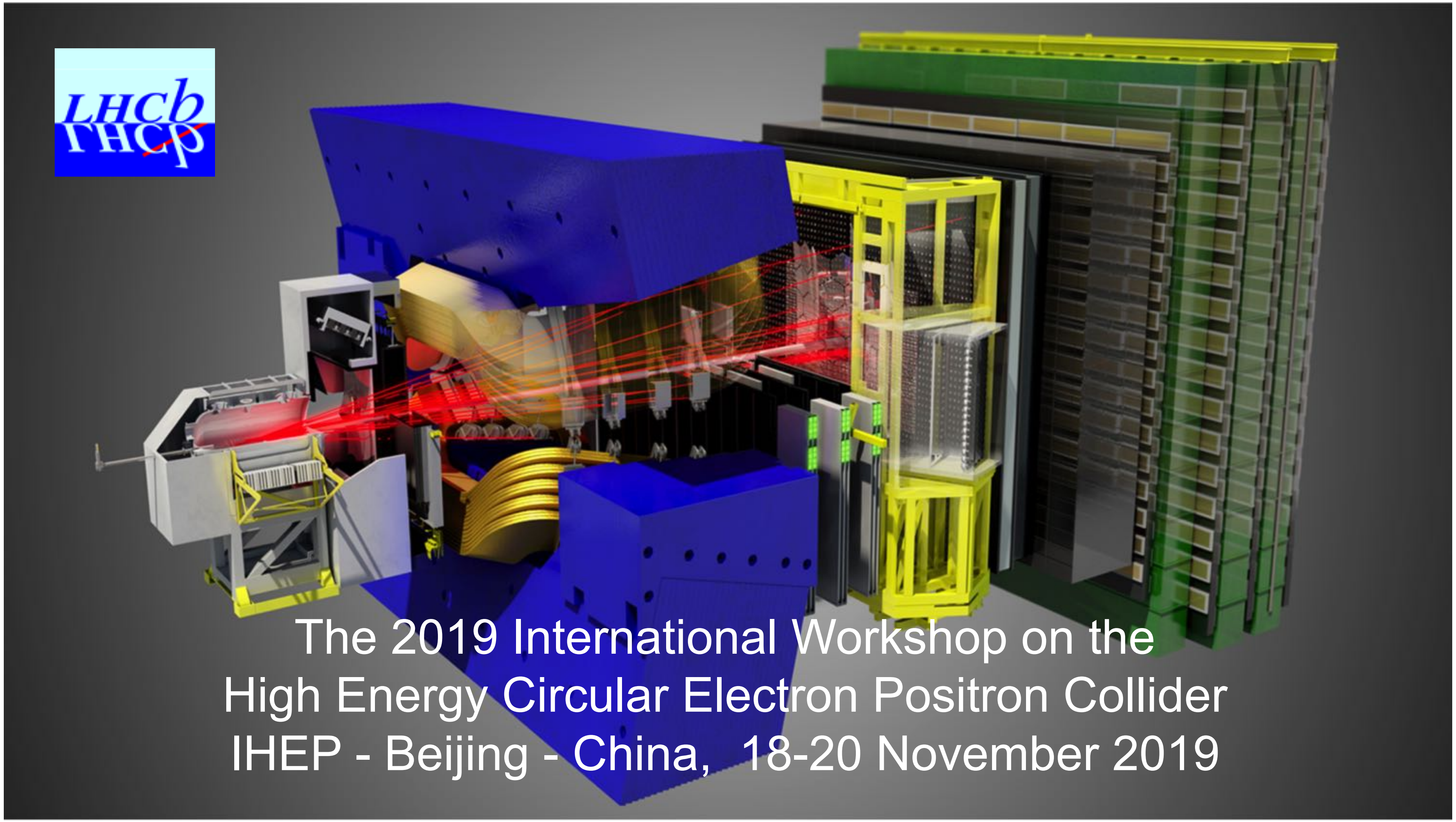
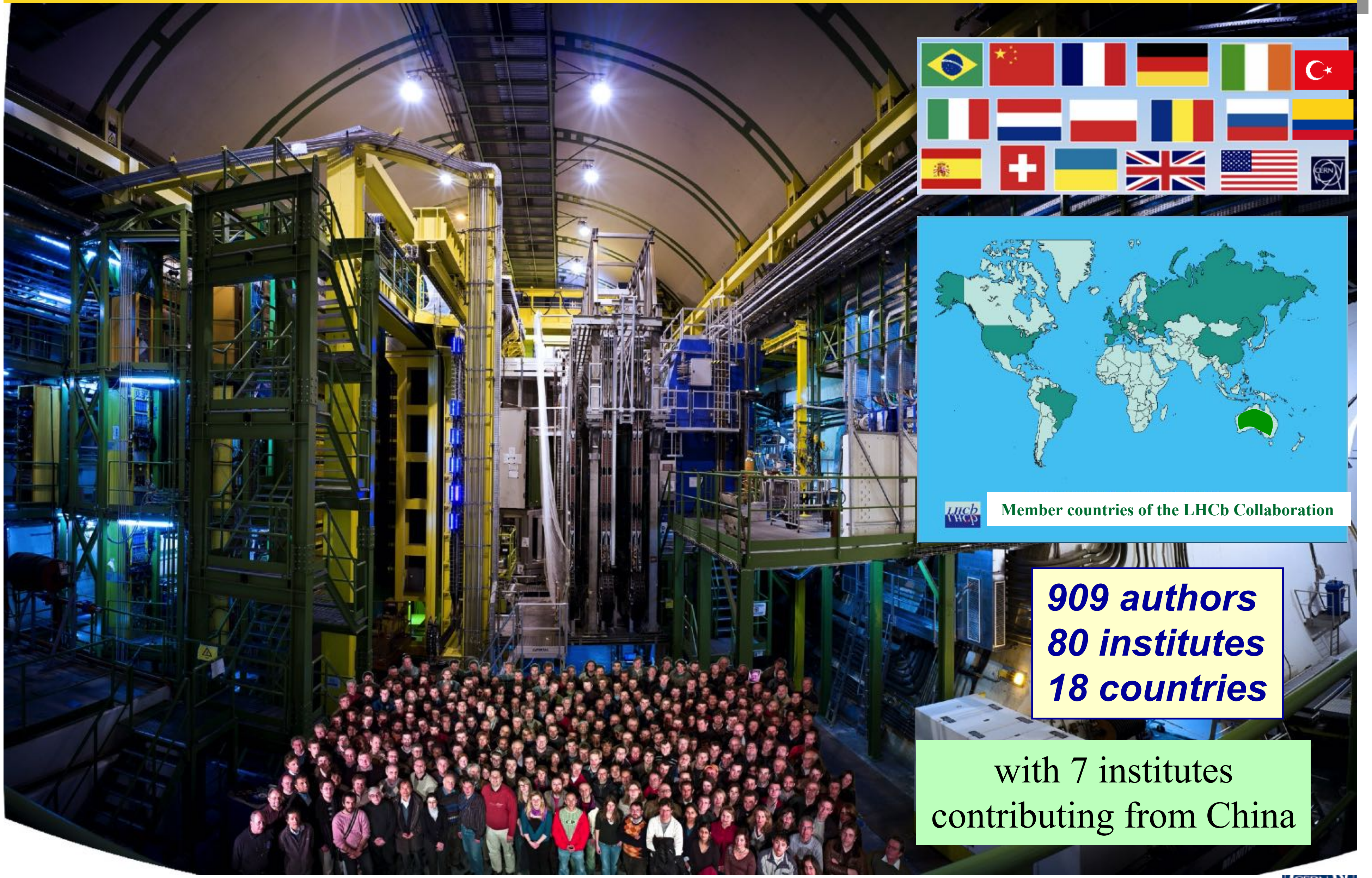
The LHCb Calorimeter Upgrade Plan



The 2019 International Workshop on the
High Energy Circular Electron Positron Collider
IHEP - Beijing - China, 18-20 November 2019

Andreas Schopper on behalf of LHCb

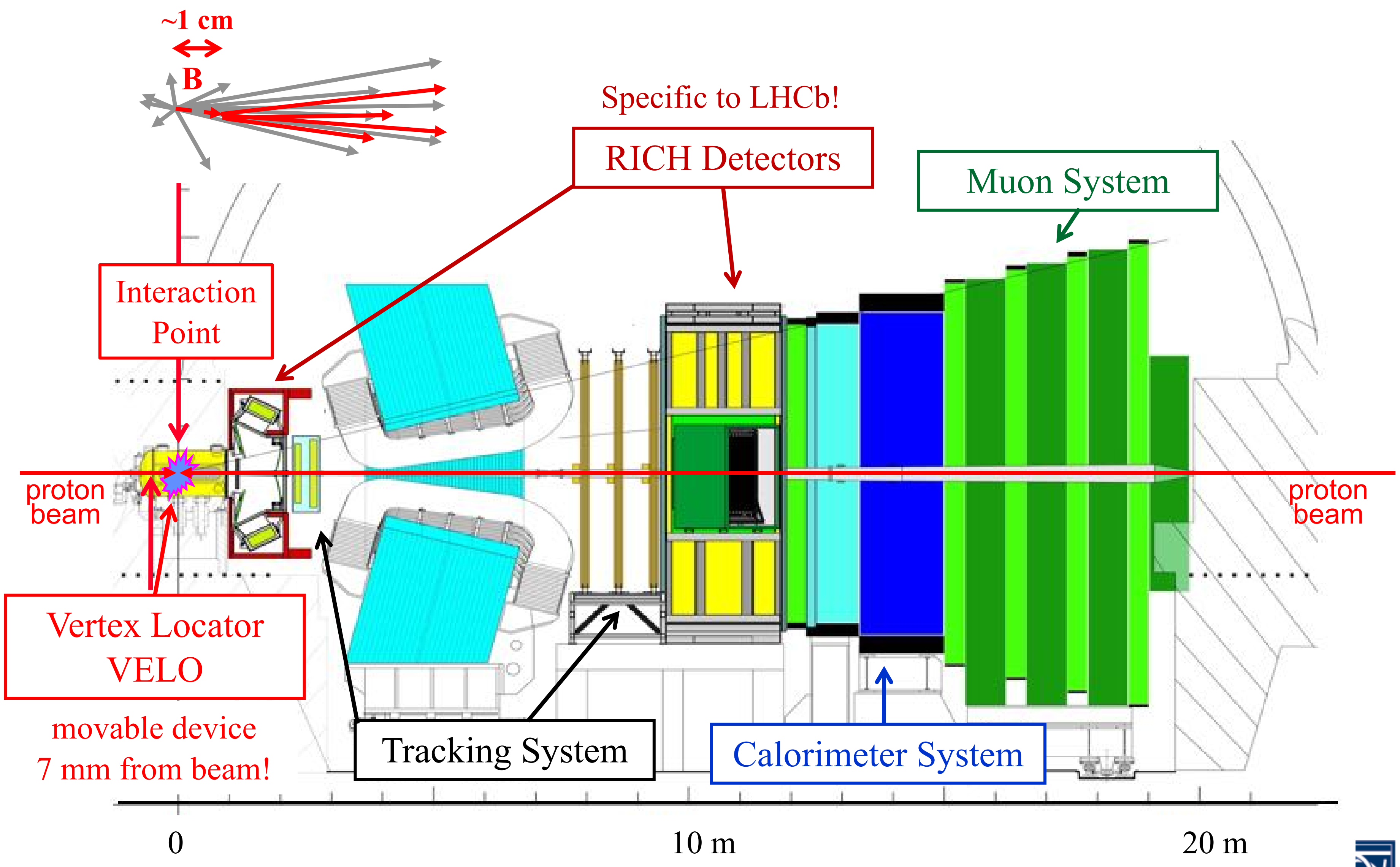
The LHCb Experiment



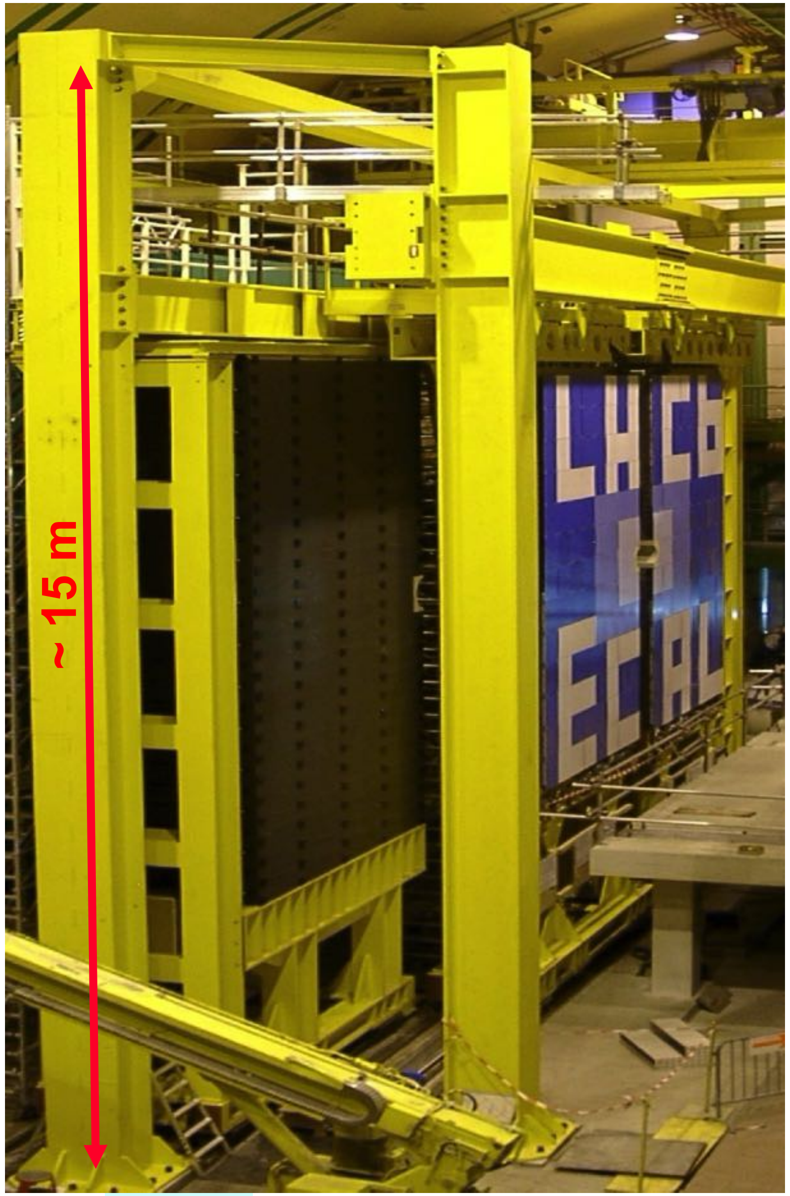
909 authors
80 institutes
18 countries

with 7 institutes contributing from China

LHCb: A dedicated flavor physics experiment at proton collider

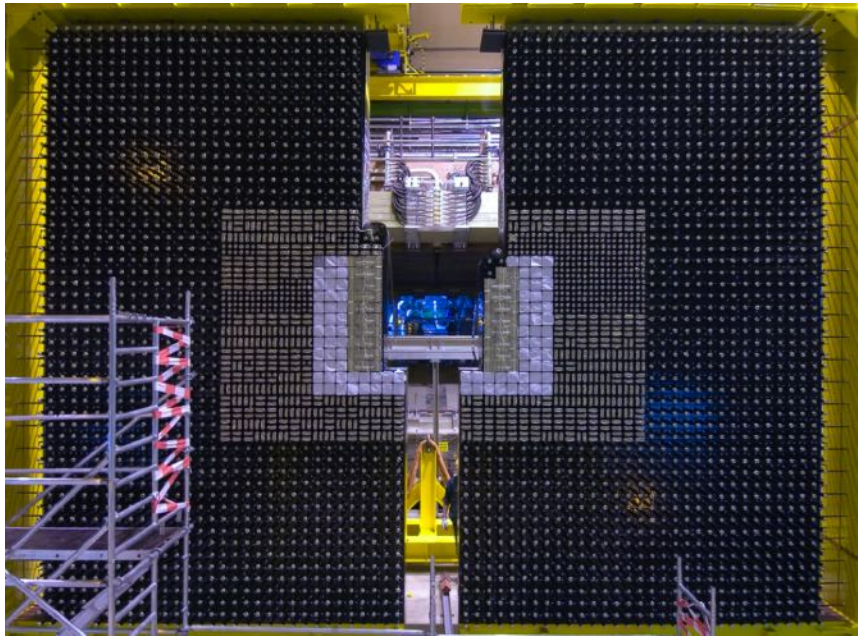


The LHCb Electromagnetic CALorimeter

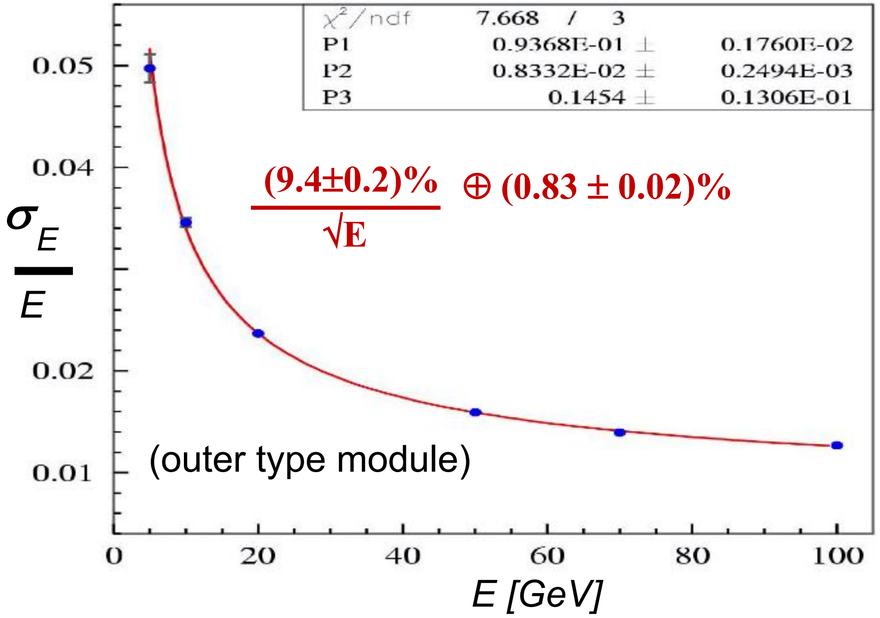


Current LHCb ECAL:

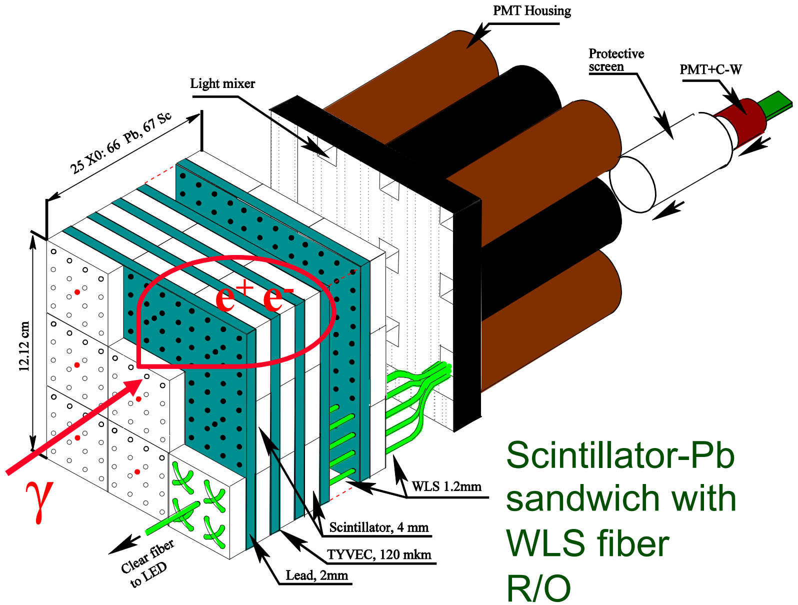
- Large Shashlik array ~50 m^2 with 3312 modules and 6016 channels
- Modular wall-like structure of ~8x7m^2, two halves open laterally
- Three sections (Inner, Middle, Outer) of cell size 4x4, 6x6, 12x12 cm^2
- **$\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$**



Energy resolution with electrons



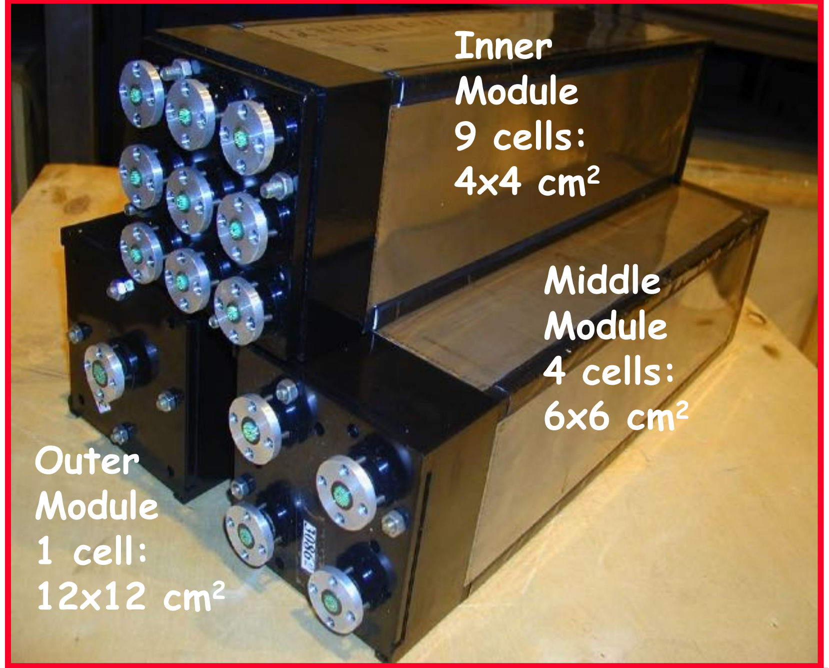
ECAL shashlik module



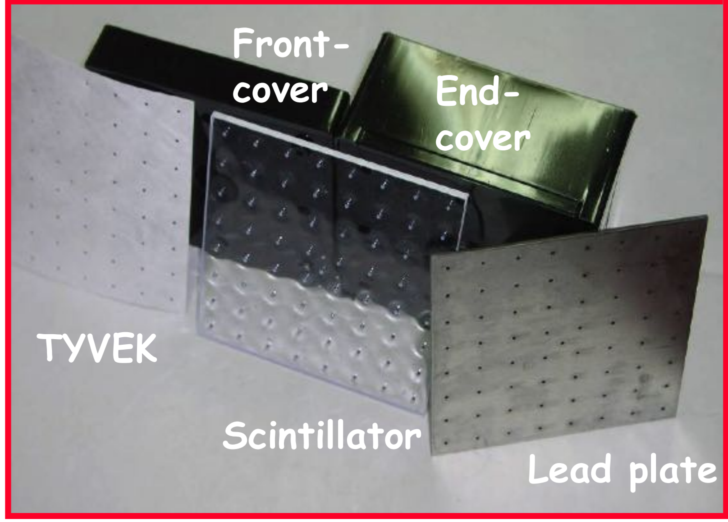
Scintillator-Pb sandwich with WLS fiber R/O

Scintillators & WLS fibers sustain radiation doses up to ~20kGy (2Mrad)

3312 shashlik modules with 25 X0 Pb

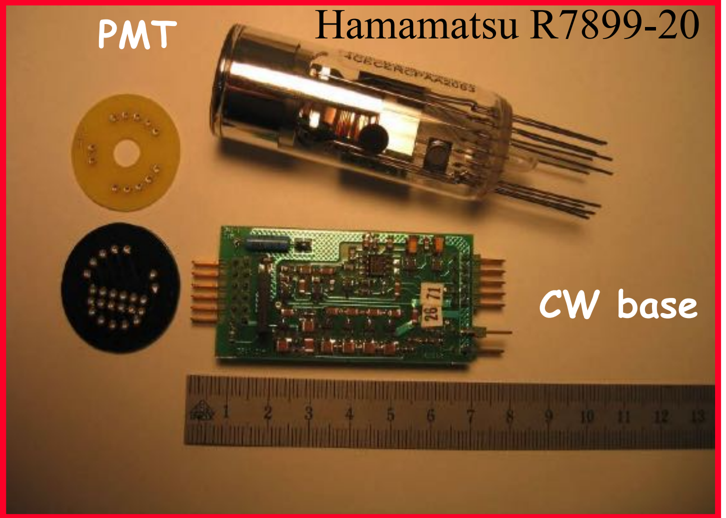


Scintillators, lead-plates, covers

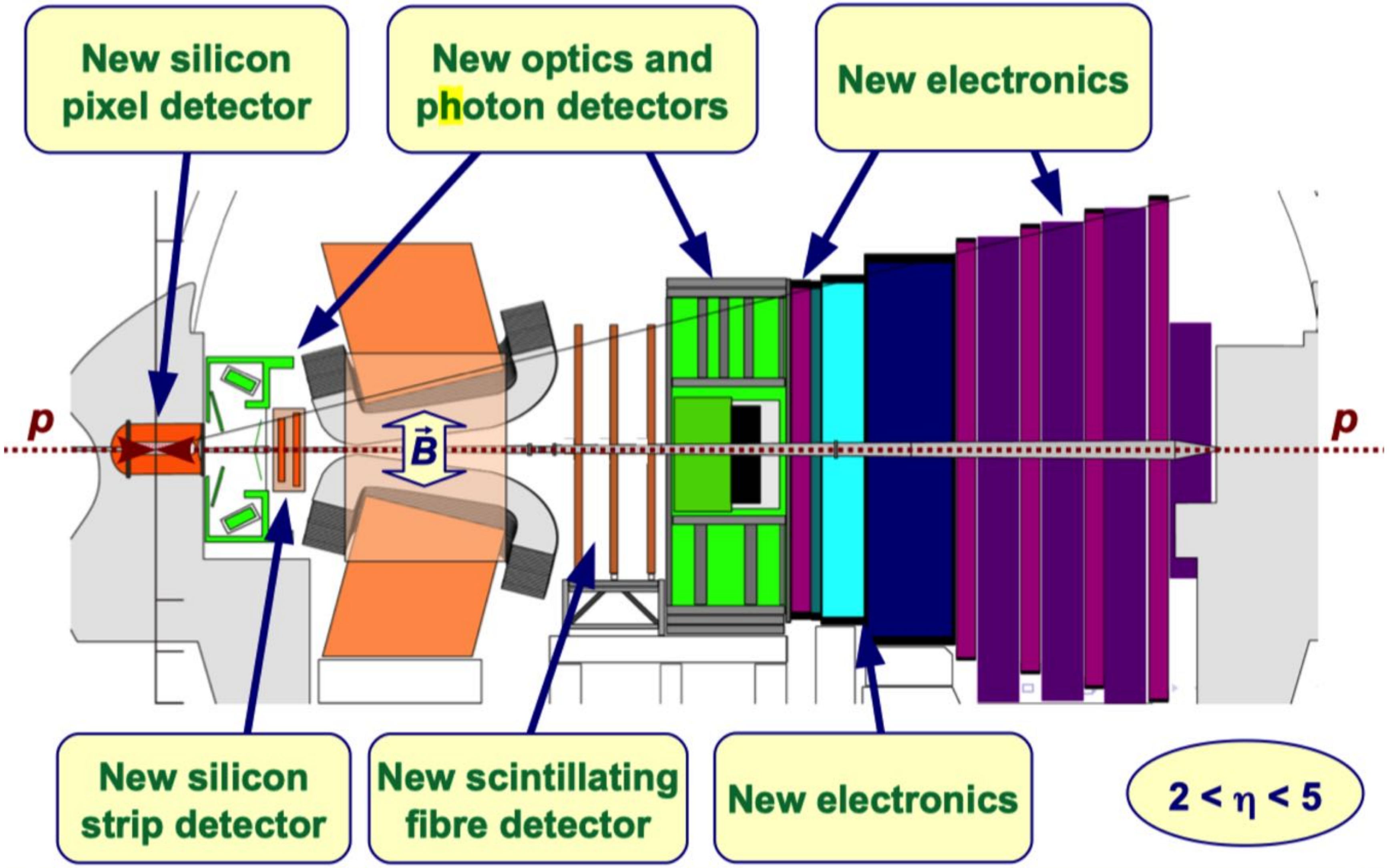


Fibres with loops

PMT and HV base



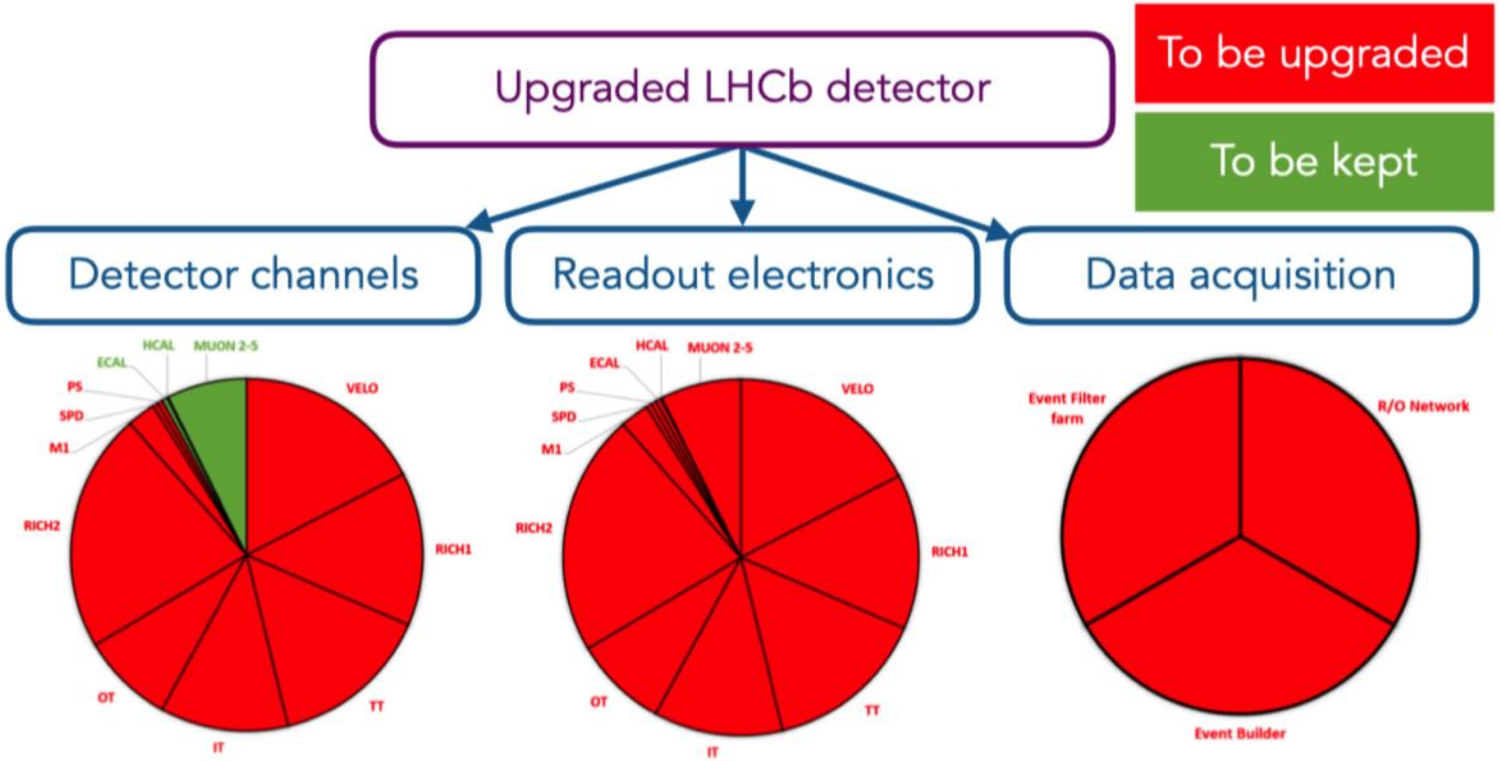
LHCb Upgrade I → Detector upgrade to 40 MHz readout



LHCb Upgrade I → A new detector…

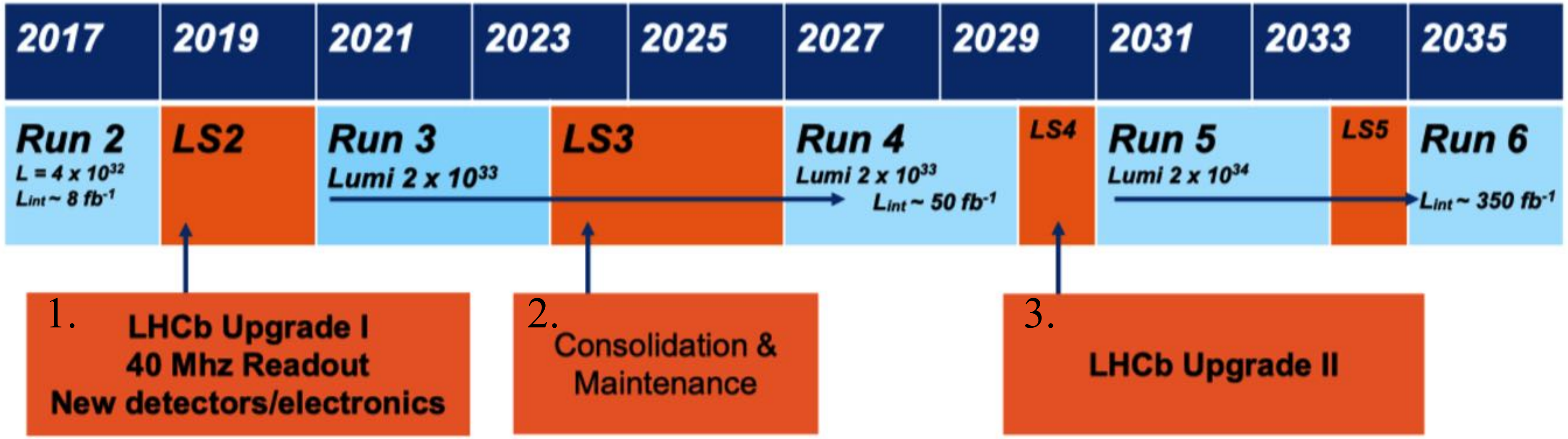
A NEW DETECTOR AT THE LHC

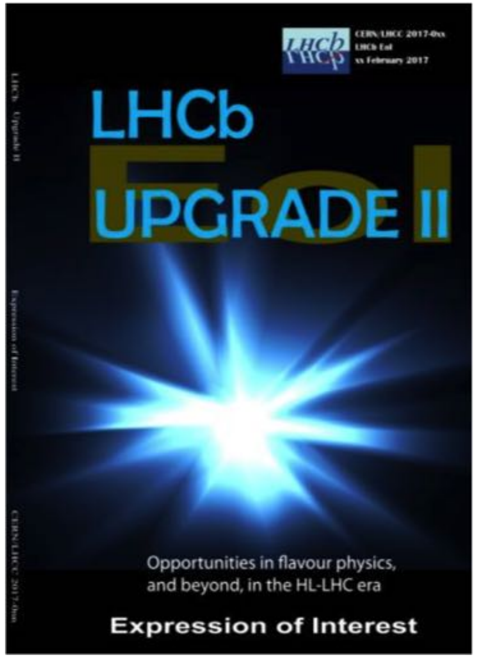
LHCb-TDR-12 13

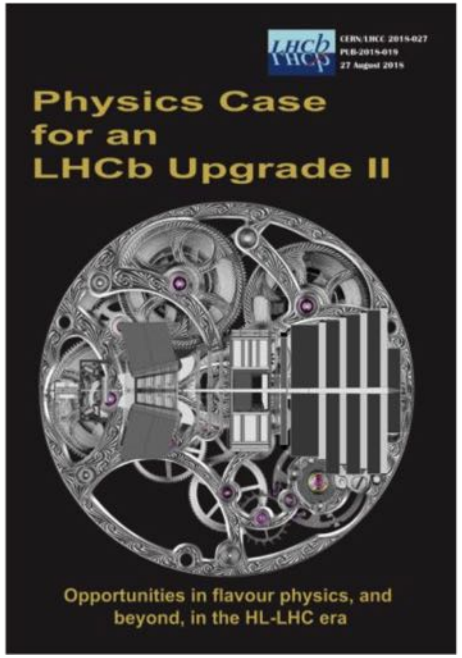


- Less than 10% of the detector will be kept
- 100% of the readout electronics will be replaced
- NEW data acquisition system and data center

The long-term roadmap of the LHCb experiment







- go ahead by LHC Committee and by the Research Board to proceed to a Framework Technical Design Report by summer 2021
- major detector R&D started

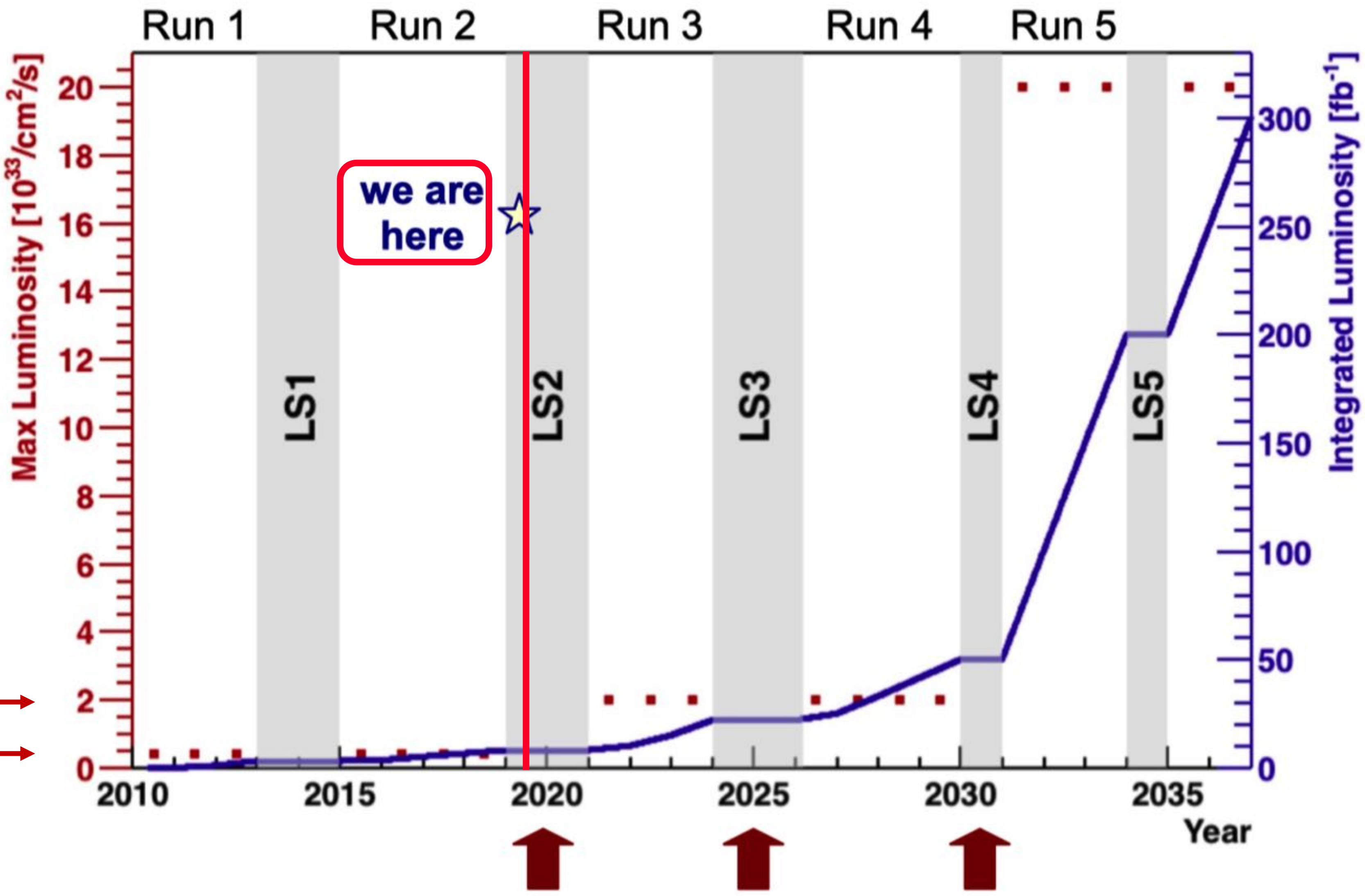
The long-term luminosity evolution of LHCb

Beam intensity

run 5 & 6

run 3 & 4

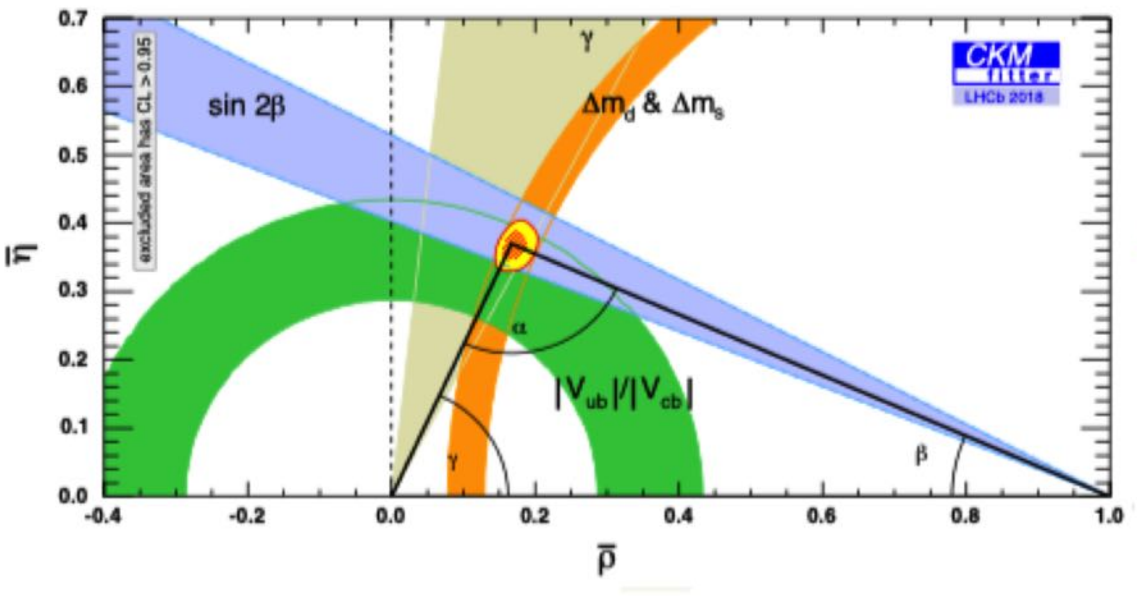
run 1 & 2



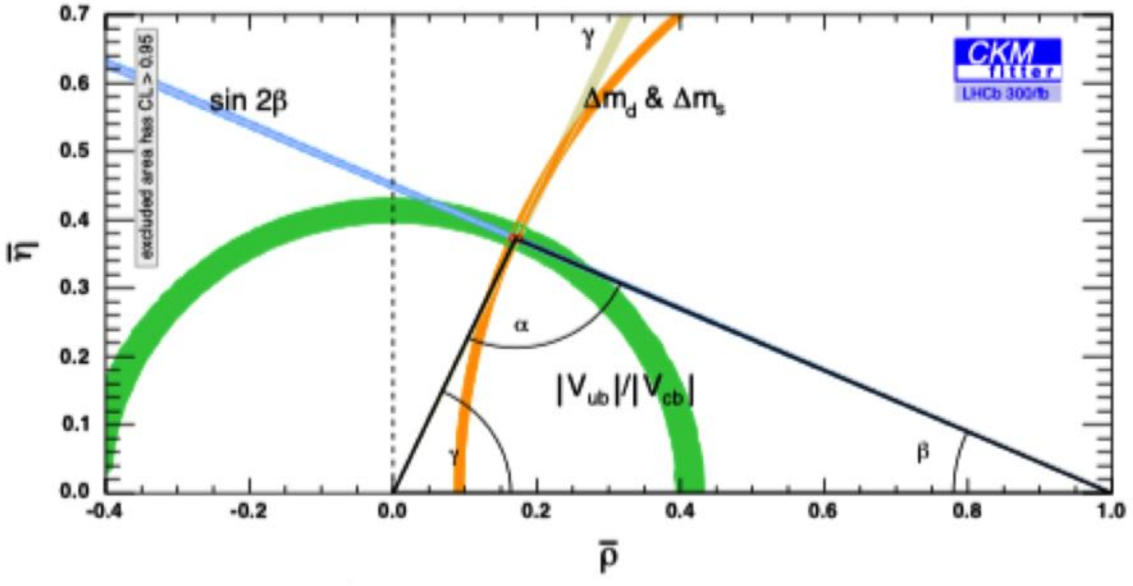
3 phases in the LHCb upgrade: upgrade I consolidation upgrade II

Why upgrading LHCb: Physics motivation

(Over-)constraining the CKM unitarity triangle



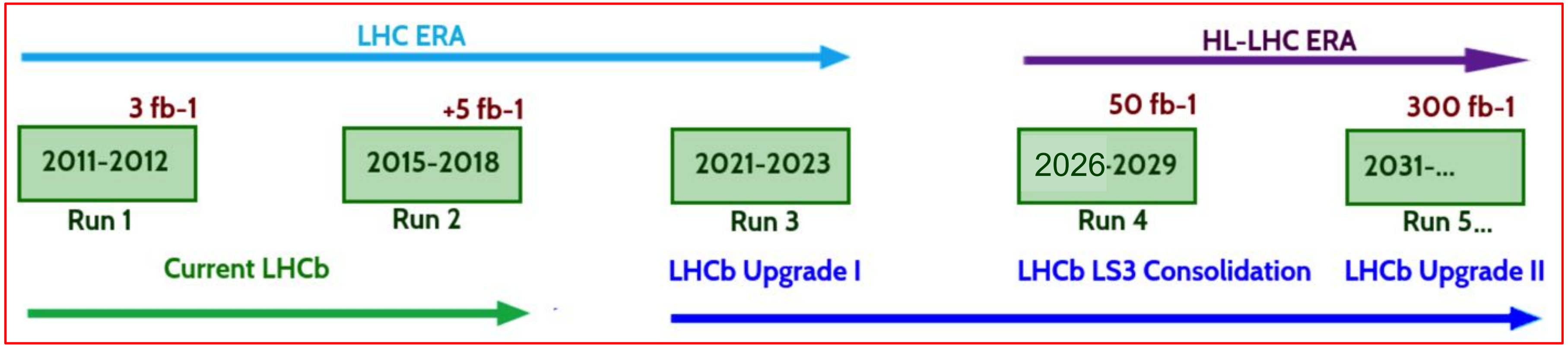
The picture before Upgrade I



The picture (not*) expected after Upgrade II

(*if not all lines cross in same point → new physics!)

LHCb ECAL Upgrade II



2020 - 2023: → submit **T**echnical **D**esign **R**eports

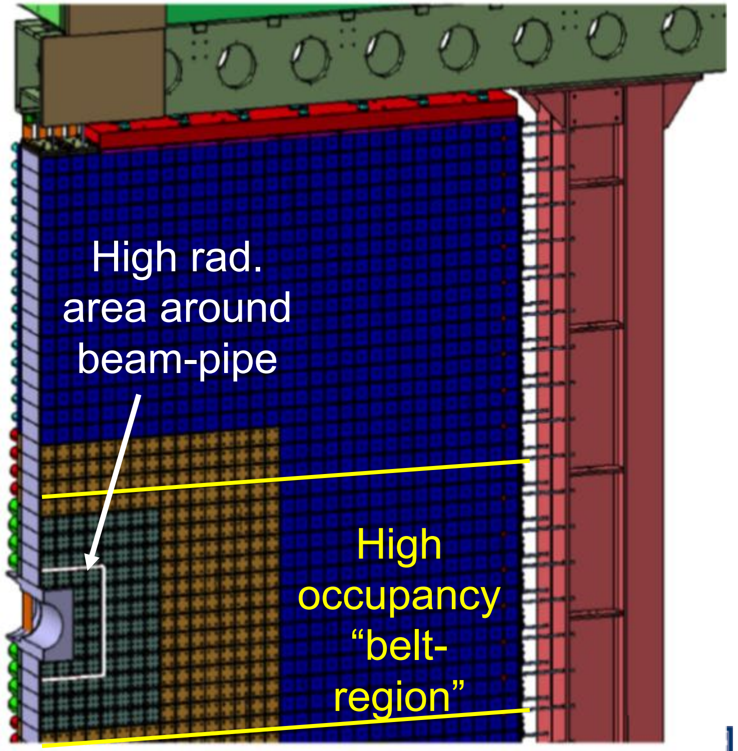
- 2021: Framework TDR for Upgrade II
  including sub-detector **"Consolidation" TDRs**
- 2023/24: Sub-detector **TDRs for Upgrade II**

LS3 in 2024/25: → **Consolidation**

- **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 $\leq$ 2x10^{34} cm^{-2}s^{-1}
- Include **timing information** to mitigate multiple interactions/crossing

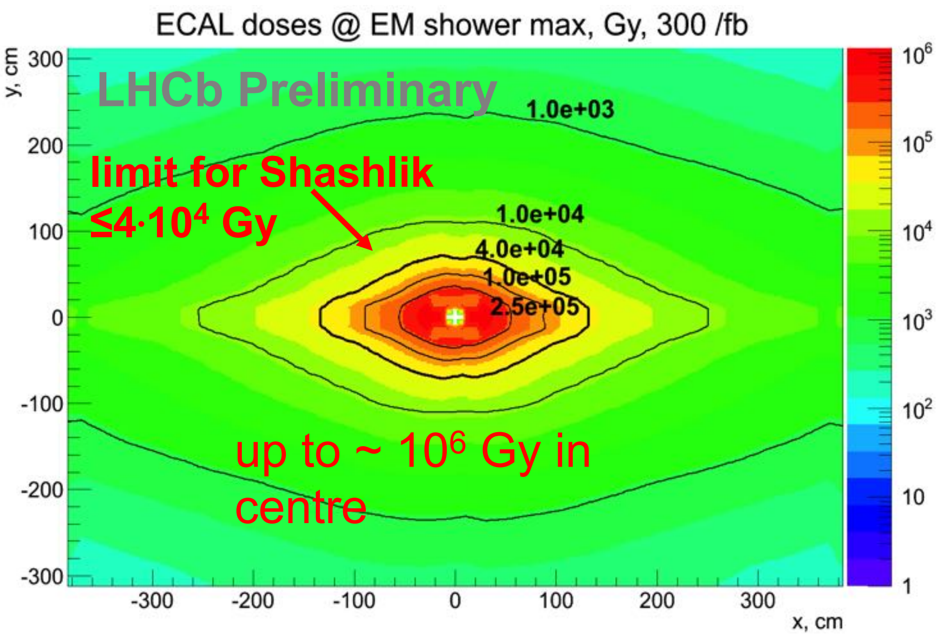


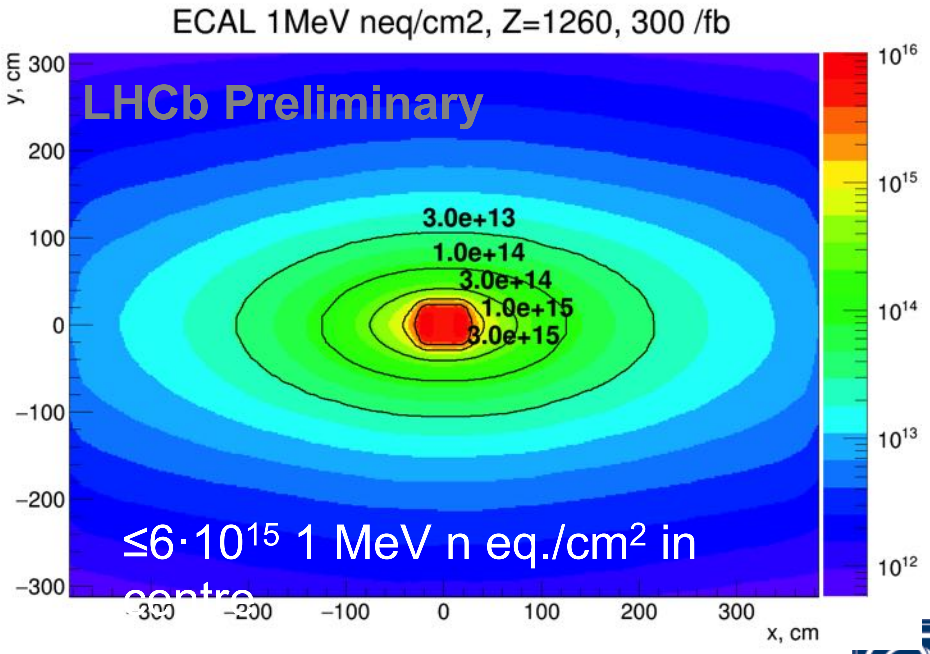
ECAL requirements for Upgrade II

Overall requirements:

- ✓ sustain **radiation doses** of up to ~1MGy and $\leq 6\cdot 10^{15}$cm^{-2} for 1MeV neq/cm^2 at 300 fb^{-1}
- ✓ include a **very fast component** ~few 10th ps for pile-up mitigation
  - ➢ into sampling modules or/and
  - ➢ with additional timing preshower
- ✓ keep good **energy resolution** of order $\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$
- ✓ handle **increased occupancy** by improving spatial resolution in inner & middle region
- ✓ respect dimensional **constraints of a module**: 12 x 12 cm^2 outer dimension

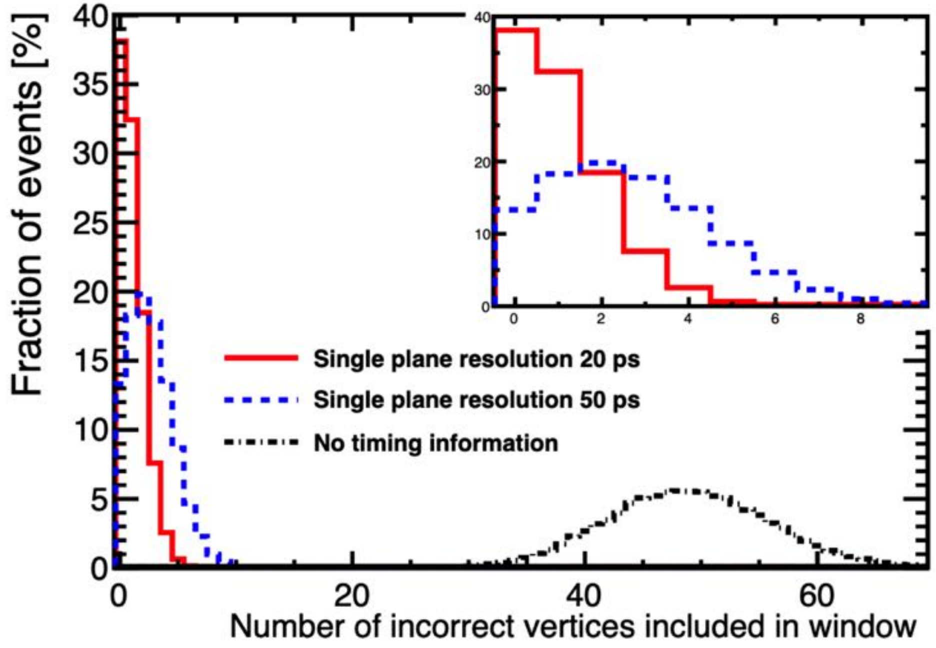
(1MGy = 100Mrad)





Pile-up mitigation with very fast timing

Impact of fast timing for 50 interactions per crossing



Pile-up conditions at Upgrade II:

- ✓ expect ~50 pp interactions per bunch crossing
- ✓ mean number of incorrect primary vertices giving rise to background hits can be reduced:
  - ➢ to 2.7 with 50 ps resolution
  - ➢ to 1.1 with 20 ps resolution

➢ need timing resolution of few 10th ps to reconstruct correct primary vertex

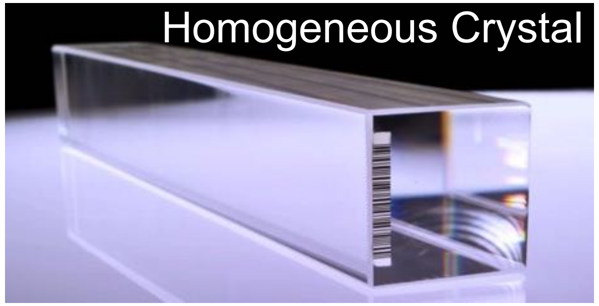
Possible options:

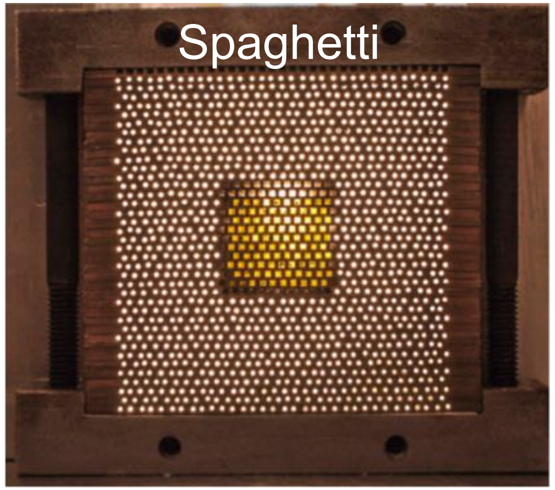
1) dedicated timing layer in front of ECAL modules ("timing pre-shower") with either silicon layers or fast crystal layers
2) "intrinsic" timing resolution of ECAL module with ~few 10th of ps timing resolution

Possible options for new ECAL modules

Pros and cons of different options:

Sampling Technologies





Homogeneous Crystal:
- requires long crystal of ~40cm to contain 25 X_0
- "given" Moliere Radius
- very good homogeneity
- potentially very good E-resolution (<10%)
- large volume of crystal → high cost

Shashlik type module:
- can be made very compact ~15-20cm
- Moliere Radius "tunable"
- **no rad. hard WLS fibers (yet) to transport light!**
- challenging optimization to reach good E-resolution
- some cost optimization possible

Spaghetti type module:
- can be made very compact ~15-20cm
- **fibers scintillate AND transports light!**
- Moliere Radius "tunable"
- challenging optimization to reach good E-resolution
- some cost optimization possible

- Started generic R&D on spaghetti type module (SPACAL)

(with Crystal Clear Collab.)

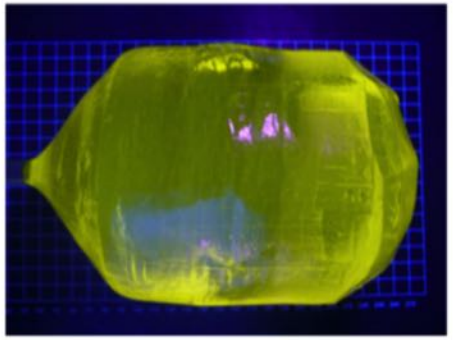
Radiation hard scintillating crystal candidates: Garnet crystals

	$Y_3Al_5O_{12}$: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	497-72	59

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

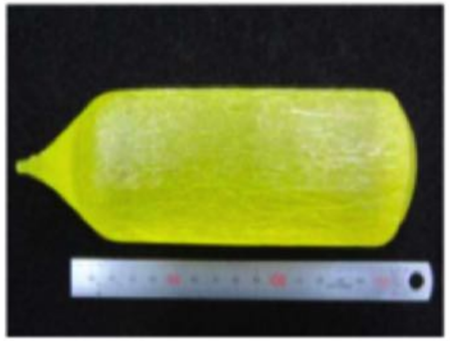
Attenuation length of Garnet crystals

YAG
$Y_3Al_5O_{12}$:Ce



(Crytur)

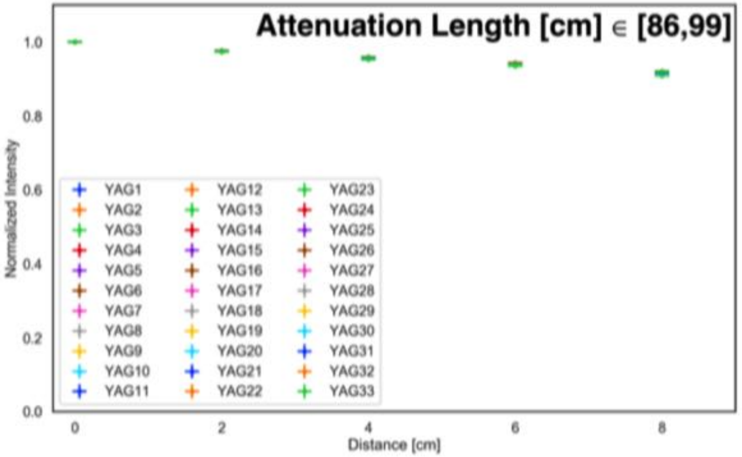
GAGG
$Gd_3Al_2Ga_3O_{12}$:Ce



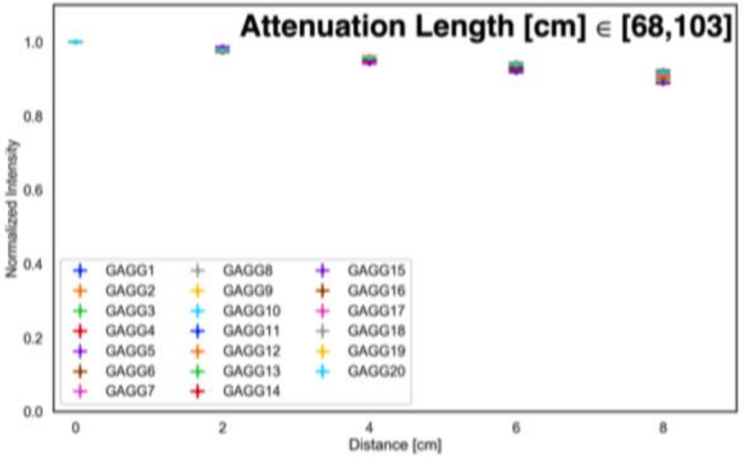
(Fomos)

➢ Typical attenuation lengths of 100 cm

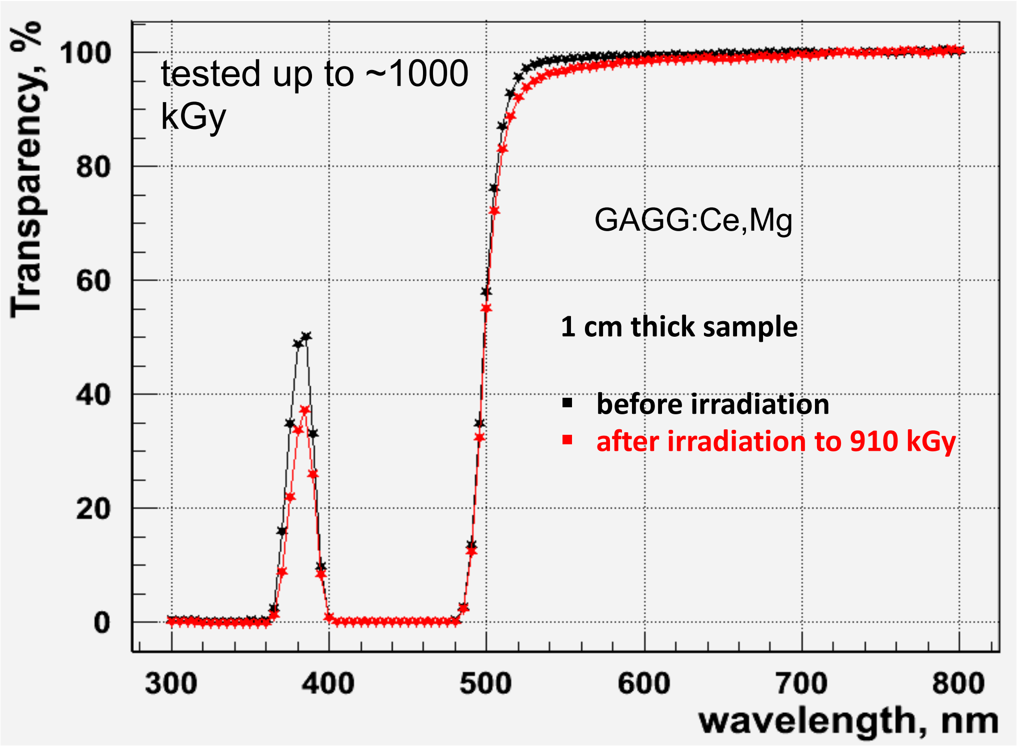
- YAG $1 \times 1 \times 100\ mm^3$



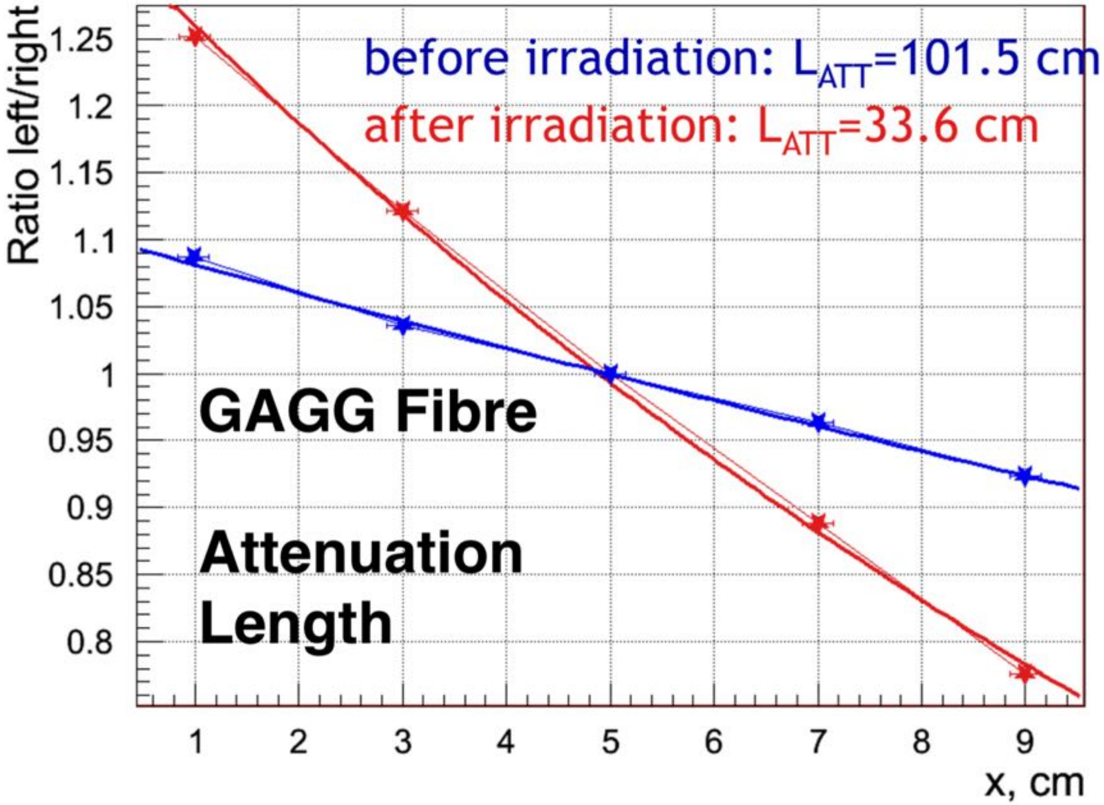
- GAGG $1 \times 1 \times 100\ mm^3$



Radiation resistants of GAGG



Irradiation by Yuri Guz

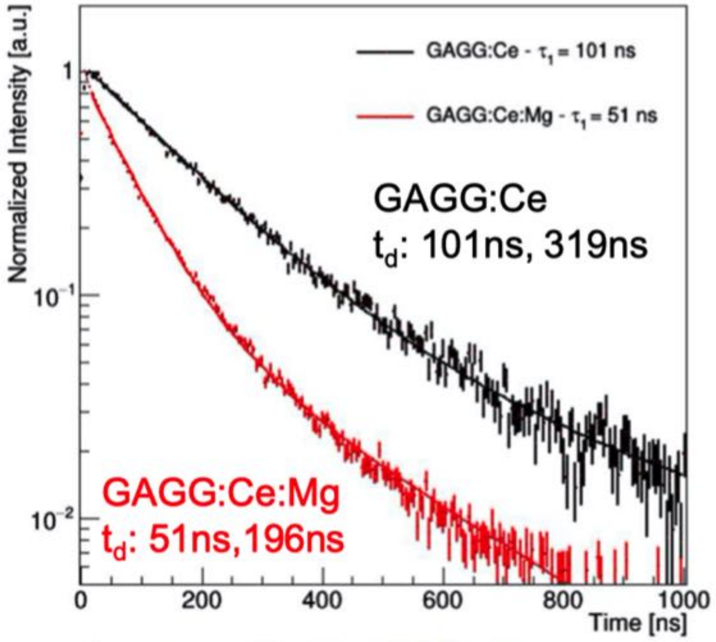


- GAGG crystals resist to radiation of ~1 MGy (100 Mrad)
- YAG crystals tested up to >100 kGy (10 Mrad),
- Next radiation campaign with new samples early 2020

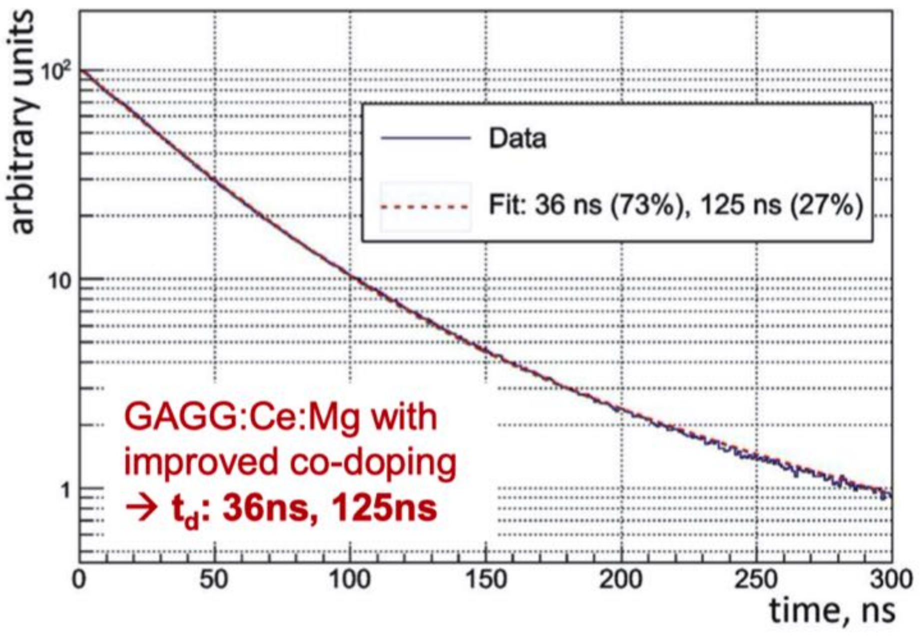
M. Lucchini et al. NIM a 816 (2016) 176-183 M. Lucchini et al. IEEE TNS 63 (2016) 586-590

R&D on timing properties of garnet crystals

Decay-time properties: t_d



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



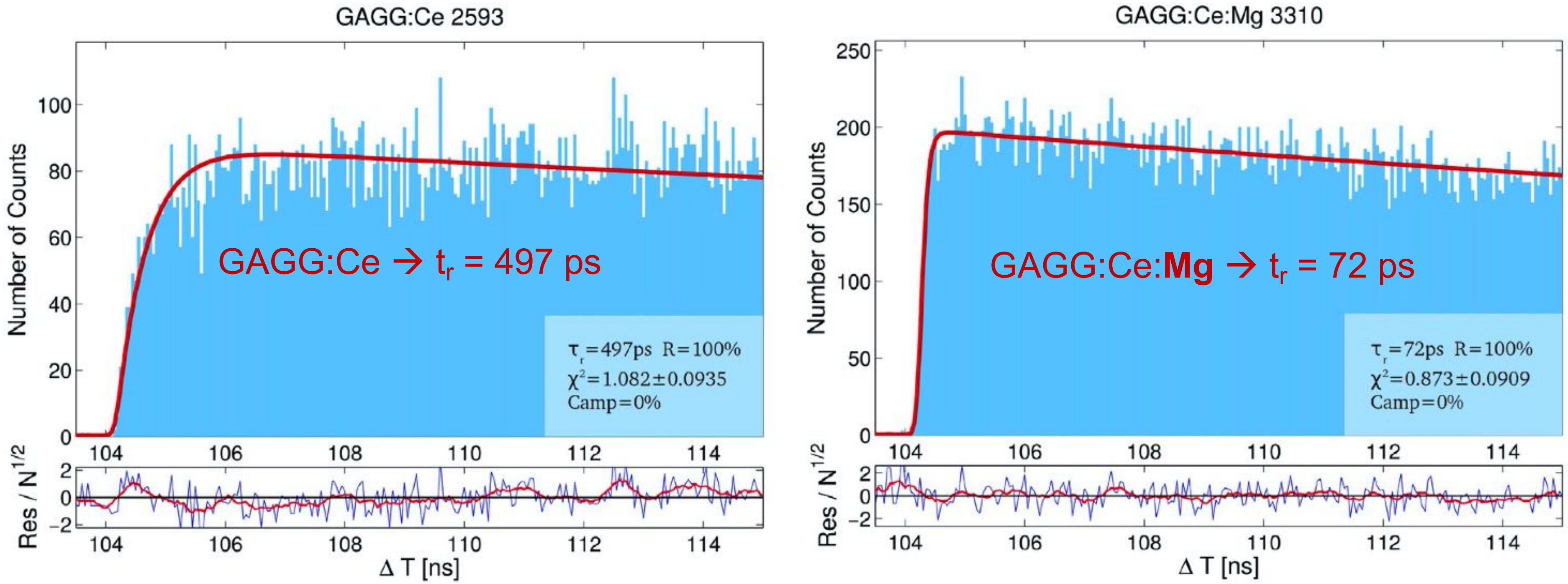
Nuclear Inst. and Methods in Physics Research, A 916 (2019) 226–229

- ✓ minimize spill-over by minimizing pulse length (25 ns LHC bunch spacing)
- ✓ the decay time can be parametrized by two components
- ✓ a shorter decay time and strong decrease of the slow component can be achieved by proper choice of Ce and Mg co-doping

➢ achieved t_d of 36 ns, optimization ongoing

R&D on timing properties of garnet crystals

Rise-time properties: t_r



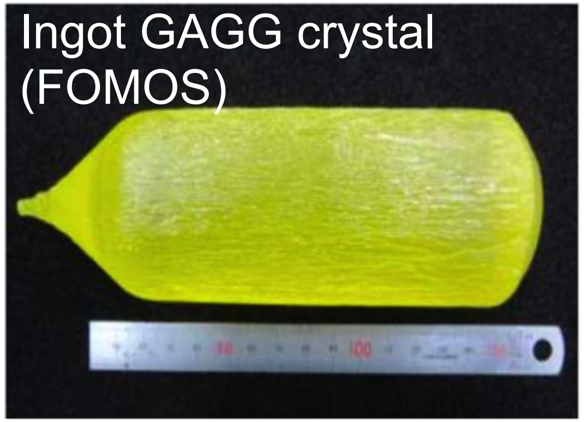
M. Lucchini et al. NIM a 816 (2016) 176-183

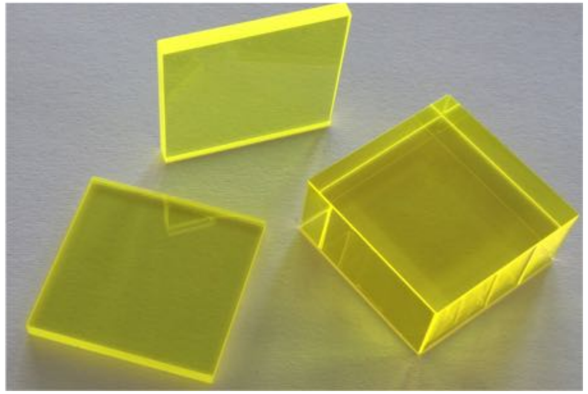
- ✓ mitigate pile-up by minimizing rise time (several 10th pp-interactions per bunch crossing)
- ✓ the rise time can be parametrized by a single component
- ✓ a fast rise time and strong decrease of slow component can be achieved by proper choice of Mg co-doping

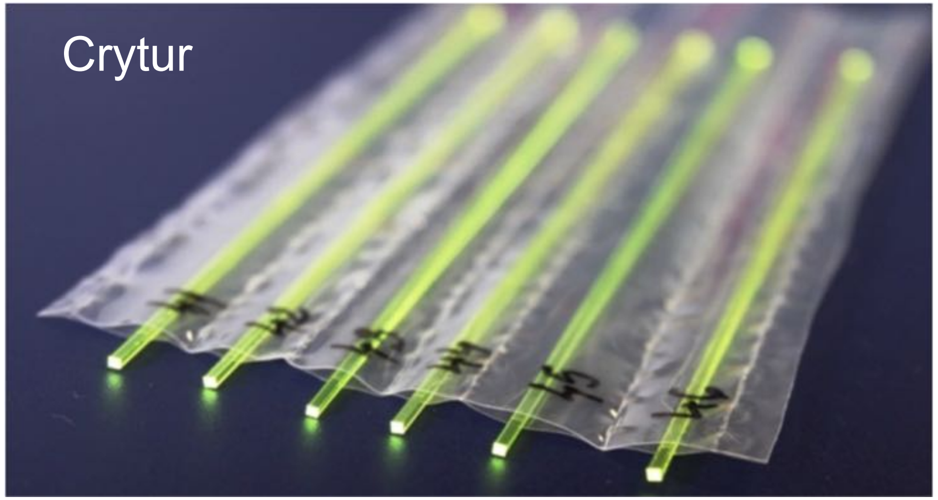
➢ achieved t_r of 72 ps, optimization ongoing

Production of radiation hard scintillating crystal fibers

Crystal growing by Czochralski method

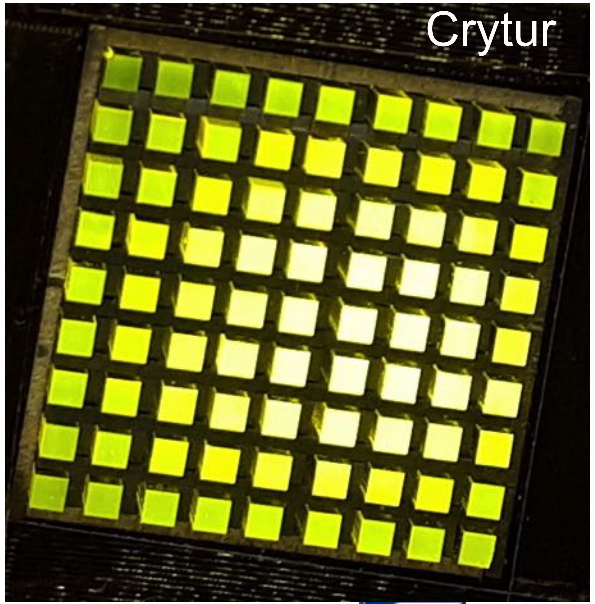




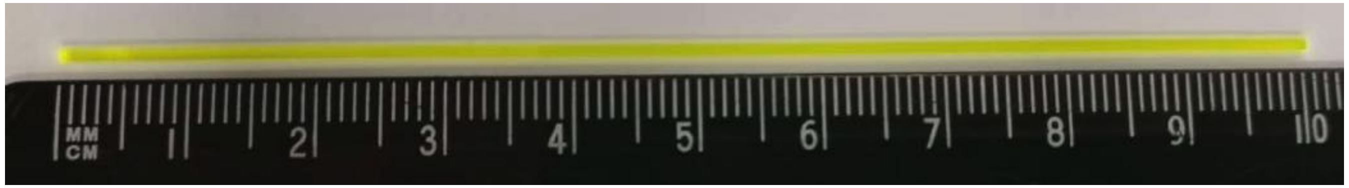


Square fibers of 1mm x 1mm x 100mm

Fibers manufactured by cutting and polishing

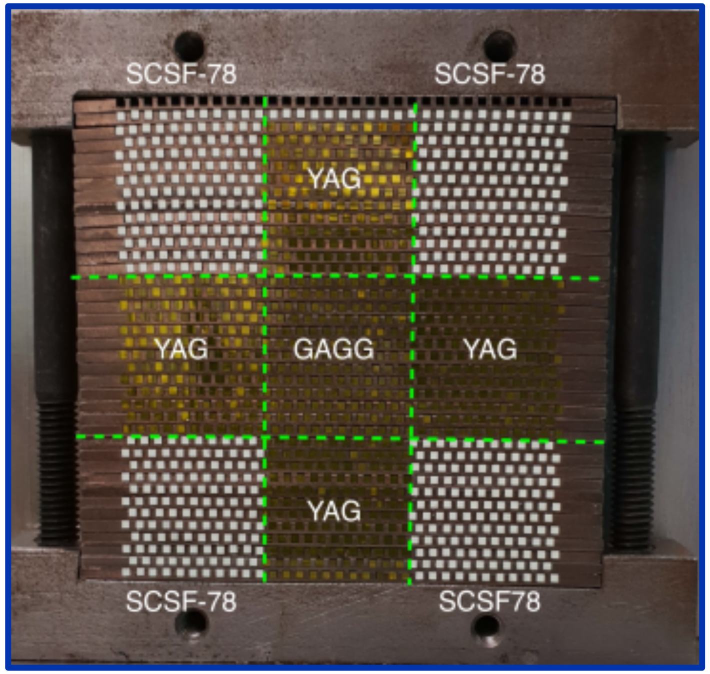


FOMOS



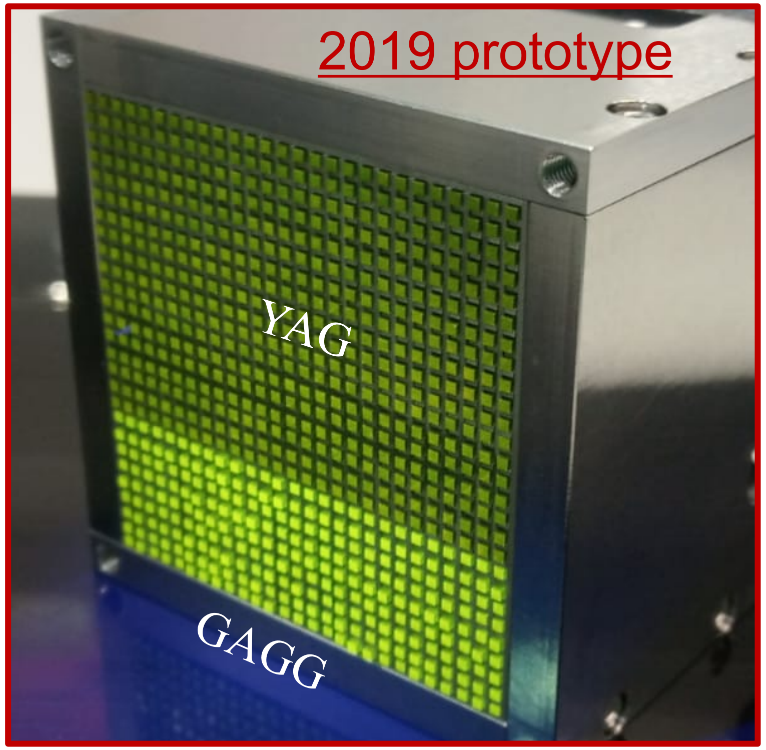
SPACAL Prototypes

2018 prototype



Study energy resolution and timing properties as function of alloy, crystal type, geometry, cell size, segmentation, photodetector, …

2019 prototype

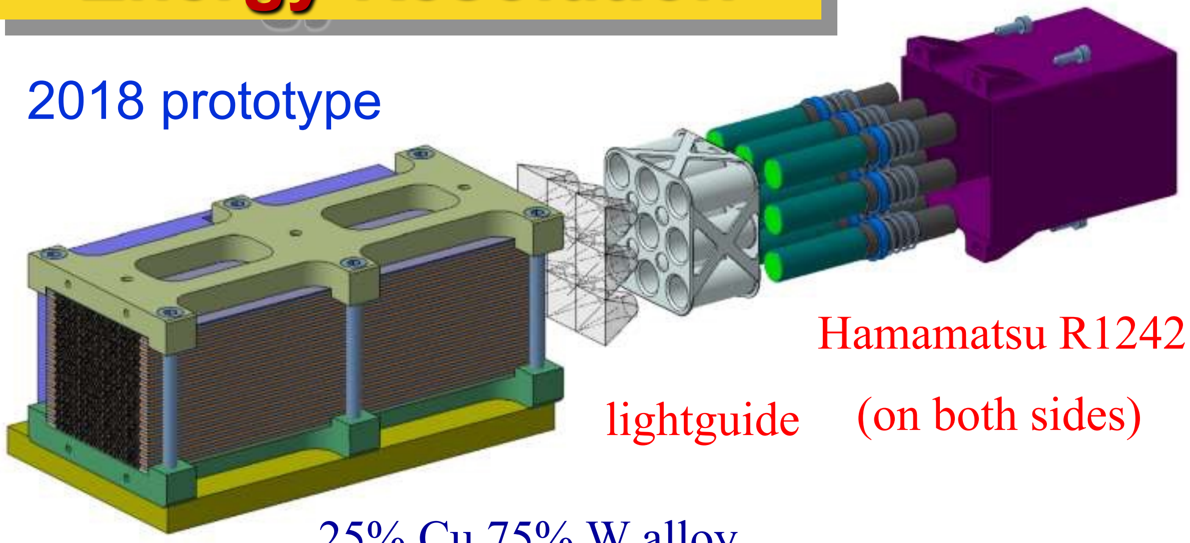


2018 prototype tested at CERN:
- ✓ Cu-W alloy with density of 14.9 g/cm^2
- ➢ 20 cm long module to reach 25 X_0
- ➢ longitudinal segmentation: 10 cm + 10 cm
- ✓ 9 cells of 2 x 2 cm^2 with M_R ~1.5 cm
- ➢ 1 cell of GAGG & 4 cells of YAG
- ➢ 4 cells of SCSF78 (KURARAY)

2019 prototype under test at DESY:
- ✓ pure W with modified geometry (fiber layout)
- ➢ reduced length of 14 cm (X_0~0.55cm)
  (→ 10 GeV γ mean free path ~0.7cm)
- ➢ longitudinal segmentation:
  4cm + 10cm (7X_0(~shower max at 10GeV) + 18X_0)
- ✓ cell size of 1.5 x 1.5 cm^2 with M_R ~ 1.2-1.3 cm
  (→ ~95% contained in cone of d~2.5 cm)
- ➢ 3 cells with GAGG & 6 with YAG

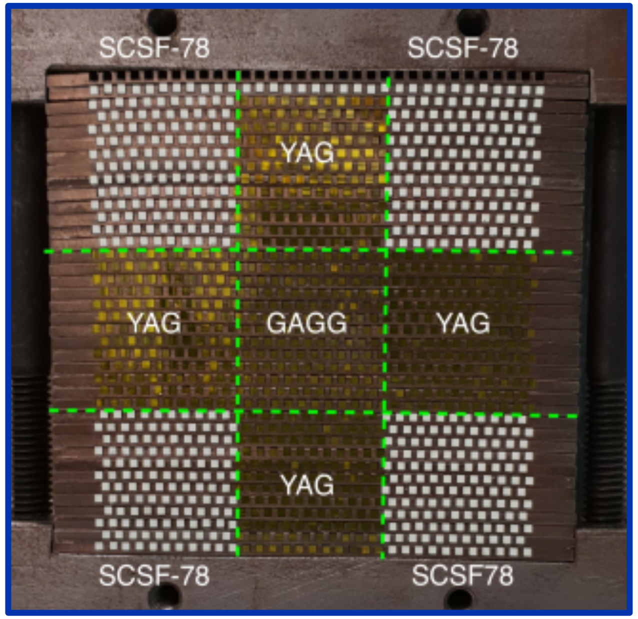
Energy Resolution

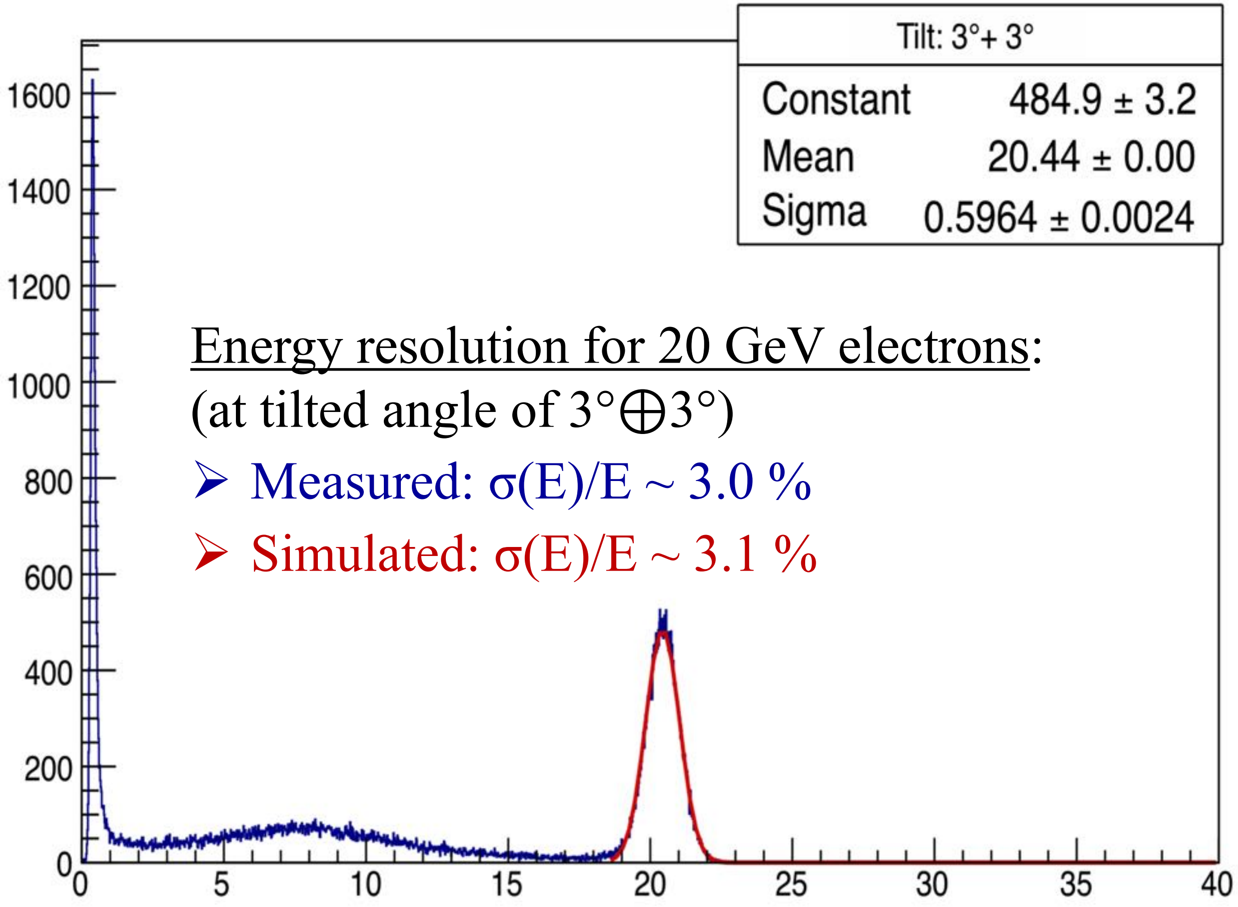
2018 prototype



Longitudinal segmentation
10cm + 10cm with
readout on both sides

Lateral segmentation
2 x 2 cm^2 cell size
144 fibers/cell
1 GAGG cell
4 YAG cells





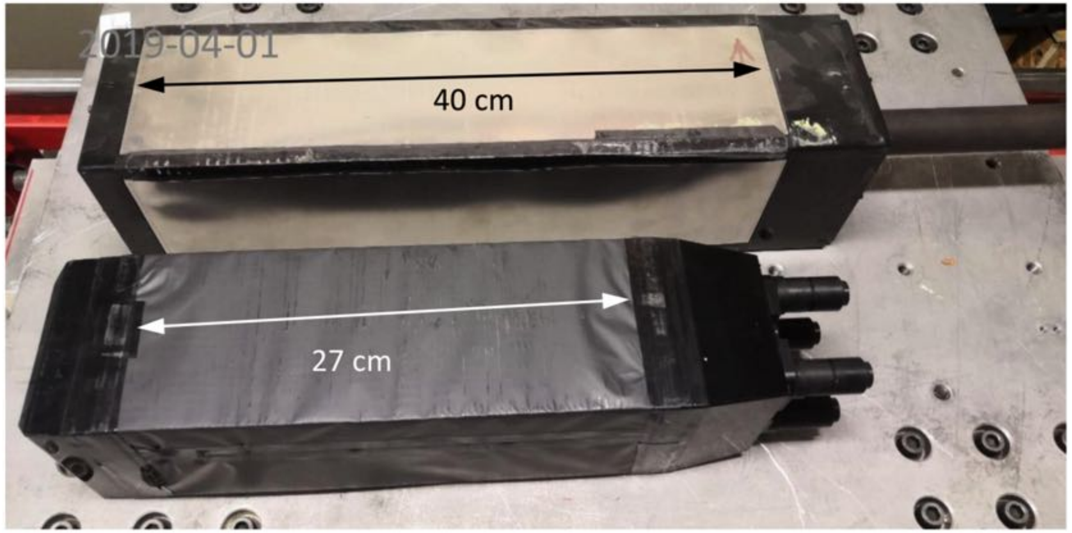
Energy resolution for 20 GeV electrons:
(at tilted angle of 3°⊕3°)

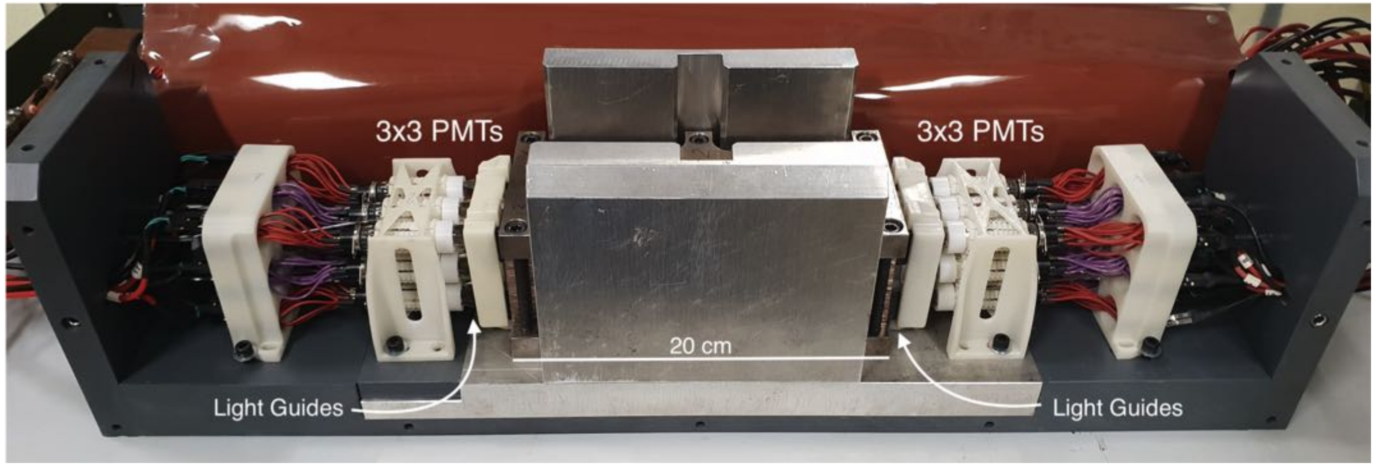
- Measured: σ(E)/E ~ 3.0 %
- Simulated: σ(E)/E ~ 3.1 %

In this 1st prototype, missing garnet crystal fibers substituted by scintillating plastic fibers → sub-optimal configuration

- Energy resolution already in the right ballpark

Time resolution measurements with prototypes





- Present ECal Shashlik module:
  - Readout - PMT Hamamatsu R7899-20.

Beam Energy [GeV]	PMT Bias [V]	Time Resolution [ps]
20	800	69
30	800	56
30	750	57
30	700	77

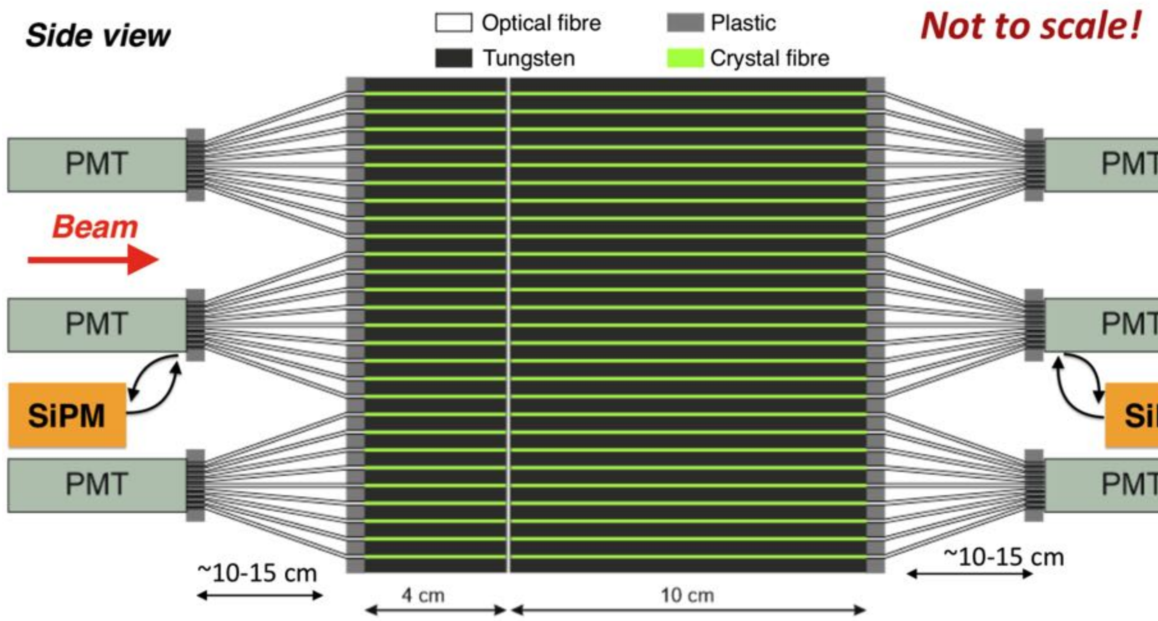
- SpaCal GAGG cell:
  - Readout - PMT Hamamatsu R12421.

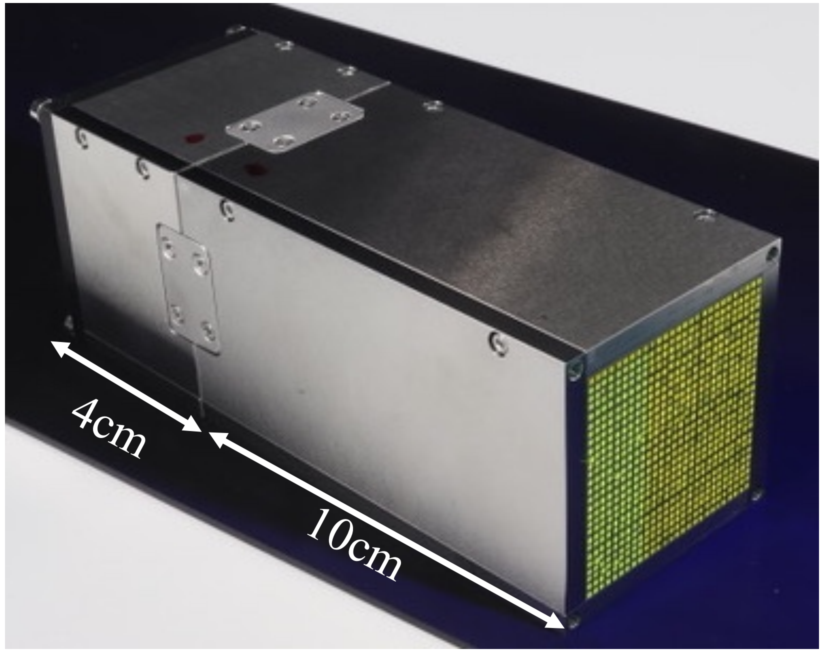
PMT Bias [V]	Time Resolution [ps]
630	85
730	78

➢ Timing resolution already in the right ballpark

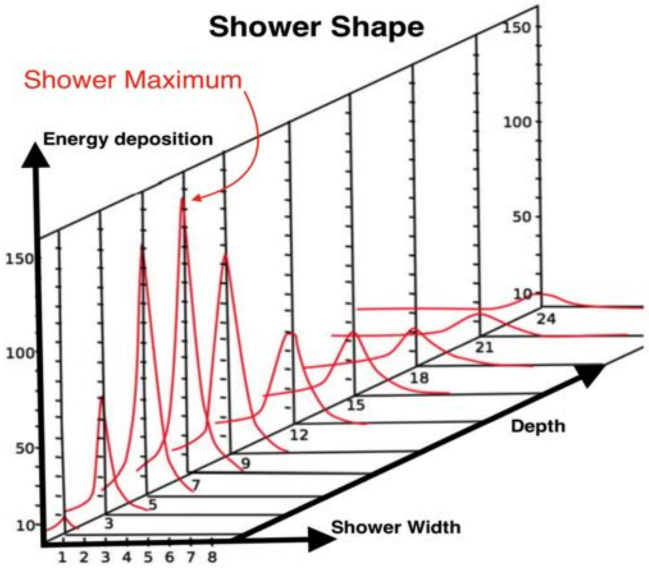
New (2019) prototype

(currently under test at DESY)





- Absorber of pure Tungsten 14 cm long
- Density: 19 g/cm3
- 2 sections: 4 + 10 cm (2 times 729 fibers)
- Cell size: 1.5×1.5 cm^2
- 6 YAG cells and 3 GAGG cells
- Fibre size: $1 \times 1 \times 40/100$ mm^3
- Each scintillating fibre coupled to an optical fibre
- Test with both, PMTs and SiPMs



Most compact SPACAL:

- pure W absorber and GAGG crystals
- 25 X_0 with 14 cm length (short fibers)
- Moliere Radius 1.25 cm (cell size 1.5 cm)

- Compare testbeam results with detailed simulation (incl. raytracing) to further optimize energy and timing resolution

R&D on absorber materials

- ✓ tune radiation length (X_0) and shower width (M_R)
  - ➢ M_R should be of same order than cell size
  - ➢ X_0 should be as small as possible (short module = short fibers)

	W	Pb	Cu	GAGG	YAG
Density [g/cm^3]	19.3	11.4	8.96	6.7	4.6
X_0 [cm]	0.35	0.56	1.44	1.59	3.53
M_R [cm]	0.93	1.60	1.57	2.10	2.76

- ✓ pure tungsten has very small Moliere radius and small radiation length but problematic mechanical properties (brittle)
  - ➢ cannot be machined and therefore strongly limits possible absorber shapes
- ✓ Cu-W (25%-75%) alloy is available on the market with good mechanical properties
  - ➢ small Moliere Radius but relatively large radiation length (long module)
- ✓ Pb-W alloy allows for same Moliere radius as Cu-W but with smaller radiation length
  - ➢ shorter module → shorter fibers!

> ➢ Lead-tungsten alloys have not yet been produced, R&D started
> ➢ New manufacturing technics for pure tungsten under investigation

Conclusions

- LHCb is undergoing a major first upgrade at present with a second upgrade foreseen in 2029.
- The electromagnetic calorimeter needs some consolidation of the most inner region by 2023 compatible with the running conditions after Upgrade II, which requires R&D on radiation hard and fast 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 and fast sampling ECAL modules of SPACAL type, with first encouraging results.
- New groups interested in contributing to the R&D (also within new EP R&D program) are most welcome!

ECAL under construction in the years 2000+