Scintillating sampling ECAL technology for the Upgrade II of LHCb

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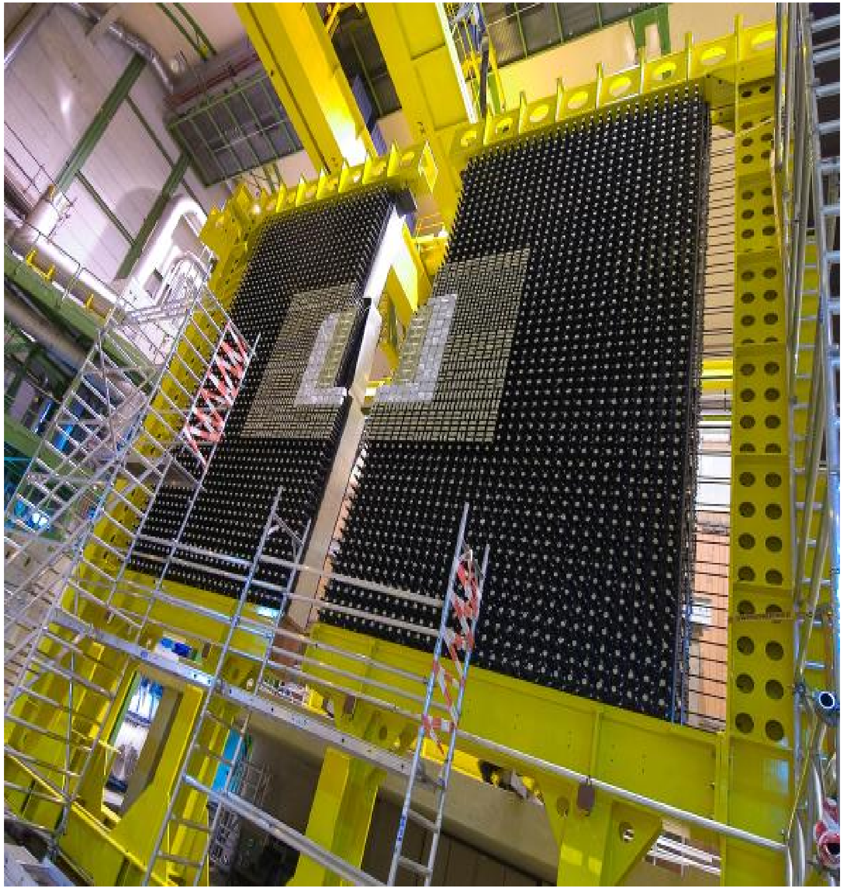
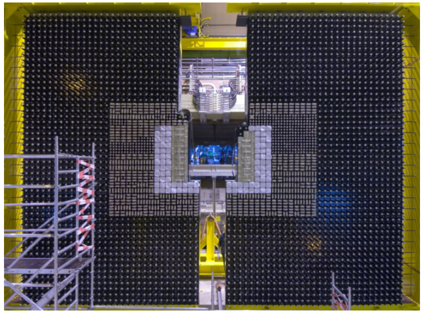
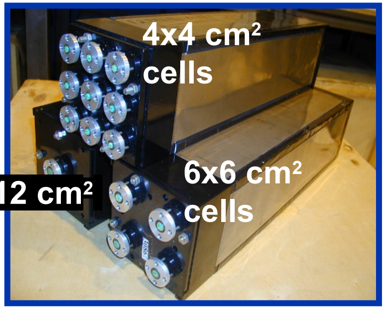


Motivation for the Upgrade II of the LHCb ECAL

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

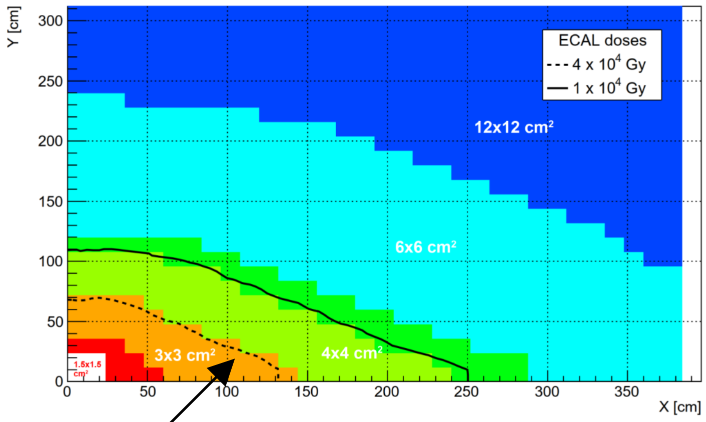




Requirements for the Upgrade II (to be installed during LS4): operation at L = 1-2 x 10^{34} $cm^{-2}s^{-1}$
• Sustain radiation doses up to 1 MGy and ≤ 6 x 10^{15} 1 MeV neq / cm^2 in the centre for 300 fb^{-1}
• Keep at least current energy resolution
• Pile-up mitigation crucial
→ Timing capabilities with O(10) ps precision, preferably directly in the calorimeter modules
→ Increased granularity in the central region with denser absorber
• Respect the outer dimensions of 12x12 cm^2 to reuse existing modules

Opportunity for some consolidation already during LS3

R&D strategy for the ECAL Upgrade II



Radiation limit of current Shashlik technology

SPACAL technology for inner region:

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

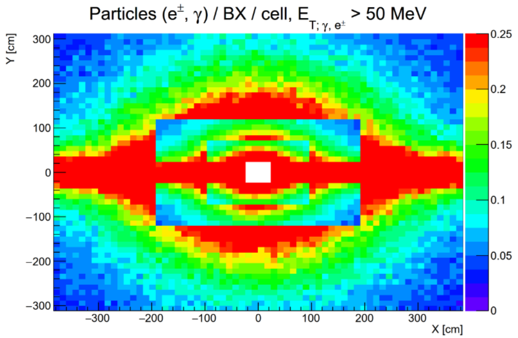
Shashlik technology:

- 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

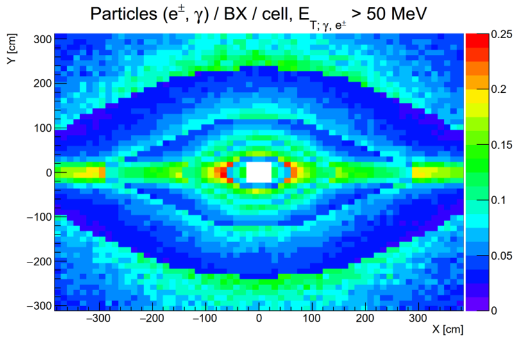
Comparison of current and Upgrade II calorimeter layouts at L = 1.5 x 10^{34} $cm^{-2}s^{-1}$

- Occupancies manageable in Upgrade II conditions
- Further pile-up mitigation from timing

Current ECAL

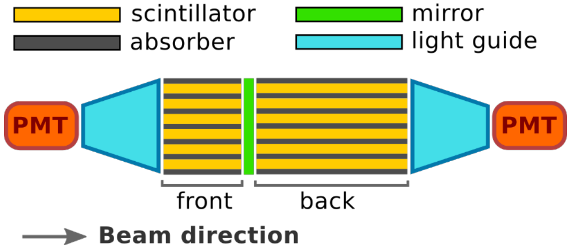


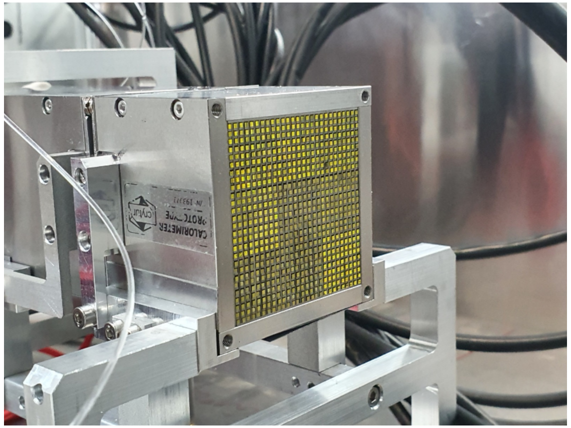
Upgrade II configuration



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

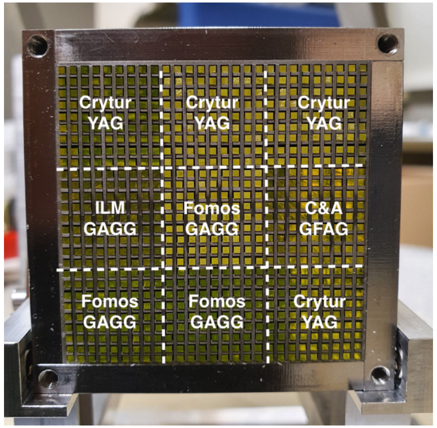
→ Characterised with laboratory measurements

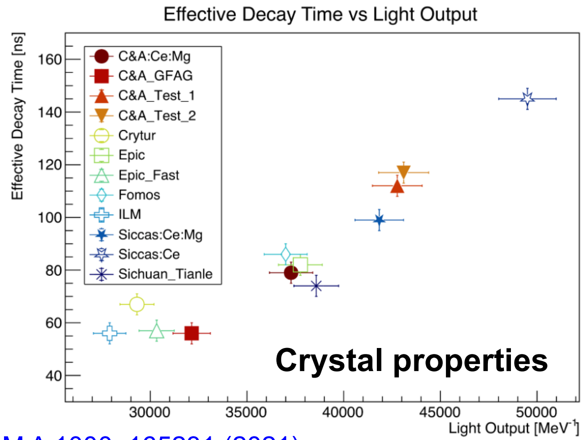
Photon detectors used in recent test beams:
- Hamamatsu R12421 for energy resolution
- Hamamatsu R7600U-20 metal channel dynode (MCD) PMT for timing due to better time resolution

Further tests performed:
- Optical coupling with 3M foil instead of dry air
- 12 m long (instead of 3 m) analog cables between sensor and front-end electronics

→ not discussed in this presentation

Configuration used at DESY in 2020 and 2021





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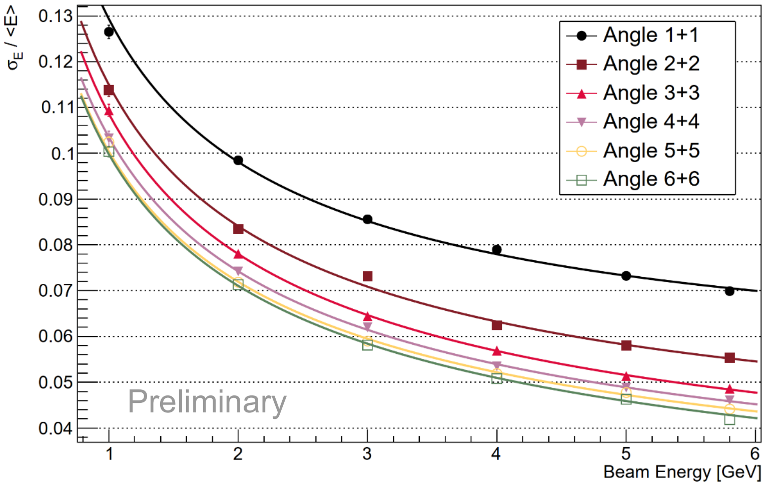
SPACAL-W with crystal fibres: test beam results

Energy resolution (DESY 2020, R12421)

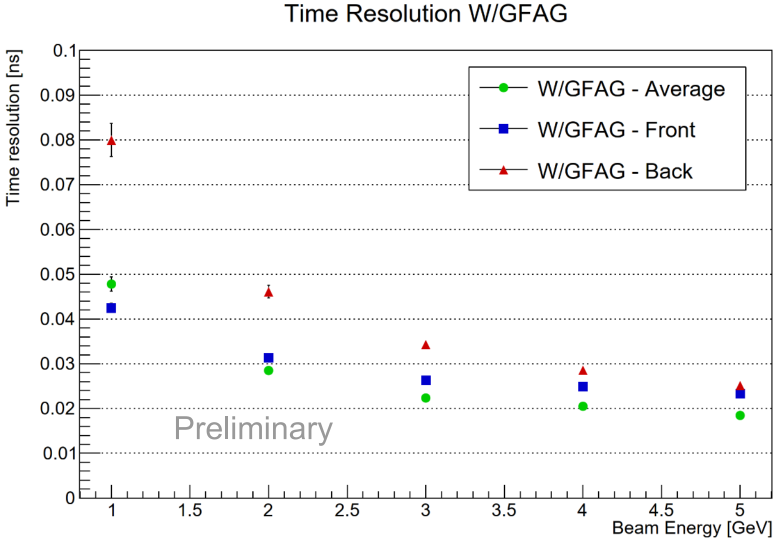


- Better energy resolution with larger incidence angles
- Preliminary analysis of data up to 5.8 GeV gives

10.6% sampling term and 1.9 ± 0.5% constant term for $\theta_X = \theta_Y = 3°$

→ Precision measurement of constant term and better calibration from ongoing test beam at CERN SPS

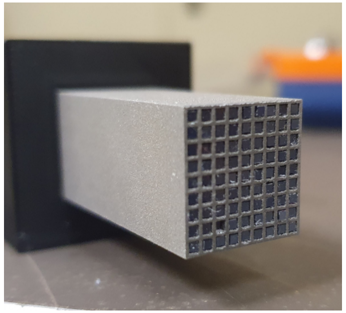
Time resolution (DESY 2021, R7600U-20)

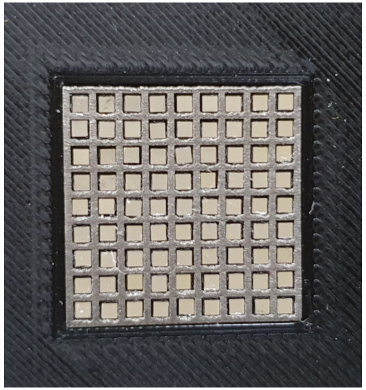


- Incidence angles: $\theta_X = \theta_Y = 3°$
- Time stamps in front and back obtained using constant fraction discrimination (CFD)
- Time resolution at 5 GeV for GFAG: 18 ps

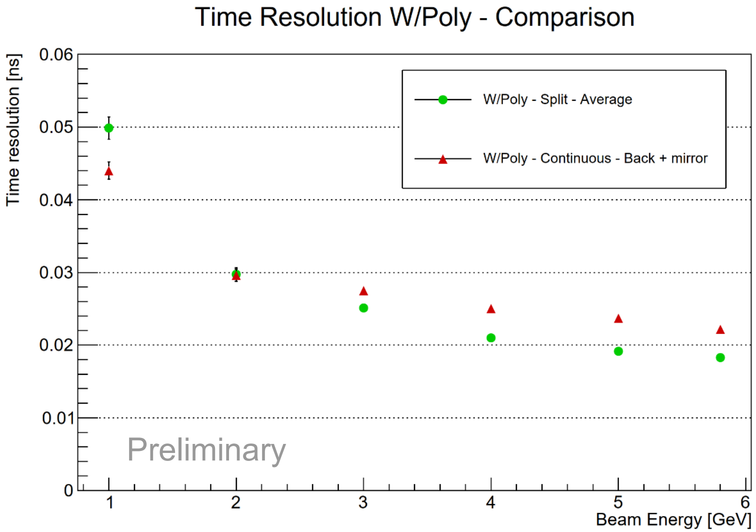
SPACAL-W with organic scintillator fibres

SPACAL prototype module with W absorber and polystyrene fibres:
- Candidate for consolidation of the innermost region during LS3
- 3D-printed pure tungsten absorber
- 1 cell of 1.5x1.5 cm^2 ($R_M \approx 1.8$ cm)
- 5+14 cm long (7+18 X_0)
- Reflective mirror between sections





Time resolution (DESY 2021, R7600U-20)



Incidence angles: $\theta_X = \theta_Y = 3°$

Two configurations tested:
- Split fibres (5+14 cm) with double readout in front and back

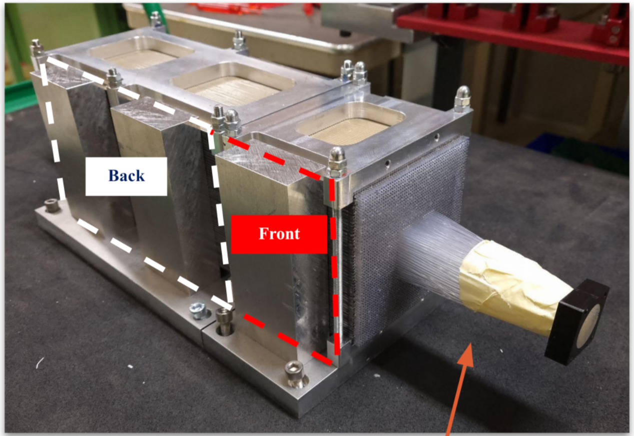
→ 19 ps time resolutions at 5 GeV
- Continuous fibres (19 cm) with single readout at the back and reflective mirror at the front

→ Only somewhat worse above 3 GeV, 24 ps at 5 GeV

SPACAL-Pb with organic scintillator fibres

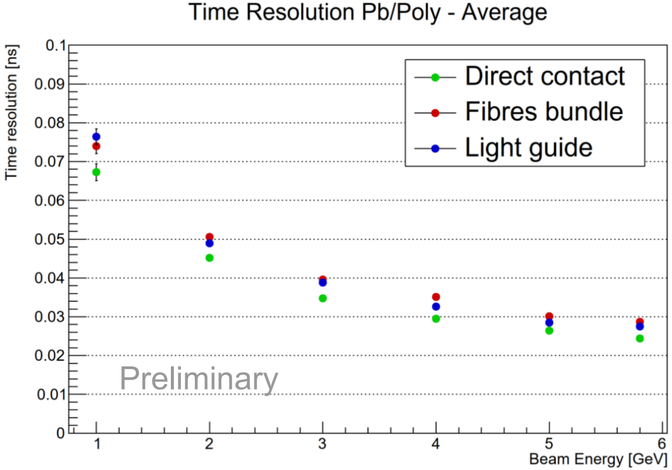
SPACAL prototype module with Pb absorber and polystyrene fibres:
- 9 cells of 3x3 cm^2 ($R_M \approx 3$ cm)
- 8+21 cm long (7+18 X_0)
- Reflective mirror between sections

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



Fibres bundle (1 cell)

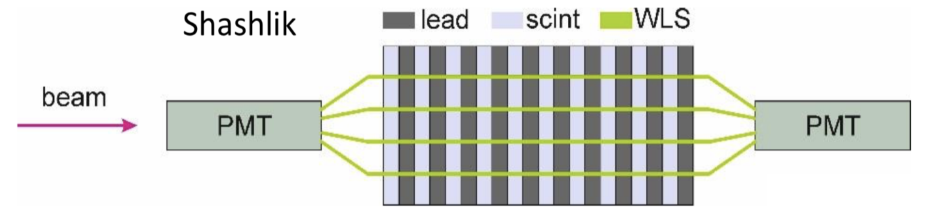
Time resolution (DESY 2021, R7600U-20)



- Incidence angles: $\theta_X = \theta_Y = 3°$
- Time stamps in front and back obtained using constant fraction discrimination (CFD)
- Only part of cell read out in direct contact due to smaller active area of PMT (1.8x1.8 cm^2) → room for improvement
- Time resolution at 5 GeV: 26 ps

Shashlik: R&D towards Upgrade II

Shashlik modules: 4 mm thick scintillating tiles and 2 mm thick lead absorber tiles with wavelength shifting (WLS) fibres

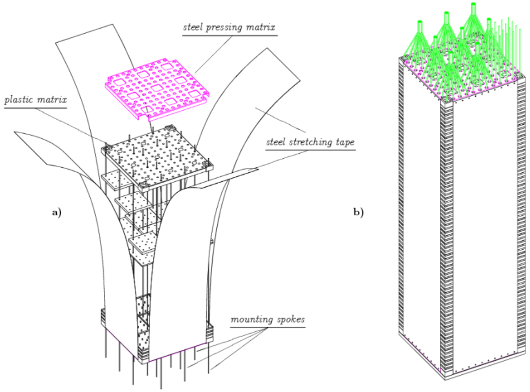


Radiation hardness limit is 40-50 kRad
→ suitable for periphery of ECAL (≈ 80-90% of area)

R&D towards better time resolution for Upgrade II:

- Double-sided readout with continuous or split fibres (to mitigate effect of longitudinal shower fluctuations)
- Usage of better PMTs with smaller transit time spread and transit time distribution on photocathode
- WLS fibres with shorter decay time. Tests at DESY in 2021:

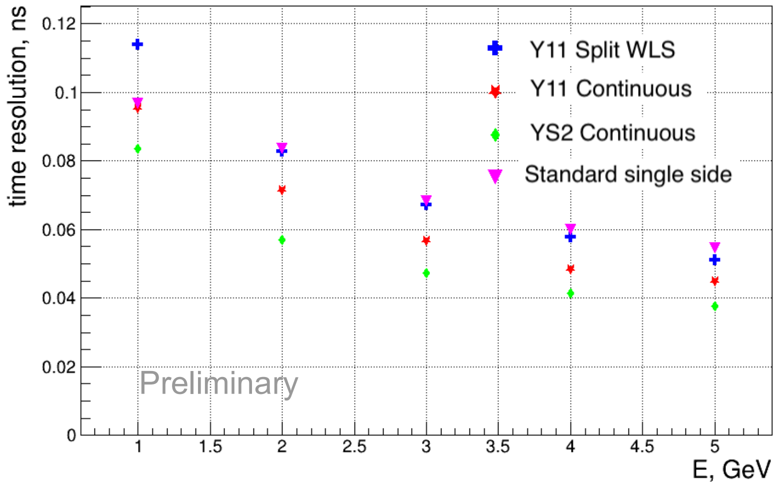
- Y11, 1.2 mm diameter (7 ns decay time) → current LHCb
- YS2, 1.0 mm diameter (3 ns decay time) → faster



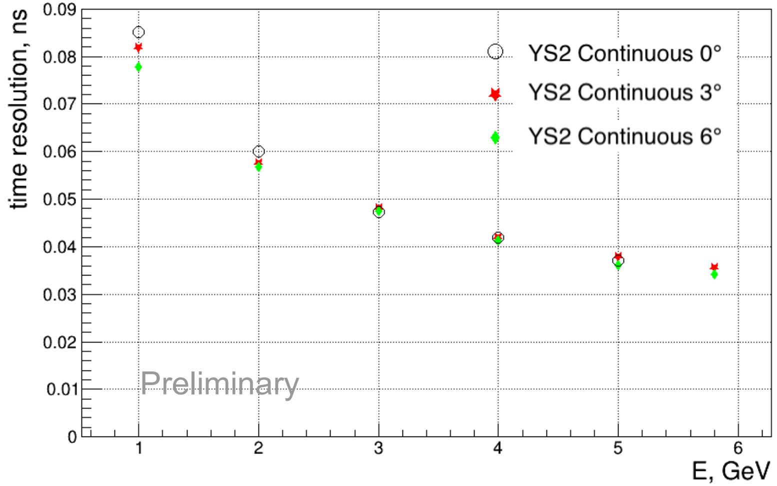
- R&D ongoing with KURARAY on faster WLS fibres, many thanks for providing preproduction samples

Shashlik: test beam results

Time resolution (DESY 2021, R7600U-20)



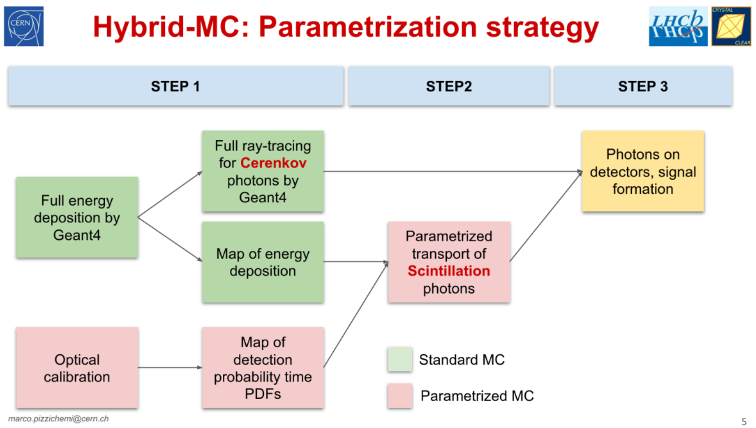
Time resolution (DESY 2021, R7600U-20)



- YS2 fibres provide significantly better time resolutions
- Continuous fibres better than split fibres
- Time resolution at 5 GeV for YS2: better than 40 ps

- No impact of incidence angle on time resolution

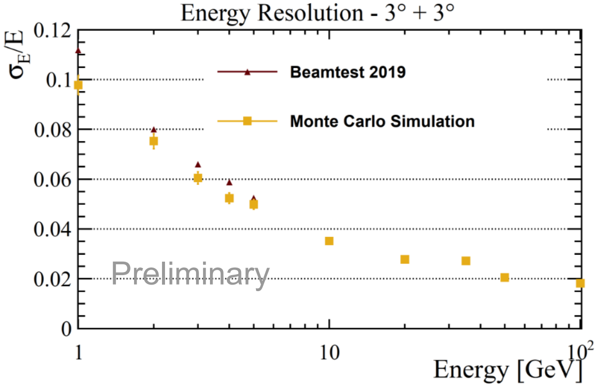
Detailed Monte Carlo simulations of SPACAL and Shashlik technology



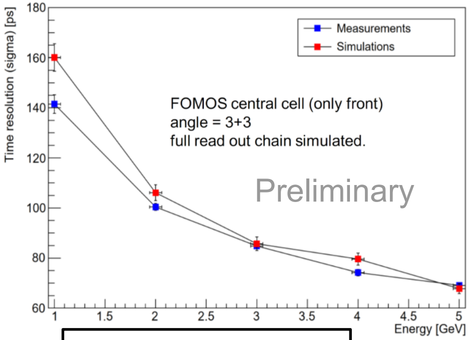
- Geant4 simulation of energy deposit and parametrised transport for scintillation photons
  → Gain in computation time by factor 1000
- Particle flux from full LHCb simulation can be included
- Different module types (SPACAL-W, SPACAL-Pb, Shashlik)
- Parametrised response of photon detector (e.g. PMT)

- Simulation validated with test beam data for SPACAL-W up to 5 GeV
  → Comparison for SPACAL-Pb in progress
- Ongoing test beam at CERN
  → Access to much higher energies

SPACAL-W: energy resolution



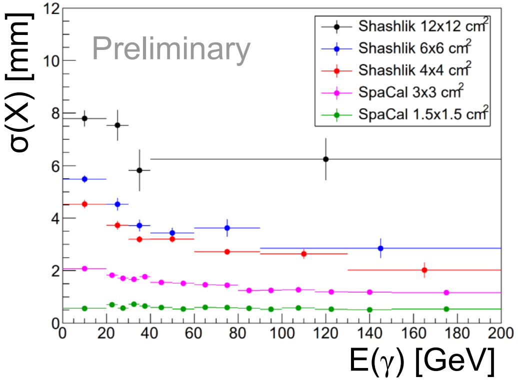
SPACAL-W: time resolution



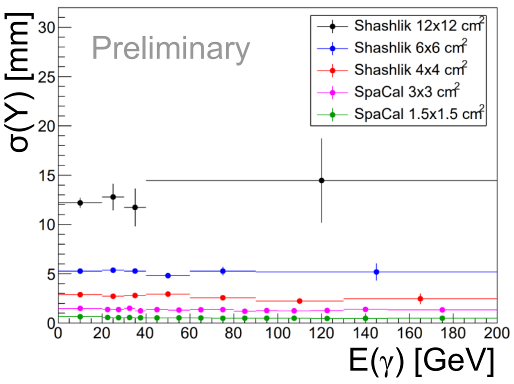
Different PMT compared to results shown previously

Position resolution and timing for pile-up mitigation

Position resolution - X



Position resolution - Y



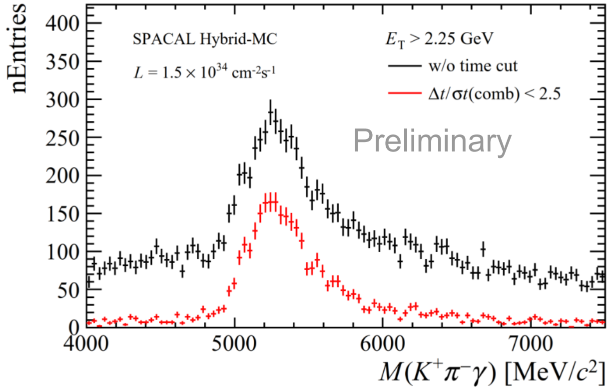
Example: photon position resolution

• Various corrections applied (e.g. leakage, transverse cluster position)

→ σ(X, Y) ≈ 0.5 mm (1.5 mm) achieved for E(γ) > 20 GeV in the SPACAL-W (SPACAL-Pb) regions

→ Precisions of several mm in the Shashlik regions

Impact of timing on $B^0 \to K^{*0}\gamma$



Example: $B^0 \to K^{*0}\gamma$ in the SPACAL regions

• Large combinatorial background in Upgrade II conditions

• Timing cuts applied on photon candidates

→ Substantial improvement of signal significance when using timing information

• Further refinement in progress ...

Summary and outlook

• SPACAL and Shashlik technology provide an attractive option for the Upgrade II of the LHCb ECAL
• A comprehensive R&D program is ongoing to address various challenges:
studies of radiation-hard scintillating fibres, production of tungsten absorber,
detailed Monte Carlo simulations, test beam measurements, …

• Several prototypes were recently tested at DESY. Time resolutions at 5 GeV:
below 40 ps for Shashlik, below 30 ps for SPACAL-Pb, below 20 ps for SPACAL-W

Ongoing test beam at CERN SPS:
• Access to higher energies
• Better energy calibration with MIPs → e.g. detailed study of constant term
• More validation of Monte Carlo simulations
• Studies of PID capabilities exploiting longitudinal segmentation
• New SPACAL-Pb prototype and larger SPACAL-W
prototype equipped with polystyrene fibres
• Shashlik with even faster WLS fibres (YS4)

Thank you!

Backup slides