Introduction to the LHCb Calorimeter Upgrade

Outline:

- Design and performance of current LHCb Electromagnetic Calorimeter
- Requirements for Upgrades I and II
- Technological options and R&D

People currently participating to ECAL Upgrade Ib/II discussions:
Etiennette Auffray Hillemanns, Gloria Corti, Adam Davis, Andrei Golutvin, Julian Garcia Pardinas, Iouri Guz, Richard Jacobsson, Matthias Karacson, Anatoli Konoplyannikov, Frederic Machefert, Markus Roehrken, Andreas Schopper, Pavel Shatalov, Evgeniy Shmanin, Sheldon Stone, Andrey Ustyuzhanin, Nigel Watson, Guy Wilkinson, Liming Zhang, and all those I forgot or that are interested to join… ;-)

ECAL choice of technology

Design requirements of current ECAL:

- energy resolution ~ $10\%/\sqrt{E} \oplus 1\%$
- fast response time compatible with LHC bunch spacing of 25 ns
- radiation hardness up to ~250 krad/year
- small transverse segmentation to separate two showers from π^o decays and to minimize pile-up
- lateral size of active area 7.8m x 6.3m
- cost effective (!)

→ sampling technology using scintillators & fibres, readout with photomultipliers and FE electronics providing a 40 MHz L0 trigger

→ ECAL "shashlik" module

Shashlik modules

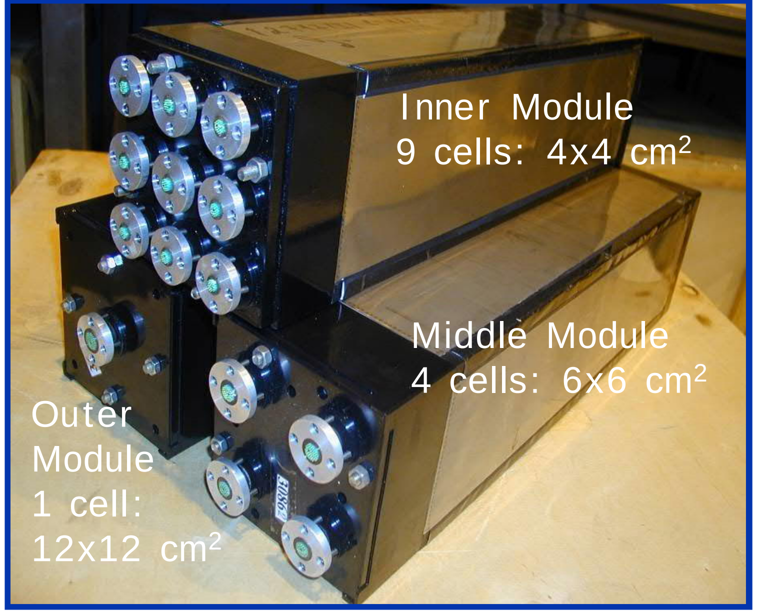
Current LHCb ECAL:

- Large Shashlik array ~50 m^2 with 3312 modules and 6016 channels
- Modular wall-like structure of 7.8 m x 6.3 m
- Three sections: Inner, Middle, Outer of cell size 4x4, 6x6, 12x12 cm^2
- $\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$

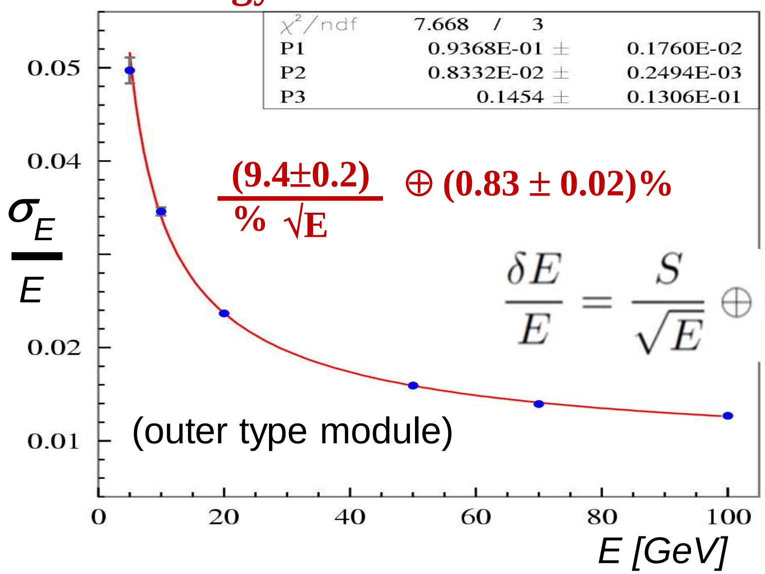
	S [$GeV^{1/2}$]	C	N [MeV]
LHCb	~10%	~0.8%	~10-20
ATLAS	10-12%	~0.2%	~250
CMS	3-6%	~0.5%	200-600

$$\frac{\delta E}{E} = \frac{S}{\sqrt{E}} \oplus C \oplus \frac{N}{E}$$

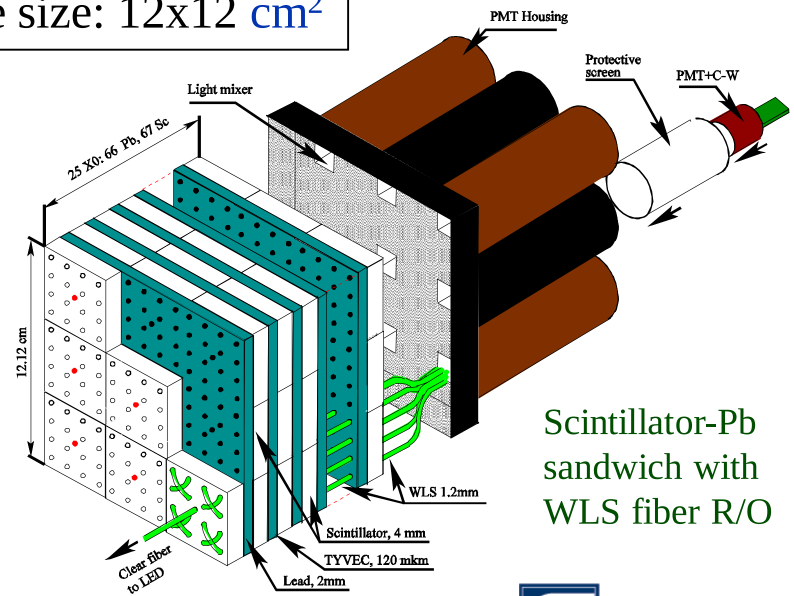
3312 shashlik modules with 25 X0



Energy resolution with electrons



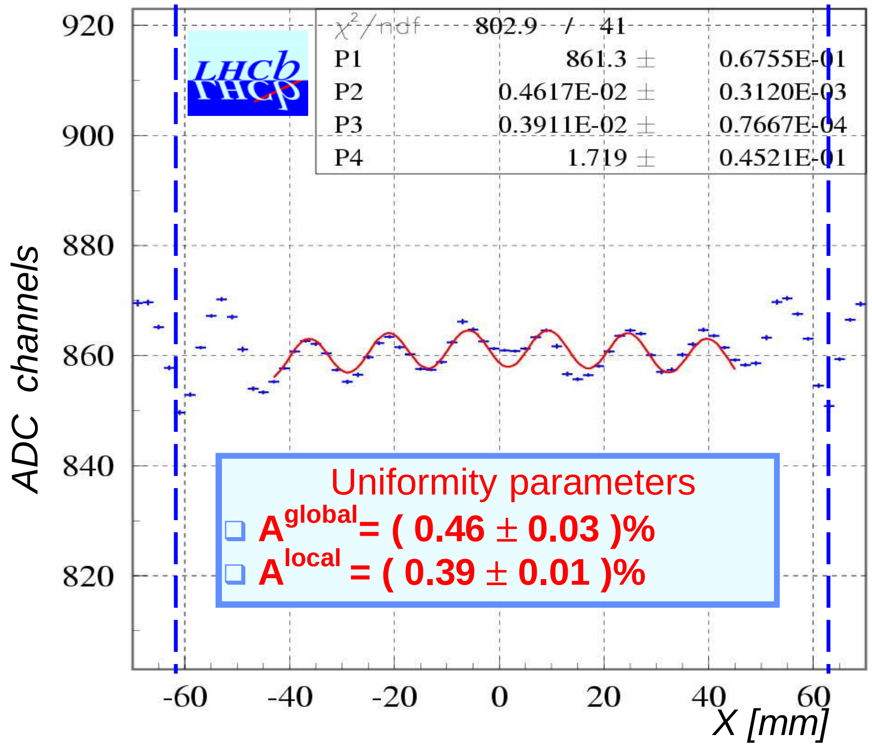
Module size: 12x12 cm^2



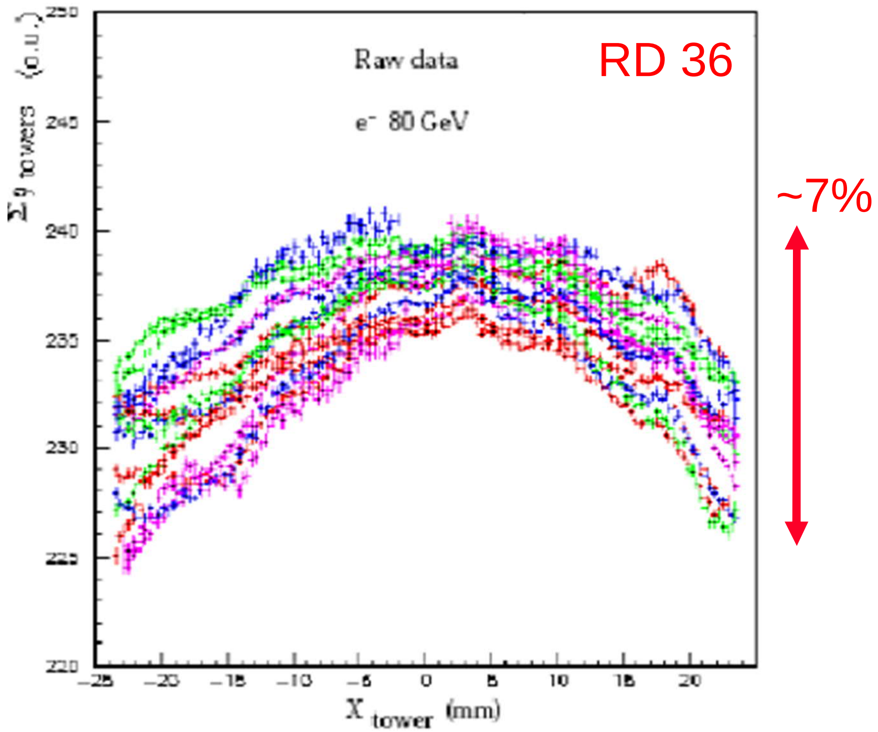
Scintillator-Pb sandwich with WLS fiber R/O

ECAL uniformity of light response

Transverse scan with 50 GeV electrons

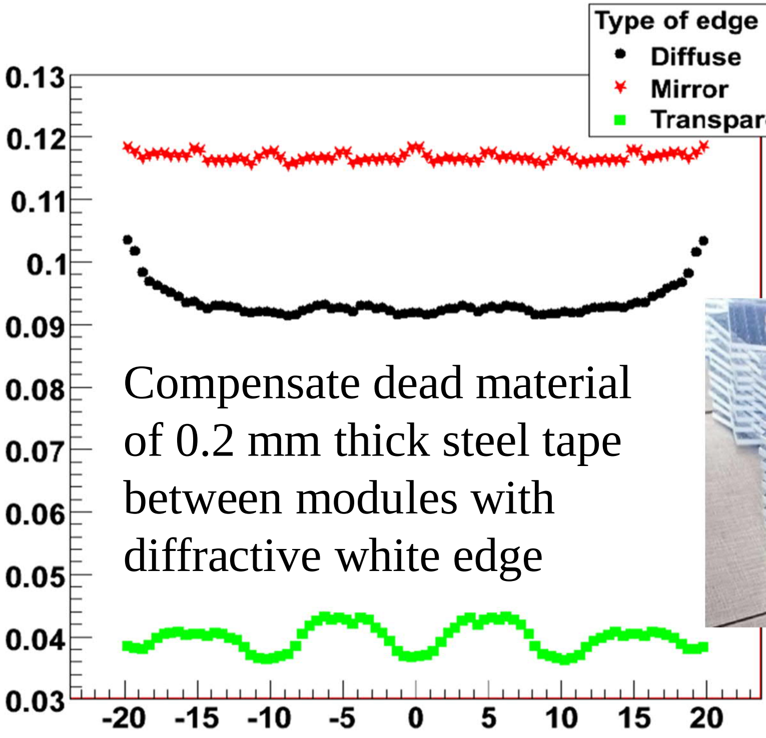


Transverse scan with 80 GeV electrons

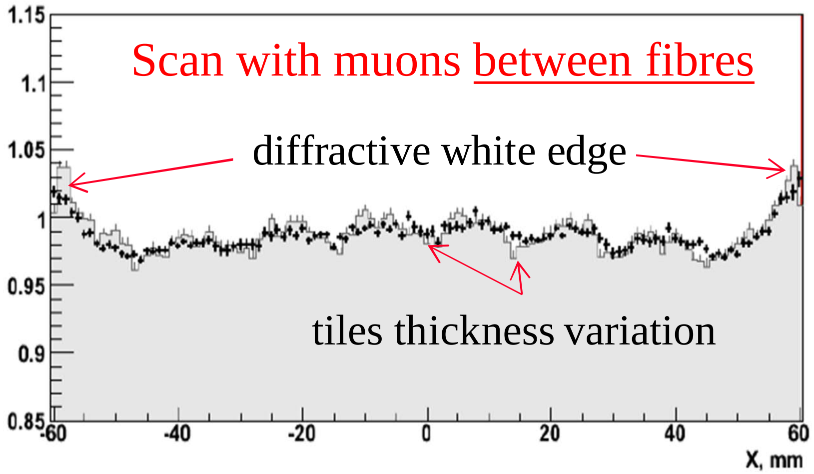


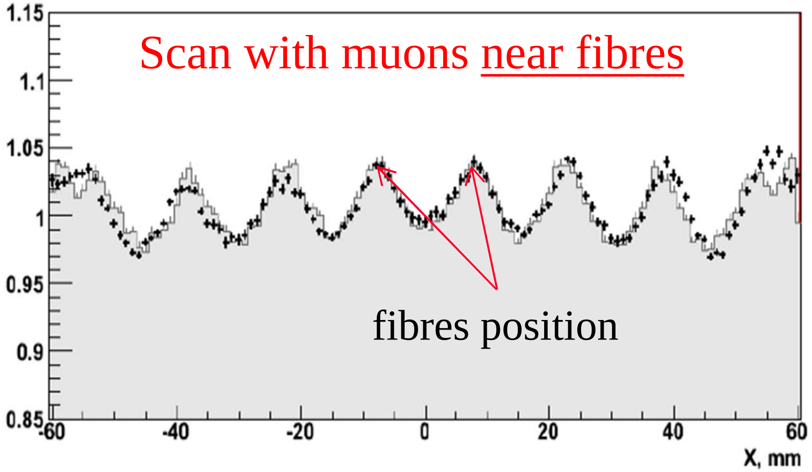
Simulation of response uniformity

MC modeling:
- light collection efficiency → ray tracer program (refraction, reflection, attenuation...)
- Scintillator thickness → measured
- Convolution with particle energy deposition → GEANT

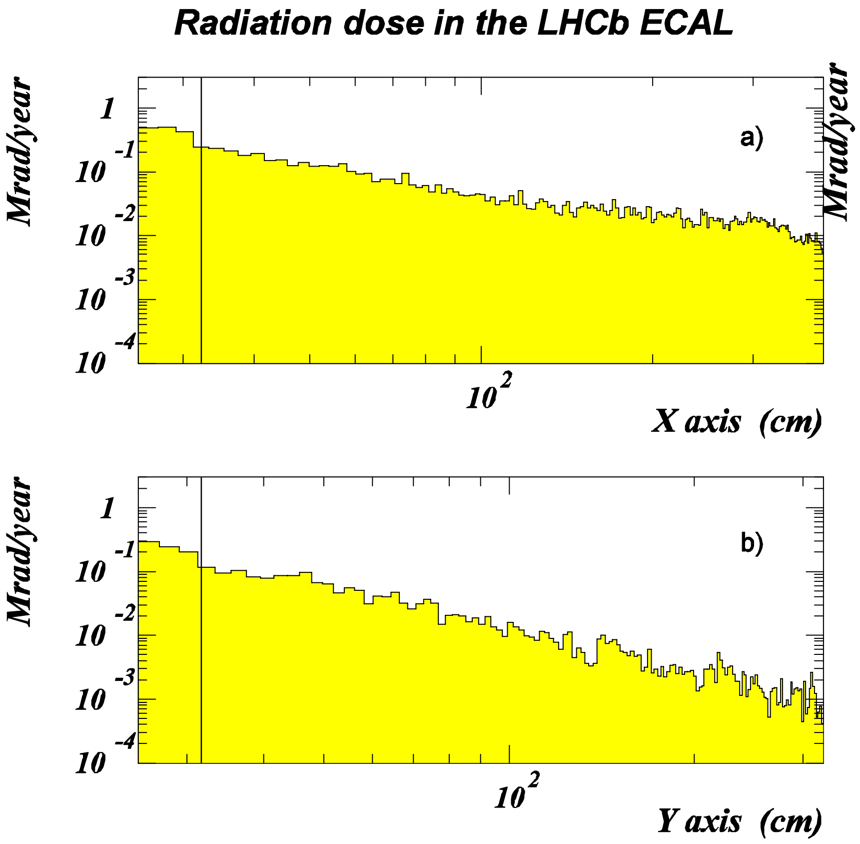


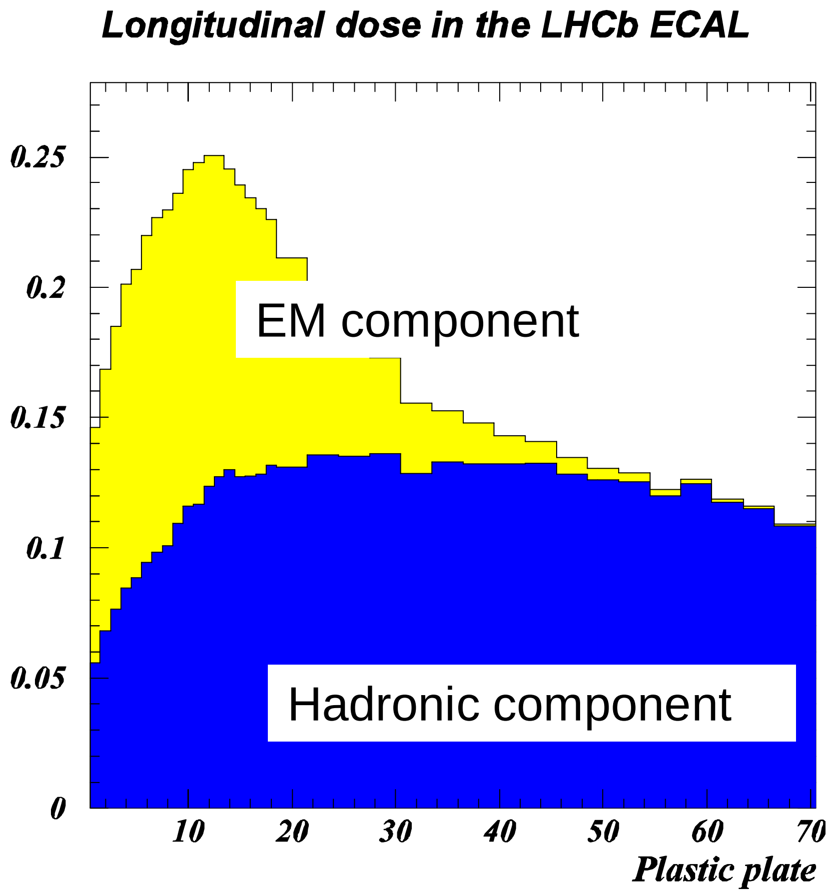
Data (points) vs simulation (grey area)





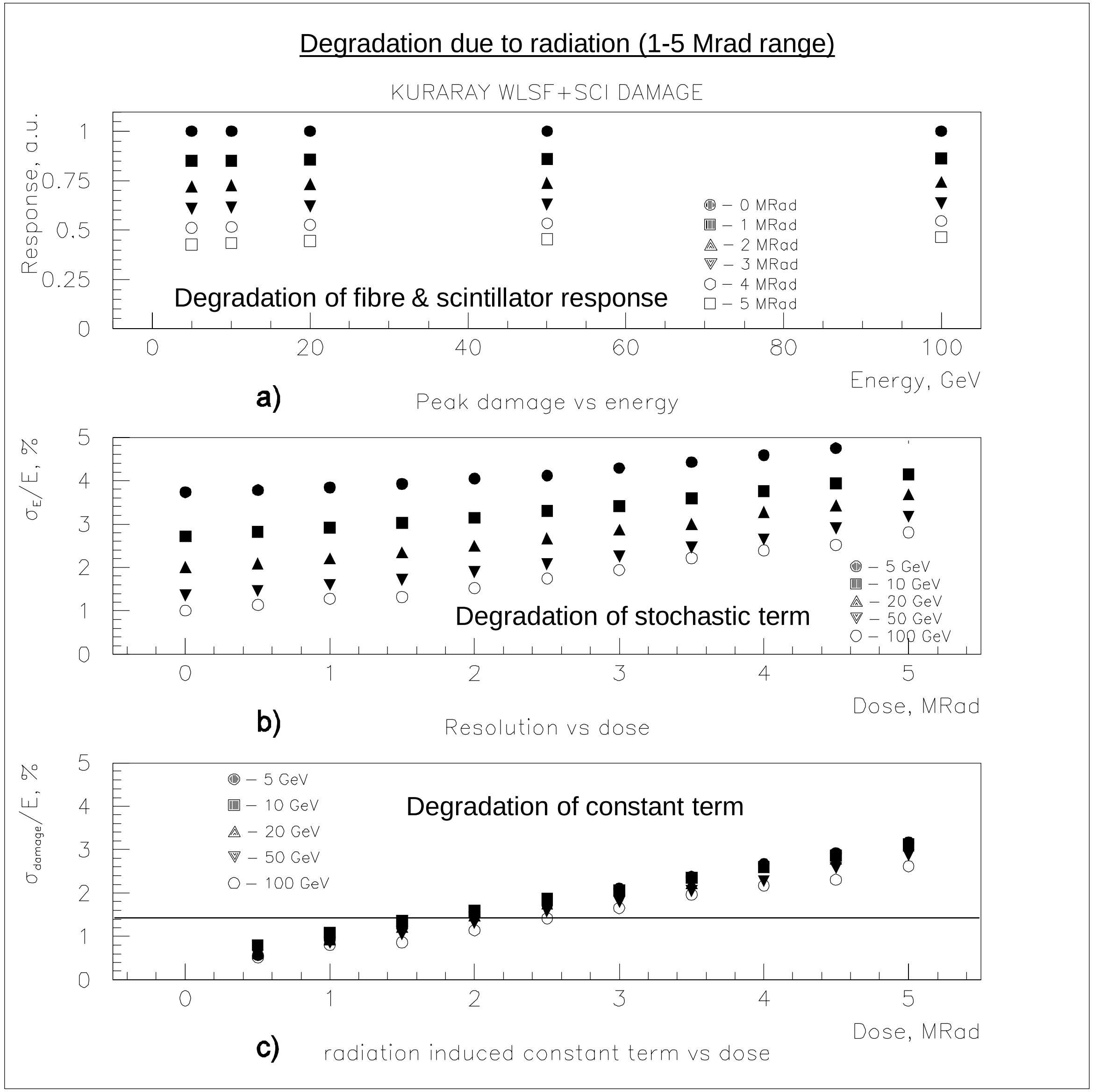
Radiation environment at L=2x10^{32} cm^{-2}s^{-1}





- maximum radiation dose in shower maximum ~250 krad/year
- ~8 years operation → ~2 Mrad total dose

Behavior of module components under irradiation



- ✓ Tested all components (fibres & scintillator) in the 1 to 5 Mrad range
- ➢ Radiation damage acceptable up to ~2 Mrad
- ➢ **Replace most inner modules in LS3 (min. 32 modules)**

Requirements due to increased radiation and occupancies:

- ✓ improve radiation hardness of components
- ✓ improve granularity due to increased occupancy
- ✓ reduce Moliere Radius
- ✓ keep excellent E-resolution
- ✓ add timing information (5D)
- ➢ **Optimize overall system for improved physics output**

Physics analysis with particular sensitivity to ECAL performance

$B \to \eta' X$
$B^+ \to K^+ \pi^0$, $B^+ \to \rho^+ \rho^0$
$\Lambda_b \to pK\eta^{(\prime)}$, $B^0 \to K^* \eta^{(\prime)}$
$B^0, B_s \to h^+ h^- \pi^0$

$D^0 \to e\mu$
$D^+ \to \pi^+ \pi^0 (\to \gamma e^+ e^-)$
$D^0 \to \Phi\gamma$, $K^*\gamma$, $\rho/\omega\gamma$

$B^+ \to D(hh\pi^0)K$
$B_s \to D_s^* K$
$B^+ \to D^* K$

$B^0 \to J/\psi \pi^0$
$B^0 \to J/\psi \omega$
$B^+ \to J/\psi \rho^+$

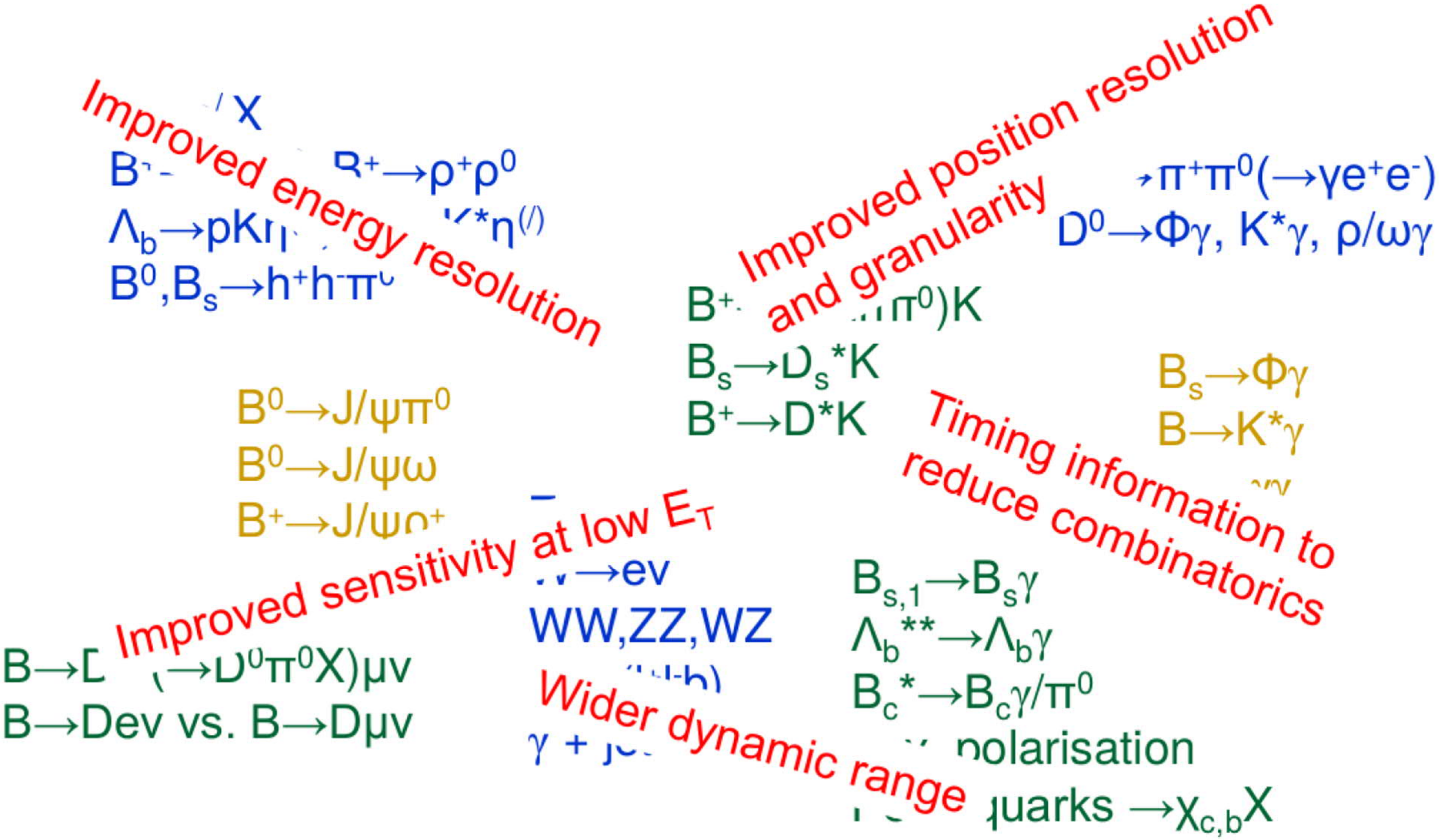
$B_s \to \Phi\gamma$
$B \to K^*\gamma$
$B_s \to \gamma\gamma$
$B \to K^* e+e-$

$Z \to e^+ e^-$
$W \to e\nu$
WW,ZZ,WZ
Top ($l^+ l^- b$)
γ + jet

$B_{s,1} \to B_s \gamma$
$\Lambda_b^{**} \to \Lambda_b \gamma$
$B_c^* \to B_c \gamma/\pi^0$
χ_c, χ_b polarisation
Pentaquarks $\to \chi_{c,b} X$

$B \to D^{**}(\to D^0 \pi^0 X)\mu\nu$
$B \to De\nu$ vs. $B \to D\mu\nu$

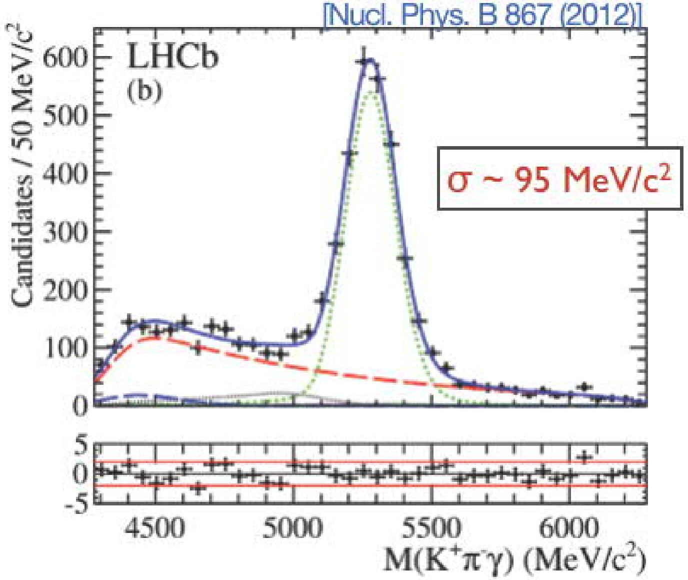
Physics analysis with particular sensitivity to ECAL performance

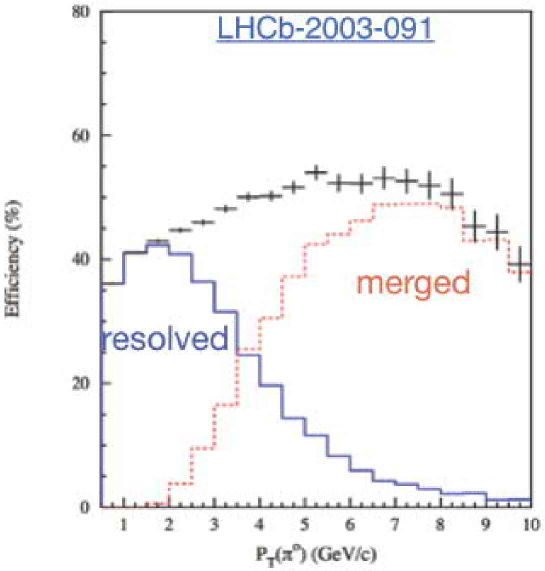


➢ Simulation studies needed to define the design parameters

Experimental Challenges

- Mass resolution dominated by photon reconstruction
  - σ~95 MeV/c^2 for B→K*γ decays, compared to ~25 MeV/c^2 for B→Kπ decays.
- Backgrounds:
  - Above transverse energies of 4 GeV, $\pi^0 \to \gamma\gamma$ reconstructed as a single cluster in the calorimeter
  - Combinatorial: $O(10)$ reconstructed photons per event





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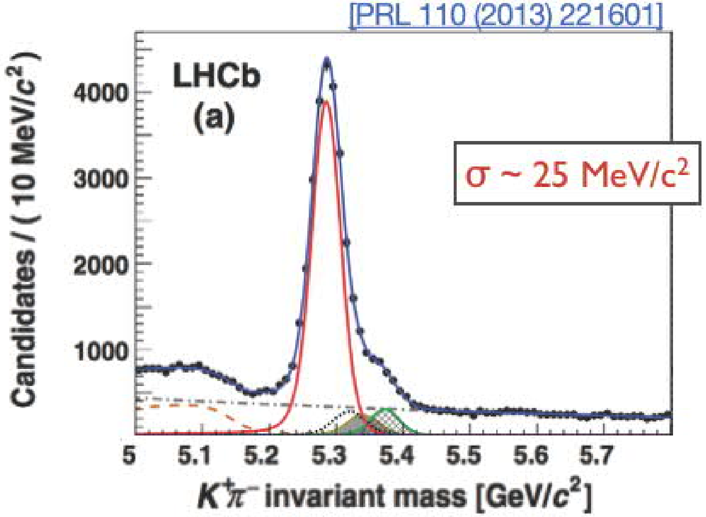
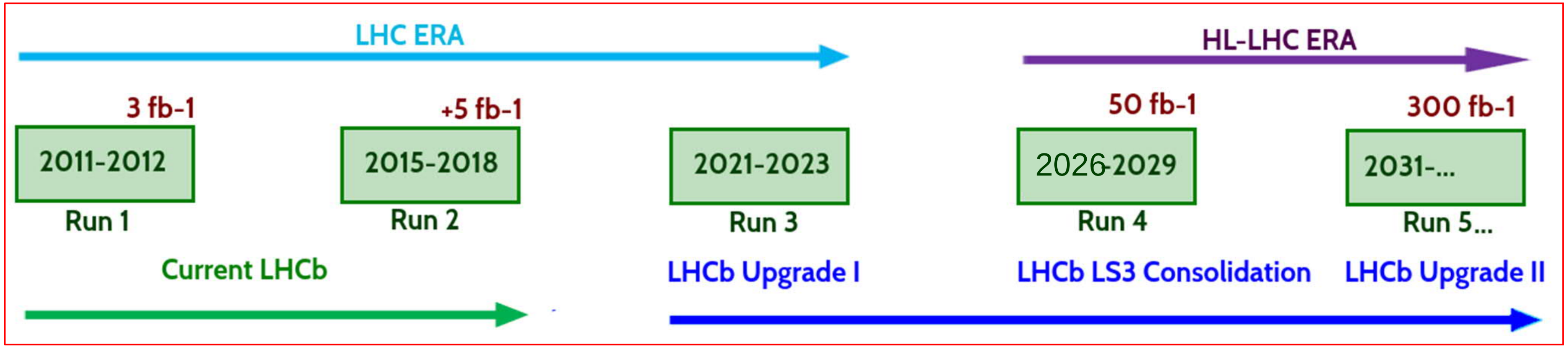


LHCb ECAL Upgrades I(b) and II



LS2 in 2019/20: → LHCb Upgrade I

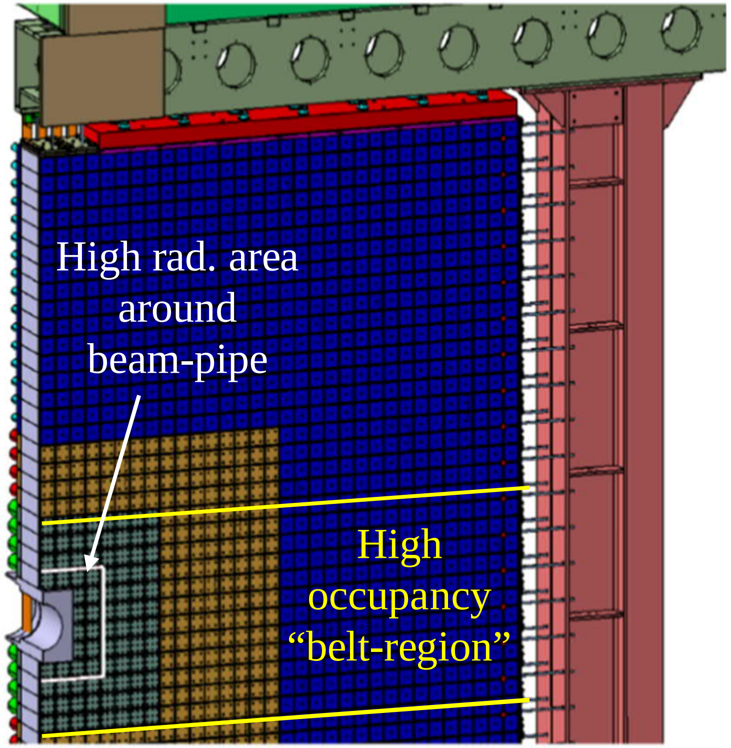
- Keep current ECAL Shashlik modules but **upgrade electronics to full 40 MHz readout**

LS3 in 2024/25: → Consolidation (1b)

- **Replace modules around beam-pipe** (≥ 32 modules) compatible with **$L=2x10^{33}$ $cm^{-2}s^{-1}$**

LS4 in 2030/31: → LHCb Upgrade II

- **Rebuilt ECAL in high occupancy "belt-region"** compatible with luminosity up to **$L=2x10^{34}$ $cm^{-2}s^{-1}$**
- Include **timing information** to mitigate multiple interactions/crossing

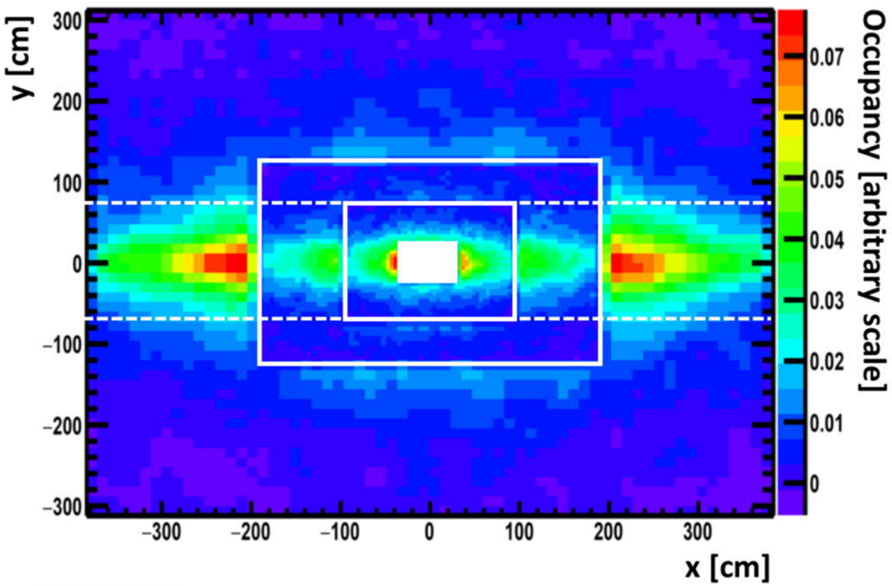


ECAL requirements for Upgrade II

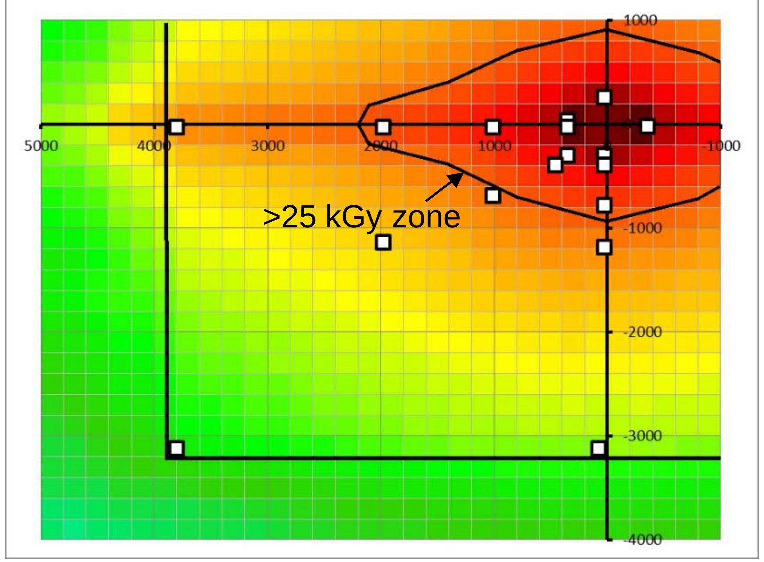
Overall requirements:

- ✓ **Sustain radiation doses of up to ~3 MGy and ~$3 \cdot 10^{15}$cm^{-2} for 1 MeV n eq. at 300 fb^{-1}**
  (in hottest region of the central part, decreasing quickly with distance from beam-pipe)
- ✓ Keep good energy resolution of order $\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$
- ✓ Reduce occupancy and improve spatial resolution in inner region
  (reduce Moliere Radius (to ~2-3cm) and cell size (inner region) to ~ 2cm x 2cm)
- ✓ Include a very fast (crystal) component (~20ps) for pile-up mitigation into sampling module or add "pre-shower timing layer" in front of module (crystal, silicon, …?)
- ✓ Respect dimensional constraints of a module: 12 x 12 cm^2 outer dimension

Occupancies in different ECAL regions



Radiation dose on ECAL front



Possible options for new ECAL modules

Possible options considered at present:

- ✓ Homogeneous crystal calorimeter with longitudinal segmentation:
  - ➢ Fast and radiation hard crystal with small Moliere Radius and excellent σ(E)
- ✓ Sampling calorimeter: (e.g. Shashlik or SpaCal type)
  - ➢ Tungsten or tungsten alloy as converter ($R_M \sim$ 1cm)
  - ➢ Radiation hard crystal as active medium with high light yield and fast response
  - ➢ Radiation hard light-guide/fibre to transport light (for Shashlik type)
  - ➢ Radiation hard photodetector
  - ➢ Include a very fast (crystal) component (~20ps) into module (for pile-up mitigation)
- ✓ Pre-shower timing: (if not included in module)
  - ➢ Add a "pre-shower timing layer" in front of the module for pile-up mitigation (we will store the current preshower lead converter when removing PS/SPD…)

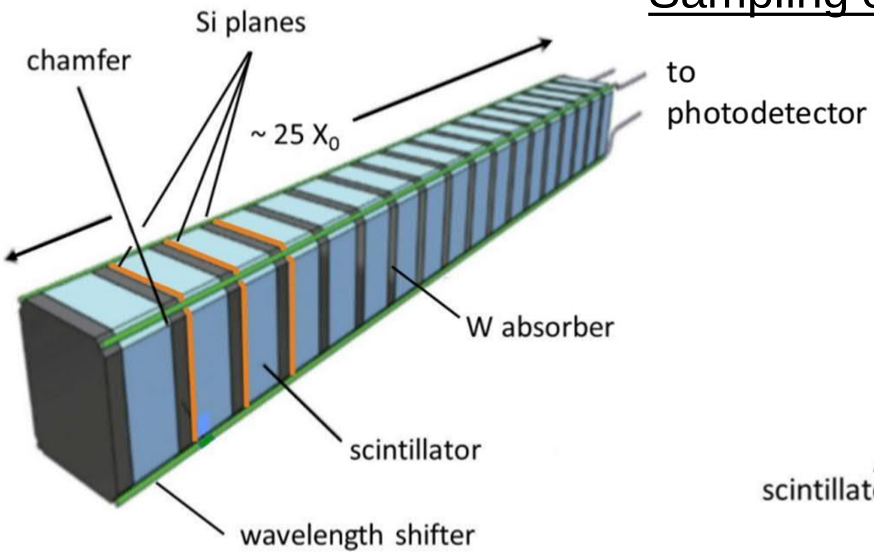
Remember: requirements in most inner region not the same as for middle or outer region → different technologies possible

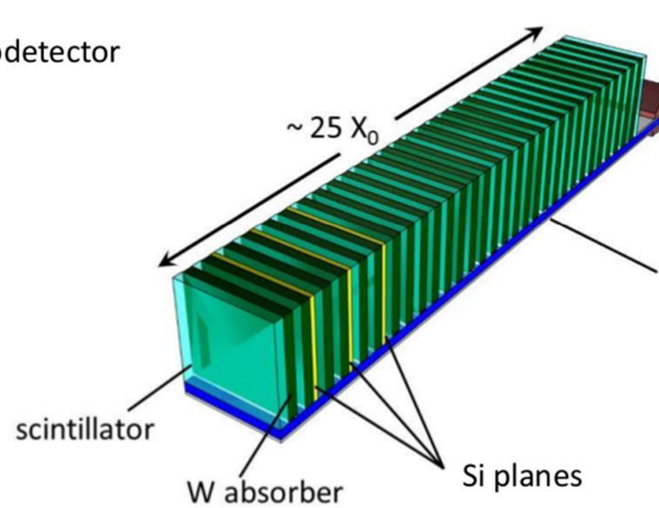
R&D has started on:

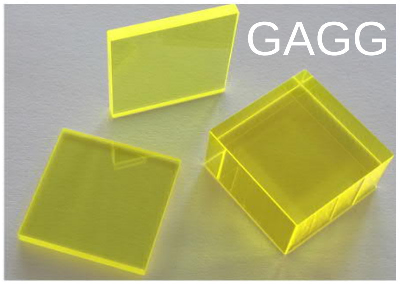
- ➢ Radiation hard scintillators (e.g. GAGG crystals)
- ➢ Radiation hardness of GaAs photodiodes with epitaxial technology
- ➢ Tungsten alloys (i.e. W-Pb)

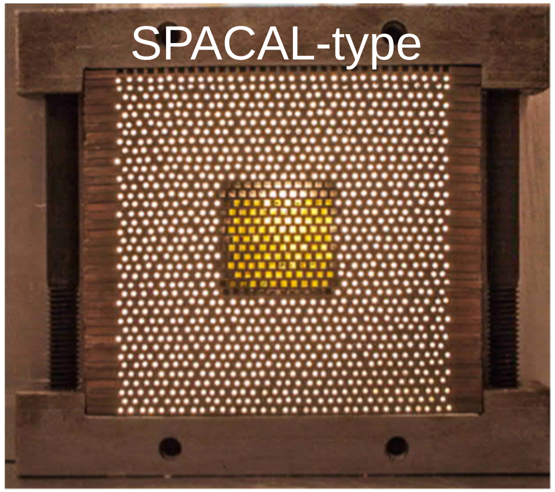
Ideas “on the market” for LHCb ECAL upgrade

Sampling calorimeters of various type

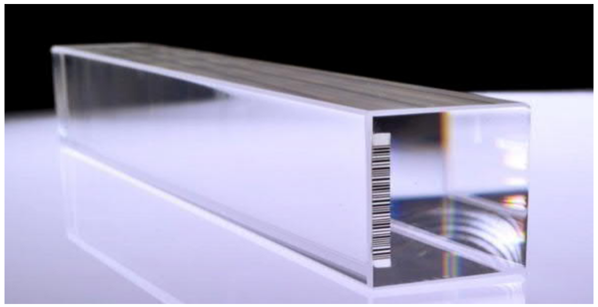








Homogeneous Crystals



[a lot of expertise in CMS and RD18]

Conclusions

- ✓ Sustain radiation doses of up to ~3 MGy and ~$3 \cdot 10^{15} cm^{-2}$ (1MeV n eq.) at 300 fb^{-1} (however only in hottest region of the central part!)
  - ➢ Replace at least 32 modules around beam pipe in LS3, compatible with LS4?
  - ➢ Rebuilt ECAL in high occupancy "belt-region" in LS4
- ✓ Perform physics and detector simulation studies to define detailed performance requirements (spatial-, energy- and timing-resolution → cell size, Moliere Radius, homogenous vs. sampling, etc.)
- ✓ Converge on design parameters and set priorities in R&D program
- ✓ Activities have started (→ next presentations):
  - ➢ Development of simulation code (GEANT and DELPHES) (→ Adam's talk)
  - ➢ Monitoring ongoing developments and starting some first R&D (→ Yuri's talk)
    - o Radiation hard and fast scintillating crystals and light guides (e.g. GAGG)
    - o Radiation hard photodetectors (e.g. GaAs photodiode)
    - o Converter material with adequate mechanical properties (e.g. tungsten alloys)