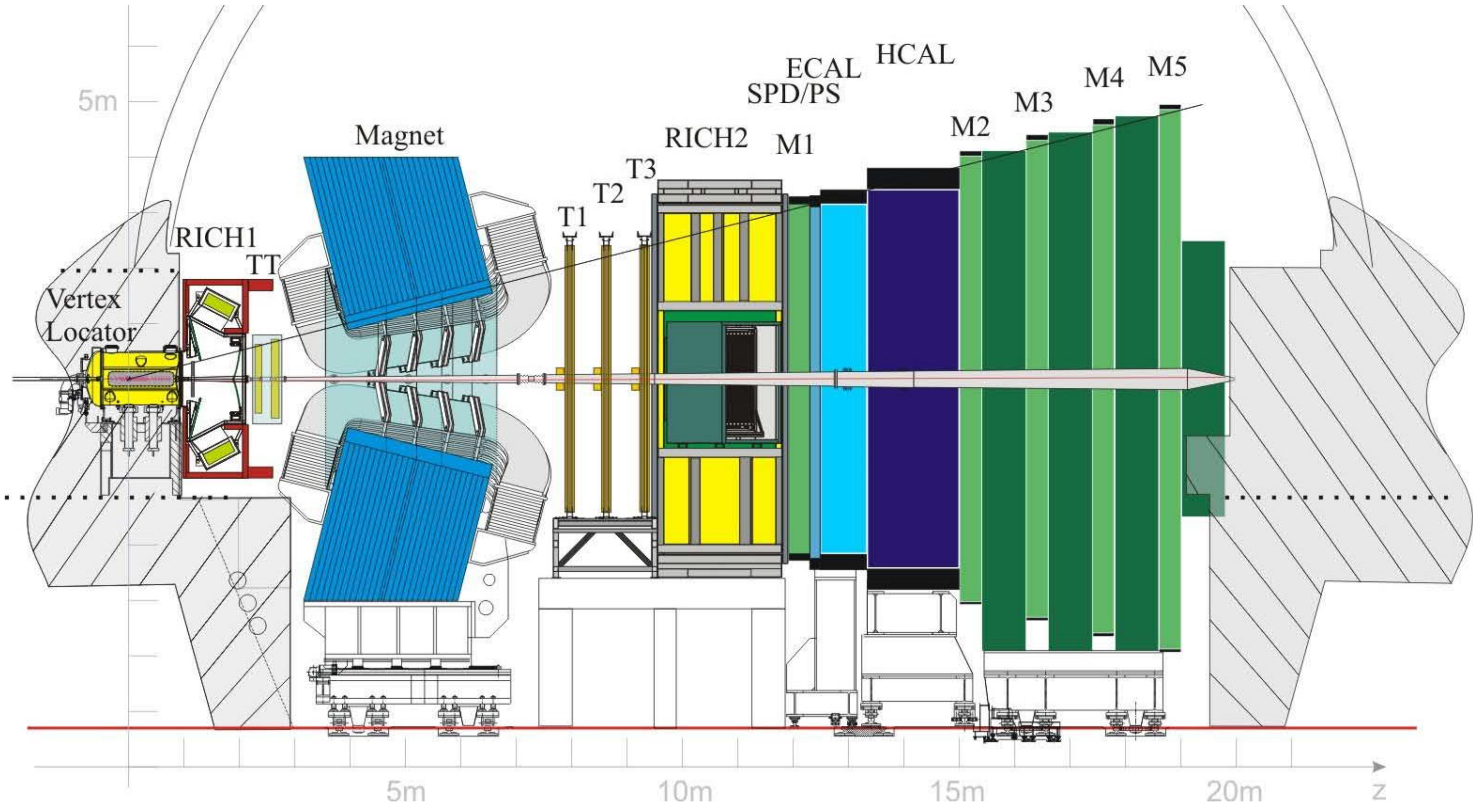
The Phase 2 Upgrade of the LHCb Calorimeter system.

Yu. Guz (IHEP Protvino)
on behalf of the LHCb collaboration

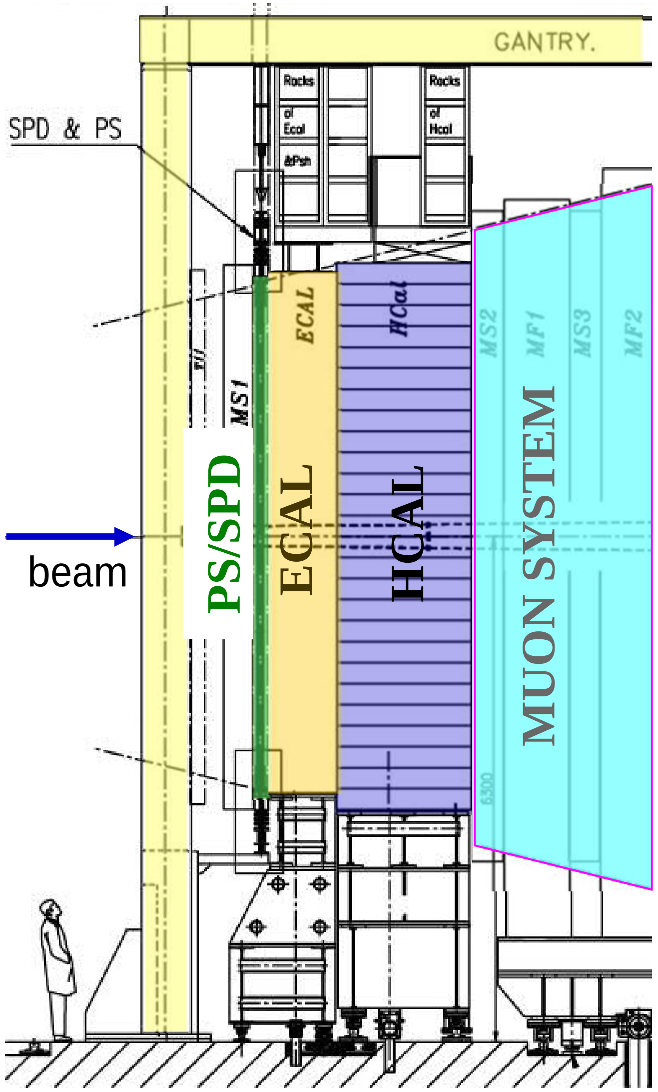
The LHCb experiment

A single arm forward spectrometer at LHC.

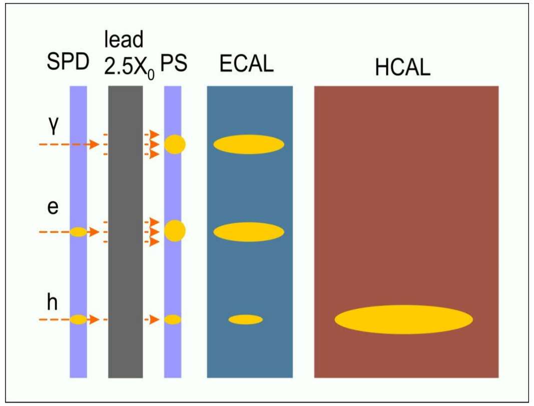
Flavor physics, CP violation, hadron spectroscopy.



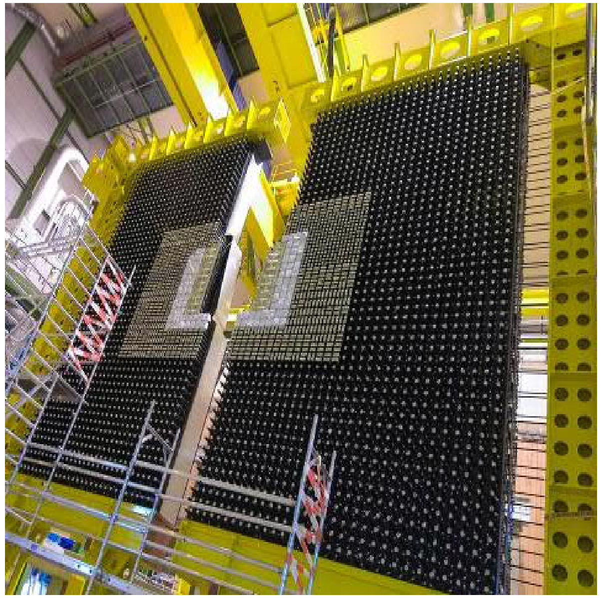
The LHCb Calorimetry System of Run I and Run II

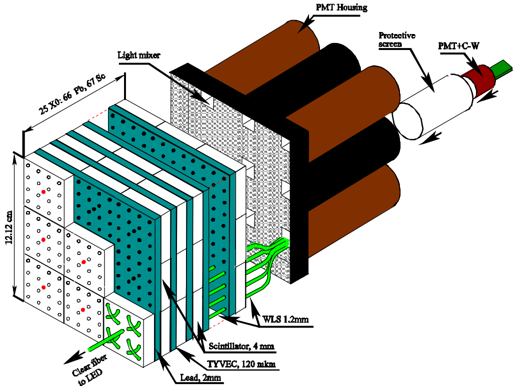


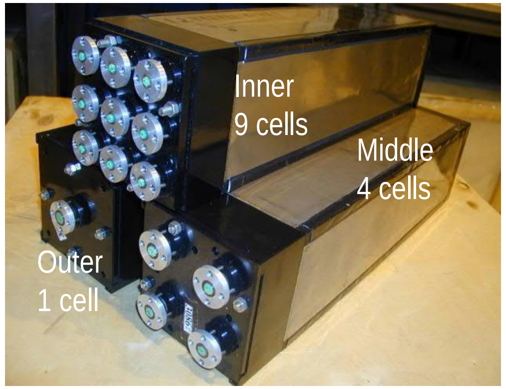
- solid angle coverage: 300x250 mrad
- distance from IP: ~12.5 m
- four subdetectors: SPD,PS,ECAL,HCAL
- based on scint./WLS technique, light readout with PMT
- provides:
  - L0 trigger on high p_T $e^\pm$, π^0, γ, hadron
  - precise energy measurement of $e^\pm$ and γ
  - particle identification: $e^\pm$/γ/hadron; contributes to Muon ID (HCAL).

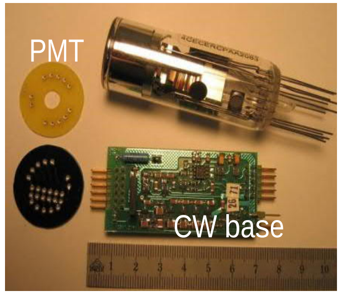


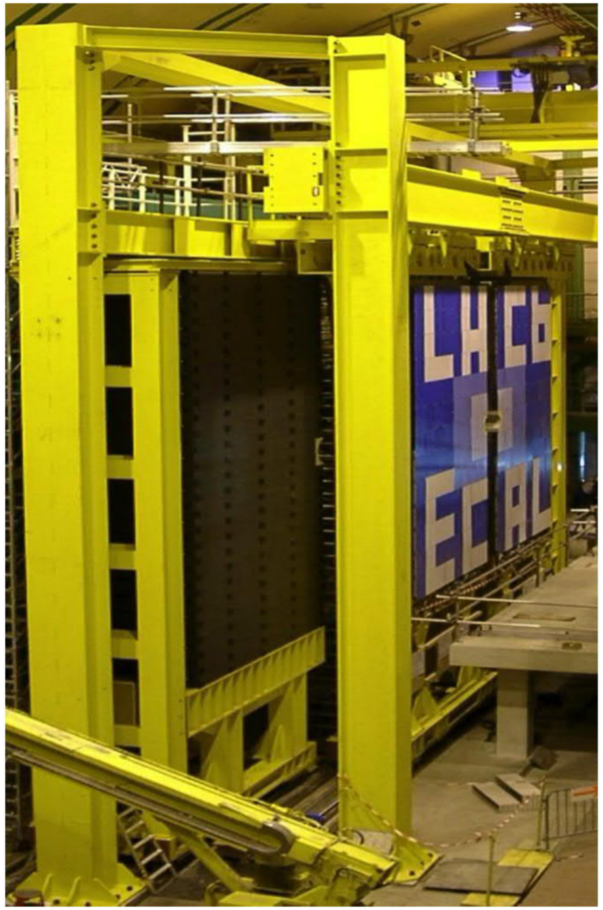
The LHCb ECAL











Shashlik technology

- 4 mm thick scintillator tiles and 2 mm thick lead plates, ~25 X_0 (1.1 λ_I); Moliere radius ~ 36 mm;
- modules 121.2 x 121.2 mm^2, 66 Pb +67 scintillator tiles;
- Segmentation: 3 zones → 3 module types, Inner (9 cells per module), Middle (4), Outer (1). Total of 3312 modules, 6016 cells, (7.7 x 6.3) m^2, ~100 tons.
- Light readout: PMT R-7899-20, HAMAMATSU. HV supply: individual Cockcroft-Walton circuit at each PMT.

Average performance figures from beam test (there is slight difference between zones):

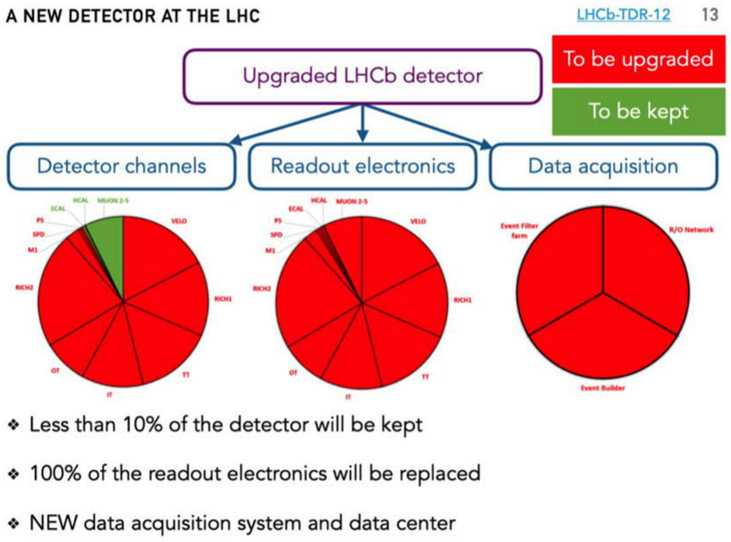
Light yield: ~ 3000 ph.el. / GeV

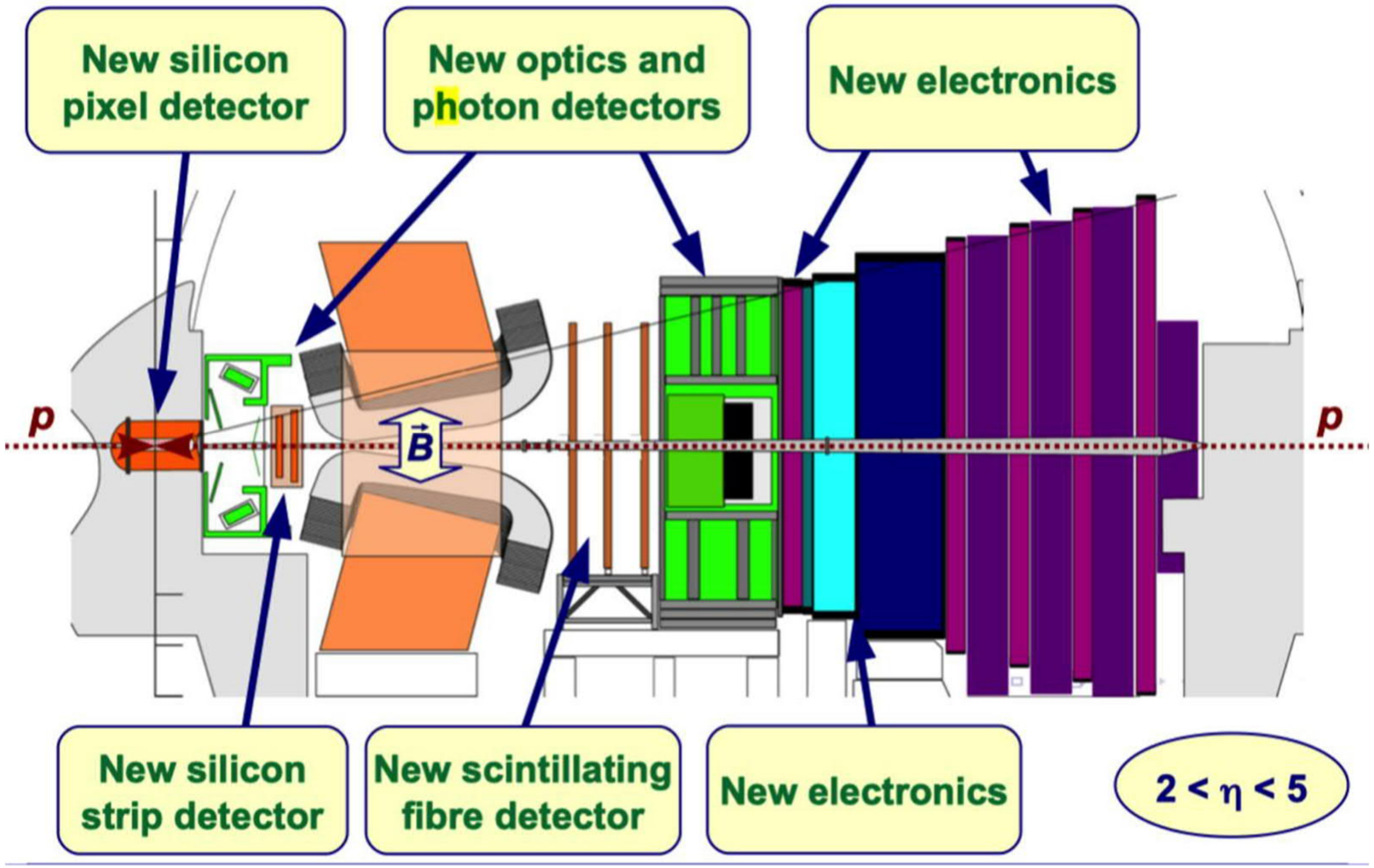
Energy resolution: $\frac{\sigma_E}{E} = \frac{(8 \div 10)\%}{\sqrt{E(GeV)}} \oplus 0.9\%$

LHCb Upgrade 1

Luminosity: 4·1032 → 2 ·1033 cm-2s-1

Detector upgrade to 40 MHz readout





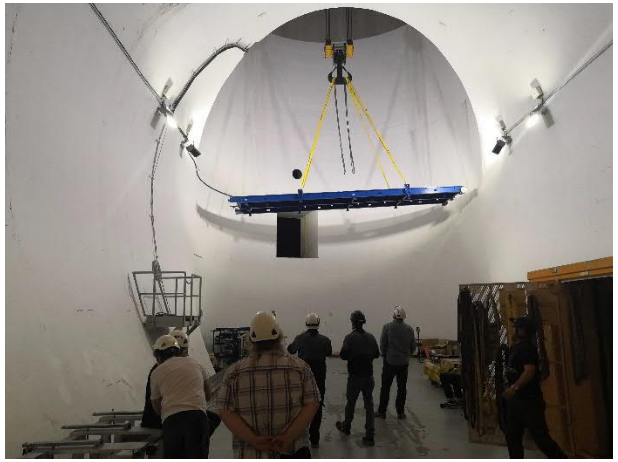
LHCb CALO Upgrade – phase 1 (ongoing)

Luminosity $2 \cdot 10^{33}$ $cm^{-2}s^{-1}$ (~5.5 ***pp*** interactions per event):

- **PS and SPD are removed**: no need for particle ID in L0
- **no change in the present ECAL and HCAL**

For Run 3:

- the frontend electronics is being replaced to new one, compatible with the new DAQ & Trigger
- The PMT gain will be reduced by factor of ~5, to reduce PMT degradation
  - PMT linearity: OK within required dynamic range
- to compensate, the FE gain will be increased x5
  - new low noise ASIC (ICECAL)
- detector maintenance will follow radiation degradation of detector components:
  - regular replacement of degraded parts (PMTs / Cockcroft-Walton HV boards)
  - LS3: replacement of ECAL Inner modules



LHCb – the long term roadmap

LHCb Upgrade I
40 MHz readout
new detectors
new electronics

Run 3
$2 \cdot 10^{33}$ cm^{-2}s^{-1}

Consolidation
& Maintenance

Run 4
$2 \cdot 10^{33}$ cm^{-2}s^{-1}
➔ 50 fb^{-1}

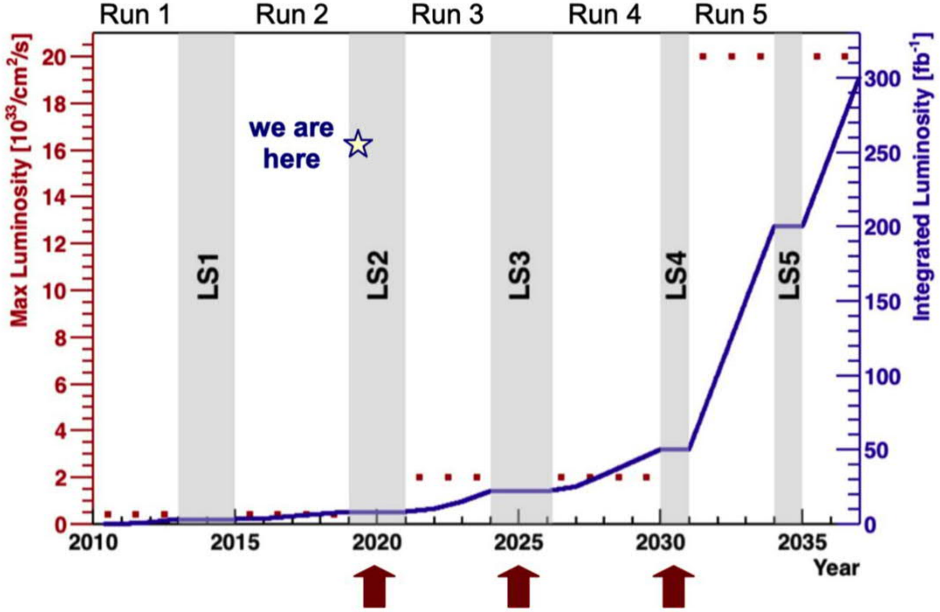
LHCb
Upgrade II

Run 5, 6
$2 \cdot 10^{34}$ cm^{-2}s^{-1}
➔ 50 fb^{-1}

➔ 300 fb^{-1}

Upgrade 2:

- luminosity up to $2 \cdot 10^{34}$ cm^{-2}s^{-1} (~55 ***pp*** interactions per event)
- ~300 fb^{-1} will be collected



LHCb – the long term roadmap

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$2{\cdot}10^{33}$ cm^{-2}s^{-1}

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➔ 50 fb^{-1}

LHCb
Upgrade II

Run 5, 6
$2{\cdot}10^{34}$ cm^{-2}s^{-1}
➔ 50 fb^{-1}

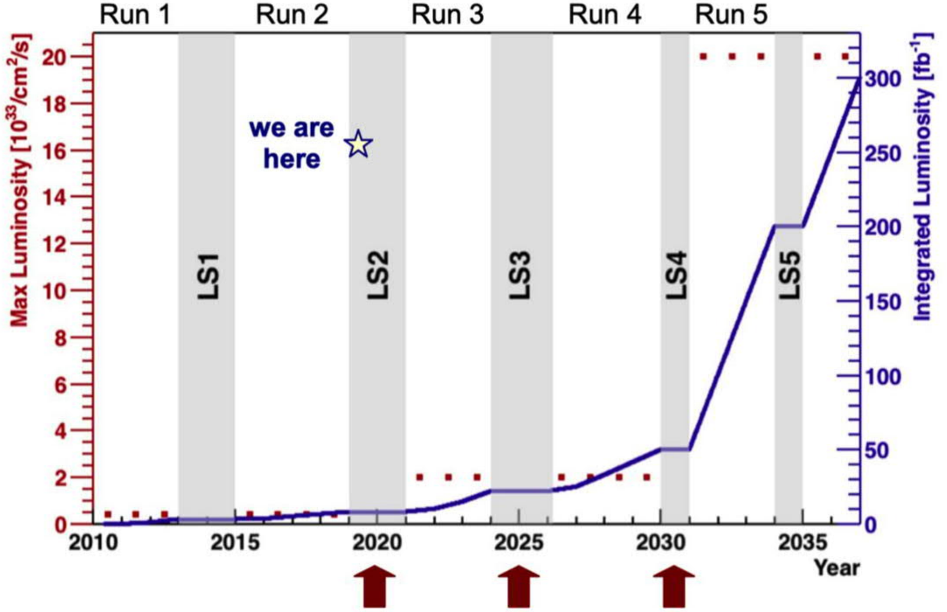
➔ 300 fb^{-1}

ECAL in LS3 (2025-2027):

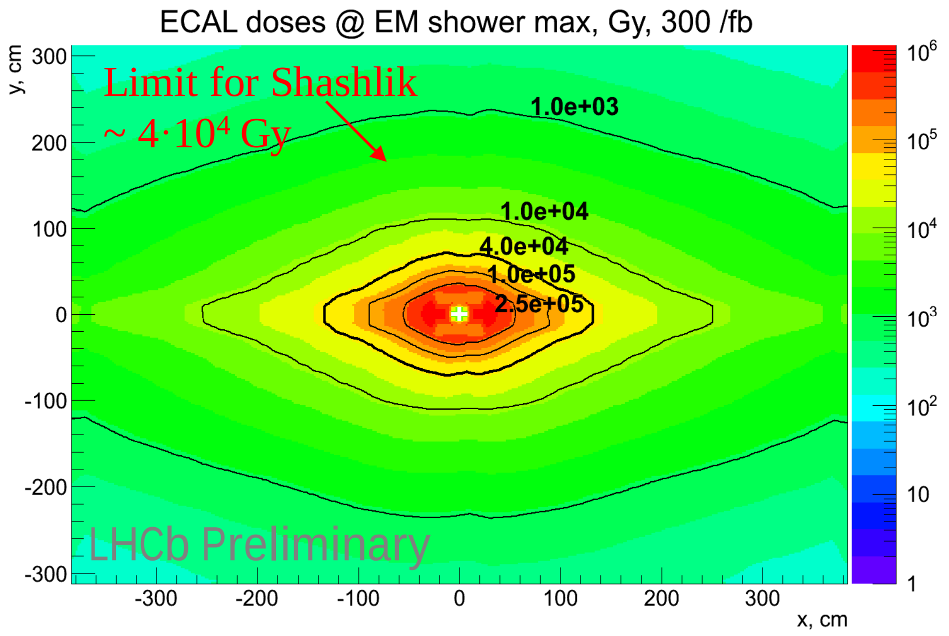
- replace modules around the beam pipe (~32 modules), to improve performance for Run 4

ECAL in LS4 (2031-2032):

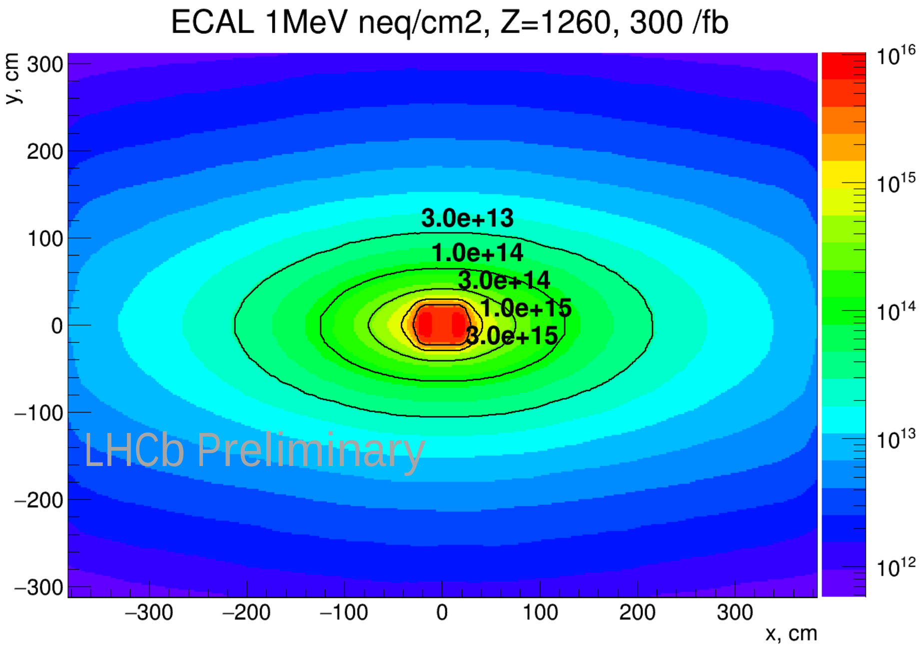
- rebuild ECAL for maximum performance at L=$2{\cdot}10^{34}$ cm^{-2}s^{-1}
- include time measurements to disentangle multiple interactions in a bunch crossing.



LHCb ECAL Upgrade II – conditions and requirements



up to ~1 MGy in the centre



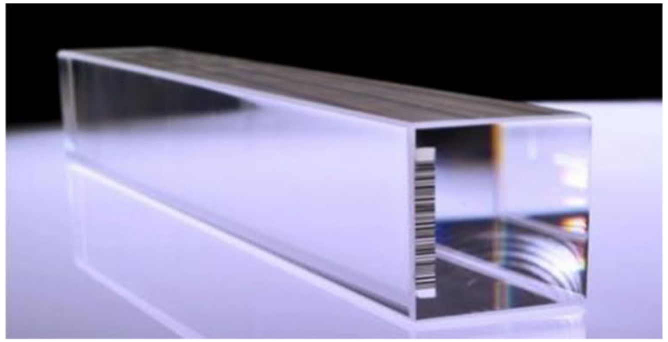
up to $6 \cdot 10^{15}$ 1MeV neq/cm^2 in the centre

LHCb ECAL Upgrade II – conditions and requirements

- need at least three areas with different granularities (maybe more)
  - two or three different technologies (e.g., for 0-20 krad, 20-200 krad, >200 krad)
- the Central area should sustain radiation doses of up to ~ 1 MGy and neutron fluences of up to $6 \cdot 10^{15}$ 1MeV neq/cm^2
  - scintillating garnet crystals
- The Outer area: Shashlik is a viable option
- The Middle area – not defined yet (e.g., PWO?)

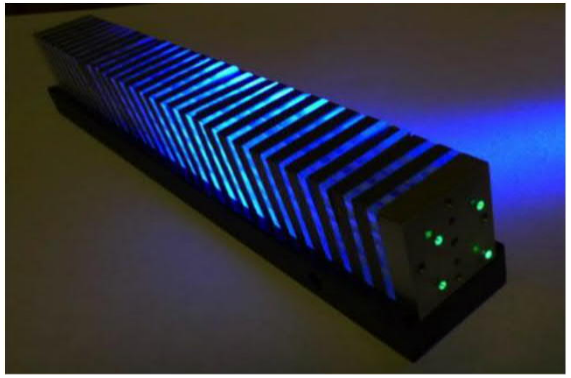
- requirements for the whole calorimeter:
  - fine granularity, which is required to handle increased occupancy
    - Molière radius should match the granularity (~1 cm at the centre → dense absorber!)
  - good energy resolution, $\sigma(E) \sim 10\%/\sqrt{E} \oplus 1\%$
  - ability to measure time with few*10ps precision – for pile-up mitigation. The options are:
    - use intrinsic time resolution of the calorimeter modules
    - add a dedicated timing layer

LHCb ECAL Upgrade II – options for the central area



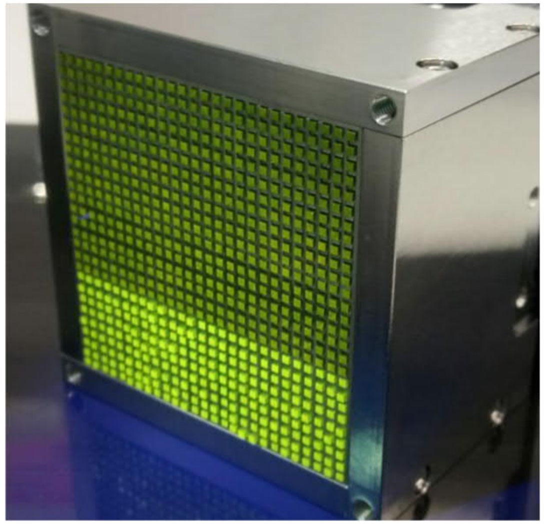
Homogeneous Crystal:

- requires long crystals to contain 25 X_0
- “fixed” Moliere Radius
- very good homogeneity → good energy resolution
- requires good radiation hardness (low rad-induced attenuation over the whole length)
  - can be mitigated by longitudinal segmentation



Shashlik type module:

- can be made very compact ~15cm
- “tunable” Molière radius
- more relaxed requirements to the scintillator rad. hardness (no att. over the cell size)
- but no rad. hard WLS fibers (yet) to transport light!



SPACAL type module:

- can be made very compact ~15cm
- “tunable” Molière radius
- fibers scintillate AND transports light! → potentially high photoelectron yield
- worsening energy resolution @ small angles
- radiation hardness requirements are similar to homogeneous crystal, mitigated by
  - compact length
  - longitudinal segmentation

➢ started R&D on SPACAL type module, together with Crystal Clear Collaboration

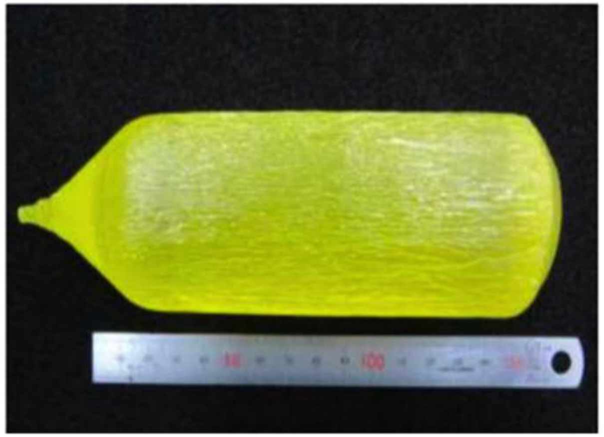
Radiation hard scintillating crystals

	$Y_3Al_5O_{12}$:Ce (YAG)*	$Lu_3Al_5O_{12}$: Ce (LuAG)*	$Gd_3Al_2Ga_3O_{12}$: Ce (GAGG)**	Lu_2SiO_5:Ce (LSO)
density (g/cm^3)	4.57	6.73	6.63	7.4
X_0 (cm)	3.5 cm	1.3	1.59	1.1
Refraction index	1.83	1.84	1.85	1.82
Λ_{max} (nm)	**550**	535	**520**	420
LY @ RT (ph/MeV)	**35000**	25000	**50000**	30000
decay time (ns)	70 + slow component	70 + slow component	60 + slow component	40
rise time (ps)	**1590-137**	**923-230**	**497-92**	**59**

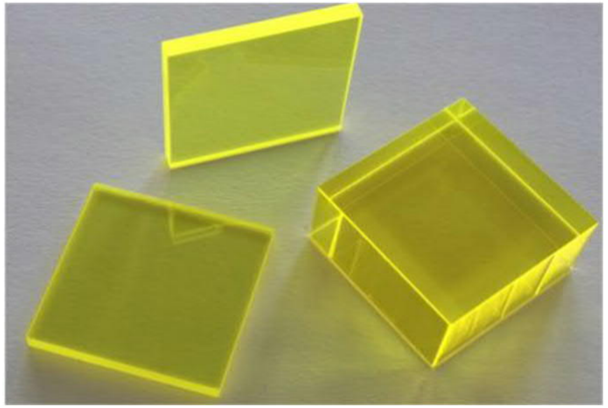
rise time: S.Gundacker, NIM A 891 (2018) 42-52

Crystal production

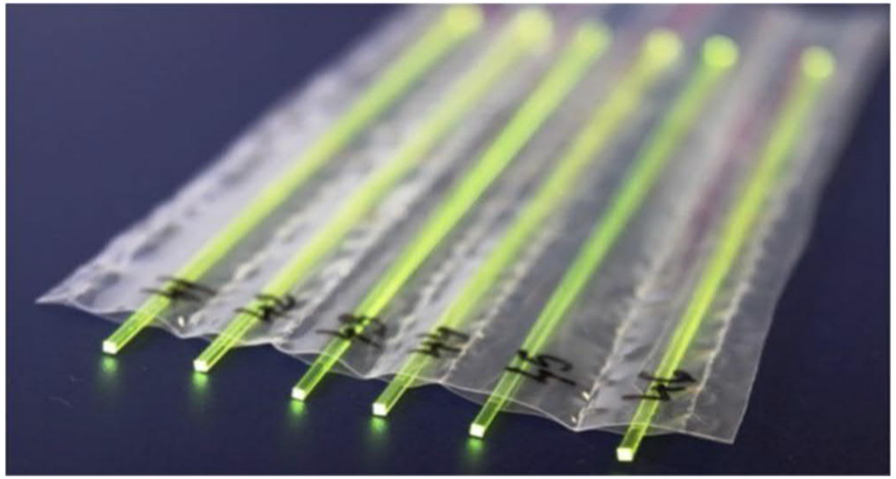
Grown by Czochralski method



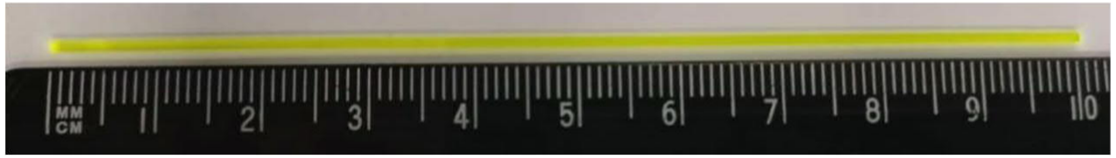
GAGG:Ce, FOMOS (RU)



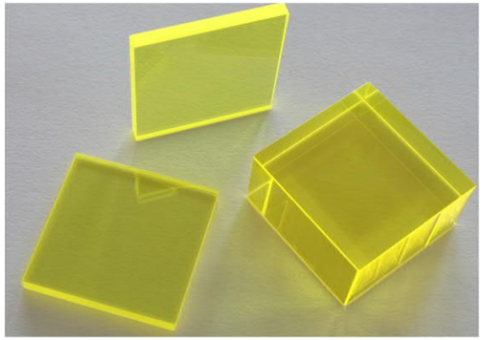
YAG:Ce, Crytur (CZ)



Square (1x1 mm^2) fibers are produced by cutting and polishing

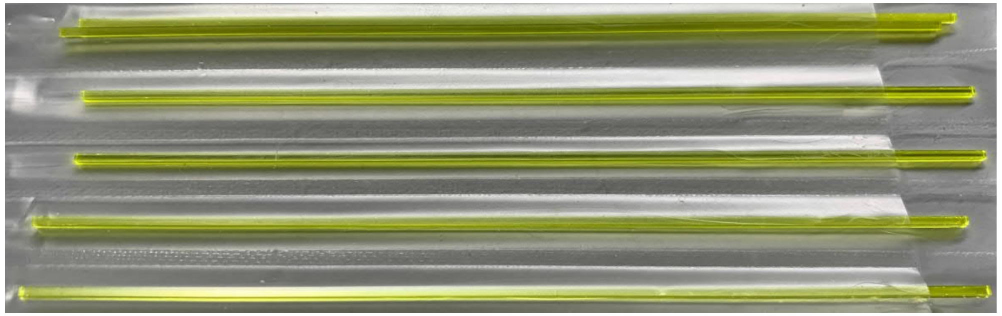


GAGG: radiation hardness

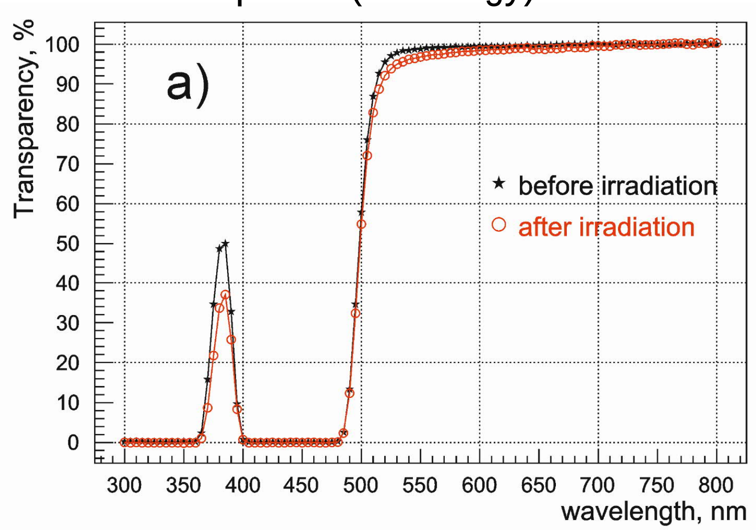


GAGG samples (FOMOS Materials, Moscow)

GAGG fibers (FOMOS Materials, Moscow)



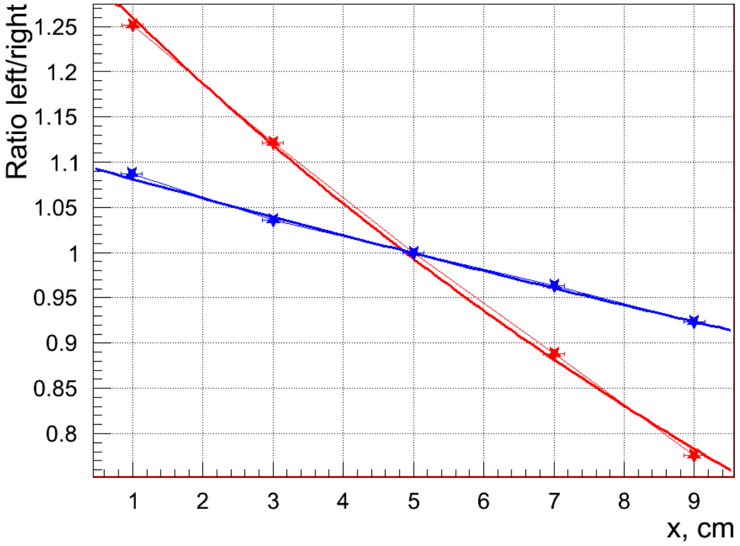
Sample irradiation, 24 GeV protons
$3.1 \cdot 10^{15}$ p/cm^2 (0.91 Mgy)



$$\kappa = \frac{1}{d} ln \frac{I_{before}}{I_{after}} = 3.6\ m^{-1} \text{ at 520 nm}$$

(significantly better than LYSO)

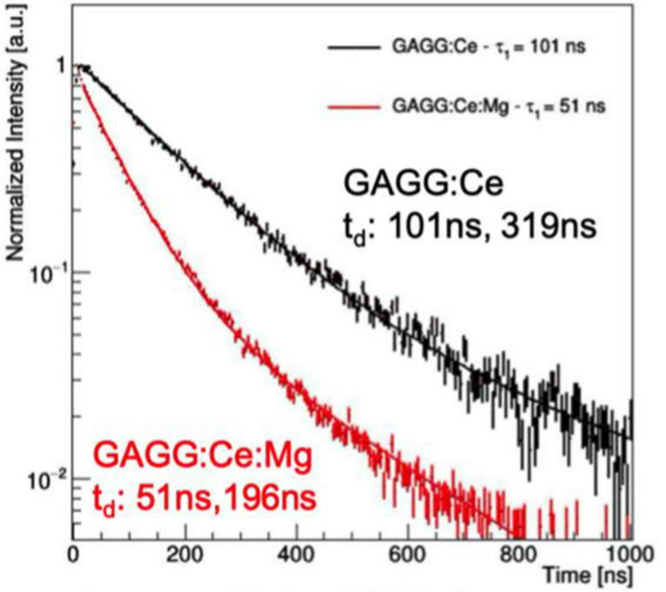
Fiber irradiation , 24 GeV protons
$3.4 \cdot 10^{15}$ p/cm^2 (1.02 Mgy)



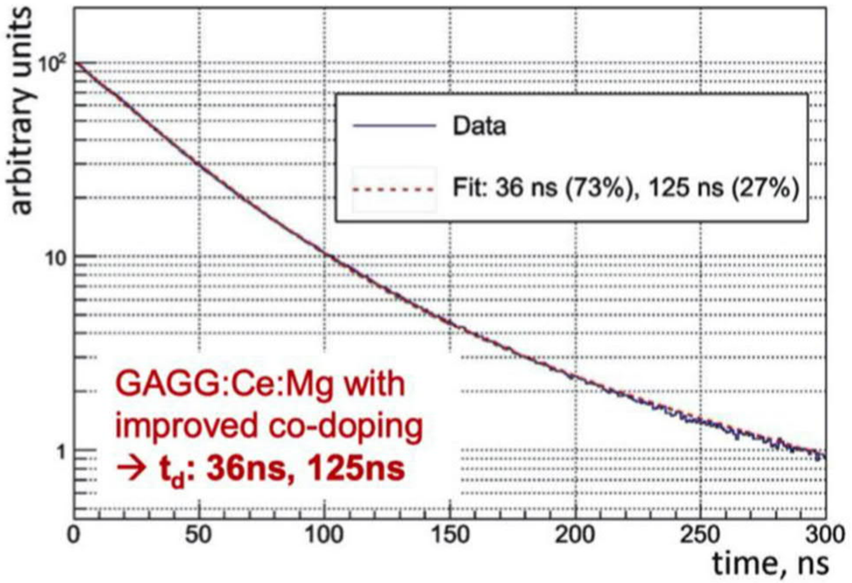
before irradiation: L_{ATT}=101.5 cm
after irradiation: L_{ATT}=33.6 cm

➔ OK for 10 cm length after 1 MGy!

timing properties: decay time



Kamada et al, O-14-3 at SCINT2015
M. Lucchini et al, NIM A Volume 816 (2016), pp 176–183,

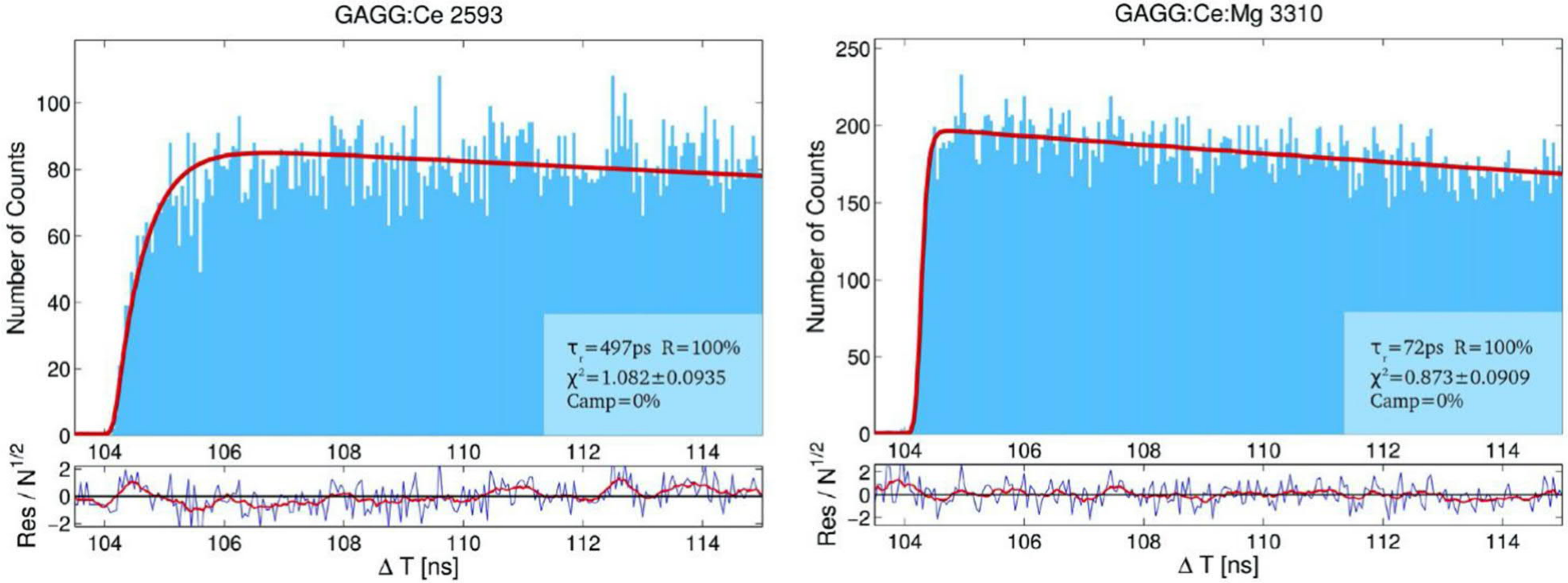


Nuclear Inst. and Methods in Physics Research, A 916 (2019) 226–229

it is important to minimize spill-over by minimizing pulse length (25 ns LHC bunch spacing)
co-doping with Mg, Ti, ... reduces decay time and fraction of “long” exponential.

* Note the R&D on the GAGG and GYAGG material (M. Korzhik, this conference; exhibition of FOMOS Materials (Moscow)).

timing properties: rise time



S.Gundacker, et al. NIM A 891 (2018) 42-52

The rise time is important for the precision of timing measurements
co-doping with Mg also improves the rise time

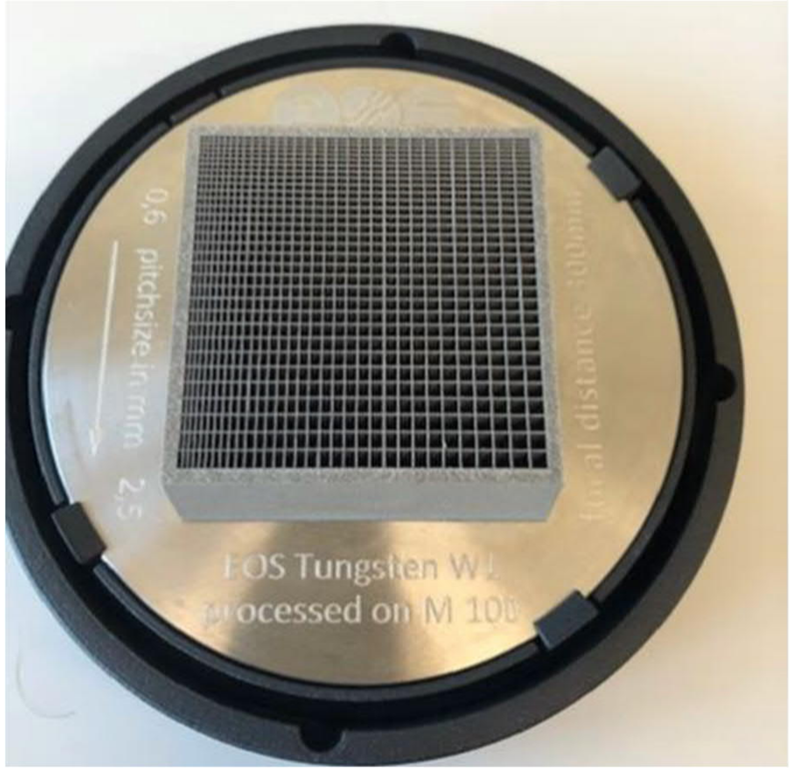
Absorber for the central area

- Should be more dense than Lead: hence Tungsten based
- should have a rather complicated shape to place crystal fibers

For the material, the options are pure W, W-Cu or W-Pb alloys

- pure W is very hard and brittle, difficult for machining
- W-Cu alloy is available on market, with good mechanical properties
- W-Pb alloy is preferable (smaller X_0 for same R_M), but is not commercially available

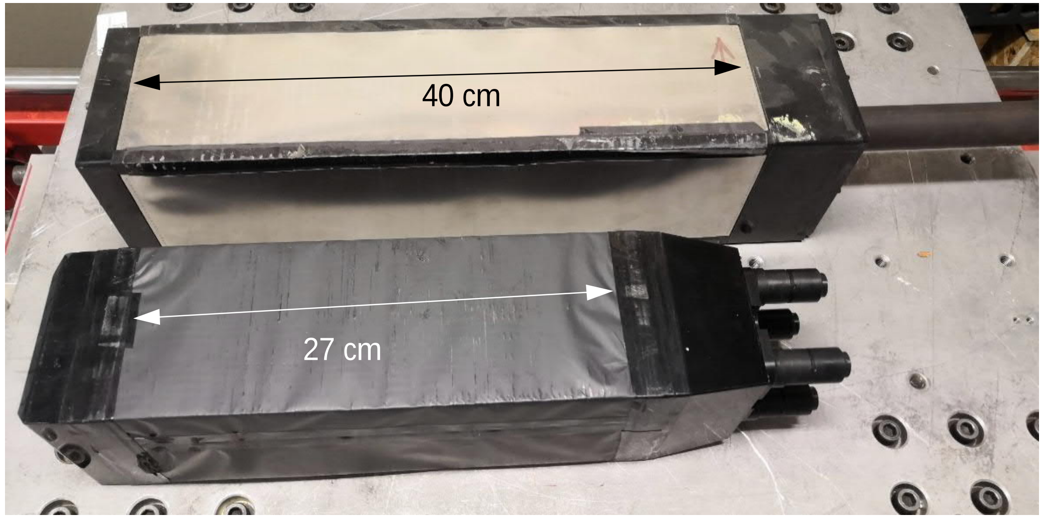
The R&D on absorber technologies is ongoing (MISIS, Moscow). Several technologies are considered: Selective Laser Melting, Chemical Vapor Deposition, Metal Injection Molding etc.



a sample produced by Selective Laser Melting, pure W (MISIS)

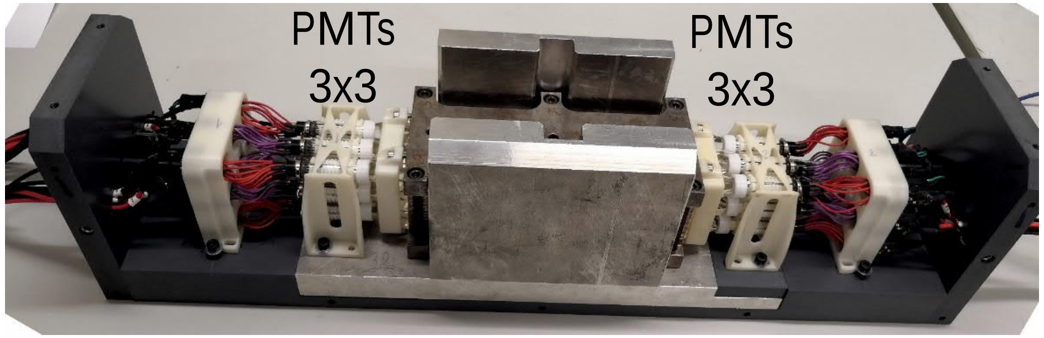
Prototype studies

Prototypes 2018



present ECAL module
shashlik, Pb:Sc = 1:2 (vol)
$25X_0$ = 40cm; R_M=36mm

"short" shashlik module
Pb:Sc = 1:1 (vol)
$25X_0$ = 27cm; R_M=27mm
(produced in Protvino, 2017)



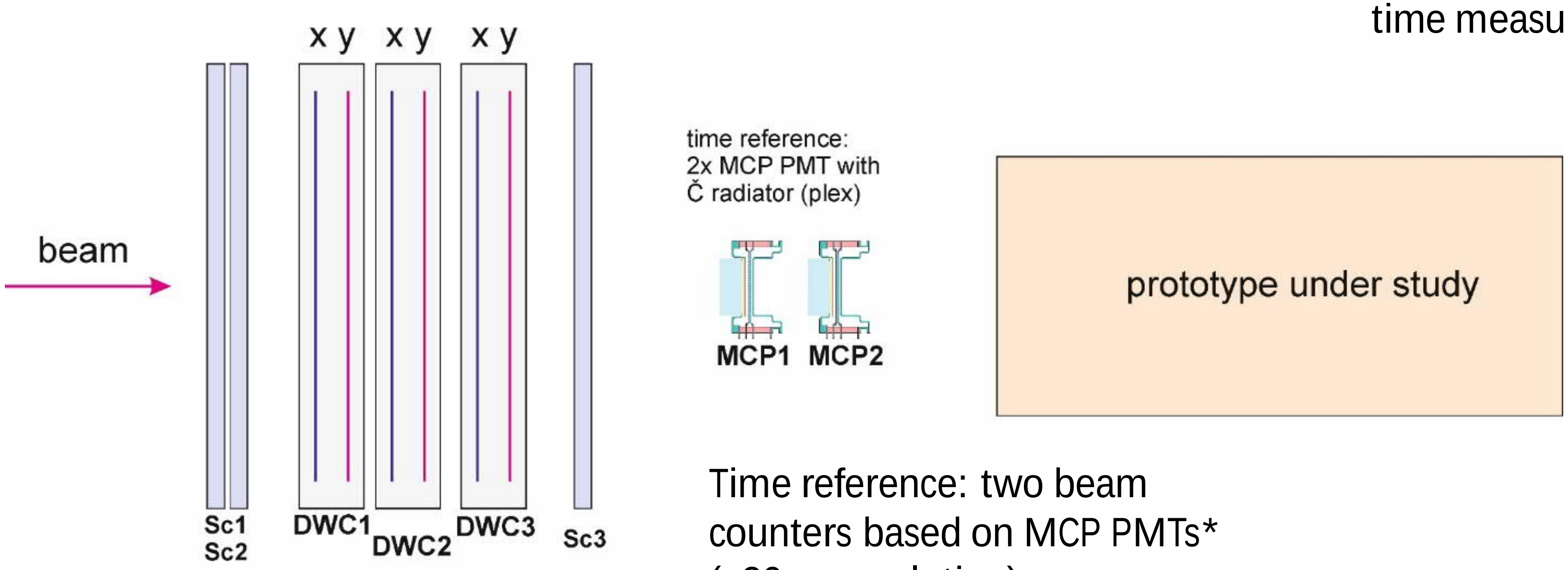
Cu-W alloy, 14.9 g/cm2
20 cm long module to reach 25 X0
longitudinal segmentation: 10+10 cm
9 cells of 2 x 2 cm2with MR~1.5 cm
1 cell of GAGG, 4 cells of YAG, 4 cells of SCSF78 (KURARAY)

beam test 2018

- Energy resolution for SPACAL prototype
- time resolution for SPACAL and Shashlik

Electronics:

- LeCroy 1182 ADC for energy measurements
- CAEN DT5742 (5 GS/s, 12 bit) digitizer for time measurements

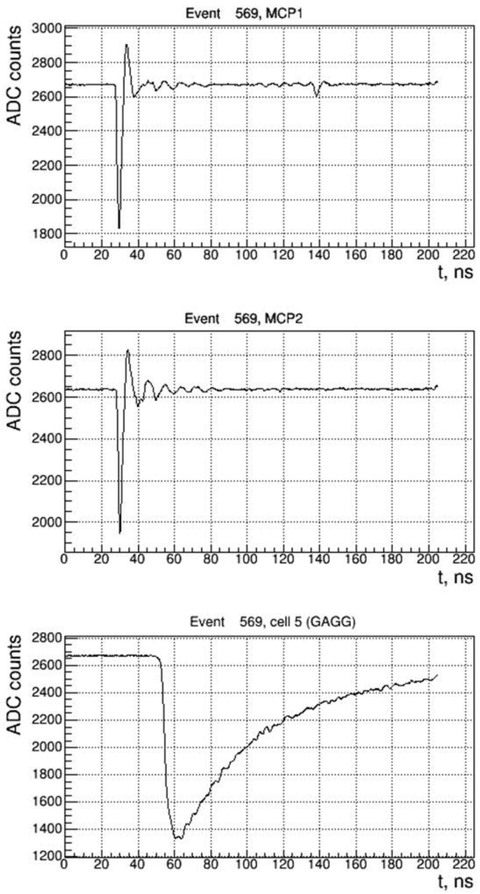


Time reference: two beam counters based on MCP PMTs* (<20 ps resolution)

DWC = Delay Wire Chamber

(*) The MCP PMTs were kindly provided by Alexander and Mikhail Barnyakov, BINP, Novosibirsk

beam test 2018



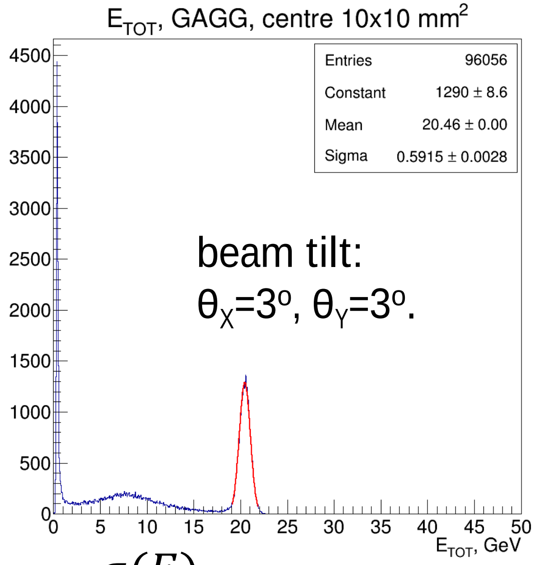
Time resolution in SPACAL, front section

E, GeV	PMT HV	σ(t), ps
20	630 V	85
20	730 V	78

Present ECAL module (Shashlik)
+ present PMT (R7899-20)

E, GeV	PMT HV	σ(t), ps
20	800 V	69
30	800 V	56
30	750 V	57

SPACAL energy resolution



beam tilt:
θ_X=3º, θ_Y=3º.

$$\frac{\sigma(E)}{E} = 2.9\%$$

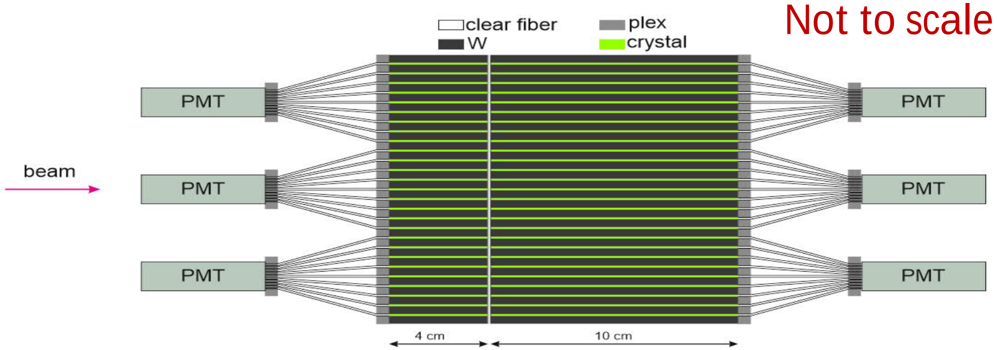
(3.1% from GEANT4 simulation)

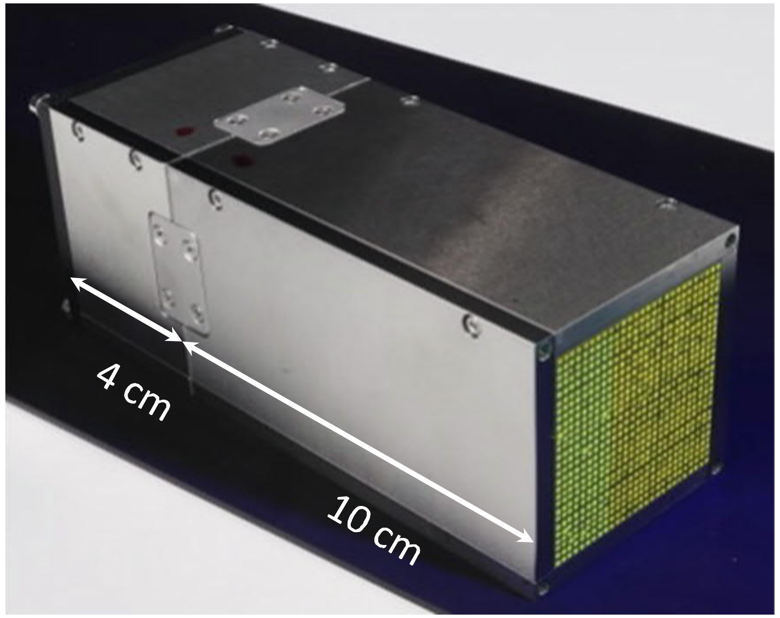
more details in:
DOI: 10.1109/TNS.2020.2975570

Prototypes 2019

Longitudinally split versions of SPACAL and Shashlik (at 7X0 - ~ shower max) improves time resolution;
also, creates a natural place for the separate timing layer

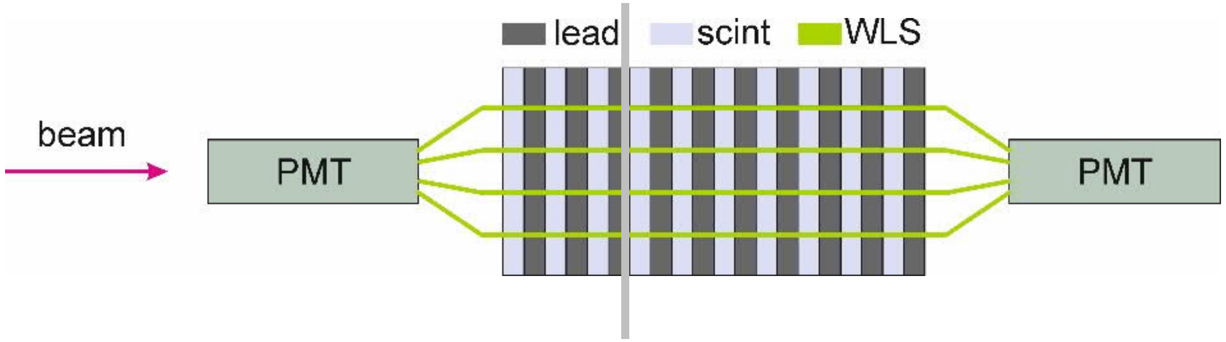
Not to scale!





Absorber: Crytur (CZ)
pure W; electroerosion cutting of 0.5mm plates

Scintillator:
YAG:Ce (Crytur), 6 cells
GAGG:Ce (FOMOS), 3 cells

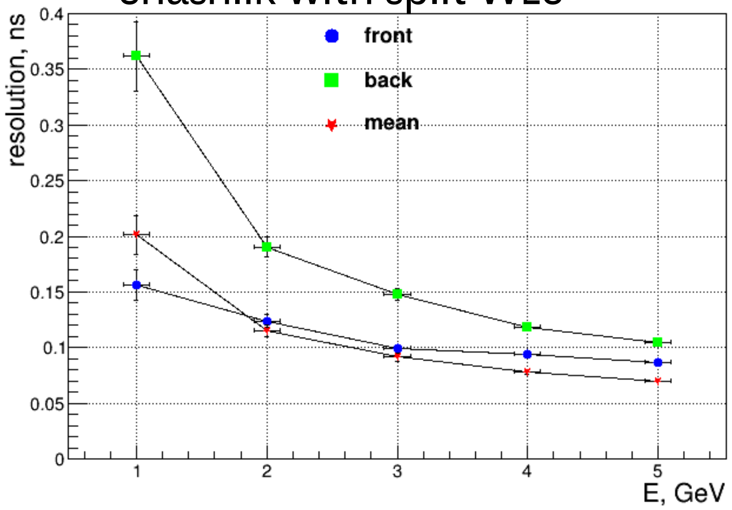


Shashlik prototypes
(several versions)

Beam test 2019 (DESY)

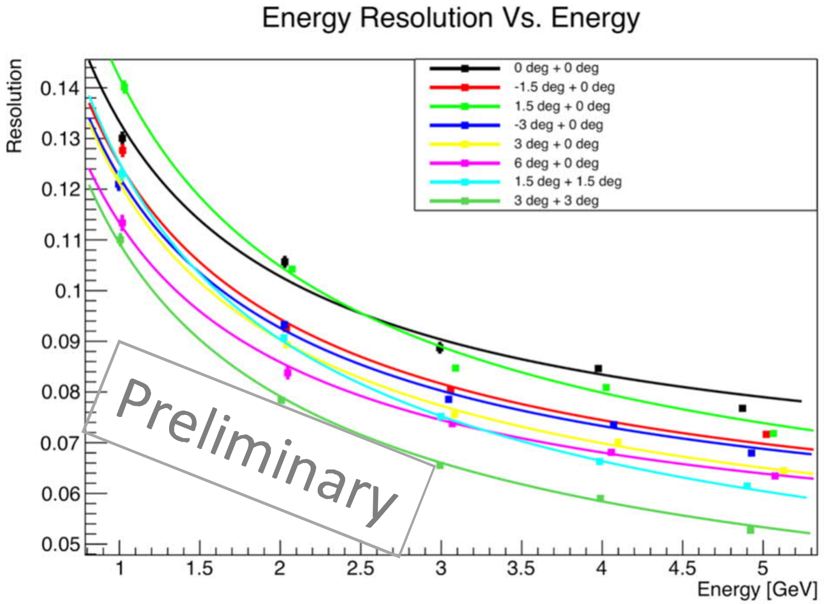
e+ beam, energies 1-5 GeV
Basically same setup as in 2018

Shashlik with split WLS



Better than the existing modules with standard readout:
70 ps resolution is achieved at 5 GeV (same as @20 GeV for the standard version)

Nearest plan: try new KURARAY WLS fibers YS-2 (much faster luminescence decay time than Y11)
→ expect improvement in the time resolution



dependence of the energy resolution on incident angle (in agreement with GEANT4 simulation).
Stochastic term within 10-13%, which is in the right ballpark.

The analysis is ongoing.

(Time resolution measurements for the SPACAL prototype failed, to be redone in May 2020).
(~50 ps @ 5 GeV expected from simulation)

Conclusions

- At present, LHCb is undergoing a major first upgrade. A second upgrade is foreseen in ~2030.
- The electromagnetic calorimeter needs some consolidation of the inner region by LHC LS3 (2025-2027) compatible with the running conditions after Upgrade II, which requires R&D on radiation hard ECAL modules.
- In Long Shutdown 4 (LS4) a major upgrade of the ECAL will be required to cope with the increased luminosity, the harsh radiation and pile-up conditions, by replacing a significant part of the modules with new technologies.
- Generic R&D and prototyping has started to develop radiation hard sampling ECAL modules of SPACAL type, as well as studies of intrinsic time resolution of ECAL modules.