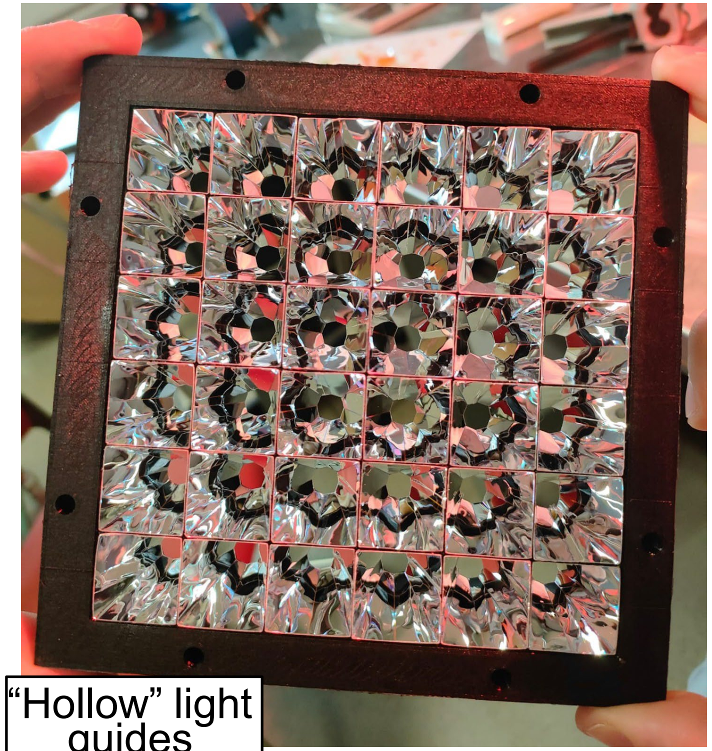
"Module 0" with tungsten absorber (2)

Full-size "module 0" with tungsten absorber assembled at CERN:

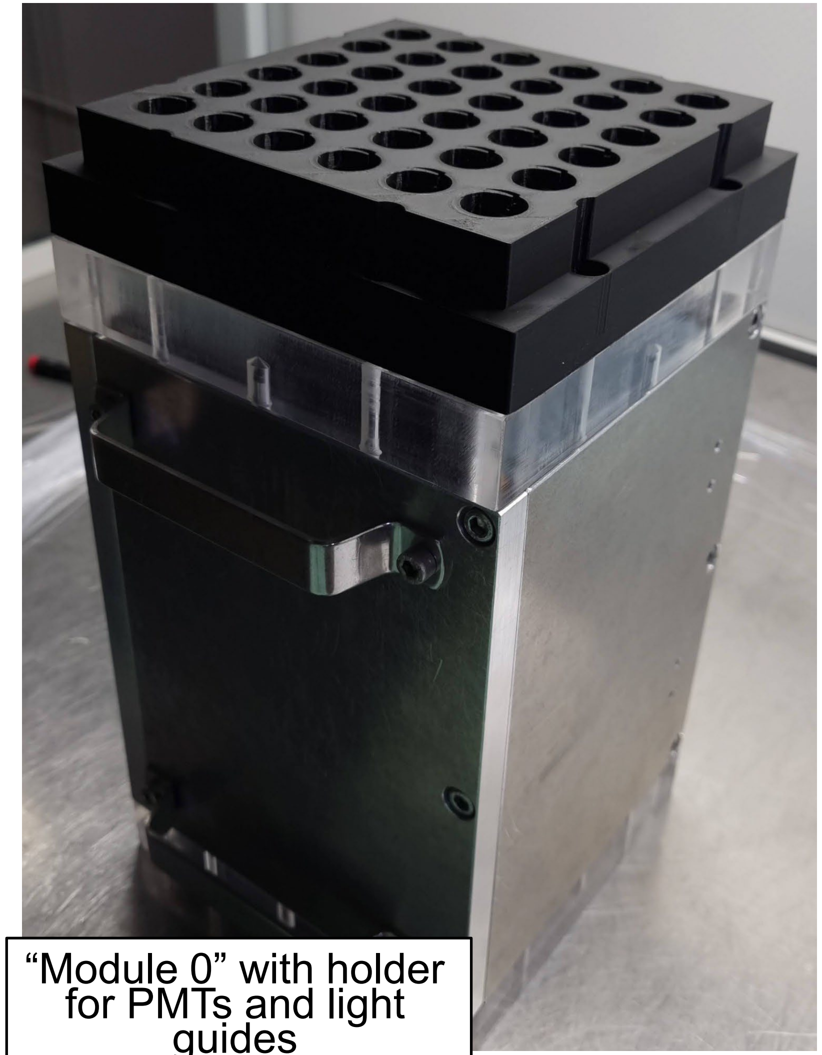
- Radiation-hard "hollow" light guides imbedded in PMT holder
- Extensive test beam characterization performed at DESY (May 2023) and CERN (June & August September 2023)



"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:

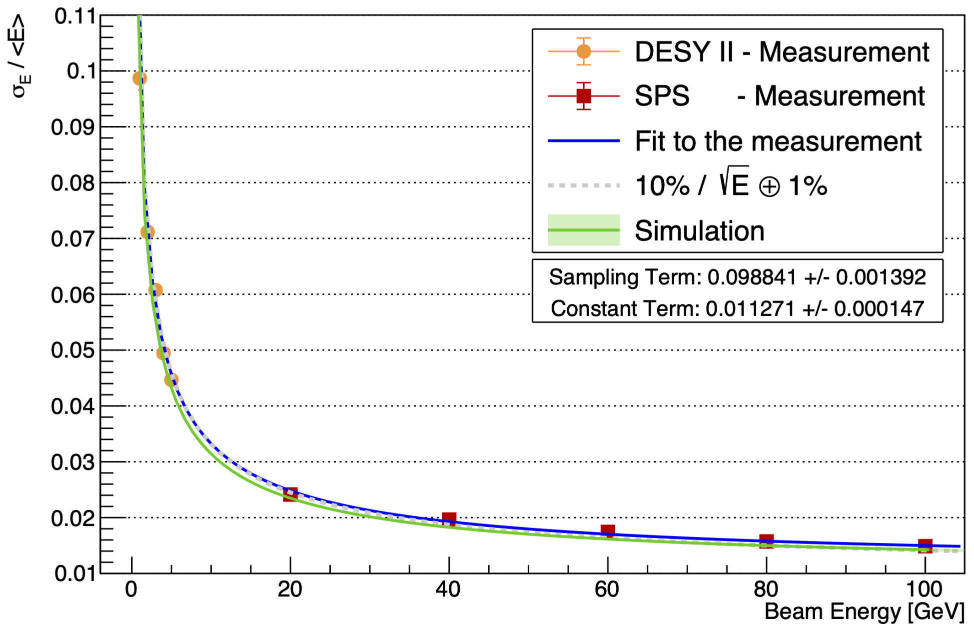
- SpaCal-W with crystal fibres for LS4
- 3D printing of absorber and “module 0”
- SpaCal-W with polystyrene fibres for LS3

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)

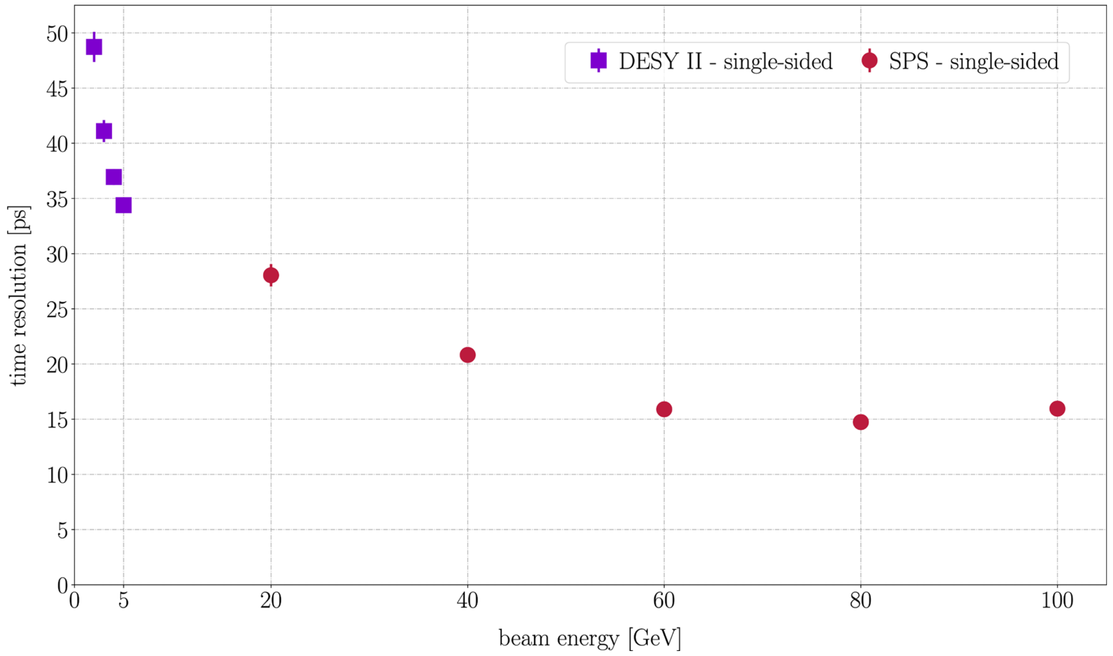


- Incidence angles: $\theta_X = \theta_Y = 3°$, single-sided readout
- "Module 0" prototype
- Noise contribution subtracted
- Sampling term: 9.9%, constant term: 1.1%

→ Very good agreement with simulation

Talk by Marco Pizzichemi: The HybridMC: a fast detailed Monte-Carlo framework for the LHCb electromagnetic calorimeter upgrade

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:

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

SpaCal with lead absorber

Shashlik with fast WLS fibres

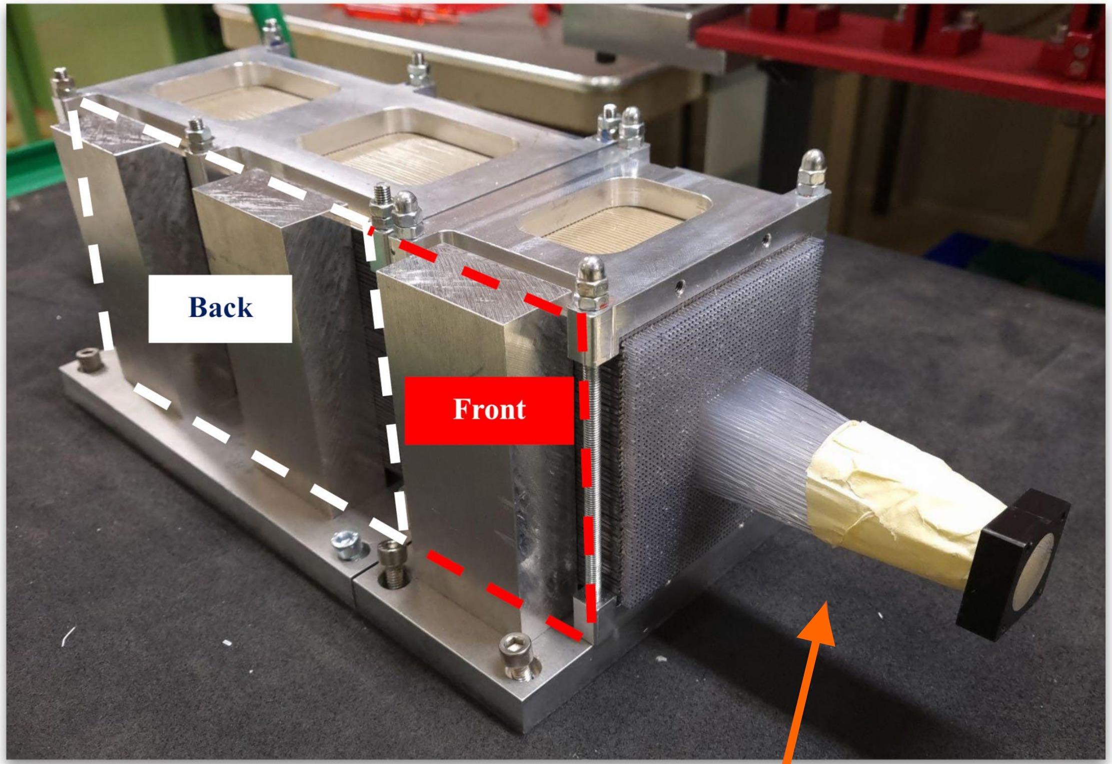
SpaCal-Pb: prototype with polystyrene fibres

- 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:

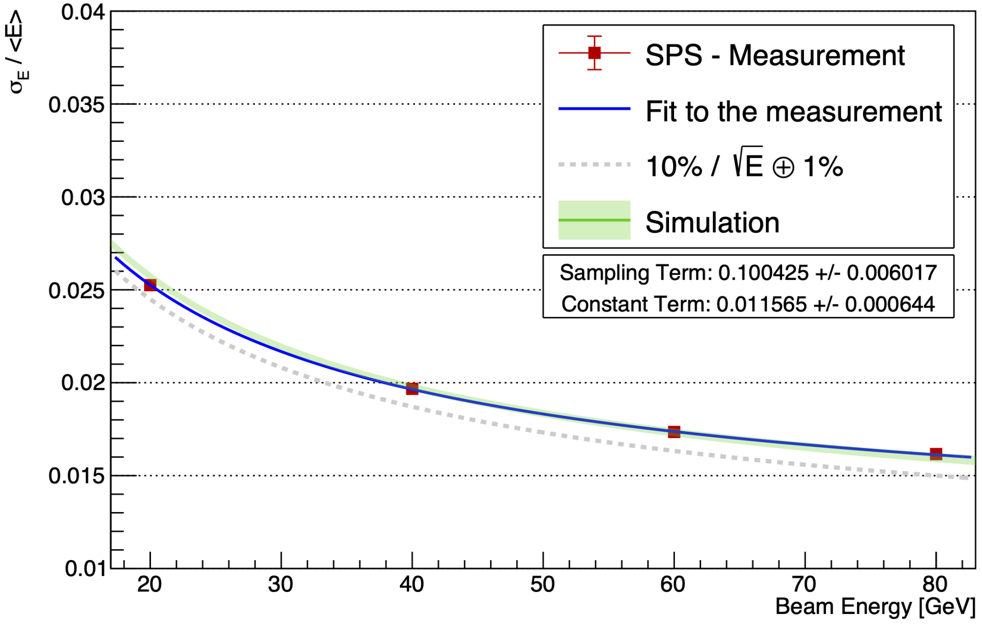
- Direct contact of MCD PMT with the scintillating fibres
- PMMA light guides
- Bundle of fibres coupled directly to MCD PMT



Fibres bundle
(1 cell)

SpaCal-Pb with polystyrene fibres: test beam results

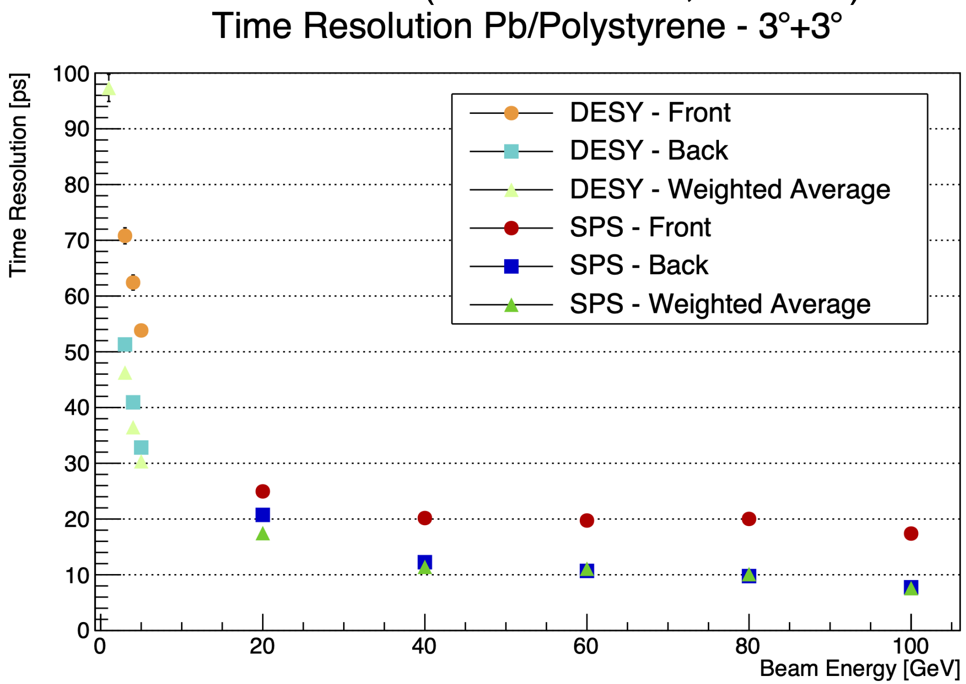
Energy resolution (CERN SPS)



- 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 than 20 ps

LHCb-TDR-024

Outline: R&D and test beam results

SpaCal with tungsten absorber:

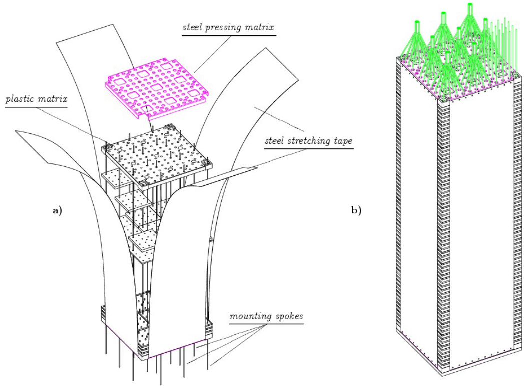
- SpaCal-W with crystal fibres for LS4
- 3D printing of absorber and “module 0”
- SpaCal-W with polystyrene fibres for LS3

SpaCal with lead absorber

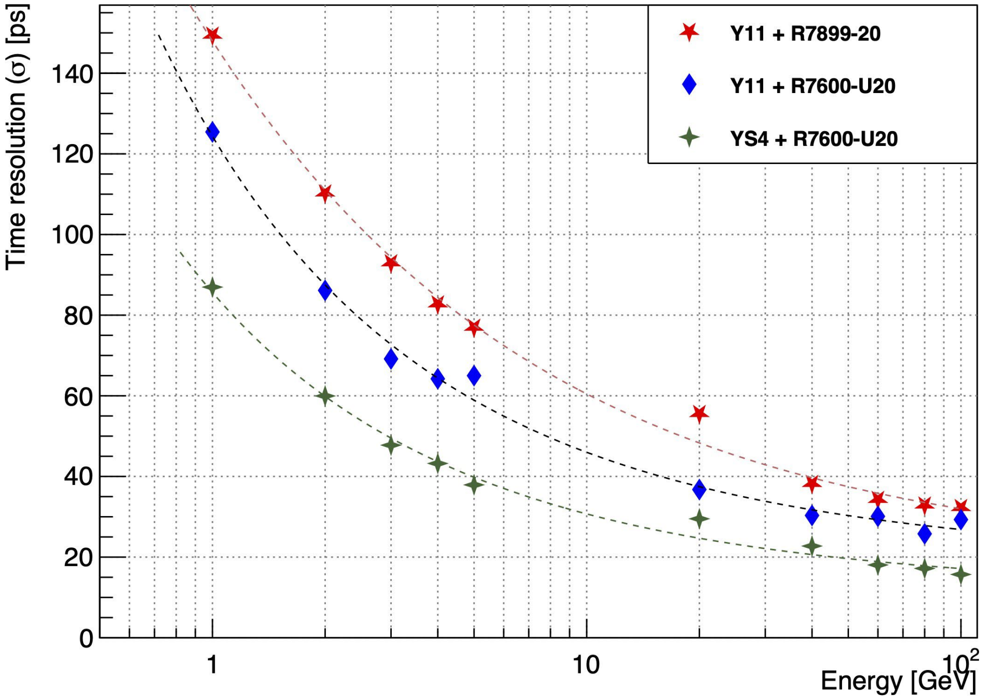
Shashlik with fast WLS fibres

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 & SPS)



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

LHCb-TDR-024

Summary and conclusions

PicoCal

- 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

- 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

- 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

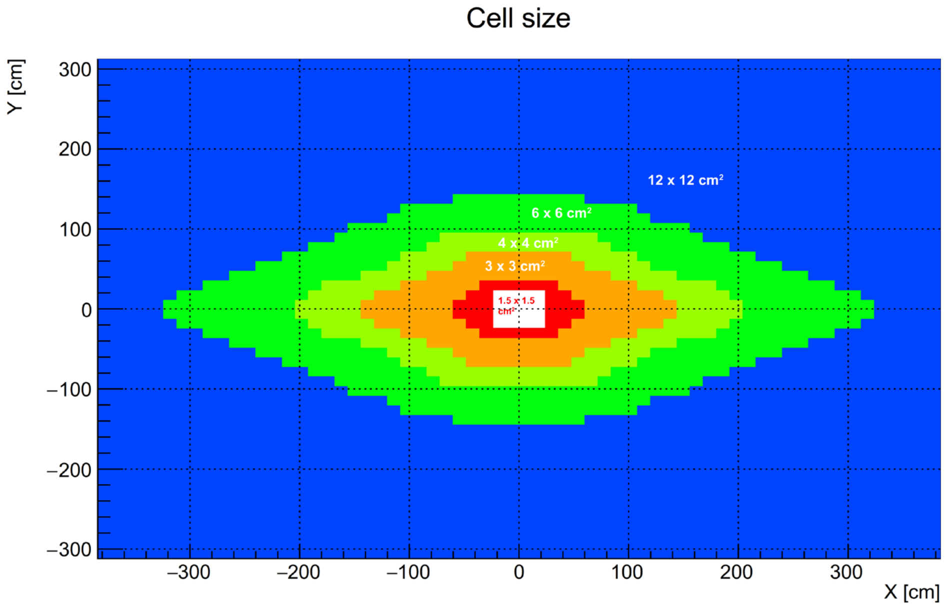
→ Study of suitable PMTs and development of readout electronics

→ Investigation of new radiation-hard and fast scintillators

Thank you!

Backup slides

Reminder: LS3 configuration



No longitudinal segmentation

Cell size:	Modules:
2 x 2 cm²	32 *new* SpaCal-W modules
3 x 3 cm²	144 *new* SpaCal-Pb modules
4 x 4 cm²	176 existing modules in rhombic configuration
6 x 6 cm²	448 existing modules in rhombic configuration
12 x 12 cm²	2’512 existing modules in rhombic configuration

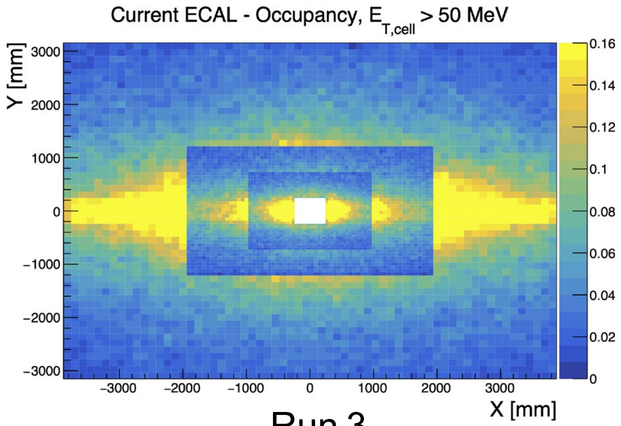
- 9’344 cells (compared to 6’064 in current ECAL)
- Modules tilted in the SpaCal region
- Existing modules will be rearranged

(4x4 cm² Shashlik modules moved out to avoid too much radiation damage, WLS fibres could be easily replaced)

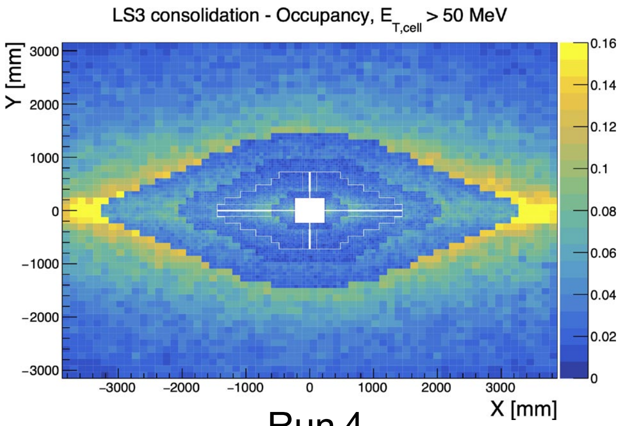
- Timing will be implemented for SpaCal region

→ requires new electronics for ≈ 3’300 cells

Occupancy at L = 2 x 10^{33} $cm^{-2}s^{-1}$



Run 3



Run 4