Scintillating Sampling ECAL Technology for the Upgrade II of LHCb

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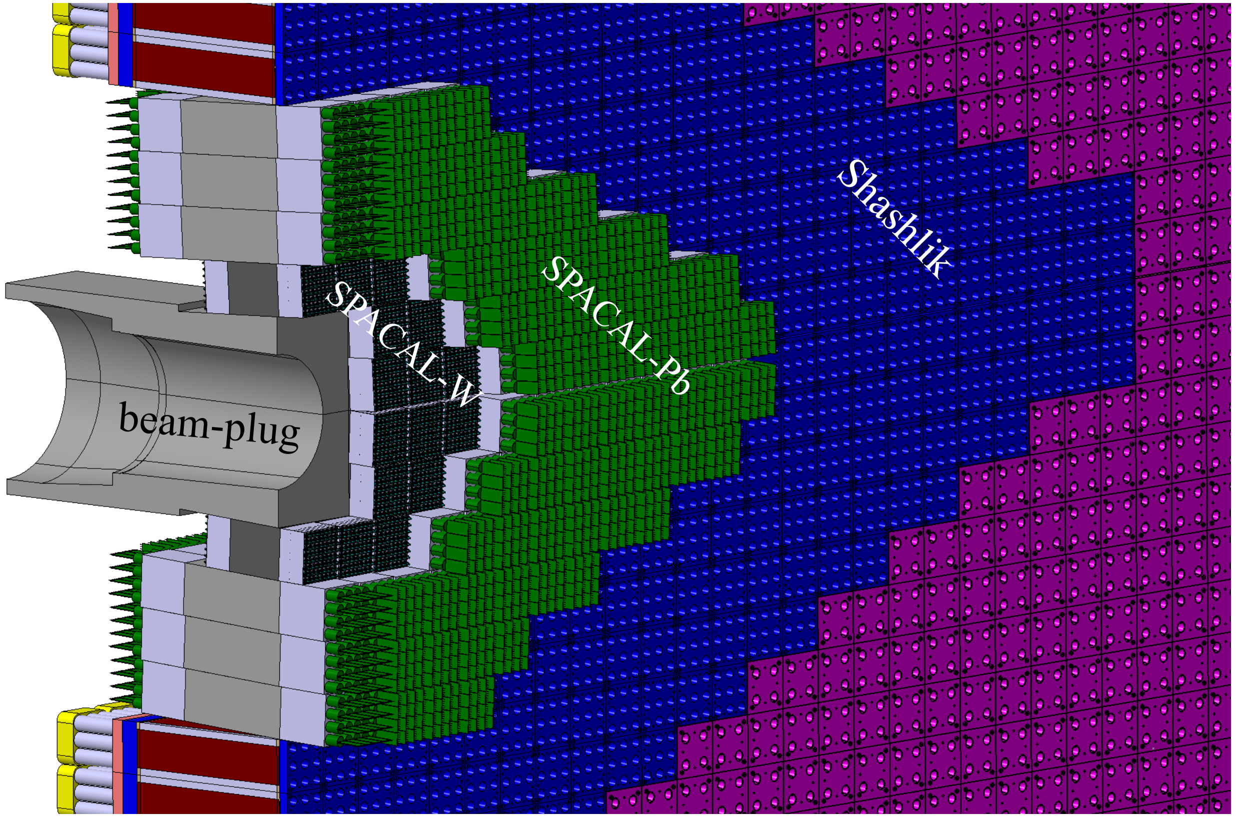
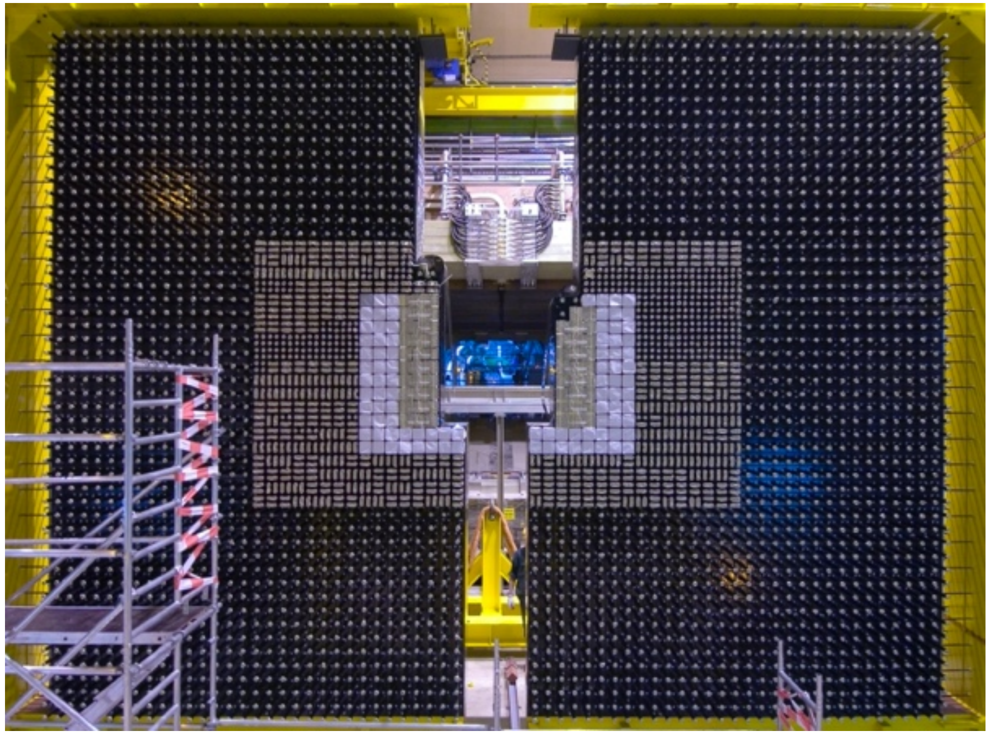
on behalf of the LHCb ECAL Upgrade R&D Group



Motivation for upgrade of the LHCb ECAL



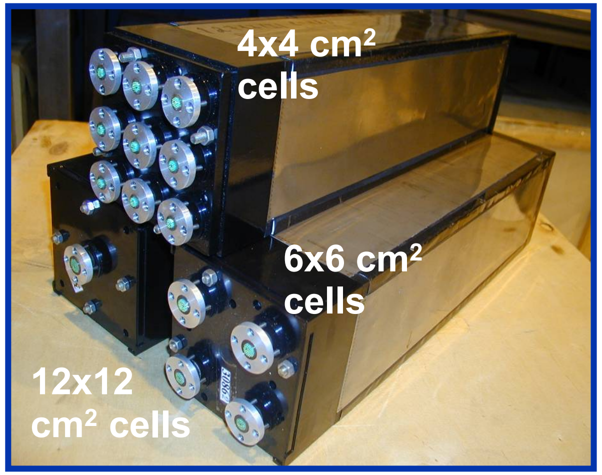
Current LHCb ECAL:

- Optimized for π^0 and γ reconstruction in the few GeV to 100 GeV region at L = 2 x 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

Requirements for the Upgrade II:

→ operation up to L = 1.5 x 10^{34} $cm^{-2}s^{-1}$ with same detector performance

- Keep current energy resolution
- Sustain radiation doses up to 1 MGy and $\leq 6 \cdot 10^{15} cm^{-2}$ for 1MeV neq/cm^2 at 300 fb^{-1}
- Mitigate high occupancies and pile-up
  - ✓ Reduce occupancy by increasing granularity (down to 1.5x1.5 cm^2)
  - ✓ Mitigate pile-up by introducing timing capabilities with O(10) ps precision
- Respect outer dimensions of the current modules: 12 x12 cm^2

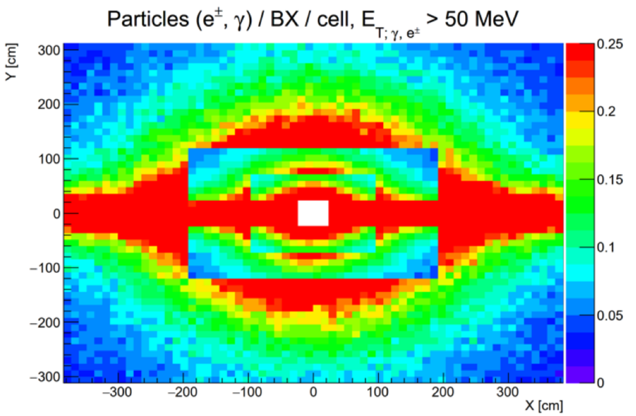


→ 5D calorimetry with precision timing!

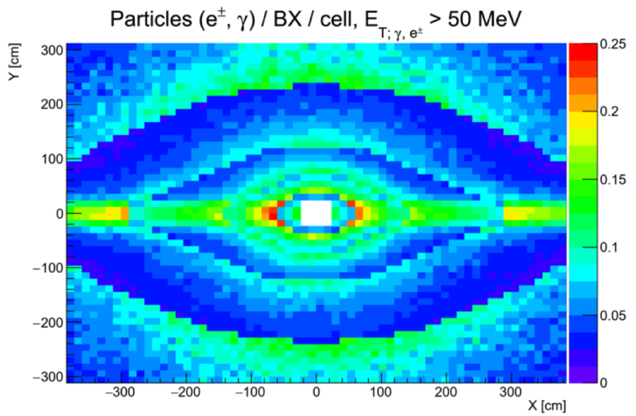
Technologies for the ECAL Upgrade II

L = 1.5 x 10^{34} cm^{-2}s^{-1} → occupancies manageable with increased granularity and rhombic shape →

Current ECAL



Upgrade II configuration



Upgraded Shashlik technology for outer region:

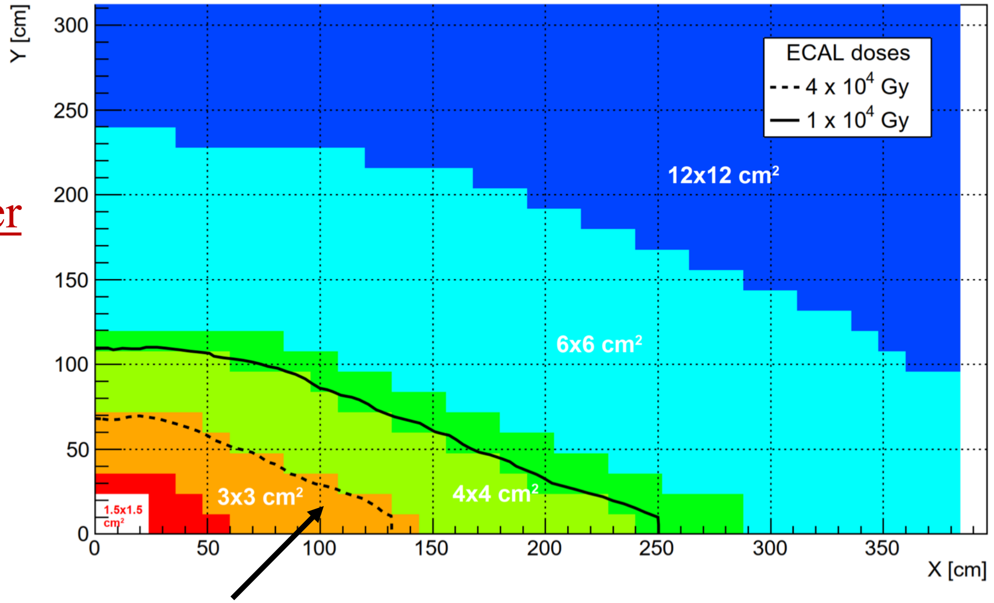
- Timing with new WLS fibres & long. segmentation
  - ✓ Cost optimisation by refurbishing ≈2000 existing modules for improved timing
  - ✓ Adapt to the required cell sizes by adding ≈1300 new modules
  - ✓ 4x4, 6x6, 12x12 cm^2 cell sizes (double side readout)

New SpaCal technology for inner region:

- 1 MGy → 200 kGy region with scintillating crystal fibres and W absorber
  - ✓ Development of radiation-hard scintillating crystals
  - ✓ 1.5x1.5 cm^2 cell size (segmentation & double side readout)
- 200 → 40 kGy region with scintillating plastic fibres and Pb absorber
  - ✓ Need radiation-tolerant organic scintillators
  - ✓ 3x3 cm^2 cell size (segmentation & double side readout)

LS3 consolidation: W absorber for innermost modules equipped with scintillating plastic fibres for 2x2 cm^2 cell size (single side R/O)

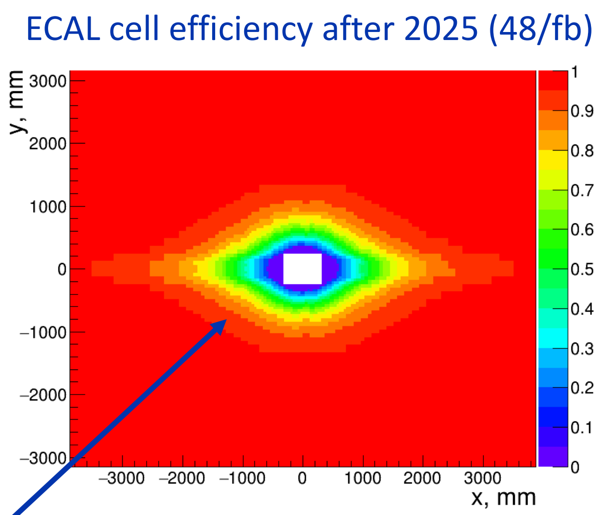
¼ ECAL

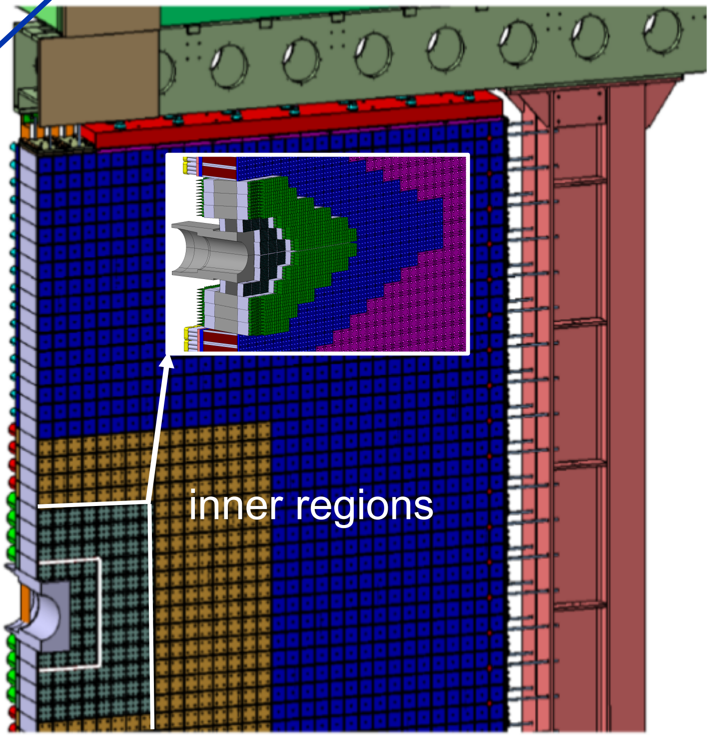


Radiation limit of current Shashlik technology

CERN/LHCC 2021-012

LHCb ECAL upgrade strategy





After LS2 in 2022-2025:

- ✓ Run with unmodified ECAL shashlik modules at L=2x10^{33} cm^{-2}s^{-1} (new 40 MHz R/O)

LS3 consolidation in 2026/28:

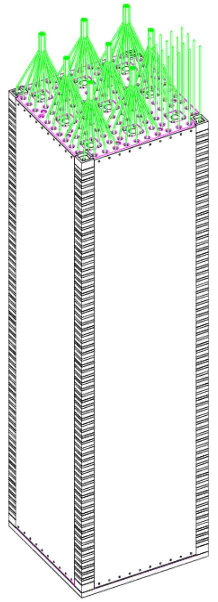
- ✓ Introduce **single section rad. tolerant** SPACAL (2x2 & 3x3 cm^2 cells) in **inner regions** and rebuilt ECAL in **rhombic shape** to improve performance at L=2(4)x10^{33} cm^{-2}s^{-1}
- ➢ 32 SPACAL-W & 144 SPACAL-Pb modules **compliant with Upgrade II** conditions
- ➢ Include **timing information with single sided R/O to inner regions**

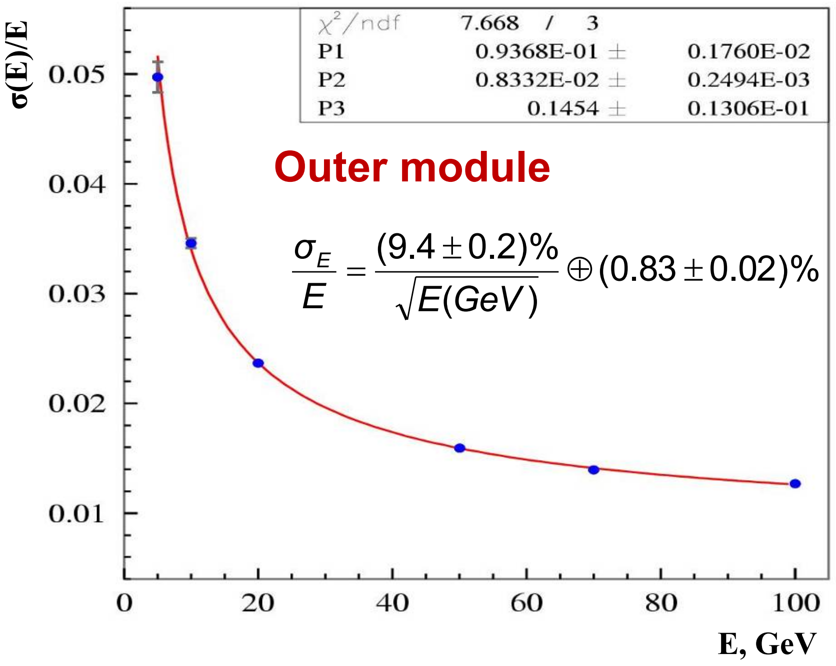
LS4 Upgrade II in ≥2035:

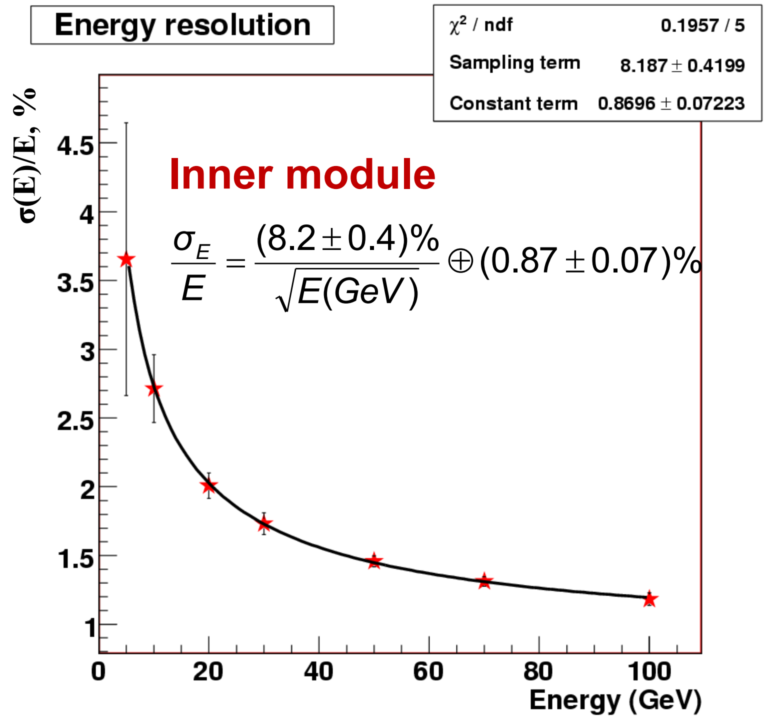
- ✓ Introduce **double section rad. hard** SPACAL (1.5x1.5 & 3x3 cm^2 cells) and improve **timing of Shashlik modules** for a luminosity of up to L=15x10^{33} cm^{-2}s^{-1}
- ➢ Include **timing information with double sided R/O to full ECAL** to mitigate pile-up

Shashlik: energy resolution

- Shashlik radiation hardness limit is 40-50 kRad
→ suitable for periphery of ECAL (≈ 94% of area)







- The performance obtained from test beams in 2003 - 2006, on average:
  - ✓ Energy resolution:

$$\frac{\sigma_E}{E} = \frac{(8 \div 10)\%}{\sqrt{E(GeV)}} \oplus (0.8 \div 0.9)\%$$

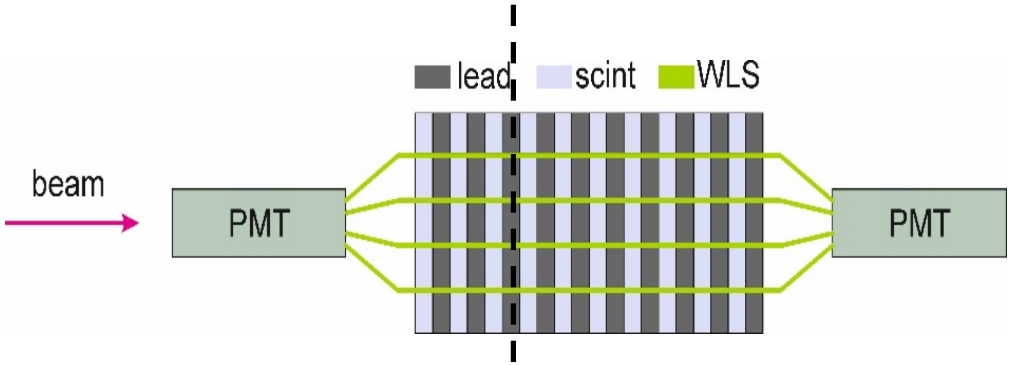
  - ✓ Photoelectron yield (with HAMAMATSU R7899-20): ≈ 3000 ph.el. / GeV
- Satisfied LHCb requirements for run 1 & 2

Shashlik: time resolution

Current Shashlik modules have already good time properties:

- further improvement by replacing WLS fibres by faster ones and introducing double side readout

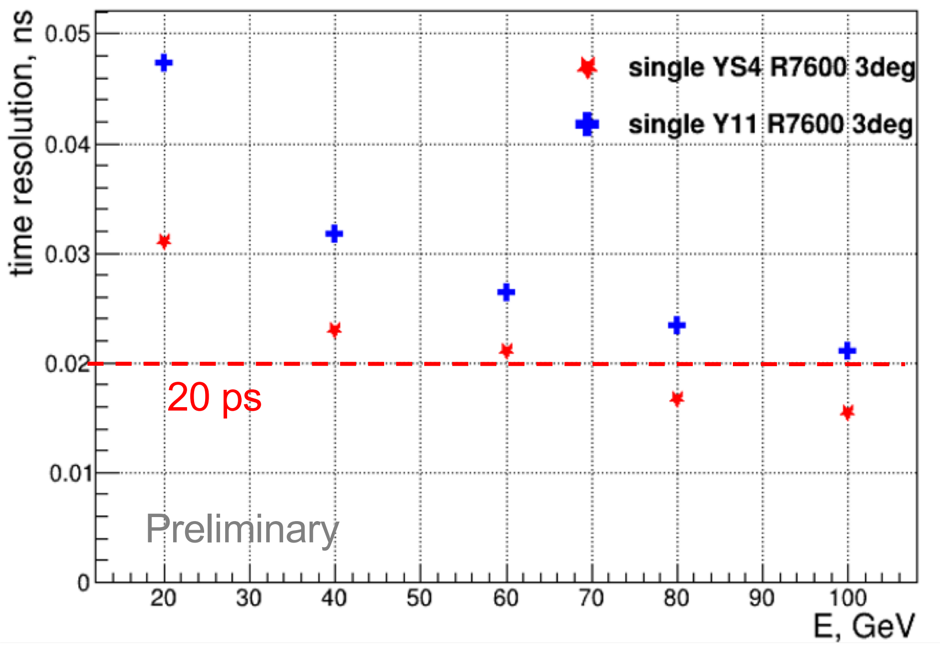
  - ✓ Y11 (7 ns decay time) → current LHCb
  - ✓ YS2 (3 ns decay time)
  - ✓ YS4 (1.1 ns decay time)



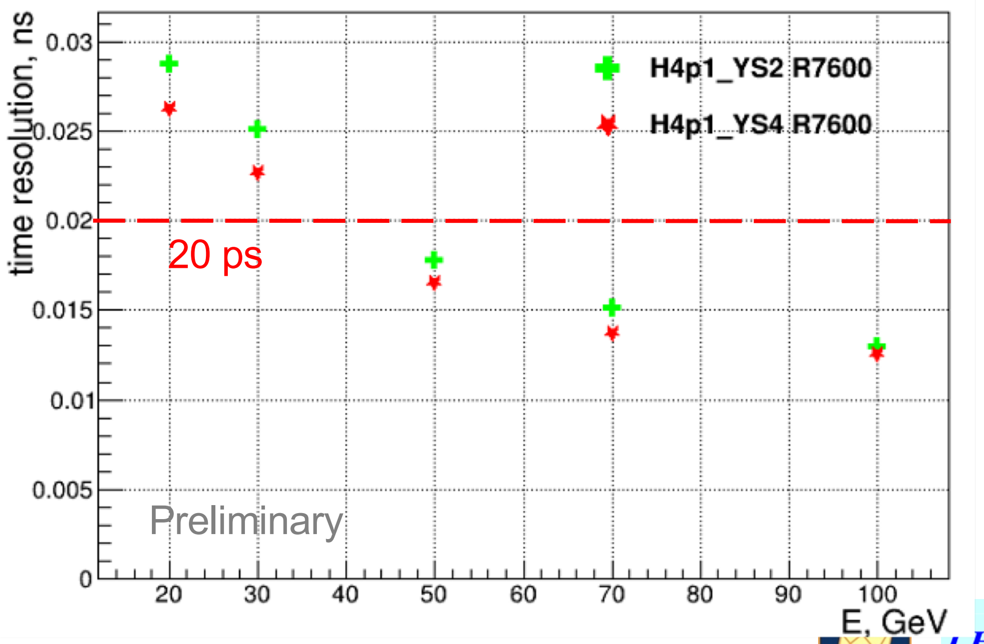
Measurements at SPS with R7600-20 PMT, $\theta_X = \theta_Y = 3°$

- **better than 20 ps achieved above 30 GeV** with double-sided readout

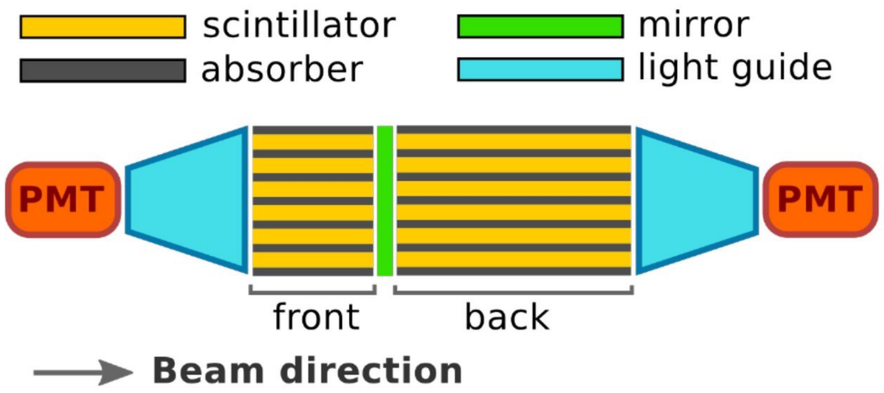
Single-side readout (CERN SPS 2022)



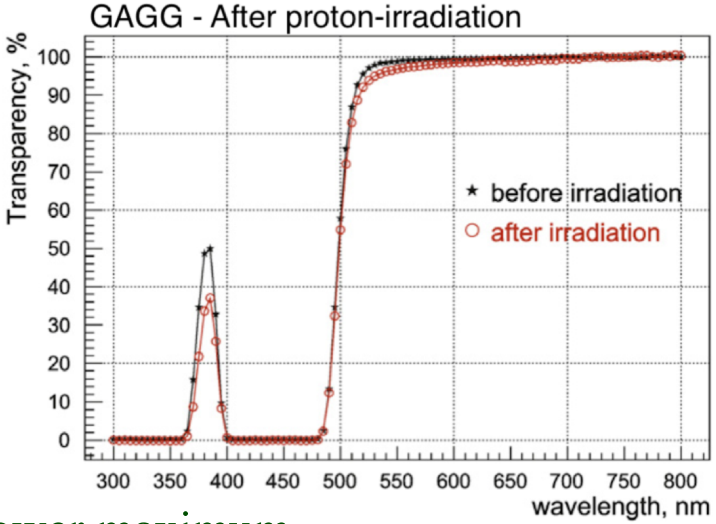
Double-side readout (CERN SPS 2021)



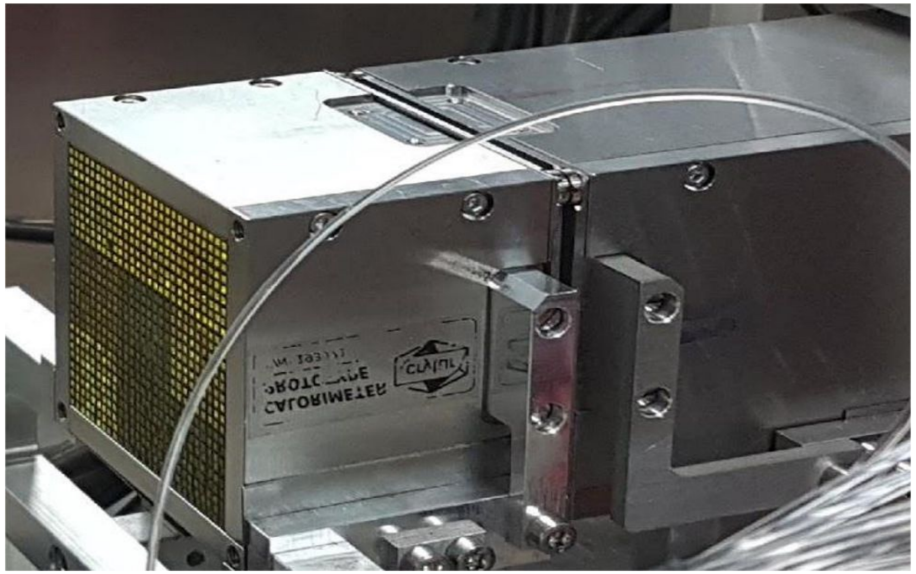
SPACAL-W & garnet crystals



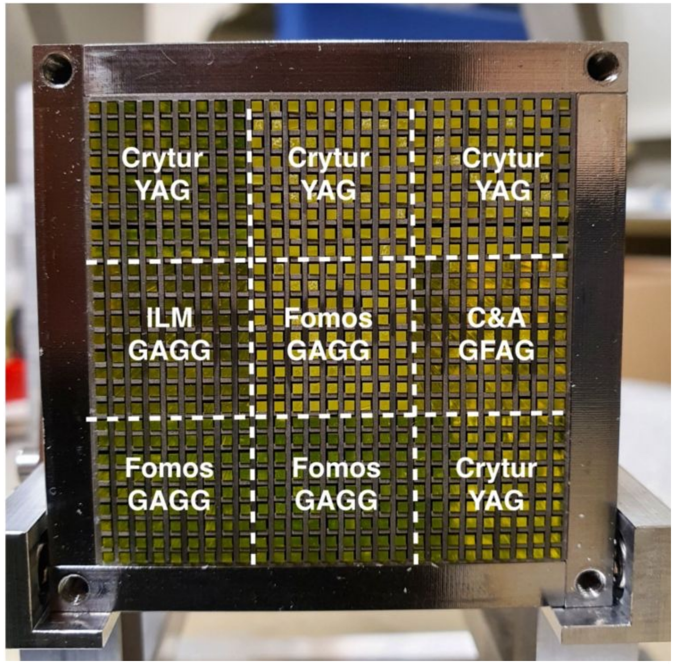
→ GAGG crystal resist up to 1MGy



- 9-cell SPACAL-W prototype:
  - ✓ Scintillating crystal garnet fibers with 1x1 mm^2 cross section
  - ✓ Tungsten absorber with 19 g/cm^3
  - ✓ Longitudinal segmentation at the shower maximum with reflective mirror (4 & 10 cm = 7 & 18 X_0)

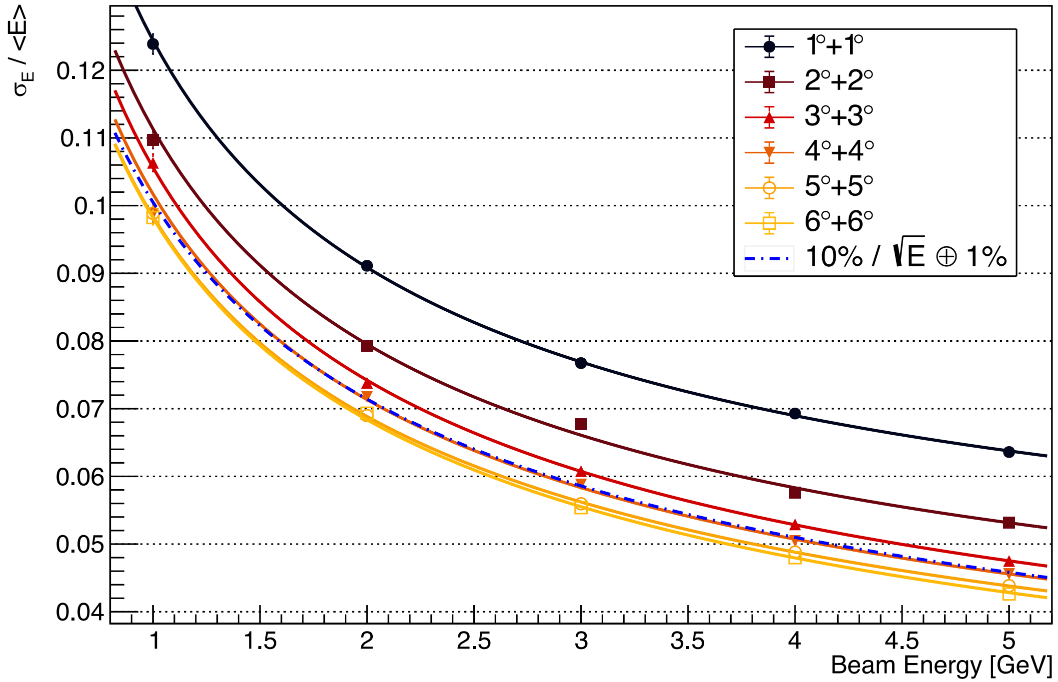


- 4 garnet types tested:
  - ✓ Crytur - YAG
  - ✓ Fomos - GAGG
  - ✓ ILM - GAGG
  - ✓ C&A – GFAG
- Different PMTs tested:
  - ✓ **Energy**: Hamamatsu R12421 and PMMA light guides
  - ✓ **Time**: Hamamatsu R7600U-20 metal channel dynodes (MCD) PMTs in direct contact

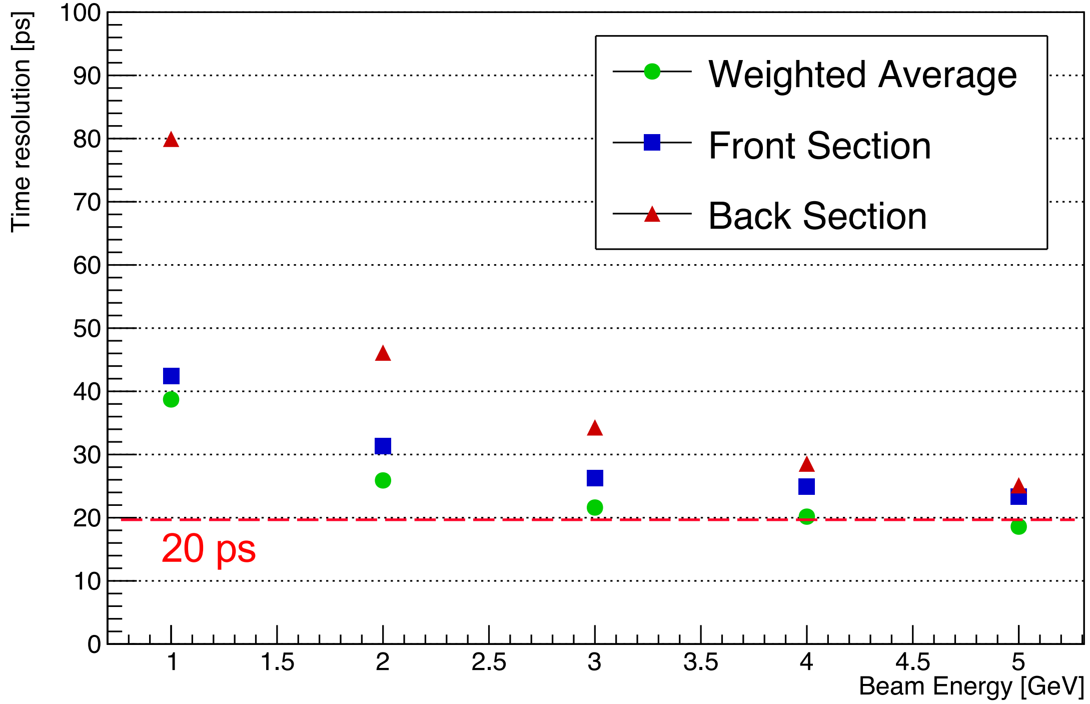


SPACAL-W & garnet crystal fibers

Energy resolution (DESY 2020 , R12421)



Time resolution (DESY 2020 , R7600-20)



- Energy resolution **improves** for larger incident angles
- Energy resolution at $3^o + 3^o$
  - ✓ sampling term of **10.2% ± 0.1**
  - ✓ constant term of **1.2% ± 0.3**

- Time resolution measured at incident angle of $3^o + 3^o$
  - ✓ Time stamps from front and back sections obtained with constant fraction discrimination (CFD)
  - ✓ Time resolution (C&A GAGG): **18.5 ± 0.2 ps @ 5 GeV**

- **Analysis of SPS data (higher energy) ongoing**

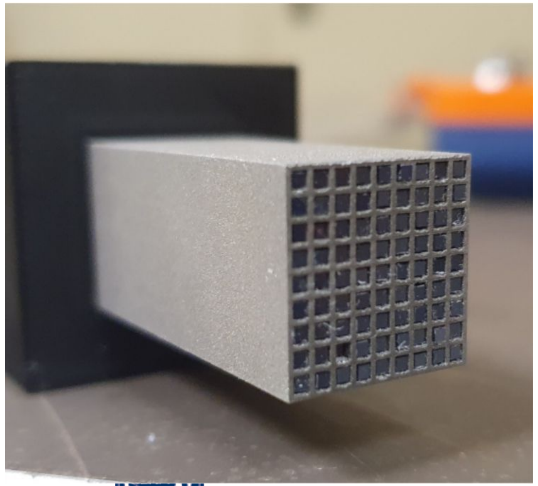
arXiv:2205.02500, submitted to NIM A

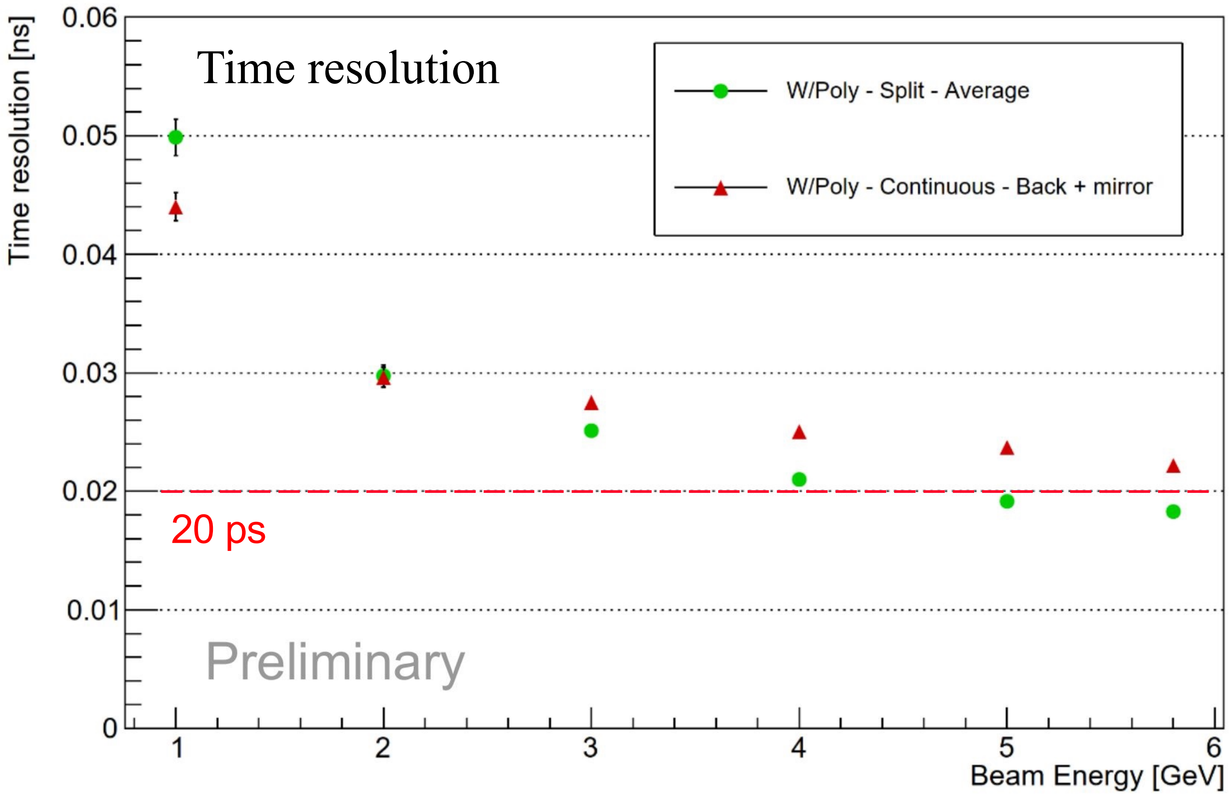
EP R&D

SPACAL-W & organic scintillating fibers

Candidate for consolidation of inner region during LS3
- 3D printed **pure tungsten** absorber
- **Polystyrene** squared scintillating fibers
- single cell: 1.5 x 1.5 cm^2 ($R_M \approx$ 1.8 cm)

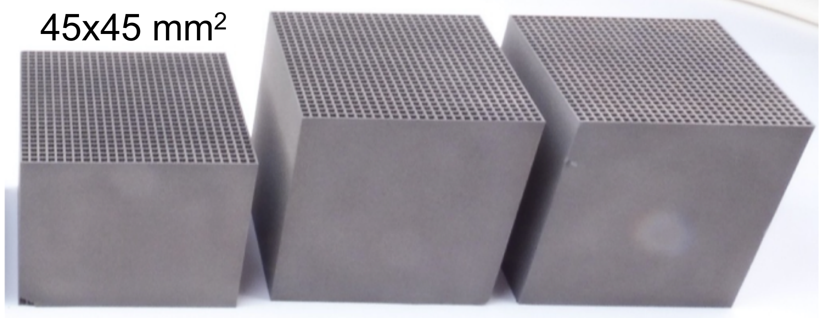
Two configurations tested:
- 5+14 cm long split cell (7+18 X0), double side readout
  - ✓ reflective mirror between sections
- 19 cm long continuous cell, single side readout at back
  - ✓ continuous fibers with mirror at front





- **Time resolution** measured at 3°+3° incidence angle:
  - ✓ Split cell: **19 ps** @ 5 GeV
  - ✓ Continuous cell: **24 ps** @ 5 GeV

SPACAL-W: R&D on absorber 3D printing



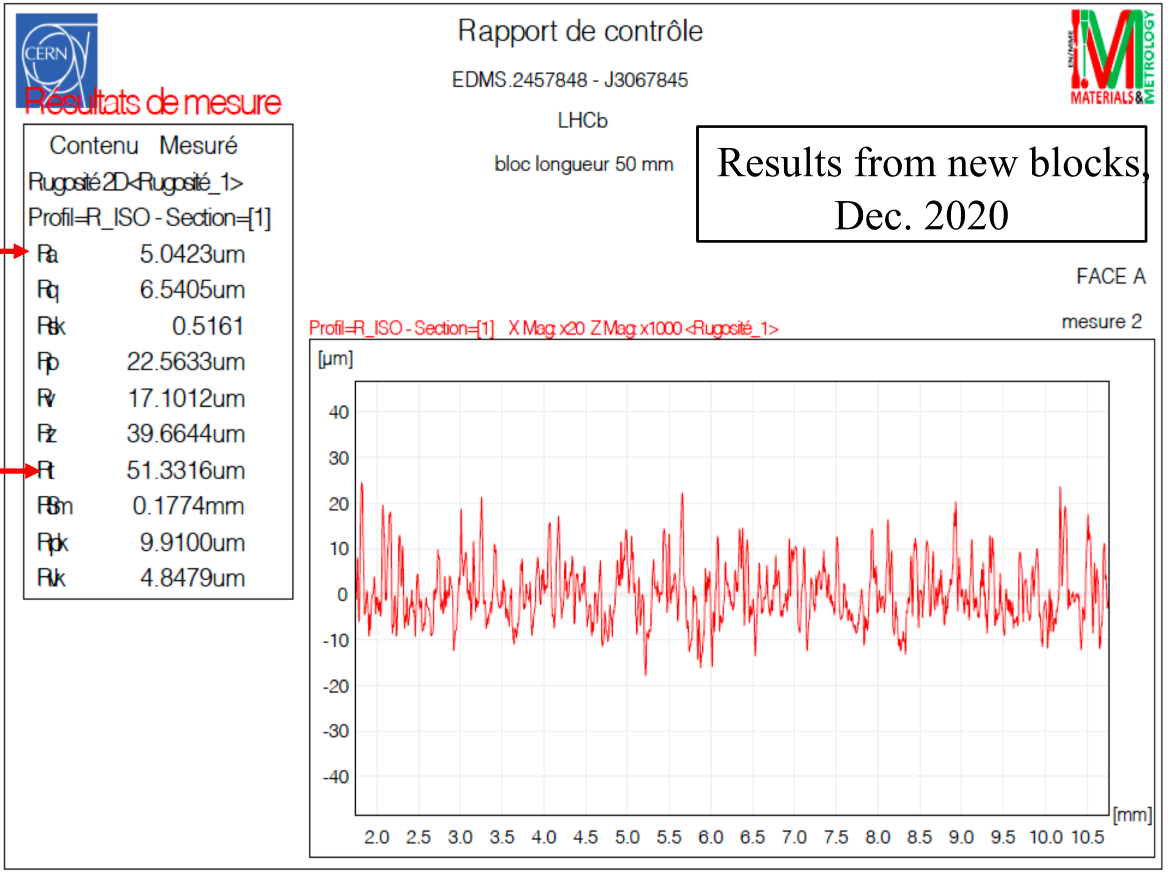
R&D on 3D printed tungsten prototypes:

- Smooth surface mandatory not to damage scintillating fiber crystals
  - ✓ Very good roughness of Ra= 5 μm achieved
  - ✓ Produced $1.5x1.5\ cm^2$ and $4.5x4.5\ cm^2$ blocks with up to 10 cm length
- **Full size module of $12x12\ cm^2$ in production (EOS/AMCM)**

Mean roughness

Total height of profile

= distance (max-min)



Rapport de contrôle

EDMS.2457848 - J3067845

LHCb

bloc longueur 50 mm

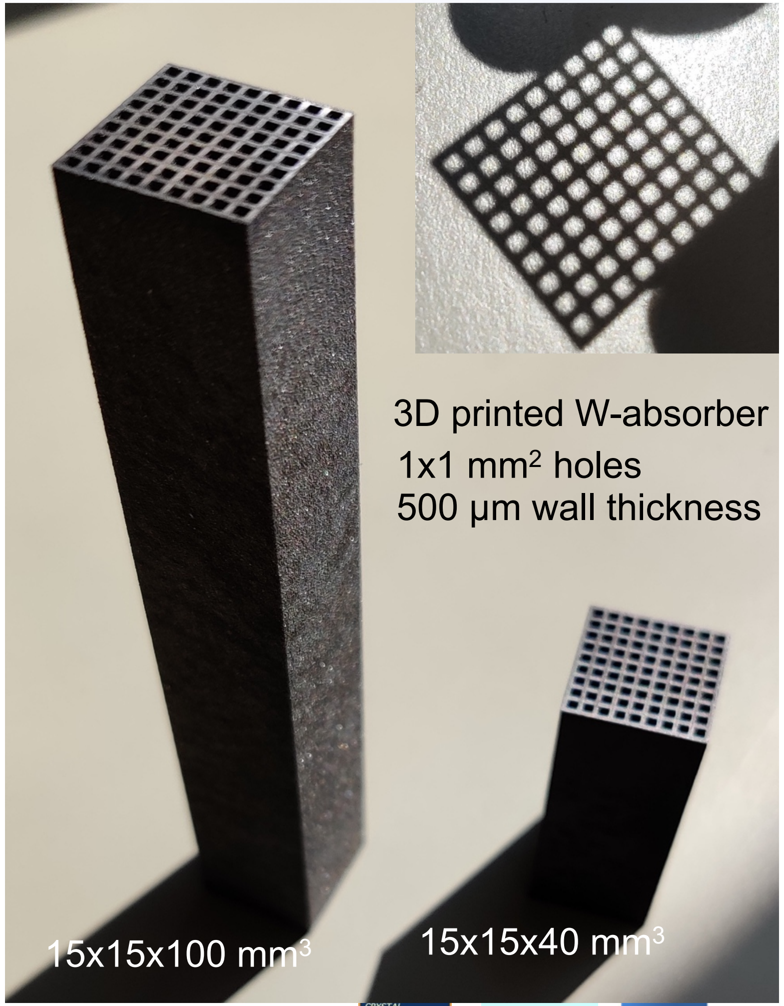
Résultats de mesure

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

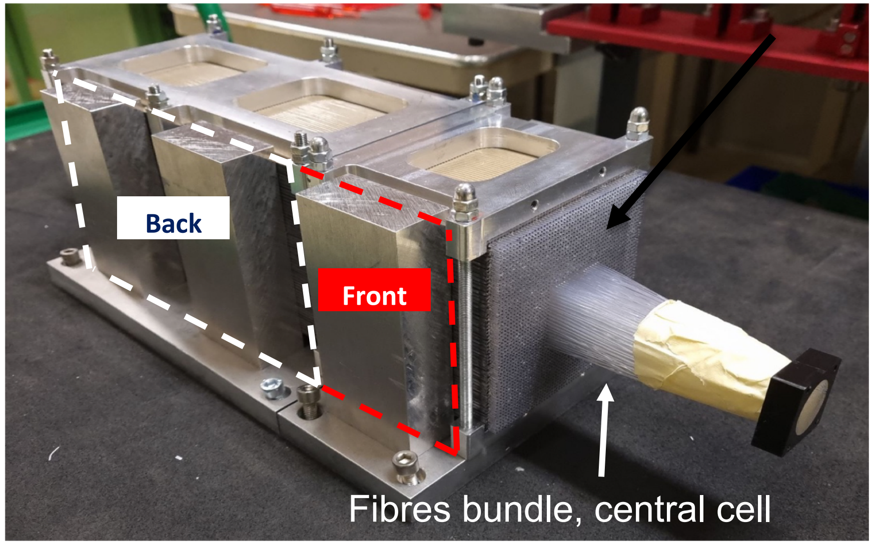
FACE A

mesure 2



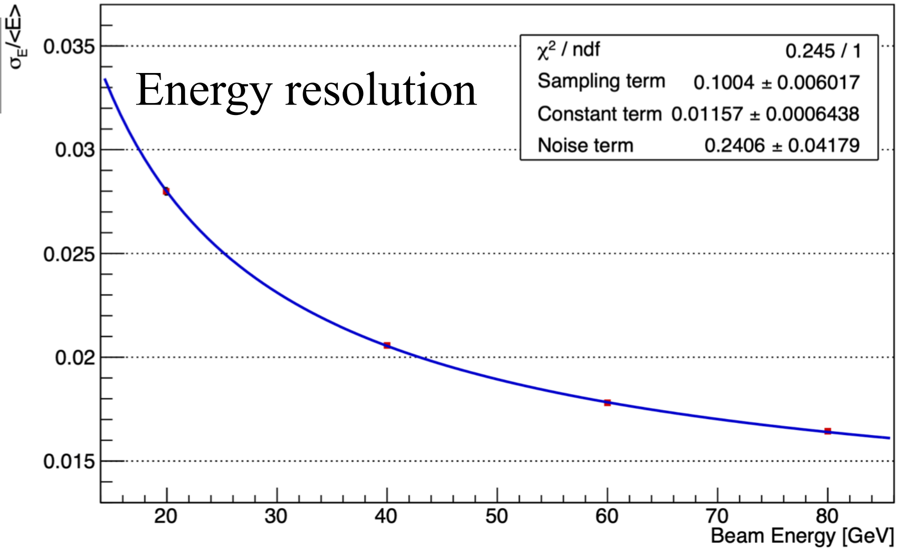
SPACAL-Pb & organic scintillating fibers

- **Lead** absorber with **polystyrene** fibres
- 9 cells, each 3 x 3 cm^2 ($R_M \approx 3$ cm)
- 8 + 21 cm long (7+18 X_0)
- Reflective mirror between sections

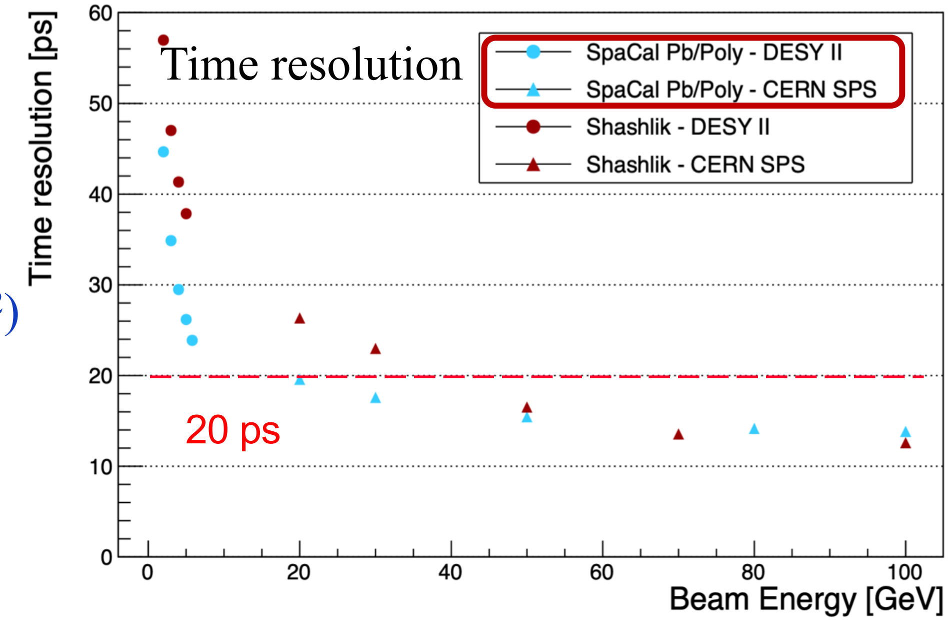


- Energy resolution:
  Hamamatsu R7899 PMT
- Time resolution:
  Hamamatsu R7600U-20
  metal channel dynode (MCD) PMT

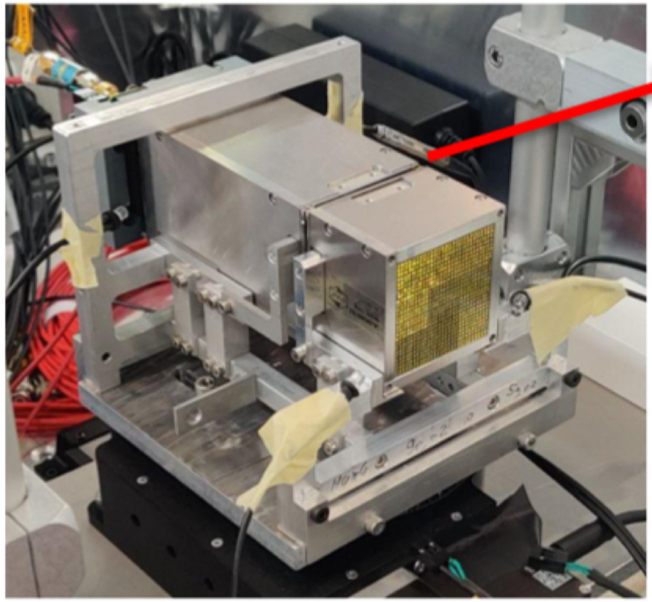
- **Energy resolution** measured at high energy at SPS CERN
- At 3°+3° incidence angle, best fit to data adding noise term
- Sampling term: **10.0%**
  Constant term: **1.16%**



- **Time resolution** at 3°+3° incidence angle, time stamps front/back sections with CFD
- Part of cell readout in direct contact due to smaller active area of the PMT (1.8 x 1.8 cm^2)
  → room for improvement
- Time resolution:
  - ✓ **26 ps** at 5 GeV
  - ✓ **~15 ps** above 30 GeV



Energy resolution & longitudinal separation

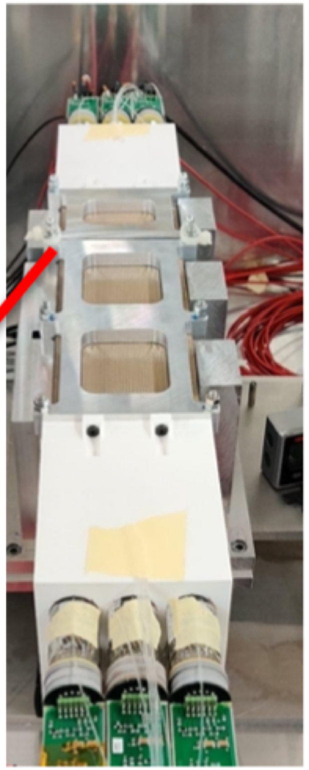


WGAGG

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

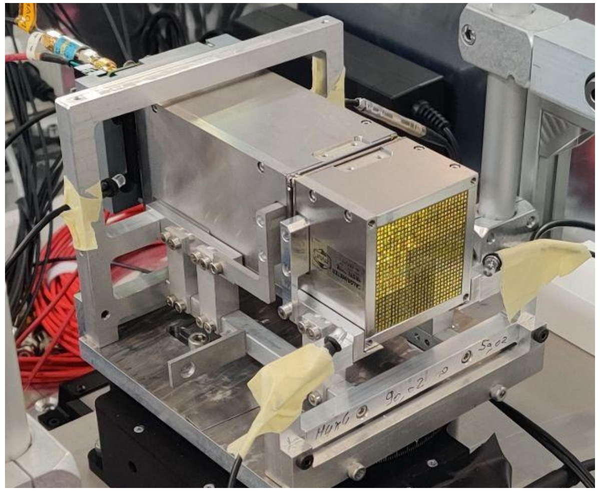
0.065 mm	ESR
2.0 mm	**Stainless**
1.0 mm	Air
2.0 mm	**Stainless**
0.065 mm	ESR



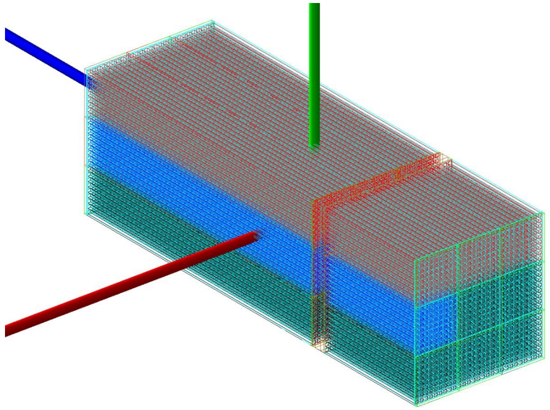
- In SPACAL prototypes produced for testbeam the **longitudinal separation** (front/back sections) is **not optimized**
- This is due to the need for flexibility to perform several tests (calibration, additional timing layer, etc.)
- Material budget between SPACAL sections is not negligible → **energy resolution is degraded**

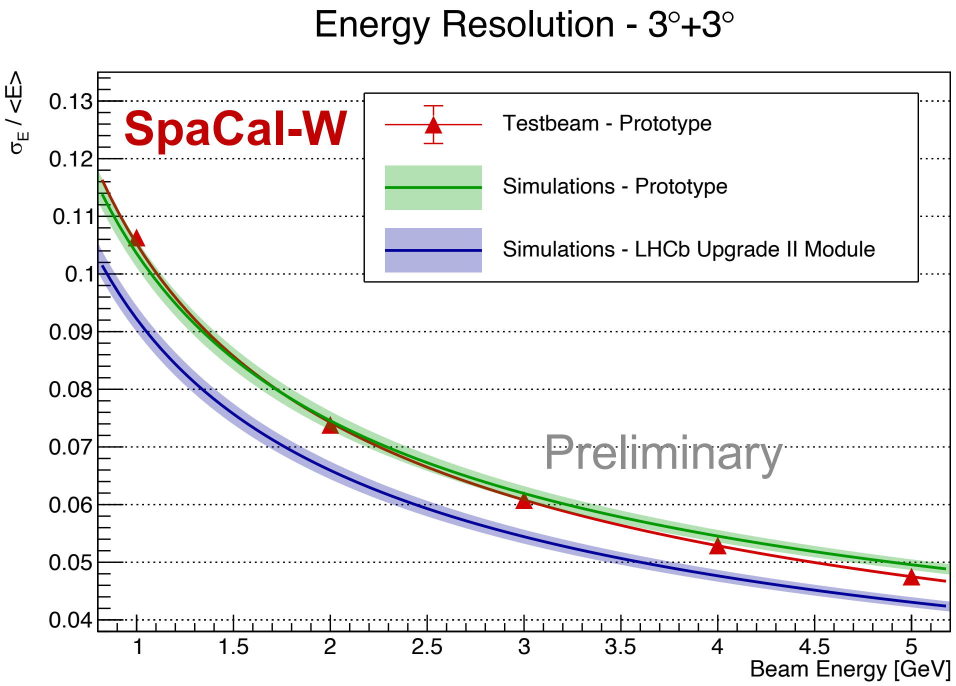
Energy resolution & longitudinal separation

Testbeam



Simulation





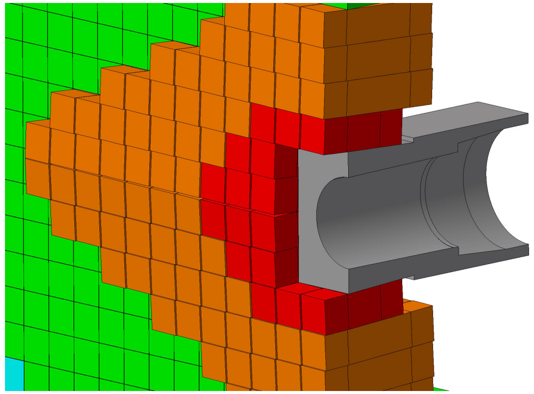
SpaCal-Pb	Measured with TB module [%]	MC simulation of TB module [%]	MC simulation of optimised module [%]
Sampling term	10.0 ± 0.6	10.3 ± 0.1	9.7 ± 0.1
Constant term	1.16 ± 0.06	0.94 ± 0.04	0.62 ± 0.06

- 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 **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**

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

Summary & Conclusion

- Prototypes of different scintillating sampling technologies produced and tested at DESY and SPS-CERN for **energy and time resolutions**
- **Time resolution** above 5 GeV
  - ✓ SPACAL W+GAGG < 20 ps (1.5x1.5 cm^2 cell size)
  - ✓ SPACAL W+Polystyrene < 20 ps (2x2 cm^2 cell size)
  - ✓ SPACAL Pb+Polystyrene < 25 ps (3x3 cm^2 cell size)
  - ✓ SHASHLIK < 40 ps (4x4 / 6x6 / 12x12 cm^2 cell size)



- **Energy resolution** of order $\sigma(E) / E \approx 10\% / \sqrt{E} \oplus 1\%$ can be reached for all technologies for final, optimized configurations
- **SPACAL and Shashlik** technologies provide the **required performance** (including radiation hardness) for the LHCb ECAL upgrades and could be interesting options for other future projects (collider, fixed target)

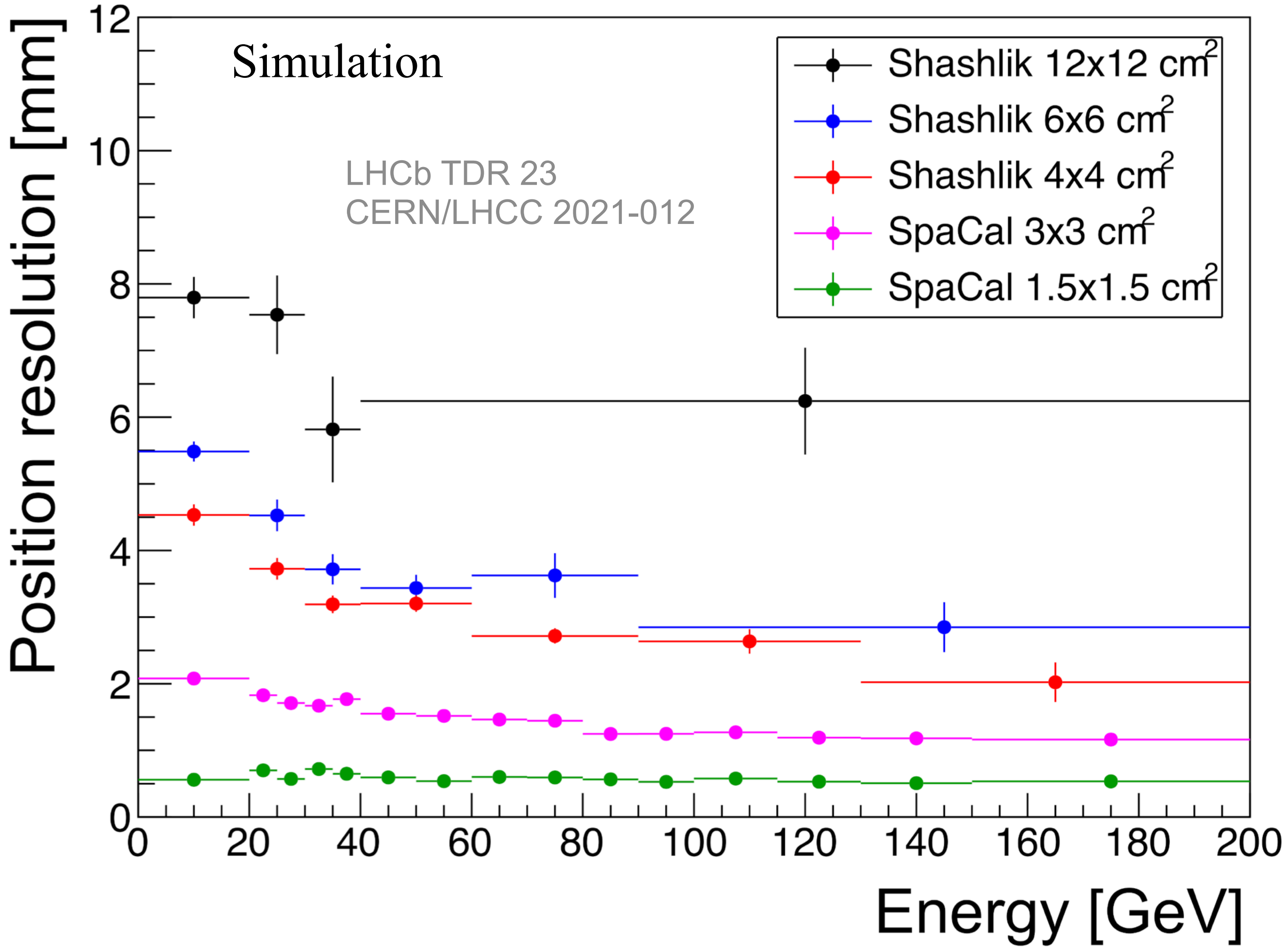
→ New collaborators to join the Upgrade II R&D activities are most welcome!

Backup

Position resolution of different ECAL technologies

- Simulation of **entire ECAL** in Upgrade II configuration
- **Position resolution** extracted from simulation studies of single photon clusters of Shashlik and SpaCal modules as function of cell size

✓ Achieve position resolutions of **≤ 1 mm** in the most inner region of the ECAL

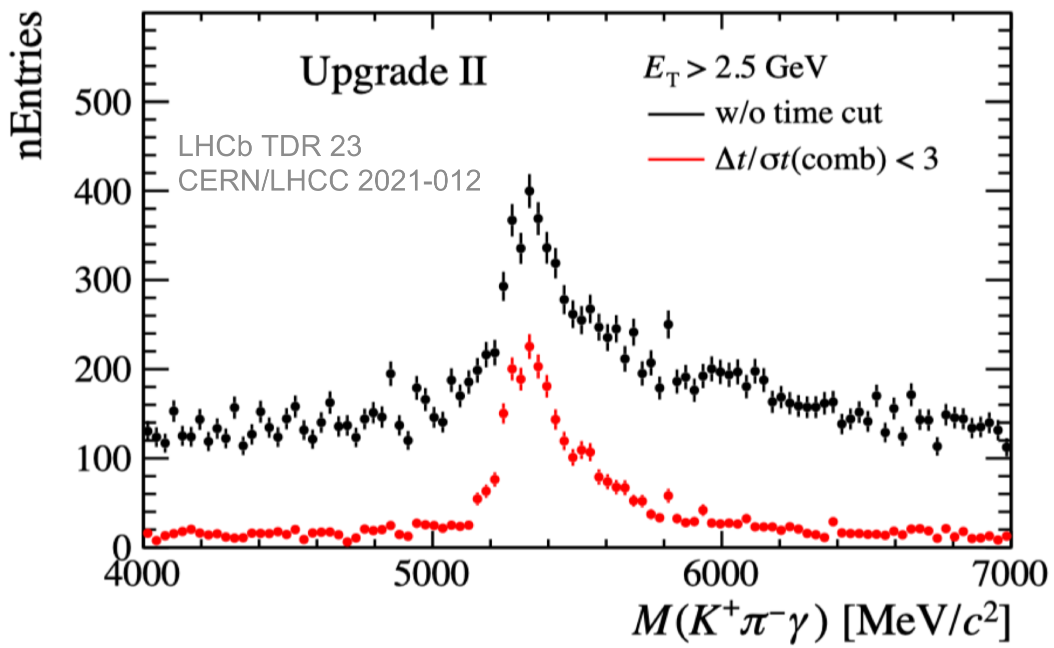


Effect of timing for pile-up mitigation

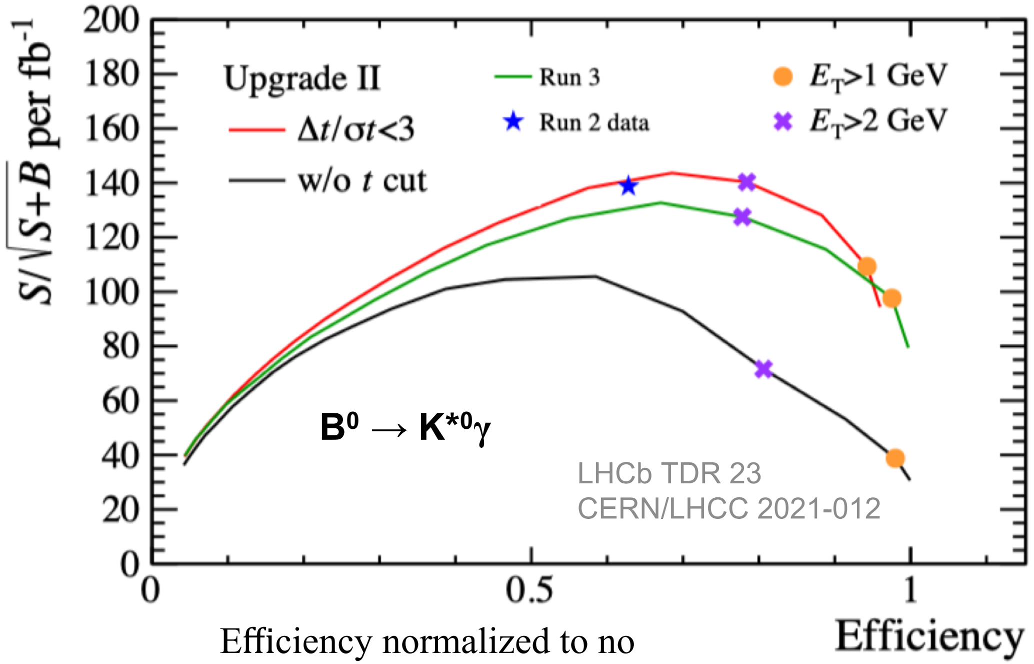
Example: $B^0 \to K^{*0}\gamma$ in the SPACAL regions

- Large combinatorial background in Upgrade II conditions
- Timing cuts applied on photon candidates
  - ✓ Detailed simulation with timing resolution validated by testbeam data
  - ✓ Substantial improvement of signal significance when using timing information
- Further refinement in progress

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



Relative comparison of significance versus efficiency



Efficiency normalized to no additional cut on the photon