Progress of LHCb ECAL Upgrade II Studies

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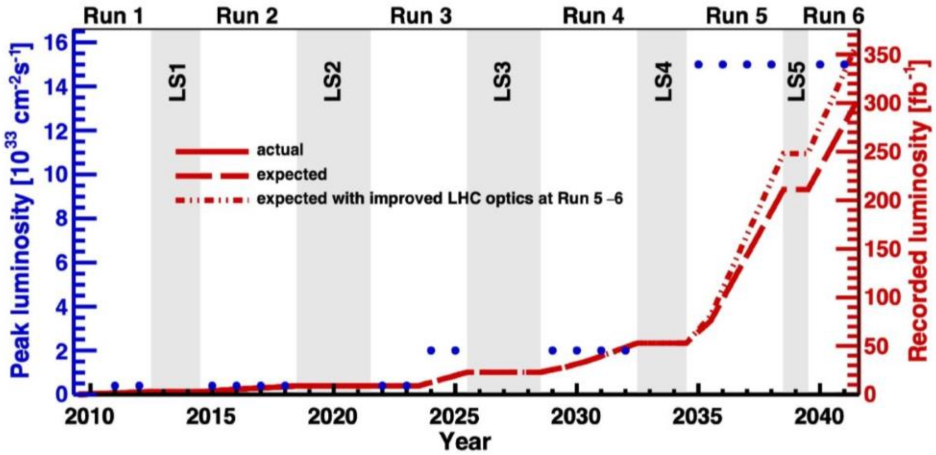
Based on Patrick Robbe (IJCLab Orsay) 's talk on FCPPL 2024, Bordeaux, 11/06/2024

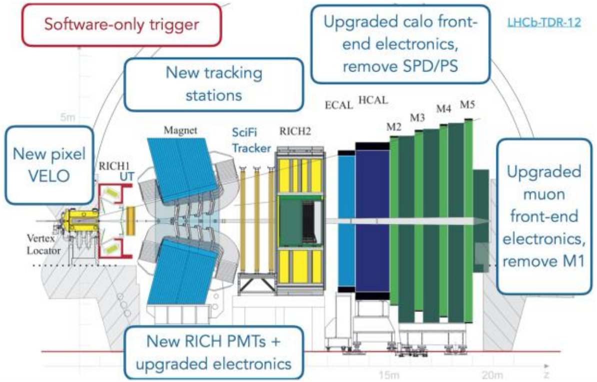
LHCb Upgrade II

- New detector proposed for LHCb during Runs 5 and 6 of the LHC to ingrate 300 fb^{-1} of data at the end of the LHC

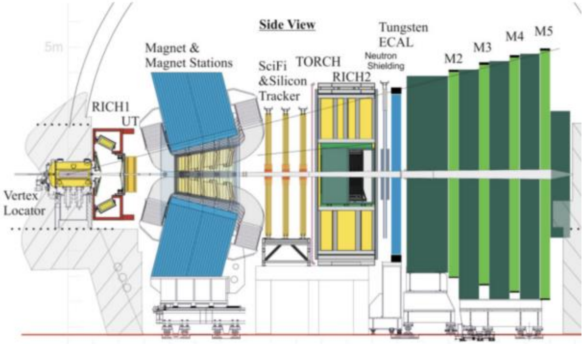


Detector for Upgrade II

- Same performances as Run 3, with a pile-up of 40 instead of 6

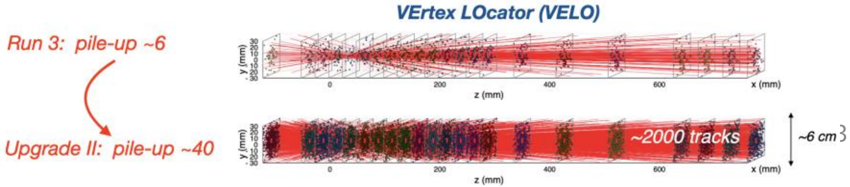


Run 3



Run 5

- Same geometry for the detector with innovative technologies for sub-detectors and data processing
- Main elements:
  - Increase granularity
  - Add timing measurement (resolutions up to 10-50 ps)
  - Radiation hardness (up to 10^{16} n_{eq}/cm^2)
  - Data rate: 200 Tb/s

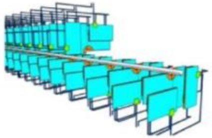


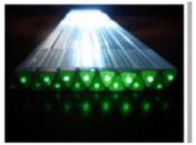
Détecteur pour Upgrade II

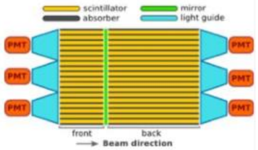
Vertex Locator (VELO):
Pixels 3D, 28nm
Timing 50ps
Nouvel RF-foil

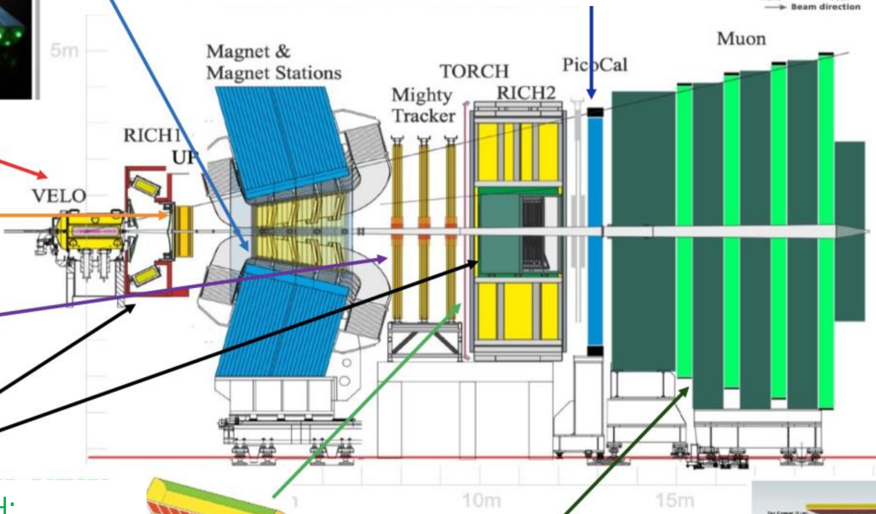
Magnet Stations (MS):
Plaques de scintillateurs
Détection de traces à basse impulsion

Picosecond ECAL (PicoCal):
Timing et segmentation
Intérieur: SpaCal
Extérieur: Shashlik

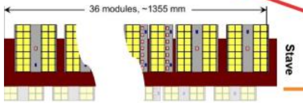




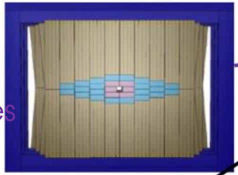




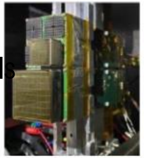
Upstream Tracker (UP):
Pixels CMOS MAPS
Résistant aux rad



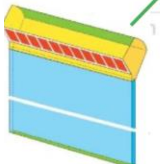
Mighty Tracker (MT):
Intérieur: pixels CMOS
Extérieur: Fibres Scintillantes (SciFi actuel)



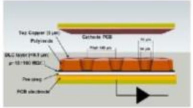
RICH1 & RICH2:
Petite taille de pixels
Mesure du temps
SiPM, MCPs



TORCH:
Time-of-flight
Plaques de quartz
SiPM, MCPs



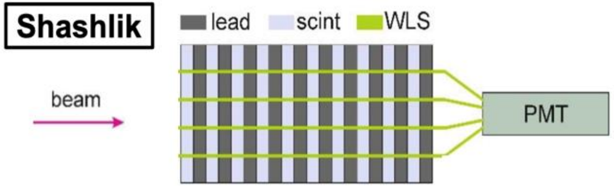
Muon System:
Intérieur: μ-Rwell
Extérieur: MWPC

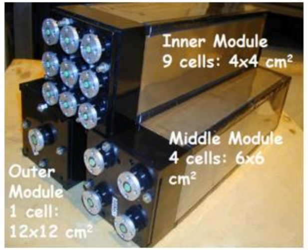


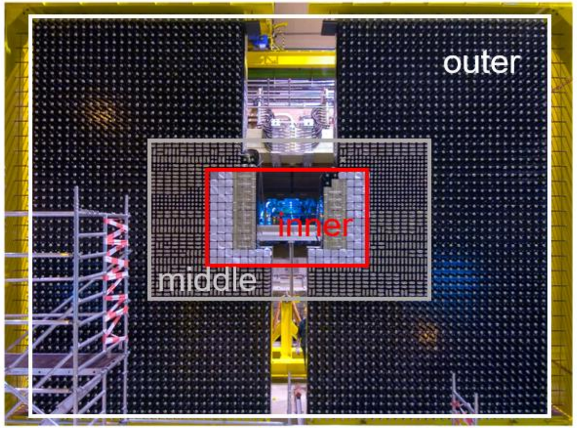
Current LHCb ECAL and upgrade Ib

- Current ECAL operating at $\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Shashlik technology:

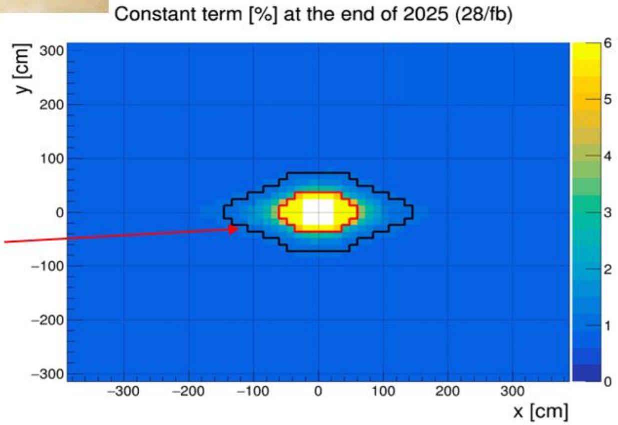
    $4 \times 4/6 \times 6/12 \times 12\ \mathrm{cm}^2$ cell size in inner/middle/outer region







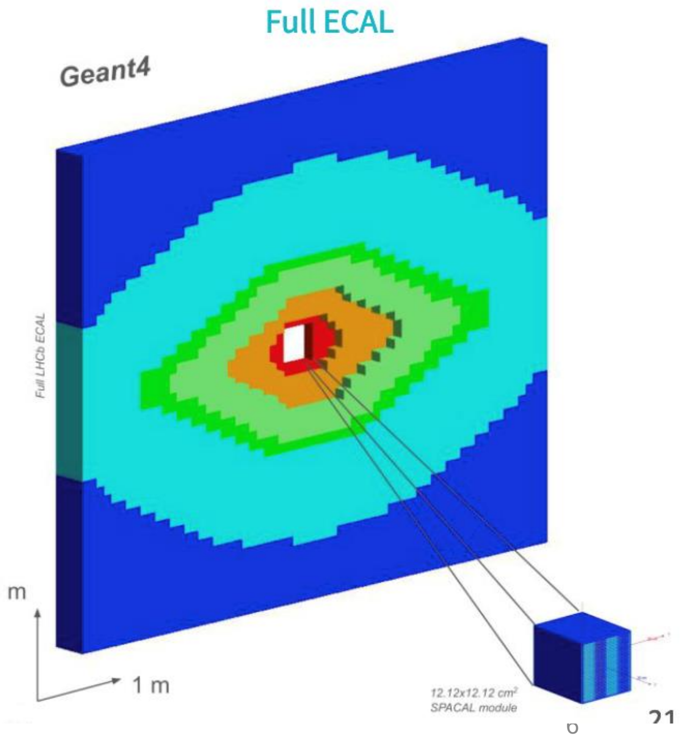
  - Radiation hard up to 40 kGy
- ECAL in upgrade Ib
  - The inner part need to be replaced due to performance degradation



[LHCb-TDR-024]

ECAL Upgrade (PicoCal): Granularity

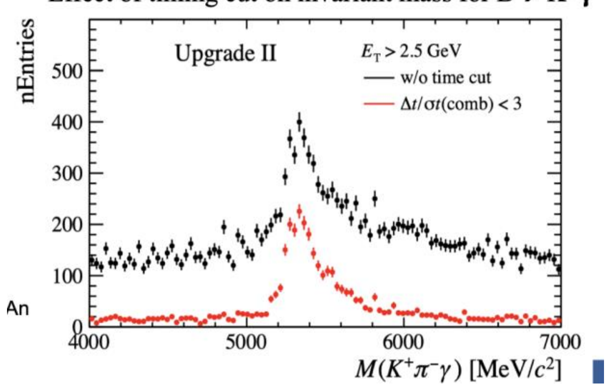
- Improve efficiently performaces at high luminosity
- Reorganize ECAL zones in rhomboic shapes to follow better the radiation and occupancy maps
- Five zones with cells of different sizes: (1 module = 1 bloc of 12x12 cm^2)
  - 1.5x1.5 cm^2: 32 modules (type SpaCal-W) – 2048 cells
  - 3x3 cm^2: 144 modules (type SpaCal-Pb) – 2304 cells
  - 4x4 cm^2: 448 modules (type Shashlik) – 4032 cells
  - 6x6 cm^2: 1344 modules (type Shashlik) – 5376 cells
  - 12x12 cm^2: 1344 modules (type Shashlik) – 1344 cells
- **Baseline option** = Add longitudinal segmentation at shower maximum (separation electron/hadron) in all cells
- One cell = 2 channels for readout (1 front and 1 back)
  - Total of **30208 voies**
- **Descoped option** = No longitudinal segmentation in outer modules (4x4 cm^2, 6x6 cm^2, 12x12 cm^2)



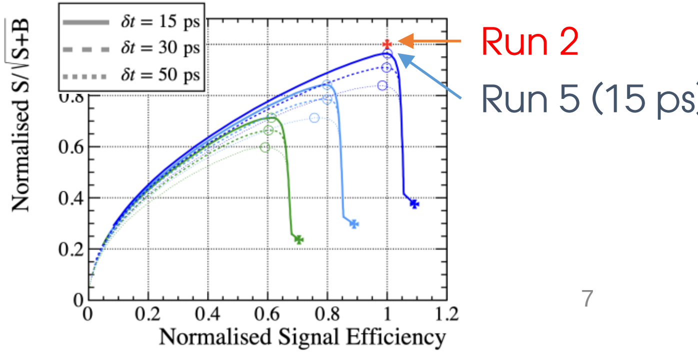
PicoCal: Precise time measurement

- To fight again the large background due to pile-up: add time measurement in ECAL with a precision of 15 ps = PicoCal
- Select cells where $|t_{ECAL}-t_{PV}|/\sigma(t)<3$
  - t_{PV} : collision time measured in other detectors (VELO for example)
  - t_{ECAL} : time measured in the ECAL, corrected from time of flight
  - $\sigma(t)$: ECAL time resolution
- <u>Participations of French and Chinese institutes</u>:
  - Performance studies with simulation in particular to compare baseline and descoped options
  - R&D and characterisation of new modules
  - R&D of new electronics

Effect of timing cut on invariant mass for B→ K*γ



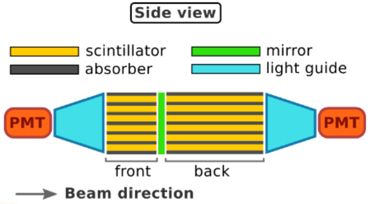
Full simulation of signal $B^0 \to K^{*0}\gamma$ with pile-u

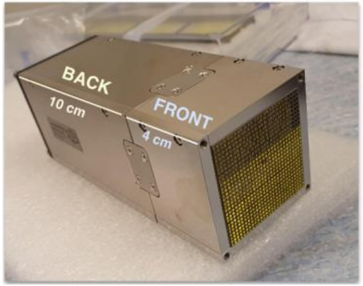


ECAL Modules

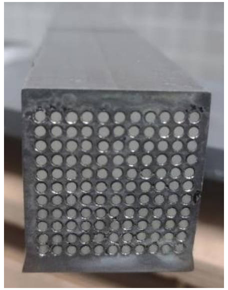
- Ongoing R&D to produce modules allowing a precise time measurement and a relative energy resolution of 10%/sqrt(E)

SPACAL:



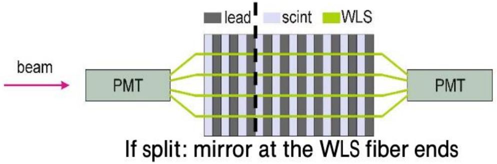


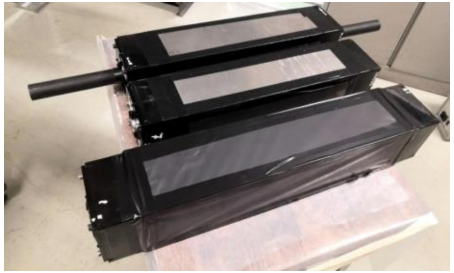
W absorber, cristal fibers (GAGG, gadolinium aluminium gallium garnet): High radiation tolerance and small Molière radius



Pb absorber, polystyrene fibers

SHASHLIK:





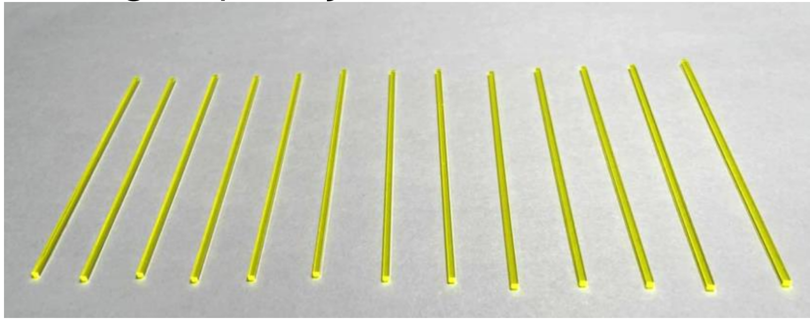
Current modules: external reg

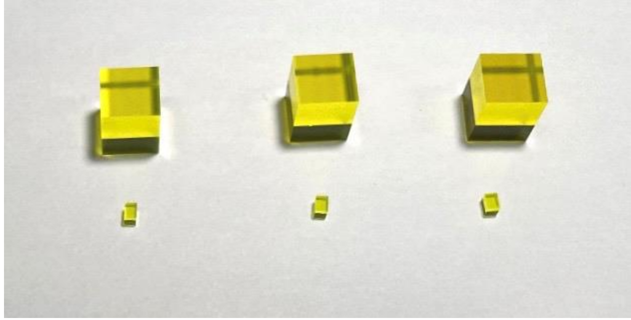
Optimisation of GAGG scintillators

- Good scintillator for innermost part of PicoCal
  - ✓ Radiation-hard
  - ✓ High density
  - ✓ High light output and fast decay time
- Commercial GAGG decay time ~50 ns, desirable ~5 ns
  - ✓ Collaborate with SIPAT to reduce decay time by tuning composition and doping

Decay time at cost of light output ~5k/MeV acceptable

  - ✓ High-quality scintillator fibres and samples obtained



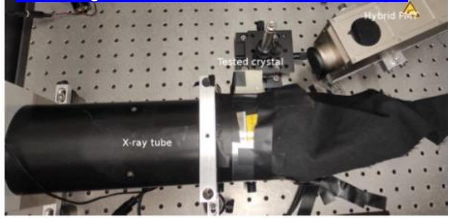


Optimisation of GAGG scintillators

- GAGG samples characterisation at CERN & PKU
  - ✓ Results feedback to SIPAT to iterate

Light output measurement

Decay time measurement



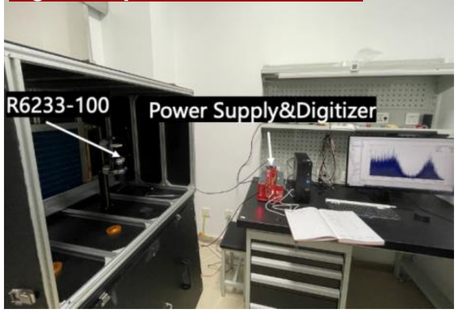
Absorbance

Perkin Elmer Lambda 650

Photoluminescence

Perkin Elmer LS55

Light output measurement



Decay time measurement

Absorbance

Edinburgh DS5

Photoluminescence

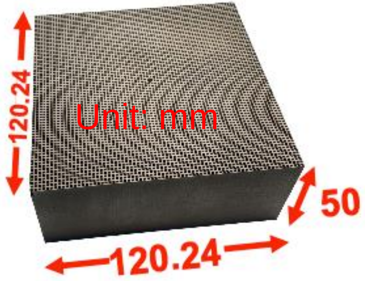
Edinburgh FLS1000

- Now decay time between $15-20$ ns; light output $\sim 10k/MeV$
- R&D still ongoing

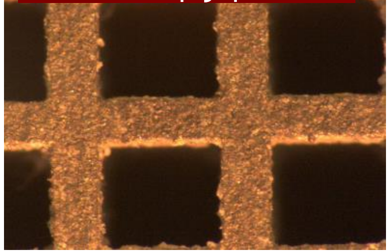
3D-printing tungsten (W) absorber

- ➢W has small radiation length and small Moliere radius
- ➢3D-printing technology to ease W matrix production
- ➢Collaboration with LaserAdd to produce W absorber
  - ✓Good samples obtained
    - Good roughness needed not to scratch fibres
    - High density
  - ✓Characterisation W samples, feedback results to LaserAdd to opti

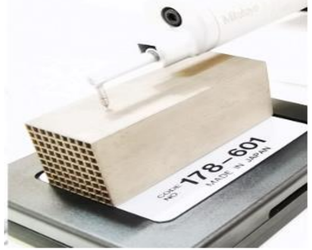
雷佳 LASERADD



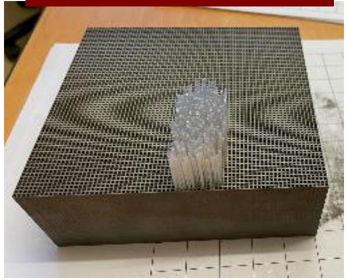
Microscopy picture



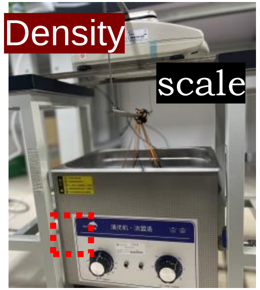
Surface roughness



Fiber insertion test



Density



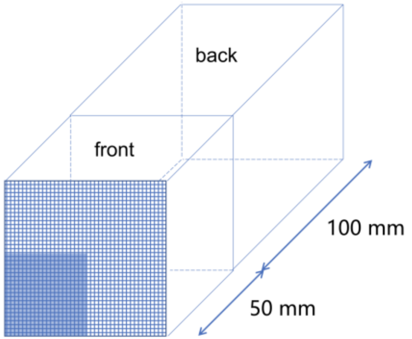
➢Good roughness $R_a \approx 4\ \mu m$ achieved, can smoothly insert fibres

➢Density (units: g/cm^3)

Pure W	LaserAdd
19.3	18.9

Prototype SPACAL-W+GAGG

- ➢New prototype in construction
  - ✓ 3 pieces of 3D-pinted tungsten absorber of $12 \times 12 \times 5\ \mathrm{cm}^3$ produced by LaserAdd

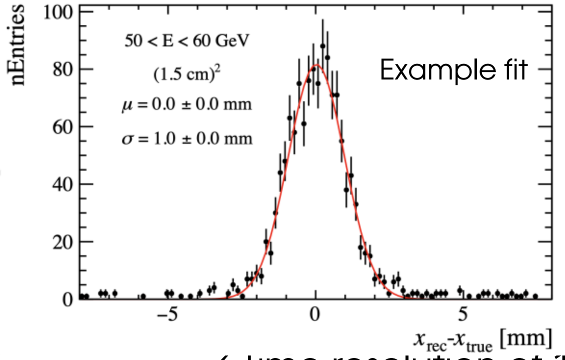


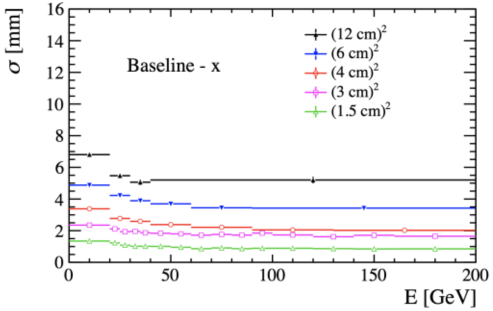
Prototype schematic

  - ✓ 4x4 cells (1296 holes) equipped by GAGG fibers from SIPAT
  - ✓ Further cells will be equipped with fibers from other producers later for time resolution studies
  - ✓ Double-sided readout
- ➢Testbeam at SPS this June

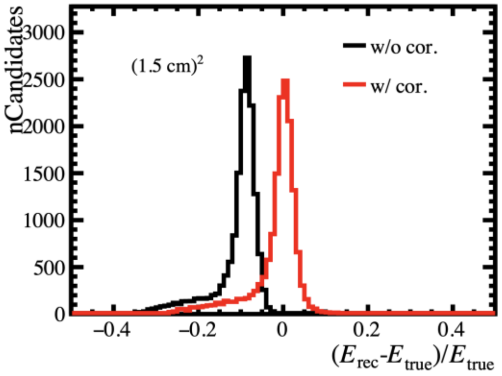
Resolution studies with full simulation

- Resolution studied with single-photon sample: good precision as expected
  - ✓ Position resolution of 1mm in the inner

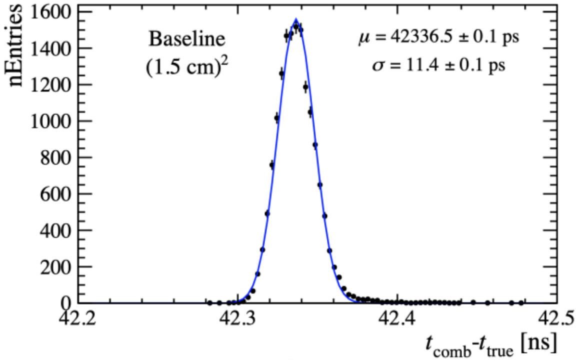




- ✓ Energy resolution: relative 10%



- ✓ Time resolution of 11ps in the central po

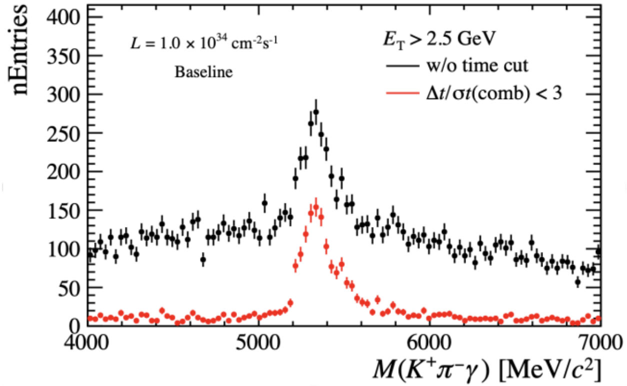


Cell size [cm^2]	Time resolution [ps]	
	Baseline	Downscoped
1.5 × 1.5	11.4	11.4
3 × 3	13.8	13.8
4 × 4	20.2	43.4
6 × 6	22.4	42.2
12 × 12	24.3	44.0

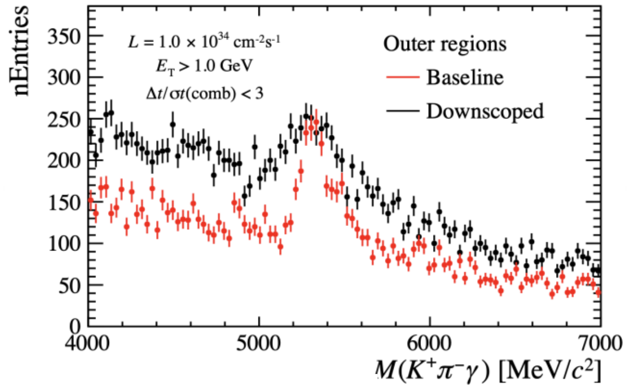
Performance studies with full simulation

- Benchmark channel: $B^0 \to K^{*0}\gamma$

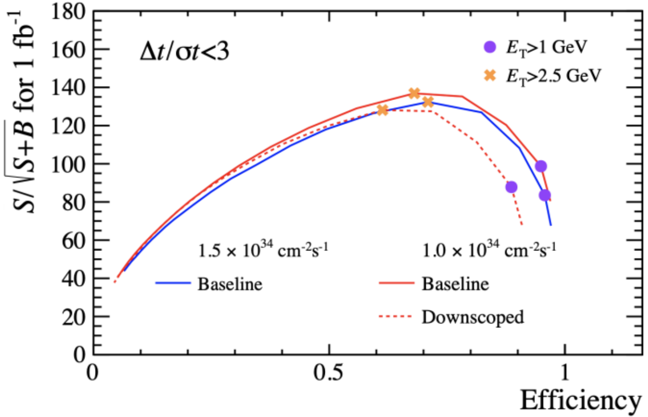
✓ Timing cut effective in reducing bkg.



✓ Larger background level with downscoped PicoCal setup (worse time resolution)

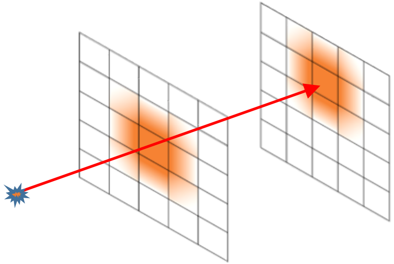


✓ Performance comparison taking $S/\sqrt{S+B}$ per fb^{-1} as Figure Of Merit :
significantly worse performance with downscoped PicoCal setup



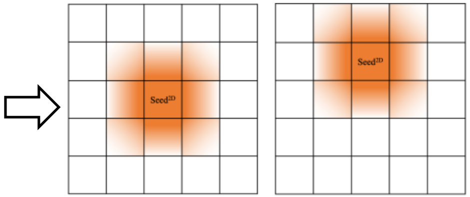
Reconstruction algorithm development

- A new reconstruction algorithm is being developed to take into account the longitudinal segmentation (i.e. Layered reconstruction)

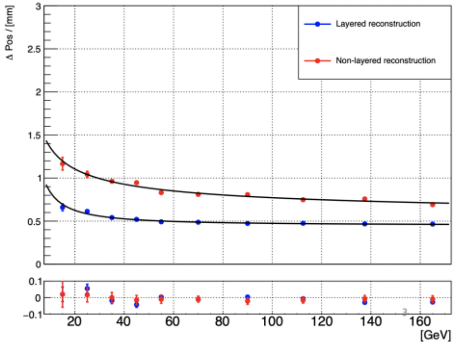


Front section

Back section



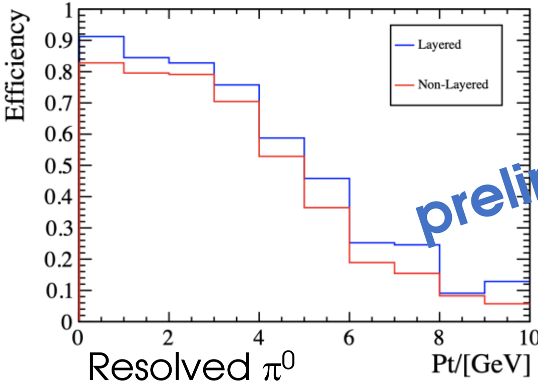
*Shift of seed cell from front to back section



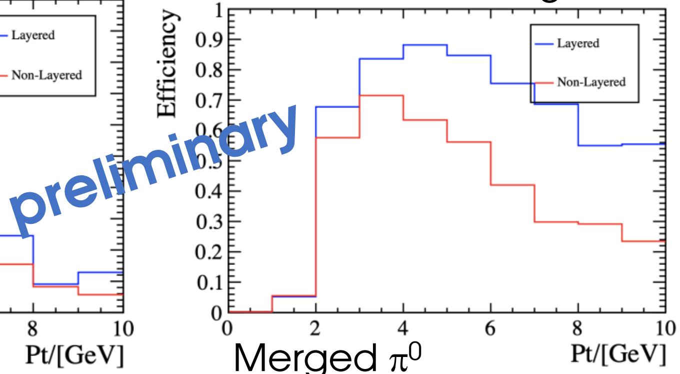
*Position resolution with single-photon:large improvement with new algorithm

- The algorithm is promising to improve π^0 reconstruction efficiency

*$B^0 \to \pi^+\pi^-\pi^0$



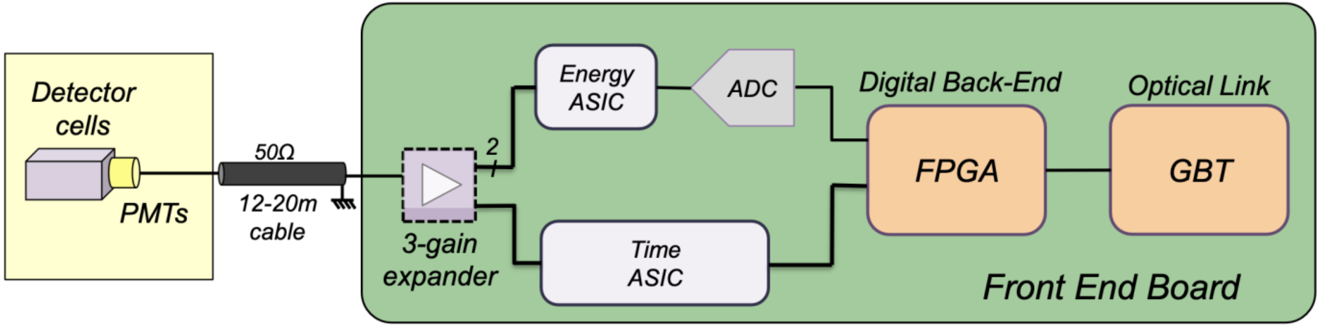
Resolved π^0



Merged π^0

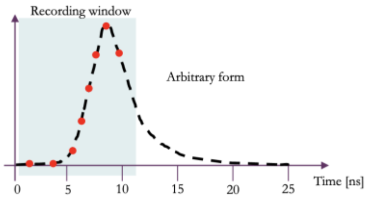
Electronics for PicoCal

- Architecture:

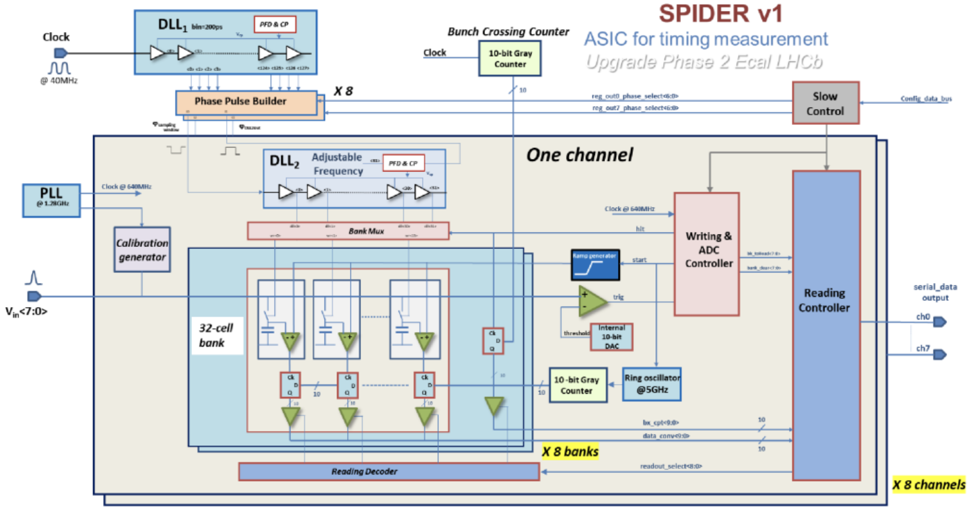


- Readout with PMTs
- Two separate paths with dedicated ASIC developed in parallel, with the same technologiy (TSMC 65 nm), running at 40 MHz:
  - **Time ASIC (SPIDER):** waveform TDC in analog memories (R&T IN2P3, Orsay/Clermont-Ferrand/Lyon/Caen/Nantes) (dynamic range of E_T = 50 MeV to 5 GeV, resolution 15ps RMS)
  - **Energy ASIC** (Barcelone, Valence), measurement of the integrated charge at 40 MHz over 12 bits with two gains (dynamic range between E_T = 0 and 40 GeV)

Mesure du temps: Waveform Digitizing



- Time measurement is done by sampling the signal shape using analog memories and a FPGA: development of a dedicated ASIC called SPIDER
- Time is computing using:
  - A counter (~1 ns step), **DLL2**
  - A DLL to define the region of interest (~100 ps step) **DLL1**
  - Samples on the signal shape: **Cell banks**
- The interpolation in a FPGA allows to measure the time with a precision of a few ps RMS with a precise calibration even with signals with small amplitudes.
- The main disadvantages that must be addressed in the new SPIDER chip:
  - Large deadtime (~ 100 µs) limiting usage at high rate (goal = 40 MHz) => ADC **massively parallel** to reach at least 50% occupancy
  - Need of a trigger: every channel is self triggered



Technologie: TSMC CMOS 65nm
- 10-bit Wilkinson ADC at 5 GHz
- Memory cells (switches/capacitors) with ~0.8V dynamic range and noise level ~0.5mV RMS
- DLL between 40 and 640 MHz

First prototype Automne 2024 (final version end 2029)

Conclusions

- Common activities in Chinese and French groups about LHCb ECAL Upgrade :
  - R&D for new modules with GAGG fibers
  - Performance studies with simulation
  - Design of ASIC to measure timing precisely
- In the near future:
  - Test beams at DESY and SPS to measure module characteristics
  - First prototype of electronics
- On the longer term:
  - Full production of innermost ECAL modules
  - Full production of Front-End electronics
  - Implementation of algorithms in FPGA to improve calorimeter reconstruction

Backup