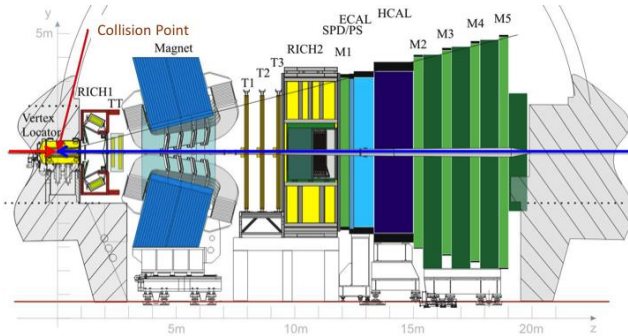# LHCb ECAL Upgrade Phase 2

Patrick Robbe, IJCLab Orsay, 7 July 2021

LHCb Calorimeters
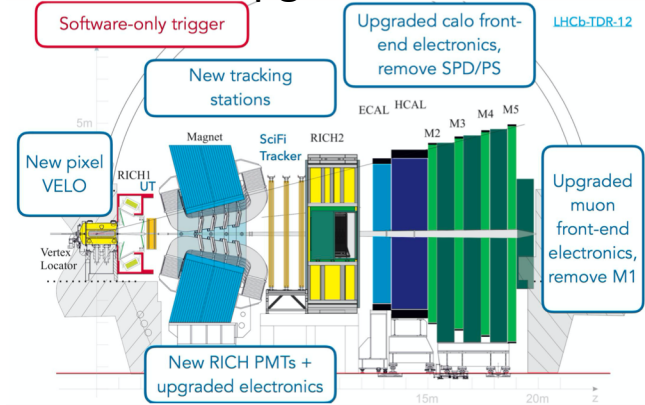

Run 1/2

Upgrade 1

SPD+PS+ECAL+HCAL

- Part of L0 hardware trigger (40 MHz)
- Readout at 1 MHz
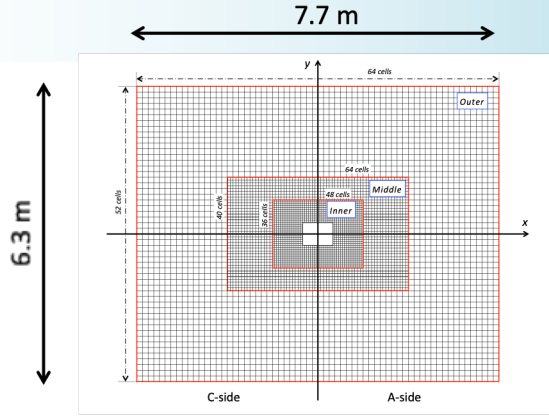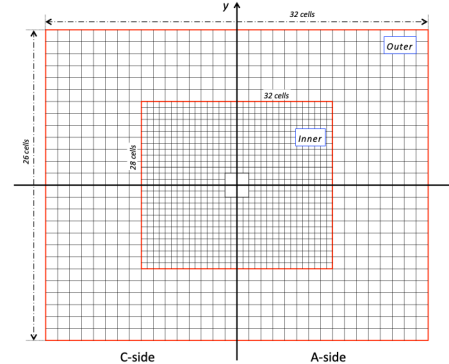- France (LAPP, LPC, IJCLab) + Russia, Spain, Italy

Same ECAL+HCAL, SPD+PS removed

- New electronics for readout at 40 MHz
- France (LAPP, IJCLab) + Russia, Spain

ECAL/HCAL hardware in Upgrade 1

7.7 m

ECAL

HCAL

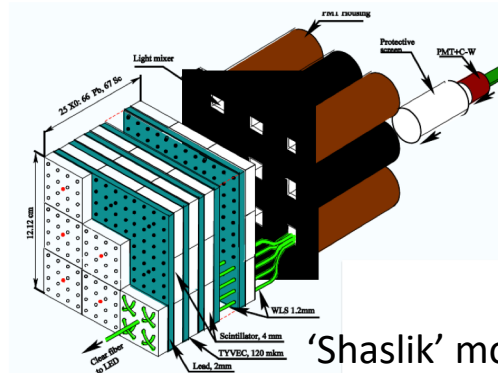Inner: 4.04 cm (1536)
Middle: 6.06 cm (1792)
Outer: 12.12 cm (2688)

6.3 m
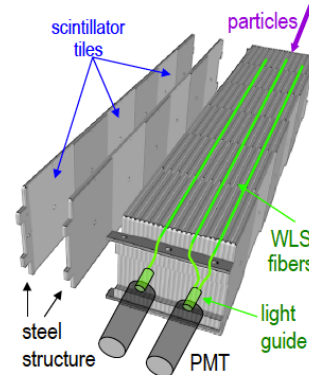
Inner: 13.1 cm (880)
Outer: 26.2 cm (608)

- ECAL and HCAL use the same principle: light from scintillation in plastic scintillator is collected by wave-length shifting fibers, and readout by PMTs.

- Calibration system with LEDs and clear fibers
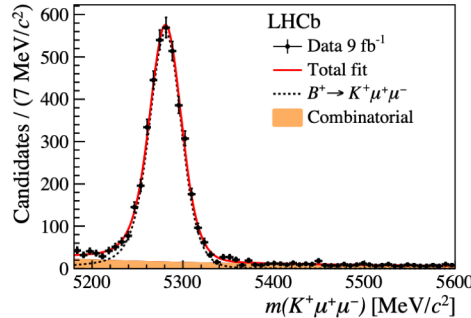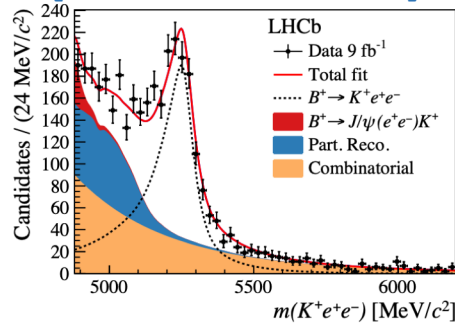

'Shaslik' modules

- Performances:
  - 10 GeV dynamic range in E_T
  - ECAL resolution 10%/sqrt(E)
  - HCAL resolution 70%/sqrt(E)

3

Physics analyses with ECAL

- Test of lepton universality with electrons identified with ECAL (E/p) and with recovery of photons from bremsstrahlung: $B^+ \to K^+ e^+ e^-$ vs. $B^+ \to K^+ \mu^+ \mu^-$

- Radiative decays with photon: $B^0 \to K^{*0}\gamma$, $B_s^0 \to \phi\gamma$: CP asymetries

[arXiv:2013.11769]

[JHEP 12 (2020) 081]

$$R_K(1.1 < q^2 < 6.0\,\text{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$
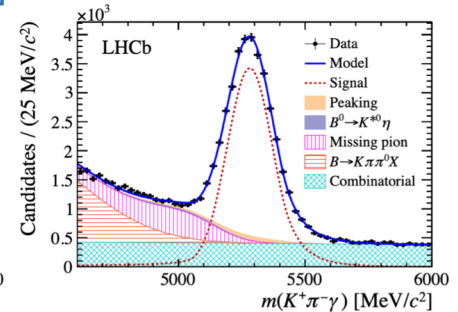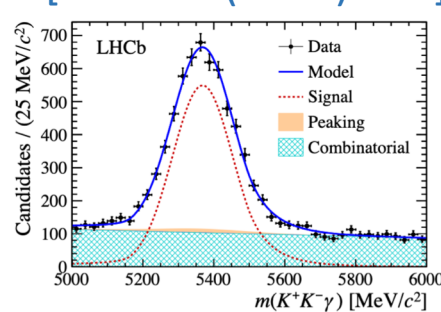
$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11,$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11,$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$$

4

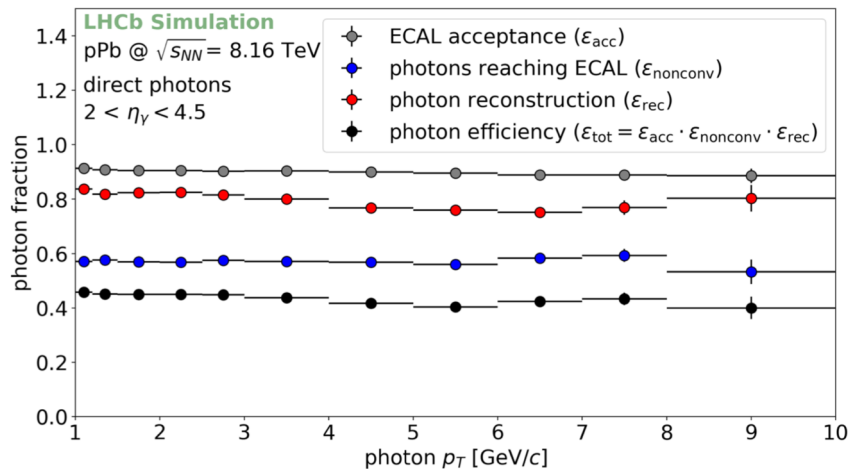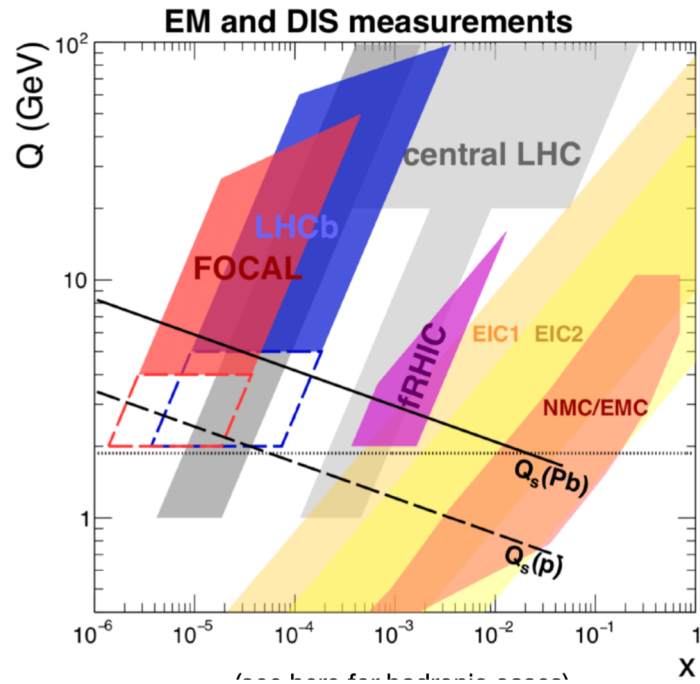# Performances in pPb collisions: direct γ

Figure 1: Transverse momentum dependence of the components involved in the non-converted direct photon detection efficiency. Sample obtained from direct photons generated by PYTHIA [1] embedded in Minimum Bias EPOS [2] pPb events at $\sqrt{s_{NN}}$ =8.16 TeV.

5

Performances in pPb collisions: π^0
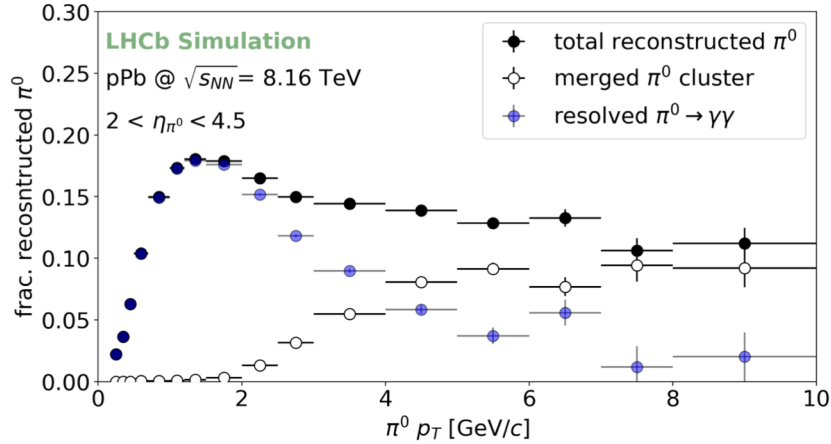
Figure 7: Fraction of π^0 decays in the LHCb acceptance which are reconstructed either as resolved $\gamma\gamma$, $\gamma(\gamma \to e^+e^-)$, $(\gamma \to e^+e^-)(\gamma \to e^+e^-)$, or $\gamma\gamma$ merged in one ECAL cluster. The π^0 reconstruction requires that each photon has $p_{T,\gamma} > 200$ MeV/c. Sample obtained from Minimum Bias EPOS [2] pPb events at $\sqrt{s_{NN}}=8.16$ TeV.
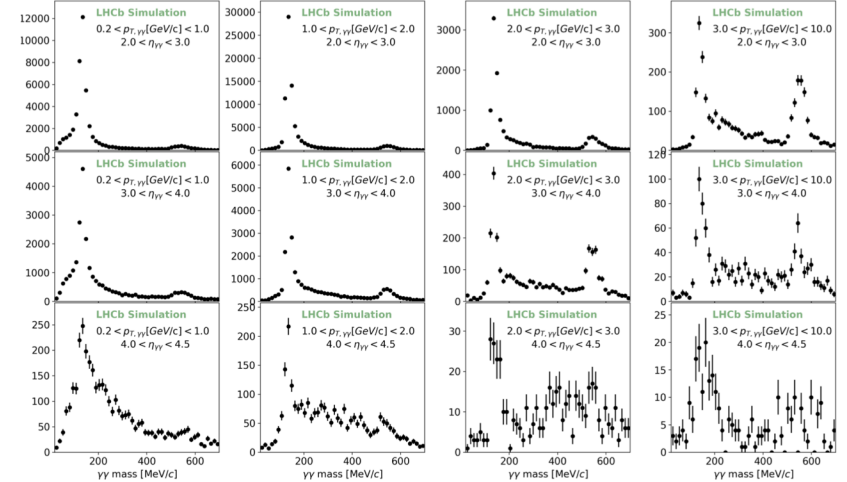
Figure 6: Invariant mass distribution of resolved $(\pi^0, \eta^0) \to \gamma\gamma$ pairs in four π^0 p_T and rapidity regions obtained from Minimum Bias EPOS [2] pPb event at $\sqrt{s_{NN}}=8.16$ TeV. No combinatorial background is included.

χ_c production in pPb collisions
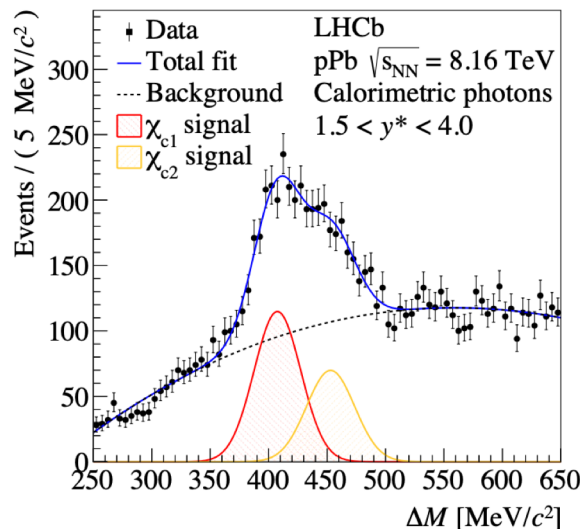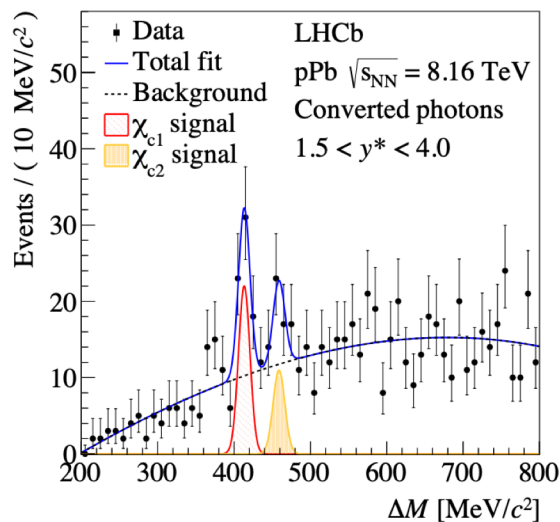
- With both unconverted and converted (e^+e^- pair identified with ECAL)

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = 1.11 \pm 0.14 \text{ (stat.)} \pm 0.10 \text{ (syst.)} \qquad \text{for } 1.5 < y^* < 4.0,$$

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = 1.14 \pm 0.16 \text{ (stat.)} \pm 0.17 \text{ (syst.)} \qquad \text{for } -5.0 < y^* < -2.5.$$

LHCb Upgrades

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034

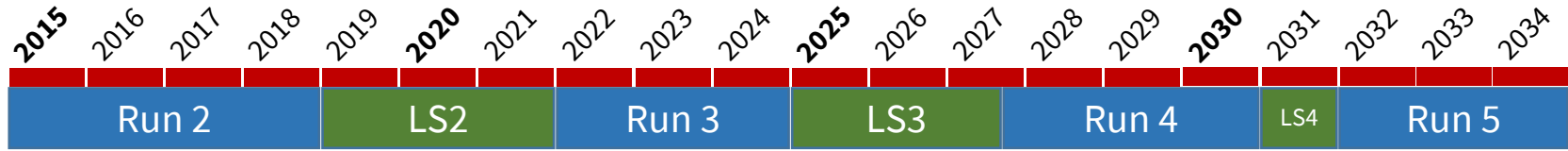| Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5

$L = 4\times10^{32}$ cm^{-2}.s^{-1}
1.1 interaction per crossing
9 fb^{-1} (Run 1 and 2)

$L = 2\times10^{33}$ cm^{-2}.s^{-1}
~5 interactions per bunch crossing
~50 fb^{-1} (Run 3 and 4)

$L = 1.5\times10^{34}$ cm^{-2}.s^{-1}
~50 interactions per bunch crossing
~300 fb^{-1} (Run 5....)

Present $L = 2\times10^{32} cm^{-2} \cdot s^{-1}$
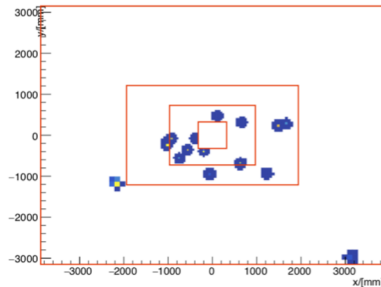
Upgrade II with $L = 1.5\times10^{34} cm^{-2} \cdot s^{-1}$
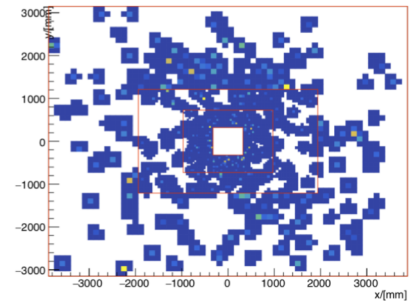
ECAL at high luminosity

- Tensions with standard model (R_K, …) will need to be explored further during Run 5 and some of the analyses rely heavily on ECAL
- Design a new detector that can work at high luminosity (pile-up of 50) still retaining:
  - Good energy resolution of ~10%/sqrt(E)
  - Good angular resolution for π^0 and bremsstrahlung recovery
  - Efficiency and background levels kept similar to what we have for upgrade 1
  - Better radiation tolerance for modules close to the beam
- Two main handles:
  - Granularity: decrease occupancy and background per cell, limited by Moliere radius
  - Timing

Granularity

- New granularity proposed based on occupancy maps

(6016 channels)

(15000 channels)
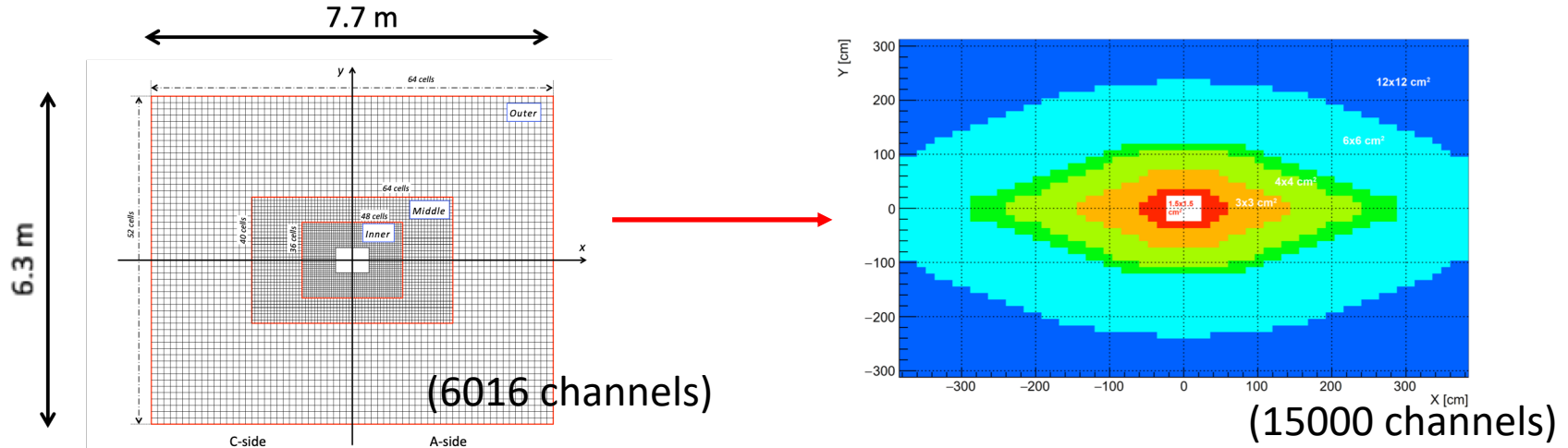
- Outer areas (cells of 4, 6 and 12 cm) can be made from rearranged current Shashlik modules

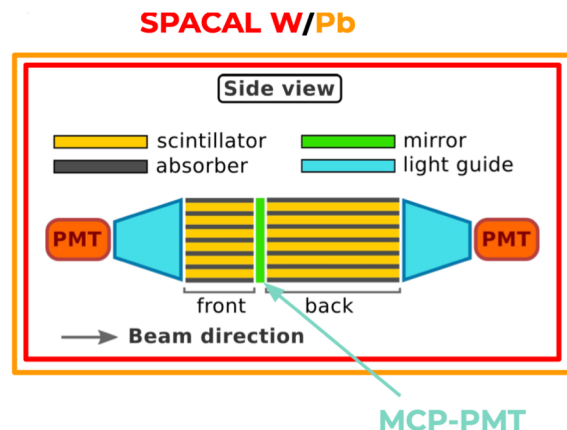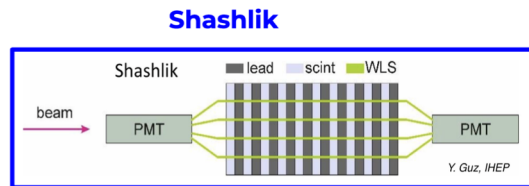- New modules for inner regions with 1.5 and 3 cm sizes.

Ongoing R&D

- Technologies envisaged:
  - Refurbish current Shashlik modules, adding double readout and faster wavelength shifting fibers

  - SPACAL modules, reading light from scintillators directly, with longitudinal segmentation
    - 1.5 cm size = Tungstene absorber and garnet crystal (or polystyrene) fibers – small Moliere radius and good radiation tolerance
    - 3 cm size = Pb absorber and polystyrene fibers

Shashlik

Shashlik ■ lead ■ scint ■ WLS

beam → PMT ... PMT

Y. Guz, IHEP

SPACAL W/Pb

Side view

■ scintillator   ■ mirror
■ absorber   ■ light guide

PMT ... PMT

front   back

→ Beam direction

MCP-PMT

Region	Module type	Cell size [mm^2]	Segmentation [mm]/[X_0]	R_M [mm]	$\sigma_E/E = A/\sqrt{E} \oplus B$ A/B [%]
1	SpaCal W/GAGG	15×15	45+105/70+180	14.5	9.1 / 1.4
2	SpaCal Pb/PS	30×30	80+210/70+180	29.5	10.4 / 0.6
3	Shashlik	40×40	Continuous fibres	35.0	10.0 / 1.0
4	Shashlik	60×60	Continuous fibres	35.0	10.0 / 1.0
5	Shashlik	120×120	Continuous fibres	35.0	10.0 / 1.0

Test beams

- All modules tested with beam (SPS or DESY) and fulfill the energy resolution requirements

Fibres bundle (1 cell)
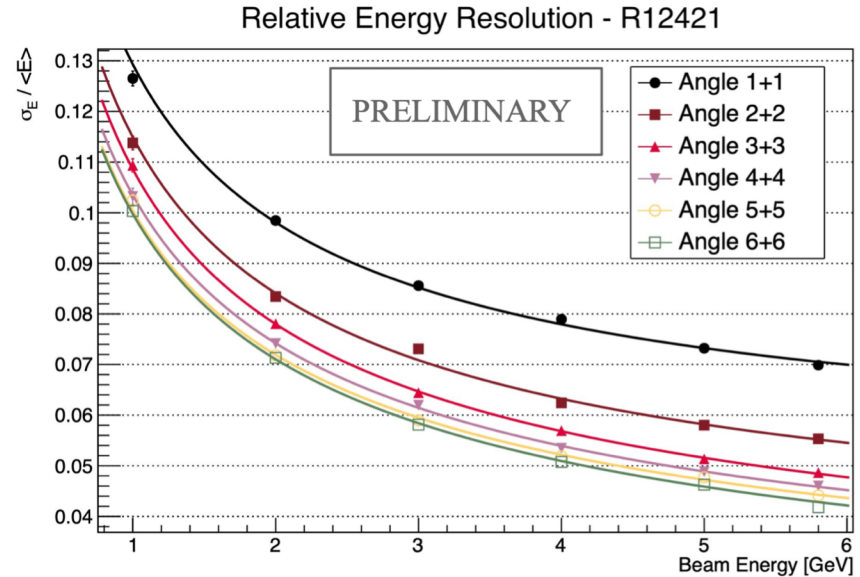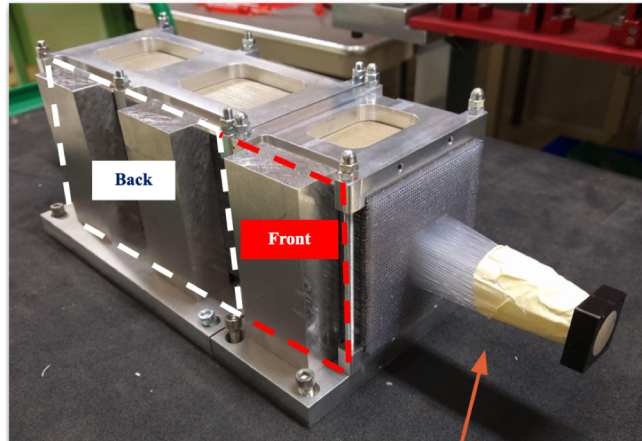
Timing

- Measurement of arrival time of photon is also an important handle to remove pile-up background:

Pulse pileup in same channel

Energy fluctuation

Signal

Sampling

Background

Time fluctuation
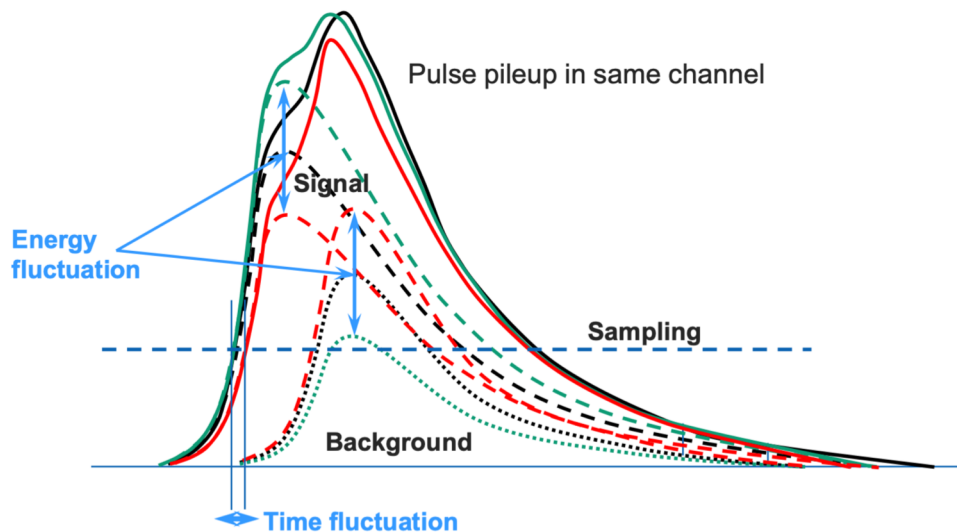
If the pile-up in the same channel is not too large, then the time measured in the cell will correspond to the time expected from the time of the primary vertex measured by the VELO:

Cut on Δt (time measured – expected from VELO) to remove cells with large pile-up background
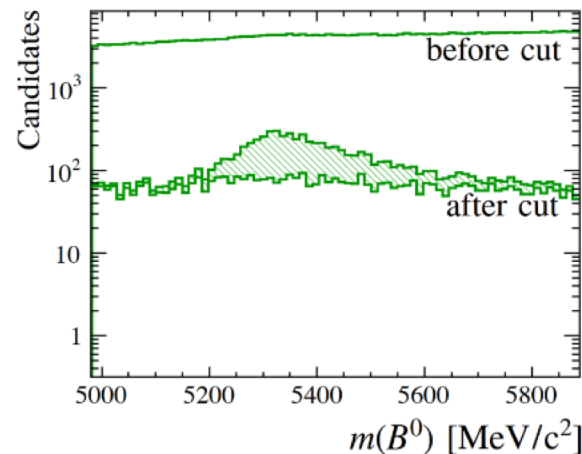
Timing

- Spread of primary vertex times is ~100 ps: need good time resolution

[Manuel Guittière - IJCLab]

Time Cut (ps)	#B_s^0	$\frac{S}{\sqrt{S+B}}(3\sigma)$	Efficiency (%)
20	147 ± 30	9.49 ± 1.94	22.9
30	242 ± 29	12.51 ± 1.51	37.6
40	322 ± 52	14.39 ± 2.35	50.2
50	372 ± 30	15.50 ± 1.25	57.9
60	473 ± 25	17.98 ± 0.96	73.7
80	549 ± 54	19.12 ± 1.89	85.5
100	571 ± 47	19.16 ± 1.58	88.9
120	588 ± 29	18.94 ± 0.94	91.6
150	634 ± 30	19.20 ± 0.94	98.8
200	654 ± 32	18.69 ± 0.93	100.
300	573 ± 42	16.06 ± 1.20	89.3

Effect of timing cut for $B^0 \to \pi^+\pi^-\pi^0$

Optimal cut for $B_s^0 \to \phi\gamma$ @80 ps = 3σ -> σ~25 ps

Timing in test beam

- New SPACAL modules have resolutions of ~20 ps and old SHASHLIK modules of 35ps measurement in test beams
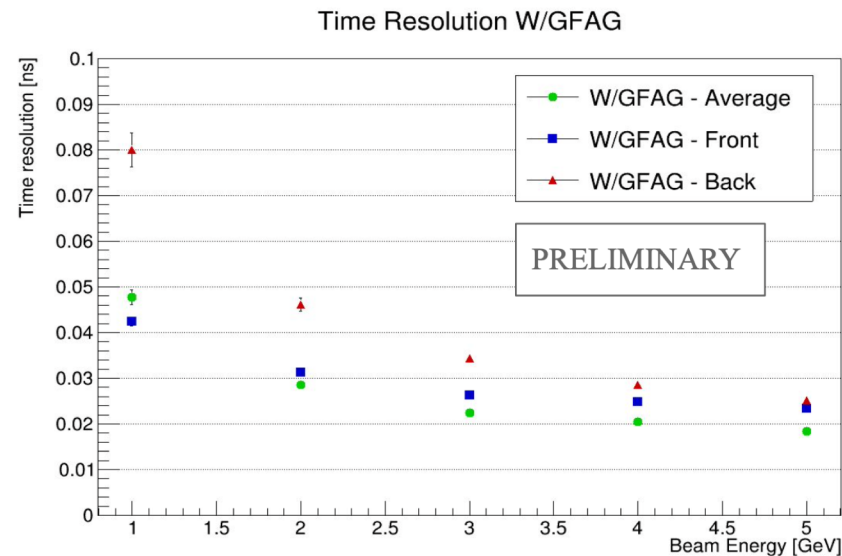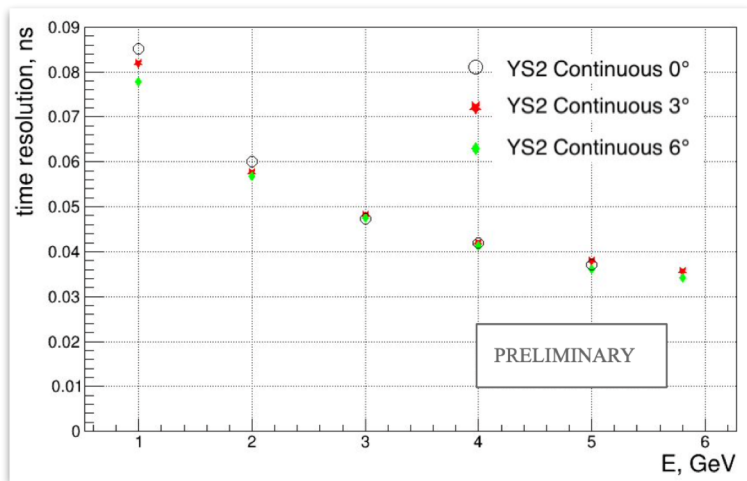
Readout

- Need now to design an electronics chain:
  - Coping with the increase of number of channels (6000 to 30000 including double readout)
  - Keeping the good time resolution of ~20ps

[Christophe Beigbeder - IJCLab, David Gascon - Barcelona]


LHCb readout
(PCIe40+, CPPM)
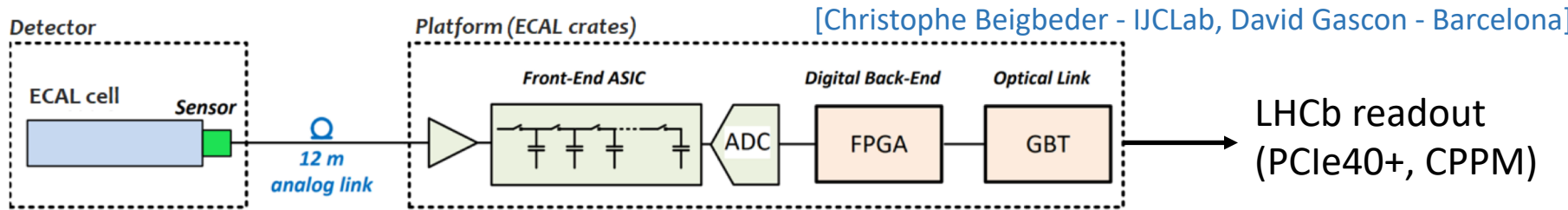
- Design of an ASIC for energy + time measurement with 20ps time resolution: brainstorming started (IJCLab, Barcelona, interest also from LPC Clermont-Ferrand)
- Need to implement data reduction in the chain: Front-End boards or in FPGAs provided by new readout cards (PCIe40+, CPPM) Discussions between IJCLab, Melbourne University, …
  - Sending all data from Front-End boards as is done for Upgrade I = 21 Tb/s.
  - Goal is to be close to current rate : 4 Tb/s

Other technologies

- Effect of pile-up and of ageing due to radiation not yet assessed on time resolution of SPACAL/Shashlik modules. If they degrade too much, possibility to add a 'timer layer' between the front and back sections of the modules:
  - LAPPD (Large Area Picosecond Photodetector)
  - Silicium layers

- Scenarios with high granular Silicium-Tungstene ECAL also studied: 1x1 cm2 cells.
  - Only with simulation so far
  - First prototypes tested end of 2021
  - Very good time and angular resolutions but worse energy resolution expected
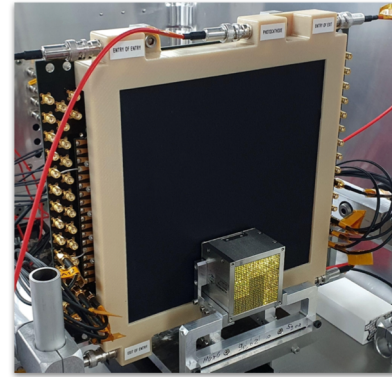
LAPPD
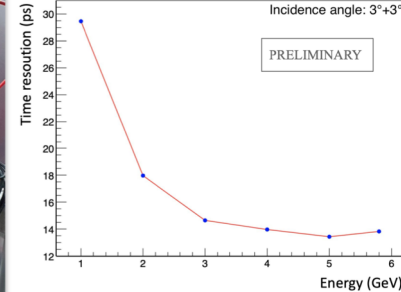
SPACAL W/Pb
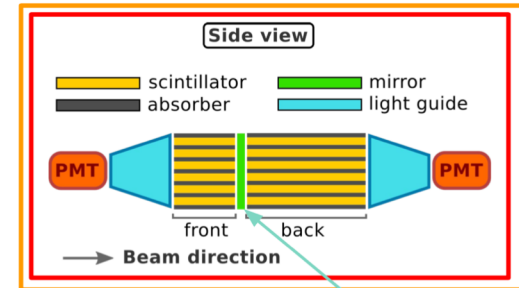
Conclusions

- First ideas for a design of a new ECAL capable of working in high luminosity conditions being documented in a Framework TDR that will be available after Summer 2021.

- Regular meetings and discussions where IJCLab Orsay, LPC Clermont and LAPP Annecy participate (Simulation, electronics, mechanics, …)

- One important future step is to have a global simulation of all sub-detectors all together: common work between several French groups involved up to now in the simulation of individual sub-detectors