FCPPN/L 2025

B_c studies and upgrade of ECAL for LHCb

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Outline

1. Introduction
2. B_c studies
3. Ongoing R&D for ECAL upgrade
    1) Absorber and large-scale production
    2) SpaCal-W with plastic fibers for LS3
    3) SpaCal-W with crystal fibers for LS4
    4) Electronics for PicoCal
4. Summary and conclusion

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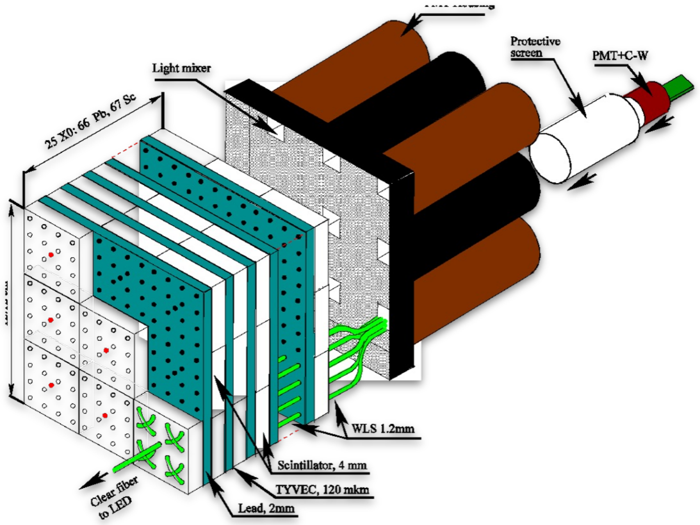
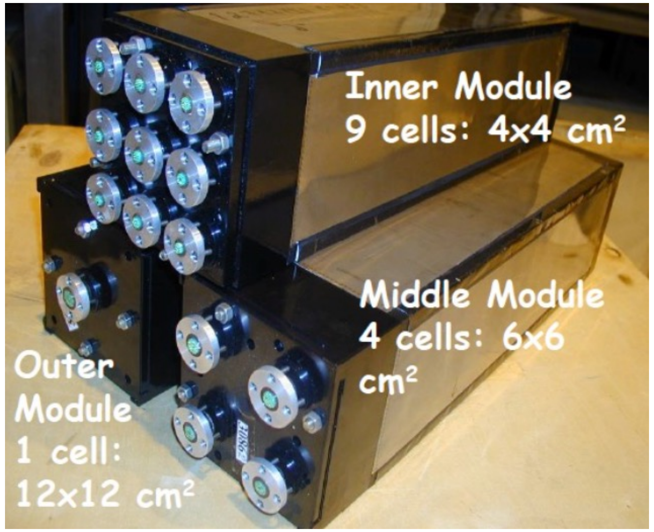
The Current LHCb ECAL

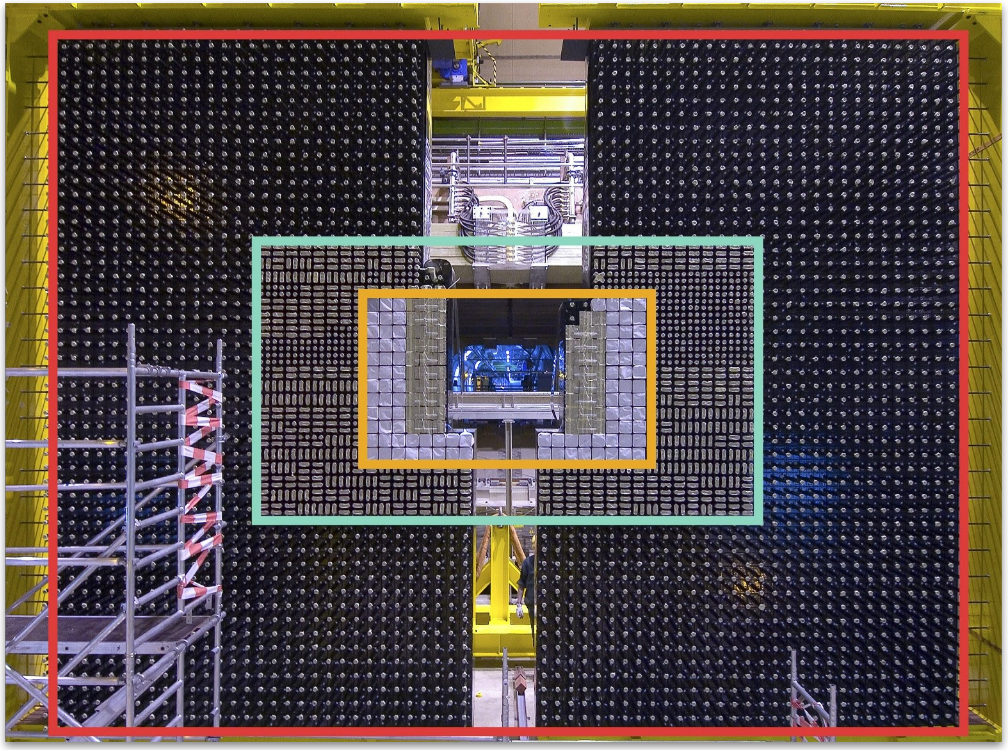
- **ECAL is essential to all measurements involving neutrals and electrons**
- **Optimized for π_0 and γ identification in the few GeV to 100 GeV region at $\mathbf{2 \times 10^{32}\ cm^{-2}s^{-1}}$**



- Shashlik technology used
- Scintillator: Polystyrene - p-terphenyl - POPOP
- WLS fibres: Kuraray Y-11



- Radiation hard up to $40\ \mathrm{kGy}$
- Energy resolution: $\sigma(E)/E \approx 10\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$



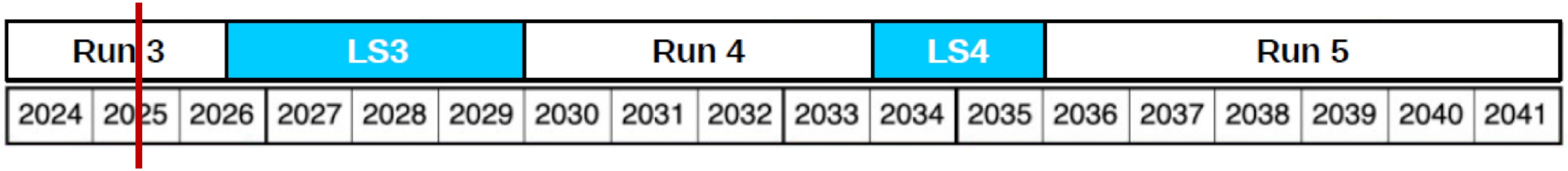
View from the back

- Large array of $\approx 50\ \mathrm{m}^2$ with 3312 modules and 6016 channels

LHCB-TDR-023, LHCB-TDR-024, LHCB-TDR-026

Motivation to upgrade

- **To fully use the opportunities provided by the HL-LHC for heavy flavor physics**



– Upgrade II to be installed at LS4: $1.5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$

Original design: $2\times10^{32}\ \text{cm}^{-2}\text{s}^{-1}$

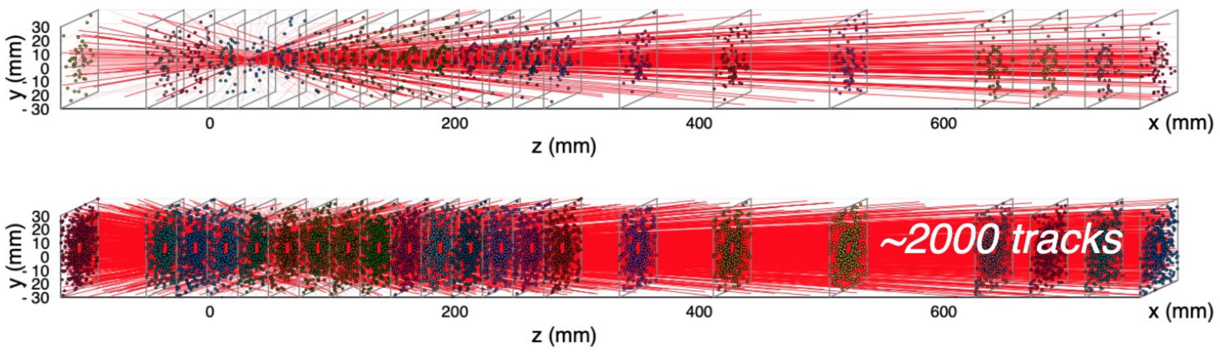
Run 3: $2\times10^{33}\ \text{cm}^{-2}\text{s}^{-1}$

High pile-up

Radiation hardness

…

VErtex LOcator (VELO)



Run 3: pile-up ~6

↓

Upgrade II: pile-up ~40

New ECAL technology R&D needed

LHCB-TDR-023, LHCB-TDR-024, LHCB-TDR-026

Motivation to upgrade

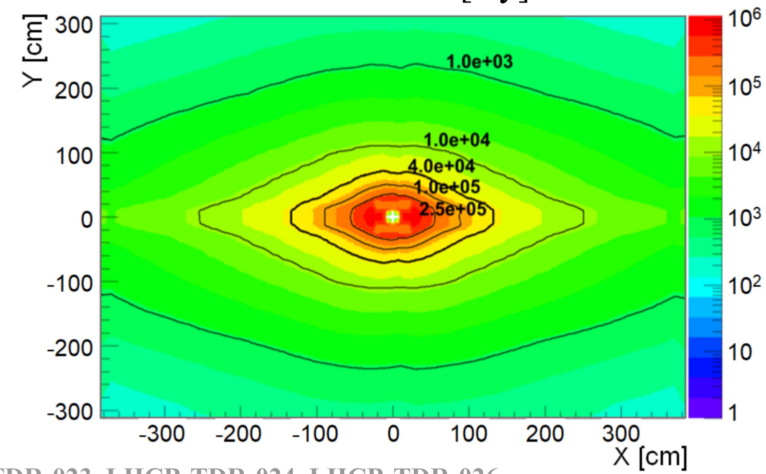
Requirements for the Upgrade II:

- **Radiation doses up to 1 MGy and $\leq 6\times10^{15}$ 1 MeV neq/cm^2 in the centre for 300 fb^{-1}**
  - New technologies required for the center
- **Pile-up mitigation crucial**
  - Timing $\mathcal{O}(10\text{ ps})$ precision
  - Increased granularity
  - longitudinal segmentation

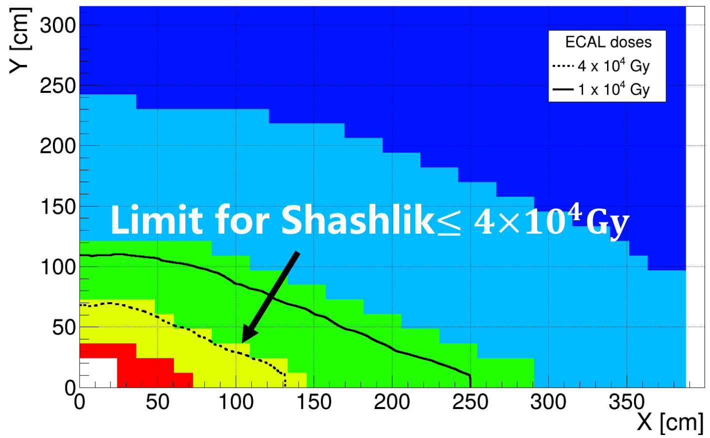
Scintillators R&D needed

- **Keep current energy resolution of $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$**

Accumulated radiation dose [Gy] after 300 fb^{-1}

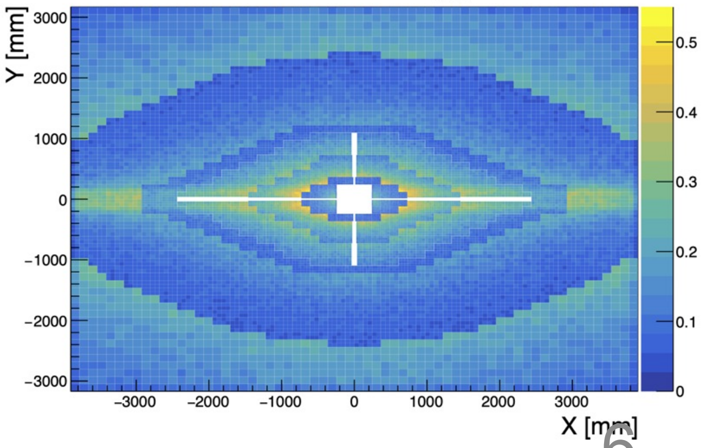


PicoCal 2024 - baseline



$L = 1.5\times10^{34}$ cm^{-2}s^{-1}

Occupancy, front section, $E_{T,cell}$ > 25 MeV



LHCB-TDR-023, LHCB-TDR-024, LHCB-TDR-026

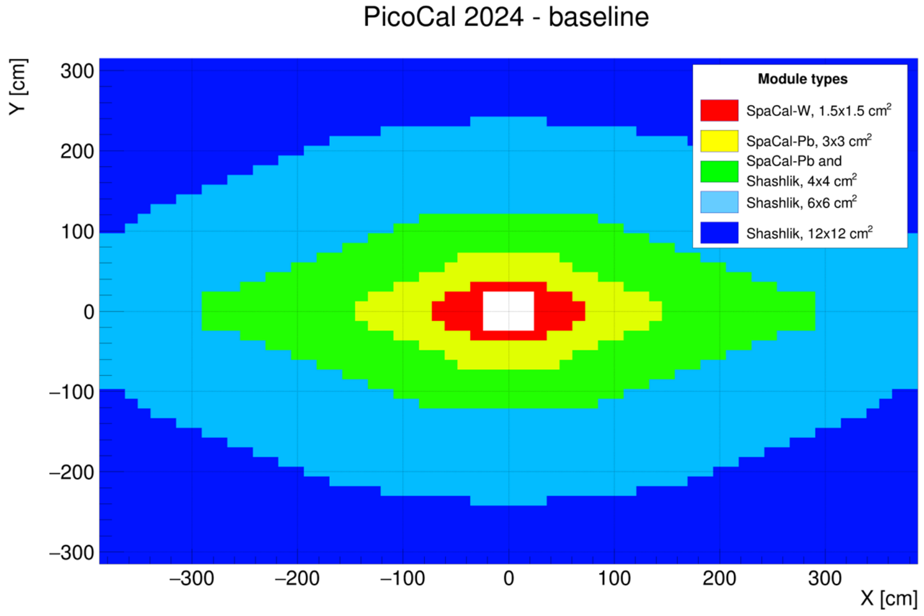
Technologies for ECAL Upgrade Ⅱ

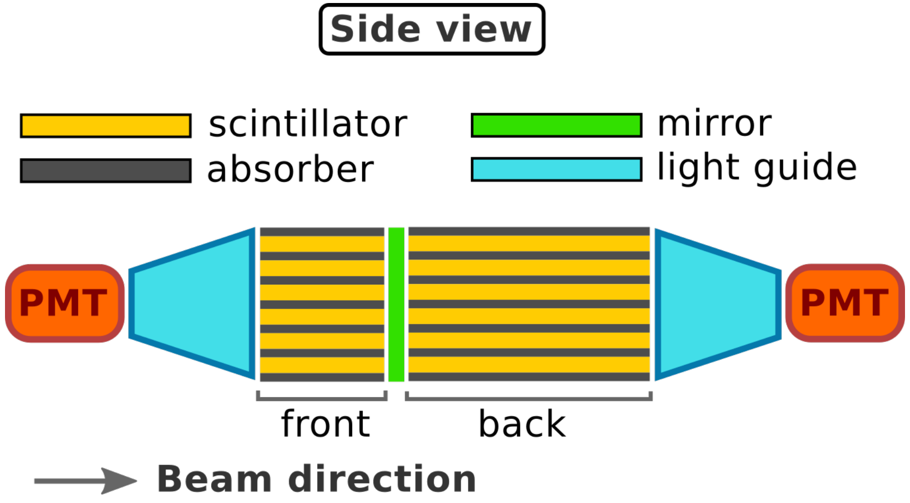
SPACAL technology for inner region.

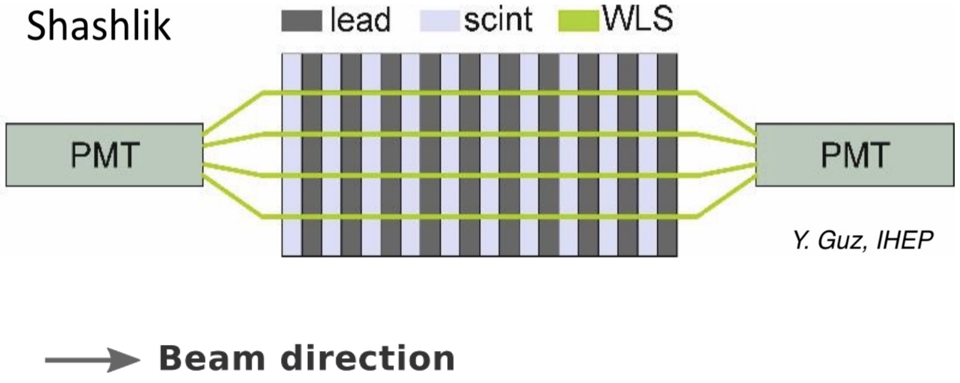
- **1.5×1.5 cm^2 cell - W absorber and crystal fibres**
  - Development of radiation-hard crystal fibres
  - Polystyrene fibres for Run 4, then replaced by crystals
- **3×3, 4×4 cm^2 cell - Pb absorber and plastic fibres:**
  - Need radiation-tolerant plastic fibres

Shashlik technology for outer region

- **4×4, 6×6, 12×12 cm^2 cell**
  - Timing improved with faster WLS fibres and double-sided readout



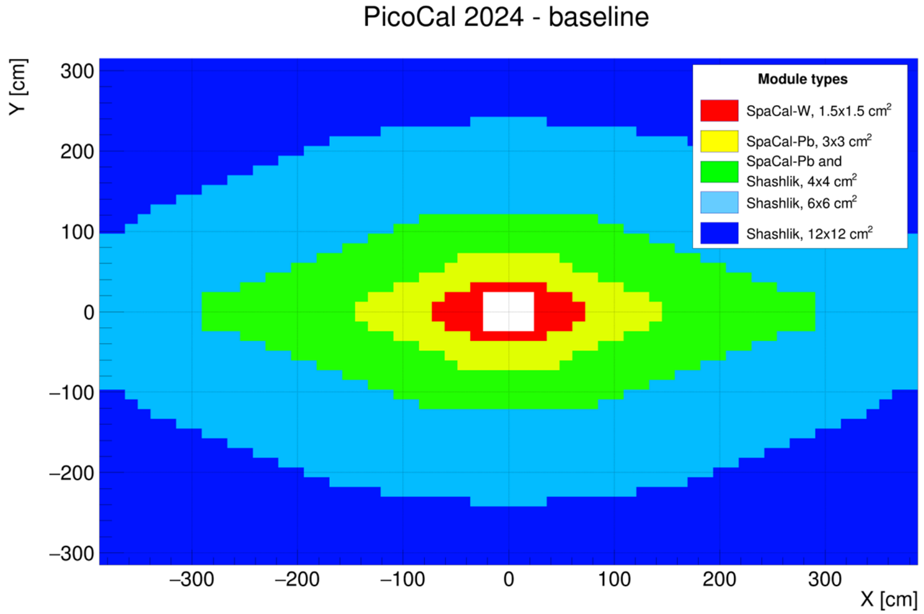




LHCB-TDR-023, LHCB-TDR-024, LHCB-TDR-026

ECAL configuration to be installed during LS3

- **176 new SpaCal modules in the inner region**
  → This region covers about 35% of photons and neutral pions from B-hadron decays over the ECAL acceptance
- **The existing modules will be rearranged in rhombic areas (32 Shashlik modules with 4×4 cm^2 cell size will be replaced)**



Cell size:	Modules:	Number of cells:
2×2 cm^2	16 new SpaCal-W modules with plastic fibres	576
2×2 cm^2	16 new SpaCal-W modules with plastic fibres - special shape	480
3×3 cm^2	104 new SpaCal-Pb modules with plastic fibres	1664
3×3 cm^2	40 new SpaCal-Pb modules with plastic fibres - special shape	480
4×4 cm^2	176 existing Shashlik modules	1584
6×6 cm^2	448 existing Shashlik modules	1792
12×12 cm^2	2’512 existing Shashlik modules	2512

LHCB-TDR-023, LHCB-TDR-024, LHCB-TDR-026

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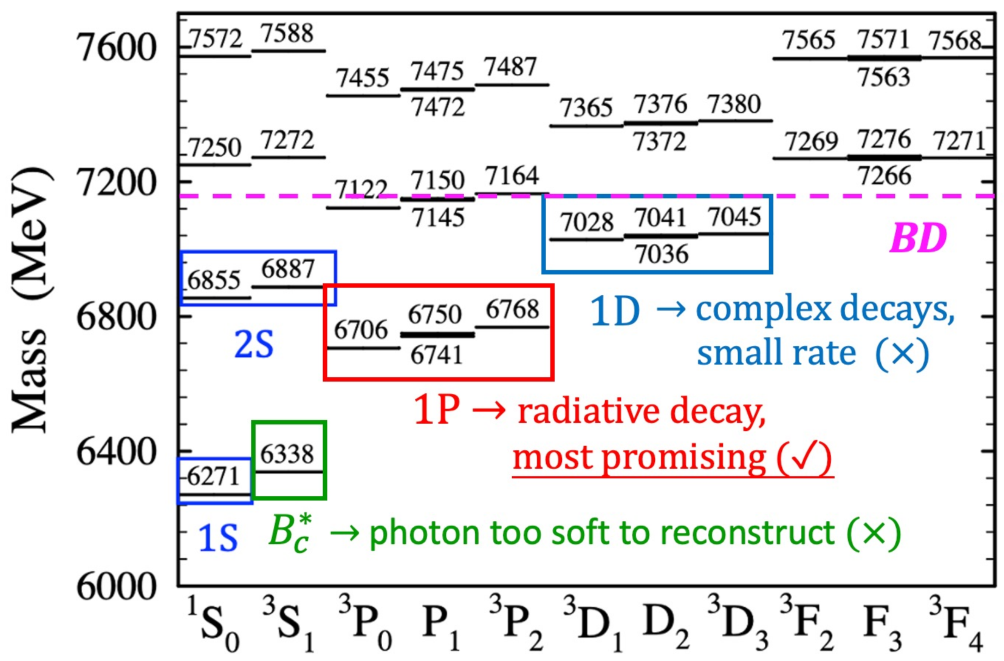
Observation of the orbitally excited B_c^+ states

- The B_c^+ meson family is the only mesons composed of two different heavy quarks ($\bar{b}c$) [arXiv:2507.02149]
- Despite its ground state, **only the 2S excitations** have been observed at the LHC [arXiv:2507.02142]
- The 1P excited states are predicted to decay solely via radiative transitions
  - ✓ most likely to be the next excitations to be observed, with predicted masses in the range of $(340, 520)$ MeV
  - ✓ four states are expected, leading to six peaks due to unreconstructed photons from B_c^* decays

[PRD 70 (2004) 054017]



$$(L=1)\otimes(S=0,1)\begin{cases} S=0 \rightarrow 1^1P_1 \\ S=1 \rightarrow 1^3P_0,\ 1^3P_1,\ 1^3P_2 \end{cases}$$

mixing

Four physical states

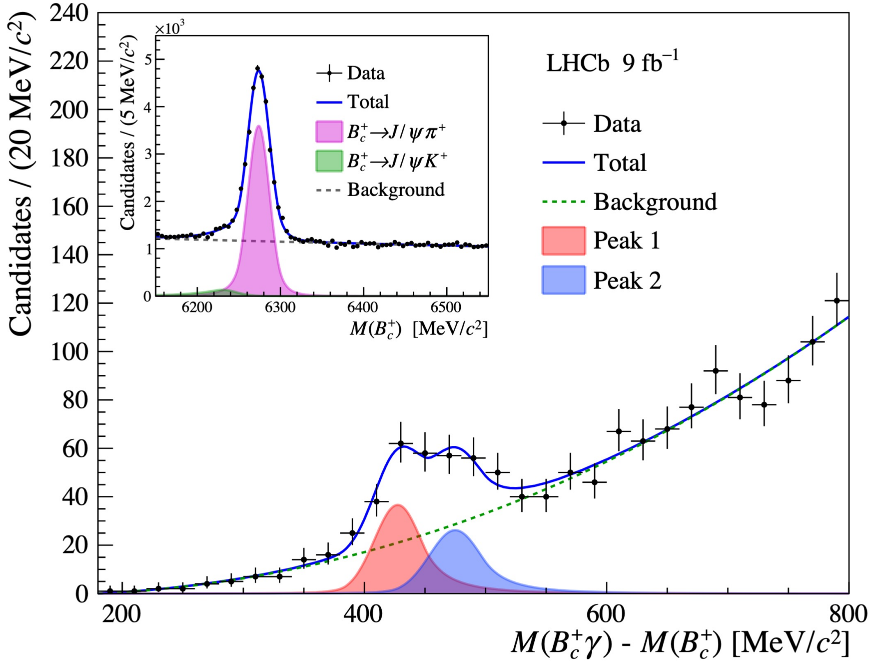
$$1^3P_0,\ 1^3P_2 \quad \begin{pmatrix}1P_1'\\1P_1\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}1^1P_1\\1^3P_1\end{pmatrix}$$

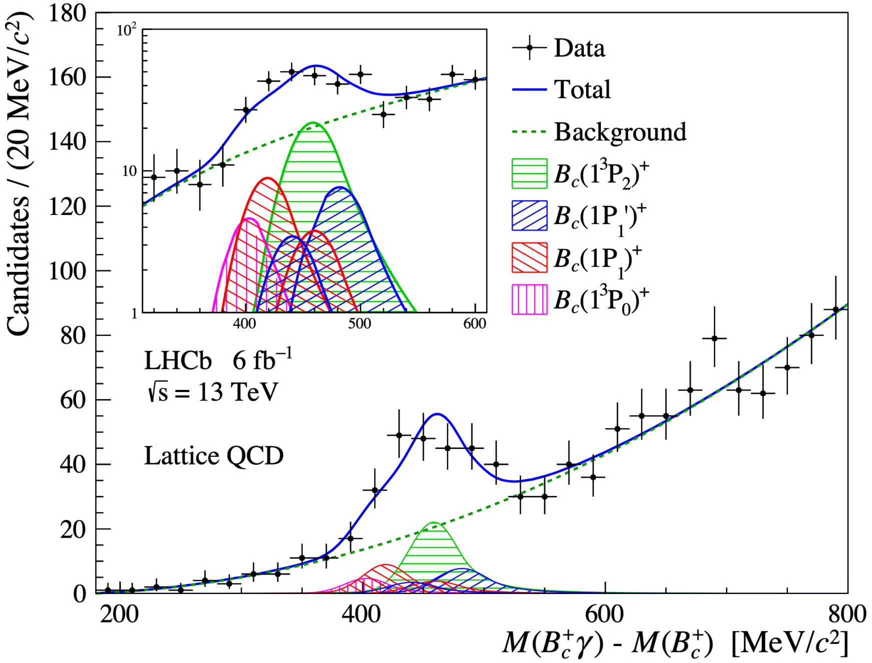
States	1^3P_0	$1P_1$	$1P_1'$	1^3P_2
Decays	$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$	$B_c^{*+}(\rightarrow B_c^+\gamma)\gamma$
#peaks	1	2	2	1

Observation of the orbitally excited B_c^+ states

- $B_c(1P)^+ \to B_c^+\gamma$, where $B_c^+ \to J/\psi\ (\to \mu^+\mu^-)\pi^+$ and photon reconstructed from calorimeter [arXiv:2507.02149]
- A pronounced wide peaking structure is seen within the predicted mass range (significance $> 7\ \sigma$) [arXiv:2507.02142]
- The visible width exceed the expectation of single-peak interpretation ⇒ a minimal effective two-peak model used
- By fixing the peak positions and relative yields to theory, different theoretical models were investigated ⇒ all generally good
- The relative production rate, representing the fraction of B_c^+ comes from $B_c(1P)^+$ is determined using the LQCD model

$$R = 0.20 \pm 0.03 \pm 0.02 \pm 0.03$$





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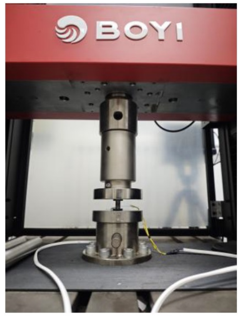
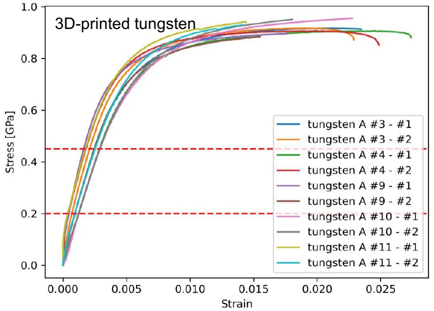
Ongoing R&D: Absorber and large-scale production

- **Requirements**
  - High density: close to $\rho_W = 19.3\ \mathrm{g/cm^3}$
  - Geometry: $120\times120\times50\ \mathrm{mm^3}$
  - 5180 square holes of $1.20\times1.20\ \mathrm{mm^2}$
  - Roughness $R_a < 5\ \mu\mathrm{m}$
- **LaserAdd (雷佳) gradually improved the W absorbers**
  - $\rho \approx 19.0\ \mathrm{g/cm^3}$, $R_a \approx 5\ \mu\mathrm{m}$
  - Young's module measured at THU, WHU, CERN
- **We are finalizing all tests and QA system for PRR in June**

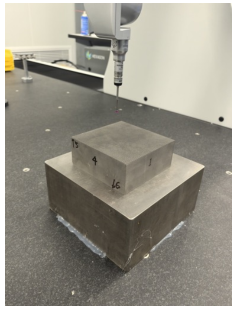
Above liquid level

Density measurement at WHU





Young's module measurement at THU



Plane	Angle (°)	
	5# at top	6# at top
1⊥2	89.9	90.1
2⊥3	90.0	90.0
3⊥4	90.0	90.1
4⊥1	90.1	89.9
5⊥1 or 6⊥1	90.1	90.0
5⊥2 or 6⊥2	90.0	90.0
5⊥3 or 6⊥3	90.1	90.0
5⊥4 or 6⊥4	90.1	90.0

Perpendicularity measurement at WHU

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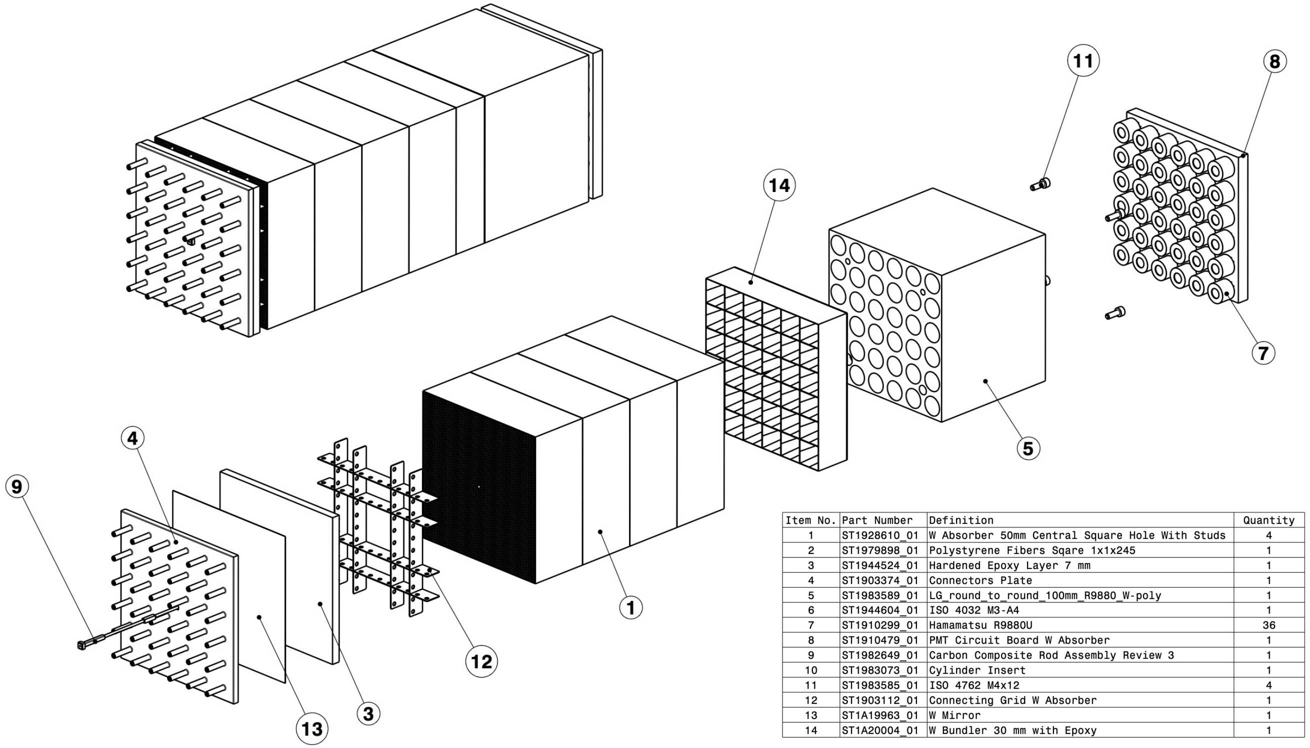
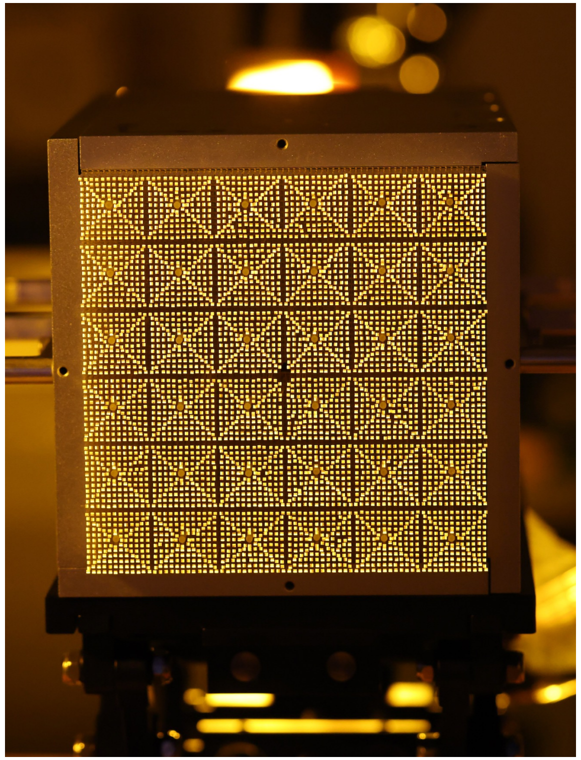
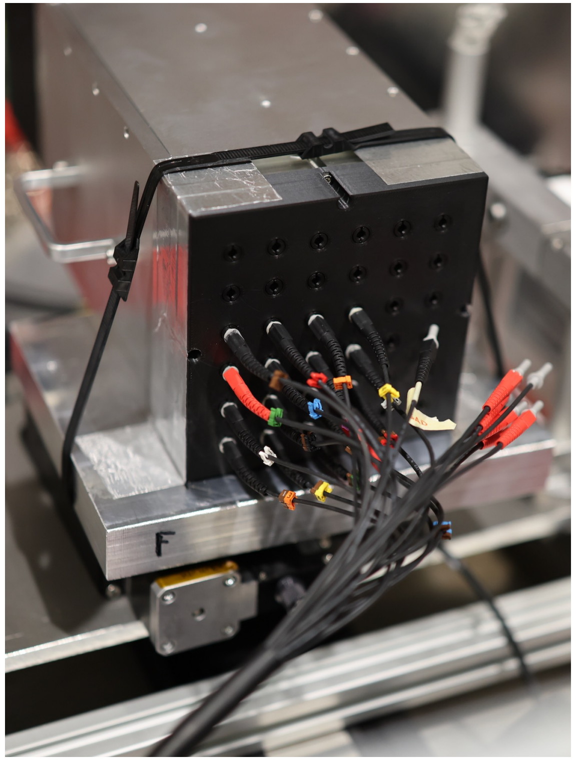
Ongoing R&D: Assembly for LS3



Item No.	Part Number	Definition	Quantity
1	ST1928610_01	W Absorber 50mm Central Square Hole With Studs	4
2	ST1979898_01	Polystyrene Fibers Sqare 1x1x245	1
3	ST1944524_01	Hardened Epoxy Layer 7 mm	1
4	ST1903374_01	Connectors Plate	1
5	ST1983589_01	LG_round_to_round_100mm_R9880_W-poly	1
6	ST1944604_01	ISO 4032 M3-A4	1
7	ST1910299_01	Hamamatsu R9880U	36
8	ST1910479_01	PMT Circuit Board W Absorber	1
9	ST1982649_01	Carbon Composite Rod Assembly Review 3	1
10	ST1983073_01	Cylinder Insert	1
11	ST1983585_01	ISO 4762 M4x12	4
12	ST1903112_01	Connecting Grid W Absorber	1
13	ST1A19963_01	W Mirror	1
14	ST1A20004_01	W Bundler 30 mm with Epoxy	1



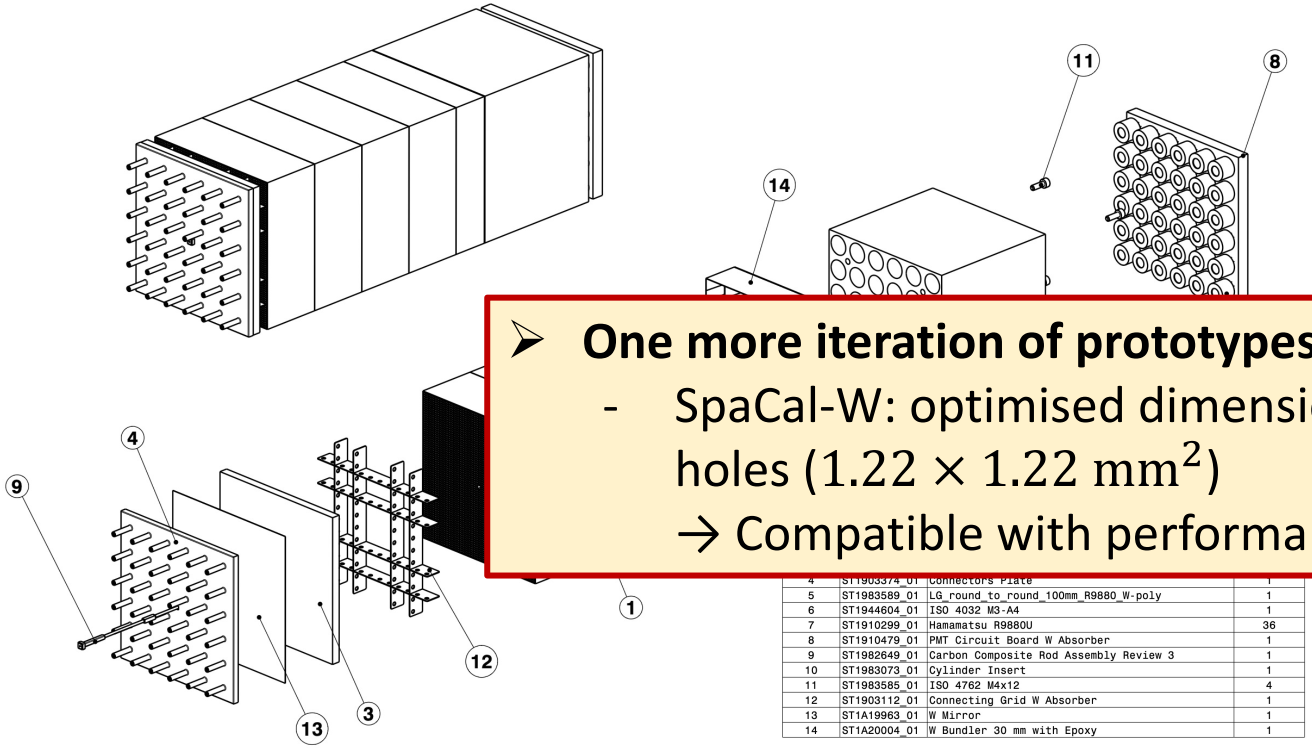


Test beam in May 2025 at CERN SPS:

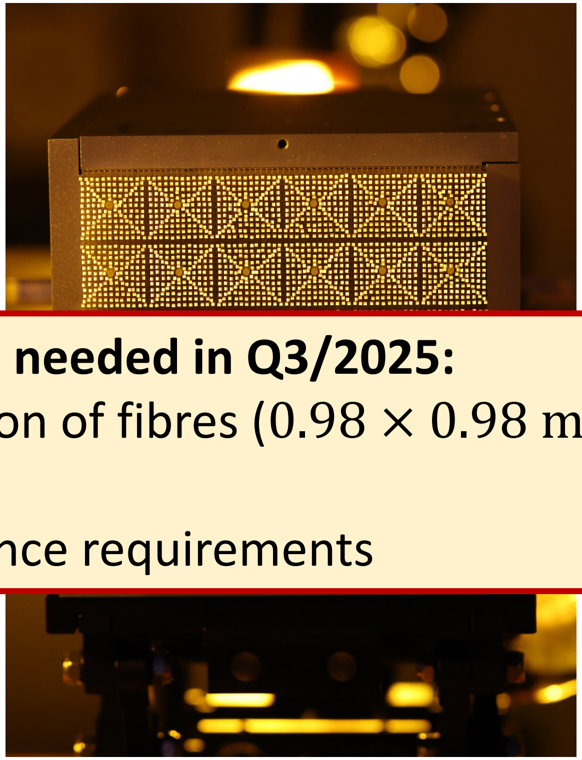
- **First test of full Run 4 chain with new prototypes:**
  - W absorbers
  - 3HF green plastic fibres (square fibres $1{\times}1\ \mathrm{mm}^2$)
  - Optics assembly with bundlers and long "hollow" light guides
  - R9880U PMTs

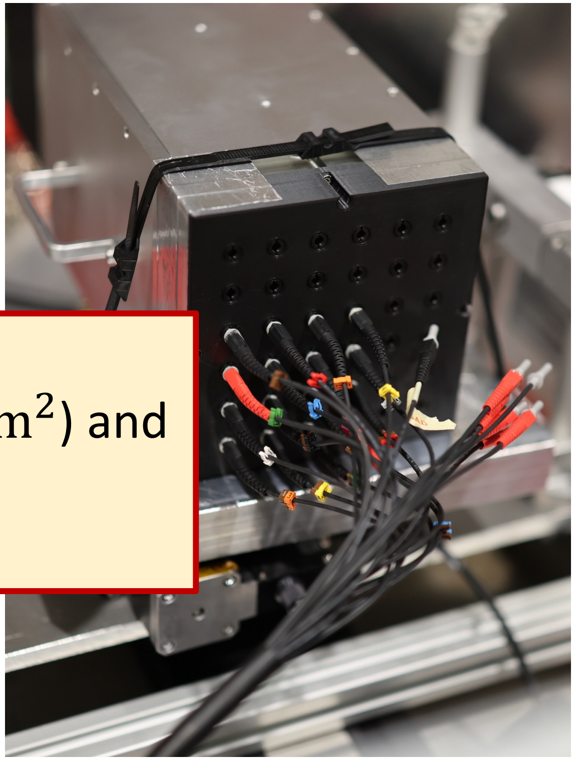
  - Cable clipping circuits
  - 10-meter signal cables
  - Read-out with Run 3 & 4 front-end boards electronics

Ongoing R&D: Assembly for LS3



4	ST1903374_01	Connectors Plate	1
5	ST1983589_01	LG_round_to_round_100mm_R9880_W-poly	1
6	ST1944604_01	ISO 4032 M3-A4	1
7	ST1910299_01	Hamamatsu R9880U	36
8	ST1910479_01	PMT Circuit Board W Absorber	1
9	ST1982649_01	Carbon Composite Rod Assembly Review 3	1
10	ST1983073_01	Cylinder Insert	1
11	ST1983585_01	ISO 4762 M4x12	4
12	ST1903112_01	Connecting Grid W Absorber	1
13	ST1A19963_01	W Mirror	1
14	ST1A20004_01	W Bundler 30 mm with Epoxy	1





- **One more iteration of prototypes needed in Q3/2025:**
  - SpaCal-W: optimised dimension of fibres ($0.98 \times 0.98\ \mathrm{mm}^2$) and holes ($1.22 \times 1.22\ \mathrm{mm}^2$)
    → Compatible with performance requirements

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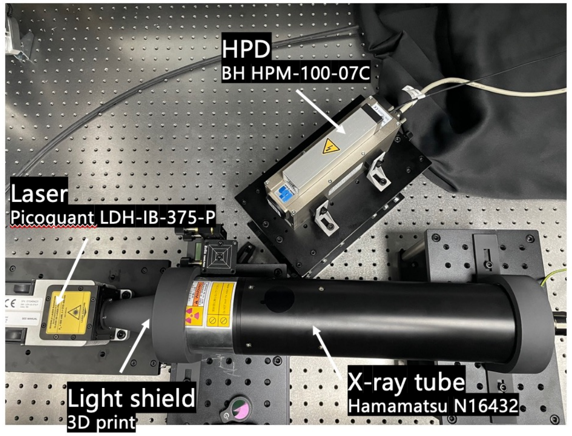
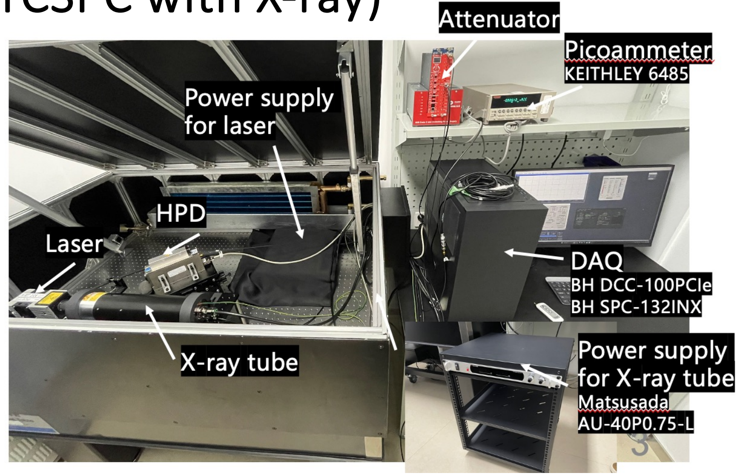
Milestone: GAGG test systems at PKU

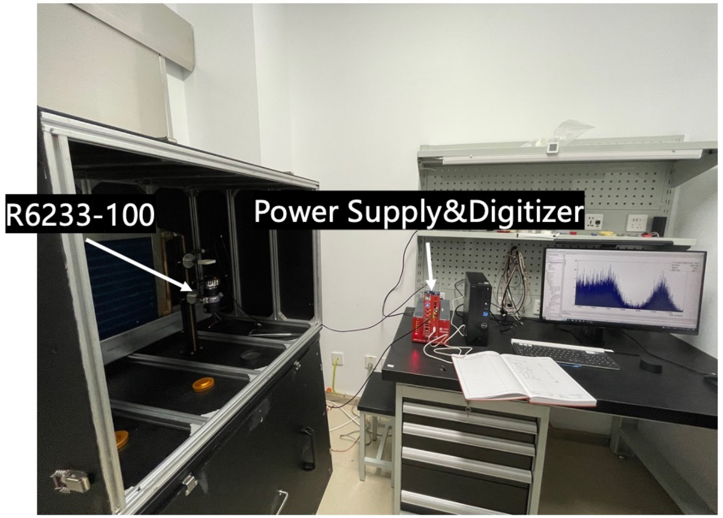
- **Test systems finished in Mar. 2024**
- **The test results from PKU are consistent with those from CERN, providing a basis for effective cooperation on GAGG testing.**

Decay time (TCSPC with X-ray)

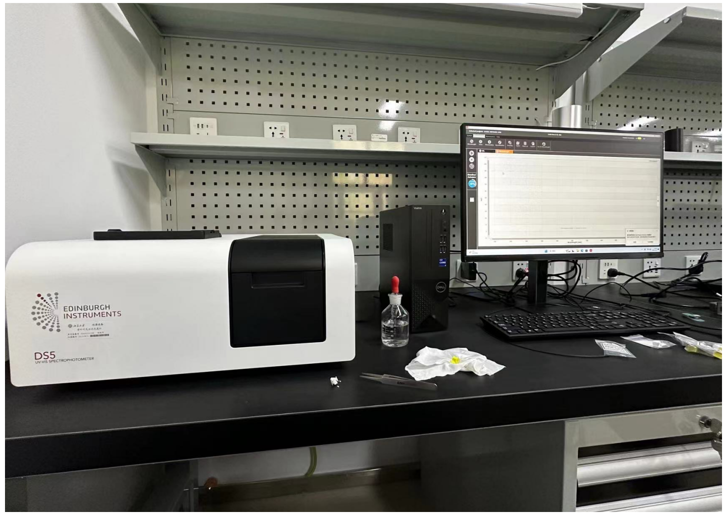




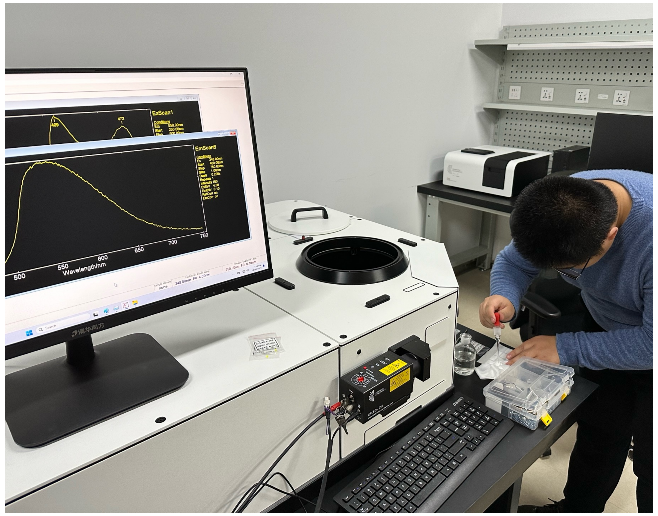
Light output



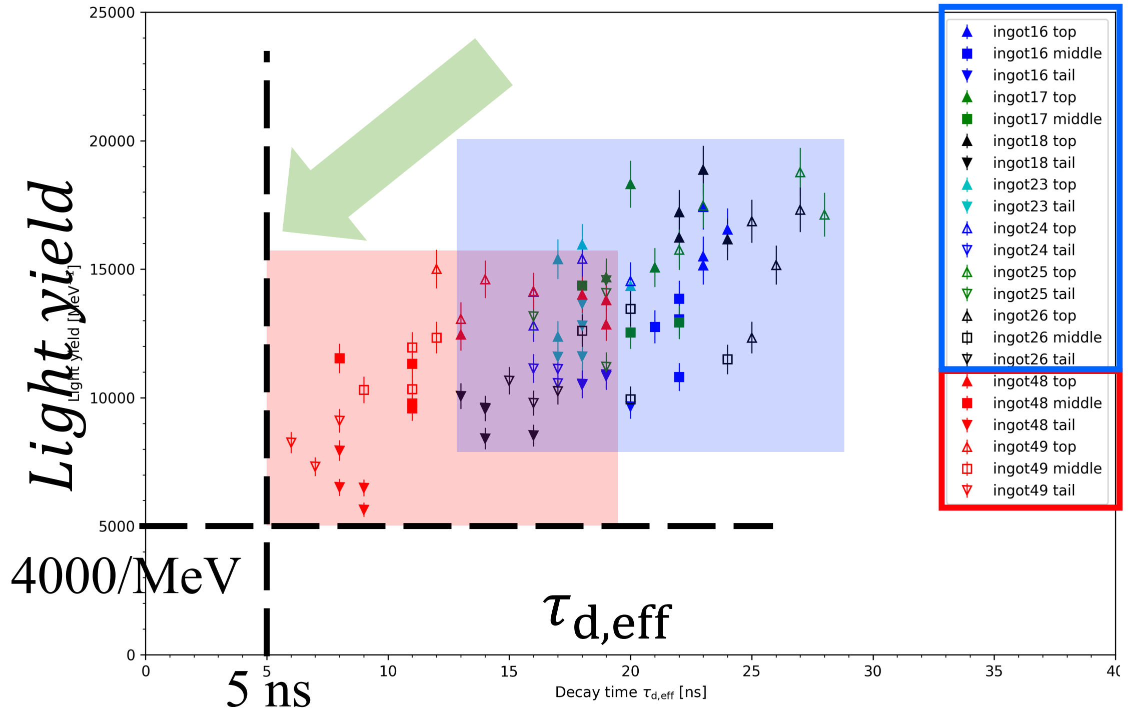
Absorbance

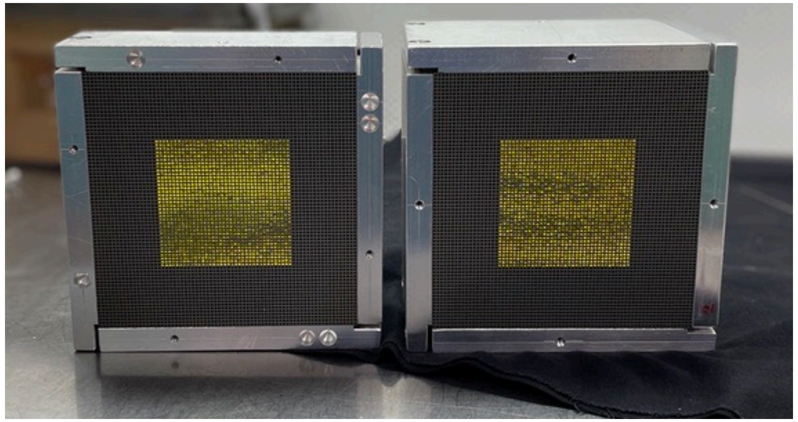


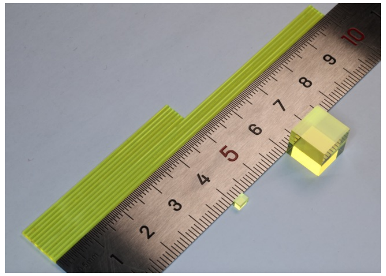
Photoluminescence spectrum



Ongoing R&D: Accelerating Scintillation



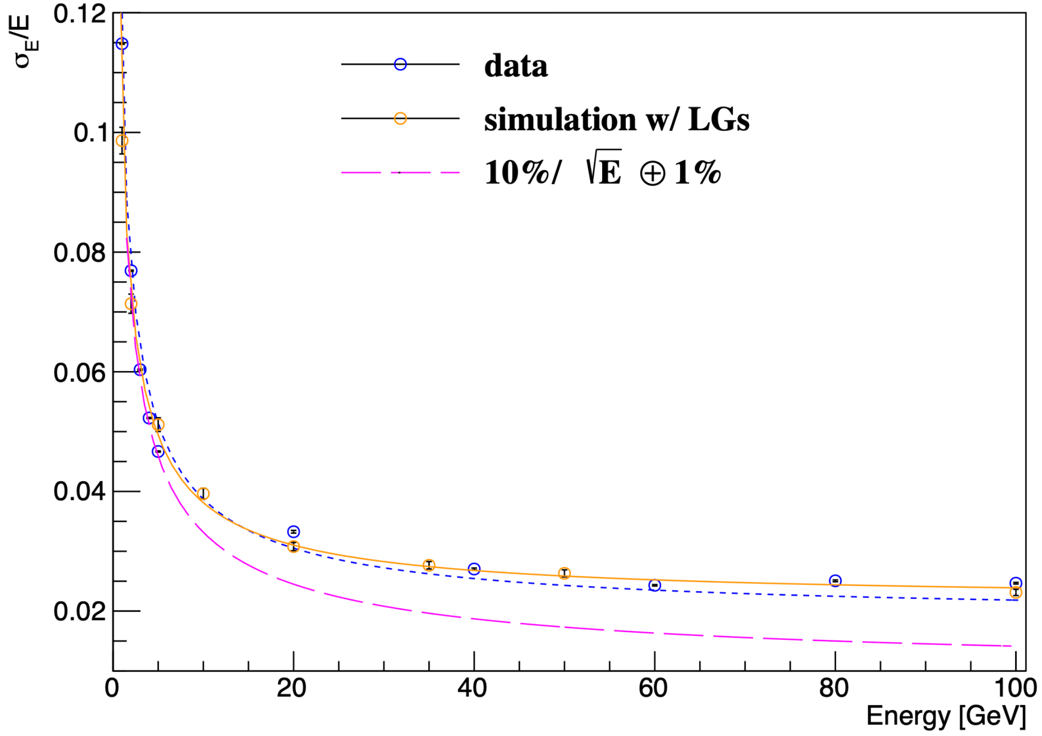




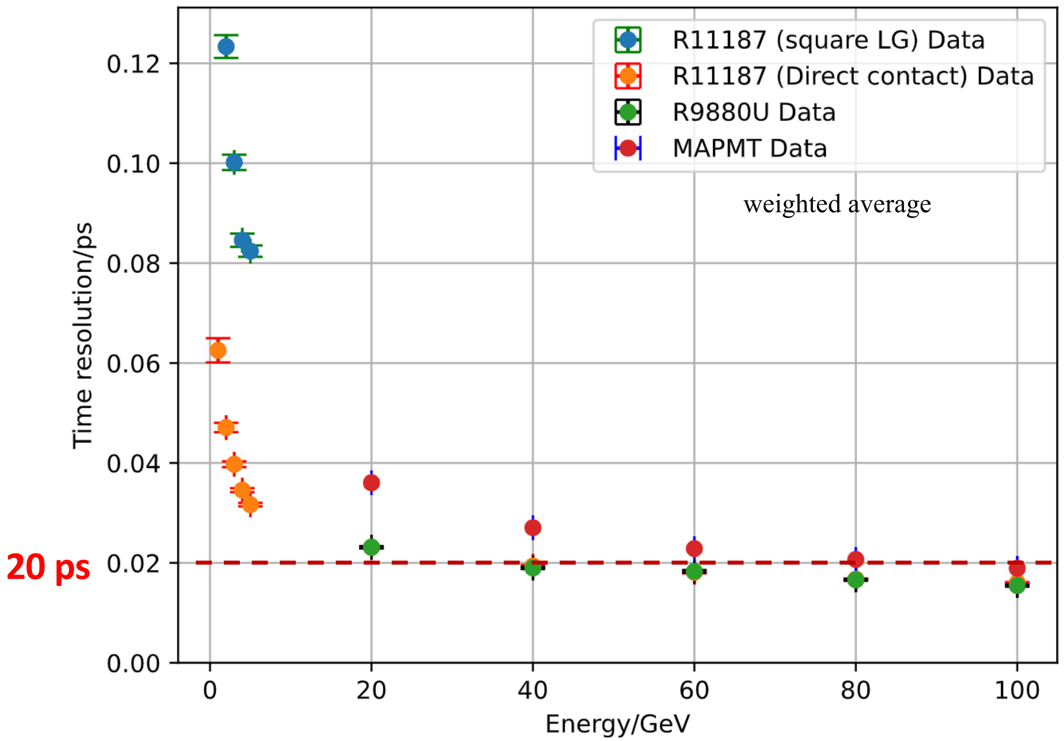
- **The issue: current commercial GAGG has scintillation decay time > 40 ns**
  - Mitigate spill-over effect on time resolution
- **Novel GAGG compositions developed to quench scintillation**
  - Light yield reduced
  - Decay time accelerated
  - Time resolution kept competitive
- **R&D to produce large-size and homogeneous Czochralski ingots**
- **Collaboration with:**
  - SIPAT(电科芯片), China
  - FZU and Crytur, Czech Republic
  - European project TWISMA including CERN, ILM & UCB, and ISMA
- **The Second prototype in June 2024**
  - SiPAT GAGG with decay time ~20 ns
  - 3D-printed absorber with LaserAdd (雷佳), China
  - Under characterization in testbeam

Testbeam: SpaCal - W Absorber - Crystal Fibres

Energy resolution



Time resolution



- **Energy resolution at 3°+3°:**
  - Sampling term: 10.6 ± 0.2 %
  - Constant term: ~2 %

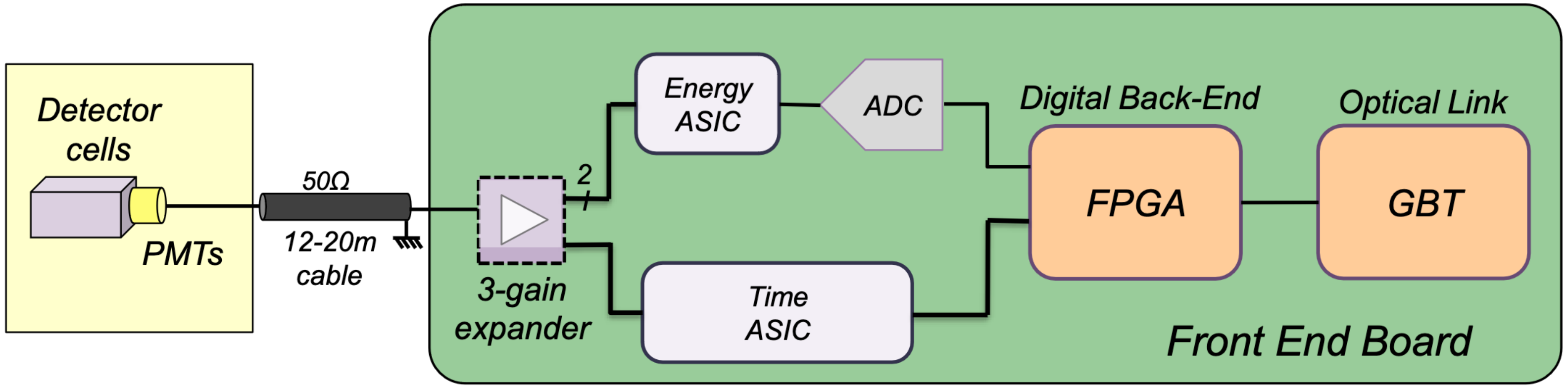
First measurements performed with non-optimal configuration degradation of energy and time resolution expected

- **Time resolution SIPAT GAGG at 3°+3°:**
  - R11187 (Direct contact) and R9880U have similar performance (<20 ps when > 20 GeV)
  - MAPMT and R11187 (square LG and only front part) much worse in time resolution

Outline

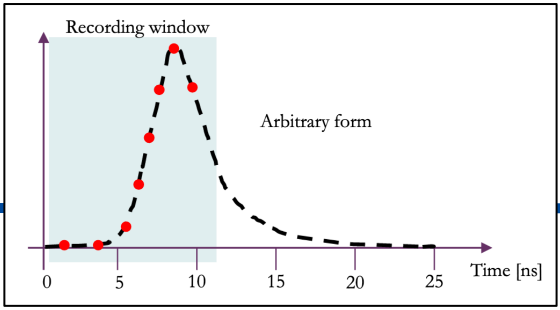
Electronics for PicoCal

- Architecture:



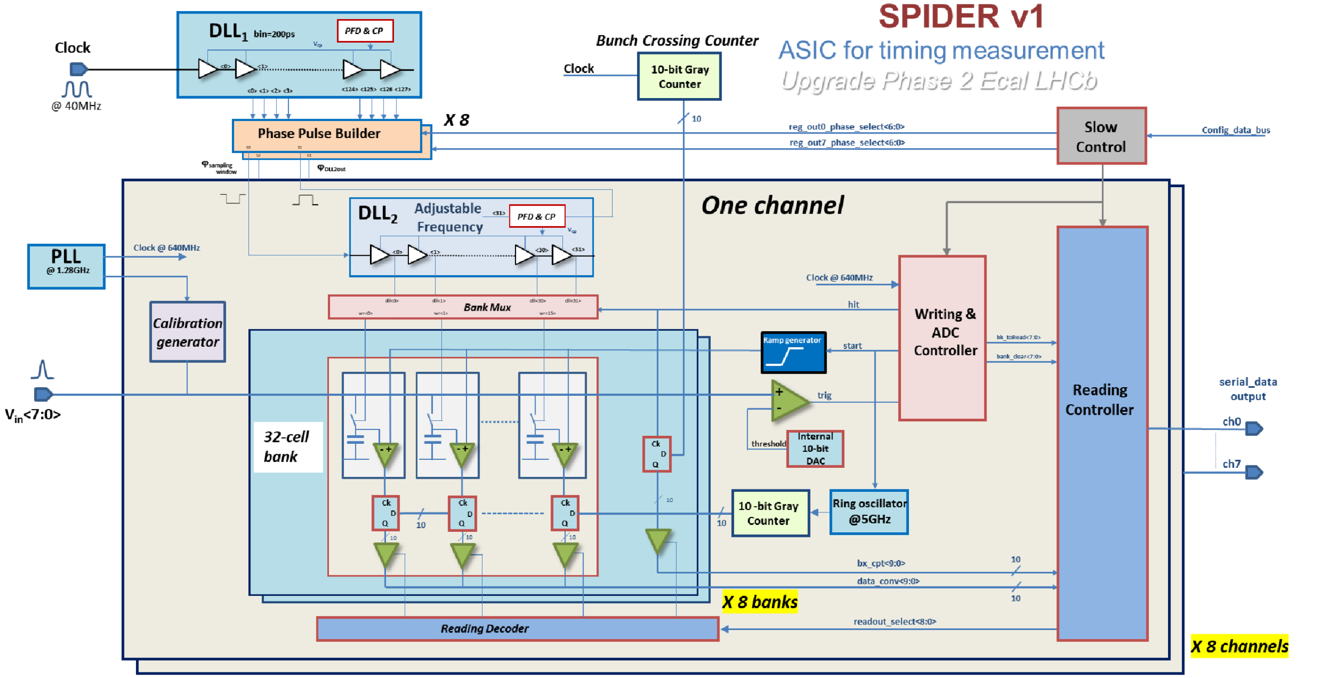
- Readout with PMTs
- Two separate paths with dedicated ASIC developed in parallel, with the same technology (TSMC 65 nm), running at 40 MHz:
  - Time ASIC (SPIDER): waveform TDC in analog memories (R&T IN2P3, Orsay/Clermont-Ferrand/Lyon/Caen/Nantes) (dynamic range of ET = 50 MeV to 5 GeV, resolution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

Measurement of Time: 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

SPIDER v1
ASIC for timing measurement
Upgrade Phase 2 Ecal LHCb



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

First prototype Automne 2024 (final version end 2029)

Outline

1. Introduction
2. B_c studies
3. Ongoing R&D for ECAL upgrade
   1) Absorber and large-scale production
   2) SpaCal-W with plastic fibers for LS3
   3) SpaCal-W with crystal fibers for LS4
   4) Electronics for PicoCal
4. Summary and conclusion

Summary and conclusion

- **Common activities in Chinese and French groups about LHCb ECAL Upgrade :**
  - Observation of the orbitally excited $\boldsymbol{B_c^+}$ states
  - R&D for modules assembly with plastic fibers for LS3
  - R&D for new modules with GAGG fibers for LS4
  - The first SPIDER ASIC prototype (v0) was produced and delivered in early July 2025
  - A test board for SPIDER(v0) was built, with testing set to start in late July 2025

- **In the near future:**
  - Test beams at DESY and SPS to measure module characteristics(One more iteration in Q3/2025)
  - The SPIDER ASIC v1 features 8 channels instead of 2 and will be produced by mid-2026

- **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

Thanks for your attention!

博士后招聘
Postdoc position

Peking University's LHCb group

北京大學 PEKING UNIVERSITY

Job description:

Core R&D tasks for a next-generation electromagnetic calorimeter in the upgraded LHCb detector (ECAL development, construction, installation, and commissioning):

- Development of ultrafast, highly radiation-resistant novel scintillation crystals
- Mass production of high density, high precision tungsten absorber
- Test beam for ECAL prototype

工作描述：

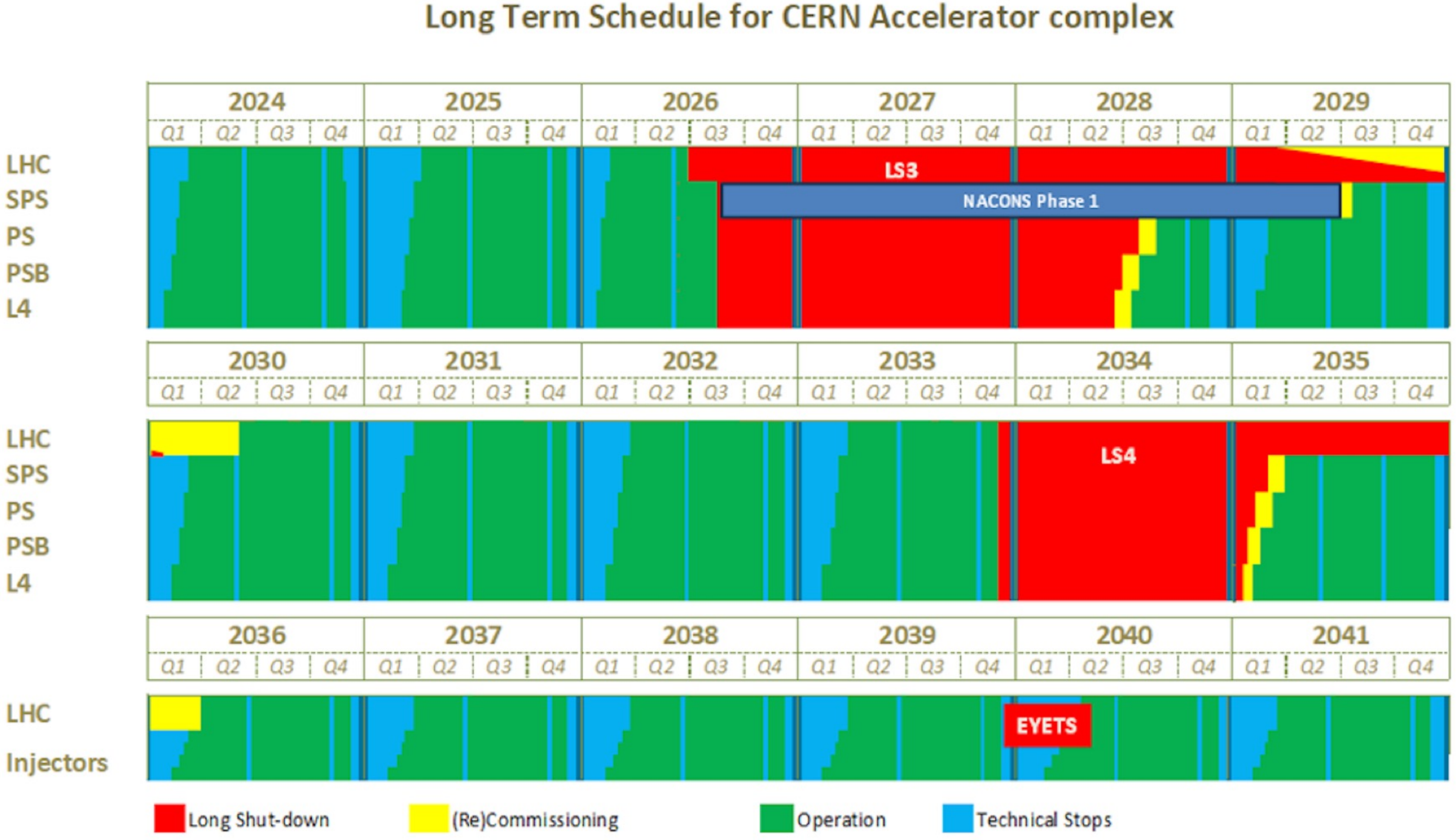
面向LHCb升级后的下一代新型电磁量能器的核心研发任务（包括ECAL的研制、建造、安装与调试）：

- 开发超快、高抗辐射性能的新型闪烁晶体
- 量产高密度、高精度钨吸收体
- ECAL原型机的束流测试任务

Contact： yangluping@pku.edu.cn
yangzw@pku.edu.cn

Back up

Updated CERN accelerator schedule



- Run 3 extended till end of June 2026
- LHC restart for Run 4 in 2030
- LHC LS4 moved by one year to 2034-35
- LS5 becomes EYTES
- Also impact on SPS test beams!