Progress of LHCb ECAL upgrade studies

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

6th Nov 2023

14th Workshop of France China Particle Physics Laboratory

Overview

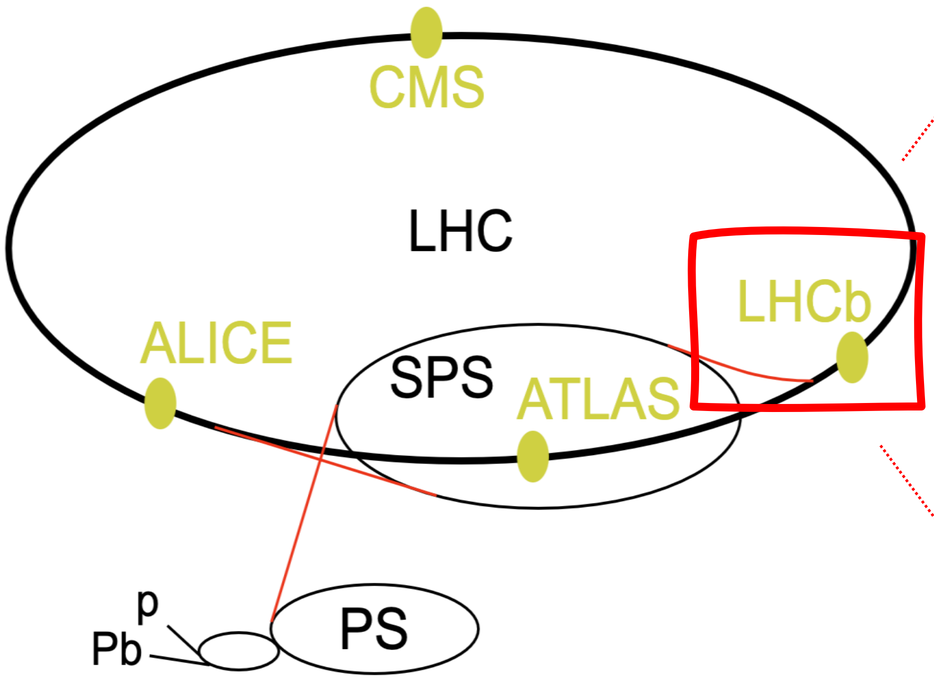
- **Introduction**
  - LHCb upgrade and **Spa**ghetti **Cal**orimeter (SpaCal)
- **Radiation-hard and fast scintillators: GAGG crystal**
- **3D-printing tungsten (W) absorber**
- **Latest test beam and results**
- **Electronics：timing ASIC**
- **Summary**

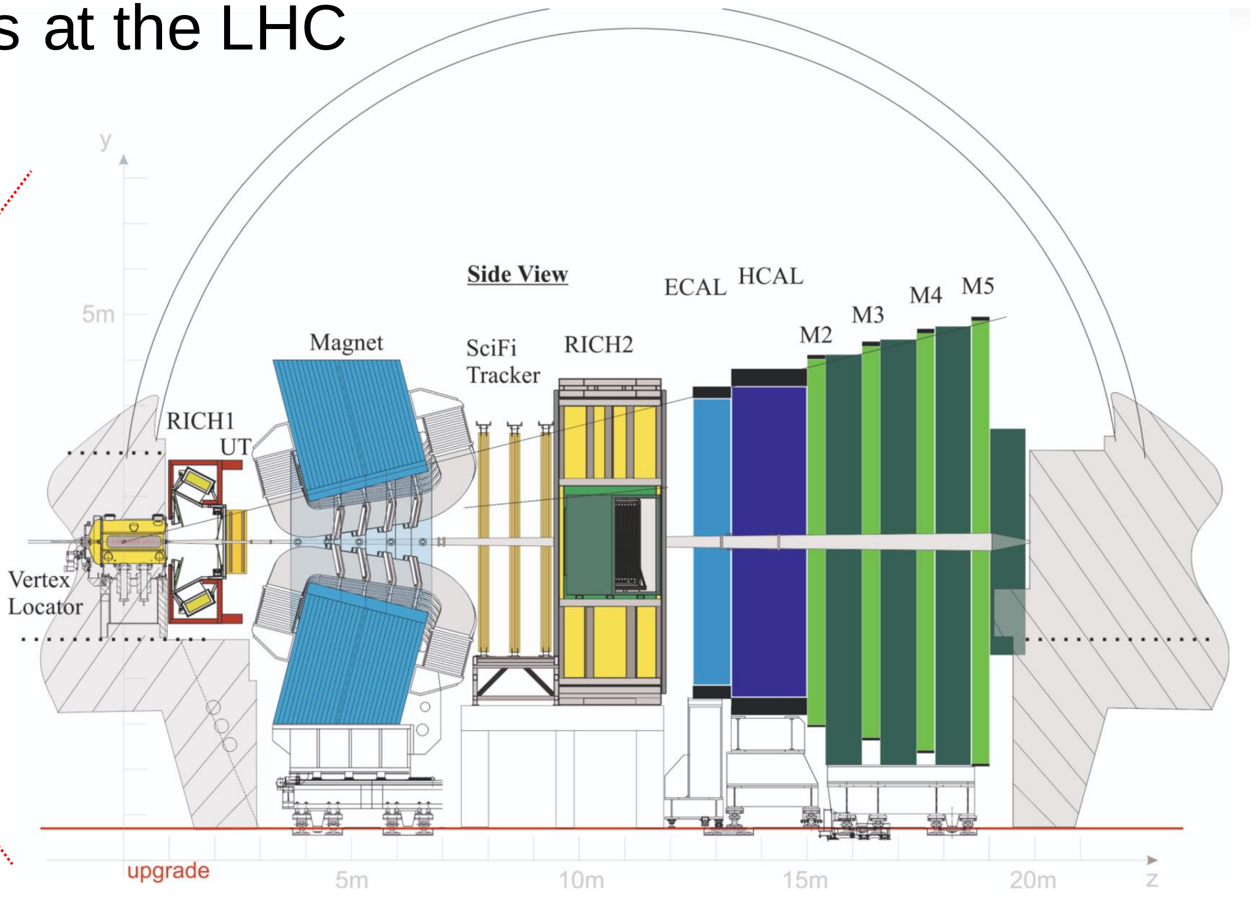
Many interesting topics not included:

- PMT and cables
- Simulation framework: Hybrid-MC
- Previous test beam activities
- …

LHCb experiment

- Designed for heavy flavor physics at the LHC

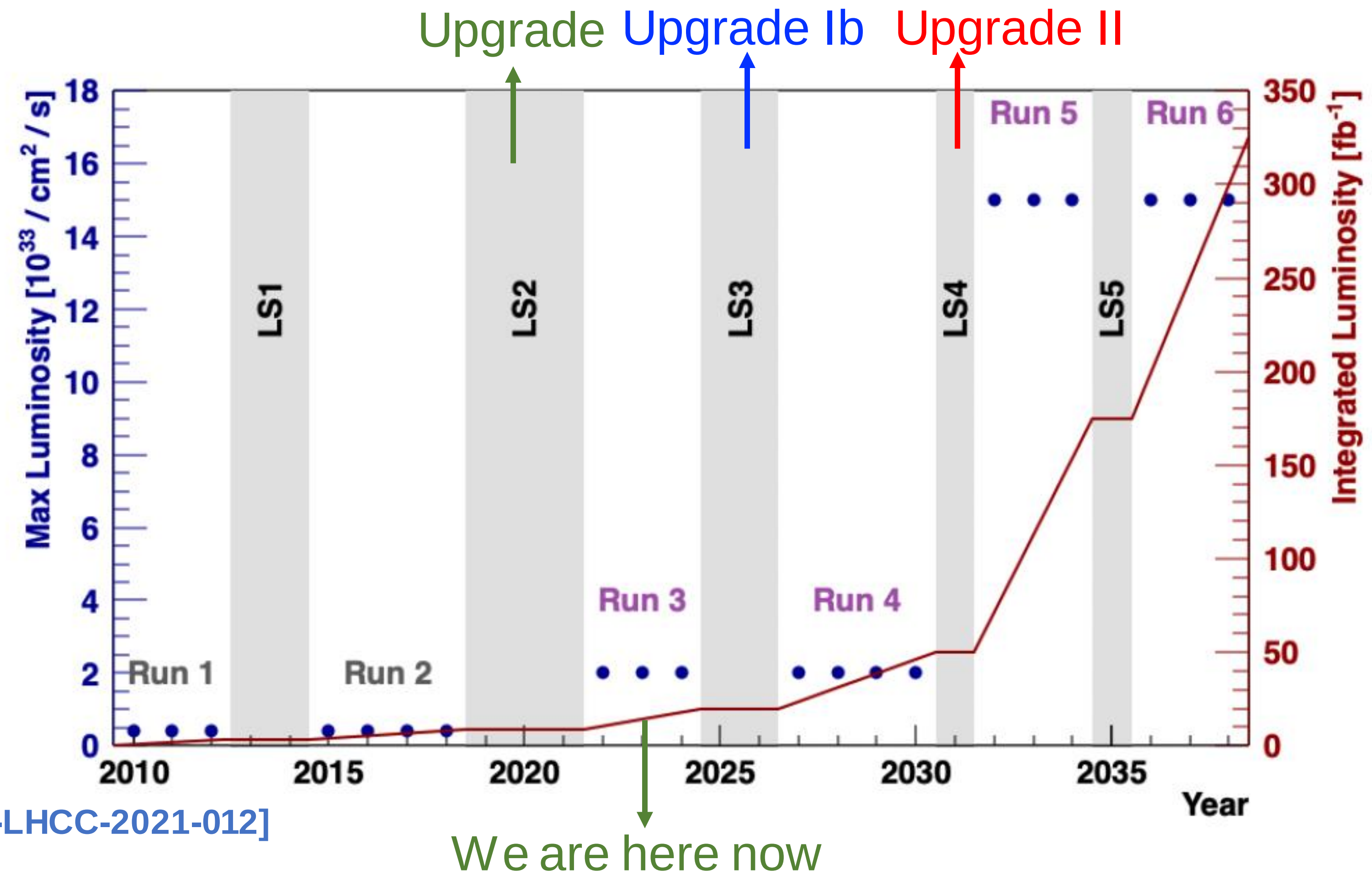




A single-arm forward spectrometer covering $2 < \eta < 5$

LHCb upgrades

- Luminosity profile for LHCb in the context of official LHC schedule of 2021

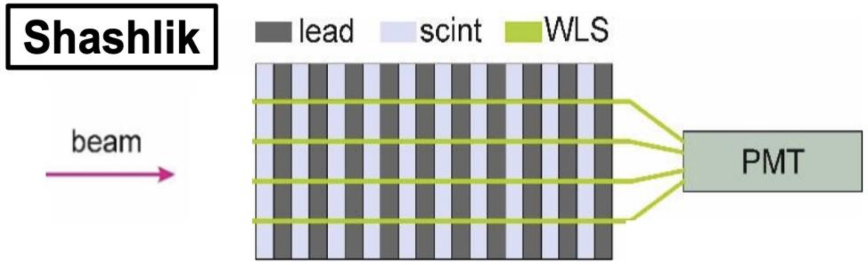


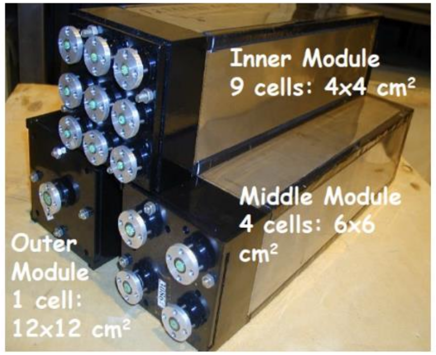
[CERN-LHCC-2021-012]

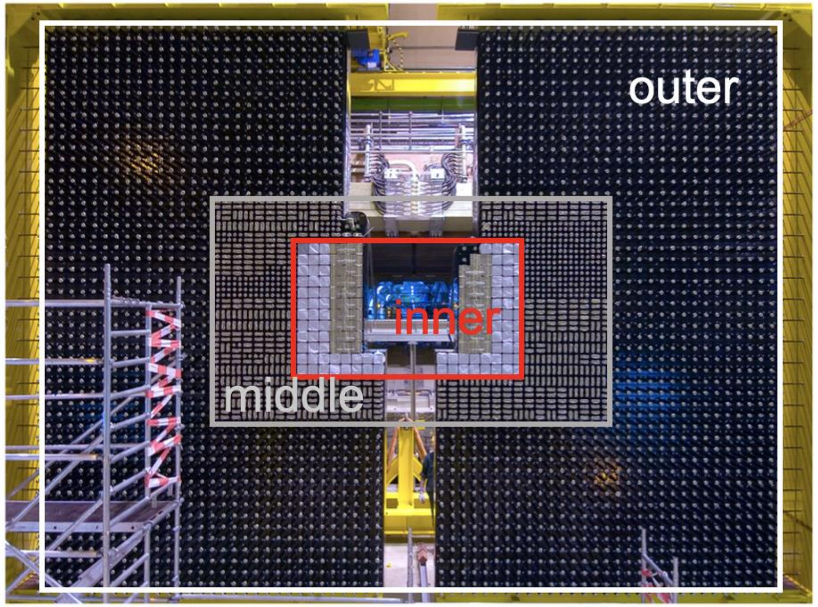
Current LHCb ECAL and upgrade Ib

- Current ECAL operating at $\mathcal{L} = 2\times10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Shashlik technology:

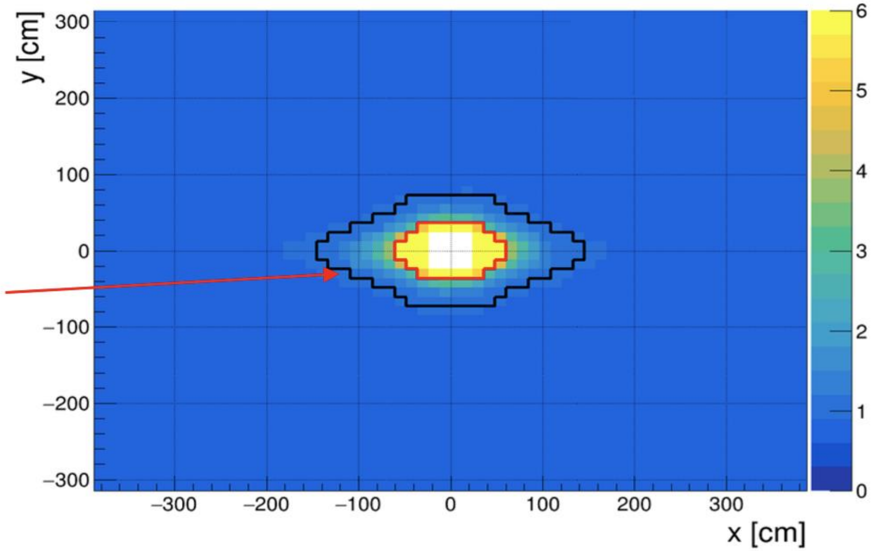
  $4\times4/6\times6/12\times12\ \mathrm{cm}^2$ cell size in inner/middle/outer region







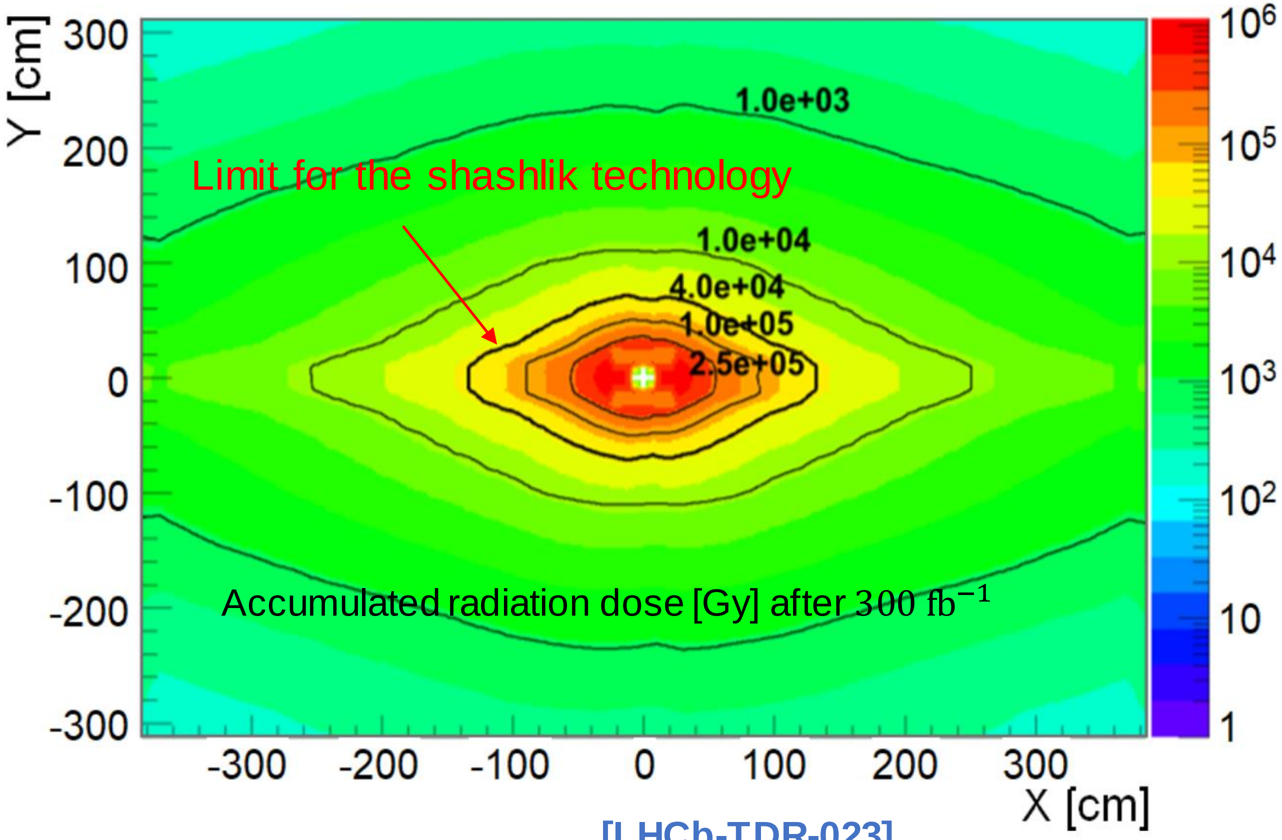
  - Radiation hard up to $40\ \mathrm{kGy}$
- ECAL in upgrade Ib
  - The inner part need to be replaced due to performance degradation



[LHCb-TDR-024]

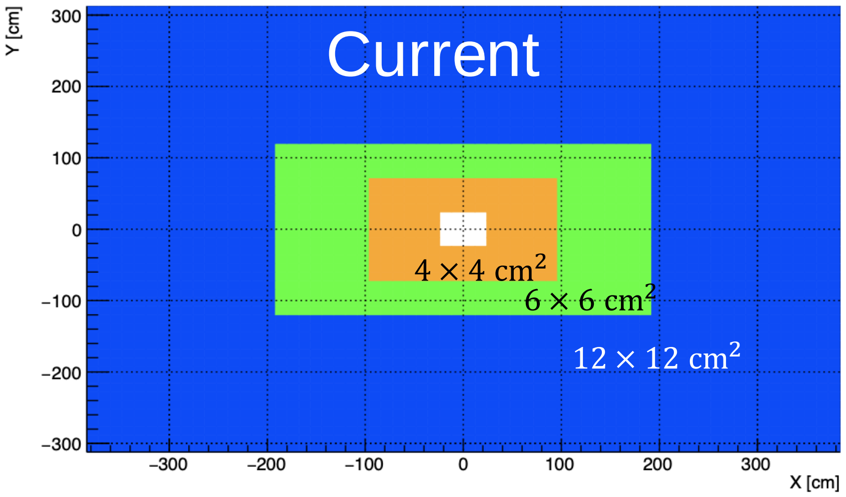
Requirement on ECAL for the upgrade II

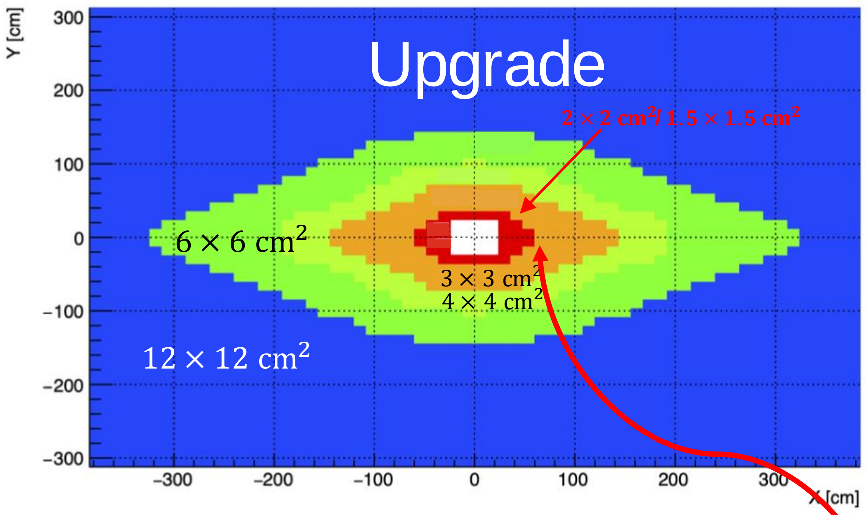
- ECAL needs to operate up to $\boldsymbol{\mathcal{L} = 1.5 \times 10^{34}\ cm^{-2}s^{-1}}$, **7.5 times higher**
  - Sustain radiation doses up to $1\ \mathrm{MGy}$ and $\leq 6 \times 10^{15}\ 1\ \mathrm{MeV\ neq/cm^2}$ in the center
  - Mitigate pile-up:
    - ✓ Increase granularity with dense absorber
    - ✓ Good timing capabilities
  - Keep current energy resolution of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$



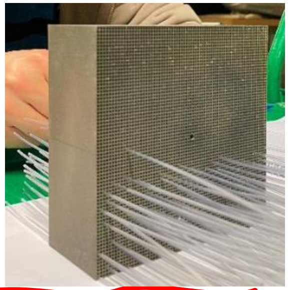
[LHCb-TDR-023]

LHCb ECAL upgrade strategy

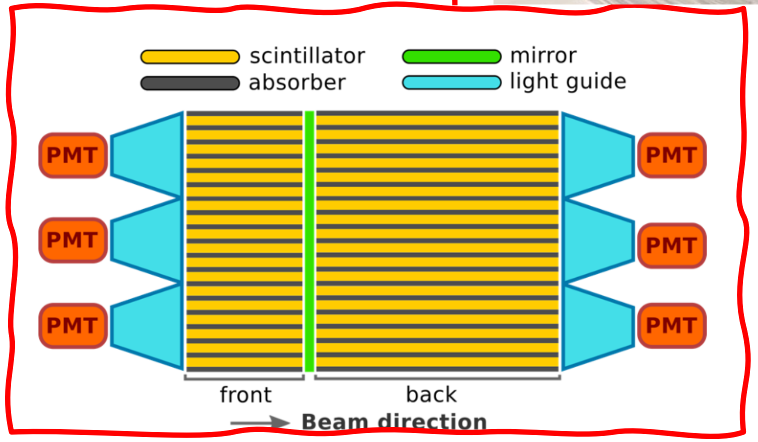




[LHCb-TDR-024]



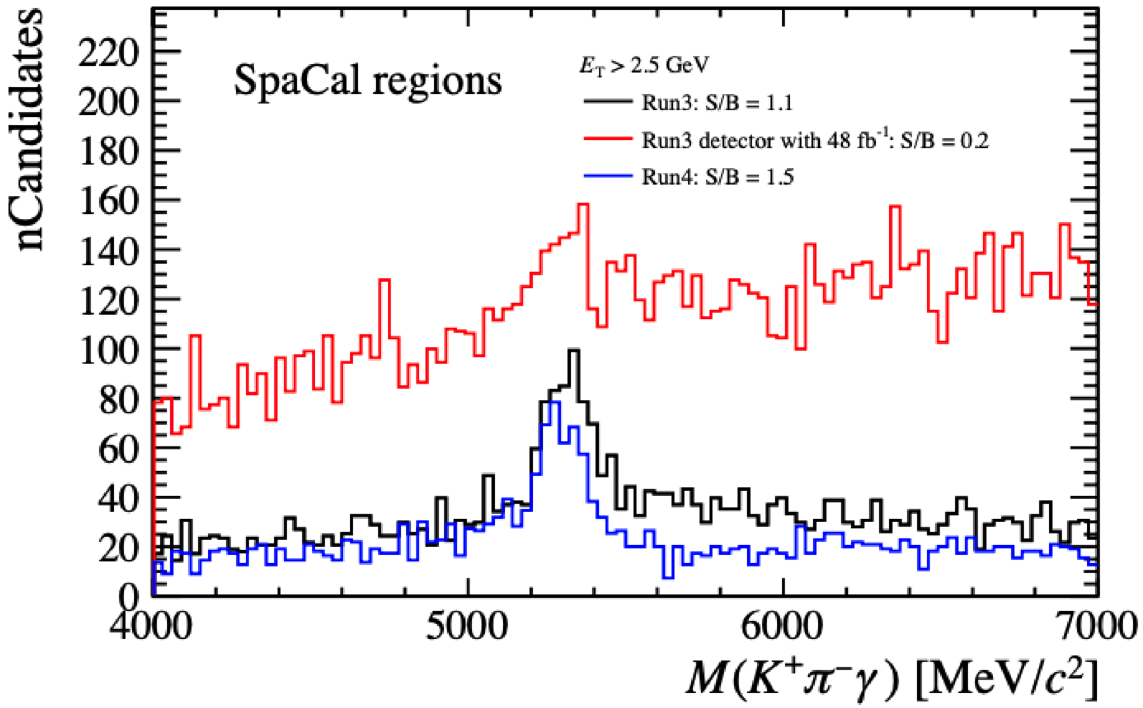
- Rebuild ECAL in rhombic shape following the radiation dose map
- Increased granularity
- Spaghetti Calorimeter (SpaCal) technology with W used in the innermost region
  - Upgrade Ib: $2 \times 2\ \mathrm{cm}^2$ cell, plastic fiber
  - Upgrade II: $1.5 \times 1.5\ \mathrm{cm}^2$ cell, crystal fiber



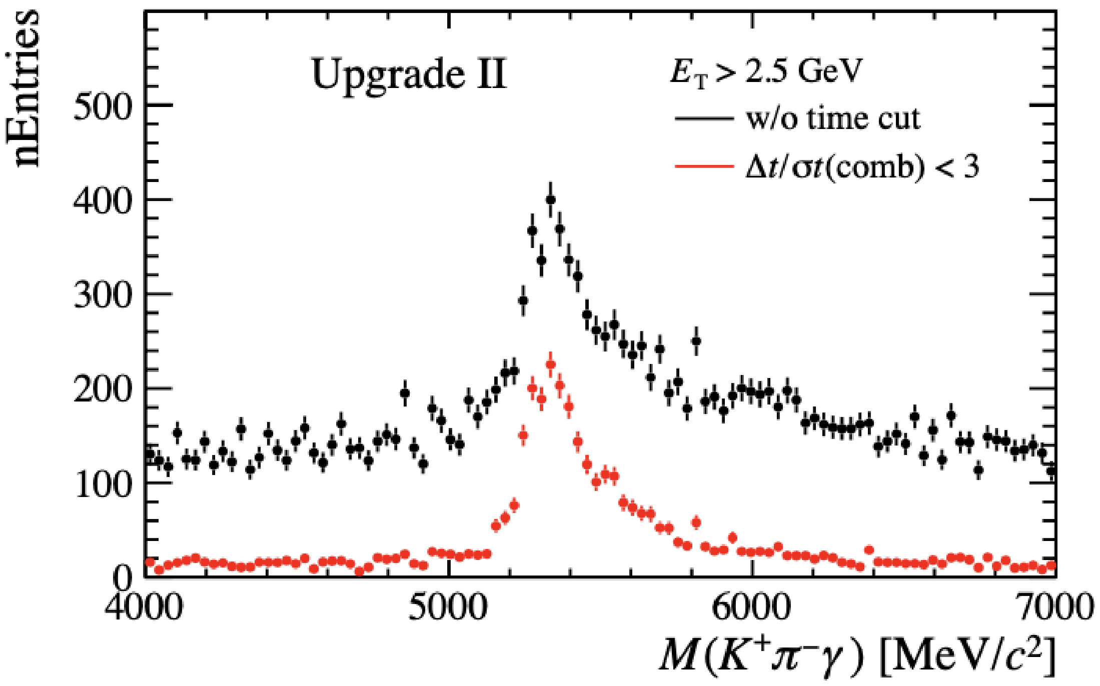
Physical benchmarking simulation

- Example: $B^0 \to K^{*0}\gamma$

[LHCb-TDR-024]



[LHCb-TDR-023]



- Upgrade Ib ECAL has better performance than current ECAL
- Time resolution $\mathcal{O}(10)$ ps important to suppress the background

Outline: R&D activities

- **Radiation-hard and fast scintillators: GAGG**

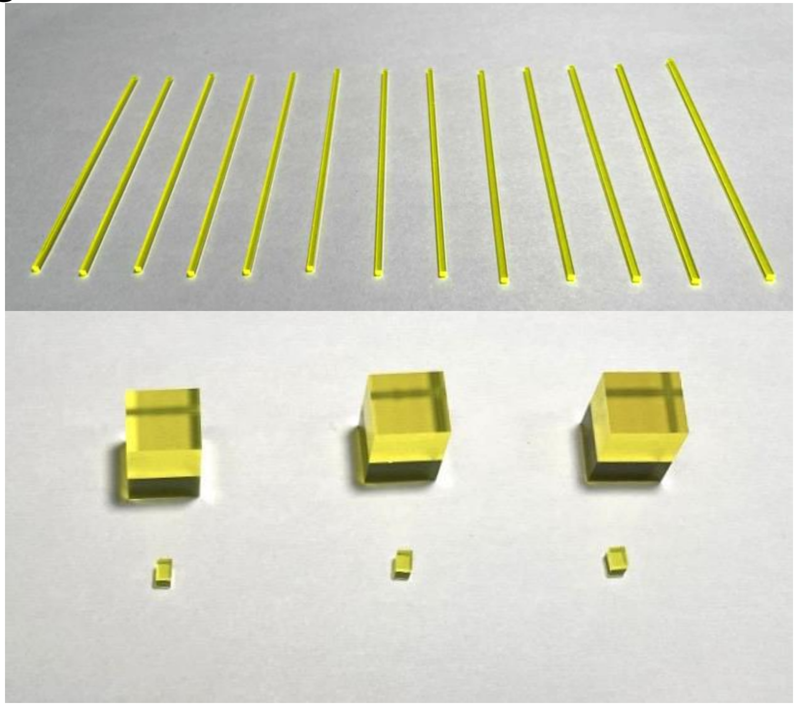
- **3D-printing tungsten absorber**
- **Latest test beam and results**
- **Electronics: timing ASIC**

Promising radiation-hard and fast scintillator: GAGG

- **Ce**rium-doped multi-component **G**adolinium **G**allium **A**luminium **G**arnet $Gd_3Al_2Ga_3O_{12}$ (**GAGG:Ce**)
  - Good radiation hardness
  - Higher density ($\sim 6.6\ g/cm^{-3}$) to other scintillators
  - High light output and relatively fast decay time ($\sim 50\ ns$) but still slower than desirable $\leq 25\ ns$
    - ✓ Tunable by changing **compositions** and **doping**

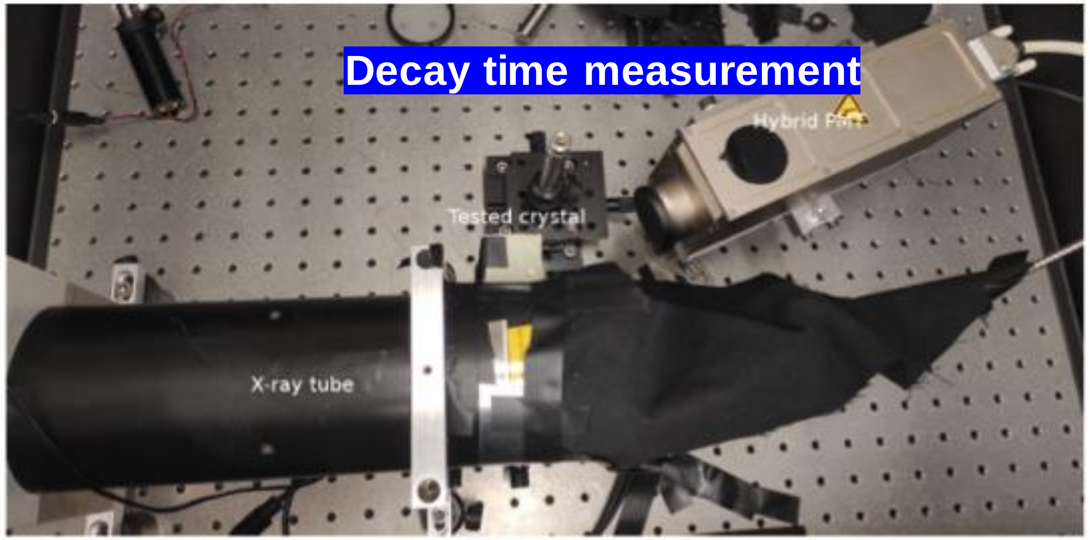
- R&D in progress with SIPAT
  - Optimize compositions and doping for shorter decay time
  - Good quality samples obtained

SIPAT 重庆胜普电子有限公司 CHONGQING SHENGPU ELECTRONICS CO. LTD

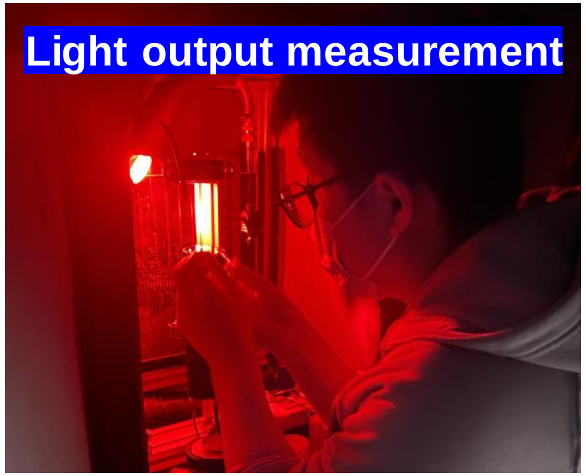


Measuring SIPAT GAGG samples

- Several samples sent to Beijing and CERN, and measured
  - **Light output**
  - **Decay time**
  - Absorbance
  - Photoluminescence spectrum
  - Coincidence time resolution



- Decay time of the samples are decreasing
  - Now at the level of $< 30\ \mathrm{ns}$ and light output at the level of $15\mathrm{k/MeV}$



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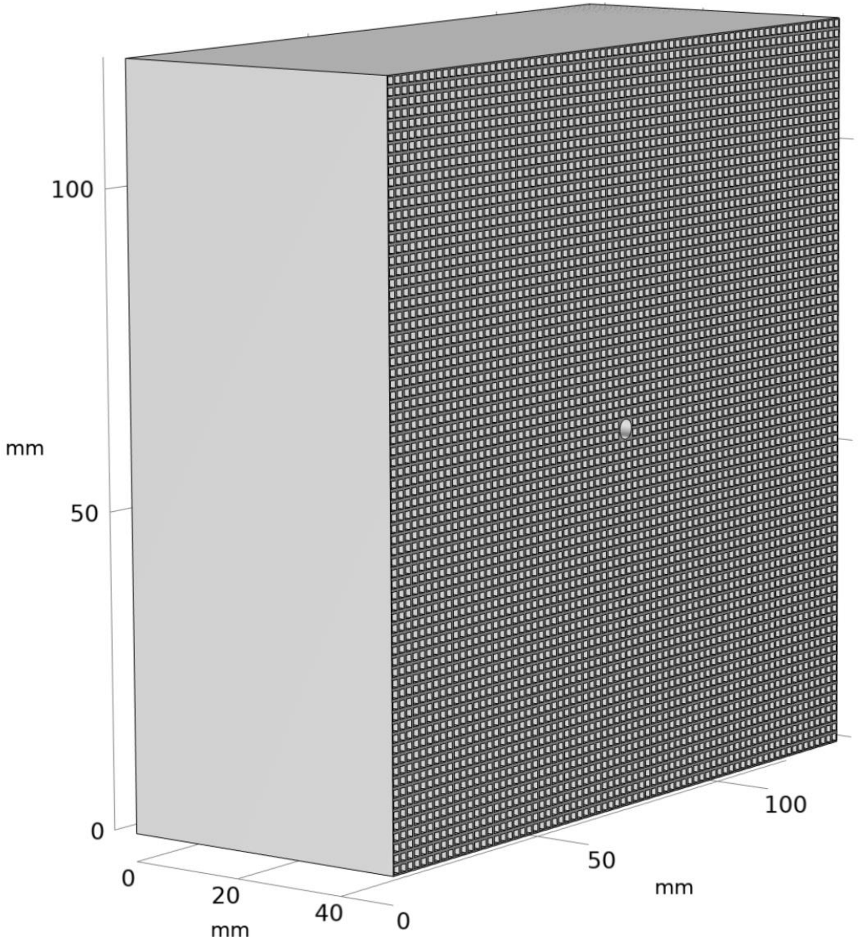
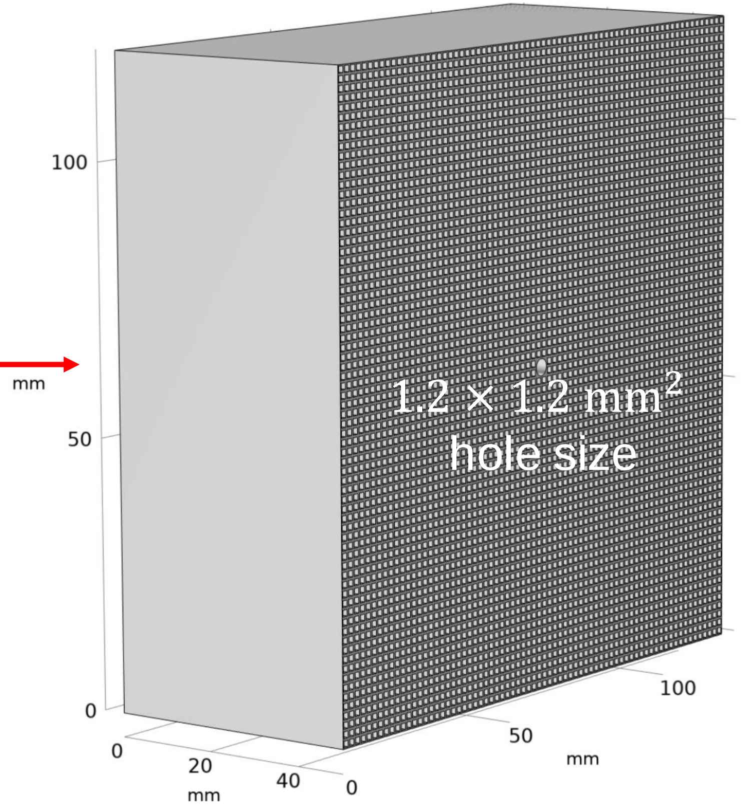
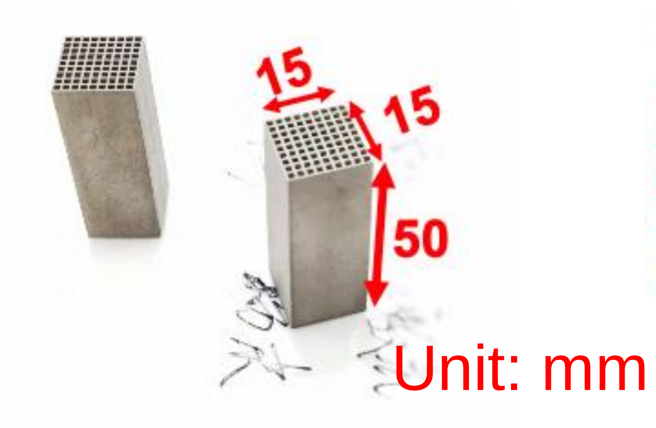
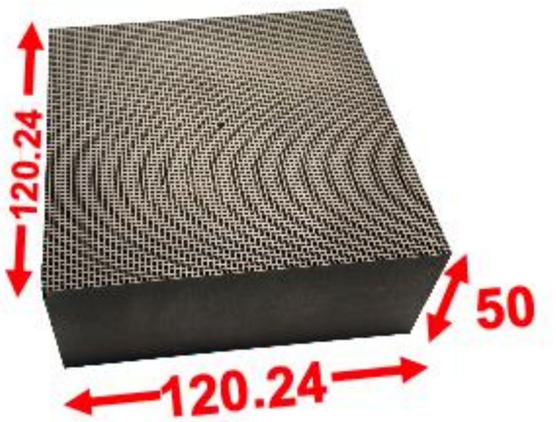


3D-printing tungsten absorber

- W has small radiation length and small moliere radius
- 3D-printing technology to ease W matrix production →
- R&D campaign
  - Collaboration with EOS, Germany
    - ✓ Full size $121 \times 121\ \mathrm{mm}^2$ absorber
  - Collaboration with LaserAdd, China
    - ✓ Good samples produced



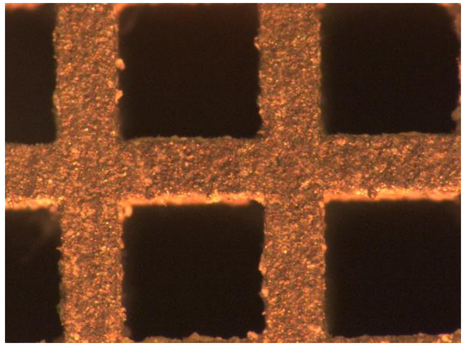




DiMetal-150 DiMetal-100H

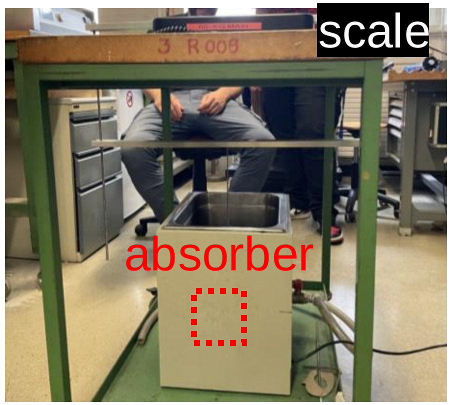
Characterization of W absorber

- The samples from LaserAdd are measured both in CERN and China

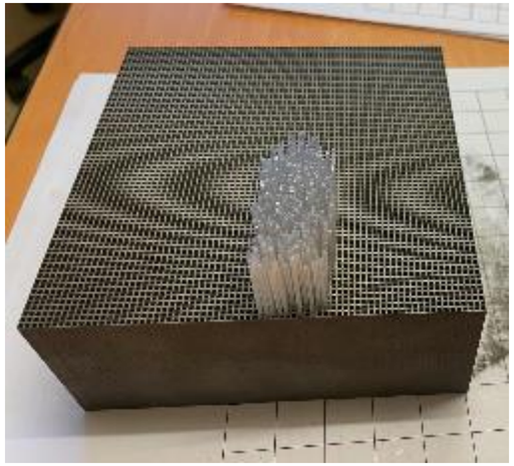


Microscopy picture

Measuring surface roughness in PKU



Measuring volume, density



Fiber insertion test

- Excellent roughness mandatory not to damage scintillating fibers
  - Relatively good roughness $R_a \approx 5\ \mu\text{m}$ achieved, but still need to improve
- Density (units: g/cm^3)

Pure W	LaserAdd	EOS
19.3	18.9	15.8

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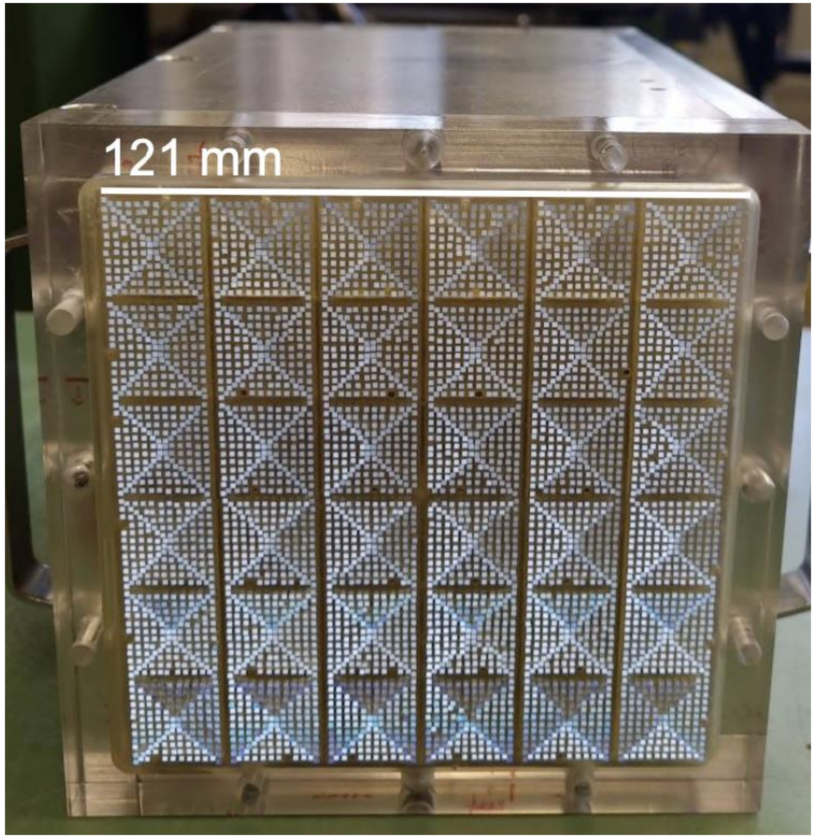
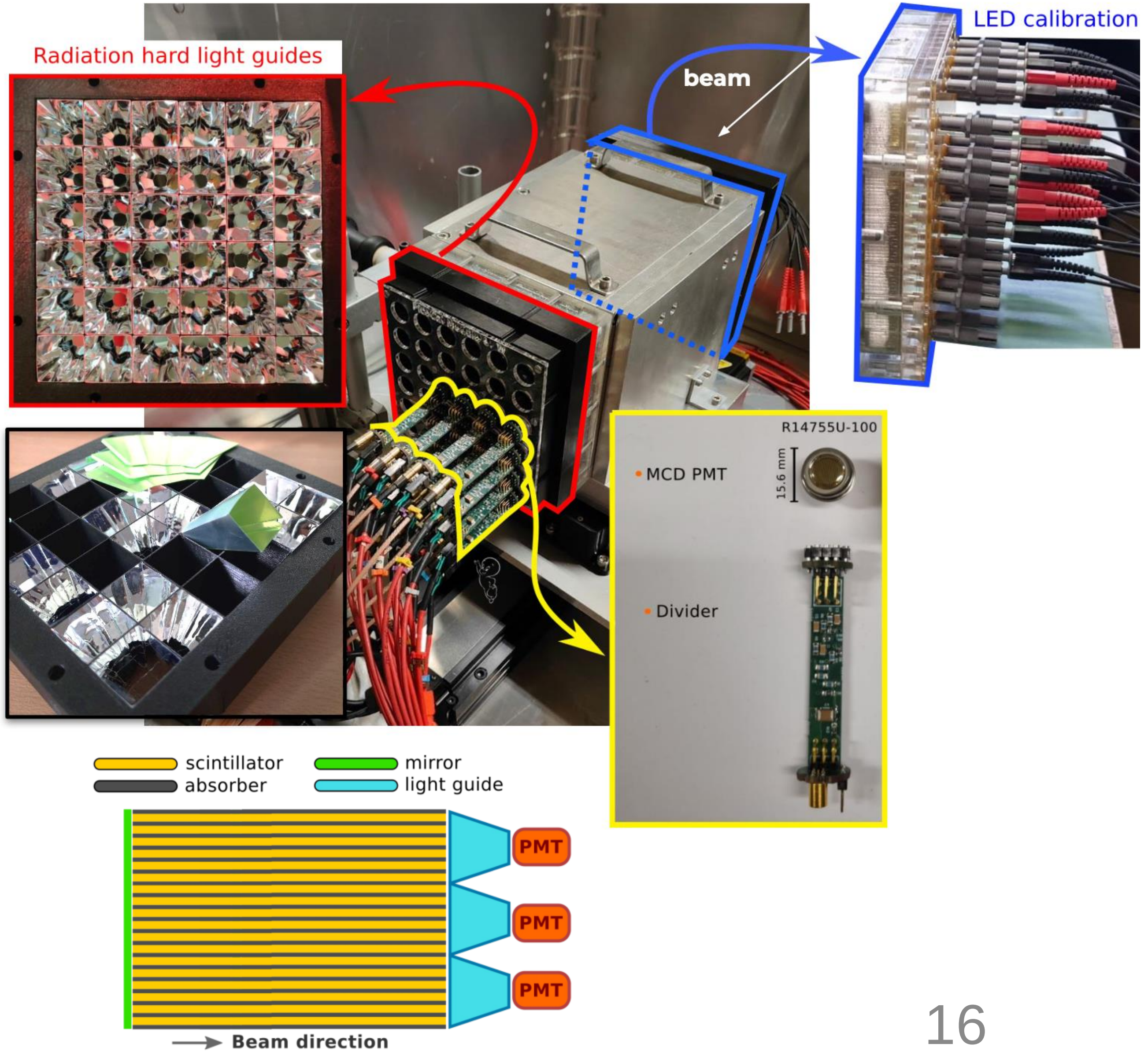


W-polystyrene “Module 0” for Upgrade Ib

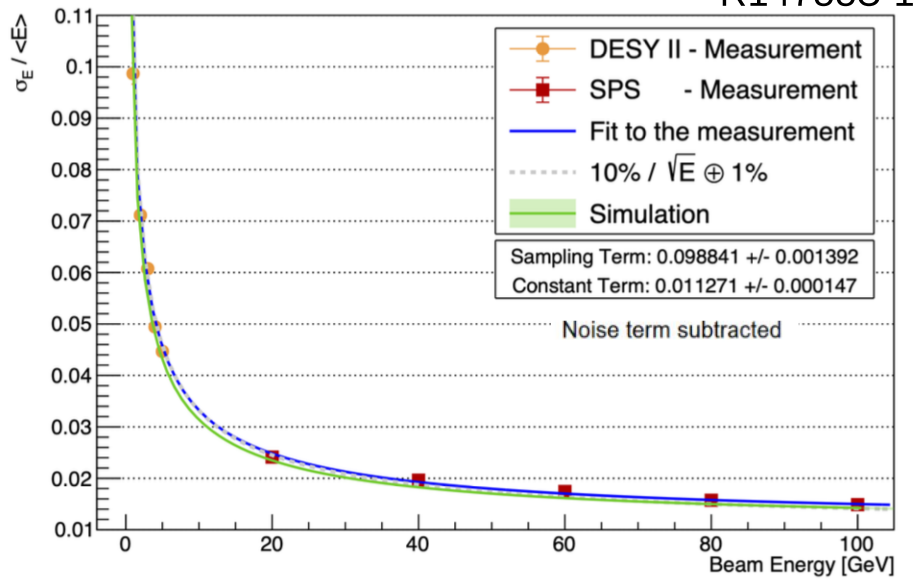
- Full size $121 \times 121\ \mathrm{mm}^2$ “module 0” with W absorber assembled at CERN
- 3D-printed W absorber (EOS)
  - $5 + 5 + 5 + 4 = 19\ \mathrm{cm}$ long
- Continuous Kuraray SCSF-78 square fibers $1 \times 1\ \mathrm{mm}^2$
- Hollow light guides made with ESR reflector
- MCD PMTs R14755U-100
- 1 calibration fiber per cell connected to LED
- Tested at DESY($1 - 5\ \mathrm{GeV}\ e^-$) and CERN SPS ($20 - 100\ \mathrm{GeV}\ e^-$)



Test beam results

- Energy resolution

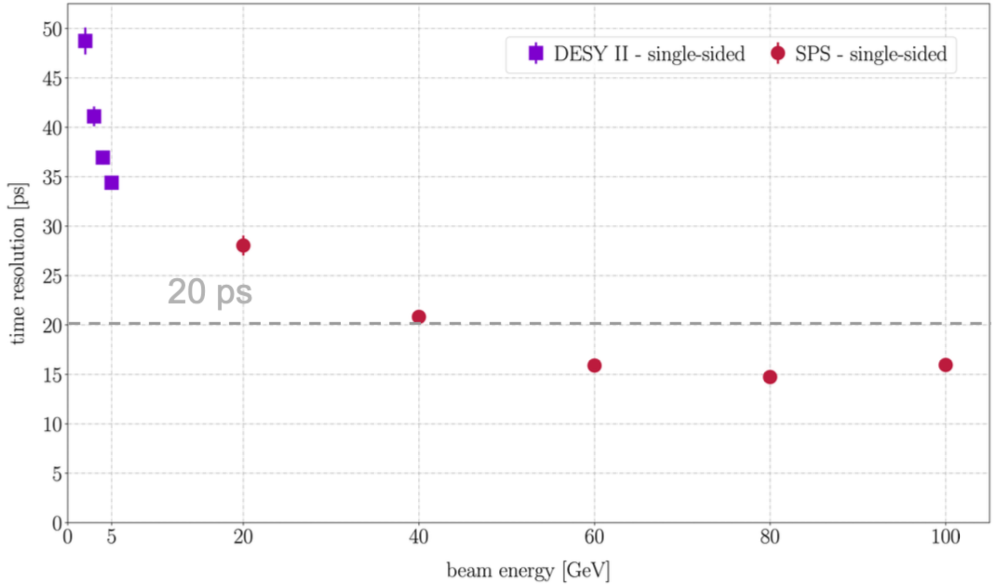
R14755U-100



- Incidence angle: $\theta_x = \theta_y = 3^\circ$
- "Module 0" prototype
- Sampling term: 9.9%, constant term: 1.1%
  - Agree with simulation

- Time resolution

R7600U-00-M4



- Incidence angle: $\theta_x = \theta_y = 3^\circ$
- Prototype with 2×2 cells
- Multi-anode PMT with 4 channels
- Time resolution: < 20 ps @ $E > 40$ GeV

[LHCb-TDR-024]

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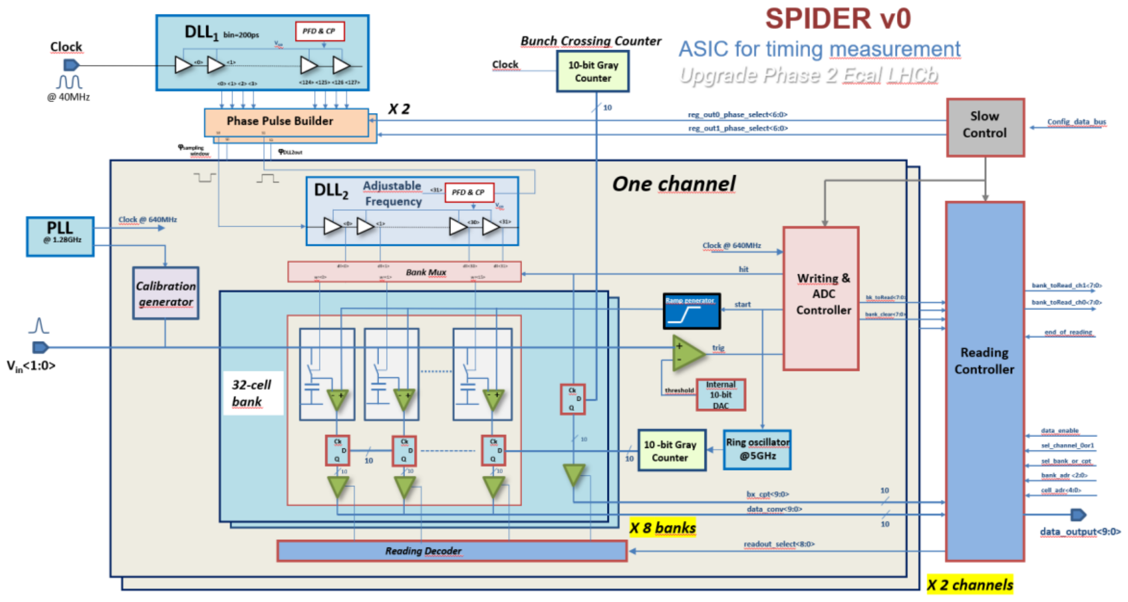
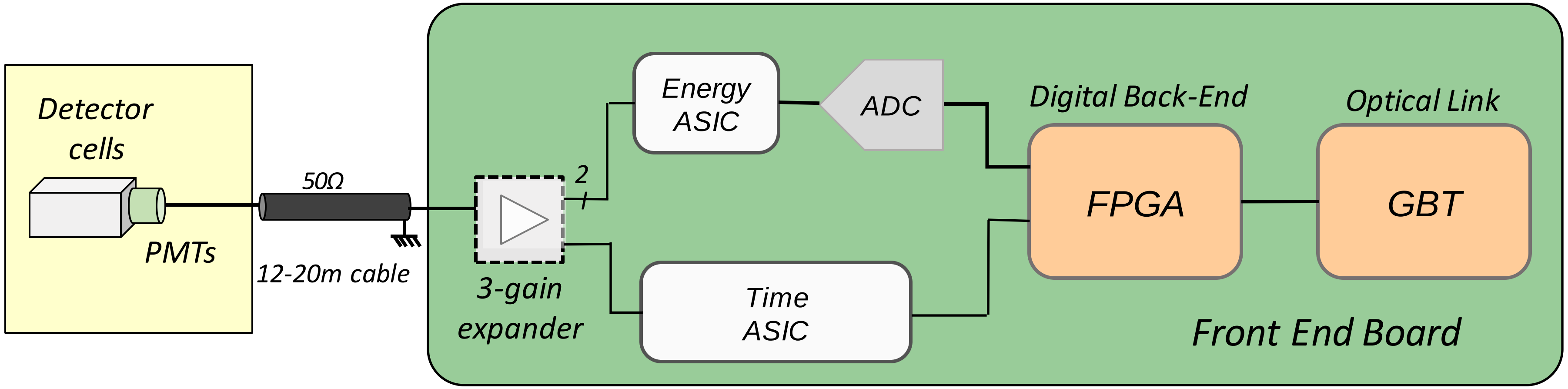


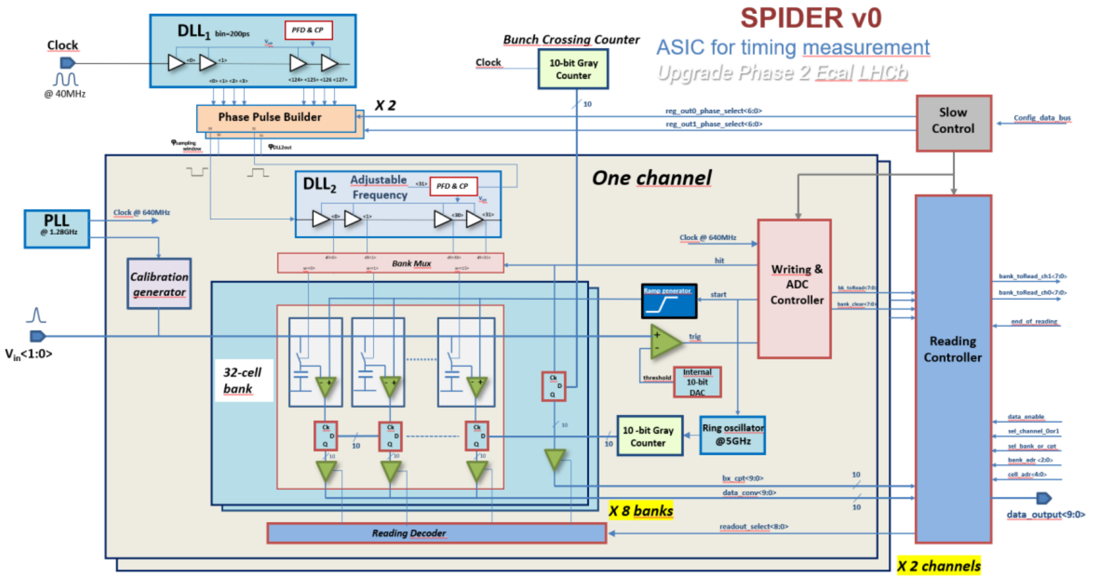
Timing ASIC



- Two separated processing paths with dedicated multi-channels ASICs (30000 channels) in
- The same technology: **TSMC CMOS 65 nm**
  - **Energy path** close to the current ICECAL scheme (mostly analog processing)
  - **Independent timing path** based on SPIDER waveform TDC : goal to have time measurement with 15ps resolution RMS for the full chain (from detector to Front-End board)
  - Development of the SPIDER (**S**wift **Pi**pelined **D**igitiz**ER**) ASIC in France (IJCLab Orsay, LPC Clermont-Ferrand, IP2I Lyon, LPC Caen)

SPIDER Design

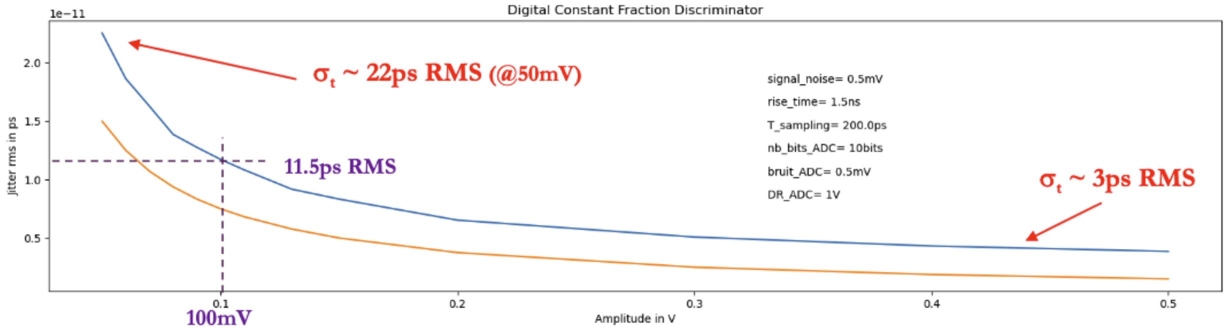
- Design of first version of the SPIDER ASIC ongoing: first prototype will be produced end of 2023
- The technology chosen is a ‘waveform TDC’ based on waveform sampling in analog memories
- Simulation shows that the required time resolution can be achieved with this technique



Schematics of the SPIDER ASIC

Timing jitter versus signal amplitude :

rise time = 1.5ns ; σ_{noise}= 500µV RMS ; σ_{SCA}= 500µV RMS



Waveform TDC simulation (Ph. Vallerand)

Summary

- LHCb ECAL scheduled for upgrade during 2026-2028 (Upgrade Ib) and 2033-2034 (upgrade II)
- SpaCal-W technology will be used in the innermost region
- Many R&D works in progress
  - GAGG crystal with a fast decay time
  - Good quality 3D-print W absorber
  - “Module 0” test beam characterization
  - Timing AISC: SPIDER
  - …

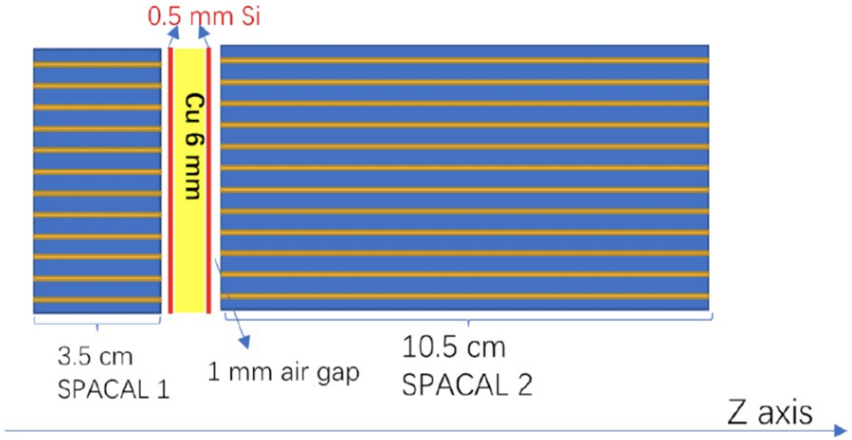
A lot work to do! Welcome to join!

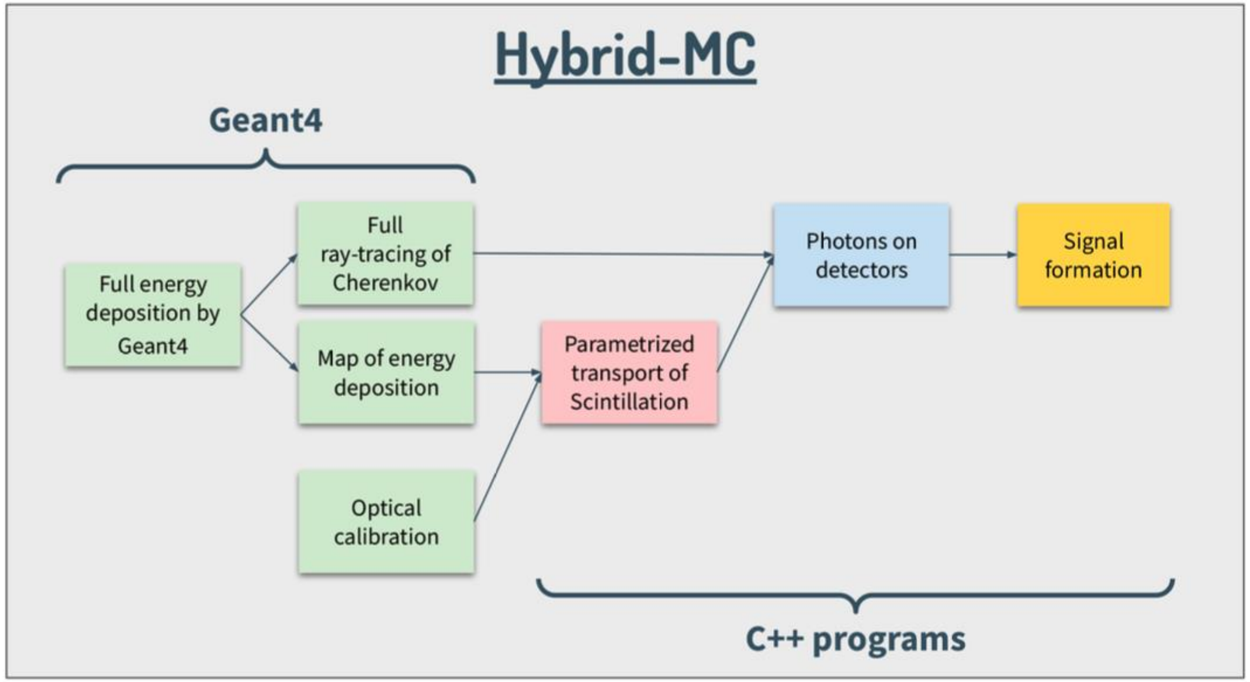
Thanks for your attention!

Backup

Parameterized simulation

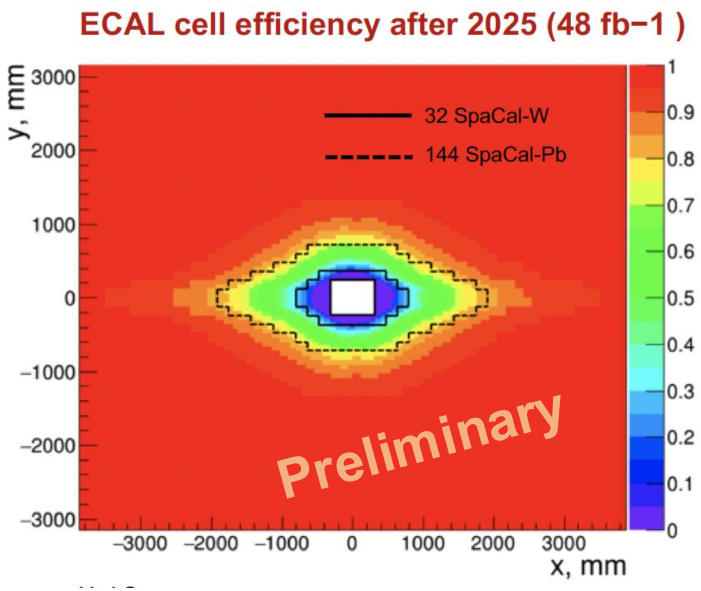
- In simulation, optical photons ray-tracing needed, but extremely CPU-consuming ➔ parametrized simulation developed
- **Hybrid-MC**: Geant4 simulation of energy deposit and parametrized transport of scintillation photons
  - Around a factor of 1000 acceleration
- Flexible for various setups
  - Including the setup adding Si time layer

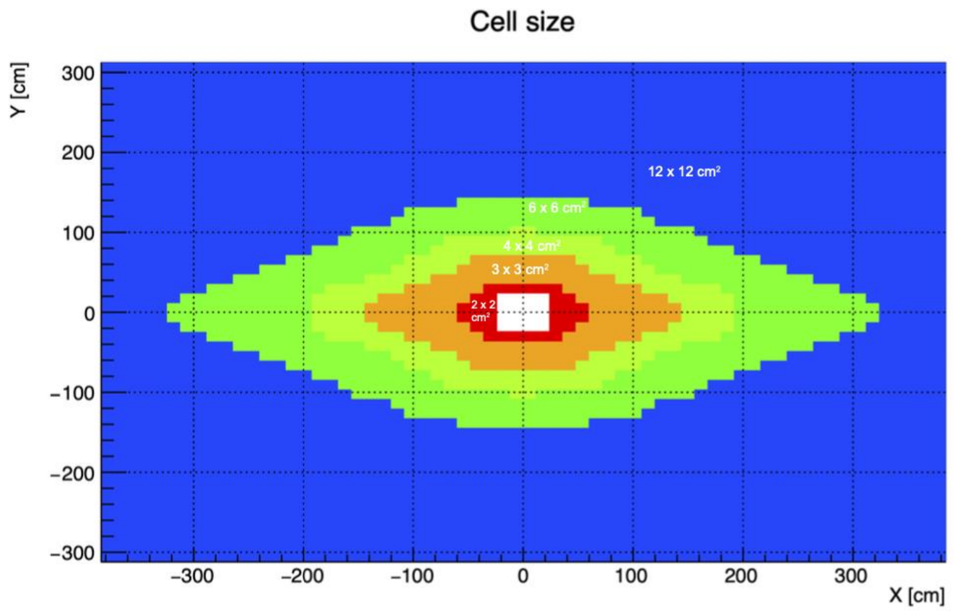




[LHCb-TDR-024]

Baseline setup for ECAL Upgrade Ib





Yuri Guz

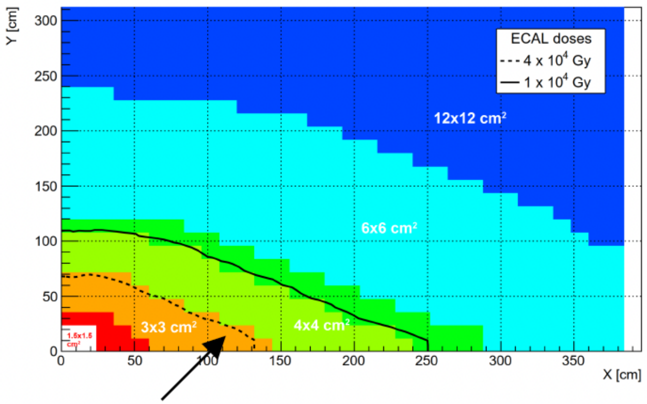
Cell size:	Modules:
2 x 2 cm^2	32 *new* SpaCal-W modules → W absorber + plastic fiber
3 x 3 cm^2	144 *new* SpaCal-Pb modules
4 x 4 cm^2	176 existing modules in rhombic configuration
6 x 6 cm^2	448 existing modules in rhombic configuration
12 x 12 cm^2	2’512 existing modules in rhombic configuration

Baseline setup for ECAL Upgrade II

5 ECAL regions matching the radiation maps:

Philipp Roloff

Cell size:	Modules:
1.5 x 1.5 cm^2	32 *new* modules for extreme conditions of up to 1 MGy
3 x 3 cm^2	144 *new* modules with "moderate" radiation requirements of up to ≈ 200 kGy
4 x 4 cm^2	272 *new* modules + 176 refurbished existing modules (add long. segmentation?)
6 x 6 cm^2	896 rebuilt + 448 refurbished existing modules (add long. segmentation?)
12 x 12 cm^2	1'344 refurbished existing modules (add long. segmentation?)



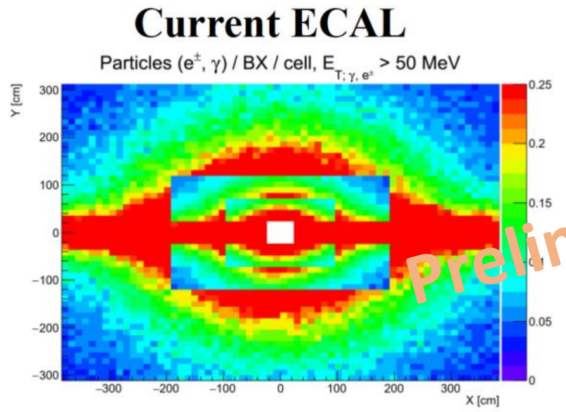
Radiation limit of current Shashlik technology

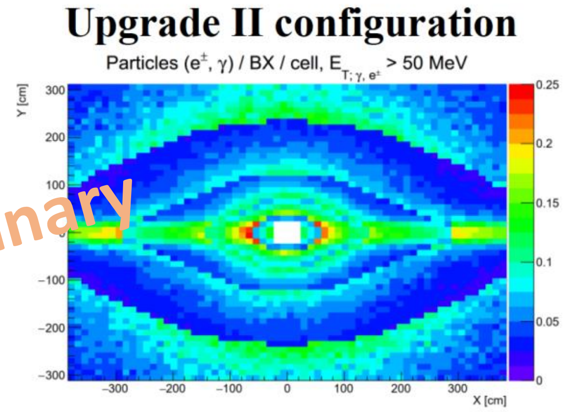
Number of channels:
Current ECAL: 6'064 cells (6'016 channels read)
Full double-sided readout (long. segmentation):
30'208 channels

The SpaCal modules need to be tiled to meet the energy resolution target

Downscoped variant: double-sided readout only for the SpaCal modules

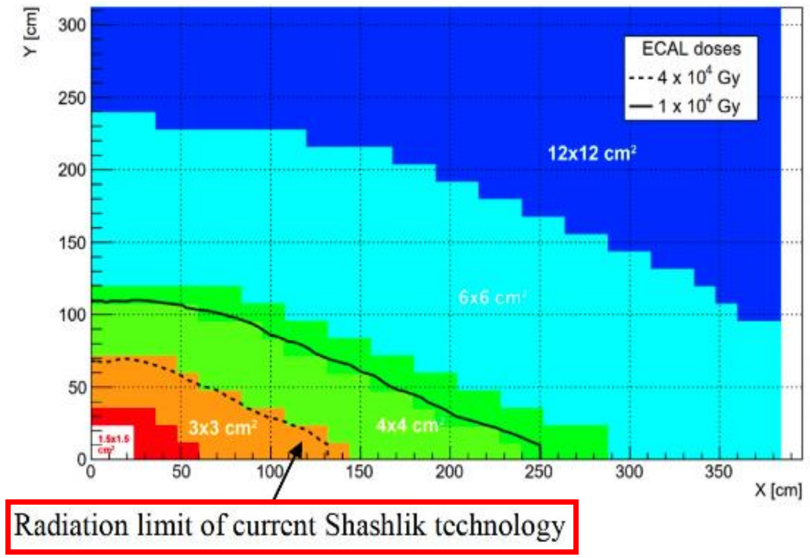
CERN/LHCC 2021-012





LHCb ECAL upgrade II strategy

- Radiation hard SpaCal with longitudinal segmentation
  - 32 innermost modules with crystal scintillating fibers and W absorber; $1.5 \times 1.5\ \mathrm{cm}^2$ cell
  - 144 next inner modules with radiation-tolerant organic scintillating plastic fibers and Pb absorber; $3 \times 3\ \mathrm{cm}^2$ cell
- Shashlik modules in outer region
- Time information and double-sided readout for the full ECAL



Much larger radiation dose
Much increased granularity

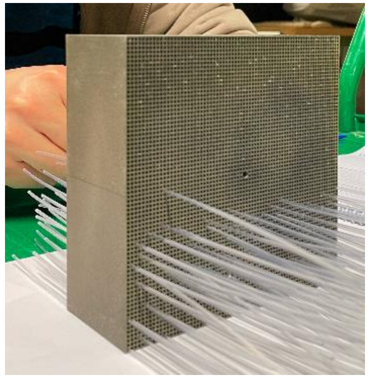
→

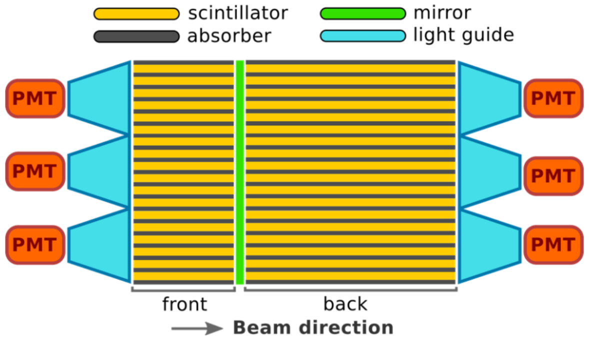
Radiation hard scintillating fibers
Smaller Moliere radius, dense materials

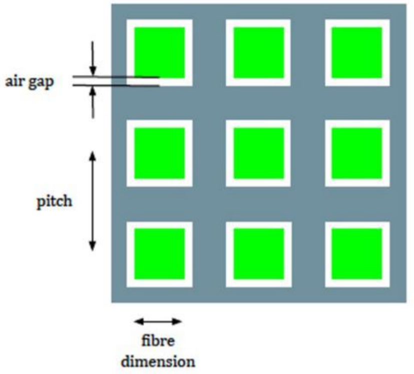
Radiation-hard scintillator and dense scintillator and absorber important

SpaCal technology

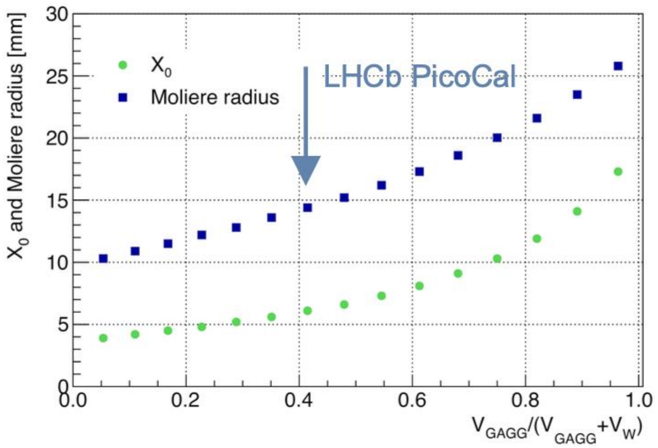
- Spaghetti Calorimeter (SpaCal) technology
  - Used in the harsh irradiation environment
  - Flexible technology for tuning radiation length, Moliere radius, and energy resolution
    - ✓ Example: Variation of fiber size with constant pitch in SpaCal-W/GAGG

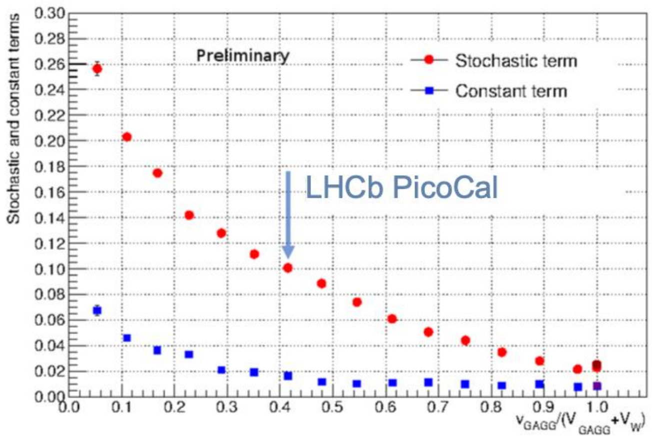






GAGG fibers/W absorber

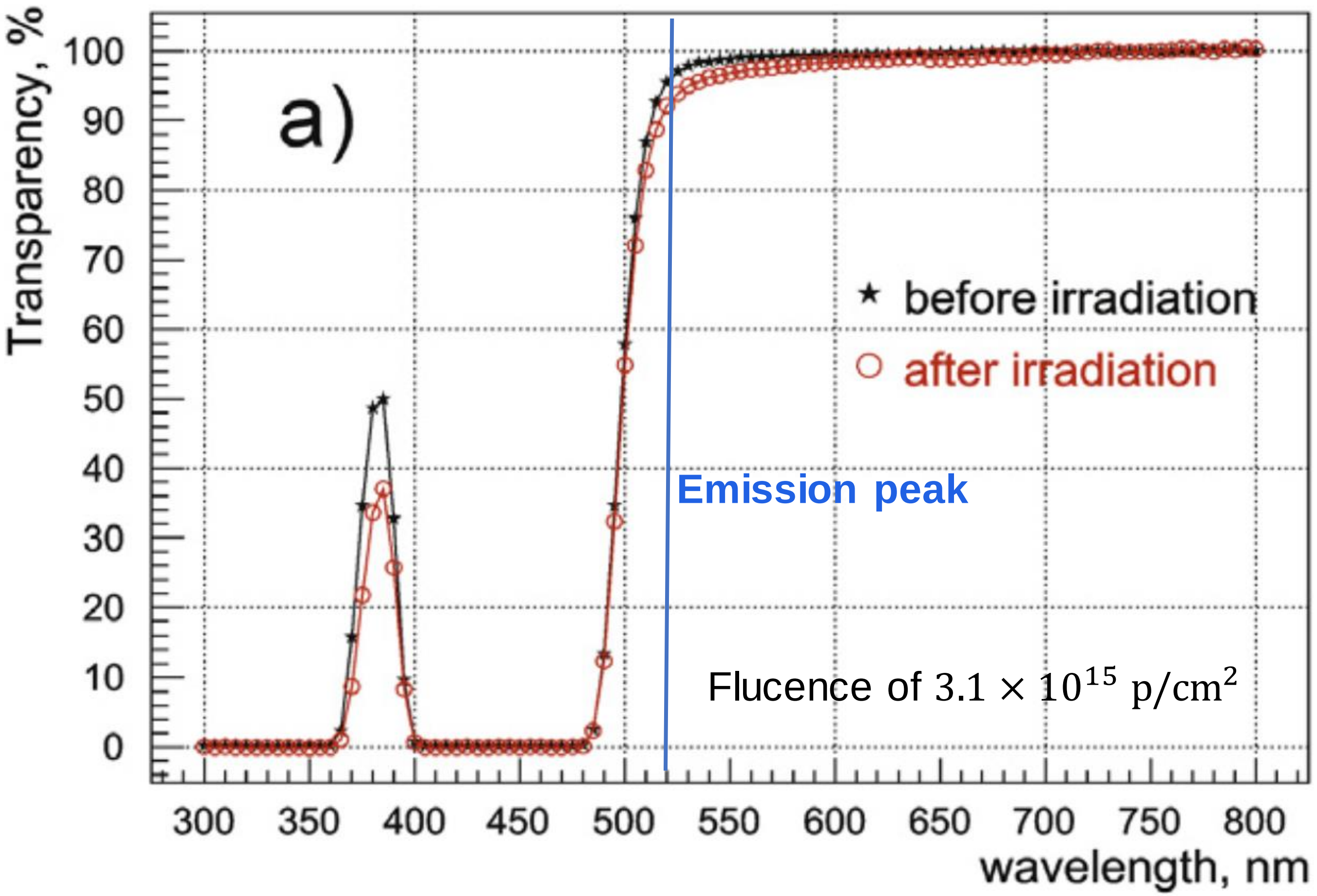




- Furthermore: longitudinal segmentation to improve timing resolution, reconstruction, particle identification and have less effect from radiation damage

Radiation hardness

[V. Alenkov et al., NIM A 816 (2016) 176]



Flucence of 3.1×10^{15} p/cm^2

Tunable scintillation properties for GAGG

[L. Martinazzoli et al., NIM A, 2021, 165231]