B_c studies and upgrade of ECAL for LHCb

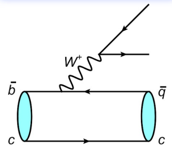
Patrick Robbe, IJCLab Orsay, 29 June 2026

Study of the B_c^+ meson

- **Heavy quarkonium:** ideal system to probe QCD both theoretically and experimentally, well-studied
- $\boldsymbol{B_c}^+$ meson: a unique system in standard model
  - Nonrelativistic system composed two different heavy quarks ($\boldsymbol{bc}$) with a mass of ~6.27 GeV
  - It can decay only via the weak interaction, providing unique opportunities to extract information on both QCD dynamics and weak interactions.
  - Decay time (~0.5 ps) three times shorter than $\boldsymbol{B}^+$, longer than quarkonia
- Limited knowledge experimentally:
  - Not produced in current e^+e^- colliders
  - Suppressed in hadronic colliders
- Leading role of LHCb in the study of the B_c^+ meson
  - Dominating precision for mass and lifetime measurements
  - Observation of new decay modes

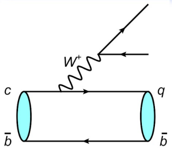
Γ_1	$J/\psi(1S)\ell^+\nu_\ell$ anything	seen
Γ_2	$J/\psi(1S)\mu^+\nu_\mu$	seen
Γ_3	$J/\psi(1S)\tau^+\nu_\tau$	seen
Γ_4	$J/\psi(1S)\pi^+$	seen
Γ_5	$J/\psi(1S)K^+$	seen
Γ_6	$J/\psi(1S)\pi^+\pi^+\pi^-$	seen
Γ_7	$J/\psi(1S)K^+\pi^-\pi^+$	
Γ_8	$J/\psi(1S)K^+K^-K^+$	
Γ_9	$J/\psi(1S)a_1(1260)$	not seen
Γ_{10}	$J/\psi(1S)K^+K^-\pi^+$	seen
Γ_{11}	$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	seen
Γ_{12}	$\psi(2S)\pi^+$	seen
Γ_{13}	$\psi(2S)\pi^+\pi^-\pi^+$	
Γ_{14}	$\psi(2S)K^+K^-\pi^+$	
Γ_{15}	$J/\psi(1S)D^0K^+$	seen
Γ_{16}	$J/\psi(1S)D^*(2007)^0K^+$	seen
Γ_{17}	$J/\psi(1S)D^*(2010)^+K^{*0}$	seen
Γ_{18}	$J/\psi(1S)D^+K^{*0}$	seen
Γ_{19}	$J/\psi(1S)D_s^+$	seen
Γ_{20}	$J/\psi(1S)D_s^{*+}$	seen
Γ_{21}	$J/\psi(1S)p\bar{p}\pi^+$	seen
Γ_{22}	$\chi_{c0}\pi^+$	$(2.4^{+0.9}_{-0.8})\times10^{-5}$
Γ_{23}	$p\bar{p}\pi^+$	not seen
Γ_{24}	D^0K^+	seen
Γ_{52}	$B_s^0\pi^+$ / B($\bar{b}\to B_s$)	seen

c-quark spectator (~20%)



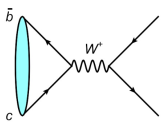
e.g. $B_c^+\to J/\psi\,\pi^+$

b-quark spectator (~70%)



e.g. $B_c^+\to B_s^0\pi^+$

$\bar{b}c\to W^+\to\bar{q}q$ (~10%)



e.g. $B_c^+\to D^0K^+$

[Phys. Rev. Lett. 136 (2026) 021804]

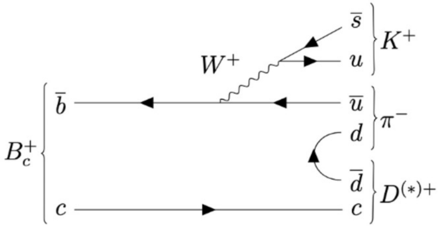
Observation of $B_c^+ \rightarrow D\, h^+\, h^-$

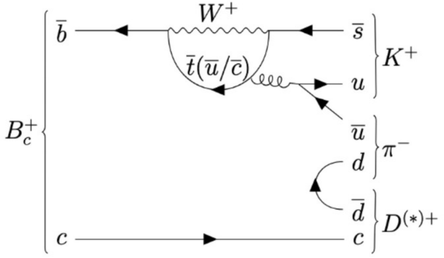
Investigate the role of annihiliation processes in B_c^+ decays, observed to be dominant in $B_c^+ \rightarrow DX$ decays.

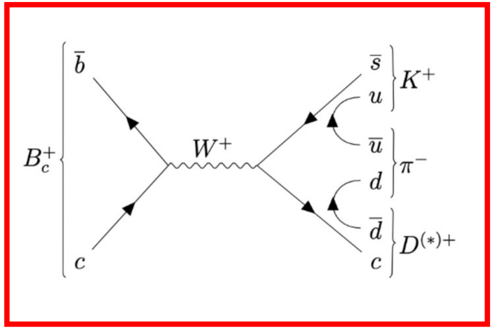
- **Search for $B_c^+ \to D^+K^+\pi^-$, $B_c^+ \to D^{*+}K^+\pi^-$, $B_c^+ \to D_s^+K^+K^-$ decays using $B_c^+ \to B_s^0\pi^+$ as the normalization channel**

$$R = \frac{\mathcal{B}(B_c^+ \to Dh^+h^-)}{\mathcal{B}(B_c^+ \to B_s^0\pi^+)} = \underbrace{\frac{N_{B_c^+ \to Dh^+h^-}}{N_{B_c^+ \to B_s^0\pi^+}}}_{\text{Signal yield}} \cdot \underbrace{\frac{\varepsilon_{B_c^+ \to B_s^0\pi^+}}{\varepsilon_{B_c^+ \to Dh^+h^-}}}_{\text{Estimated from simulation}} \cdot \underbrace{\frac{\mathcal{B}(B_s^0)}{\mathcal{B}(D_{(s)}^{(*)+})}}_{\text{BF rom PDG}}$$

- Possible diagrams for the $B_c^+ \to D^{(*)+}K^+\pi^-$ decay





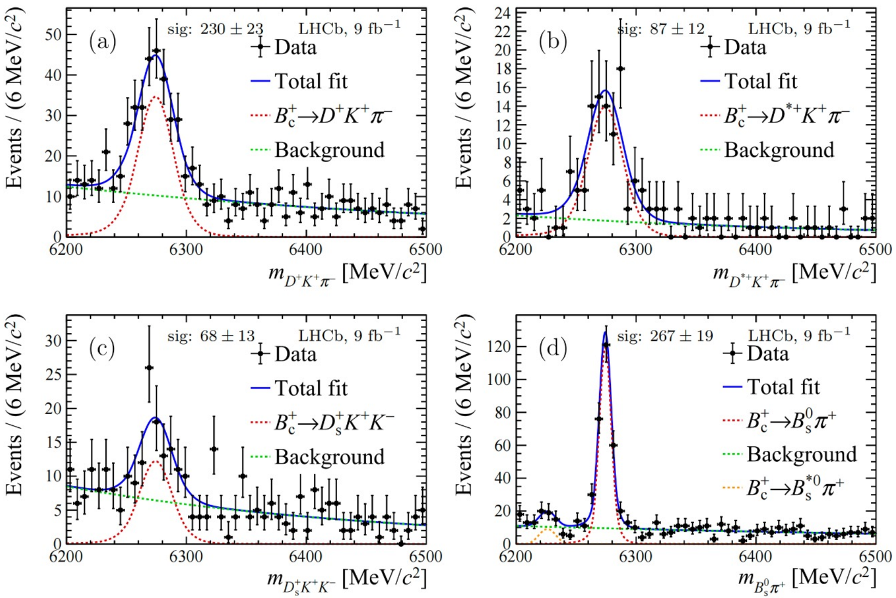


Annihilation

[Phys. Rev. Lett. 136 (2026) 021804]

Observation of $B_c^+ \rightarrow D\, h^+ h^-$

Analysis using Run 1+2 data = 9 fb^{-1}



Conclusion

- ***Yields:***

	$B_c^+ \to D^+K^+\pi^-$	$B_c^+ \to D^{*+}K^+\pi^-$	$B_c^+ \to D_s^+K^+K^-$
Yield	230 ± 23	87 ± 12	68 ± 13

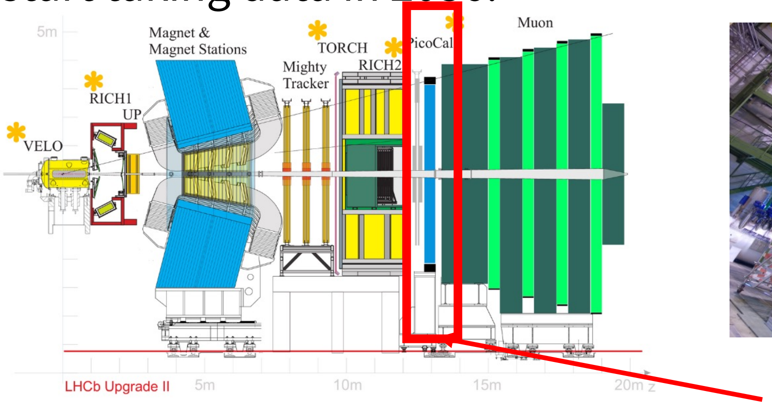
- *All three decay modes are observed with significance above 5σ → 1st Observation*

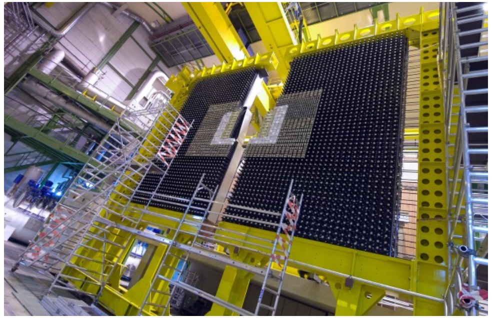
$$\mathcal{R}(B_c^+ \to D^+K^+\pi^-) = (1.96 \pm 0.23 \pm 0.08 \pm 0.10) \times 10^{-3}$$
$$\mathcal{R}(B_c^+ \to D^{*+}K^+\pi^-) = (3.67 \pm 0.55 \pm 0.24 \pm 0.20) \times 10^{-3}$$
$$\mathcal{R}(B_c^+ \to D_s^+K^+K^-) = (1.61 \pm 0.35 \pm 0.13 \pm 0.07) \times 10^{-3}$$

- *Using $BF(B_c^+ \to B_s^0\pi^+) \sim 16.4\,\%$, the study gives the absolute BFs $\sim 10^{-4}$* [arXiv:hep-ph/0211021]

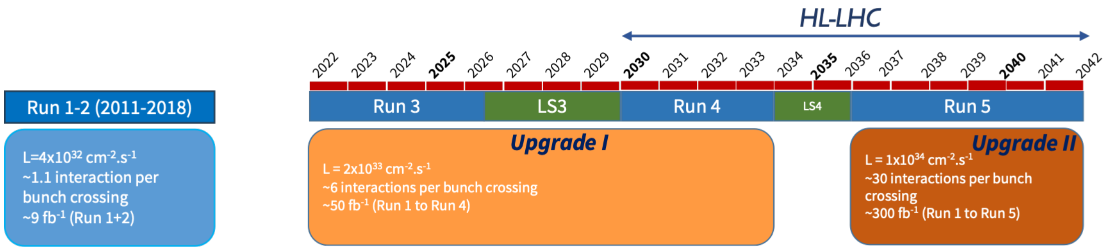
Calorimeter for Upgrade 2

- LHCb is designing a new detector to replace the current one: ”LHCb Upgrade 2” which will start taking data in 2036.



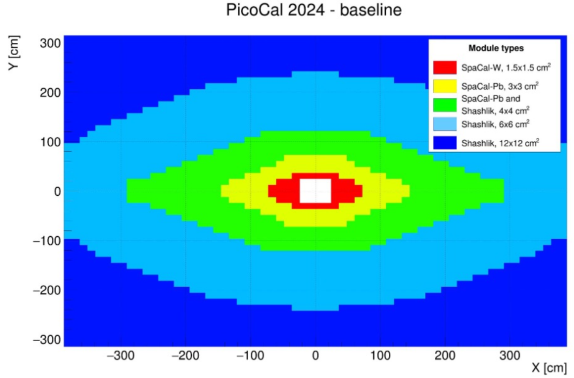


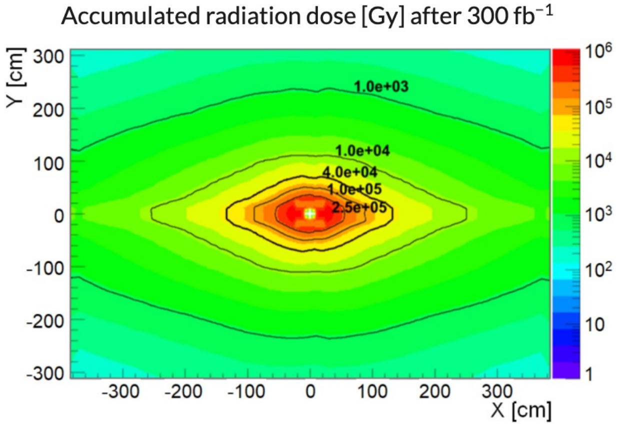
- It will contain an electromagnetic calorimeter: PicoCal, new detector built by institutes from China, France, CERN, Italy, Spain, USA, Kazakhstan.



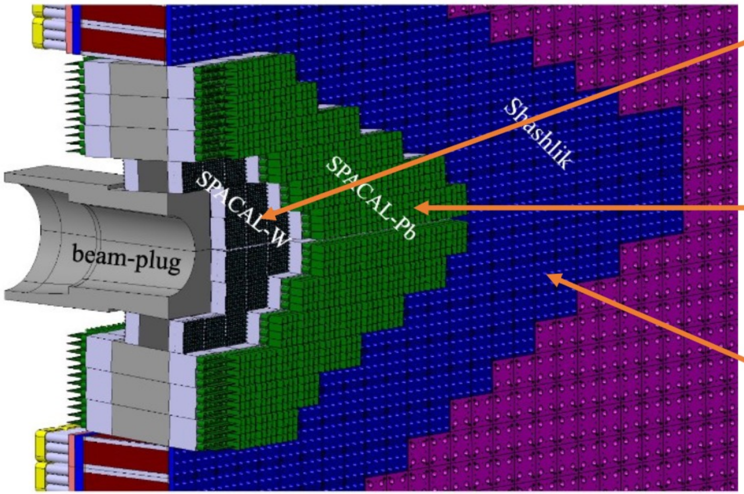
Electromagnetic Calorimeter in LHCb

- Optimised for γ and $\pi^0(\to\gamma\,\gamma)$ identification for energies between 1 and 100 GeV
- Energy resolution of $\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 1\%$
- For operation at luminosity during Upgrade 2 ($1\mathrm{x}10^{34}$ cm^{-2} s^{-1}) it is required to:
  - Sustain **radiation** dose up to 1 MGy and $6\mathrm{x}10^{15}$ neq/cm^2 in the center
  - Measure **time** of arrival of particles with precision of 15ps (for the entire data processing chain)
  - Have high **granularity** on the center with denser absorber
  - **Segment** longitudinally for particle identification





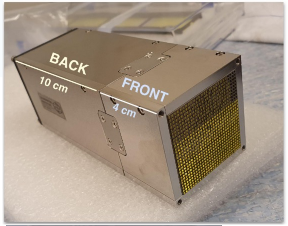
LHCb PicoCal

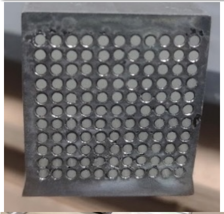


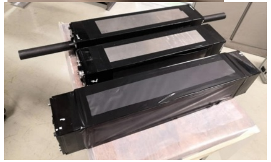
SPACAL: W absorber + crystal fibres (GAGG = Gadolinium Aluminium Gallium Garnet)
1.5x1.5 cm²

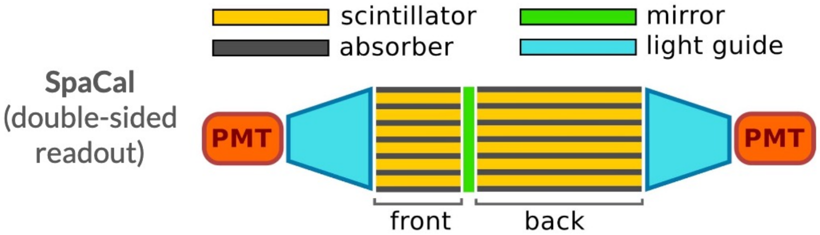
SPACAL: Pb absorber + plastic fibres
3x3, 4x4 cm²

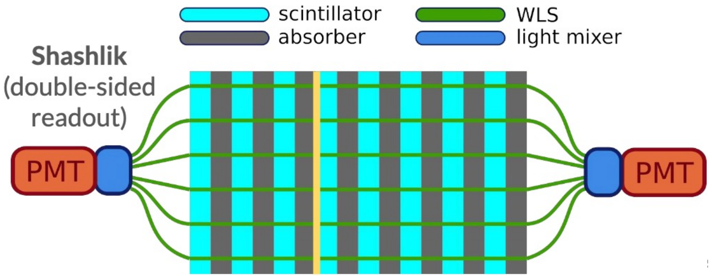
Shashlik: Pb absorber + plastic tiles + WLS fibres
4x4, 6x6, 12x12 cm²



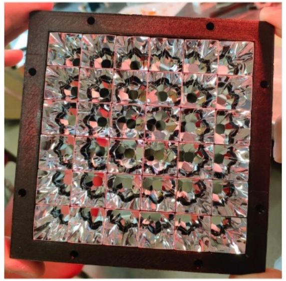








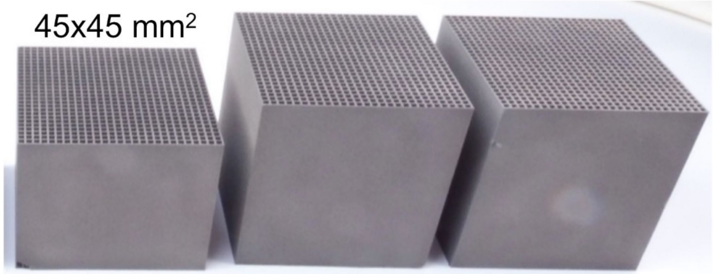
R&D - Tungsten prototypes

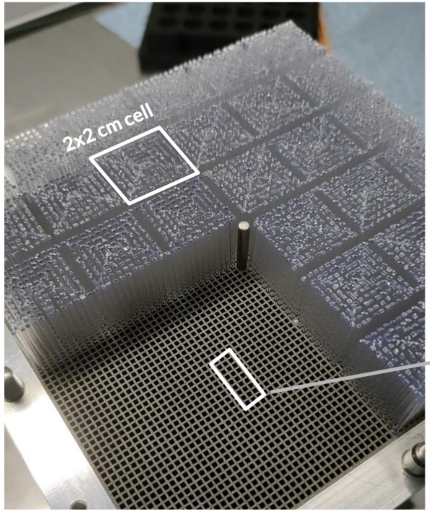


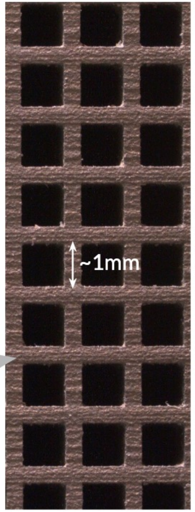
- 3D-printed tungsten absorber: R&D by EOS (Germany) and LaserAdd Technology (China)
- “Hollow” light guides made of 3D-printed plastic structures covered with ESR film
- Two-staged optical coupling: fibre bundle + hollow light guides
- R&D to accelerate the scintillation of garnet crystals → novel GAGG composite developed

Module size prototypes:

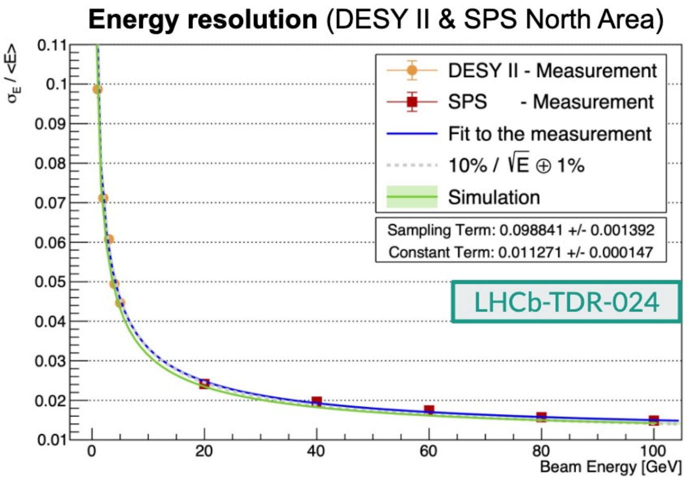
- [2024] SpaCal-W with GAGG fibers (LS4)
- [2023] SpaCal-W with plastic scintillating fibres (LS3)

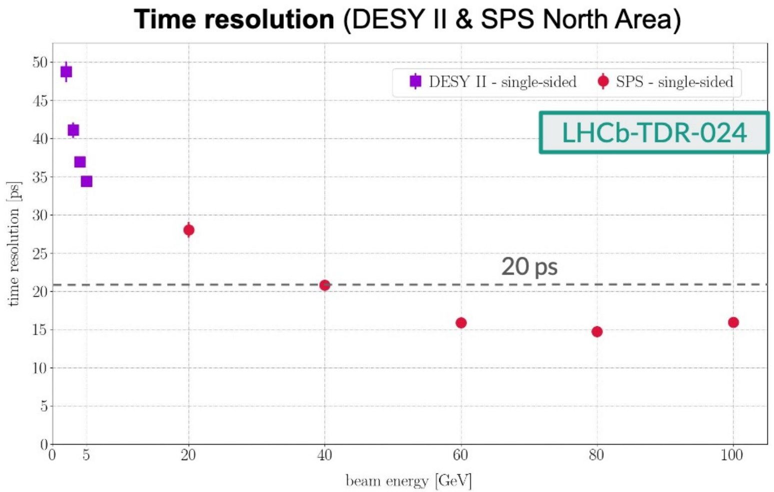






R&D – Tungsten prototype



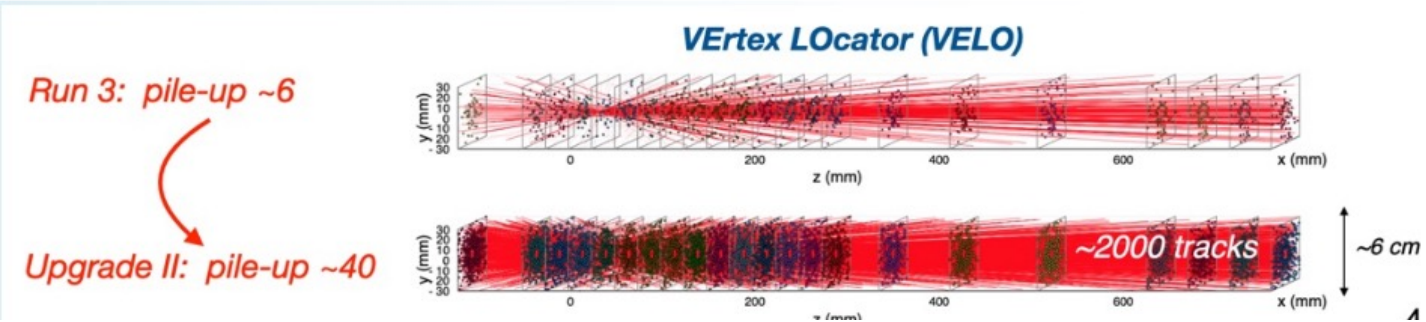


- Electron beam incidence angle: 3°+3°
- Single-sided readout & Hamamatsu R14755U-100
- Sampling term: 9.9%, constant term: 1.1% (Noise term subtracted)
- Good agreement with simulations

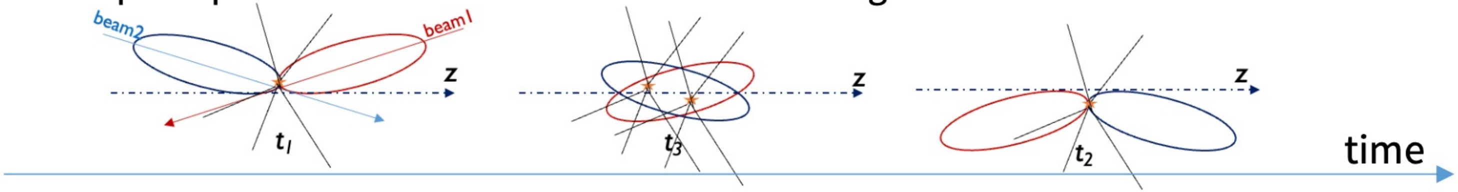
- Electron beam incidence angle: 3°+3°
- Single-sided readout & Hamamatsu R7600U-M4
- Optical coupling with a hollow light guide
- Time resolution ~20 ps above 40 GeV

Time measurement

Pile-up = several proton-proton collisions when the beam cross each other



- Time spread of *pp* interaction region ~200 ps (t_2-t_1): measurement of time of particles with ***~15ps precision*** to distinguish different pile-up interactions in the same bunch crossing.



[arXiv:2512:17355]

L. Alvado[c], N. Arveuf[b], E. Bechetoille[d], G. Blanchard[b], D. Breton[a,1], B. Joly,[b,2], L. Leterrier[c], J. Maalmi[a], S. Manen[b], H. Mathez[d], C. Sylvia[a], P. Vallerand[a], R. Vandaele[b]

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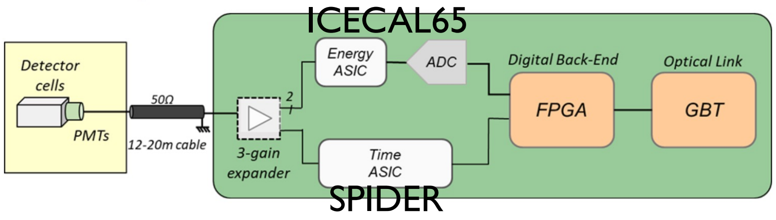
[c] CNRS / IN2P3 / LPC, Caen, France
[d] CNRS / IN2P3 / IP2I, Lyon, France

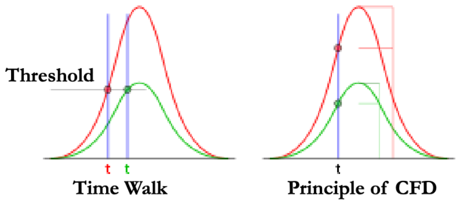
Time measurement

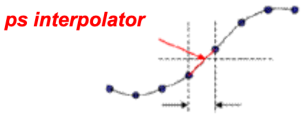
- A dedicated ASIC (Application-specific integrated circuit), SPIDER, is developed for the time measurement



- Requirements for timing electronics
  - Time measurement in range E_T = [50 MeV - 5 GeV]
  - Time resolution target ***15 ps*** for E_T = [1-5 GeV] (for the entire detector)
  - Below 1GeV, time resolution as low as permitted by input signal and noise
  - PMT signal rise time between 1.5 ns and 4 ns (R&D ongoing)
  - Max occupancy up to ~30% per channel

Waveform TDC = waveform digitiser + algorithm
- ex. constant fraction discriminator or smarter algorithms*
- **Few ps** precision achievable on large dynamic range
- SAMPIC circuit (IJCLab/IRFU)

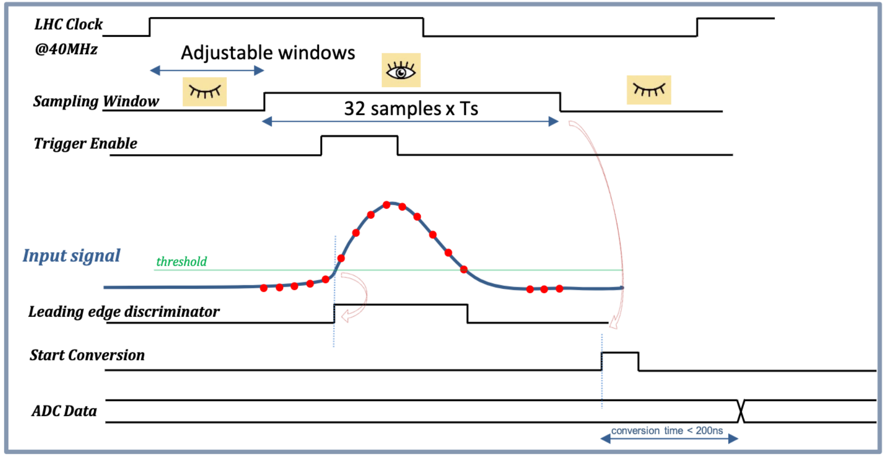


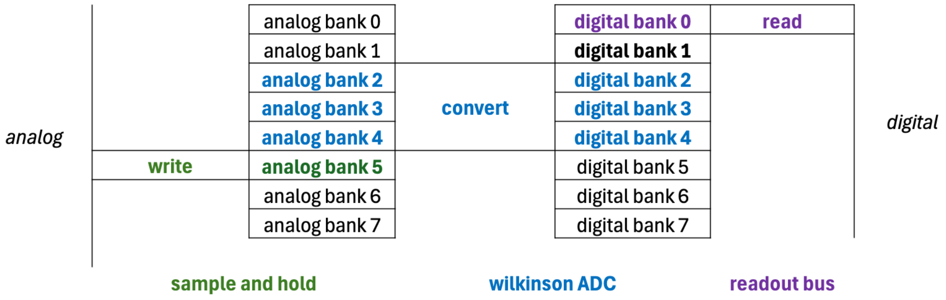


[arXiv:2512:17355]

SPIDER – Swift Pipelined Digitizer

- Analog sampling of input signals
  - in configurable time window w.r.t. LHC clock, adjustable per channel, by steps of 200ps
  - Sampling period adjustable from 50ps to 600ps
  - Sampling window of 32 samples, duration: 1.6ns to 19.2ns
  - Analog bandwidth compatible with minimal rise time ~250ps
- Self-triggered digitization on 10 bits, voltage range 0-800mV
- Noise target < 0.5mV rms
- Pipelined operation:
  - 8 banks of 32 samples
  - write/convert/read **simultaneously** on different banks
- Peak finder allows to read only a few samples (typ. 8) to reduce extraction time (smart read mode)
- On-chip calibration generators (ADC, timing)
  - ADC and time calibrations (asynchronous for time INL and synchronous for phase vs LHC clock) are required





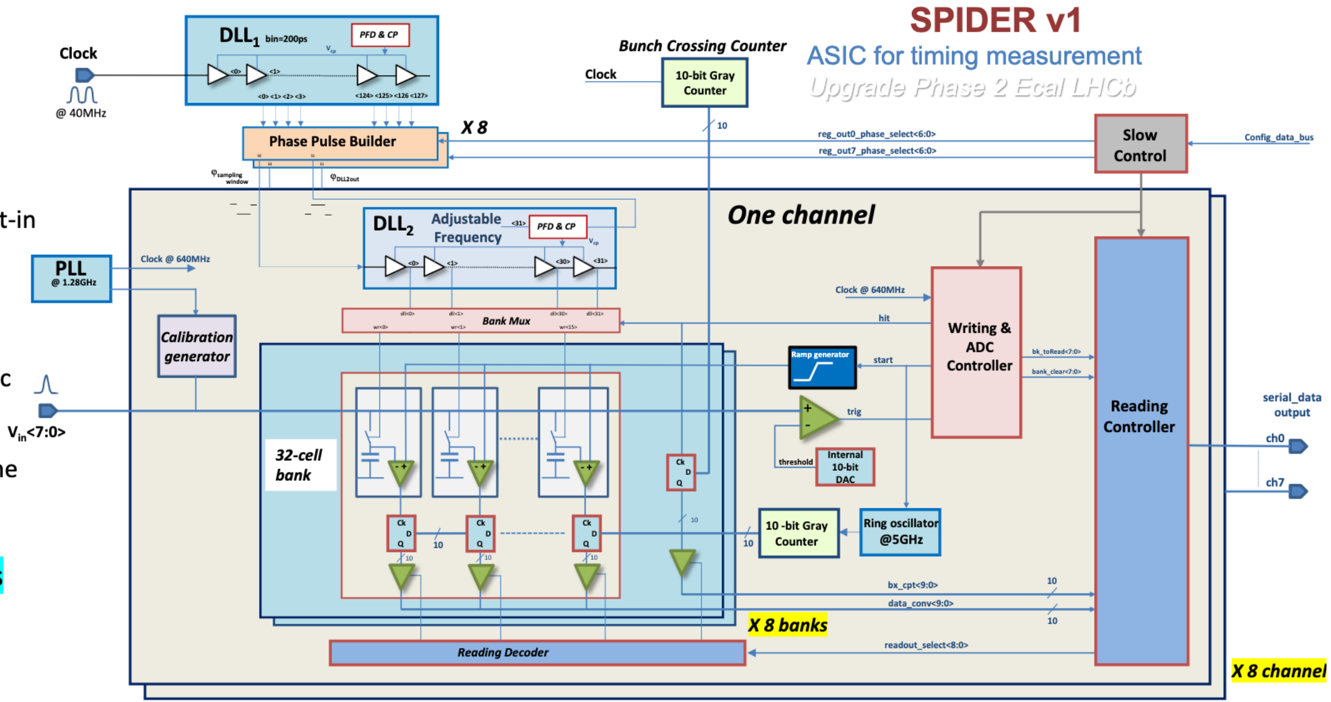
Bank management during acquisition

[arXiv:2512:17355]

SPIDER architecture

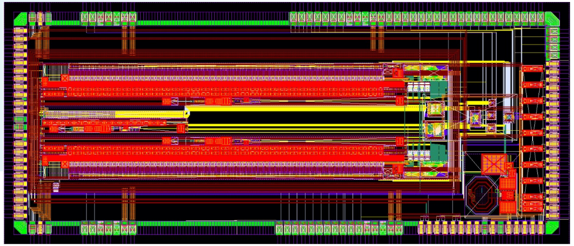
Architecture specifications – standard version with 8 channels ("V1")

- TSMC 65nm, VDD 1.2V
- 8 self-triggering channels
- Clock distribution & DLLs
- Memory cell
  - Sample & hold with bootstrap, built-in Wilkinson ADC
- Multi-bank system
  - Derandomization buffer
  - 8 banks of 32 cells, sequencing logic
- 10-bit Wilkinson ADC @5 GHz
  - Fast counter to limit conversion time (max 200 ns for 10 bits i-e 8 LHC periods, for 800 mV signals)
- PLL and DAC + buffer for calibrations
- Serial readout interface
  - Digital buffers
  - Up to 2.56 Gb/s on each channel, ASIC-driven ("push" mode)

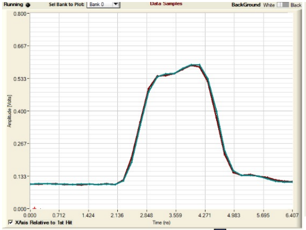


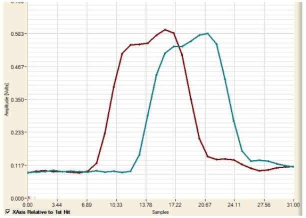
[arXiv:2512:17355]

SPIDER tests



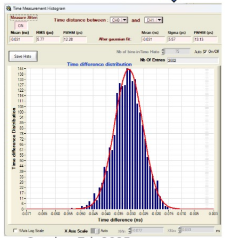
- First prototype produced in 2025 is functional
- Giving expecting performances and used in test beams with PicoCal prototypes



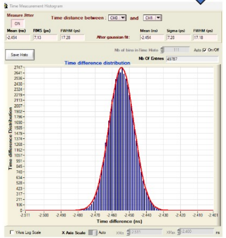


- Time Difference Resolution (TDR) of two pulses (**random** source, 500 mV, rise time of 800ns, FWHM of 2ns) between the two channels **without time calibration, all banks involved.**
- Measurement performed via **simple CFD algorithm.**
- **Next: calibration of time non-linearity**

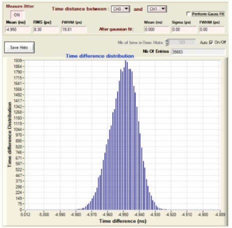
No delta t,
same windows,
5.8 ps rms

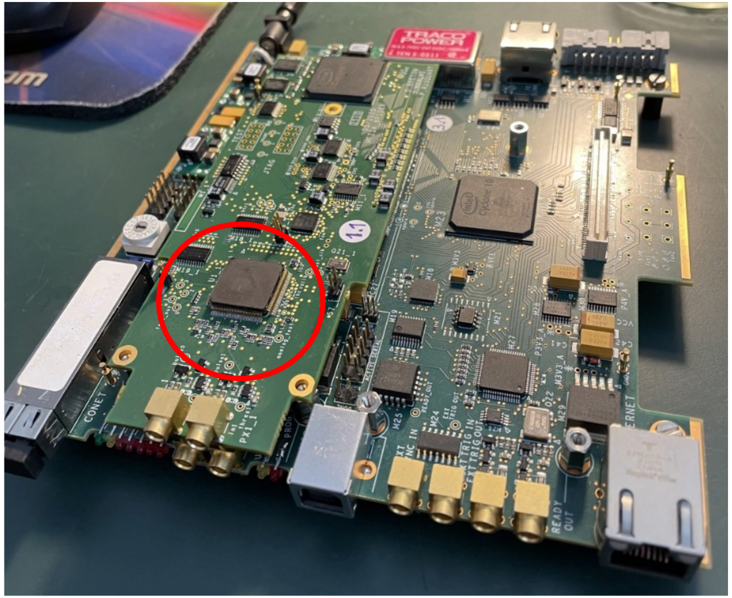


Delta t of 2.5ns,
all windows shifted by
2.5ns on channel 1,
7.1 ps rms



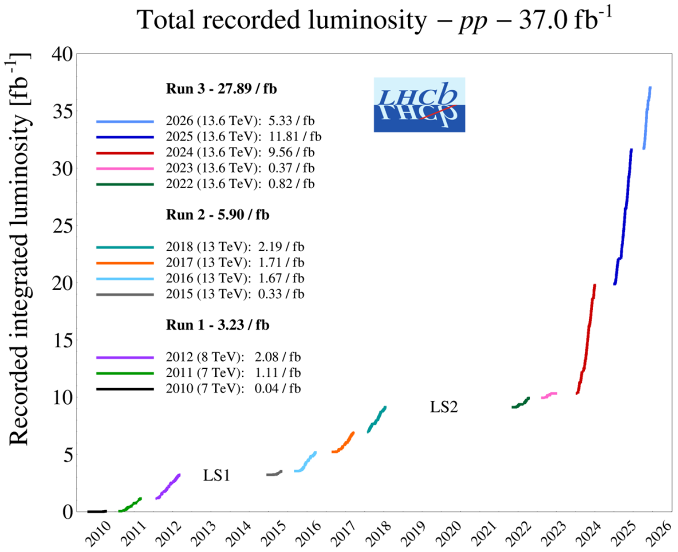
Delta t of 5ns,
all windows shifted
by 5ns on channel 1
8.3 ps rms





Conclusions

- New measurements of B_c^+ decay modes: large step forward expected with Run 3 dataset.
- New calorimeter is under design for LHCb Upgrade 2 and the difficult environment during Run 5 of the LHC.
- Intense R&D phase to have modules and electronics allowing to sustain radiation, have higher granularity and perform precise time measurements.
- A large part of the new PicoCal modules will be installed already in 2029-2030 to operate during Run 4 (2030-2033) and will be kept for Run 5 (2036-2041).

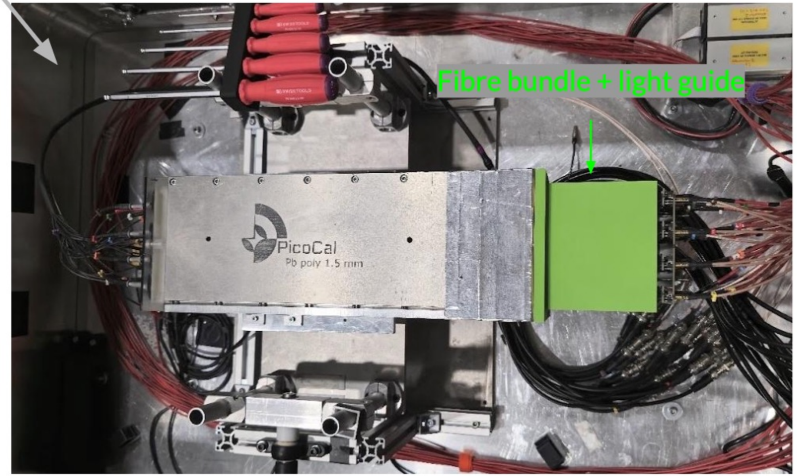


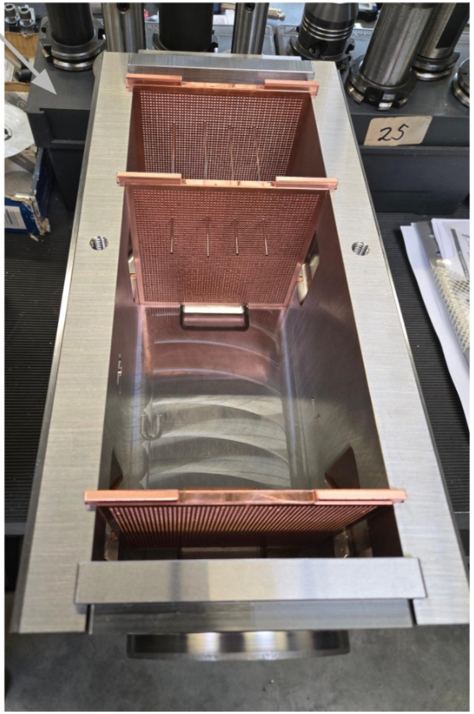
R&D – Lead prototypes

- Lead absorber produced by low-pressure casting with stainless steel capillary tubes aligned with copper matrices

Module size prototypes:

- [2020] SpaCal-Pb 9-cell with polystyrene fibers (LS4)
- [2024] SpaCal-Pb 16-cell with plastic scintillating fibers (LS3)

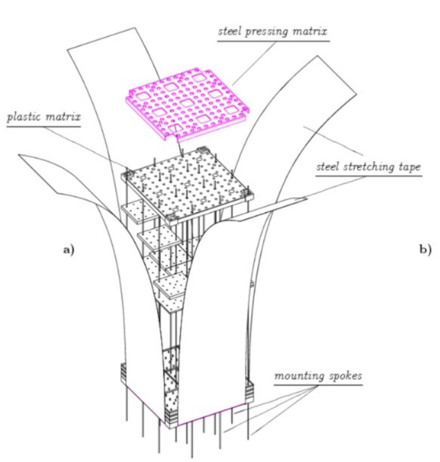


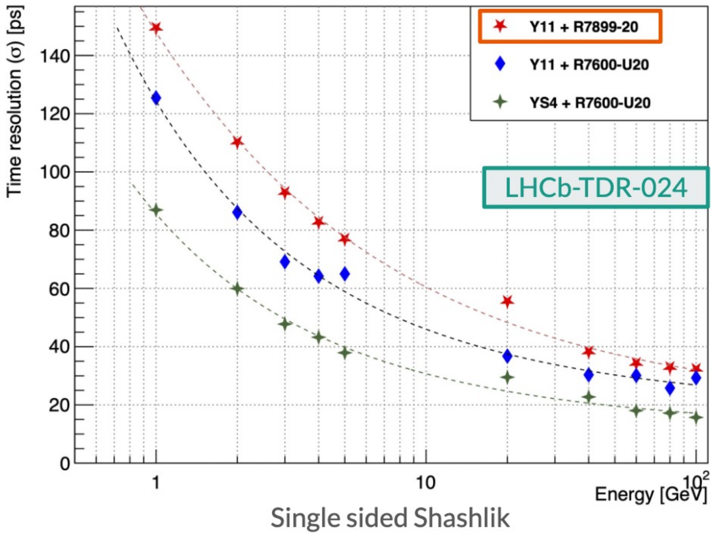


R&D – Shashlik modules

- Shashlik with fast WLS fibers (LS4)
  - Good timing properties already, further improvements possible by replacing fibers with faster ones and faster PMTs
  - Time resolution ~20 ps above 40 GeV
  - Documented in the LS3 Enhancement TDR

WLS fiber	YS2	YS4	Y11
Decay time	1.1 ns	3 ns	7 ns





Single sided Shashlik

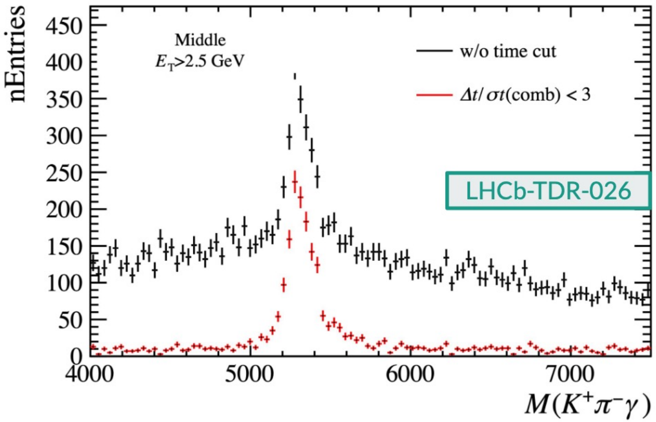
Performances

Expected performances of PicoCal are estimated with simulation for decays with photons

Photon and neutral pion identification

- A cut on the arrival time of the photon is very effective to reduce the background

  Ex: K+π−γ invariant mass distribution for selected B0 → K^{*0}γ candidates



Electron identification:

- The impact of double-sided readout in the electron-hadron separation is particularly pronounced.

  Ex: Rate of background from misidentified B^0 → K^{*0}π+π− decays as a function of the efficiency to select B^0 → K^{*0}e+e− events