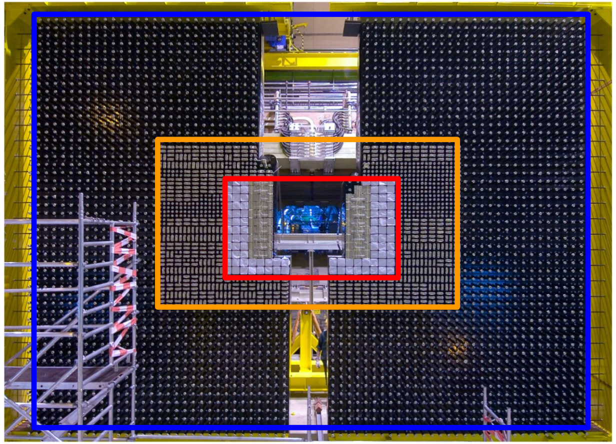
Scintillating sampling ECAL technology for the LHCb PicoCal

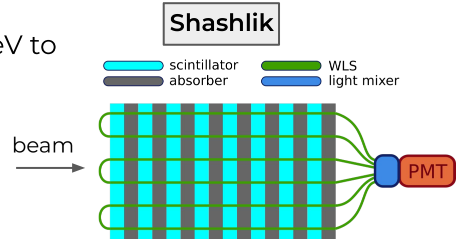
Matteo Salomoni, on behalf of the LHCb ECAL Upgrade II group.

August 23rd 2023, EPS Hamburg

Current LHCb ECAL configuration



- **Optimised for π^0 and γ identification** in the few GeV to 100 GeV region at 2 x 10^{32} $cm^{-2}s^{-1}$
- Shashlik technology:
  - 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

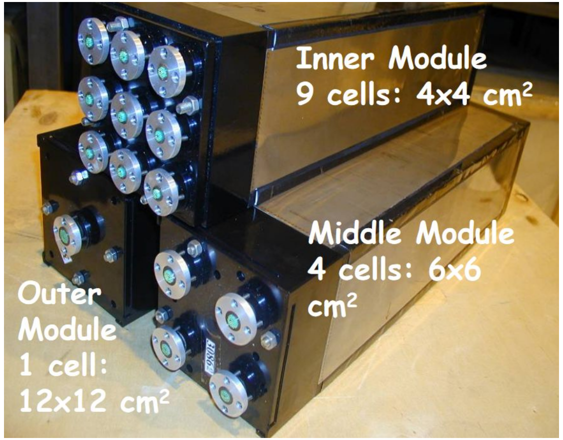


→ three square sections:

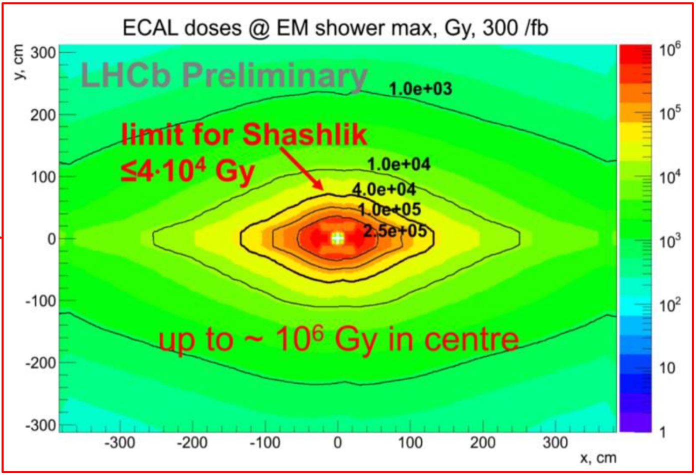
176 modules with 4 x 4 cm^2 cell size

448 modules with 6 x 6 cm^2 cell size

2688 modules with 12 x 12 cm^2 cell size



Requirements for ECAL Upgrade II

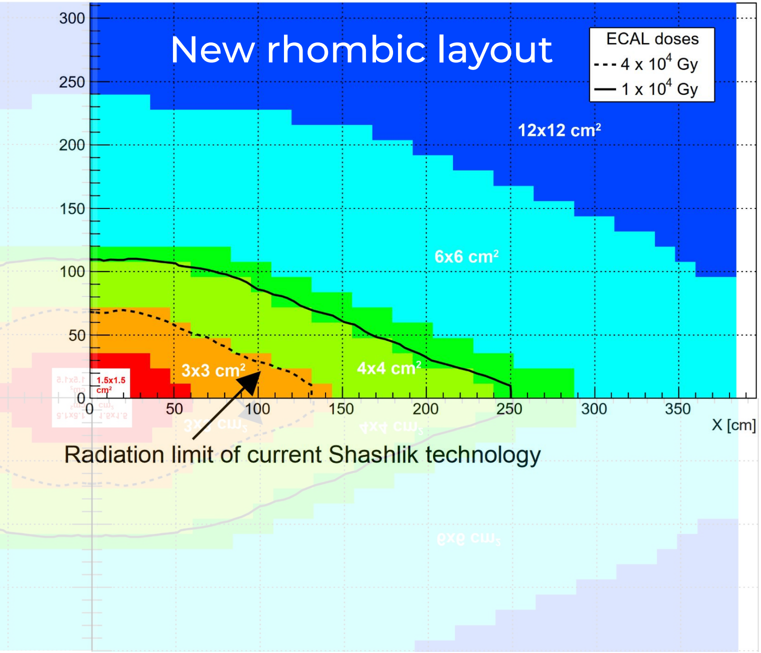


1. Sustain radiation doses up to 1 MGy and ≤ 6×10^{15} 1 MeV n_{eq} /cm^2
2. Pile-up mitigation
   → Timing capabilities with O(10) ps precision
   → Increased granularity in the central region with denser absorber
3. Keep current energy resolution of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$

From LHCb TDR 24
https://cds.cern.ch/record/2866493/files/LHCB-TDR-024.pdf

Sampling calo technology for Upgrade II:

(double-sided readout)



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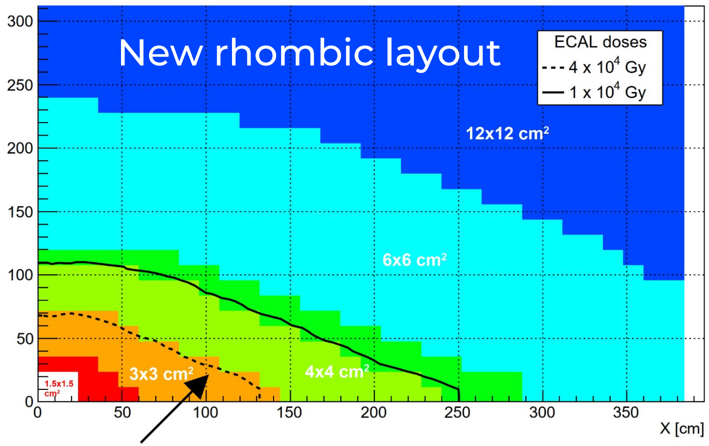
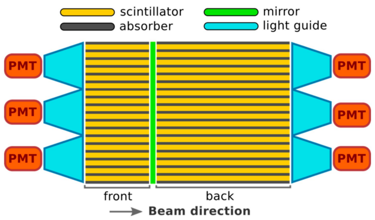


Radiation limit of current Shashlik technology



SpaCal for inner regions (32 ▣, 144 ▣):

- ▣ Innermost modules (> 200 kGy) with scintillating crystal fibers and **W absorber**
  - ➔ Development of radiation-hard scintillating crystal fibers, 1.5x1.5 cm^2 cell size.

Both regions are tilted 3+3 degrees

- ▣ 40-200 kGy region with scintillating plastic fibers and **Pb absorber**
  - ➔ Longitudinal segmentation can mitigate the radiation damage.

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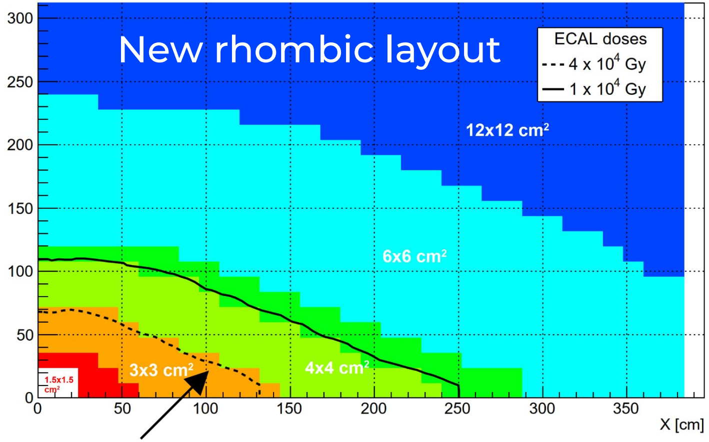

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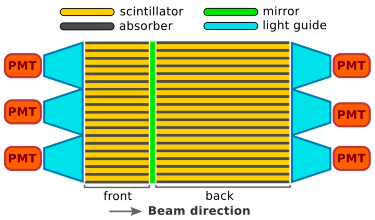
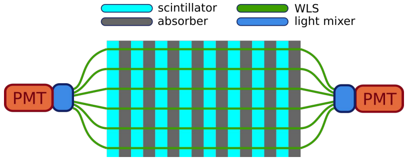
SpaCal



Shashlik



Shashlik for outer regions (■, ■, ■):

- Timing with new WLS fibers
- Cost optimisation by refurbishing existing modules for timing could be possible

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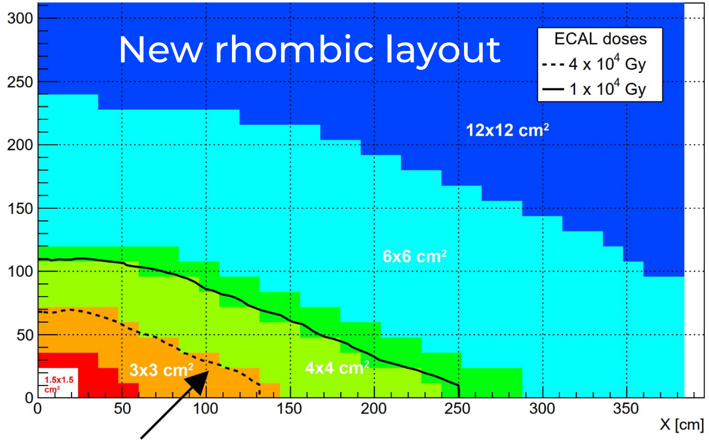

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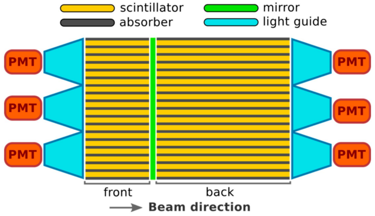
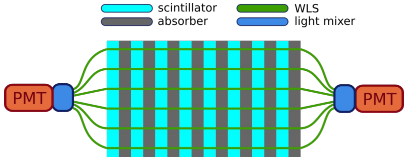
SpaCal



Shashlik



Shashlik for outer regions (■, ■, ■):

- Timing with new WLS fibers
- Cost optimisation by refurbishing existing modules for timing could be possible

LS3 enhancement (single-sided readout):

■ equipped with scintillating plastic fibers for 2x2 cm^2 cell size. ■ same. ■, ■, ■ only existing modules.

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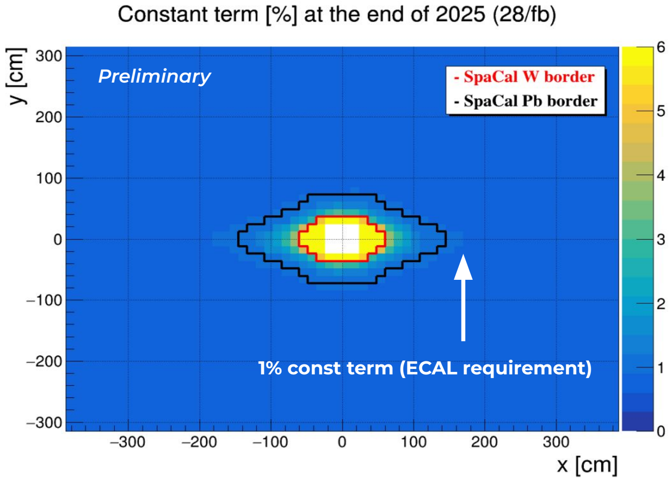
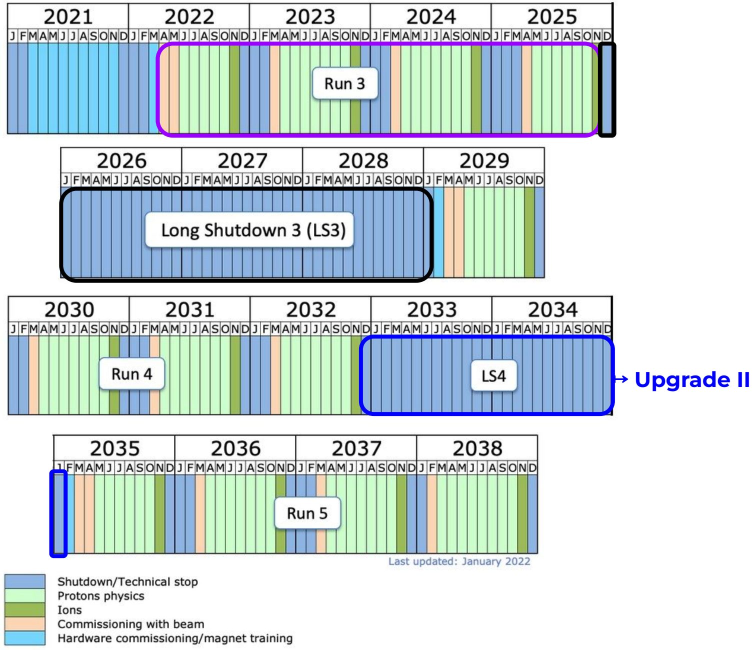
https://cds.cern.ch/record/2776420/files/LHCB-TDR-023.pdf

Strategy motivation

LS3 enhancement:
Run 3 with Shashlik modules at L=2 x 10^{33} $cm^{-2}s^{-1}$ will already suffer enough radiation damage to increase the constant term of the modules:

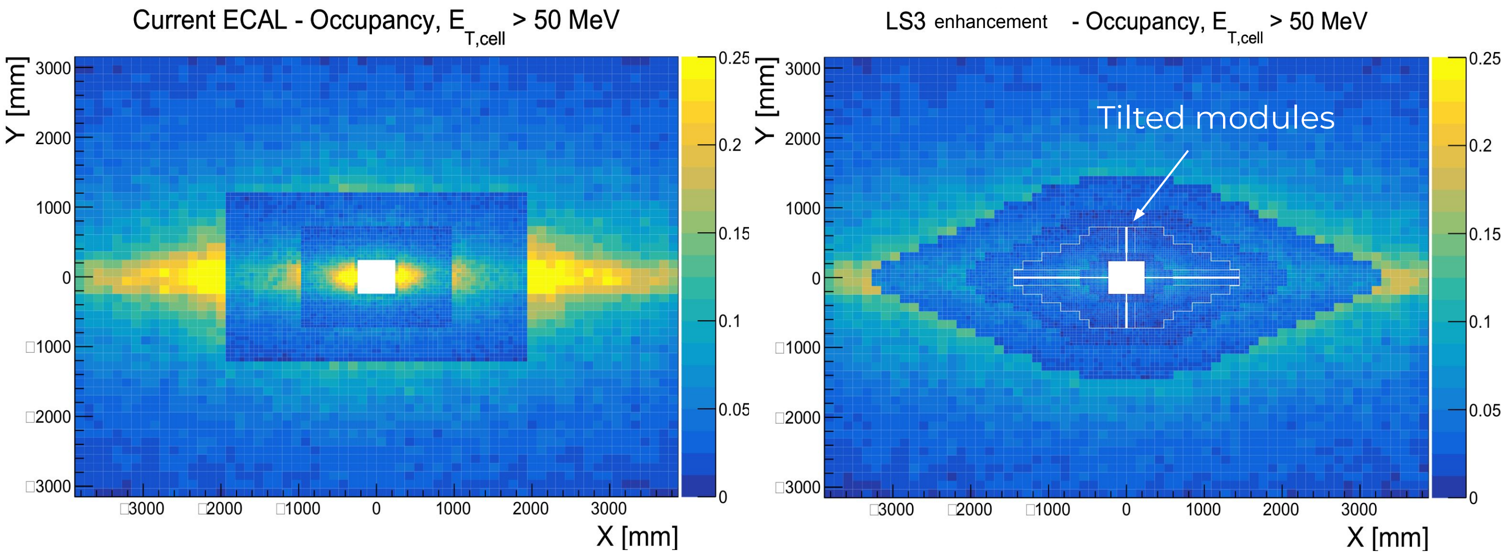




LS4:
(on top of high rad. tolerant scintillator and time resolution implem.)
Benefits of double-side readout: radiation hardness, time resolution, events reconstruction and particle ID.

Effect of improved granularity

Simulated LS3 conditions, assuming a luminosity: $L = 2 \times 10^{33}\ cm^{-2}s^{-1}$ and including the hadronic component:
(No time resolution information used)



➔ Sizeable occupancy in large regions before LS3 (Run 3) (e.g. challenge for neutral pion reconstruction)
➔ Occupancy map after LS3 enhancement reasonably flat.

From LHCb TDR 24
https://cds.cern.ch/record/2866493/files/LHCB-TDR-024.pdf

Physics performance: $B^0 \to K^{*0}\gamma$

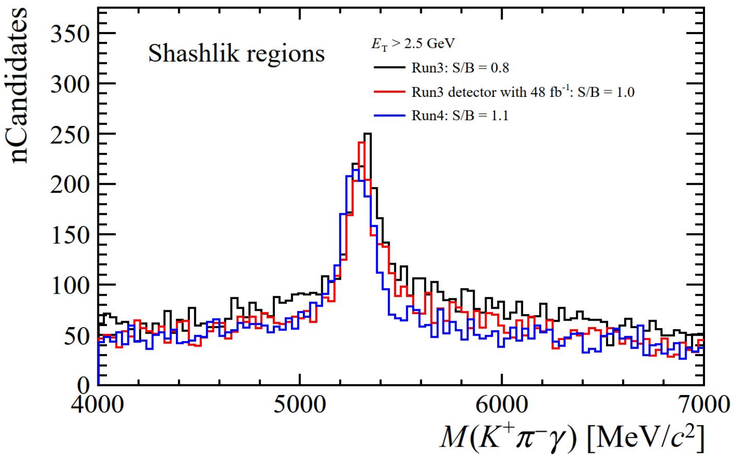
Reshuffled Shashlik region:

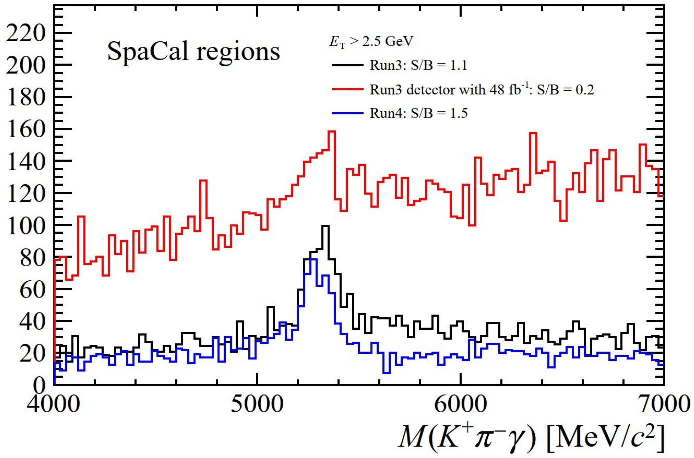
➔ As expected, the rearrangement of the modules produces just small improvement in S/B

SpaCal region (35% of the photons from $B^0 \to K^{*0}\gamma$ decays):

➔ improvement due to the smaller cell sizes in Run 4.

➔ combinatorial background expected for the Run 3 detector strongly increases with the radiation damage.





From LHCb TDR 24
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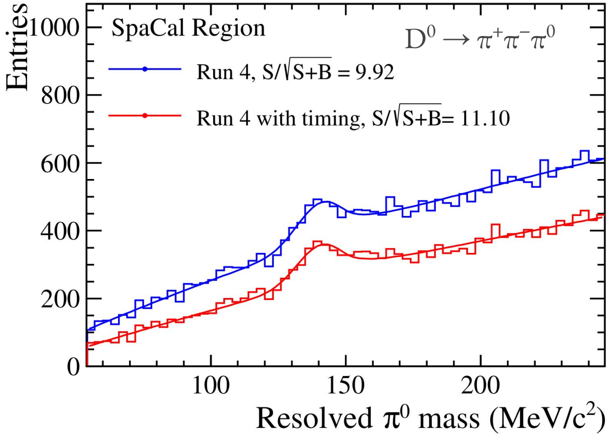
Effect of improved time resolution

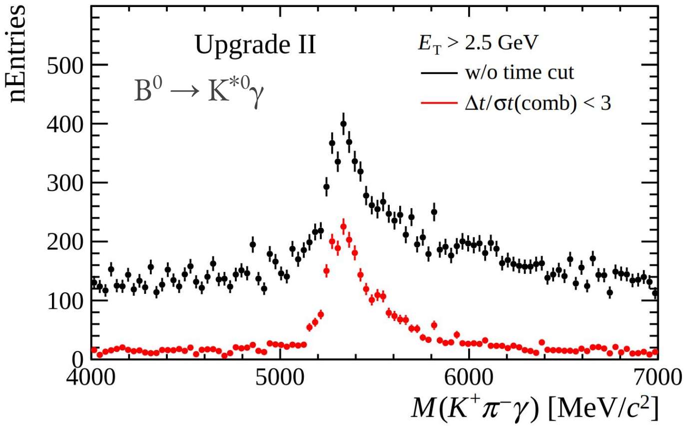
$D^0 \rightarrow \pi^+\pi^-\pi^0$:

➔ time resolution of O(10) ps in the SpaCal region would improve significance by ~10% after LS3

$B^0 \rightarrow K^{*0}\gamma$:

➔ time resolution cut is expected to improve mass resolution in Upgrade II





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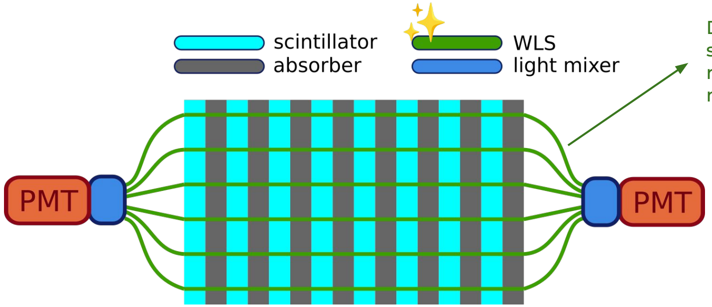
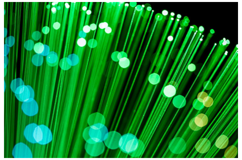
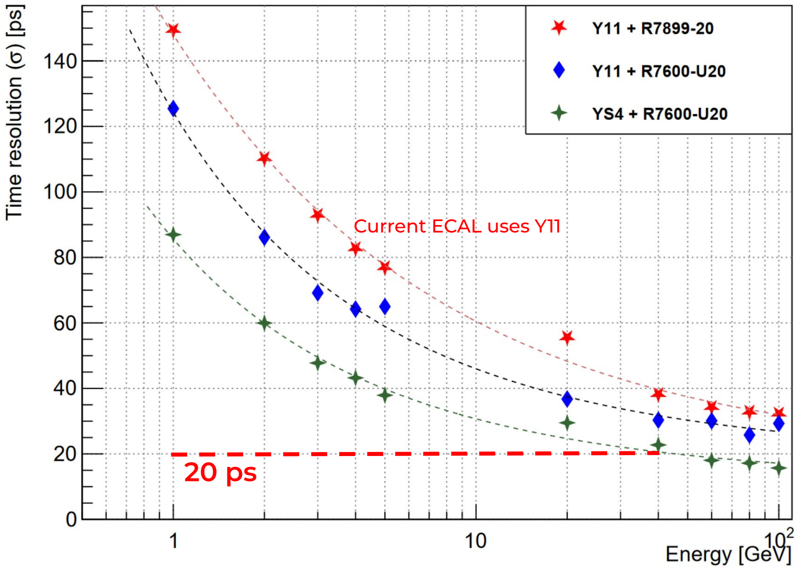
Shashlik: R&D towards Upgrade II



Double - side readout + new WLS!



Test beam results (electrons)



Energy resolution: better than 10%/√E ⊕ 1%
Time resolution: 20 ps at 100 GeV with YS4
Moliere radius: 3.6 cm
Length: 42 cm (25 X_0)
Double-side readout
YS2 or YS4 WLS
Hamamatsu R7600-U20/R11187 PMT
Radiation tolerance: up to 40 kGy

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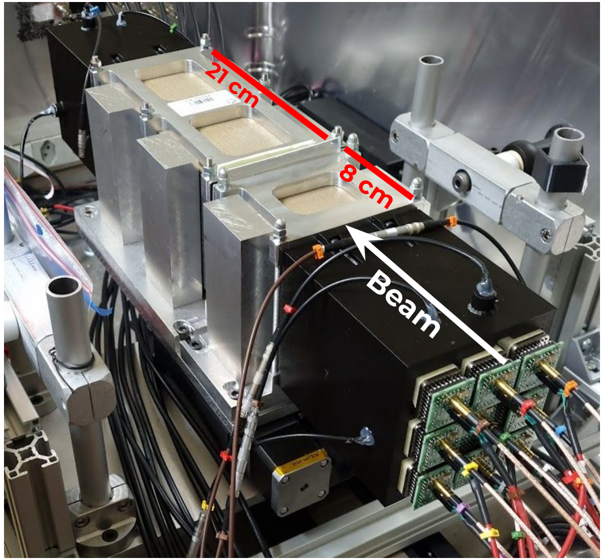
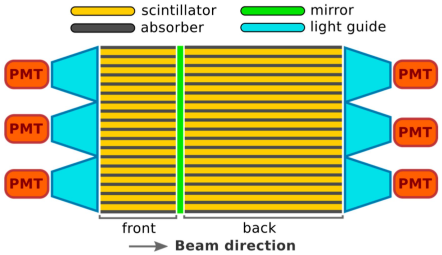
https://cds.cern.ch/record/2866493/files/LHCB-TDR-024.pdf

Prototype: SpaCal-Pb LS4



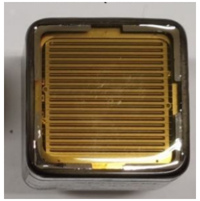
9-cell double-side readout prototype:

- $3x3\ cm^2$ cells
- Lead absorber
- Kuraray polystyrene scintillating fibers SCSF-78, single cladding, round section
- Fiber dimension: 1 mm
- Pitch between fibers: 1.67 mm
- Total length: 29 cm, 25 X_0 (8 front section + 21 back section in **LS4**)



PMTs:

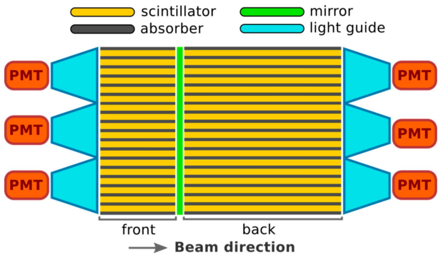
Hamamatsu R7600U-20
metal channel dynode (MCD) PMT

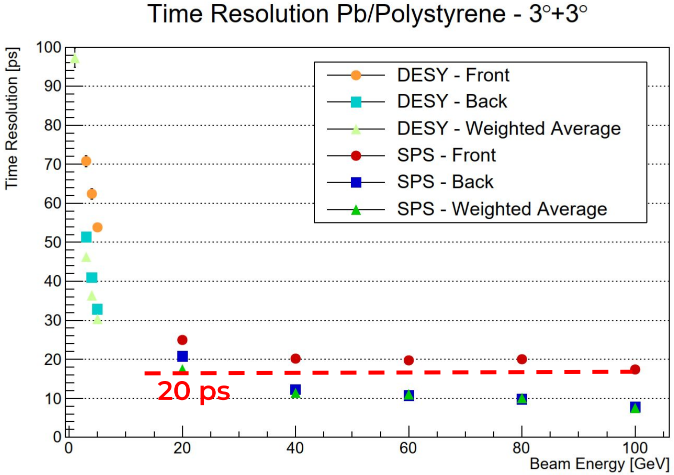


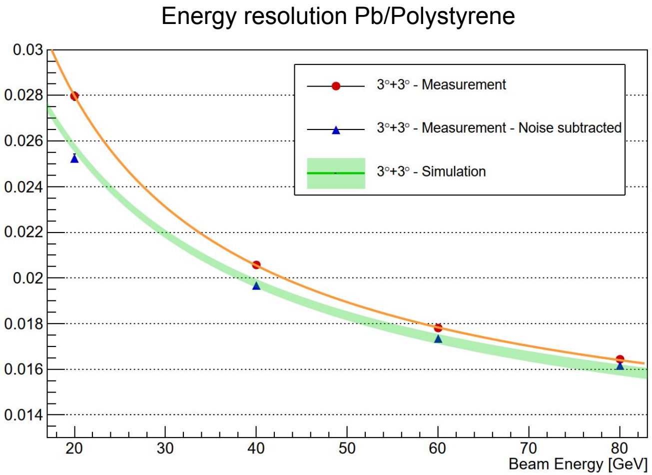
Prototype: SpaCal-Pb LS4

Test beam results:

- Time resolution of 20 ps at 20 GeV (front and back section weighted average, seed cell)
- $\sigma(E)/E = (10.0 \pm 0.6)\%/\sqrt{E} \oplus (1.2 \pm 0.1)\%$
- Good matching with simulations (with noise term subtraction)





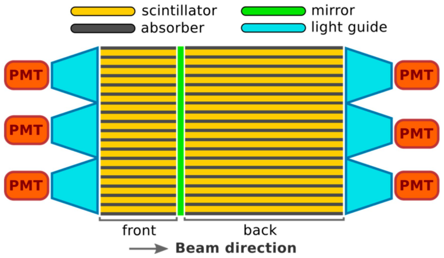


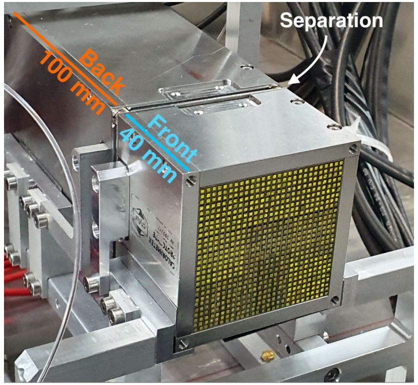
From LHCb TDR 24
https://cds.cern.ch/record/2866493/files/LHCB-TDR-024.pdf

Prototype: SpaCal-W LS4

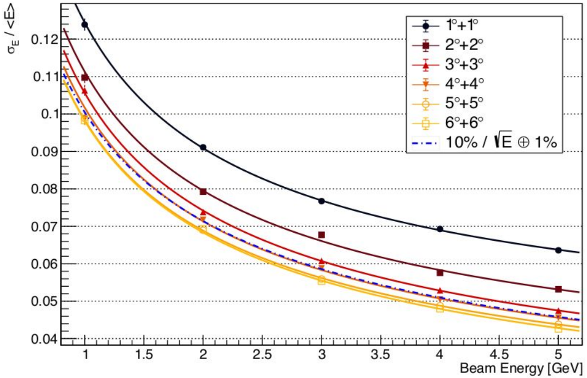
Pure tungsten absorber with 19 g/cm³

- Crystal garnet scintillating fibers (1x1 cm², cut from ingot)
- 9 cells, each 1.5 x 1.5 cm² (RM ≈ 1.45 cm)
- Longitudinal segmentation at the shower maximum
- 4 + 10 cm long split (7+18 X_0), pitch 1.7 mm
- Reflective mirror between sections
- Two photodetectors readout:
  - Energy resolution: Hamamatsu R12421 ⟿ (10.2 ± 0.1)% ⊕ (1.2 ± 0.3)%.
  - Timing resolution: Hamamatsu R7600U-20 metal channel dynodes ⟿ 20 ps @ 5 GeV

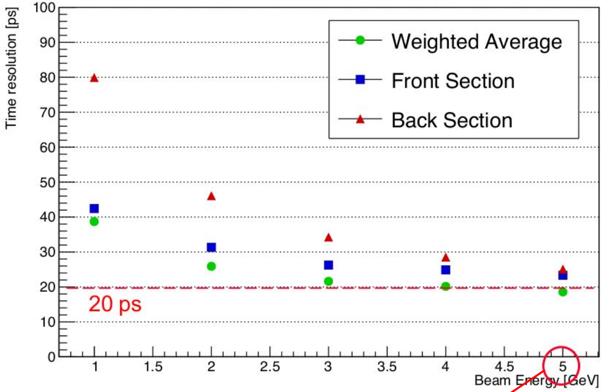




Energy resolution (DESY 2020 , R12421)



Time resolution (DESY 2020 , R7600-20)



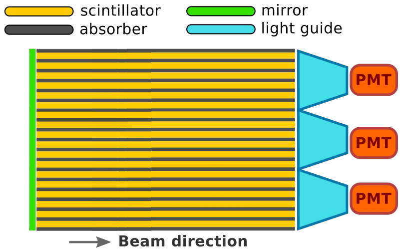
Expected to improve at higher energies

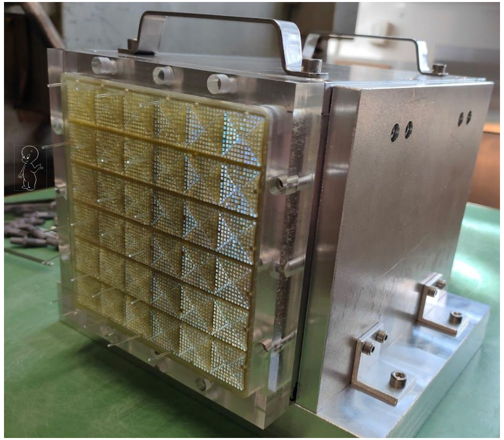
NIM A 1045, 167629 (2023)
https://arxiv.org/abs/2205.02500

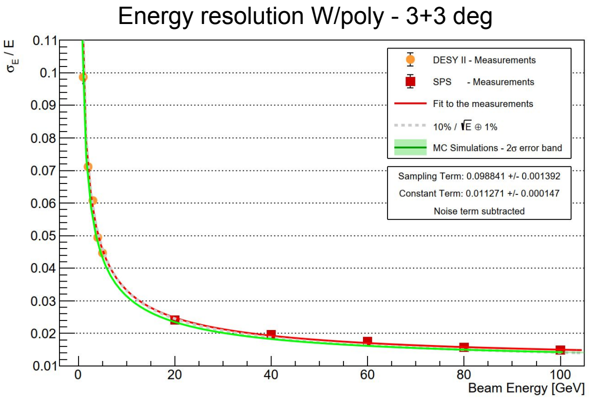
Prototype: SpaCal-W for LS3

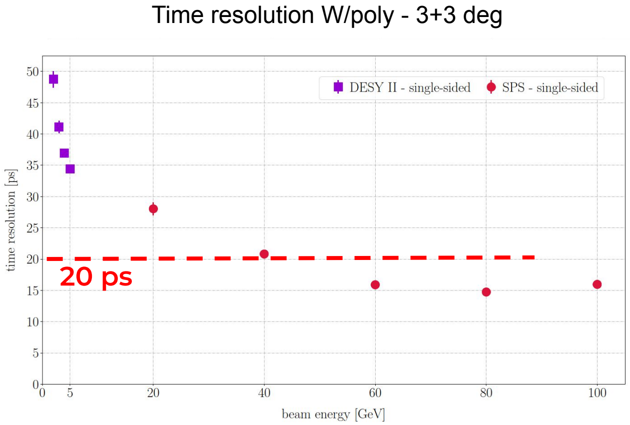
36-cell prototype:

- 2x2 cm^2 cells
- 3D printed tungsten absorber
- Kuraray polystyrene scintillating fibers SCSF-78, single cladding, square section
- Fiber dimension: square, 1 mm
- Pitch between fibers: 1.67 mm
- Single section, continuous fibers.
- Total length: 19 cm
- Energy resolution: $(9.9 \pm 0.1)\% \oplus (1.11 \pm 0.02)\%$.
- Timing resolution: 20 ps @ 40 GeV









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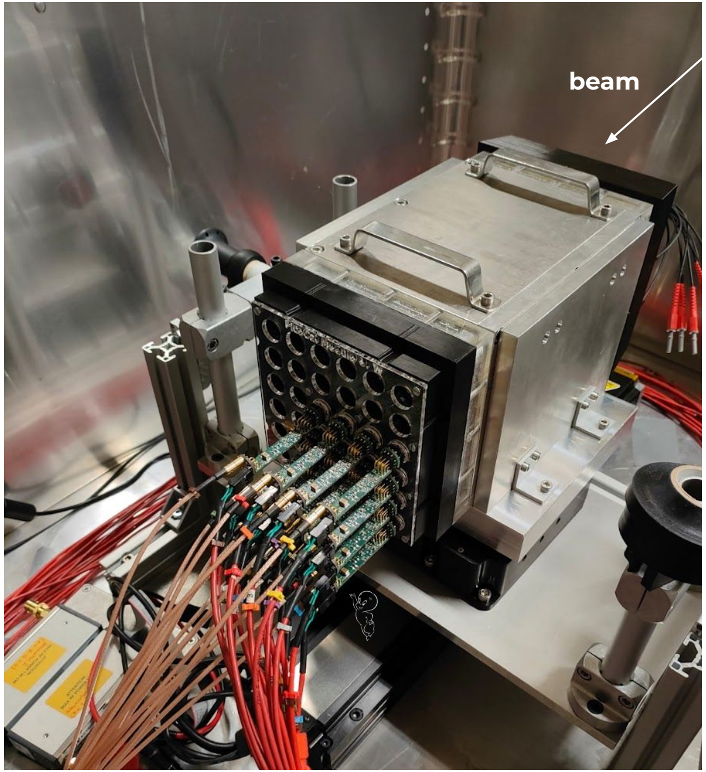
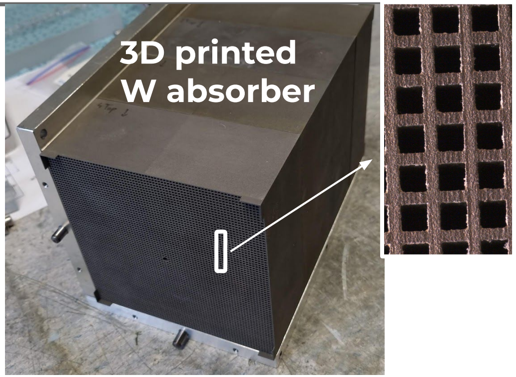
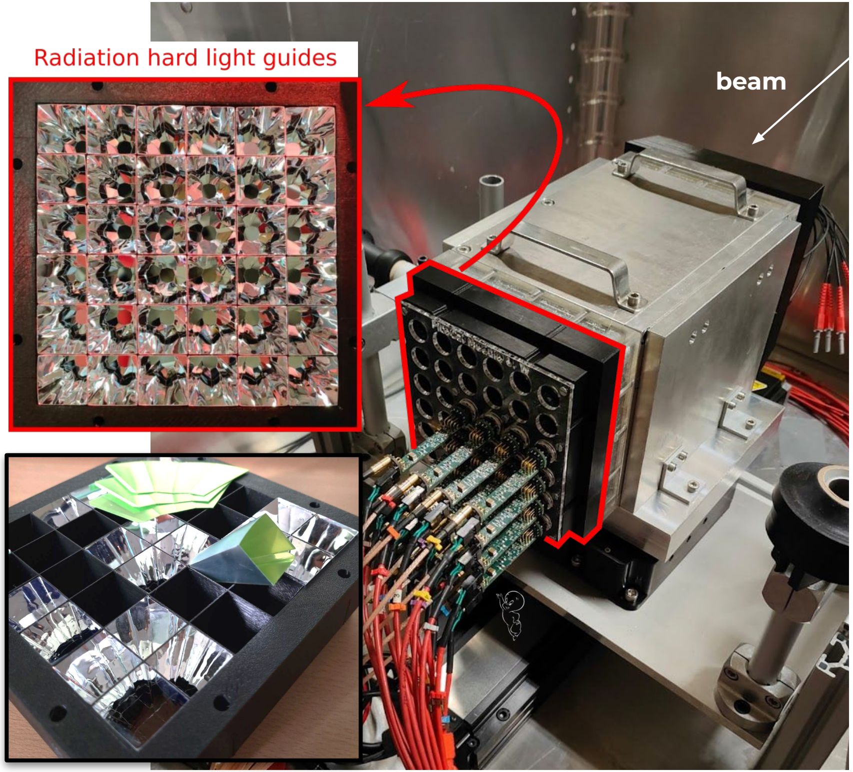


SpaCal-W for LS3





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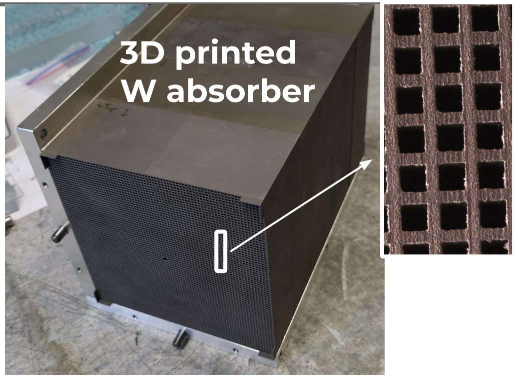

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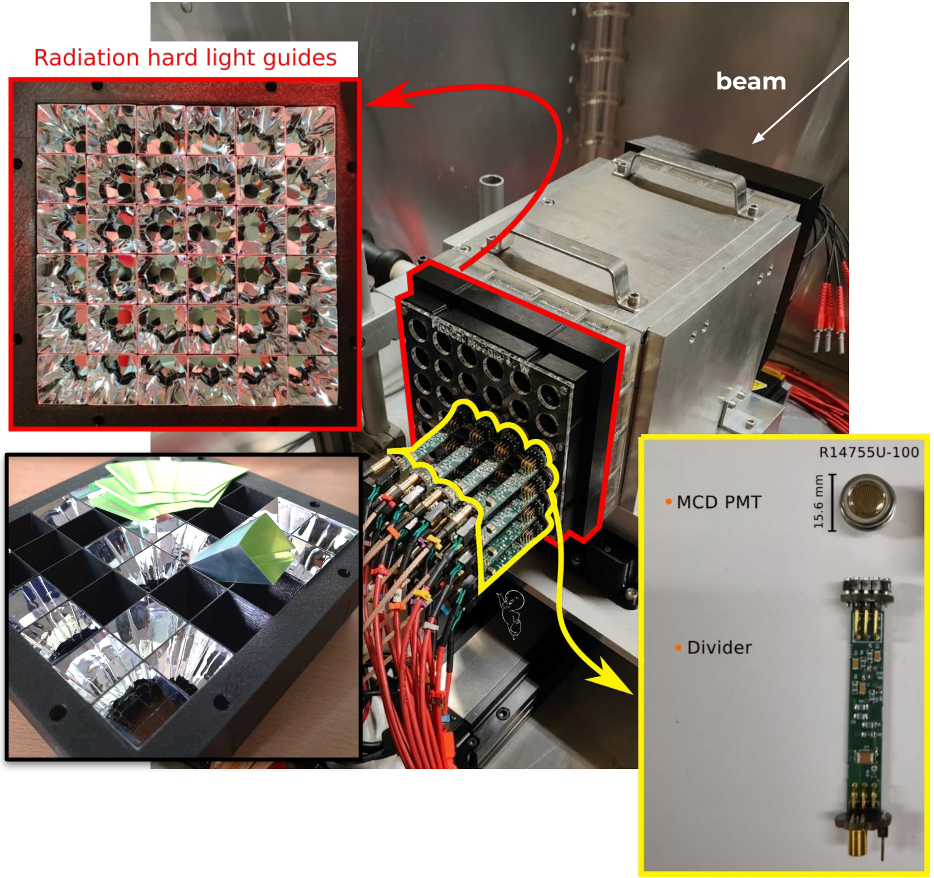
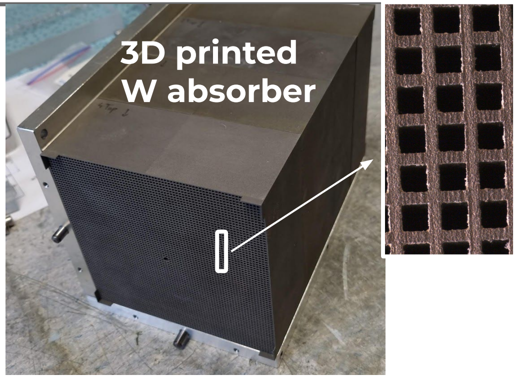
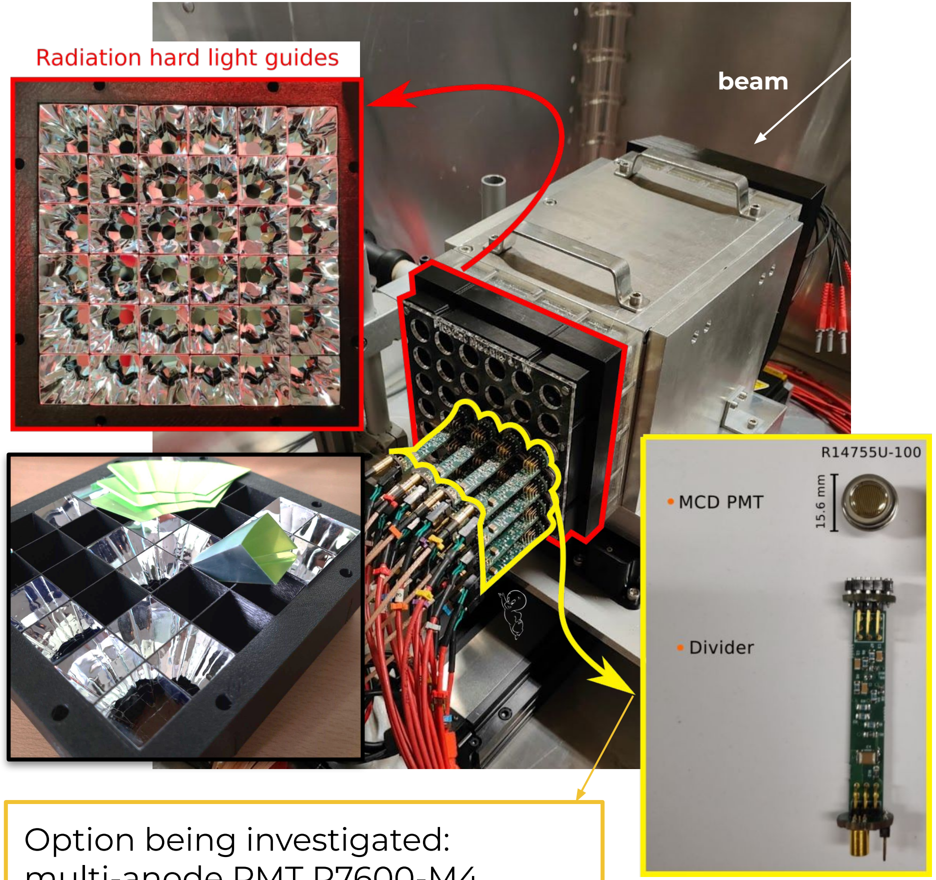
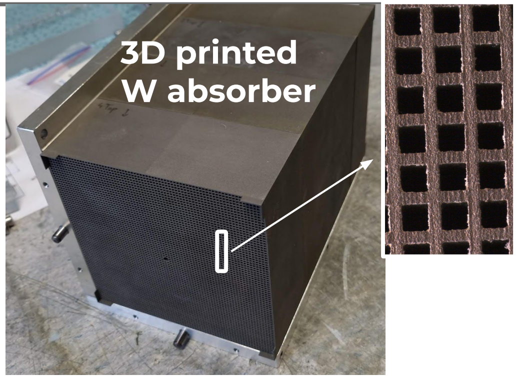




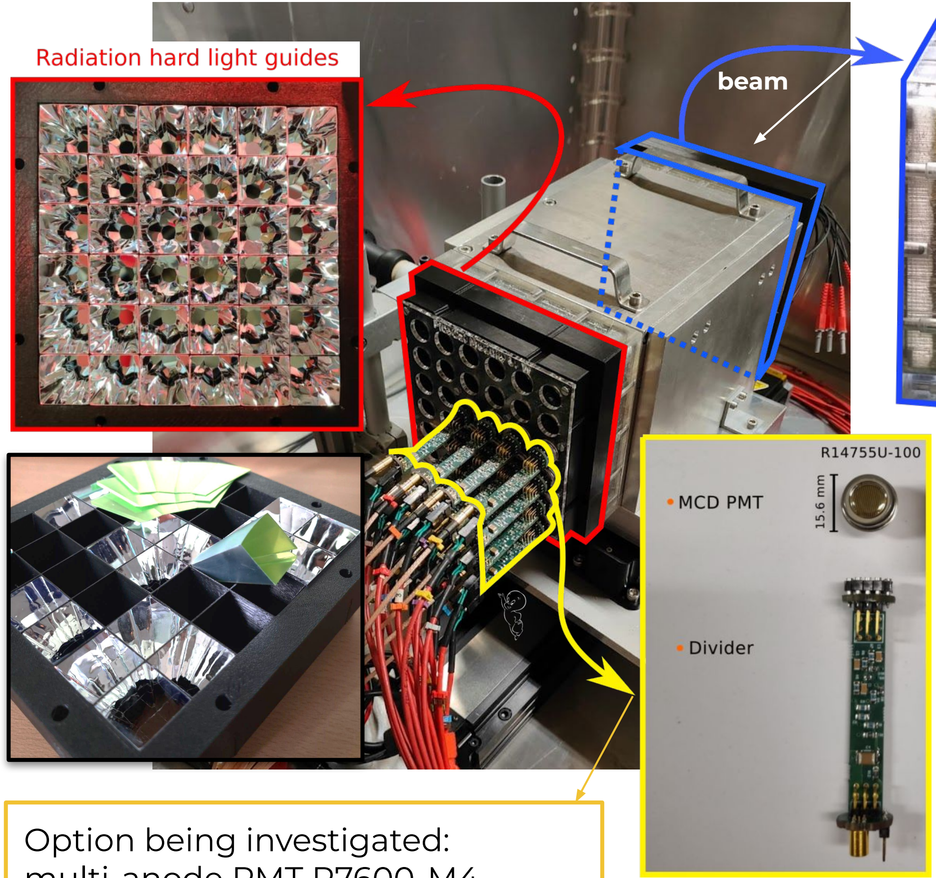


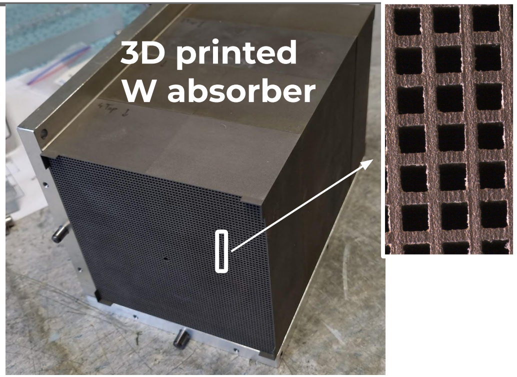
Option being investigated:
multi-anode PMT R7600-M4,
Hamamatsu MCD technology

SpaCal-W for LS3



SpaCal-W for LS3





Option being investigated:
multi-anode PMT R7600-M4,
Hamamatsu MCD technology

Conclusions

1. **The expected radiation damage requires the replacement of 176 ECAL modules in LS3**

2. **Prototypes performance at test beam level for LS3 (single readout, plastic fibers) and LS4 (double-side readout, rad hard up to 1 MGy in the innermost region):**

   a. The **SpaCal-W** and **SpaCal-Pb** prototypes proposed for installation during LS3 and LS4
      i. energy resolution in line with requirements
      ii. time resolution better than 20 ps above 20 GeV for SpaCal double-side readout, 20 ps above 40 GeV for single-side readout.

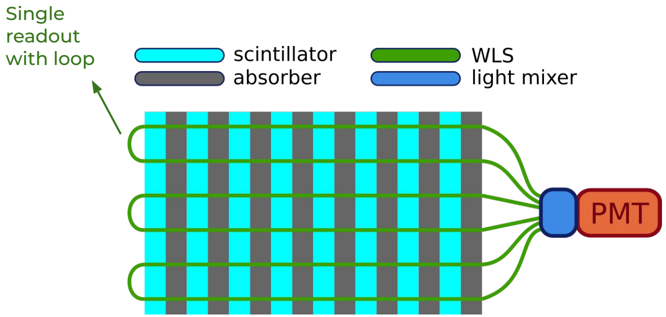
   b. The **Shashlik** modules will be reshuffled during LS3 and could be refurbished in LS4
      i. Time resolution with improved WLS and double-side readout shows better than 30 ps above 20 GeV.

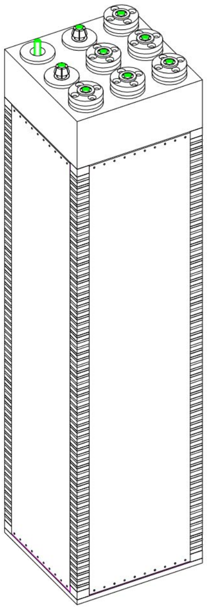
➔ **Good match with LS3 enhancement and Upgrade II requirements**

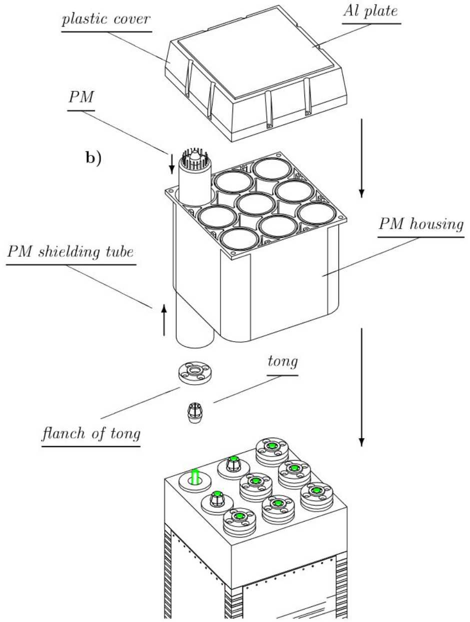
3. **Detailed simulations on occupancies and physics benchmark channels motivate both upgrades further.**

Backup

Shashlik: current properties





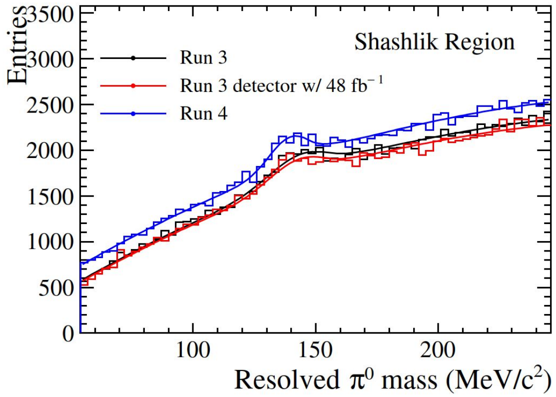


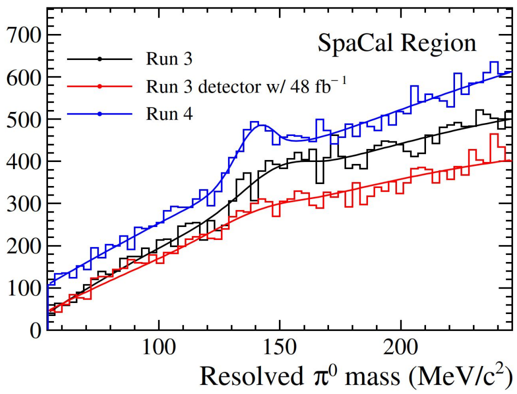
Energy resolution: better than 10%/√E ⊕ 1%
Moliere radius: 3.6 cm
Length: 42 cm (25 X_0)
Low activation
Single side readout
Y11 WLS fibers
Hamamatsu R7899-20 PMT
Radiation tolerance: up to 40 kGy

Physics performance: $D^0 \to \pi^+\pi^-\pi^0$

For "resolved" neutral pions.
Reshuffled Shashlik region:
- ➔ rearrangement of the modules produces small differences

SpaCal region (28% of the neutral pions):
- ➔ improved granularity of the SpaCal technology is needed to reconstruct neutral pions in the inner region.





From LHCb TDR 24
https://cds.cern.ch/record/2866493/files/LHCB-TDR-024.pdf