2026年超级陶粲装置研讨会
2026年6月30日至7月5日，西安

LHCb ECAL Upgrade II

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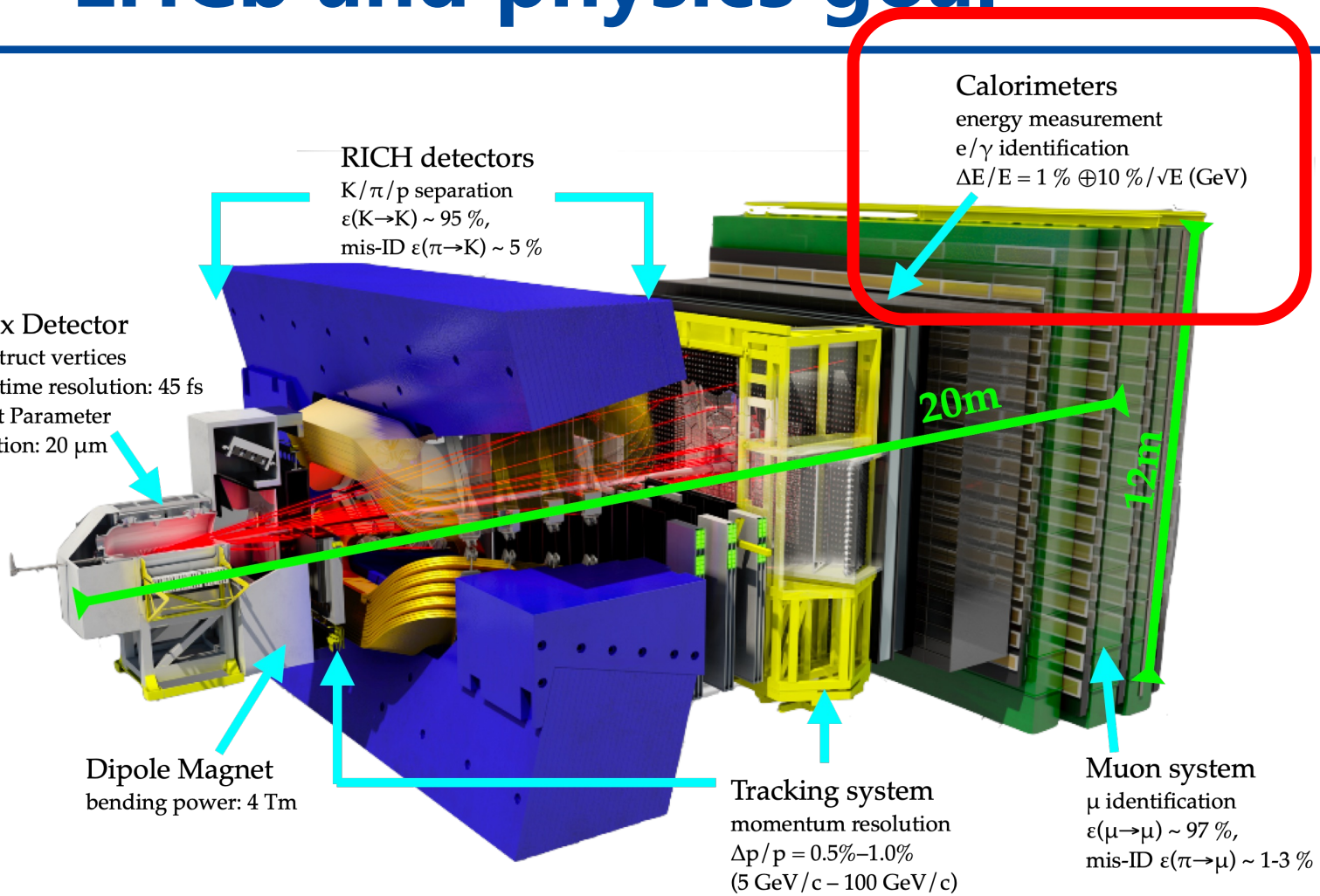
on behalf of the LHCb ECAL upgrade II working group

LHCb and physics goal



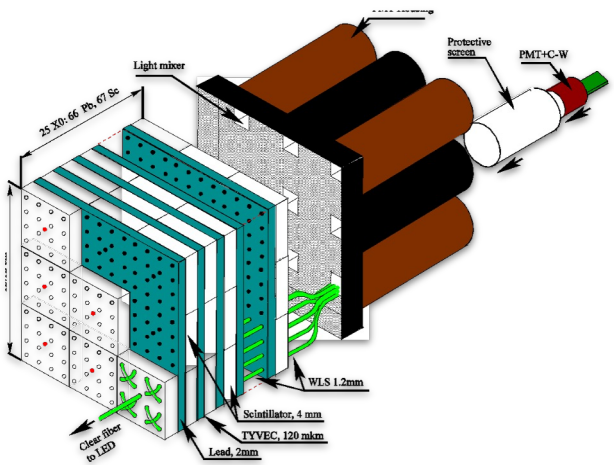
- **LHCb is the only dedicated detector (at LHC) fully instrumented in forward region with unique kinematic coverage**

  $2 < \eta < 5$

- **Designed for heavy flavor and CPV measurements, also good for hadron spectroscopy , rare decays, EW/Higgs/Top, and Heavy Ion physics.**

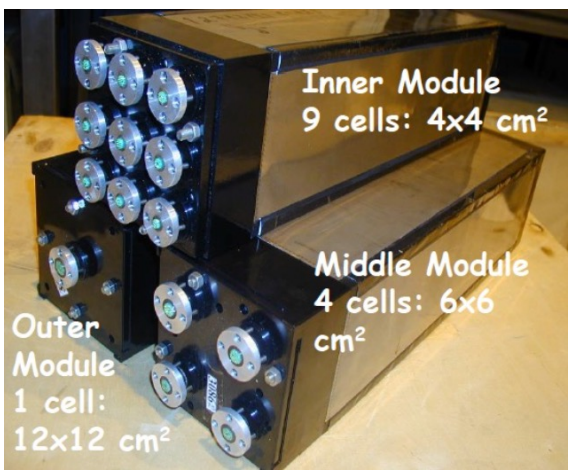
The Current LHCb ECAL

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

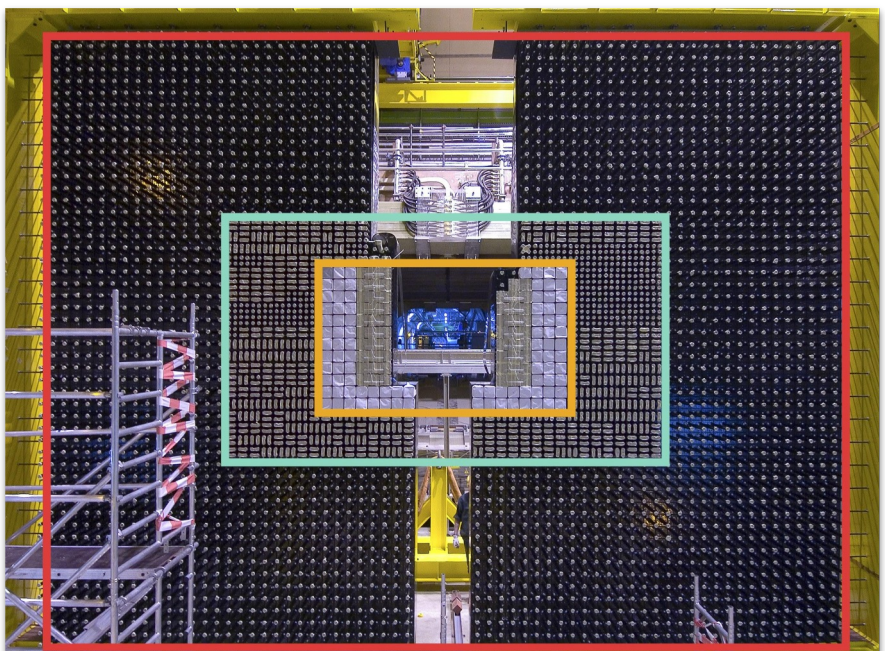


LHCB-TDR-023, LHCB-TDR-024, LHCB-TDR-026

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



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



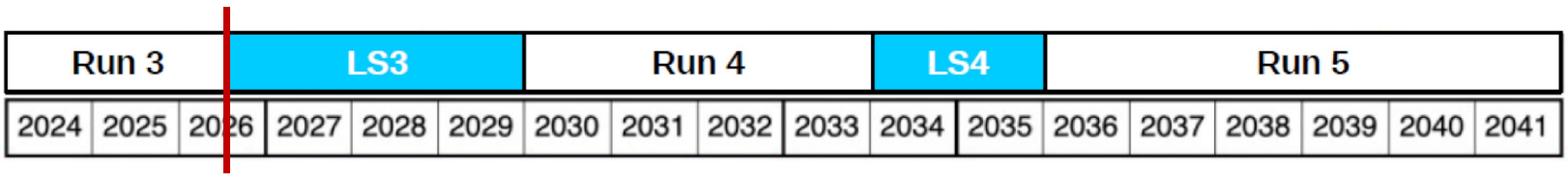
View from the back

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

Motivation to upgrade

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

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

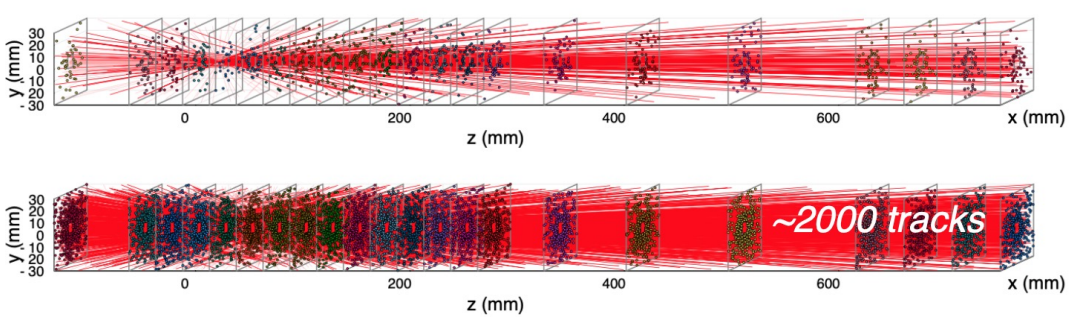


— Upgrade II to be installed at LS4: $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Original design: $2 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Run 3: $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

VErtex LOcator (VELO)



Run 3: pile-up ~6

Upgrade II: pile-up ~28

High pile-up
Radiation hardness
…

New ECAL technology R&D needed

Motivation to upgrade

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

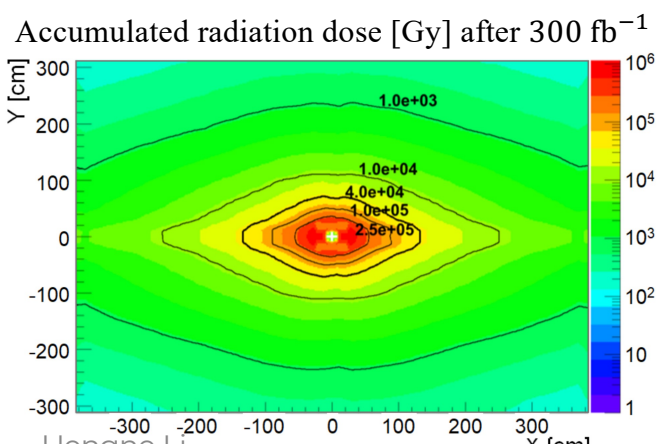
Requirements for the Upgrade II:

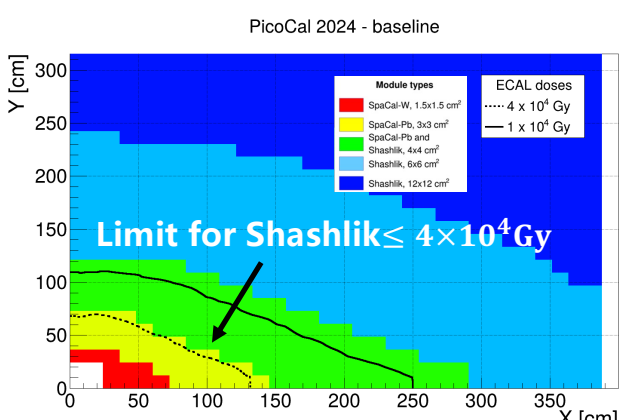
- **Radiation doses up to 1 MGy and $\leq 6\times10^{15}$ 1 MeV neq/cm^2 in the centre for 300 fb^{-1}**
  - New technologies required for the center

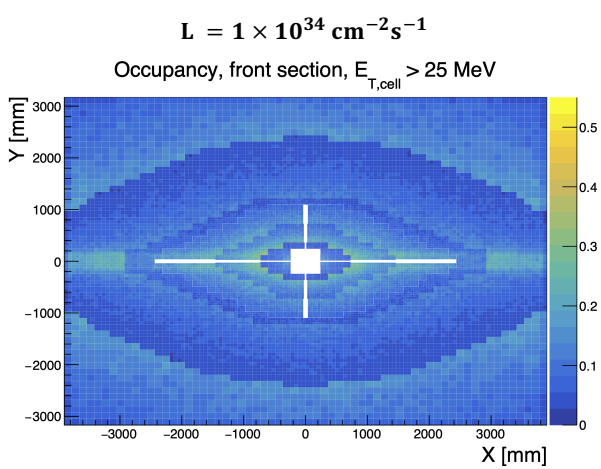
- **Pile-up mitigation crucial**
  - Timing $\mathcal{O}(10\ \mathrm{ps})$ precision
  - Increased granularity
  - longitudinal segmentation

Scintillators R&D needed

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







The Upgrade Strategy

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

Run 3			LS3			Run 4				LS4	Run 5						
2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041

Run 3 in 2022-Q2/2026:

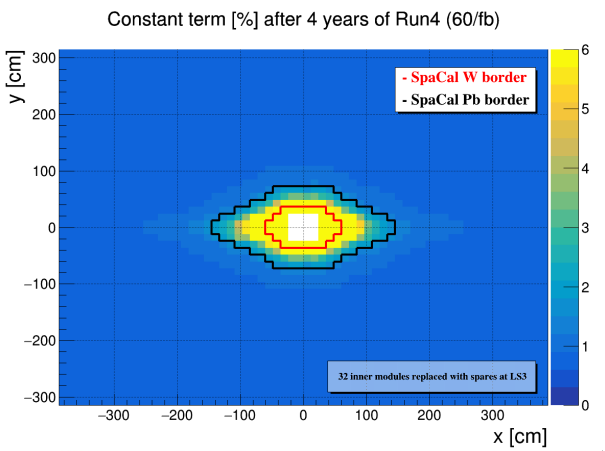
- **Run with unmodified ECAL Shashlik modules at $\mathbf{L = 2\times10^{33}\,cm^{-2}s^{-1}}$ (new 40 MHz readout)**

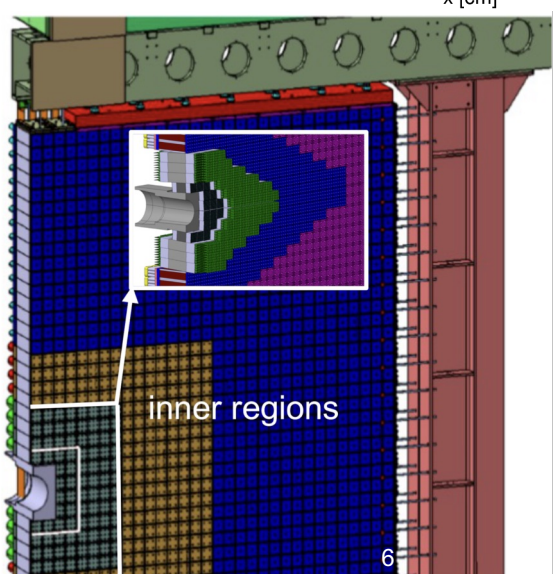
LS3 consolidation in Q3/2026-2029:

- **Introduce single-section rad. tolerant SPACAL (2×2 and 3×3 cm^2 cells) in inner regions and rebuild ECAL in rhombic shape to improve performance at $\mathbf{L = 2\times10^{33}\,cm^{-2}s^{-1}}$**
  - 32 SPACAL-W & 144 SPACAL - Pb modules with plastic fibres compliant with Upgrade II conditions

LS4 Upgrade II in 2034-2035 (PicoCal):

- **Introduce double-section rad. hard SPACAL (1.5×1.5, 3×3 & 4×4 cm^2 cells) and improve timing of Shashlik modules for a luminosity of up to $\mathbf{L = 1\times10^{34}\,cm^{-2}s^{-1}}$**
  - Innermost SPACAL-W modules equipped with crystal fibres
  - Include timing information and double-sided readout for pile-up mitigation

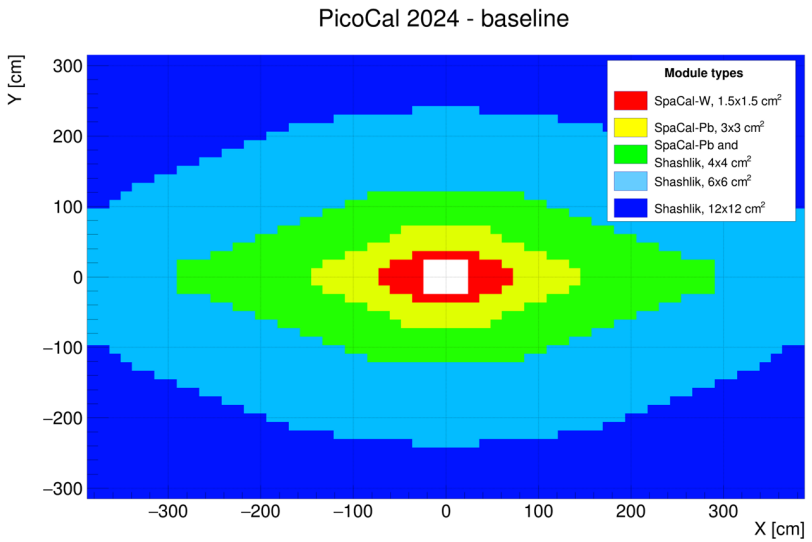


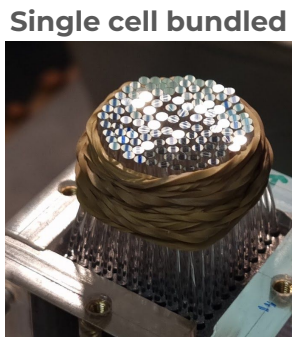


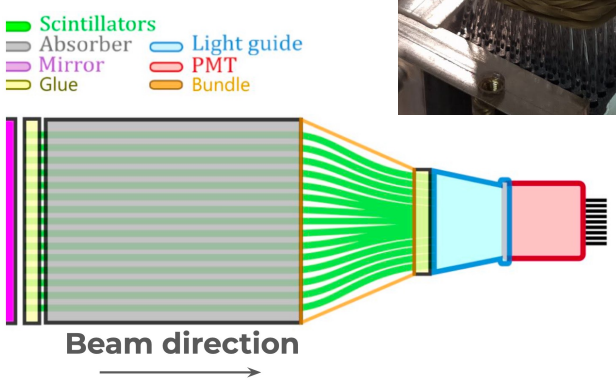
ECAL configuration to be installed during LS3

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

- **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

Technologies for ECAL Upgrade II

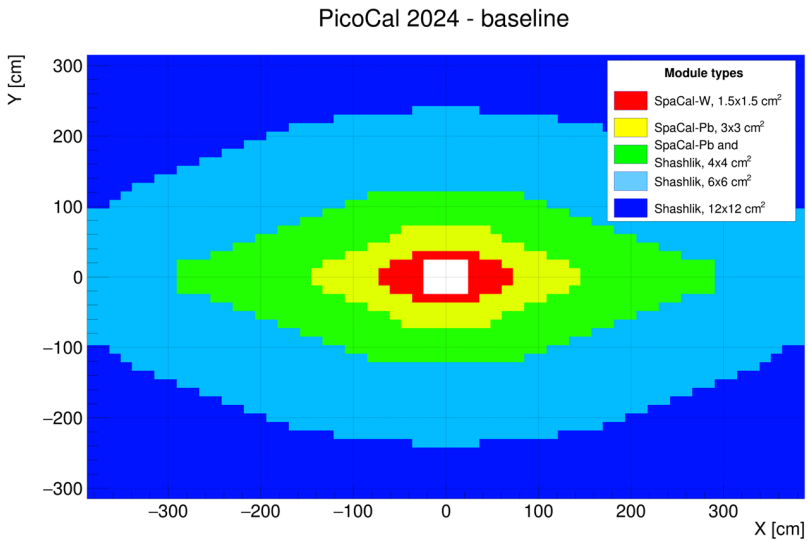
LHCB-TDR-023, LHCB-TDR-024, LHCB-TDR-026

SPACAL technology for inner region.

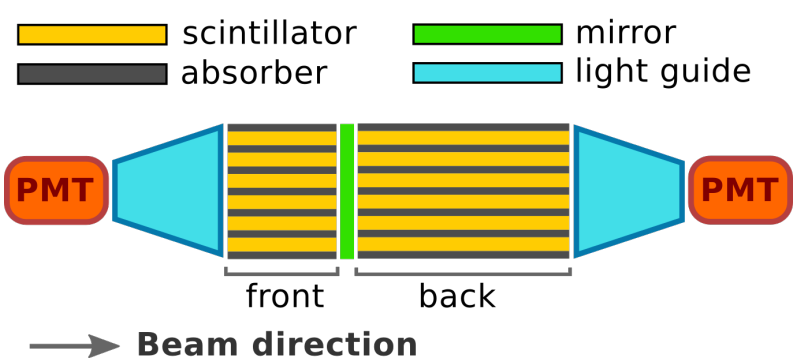
- **1.5×1.5 cm^2 cell - W absorber and crystal fibres**
  - Development of radiation-hard crystal fibres
  - Polystyrene fibres for Run 4, then replaced by crystals
- **3×3, 4×4 cm^2 cell - Pb absorber and plastic fibres:**
  - Need radiation-tolerant plastic fibres

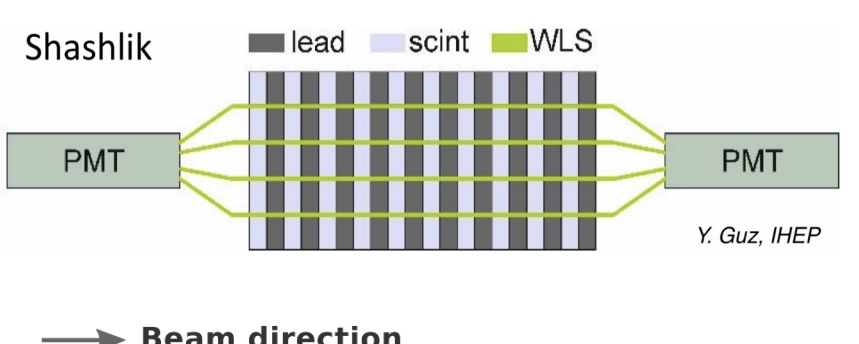
Shashlik technology for outer region

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



Side view





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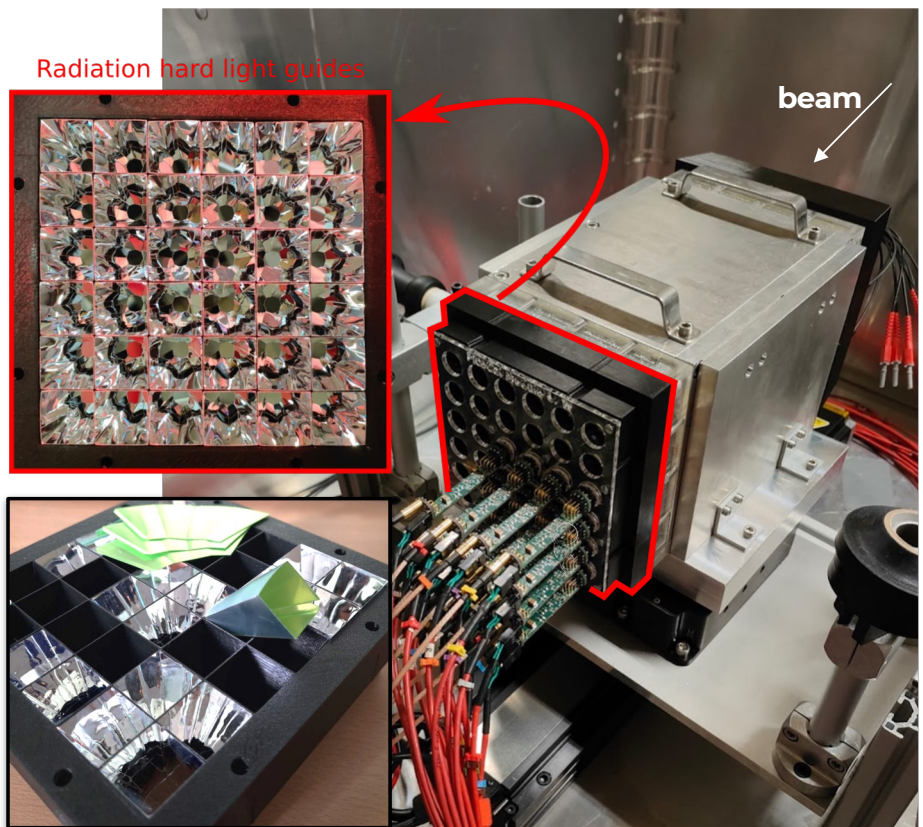
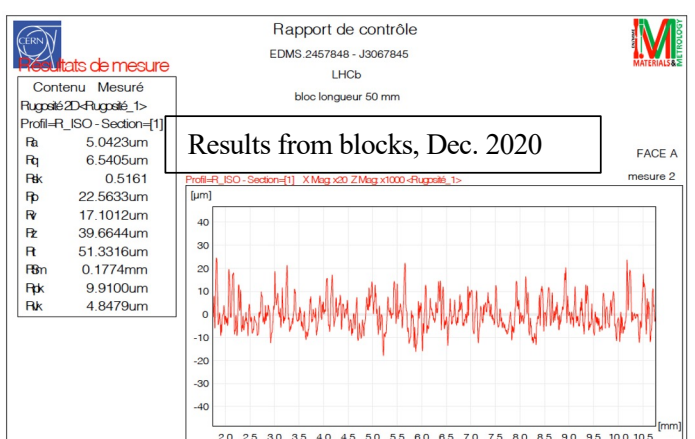
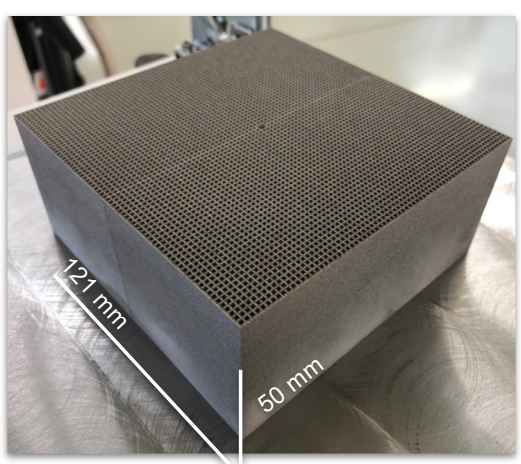
SpaCal - W Absorber - Polystyrene Fibres



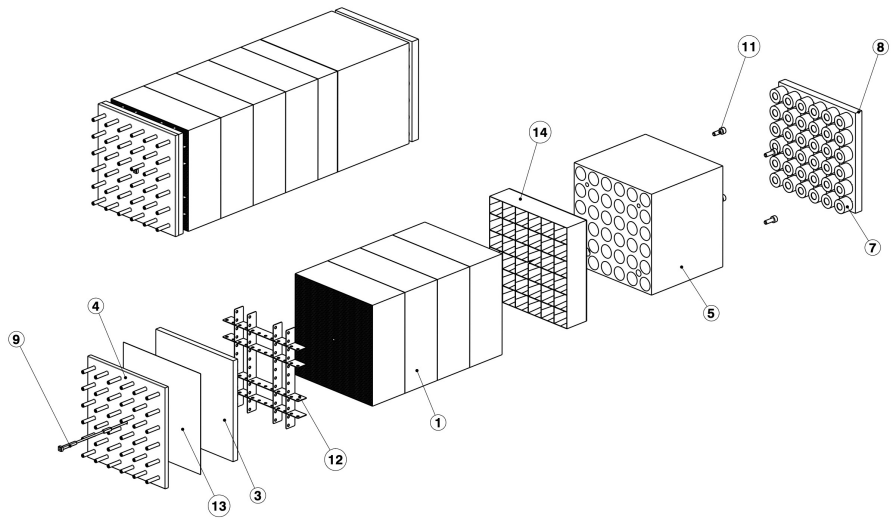
- **Full size $121\times121\ \mathrm{mm}^2$ *Module 0* assembled at CERN in 2023:**
- **Passive materials:**
  - 3D-printed W absorber
    - 3×50 mm + 1×40 mm long blocks
    - R&D performed with EOS, Germany
  - Very good mean roughness $R_a = 5\ \mu\mathrm{m}$ achieved
    - Smooth surface mandatory not to damage fibres
  - Radiation-hard “hollow light guides” made of 3M ESR
- **Active materials:**
  - Single-cladded Kuraray SCSF-78 square fibres $1\times1\ \mathrm{mm}^2$

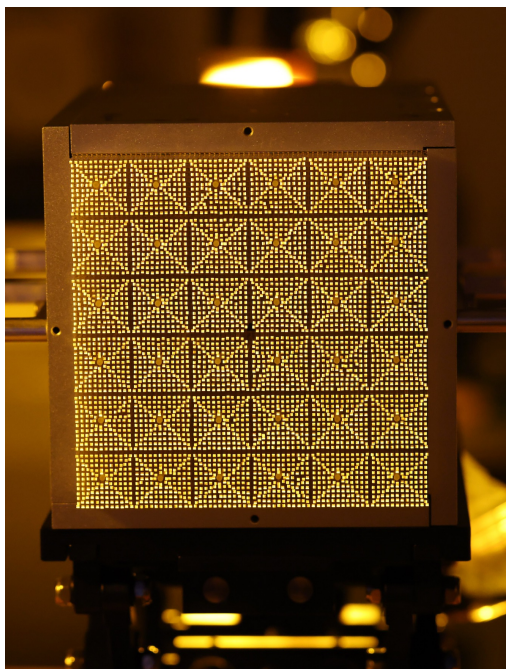
LS3 Enhancement

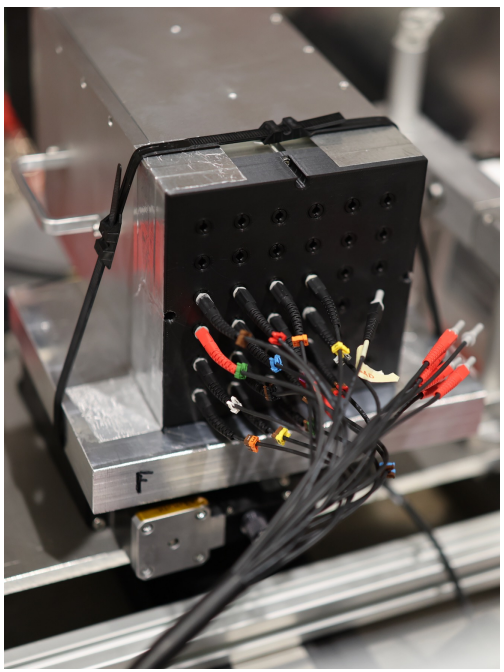




Ongoing R&D: W-absorber assembly for LS3







Test beam in May and Sept. 2025 at CERN SPS:

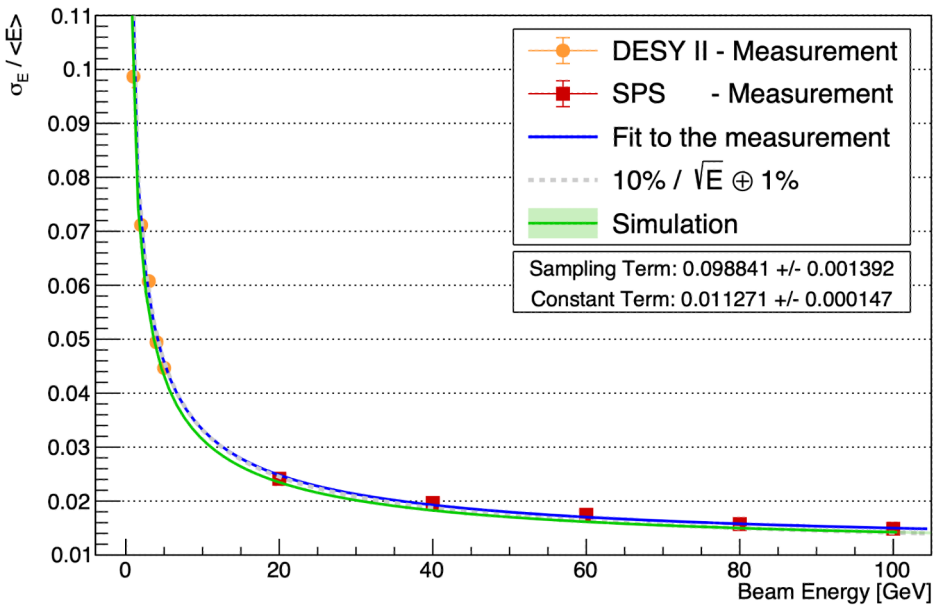
- First test of full Run 4 chain with new prototypes:
  - W absorbers
  - 3HF green plastic fibres (square fibres $1\times1\ \mathrm{mm}^2$)
  - Optics assembly with bundlers and long “hollow” light guides
  - R9880U PMTs

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

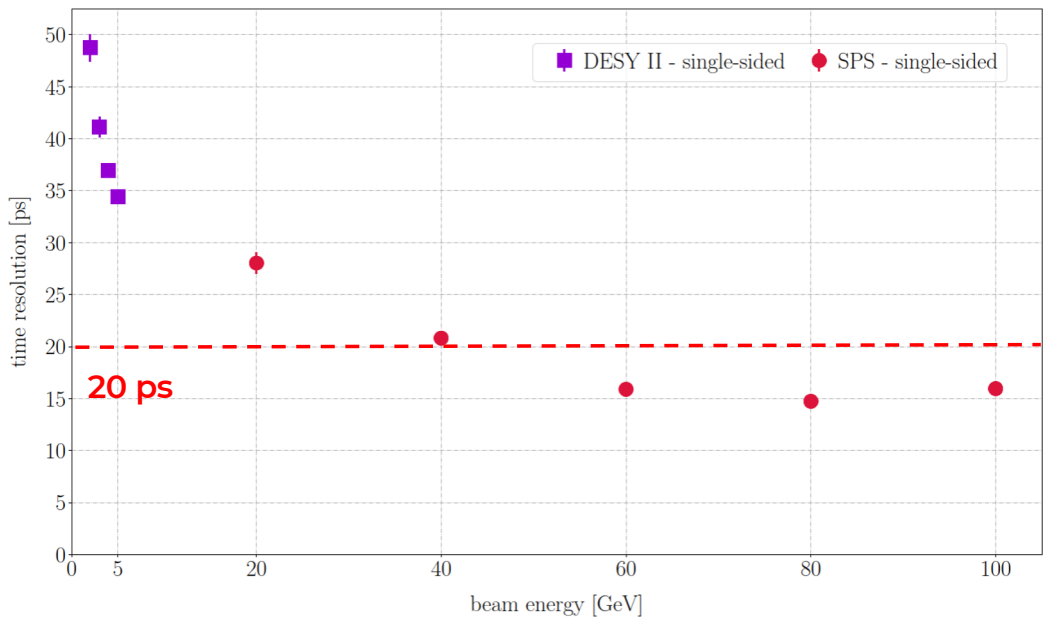
SpaCal - W Absorber - Polystyrene Fibres

LHCB-TDR-024 NIM A 1079, 170608 (2025)

Energy resolution



Time resolution



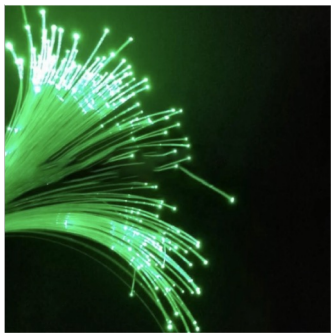
- **Energy resolution at 3°+3°:**
  - Noise contribution subtracted
  - R14755U-100 PMT
  - Symmetric LGs: square to octagon
  - Sampling term: 9.9 ± 0.1 %
  - Constant term: 1.13 ± 0.01 %
  - Very good agreement with simulation

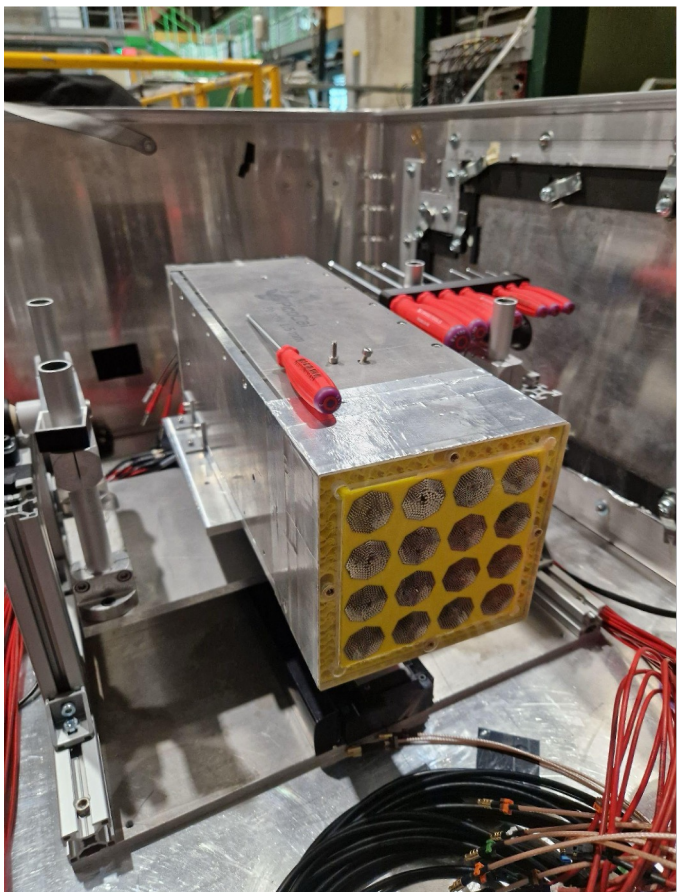
- **Time resolution at 3°+3°:**
  - Multi-Anode(R7600U-M4) PMT with 4 channels
  - Asymmetric LGs: square to square
  - Single-sided readout
  - Time resolution above 40 GeV: better than 20 ps

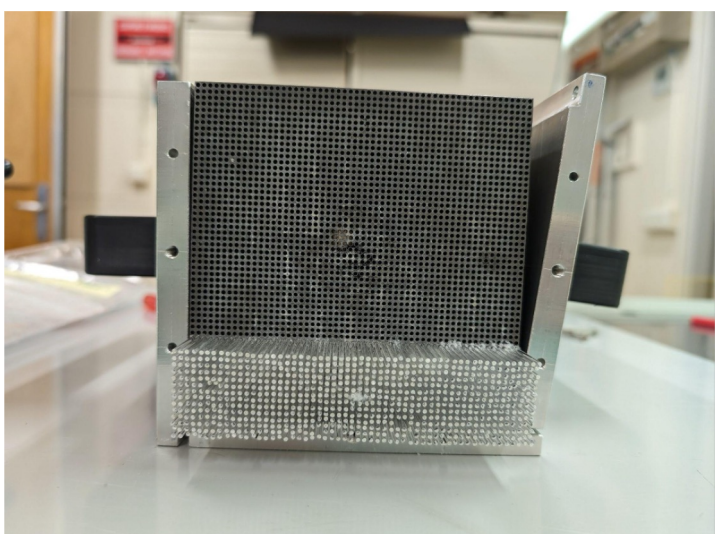
Performance in line with targets

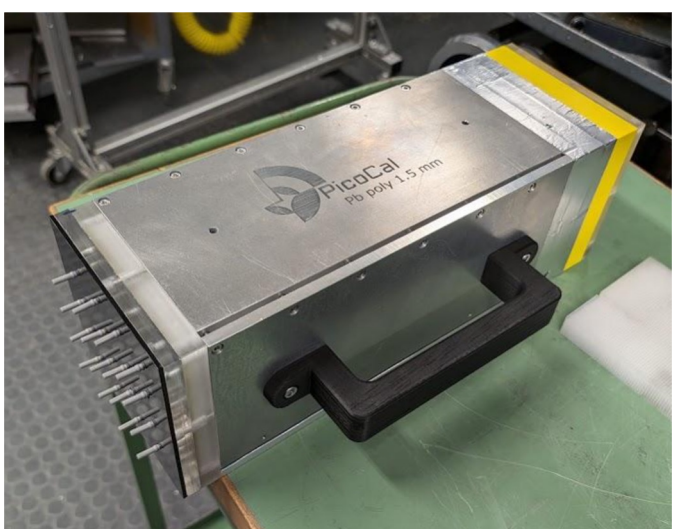
SpaCal - Pb Absorber - Polystyrene Fibres

- **Module 0 prototype assembled in June 2024**
  - Pb casting technology for absorber production
  - Kuraray 3HF green fibres Ø 1.5 mm

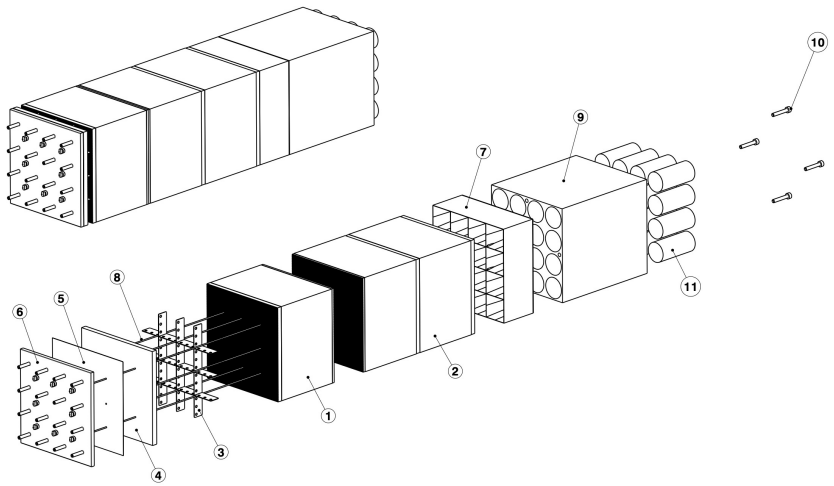


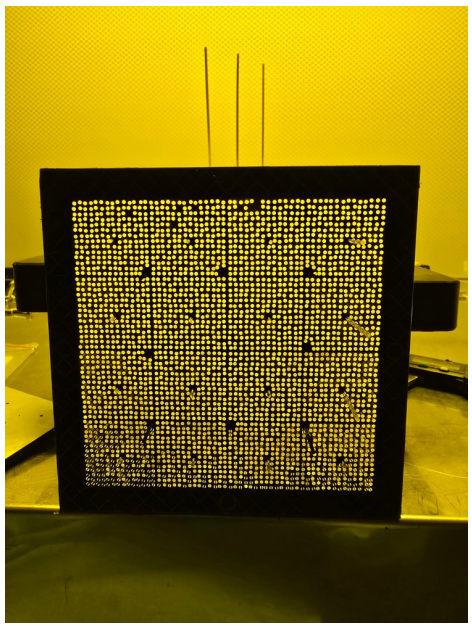


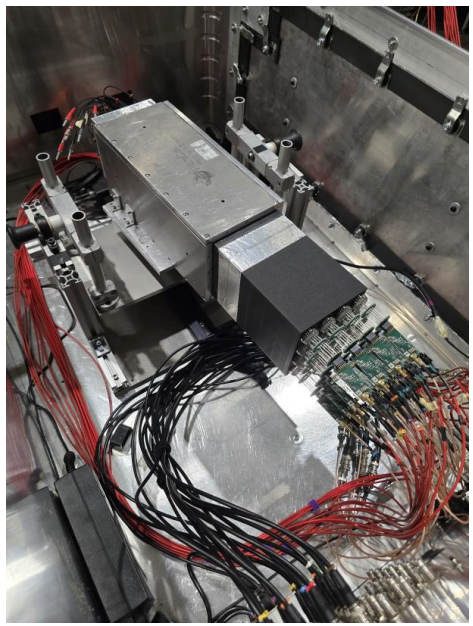




Ongoing R&D: Pb-absorber assembly for LS3







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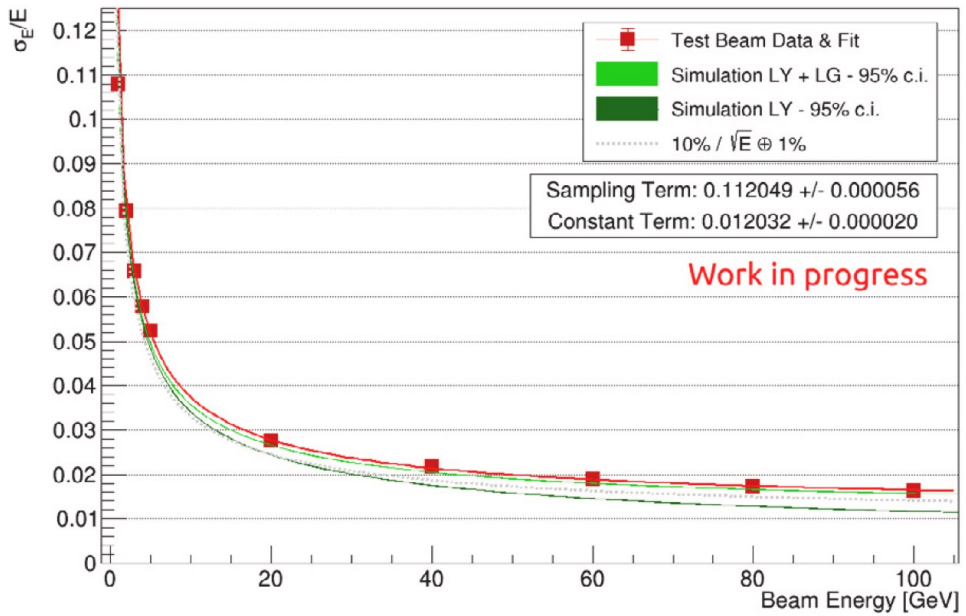
  - 3HF green plastic fibres (round fibres Ø=1.5 mm)
  - Optics assembly with bundlers and long “hollow” light guides
  - R9800 PMTs

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

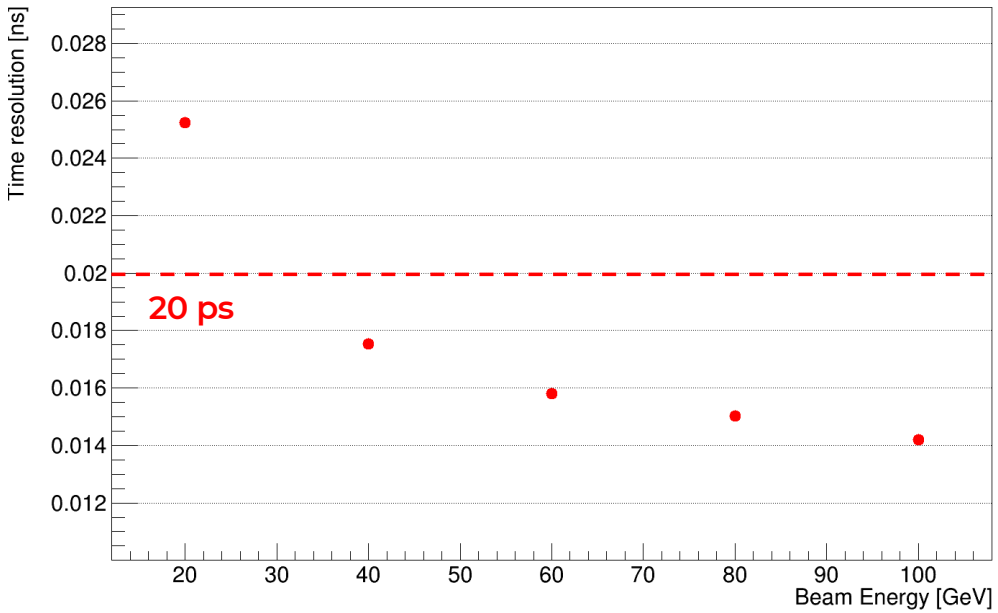
SpaCal - Pb Absorber - Polystyrene Fibres

NIM A 1079, 170608 (2025)

Energy resolution



Time resolution



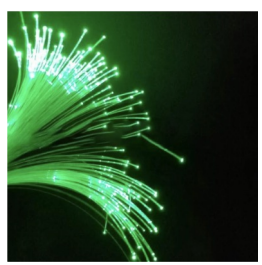
- **Energy resolution at 3°+3°:**
  - R11187 PMT
  - Symmetric LGs
  - Single-sided readout
  - Sampling term: 11.2 ± 0.1 %
  - Constant term: 1.20 ± 0.01 %
  - Very good agreement with simulation

- **Time resolution at 3°+3°:**
  - Multi-Anode(R7600U-20) PMT with 4 channels
  - Asymmetric LGs
  - Double-sided readout
  - Time resolution above 20 GeV: better than 20 ps

Performance in line with targets

Ongoing R&D: Plastic Scintillator

- **3HF-based green fibres will be used for LS3 enhancement:**
  - Better radiation tolerance than SCSF-78 matches requirements
  - However, longer decay time would affect time resolution



- **Required for LS4 (Upgrade II):**
  - Radiation hardness up to 100-200 kGy (hadrons)
  - Fast timing performance
  - Cost effectiveness

- **R&D ongoing on alternative materials:**
  - Hosts other than polystyrene
  - Red and Green emitters

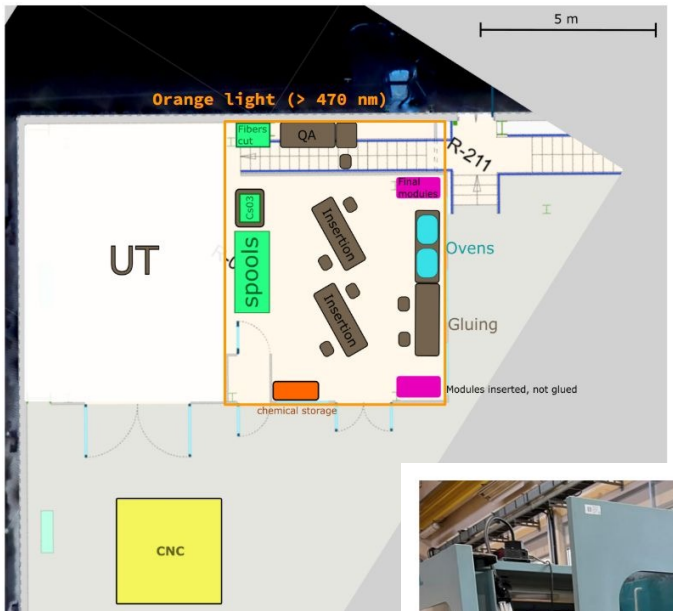
Formulations [1]

Kuraray Datasheet

Description	Emission			Decay Time [ns]	Att.Leng.[2] [m]
	Color	Spectra	Peak[nm]		
SCSF-78	blue	See the following figure	450	2.8	>4.0
SCSF-81	blue		437	2.4	>3.5
SCSF-3HF(1500)	green		530	7	>4.5

LS3 Production Readiness (176 Modules)

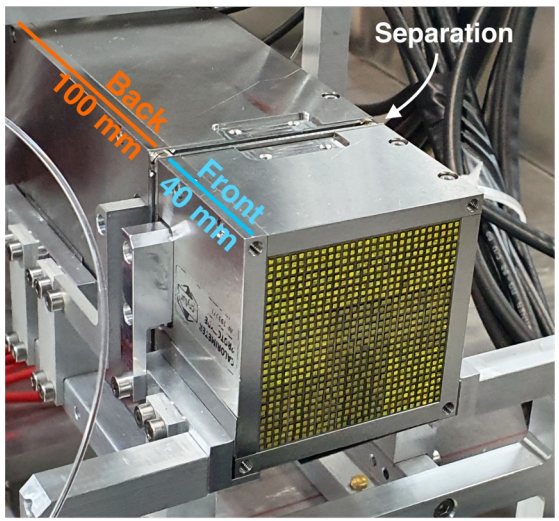
- **Absorbers:** SpaCal-W 3D-printed W (18.9 g/cm³, ~96% pure), 1 mm square holes; SpaCal-Pb 154 absorbers, Pb cast around ~3000 capillaries (1.55 mm ID) each
- **Fibers:** 3HF scintillating, 60 km (W) + 240 km (Pb), ~6000 ph/MeV, λ_att > 4 m, > 20 cm after 200 kGy
- **PMTs:** 1400× Hamamatsu R9880 (W) + 2600× R9800/NNVT (Pb); production 02/2027–02/2028, QA across 6 institutes
- **Assembly:** CERN facility (Bldg 3852/R-002, near LHCb Pit 8), light-protected, CNC + fiber cutting/gluing/insertion; 3 SpaCal-Pb pre-series modules
- **Schedule:** ECAL dismantling Jul 2026 – Apr 2027, re-assembly 2027–2028; existing pile-up test bench reused for SpaCal tooling



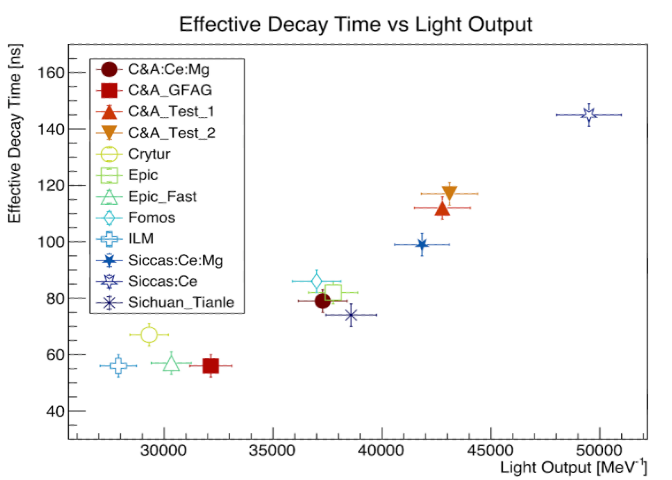
SpaCal - W Absorber - Crystal Fibres

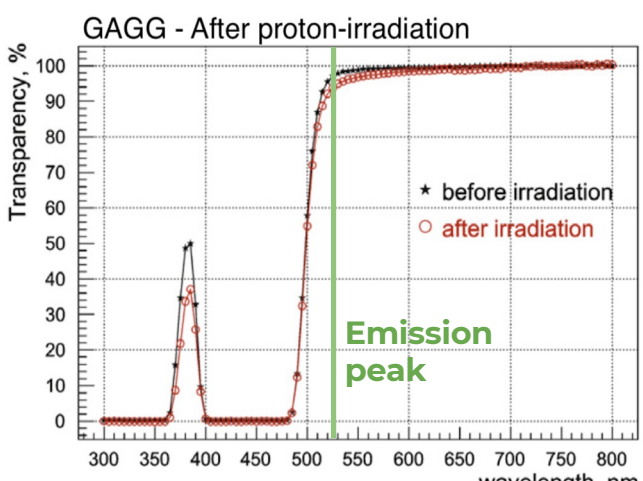
NIM A 1000, 165231 (2021) NIM A 816 (2016) 176

SPACAL prototype with W absorber and garnet crystals



- **Module details:**
  - Absorber in pure tungsten $19\ \mathrm{g/cm^3}$
  - 9 cells of $1.5\times1.5\ \mathrm{cm^2}$ ($R_M \sim 1.5$ cm)
  - $4 + 10$ cm long ($7 + 18\ X_0$)
  - Reflective mirror between sections
  - Squared garnet crystal fibres ($1\times1\ \mathrm{mm^2}$ cross section)





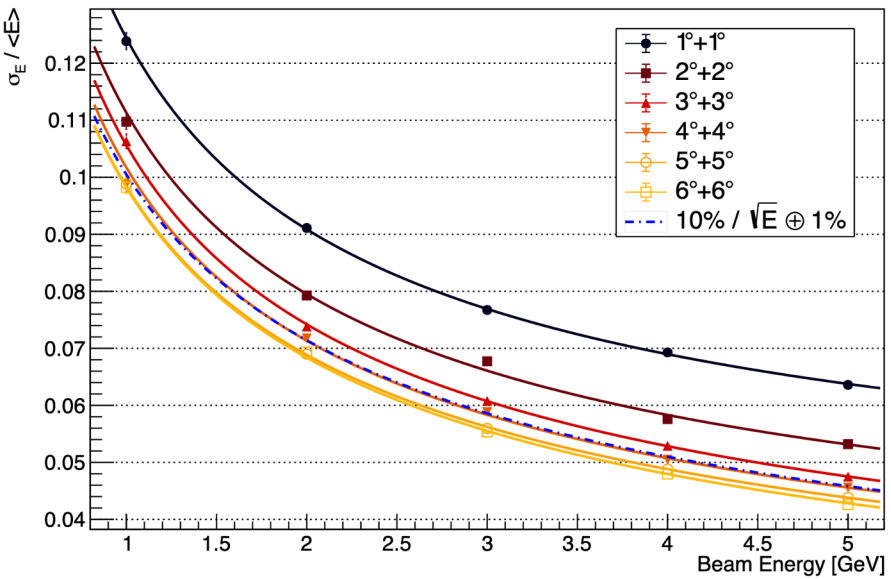
GAGG as scintillating material

- **High light output and relatively fast decay time (~50 ns)**
  - Tunable scintillation properties
- **Radiation hardness tested up to 1 MGy**

SpaCal - W Absorber - Crystal Fibres

NIM A 1045, 167629 (2022)

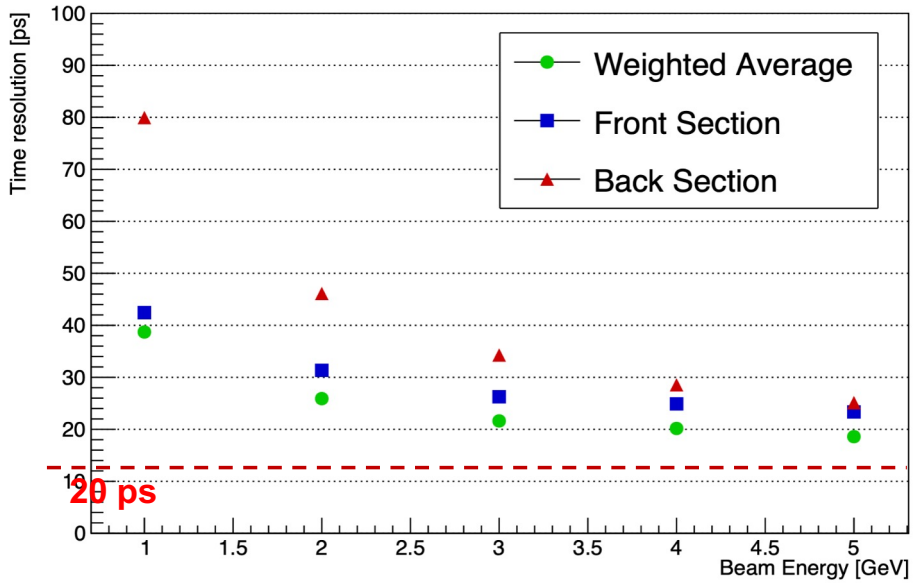
Energy Resolution



- **Resolution improves increasing the incidence angle**
- **Energy resolution at 3°+3°:**
  - Sampling term: 10.2 ± 0.1 %
  - Constant term: $1 - 2$ %

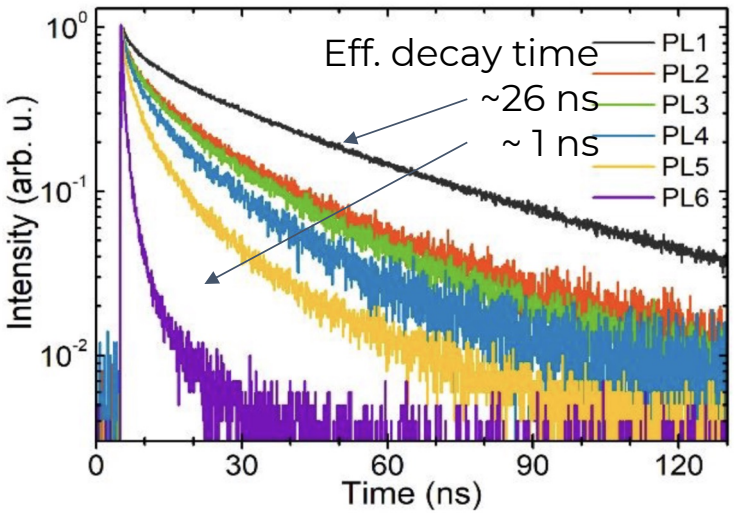
Performance in line with targets

Time Resolution C&A GFAG

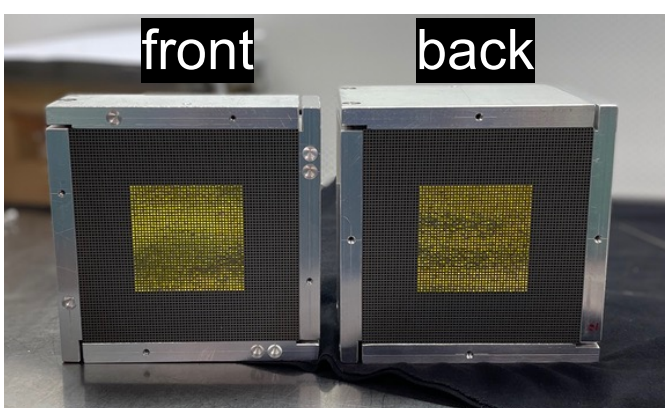


- **Time stamps obtained using CFD algorithm**
- **Time resolution C&A GAGG at 3°+3°:**
  - Measurement in direct contact with MCD(R7600U-20) PMTs for ultimate performance
  - Double-sided readout
  - 18.5 ± 0.2 ps @ 5 GeV

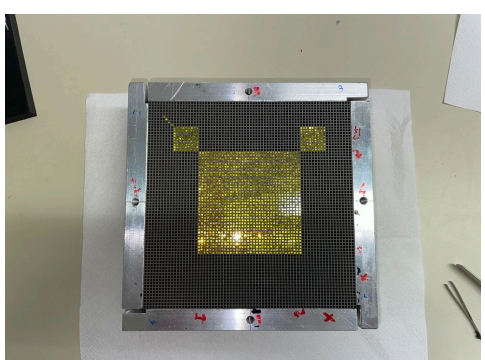
Ongoing R&D: Accelerating Scintillation



Material Advances, 2022, 3, 6842

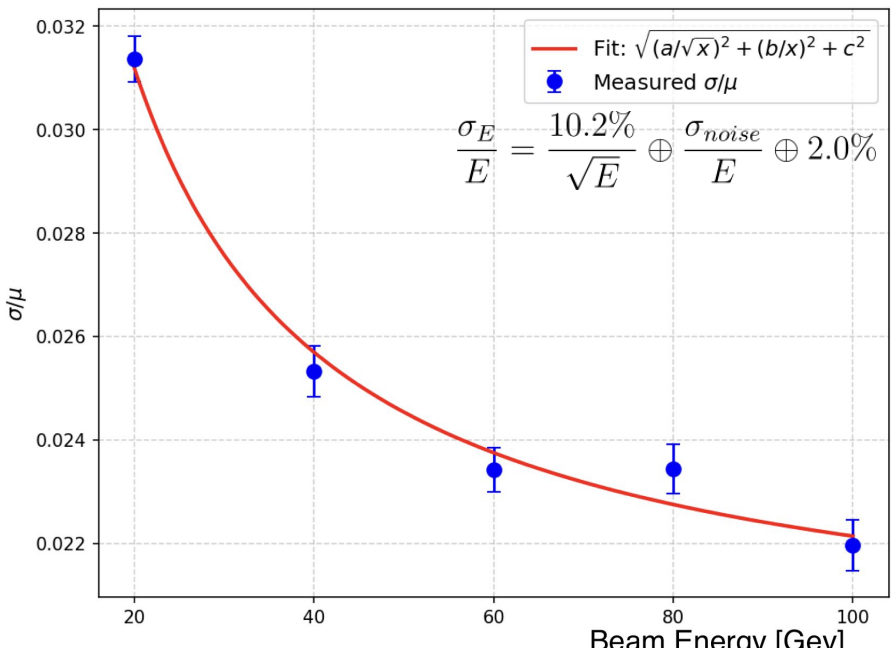


- **The issue: current commercial GAGG has scintillation decay time > 40 ns**
  - Mitigate spill-over effect on time resolution
- **Novel GAGG compositions developed to quench scintillation**
  - Light yield reduced
  - Decay time accelerated
  - Time resolution kept competitive
- **R&D to produce large-size and homogeneous Czochralski ingots**
- **Collaboration with:**
  - SiPAT, 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, China
  - Two more cells filled in 2025 with new GAGG fibers with decay time ~10 ns
    - One with GAGG from FZU/Crytur
    - One with GAGG from SiPAT

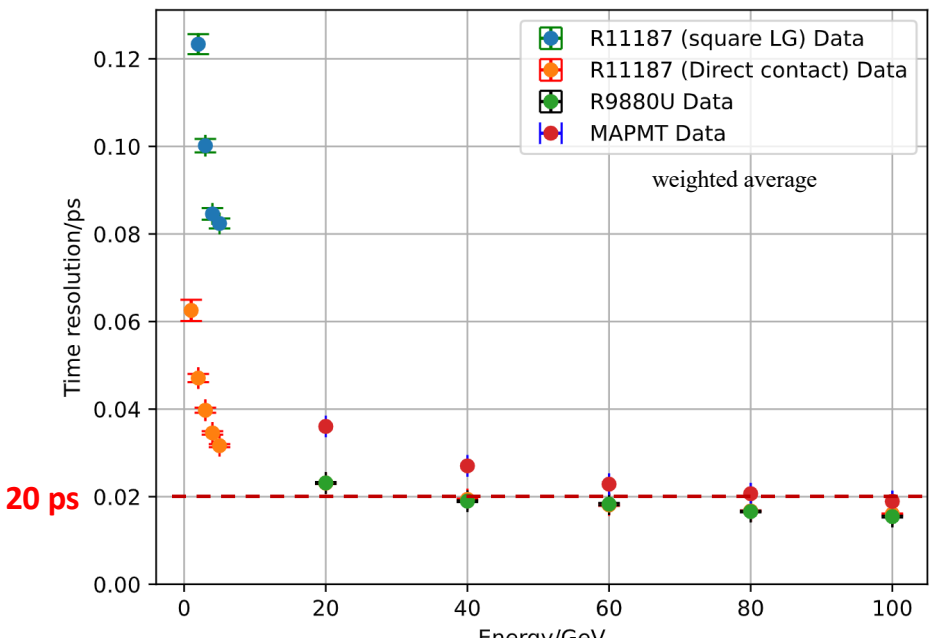


SpaCal - W Absorber - Crystal Fibres

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

Shashlik R&D

LHCB-TDR-024 NIM A 1079, 170608 (2025)

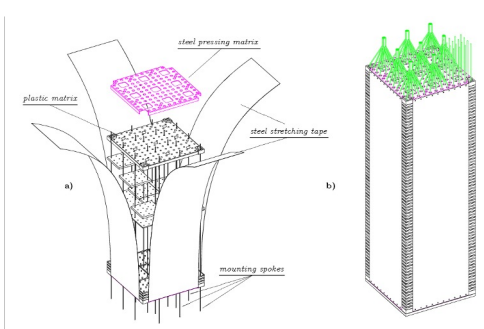
- **Current LHCb Shashlik modules have good time properties**

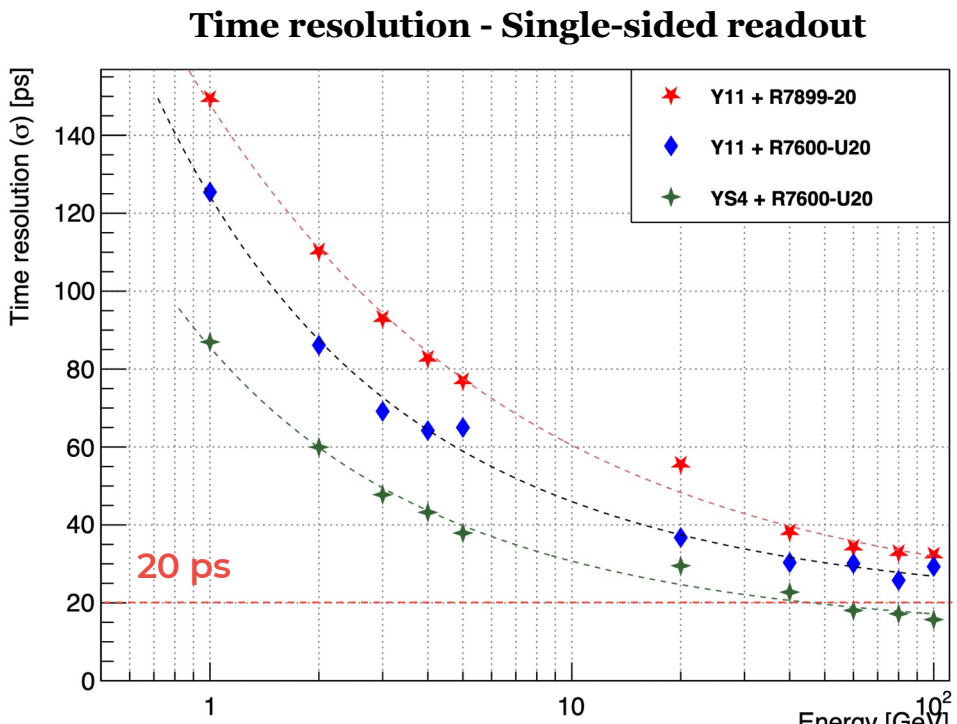
- **Improvements:**
  - Replacing WLS fibres (Kuraray)

    - Y-11 (7 ns decay time) ← Current LHCb
    - YS-2 (3 ns decay time)
    - YS-4 (1.1 ns decay time)

  - Double-sided readout

- **Time resolution at 3°+3°:**
  - Current(R7899-20) and faster(R7600-20) PMT
  - Time resolution above 40 GeV: better than 20 ps (single-sided readout)





Summary and conclusion

The LHCb ECAL needs to be enhanced and upgraded during the LHC LS3 and LS4

- **The innermost 176 modules need to be replaced in LS3 due to radiation damage**
  - SpaCal with Tungsten/Lead absorber and plastic fibres meets the requirements
- **The Upgrade II in LS4 introduces picosecond-level timing and more demanding radiation hardness requirements**
  - Better than 20 ps achieved with Shashlik and SpaCal at high energy
- **Comprehensive R&D ongoing (also interesting for other future projects)**
  - Test beam measurements with prototypes
  - Detailed Monte Carlo simulations
  - Study of novel absorber production techniques
  - Study of suitable LGs, bundlers, PMTs and development of readout electronics
  - Investigation of new radiation-hard and fast scintillators

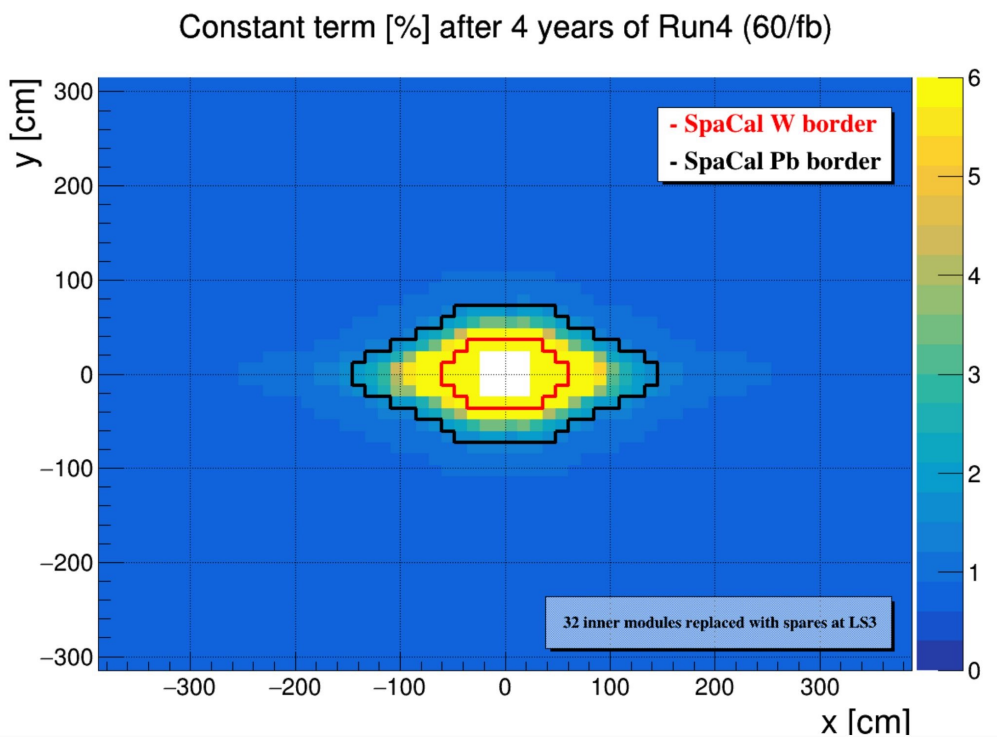
Thanks for your attention!

PicoCal

Back up

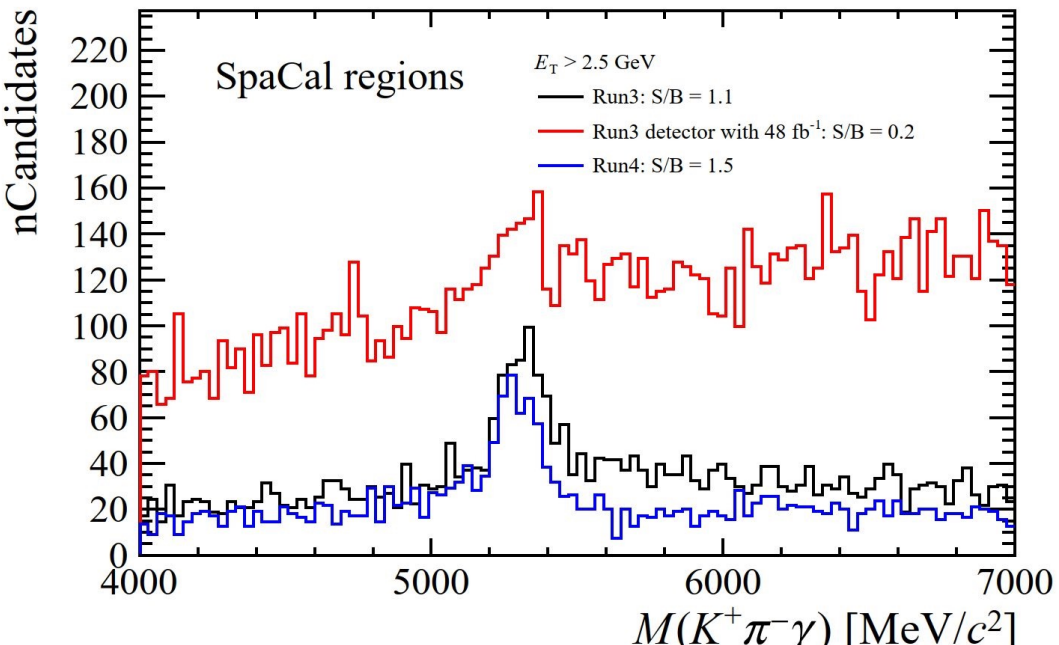
Radiation Damage Before the LS3 Upgrade

- ECAL constant-term degradation map (x-y, ±300 cm) after 4 yr of Run 4 at 60 fb^{-1} shows a bright central core (LHCb TDR-024)
- Drives replacement of the 32 innermost modules during LS3
- **LS3 inner-region target:** withstand up to 200 kGy, $\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$

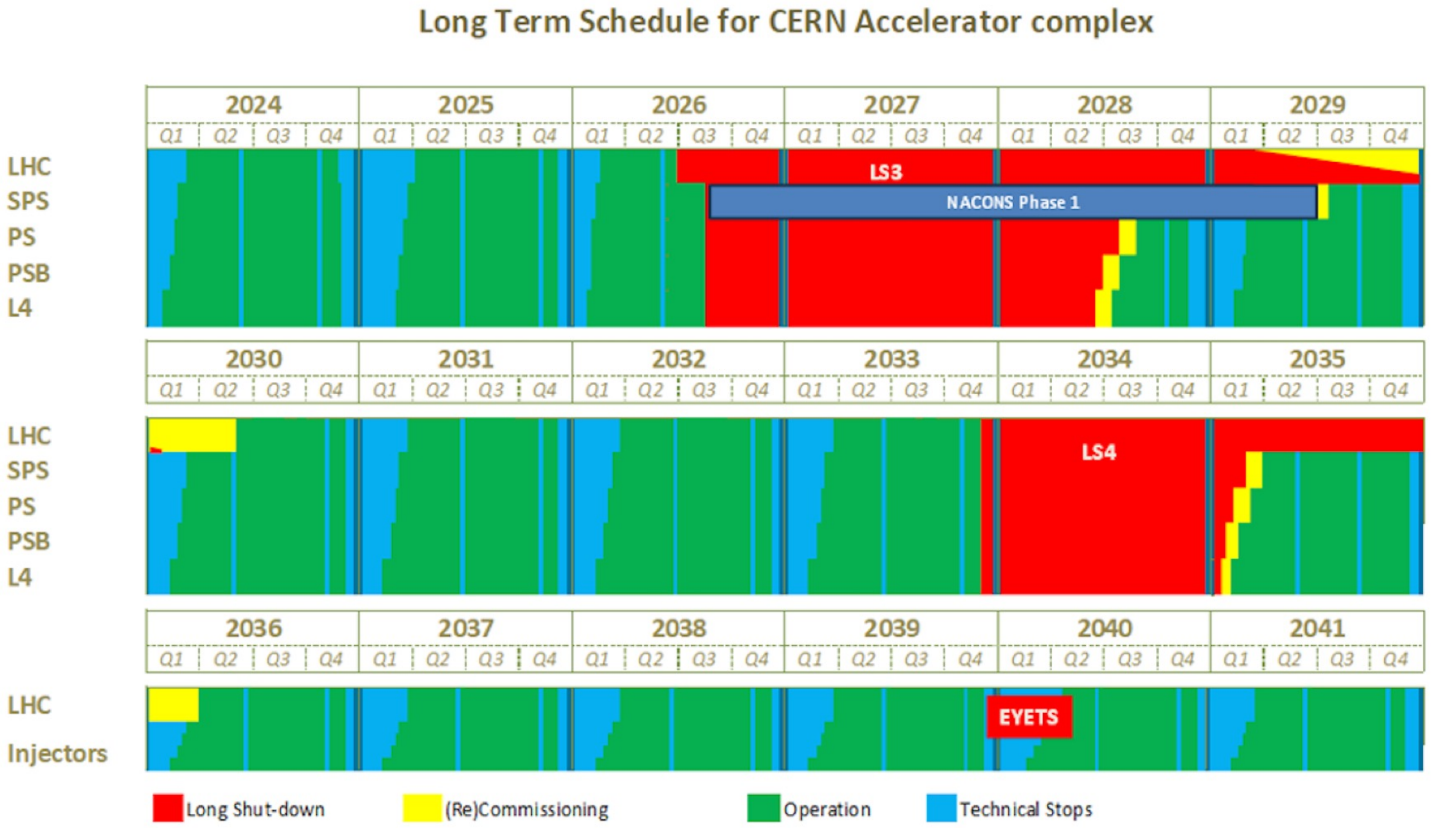


$B^0 \to K^{*0}\gamma$ Physics Reach

- SpaCal region captures ~35% of photons from $B^0 \to K^{*0}\gamma$
- **S/B for Eγ > 2.5 GeV:** 1.5 (Run 4, upgraded), 1.1 (Run 3), 0.2 (Run-3 detector after 48 fb^{-1} radiation)
- Upgrade recovers and extends LHCb physics reach beyond Run 3



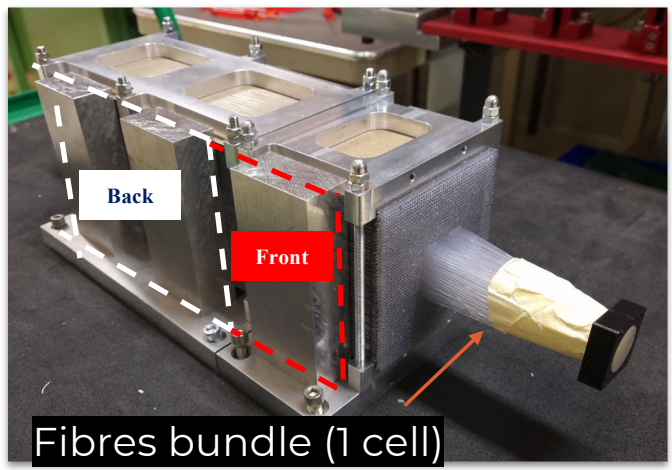
Updated CERN accelerator schedule

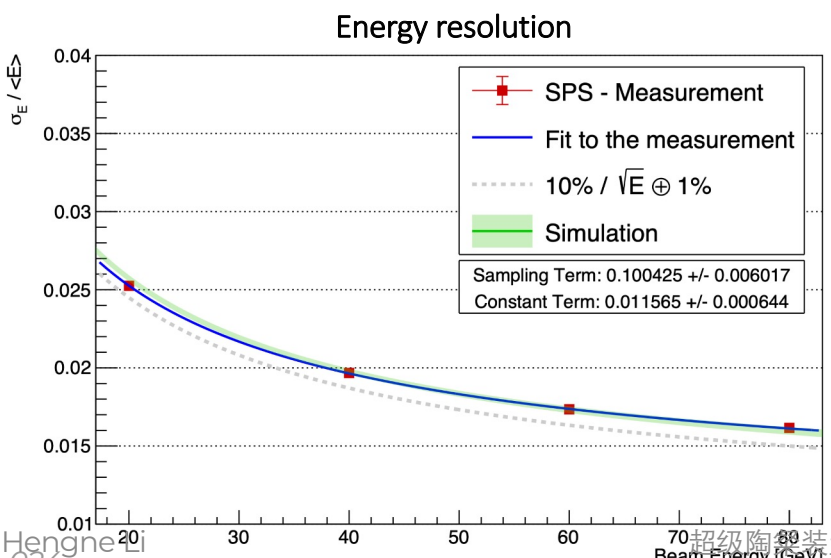


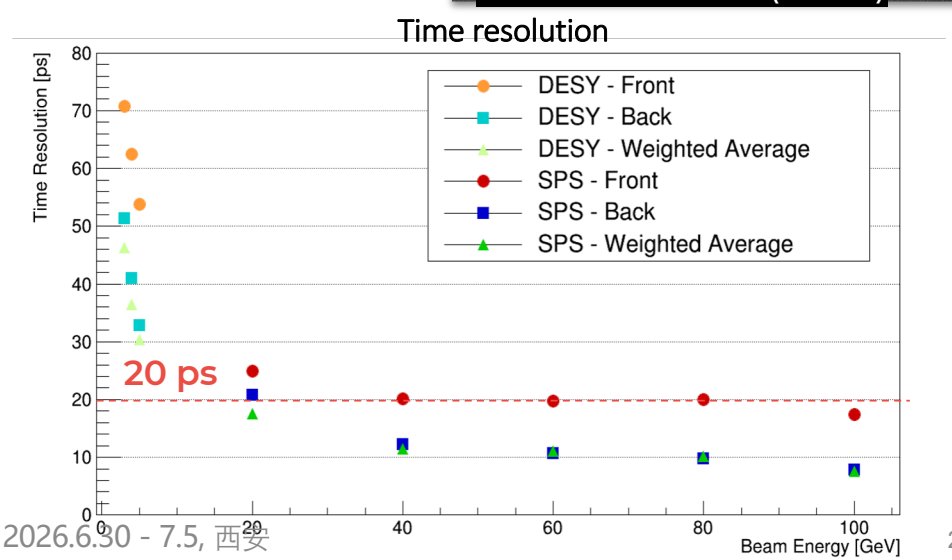
- Run 3 extended till end of June 2026
- LHC restart for Run 4 in 2030
- LHC LS4 moved by one year to 2034-35
- LS5 becomes EYTES
- Also impact on SPS test beams!

SpaCal - Pb Absorber - Polystyrene Fibres

- **Pb absorber and polystyrene fibres:**
  - $8 + 21$ cm long $(7 + 18\ X_0)$
  - Reflective mirror between sections
  - Kuraray SCSF-78 round fibres $Ø = 1.0$ mm







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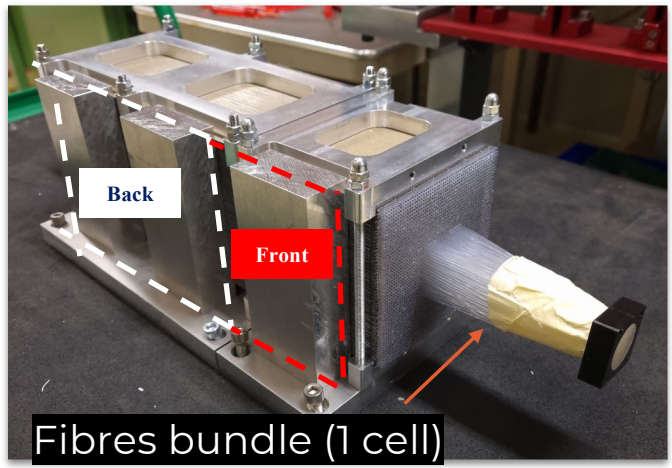
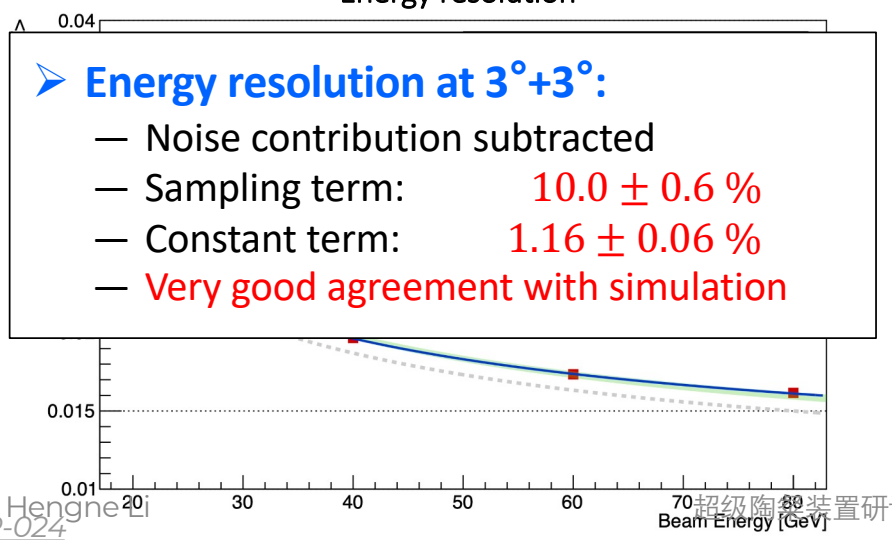


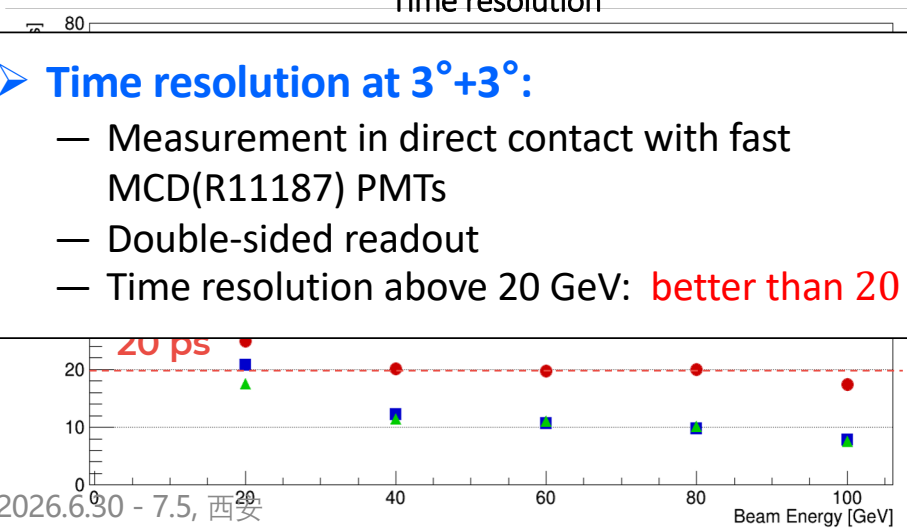
Performance in line with targets

Energy resolution



- **Energy resolution at 3°+3°:**
  - Noise contribution subtracted
  - Sampling term: 10.0 ± 0.6 %
  - Constant term: 1.16 ± 0.06 %
  - Very good agreement with simulation

Time resolution



- **Time resolution at 3°+3°:**
  - Measurement in direct contact with fast MCD(R11187) PMTs
  - Double-sided readout
  - Time resolution above 20 GeV: better than 20 ps

LHCB-TDR-024