EPS-HEP 2025

# The LHCb PicoCal


Zhiyang Yuan

on behalf of the LHCb ECAL Upgrade II R&D Group

Peking University, Beijing, China


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# Outline

1. Introduction
2. R&D and latest test beam results
    1) SpaCal-W with polystyrene fibers for LS3
    2) SpaCal-Pb with polystyrene fibers
    3) SpaCal-W with crystal fibers for LS4
    4) Shashlik with fast WLS fibers
3. Summary and conclusion

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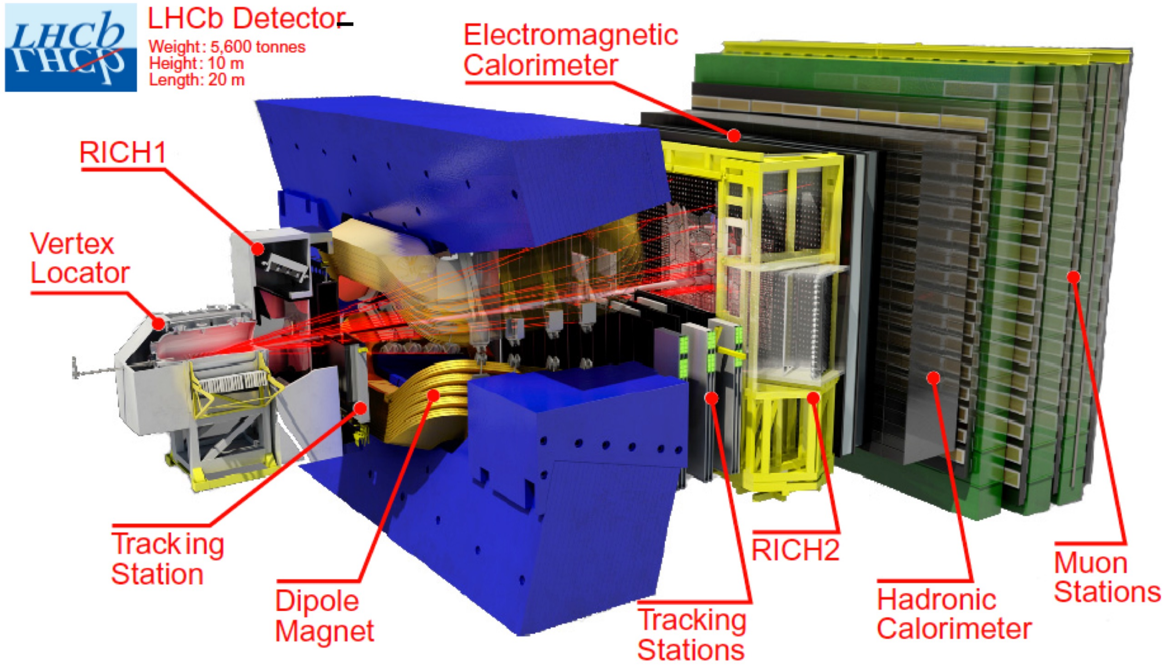
# LHCb and physics goal

- **LHCb(LHC beauty) is designed for heavy flavor physics at the LHC：**
  - Goal: to look for new physics in CP violation, rare decays and spectroscopy
  - Also, excellent capabilities in other domains:
    - Electroweak physics
    - Heavy ions
    - Fixed target

| | |
|---|---|
| Vertex: | $\sigma_{\mathrm{IP}} = 20\mu\mathrm{m}$ |
| Time: | $\sigma_{\tau} = 45\mathrm{fs}$ for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$ |
| Momentum: | $\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\mathrm{GeV}/c)$ |
| Mass: | $\sigma_m = 8\ \mathrm{MeV/c^2}$ for $B \to J/\psi\mathrm{X}$ ($m_{J/\psi}$ constrainted) |
| Hadron ID: | $\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$ |
| Muon ID: | $\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$ |
| ECAL: | $\Delta E/E = 10\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$ |



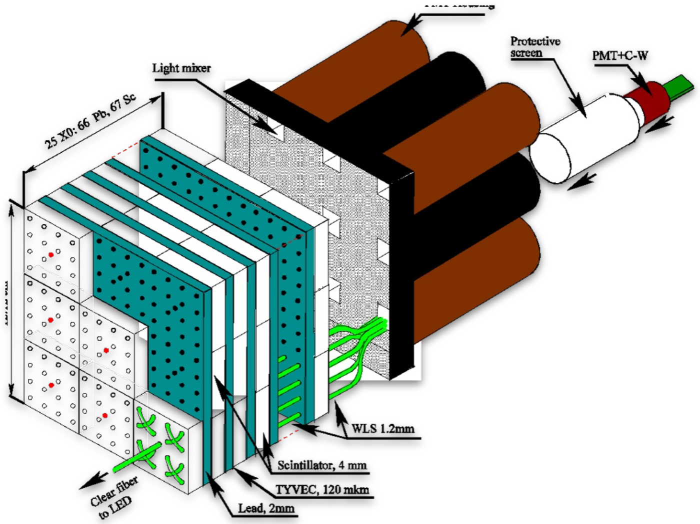

A single-arm forward spectrometer covering $2 < \eta < 5$



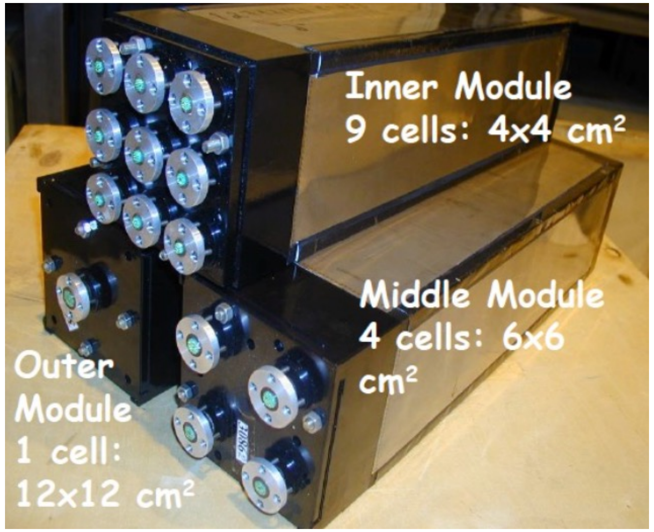
LHCB-TDR-023, LHCB-TDR-024, LHCB-TDR-026

# The Current LHCb ECAL

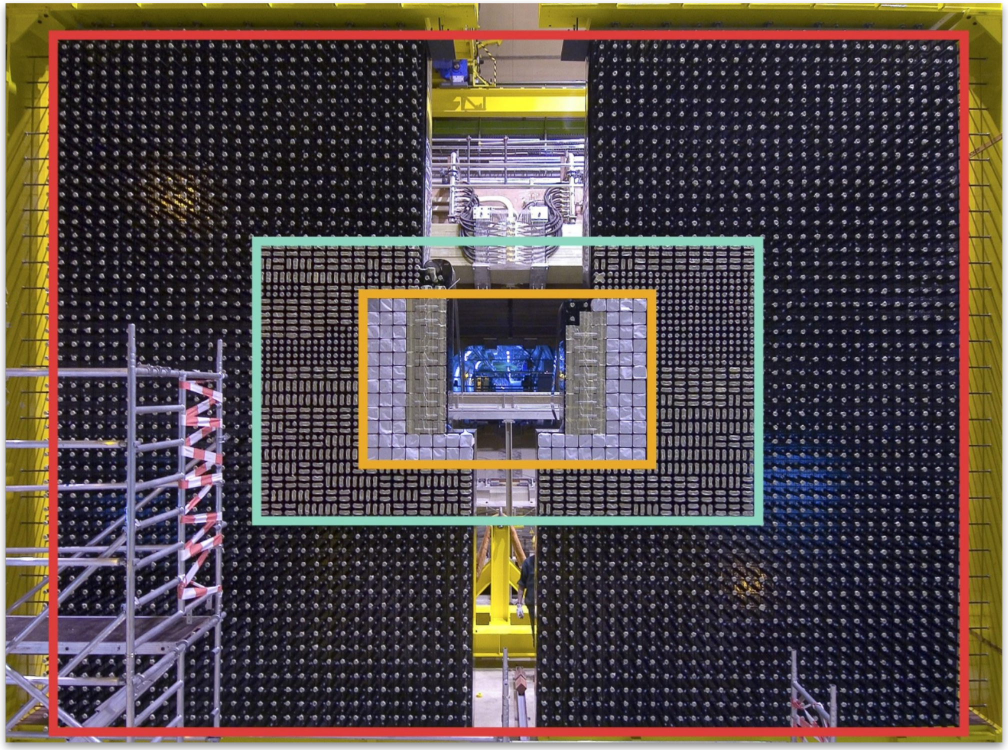
- **ECAL is essential to all measurements involving neutrals and electrons**
- **Optimized for $\pi_0$ and $\gamma$ identification in the few GeV to 100 GeV region at $\mathbf{2 \times 10^{32}\ cm^{-2}s^{-1}}$**




- 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**

| 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 |

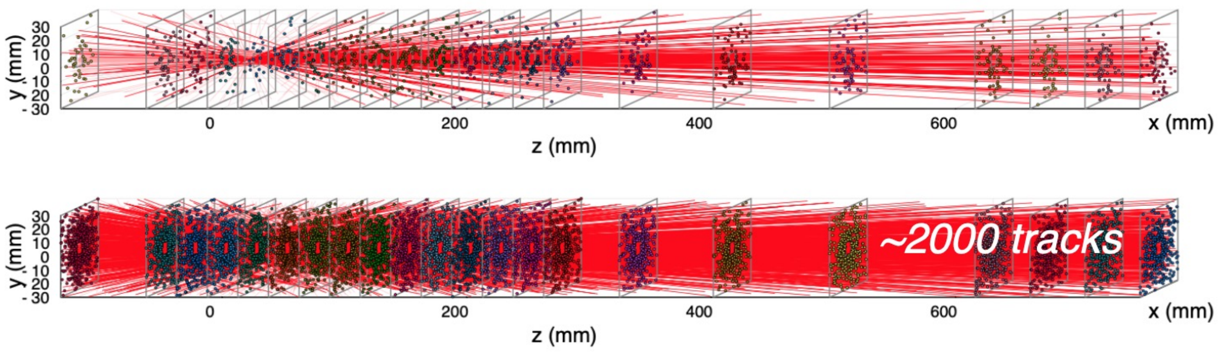
– Upgrade II to be installed at LS4: $1.5\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

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

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

**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

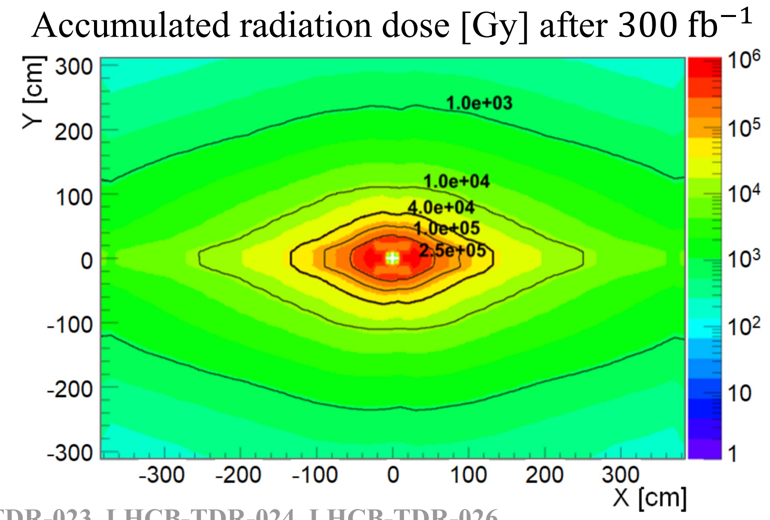
# Motivation to upgrade

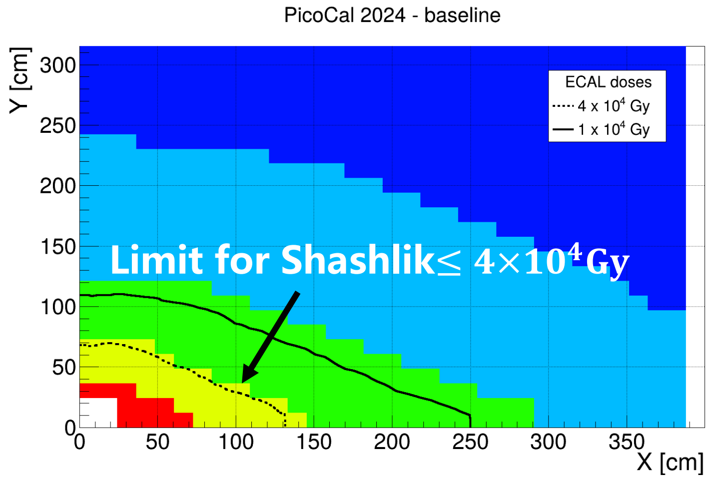
**Requirements for the Upgrade II:**

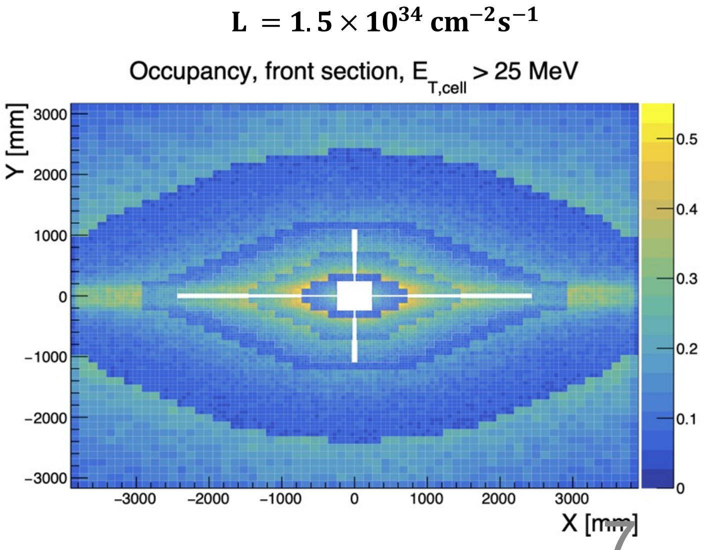
- **Radiation doses up to $\mathbf{1\ MGy}$ and $\leq 6\times10^{15}$ 1 MeV neq/cm$^2$ in the centre for $300\ \mathrm{fb}^{-1}$**
  - New technologies required for the center
- **Pile-up mitigation crucial**
  - Timing $\mathcal{O}(10\ \mathrm{ps})$ precision
  - Increased granularity
  - longitudinal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

**Scintillators R&D needed**

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



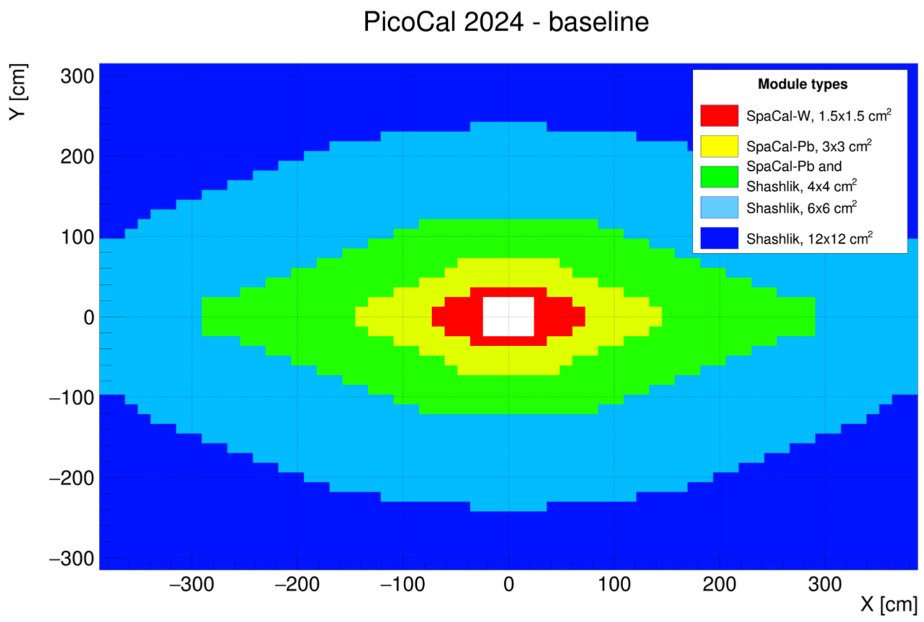
# Technologies for ECAL Upgrade II

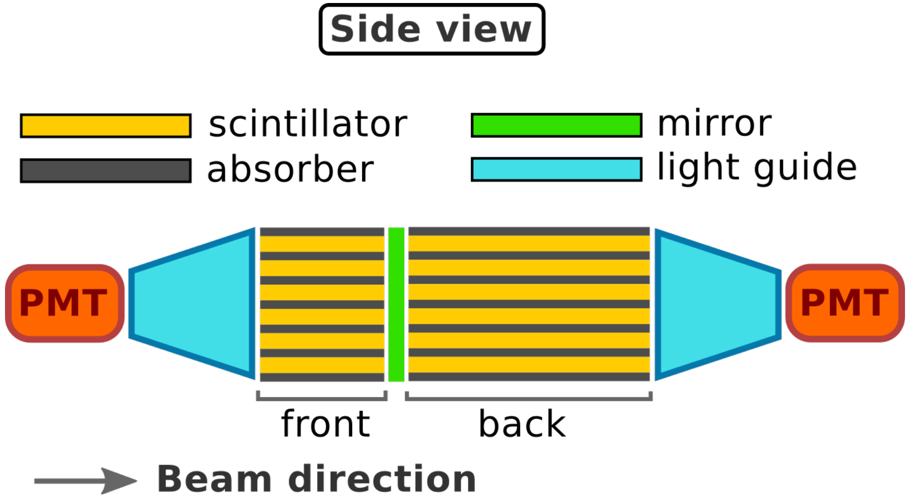
**SPACAL technology for inner region.**

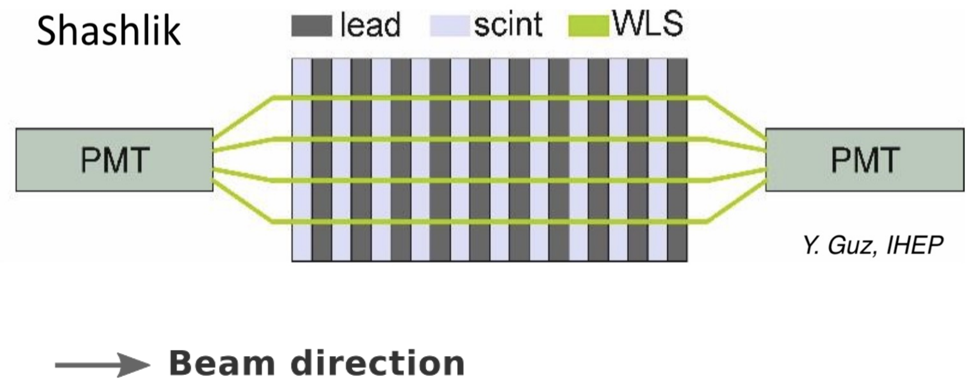
- **$1.5\times1.5$ cm$^2$ cell - W absorber and crystal fibres**
  - Development of radiation-hard crystal fibres
  - Polystyrene fibres for Run 4, then replaced by crystals
- **$3\times3$, $4\times4$ cm$^2$ cell - Pb absorber and plastic fibres:**
  - Need radiation-tolerant plastic fibres

**Shashlik technology for outer region**

- **$4\times4$, $6\times6$, $12\times12$ cm$^2$ cell**
  - Timing improved with faster WLS fibres and double-sided readout



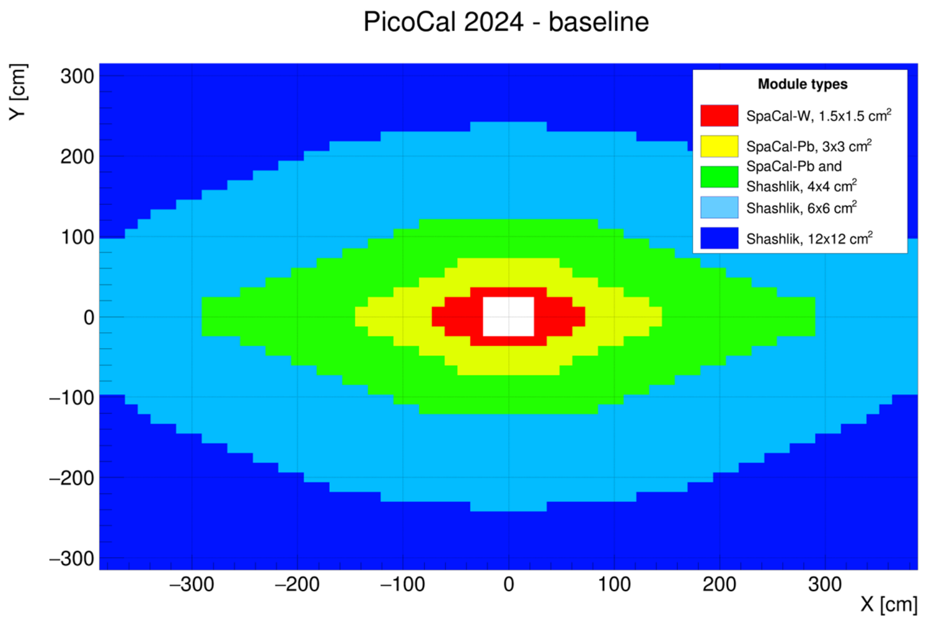




LHCB-TDR-023, LHCB-TDR-024, LHCB-TDR-026

# ECAL configuration to be installed during LS3

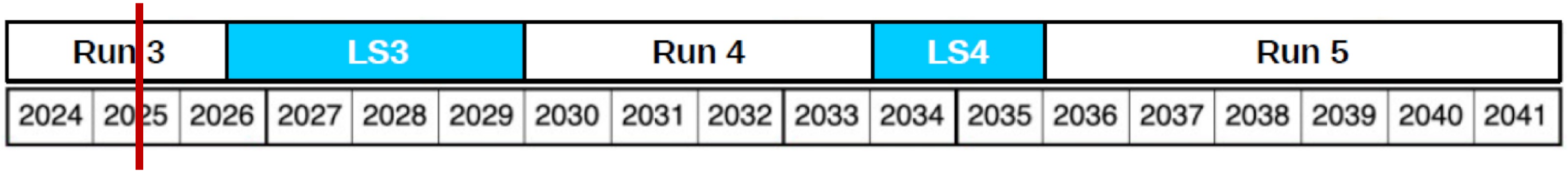
- **176 new SpaCal modules in the inner region**
  → This region covers about 35% of photons and neutral pions from B-hadron decays over the ECAL acceptance
- **The existing modules will be rearranged in rhombic areas (32 Shashlik modules with $4 \times 4$ cm$^2$ cell size will be replaced)**

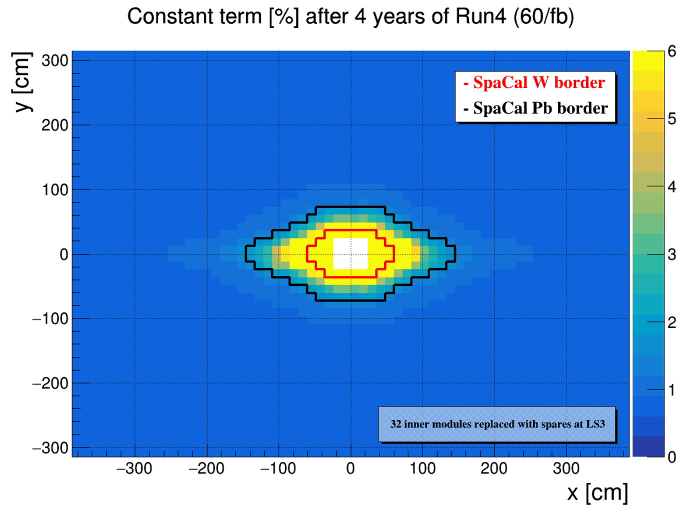



| Cell size: | Modules: | Number of cells: |
|---|---|---|
| $2 \times 2$ cm$^2$ | 16 new SpaCal-W modules with plastic fibres | 576 |
| $2 \times 2$ cm$^2$ | 16 new SpaCal-W modules with plastic fibres - special shape | 480 |
| $3 \times 3$ cm$^2$ | 104 new SpaCal-Pb modules with plastic fibres | 1664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

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

# The Upgrade Strategy




## Run 3 in 2022-Q2/2026:

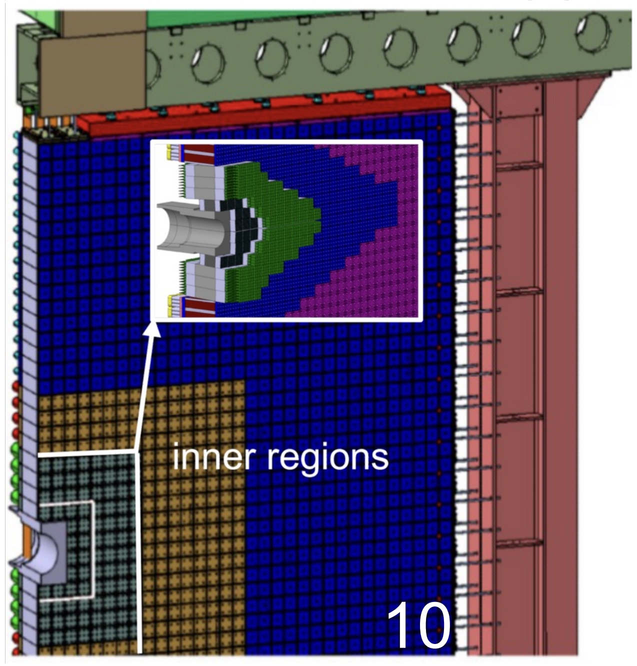
- **Run with unmodified ECAL Shashlik modules at $\mathbf{L = 2{\times}10^{33}\,cm^{-2}s^{-1}}$ (new 40 MHz readout)**

## LS3 consolidation in Q3/2026-2029:

- **Introduce single-section rad. tolerant SPACAL ($\mathbf{2{\times}2}$ and $\mathbf{3{\times}3\ cm^2}$ cells) in inner regions and rebuild ECAL in rhombic shape to improve performance at $\mathbf{L = 2{\times}\,10^{33}\ cm^{-2}s^{-1}}$**
  - 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 ($\mathbf{1.5{\times}1.5, 3{\times}3\ \&\ 4{\times}4\ cm^2}$ cells) and improve timing of Shashlik modules for a luminosity of up to $\mathbf{L = 1.5\times10^{34}\ cm^{-2}s^{-1}}$**
  - Innermost SPACAL-W modules equipped with crystal fibres
  - Include timing information and double-sided readout for pile-up mitigation




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

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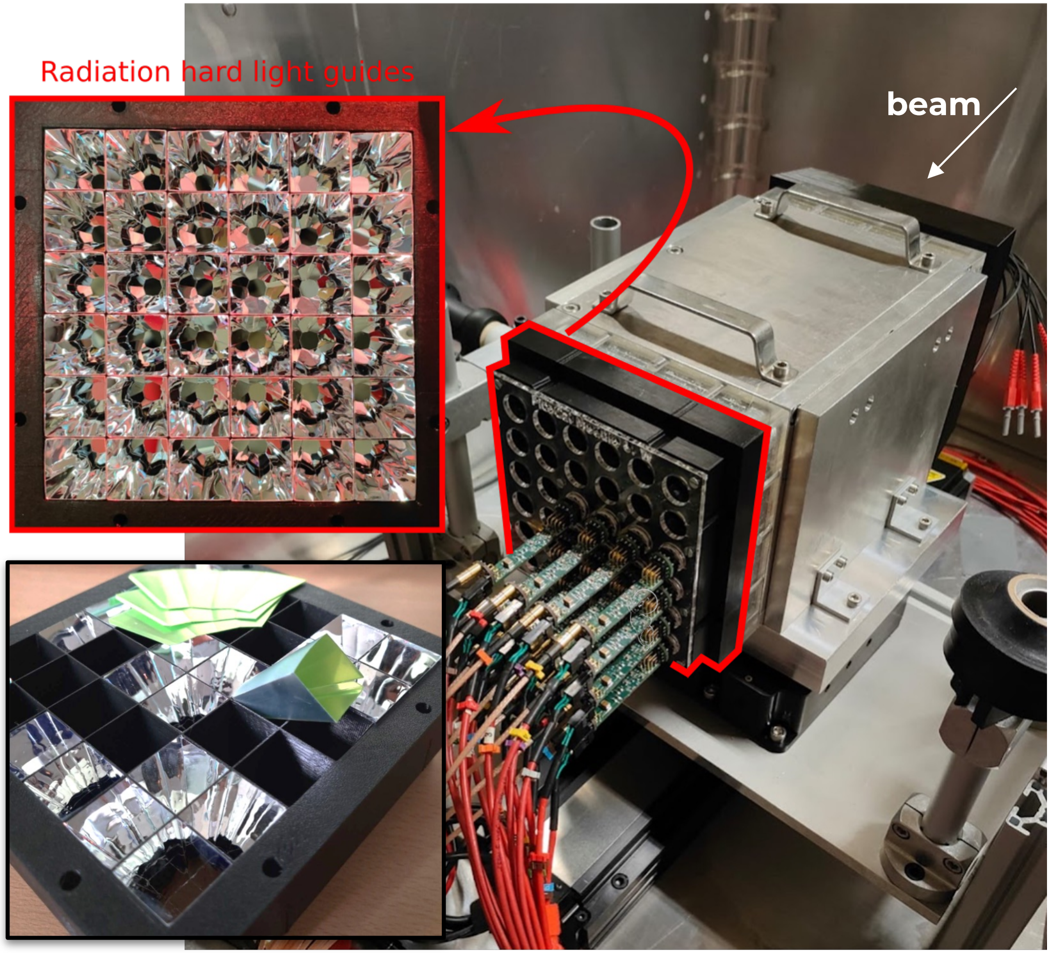
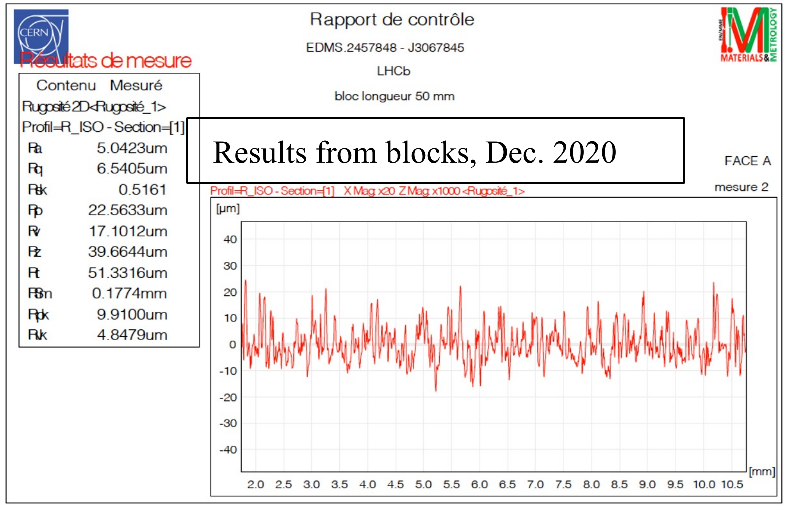
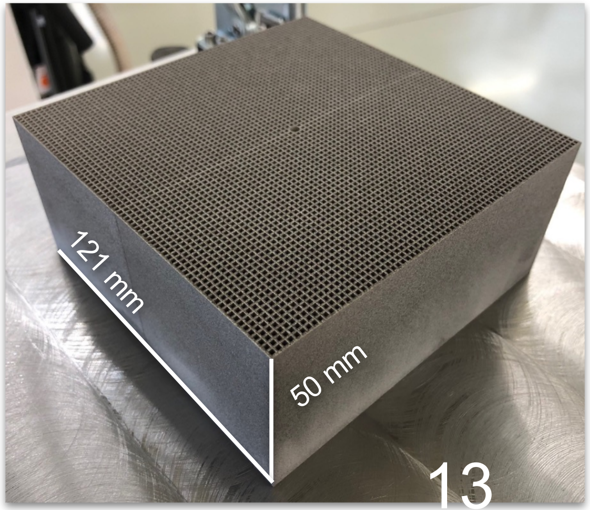
# SpaCal - W Absorber - Polystyrene Fibres

- **Full size $121\times121\ \mathrm{mm}^2$ *Module 0* assembled at CERN:**
- **Passive materials:**
  - 3D-printed W absorber
    - $3\times50$ mm + $1\times40$ mm long blocks
    - R&D performed with EOS, Germany
  - Very good mean roughness $\mathrm{R_a} = 5\ \mu\mathrm{m}$ 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

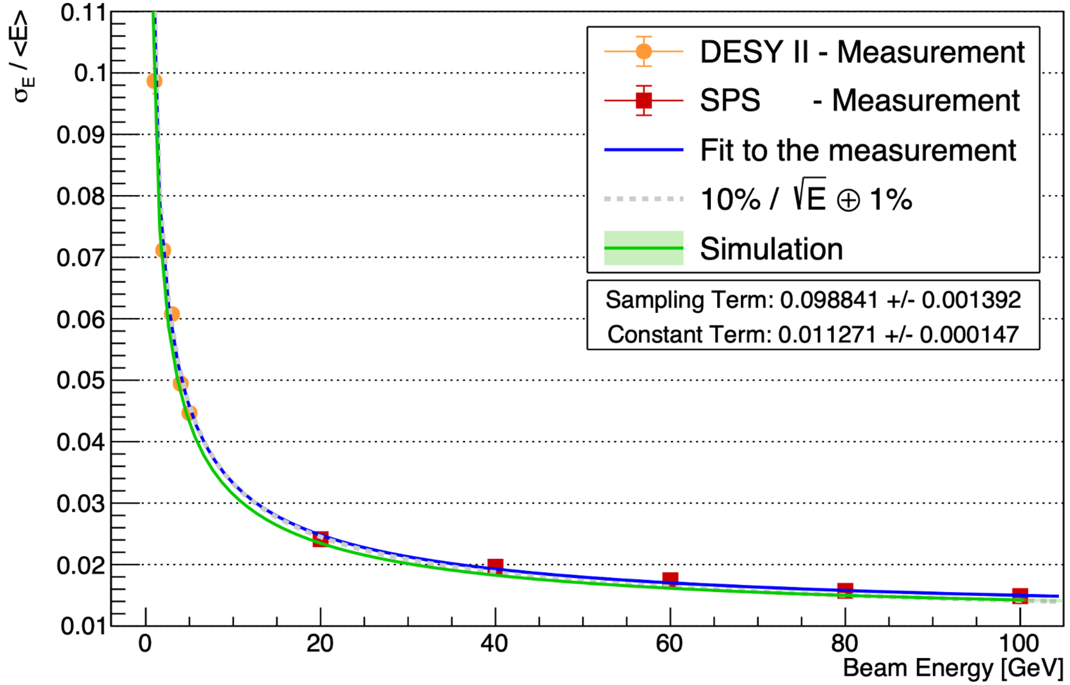


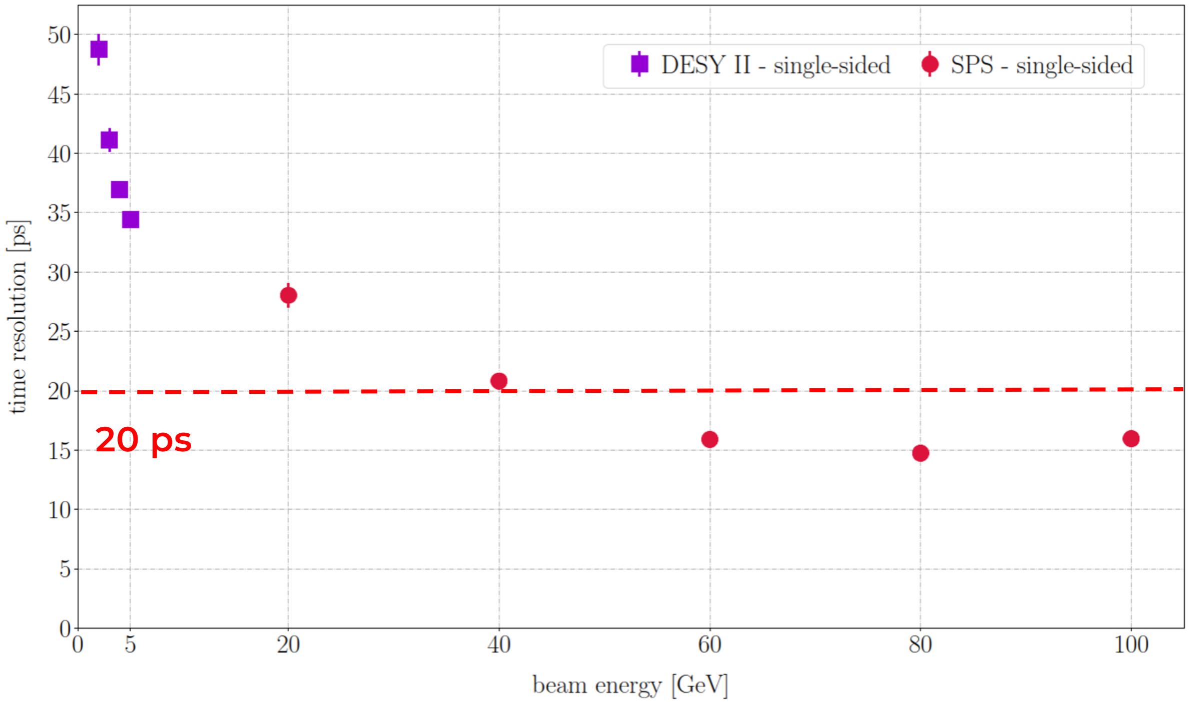



# SpaCal - W Absorber - Polystyrene Fibres

Energy resolution




Time resolution



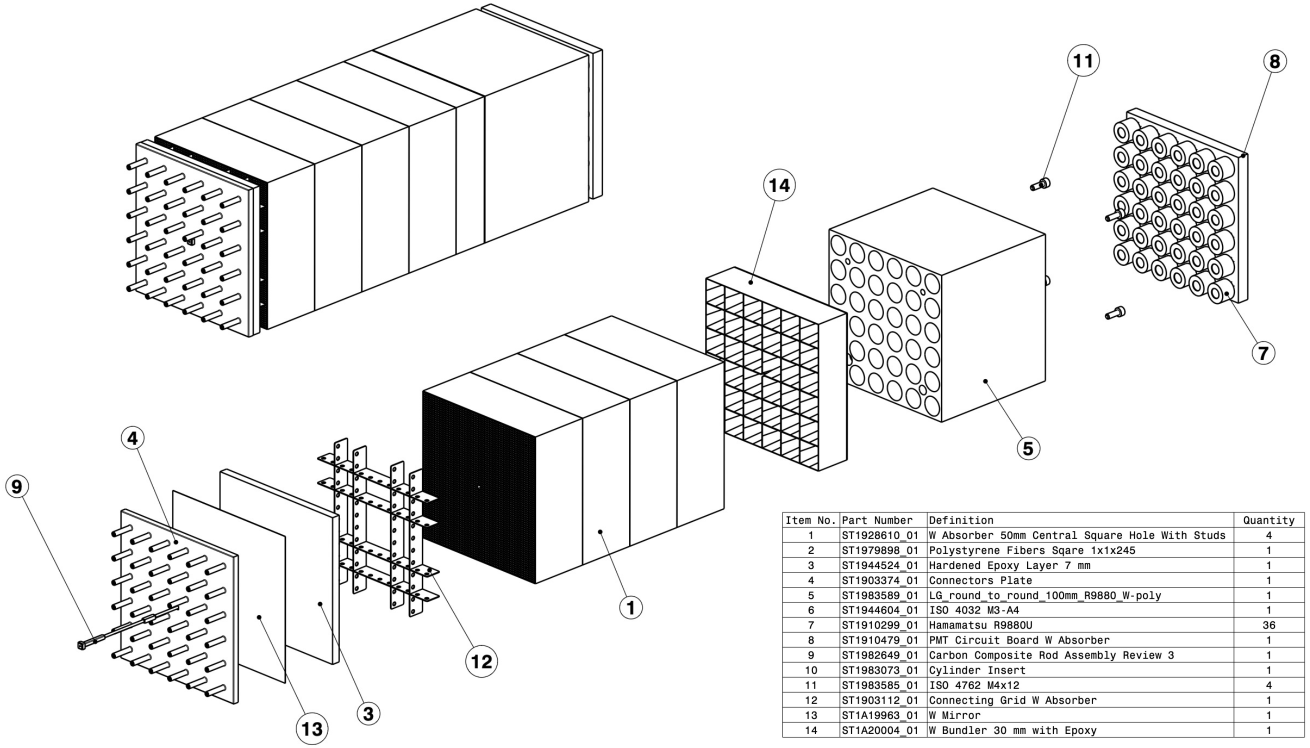

- **Energy resolution at 3°+3°:**
  - Noise contribution subtracted
  - R14755U-100 PMT
  - Symmetric LGs: square to octagon
  - Sampling term: $9.9 \pm 0.1$ %
  - Constant term: $1.13 \pm 0.01$ %
  - Very good agreement with simulation

- **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

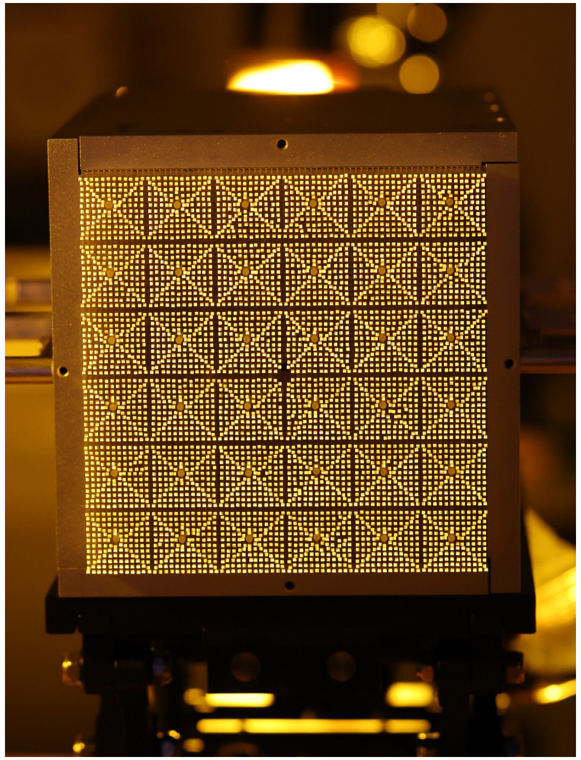
**Performance in line with targets**

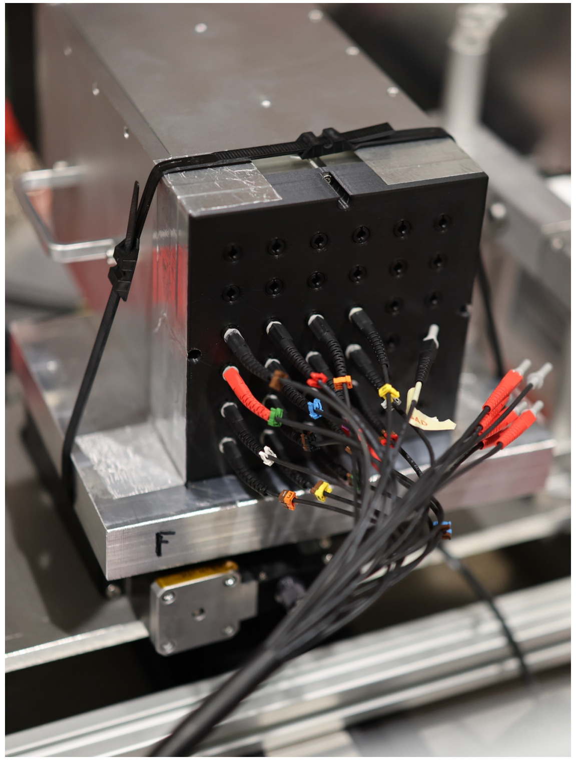
LHCB-TDR-024 NIM A 1079, 170608 (2025)

# 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 |

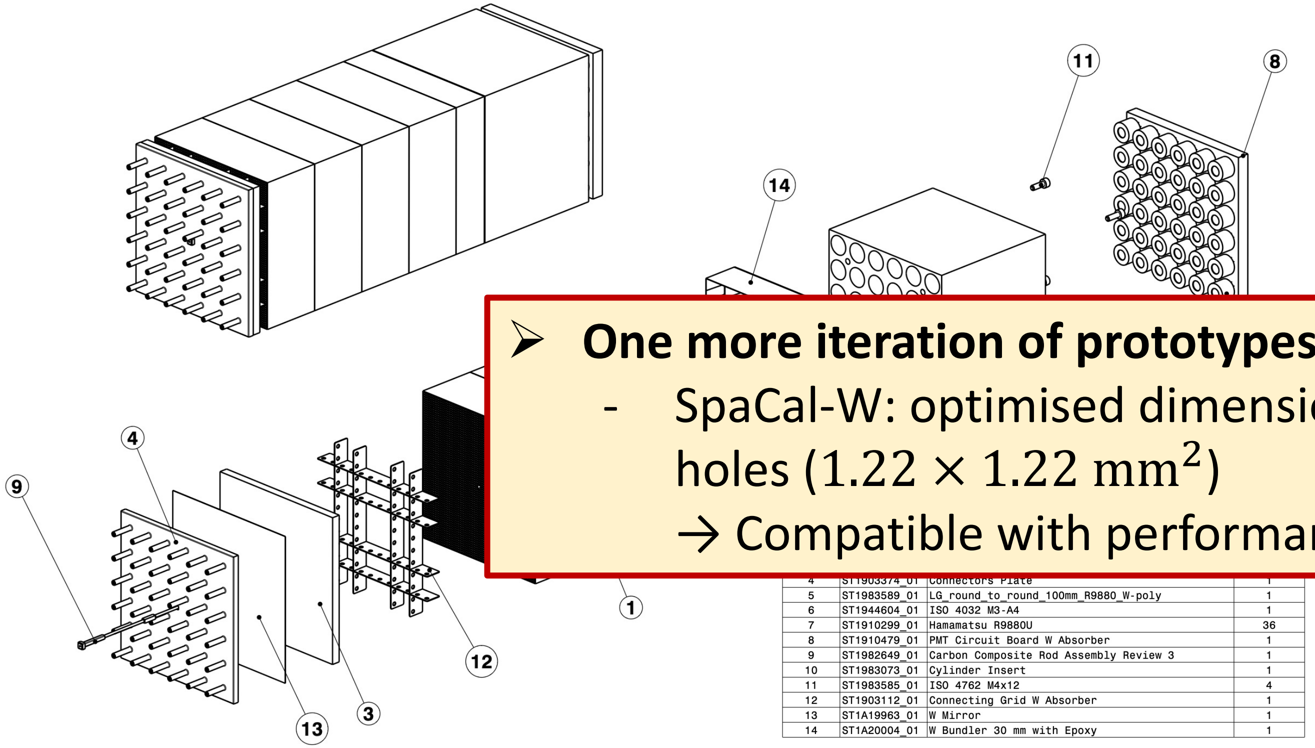




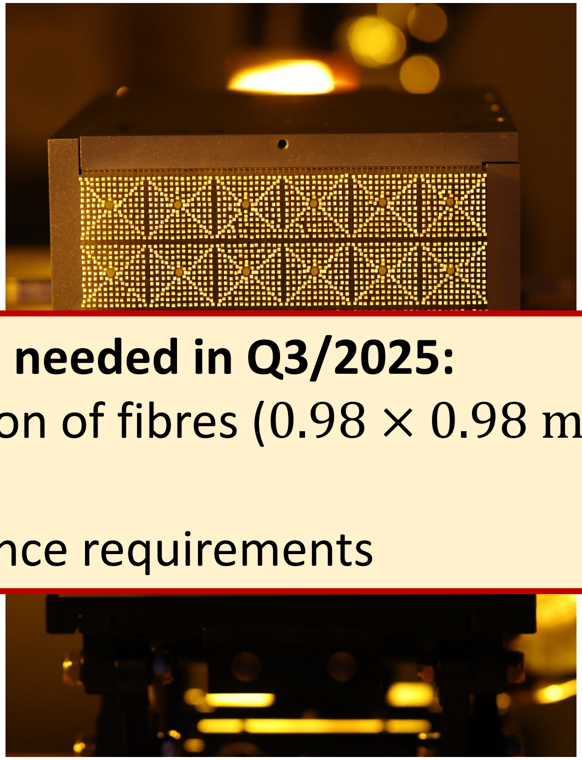

Test beam in May 2025 at CERN SPS:

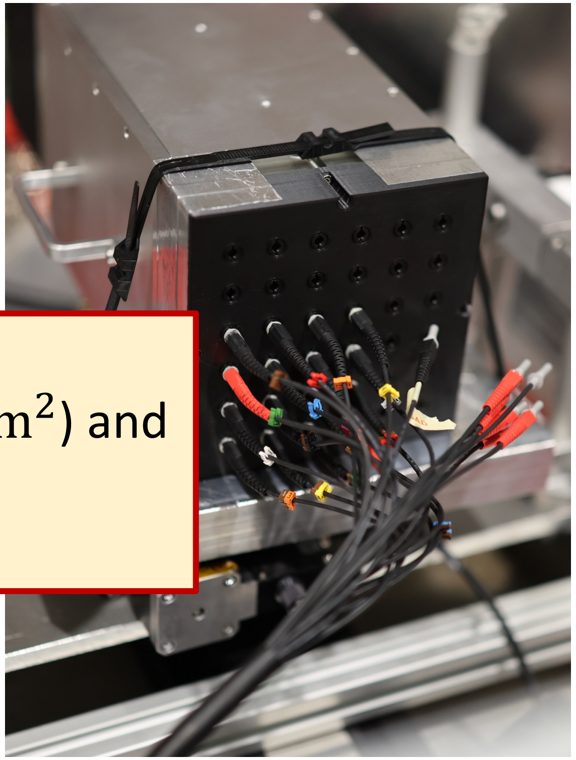
- First test of full Run 4 chain with new prototypes:
  - W absorbers
  - 3HF green plastic fibres (square fibres $1{\times}1\ \mathrm{mm}^2$)
  - Optics assembly with bundlers and long “hollow” light guides
  - R9880U PMTs
  - Cable clipping circuits
  - 10 meter signal cables
  - Read-out with Run 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

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

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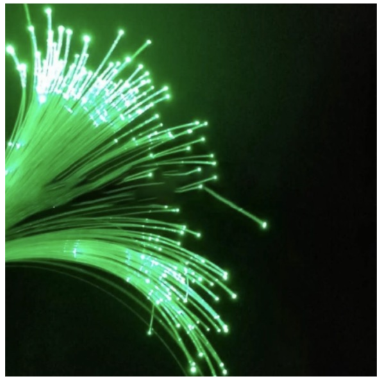
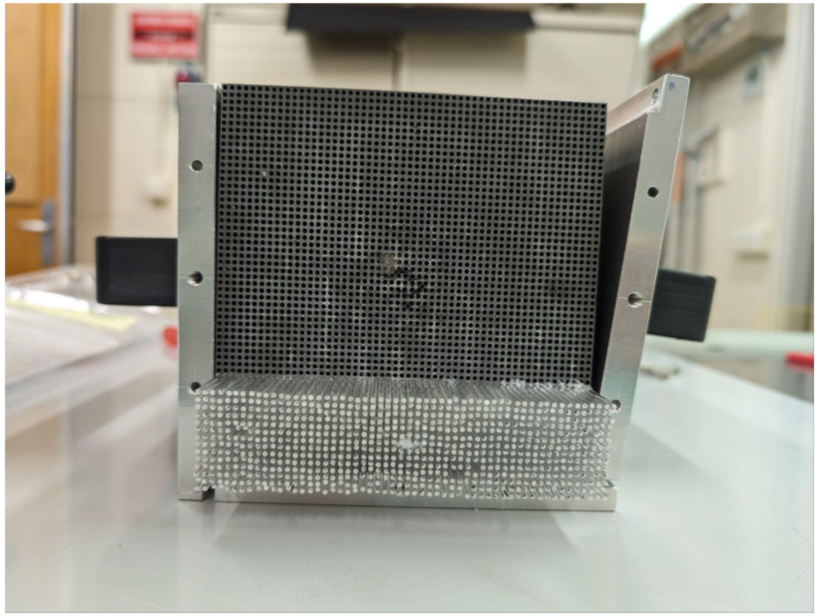
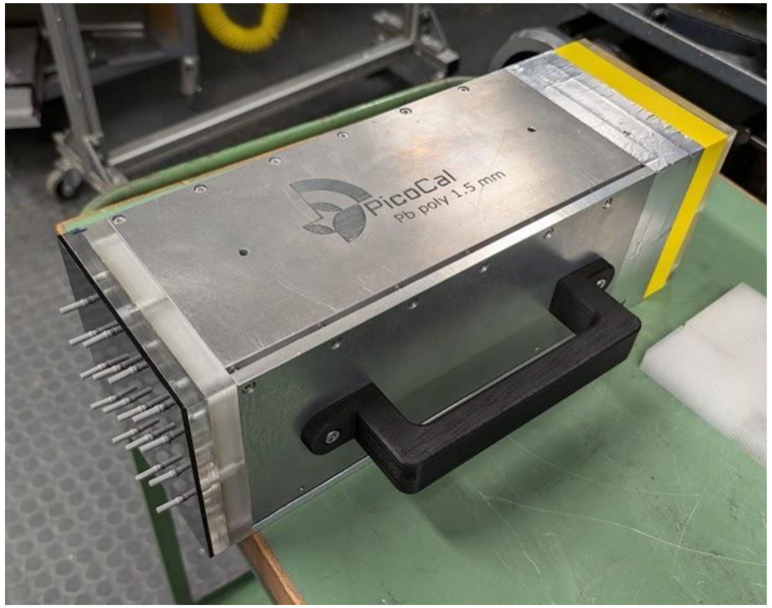
# SpaCal - Pb Absorber - Polystyrene Fibres

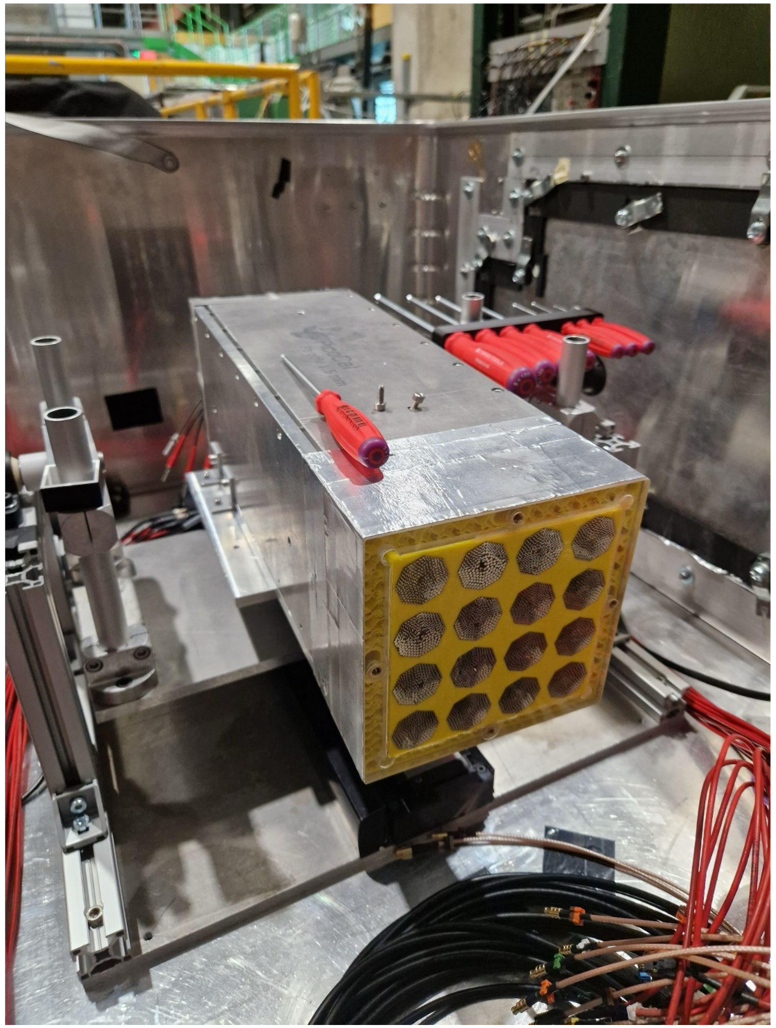
- **Module 0 prototype assembled in June 2024**
  - Pb casting technology for absorber production
  - Kuraray 3HF green fibres Ø 1.5 mm





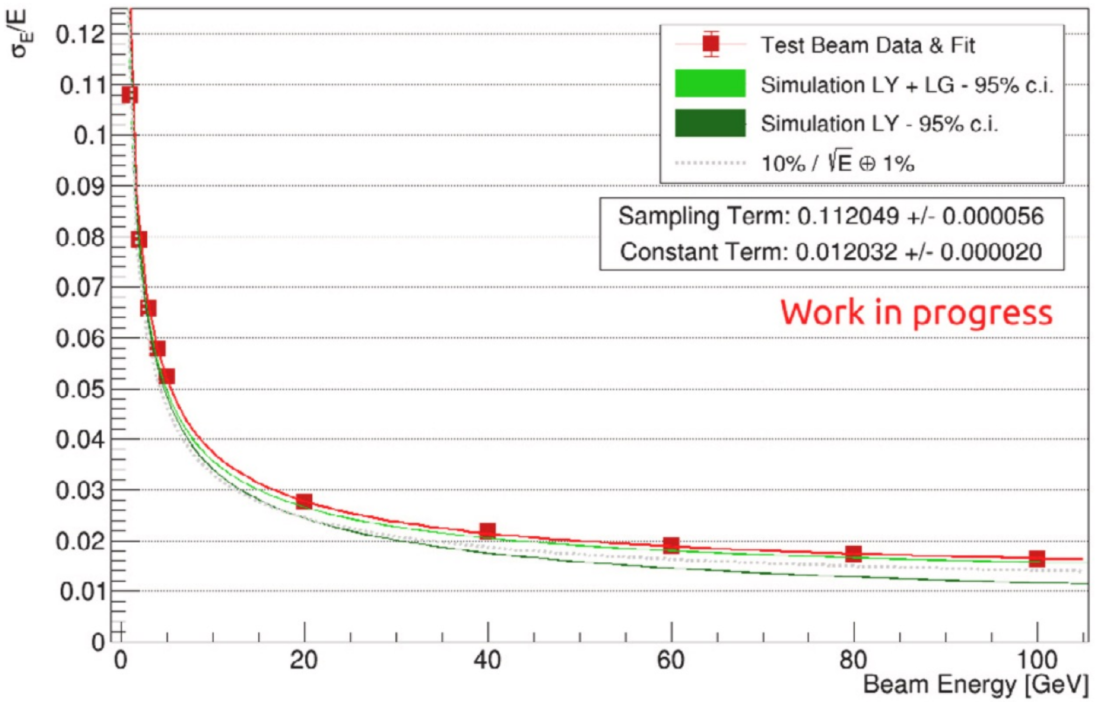




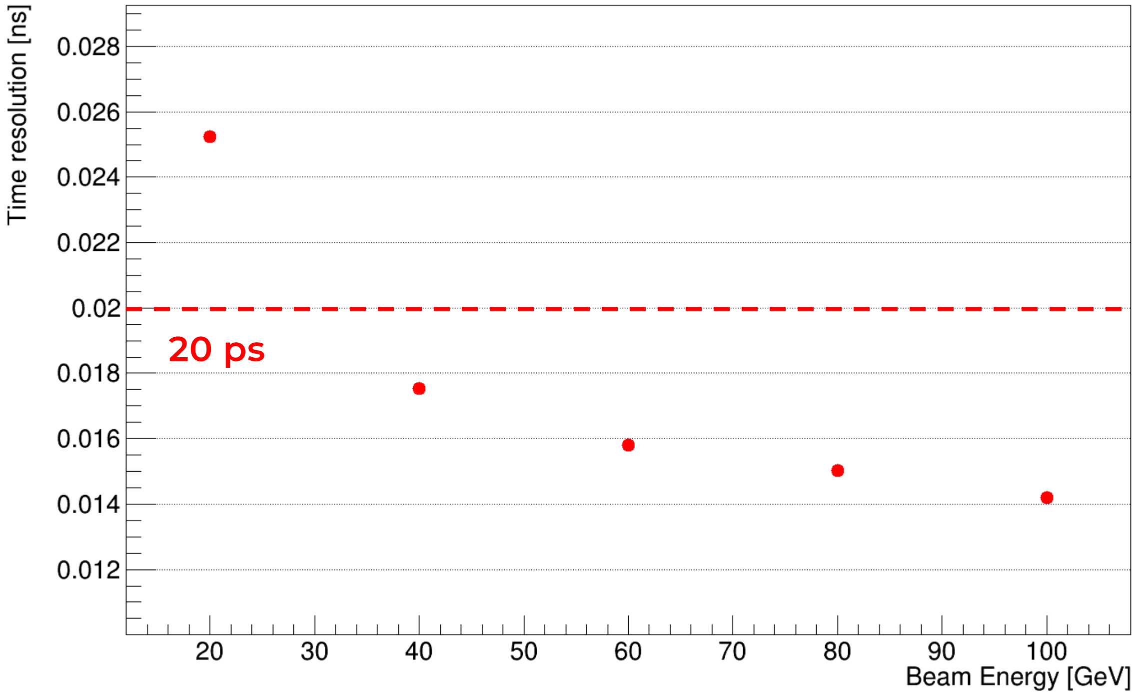


# SpaCal - Pb Absorber - Polystyrene Fibres

Energy resolution




Time resolution




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

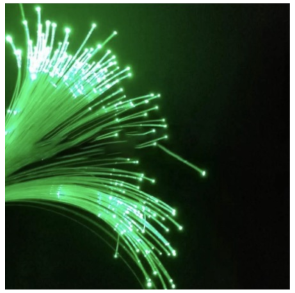
- **Time resolution at 3°+3°:**
  - Multi-Anode(R7600U-20) PMT with 4 channels
  - Asymmetric LGs
  - Double-sided readout
  - Time resolution above 20 GeV: better than 20 ps

**Performance in line with targets**

NIM A 1079, 170608 (2025)

# Ongoing R&D: Plastic Scintillator

- **3HF-based green fibres are a candidate material for the <u>Upgrade II</u>:**
  - Better radiation tolerance than SCSF-78 matches requirements
  - However, longer decay time affects time resolution

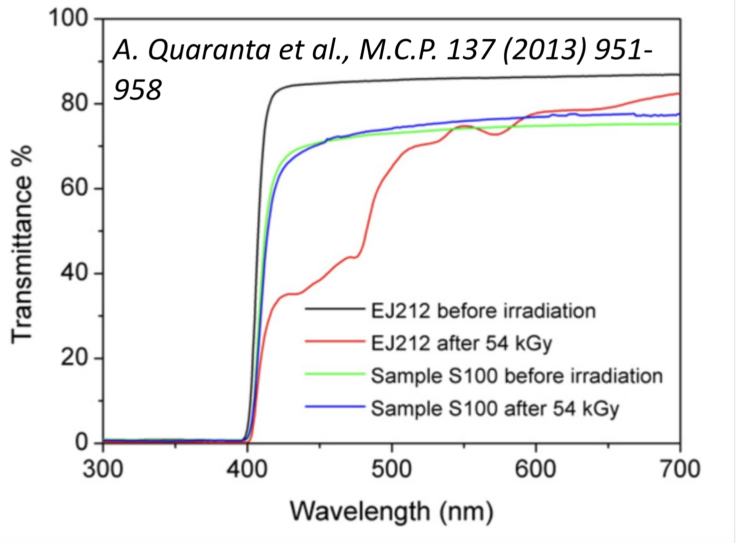


Formulations [1)]

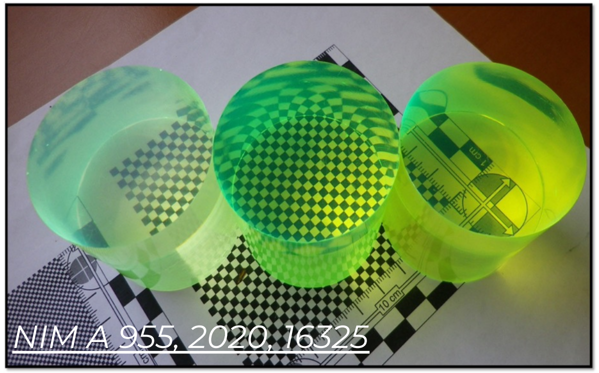
*Kuraray Datasheet*

| Description | Emission Color | Emission Spectra | Emission Peak[nm] | Decay Time [ns] | Att.Leng. [2)] [m] |
|---|---|---|---|---|---|
| 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 |

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

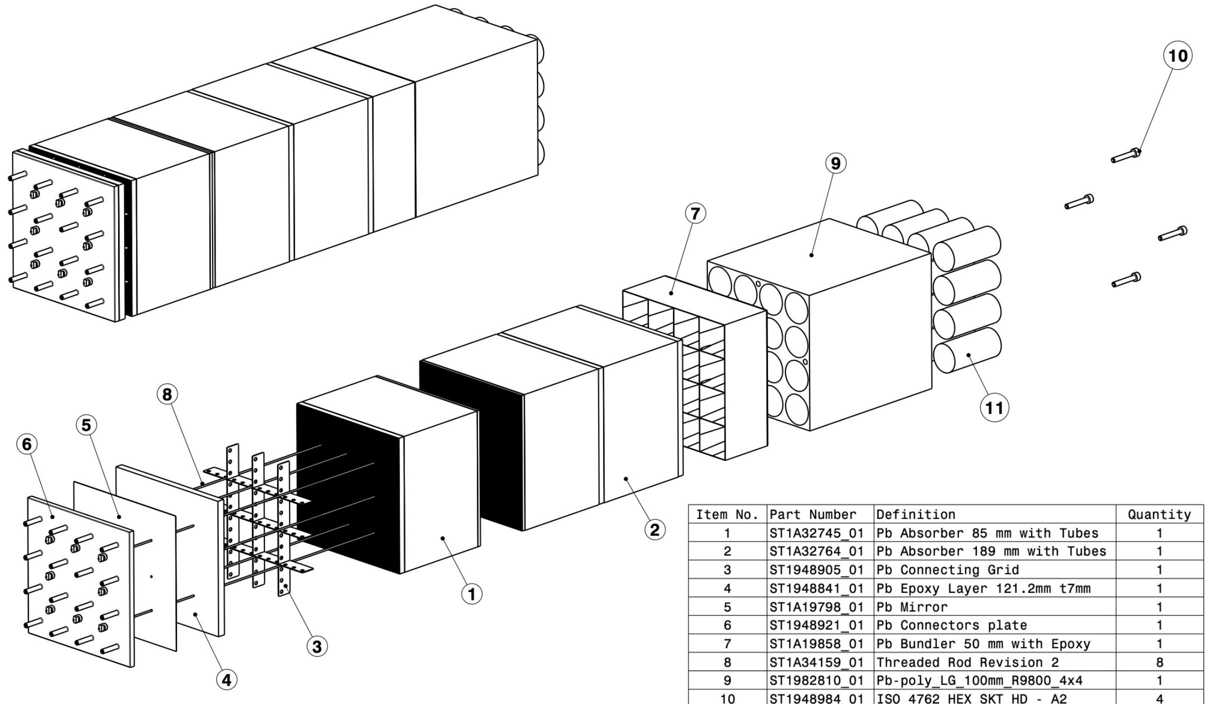



- **R&D ongoing on alternative materials:**
  - Hosts other than polystyrene
  - Green emitters
  - Scintillating glasses

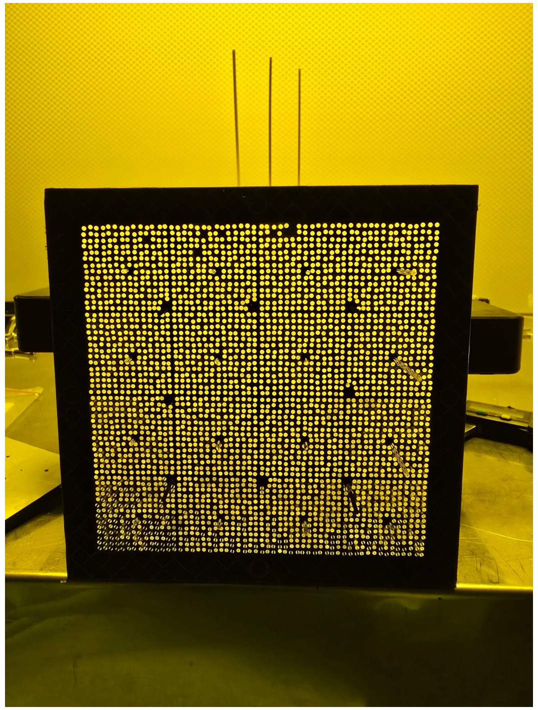


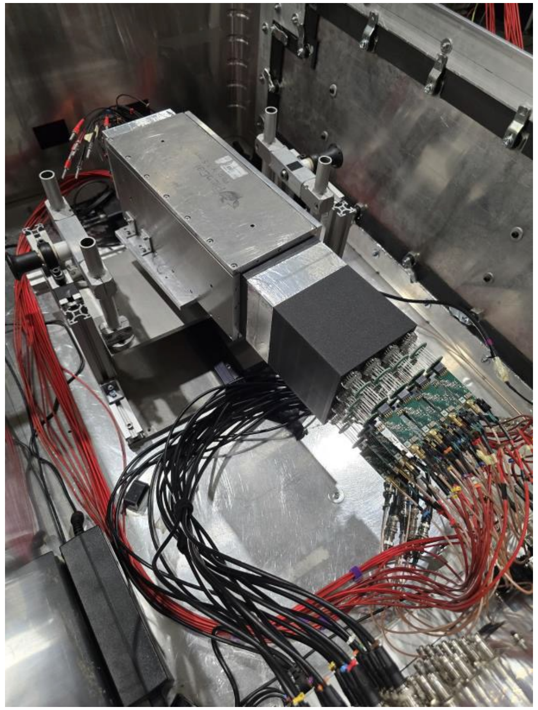
NIM A 955, 2020, 16325

# Ongoing R&D: Assembly for LS3




| Item No. | Part Number | Definition | Quantity |
|---|---|---|---|
| 1 | ST1A32745_01 | Pb Absorber 85 mm with Tubes | 1 |
| 2 | ST1A32764_01 | Pb Absorber 189 mm with Tubes | 1 |
| 3 | ST1948905_01 | Pb Connecting Grid | 1 |
| 4 | ST1948841_01 | Pb Epoxy Layer 121.2mm t7mm | 1 |
| 5 | ST1A19798_01 | Pb Mirror | 1 |
| 6 | ST1948921_01 | Pb Connectors plate | 1 |
| 7 | ST1A19858_01 | Pb Bundler 50 mm with Epoxy | 1 |
| 8 | ST1A34159_01 | Threaded Rod Revision 2 | 8 |
| 9 | ST1982810_01 | Pb-poly_LG_100mm_R9800_4x4 | 1 |
| 10 | ST1948984_01 | ISO 4762 HEX SKT HD - A2 | 4 |
| 11 | ST1986509_01 | R9800U Base Set | 16 |



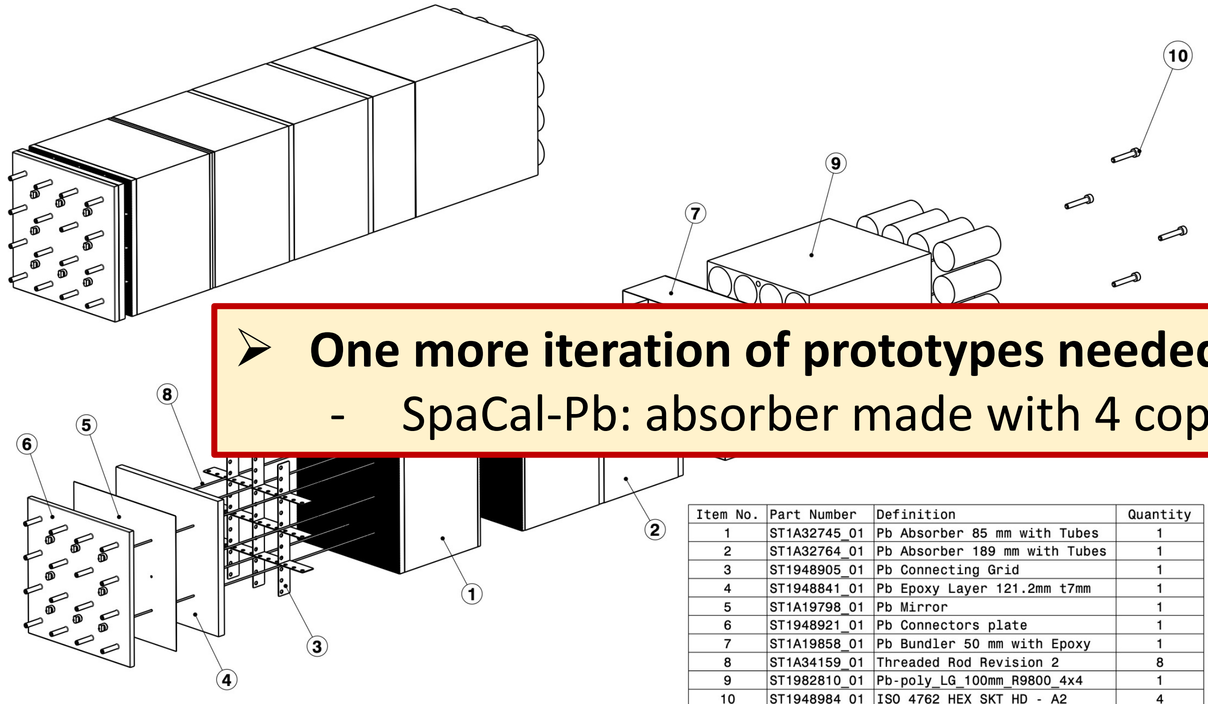


Test beam in May 2025 at CERN SPS:

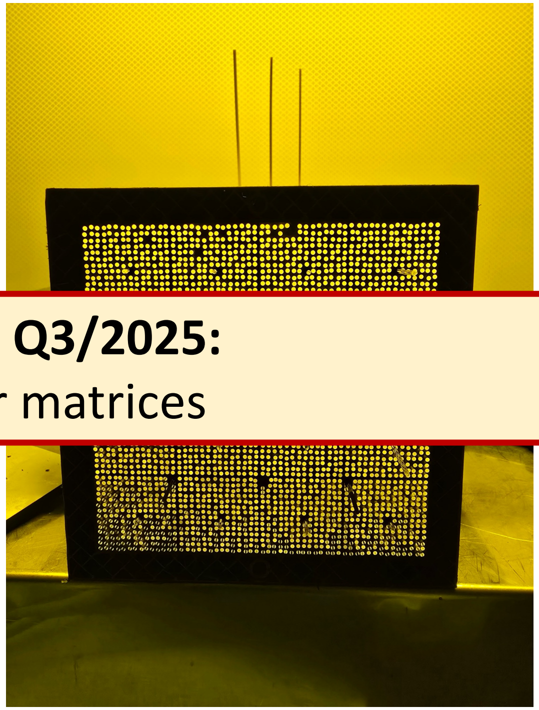
➢ First test of full Run 4 chain with new prototypes:

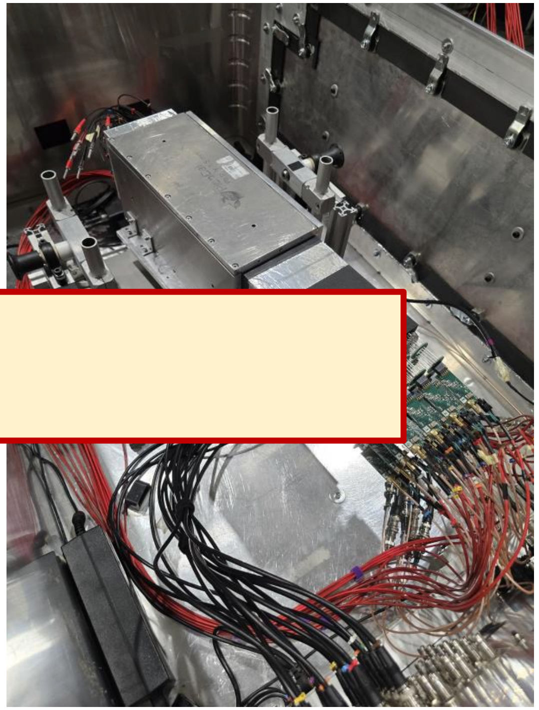
- Pb absorbers
- 3HF green plastic fibres (round fibres Ø=1.5 mm)
- Optics assembly with bundlers and long “hollow” light guides
- R9800 PMTs
- Cable clipping circuits
- 10 meter signal cables
- Read-out with Run 3 & 4 front-end boards electronics

# Ongoing R&D: Assembly for LS3




| Item No. | Part Number | Definition | Quantity |
|---|---|---|---|
| 1 | ST1A32745_01 | Pb Absorber 85 mm with Tubes | 1 |
| 2 | ST1A32764_01 | Pb Absorber 189 mm with Tubes | 1 |
| 3 | ST1948905_01 | Pb Connecting Grid | 1 |
| 4 | ST1948841_01 | Pb Epoxy Layer 121.2mm t7mm | 1 |
| 5 | ST1A19798_01 | Pb Mirror | 1 |
| 6 | ST1948921_01 | Pb Connectors plate | 1 |
| 7 | ST1A19858_01 | Pb Bundler 50 mm with Epoxy | 1 |
| 8 | ST1A34159_01 | Threaded Rod Revision 2 | 8 |
| 9 | ST1982810_01 | Pb-poly_LG_100mm_R9800_4x4 | 1 |
| 10 | ST1948984_01 | ISO 4762 HEX SKT HD - A2 | 4 |
| 11 | ST1986509_01 | R9800U Base Set | 16 |





- **One more iteration of prototypes needed in Q3/2025:**
  - SpaCal-Pb: absorber made with 4 copper matrices

Test beam in May 2025 at CERN SPS:

- First test of full Run 4 chain with new prototypes:
  - Pb absorbers
  - 3HF green plastic fibres (round fibres Ø=1.5 mm)
  - Optics assembly with bundlers and long “hollow” light guides
  - R9800 PMTs

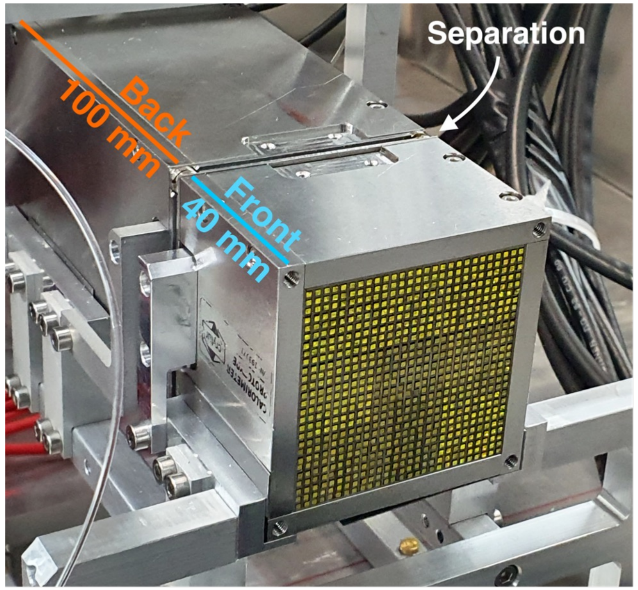
  - Cable clipping circuits
  - 10 meter signal cables
  - Read-out with Run 3 & 4 front-end boards electronics

# Outline

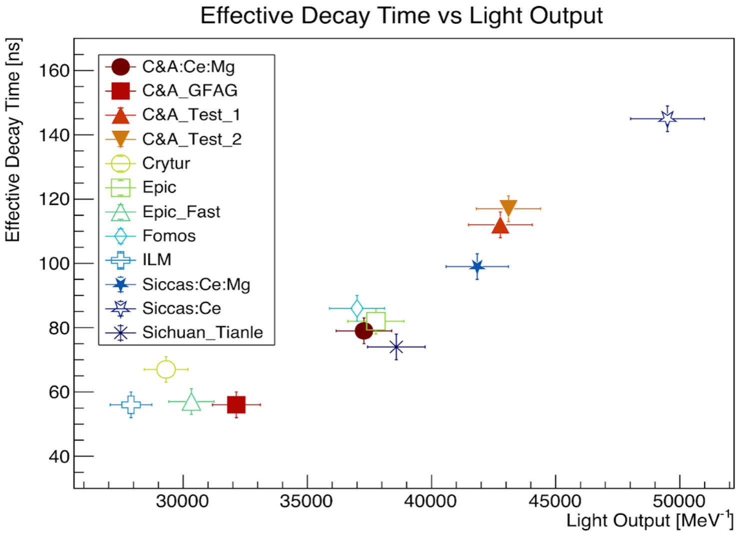
1. Introduction
2. R&D and latest test beam results
   1) SpaCal-W with polystyrene fibers for LS3
   2) SpaCal-Pb with polystyrene fibers
   3) SpaCal-W with crystal fibers for LS4
   4) Shashlik with fast WLS fibers
3. Summary and conclusion

# SpaCal - W Absorber - Crystal Fibres

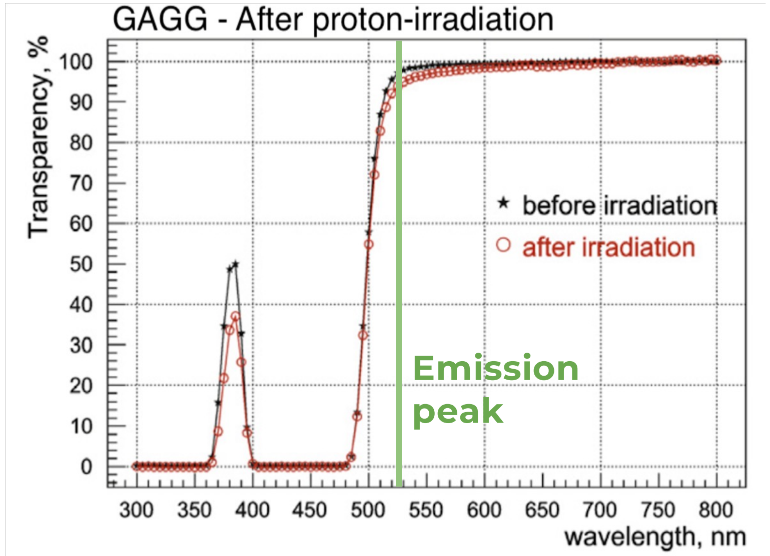
**SPACAL prototype with W absorber and garnet crystals**




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




NIM A 1000, 165231 (2021)

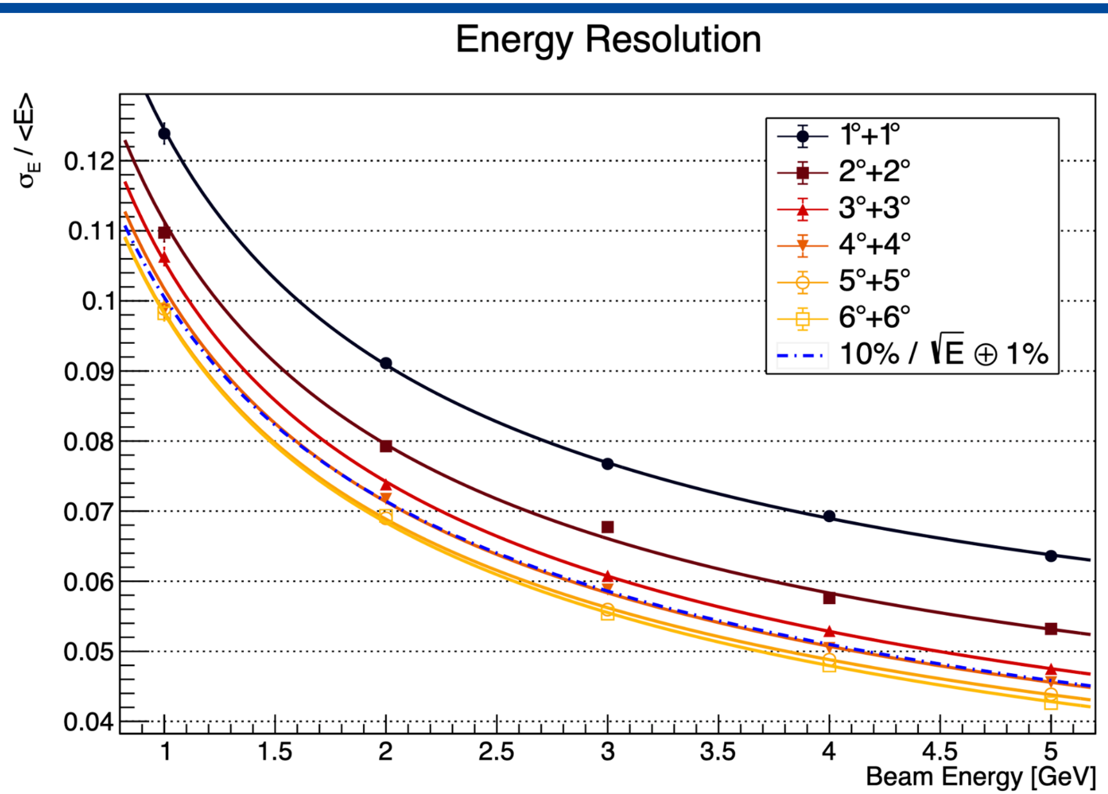


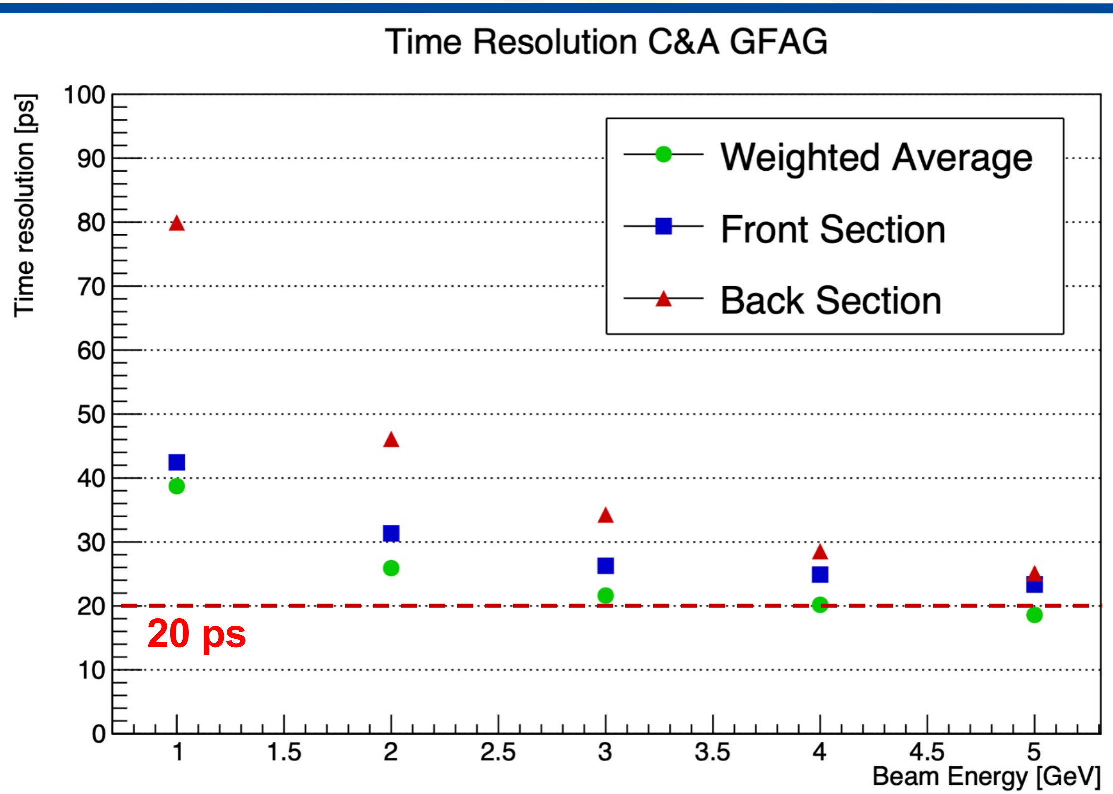

NIM A 816 (2016) 176

**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



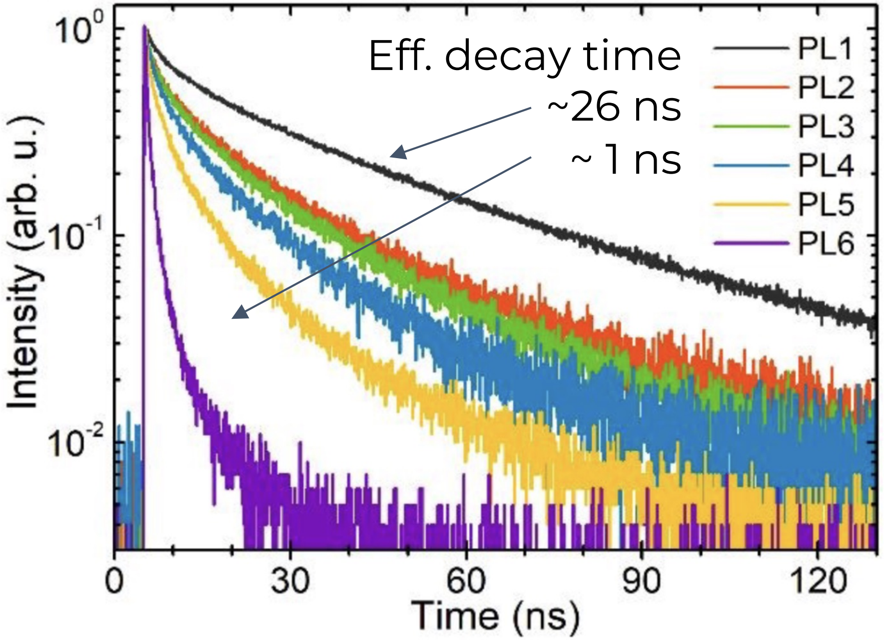

- **Resolution improves increasing the incidence angle**
- **Energy resolution at 3°+3°:**
  - Sampling term: $10.2 \pm 0.1\ \%$
  - Constant term: $1 - 2\ \%$

- **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
  - $18.5 \pm 0.2$ ps @ 5 GeV

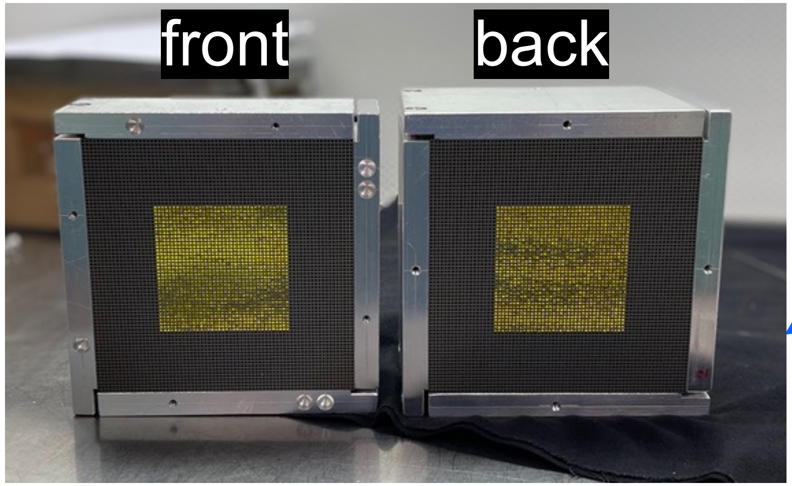
NIM A 1045, 167629 (2022)

**Performance in line with targets**

# Ongoing R&D: Accelerating Scintillation

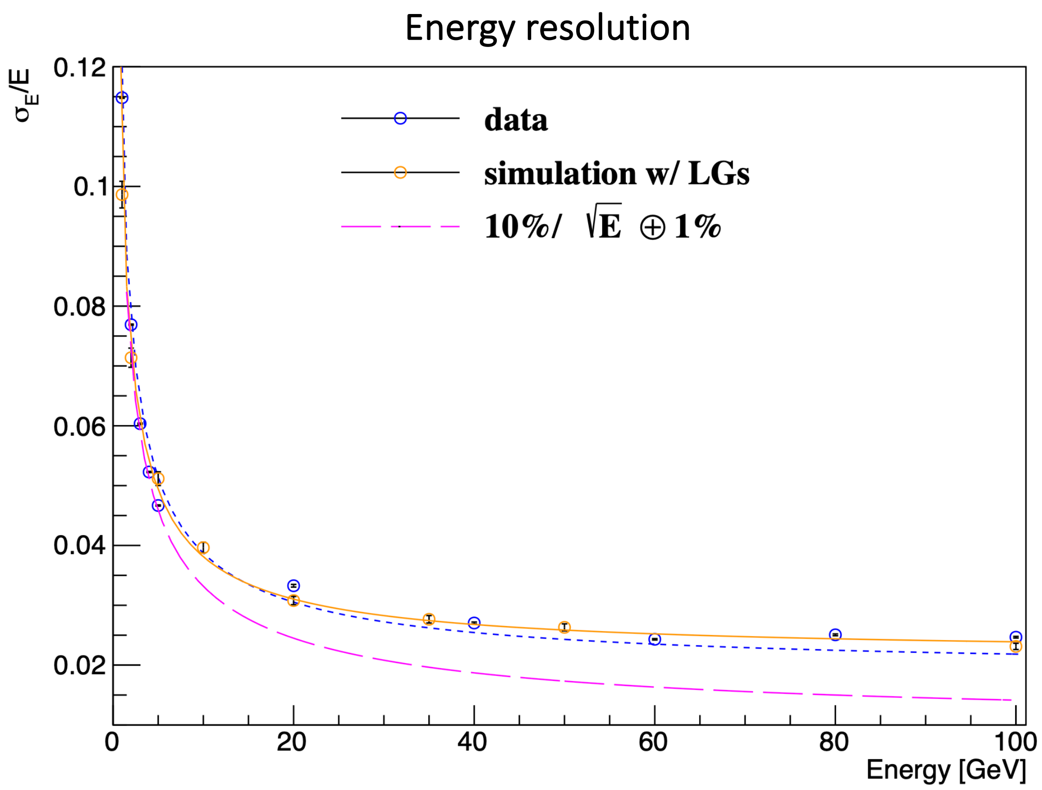


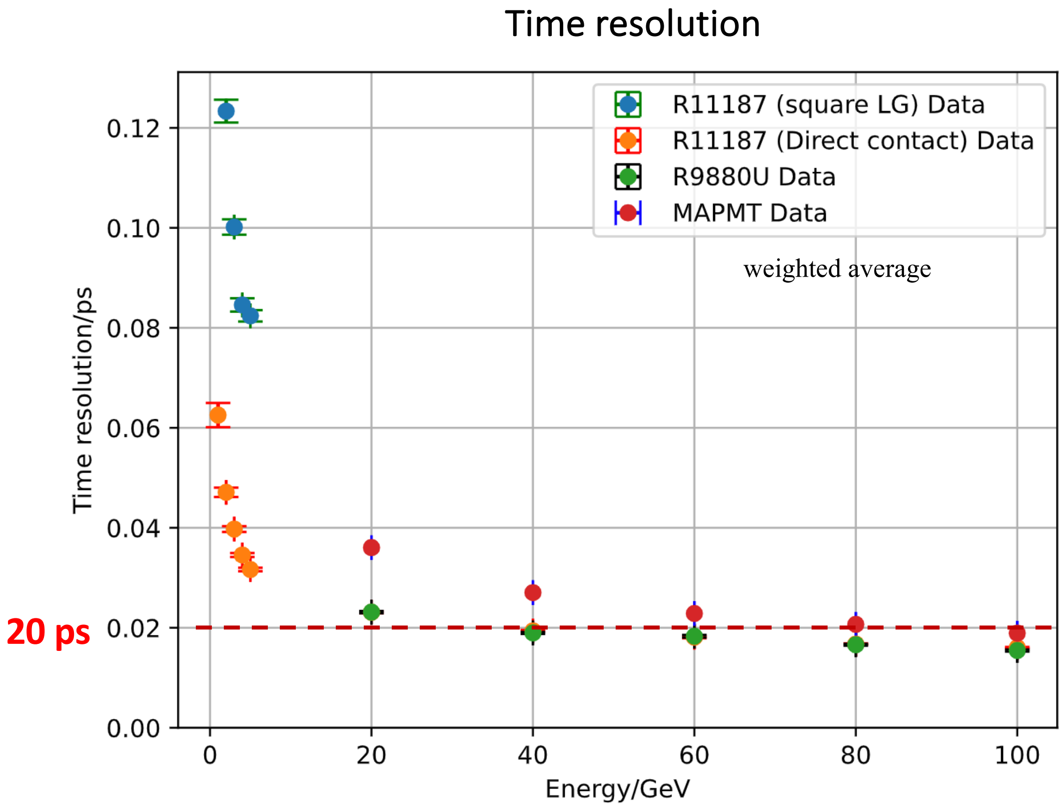

*Material Advances, 2022, 3, 6842*




- **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 $\sim 20$ ns
  - 3D-printed absorber with LaserAdd, China
  - Under characterisation in testbeam

# SpaCal - W Absorber - Crystal Fibres




- **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

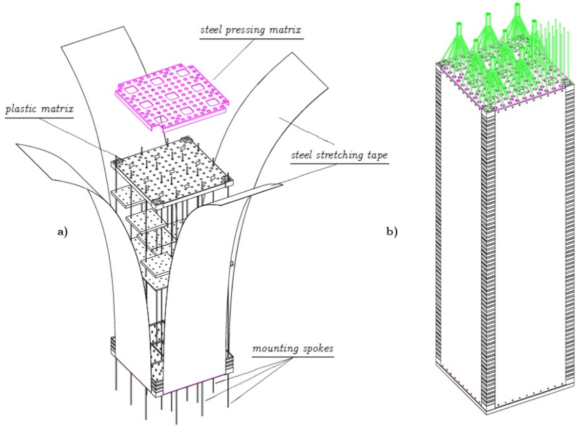
# Shashlik R&D

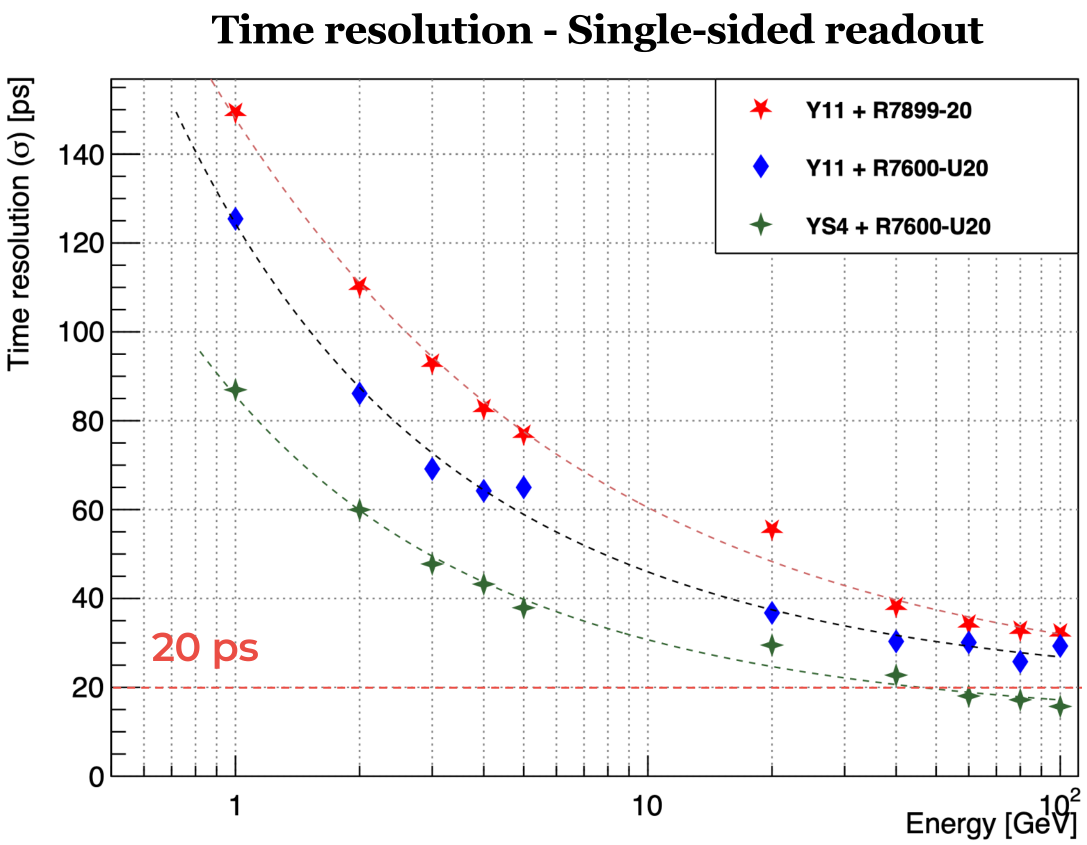
- **Current LHCb Shashlik modules have good time properties**
- **Improvements:**
  - Replacing WLS fibres (Kuraray)

    - 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)




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

# Outline

1. Introduction
2. R&D and latest test beam results
    1) SpaCal-W with polystyrene fibers for LS3
    2) SpaCal-Pb with polystyrene fibers
    3) SpaCal-W with crystal fibers for LS4
    4) Shashlik with fast WLS fibers
3. Summary and conclusion

# Summary and conclusion

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

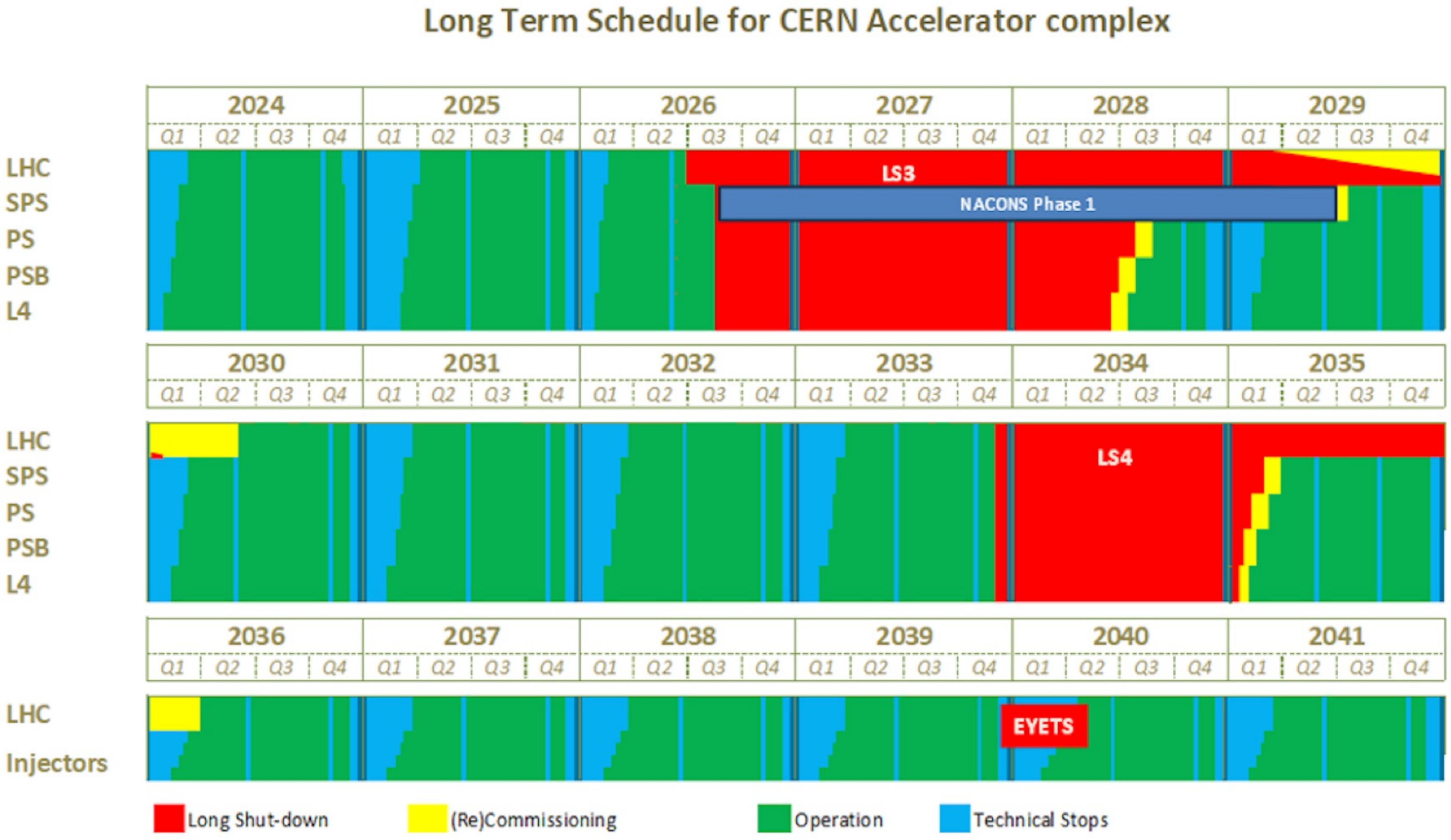
- **The innermost 176 modules need to be replaced in LS3 due to radiation damage**
  - SpaCal with Tungsten/Lead absorber and plastic fibres meets the requirements
- **The Upgrade II in LS4 introduces picosecond-level timing and more demanding radiation hardness requirements**
  - Better than 20 ps achieved 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

PicoCal

Thanks for your attention!

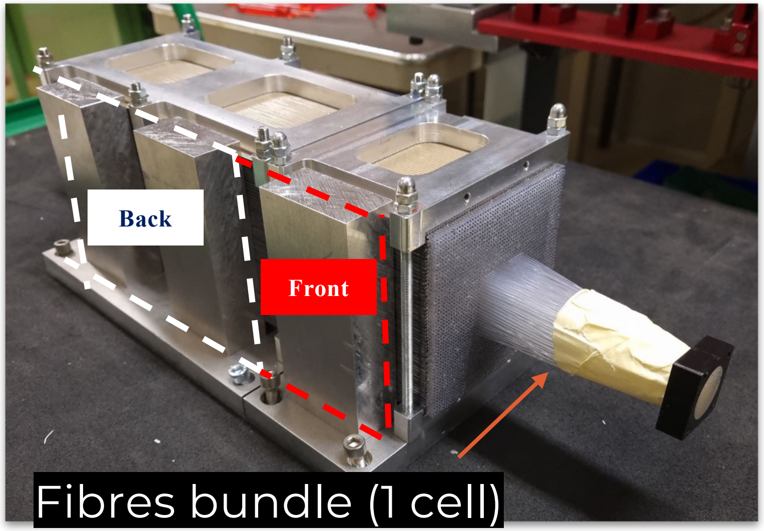
# Back up

# Updated CERN accelerator schedule



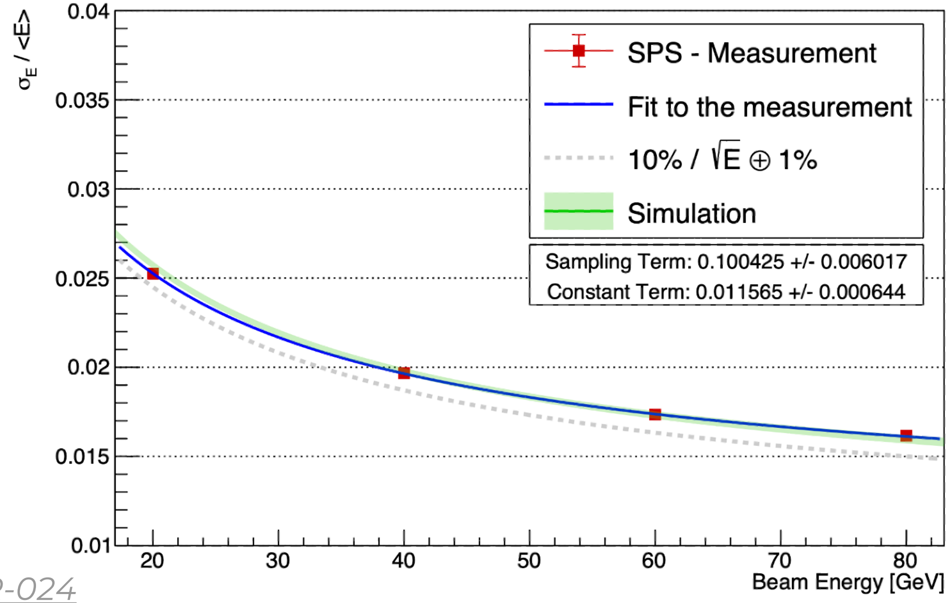

- Run 3 extended till end of June 2026
- LHC restart for Run 4 in 2030
- LHC LS4 moved by one year to 2034-35
- LS5 becomes EYTES
- Also impact on SPS test beams!

# SpaCal - Pb Absorber - Polystyrene Fibres

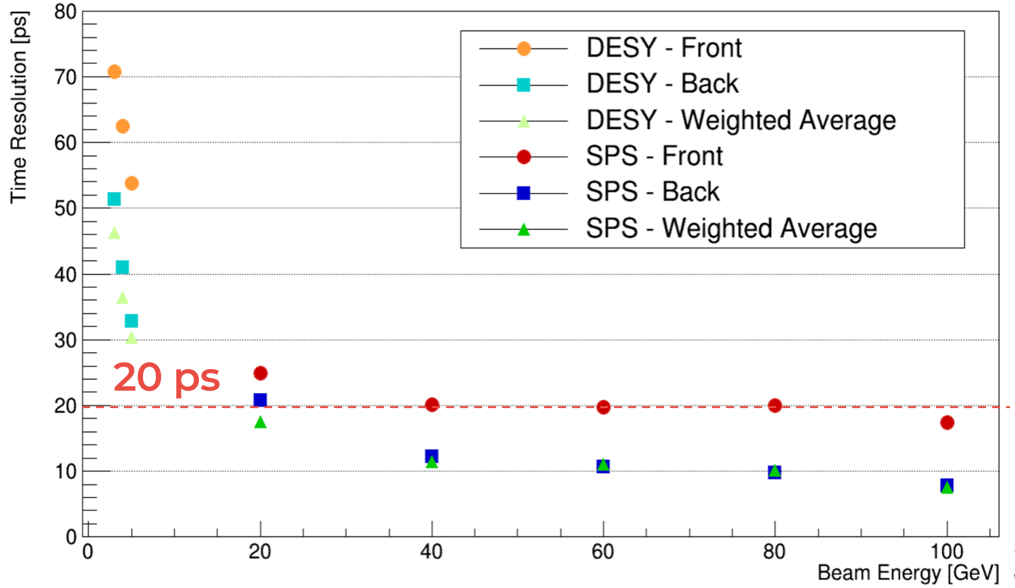



- **Pb absorber and polystyrene fibres:**
  - 8 + 21 cm long (7 + 18 $X_0$)
  - Reflective mirror between sections
  - Kuraray SCSF-78 round fibres $\text{Ø} = 1.0$ mm

Energy resolution




Time resolution




LHCB-TDR-024

# SpaCal - Pb Absorber - Polystyrene Fibres

- **Pb absorber and polystyrene fibres:**
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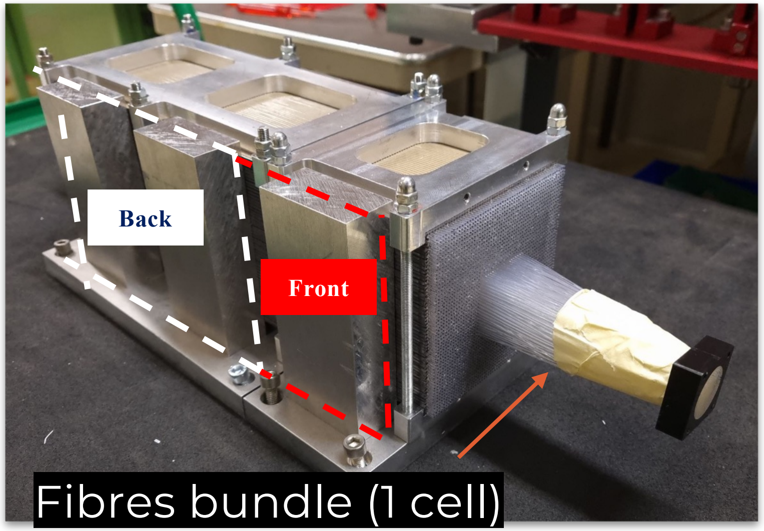
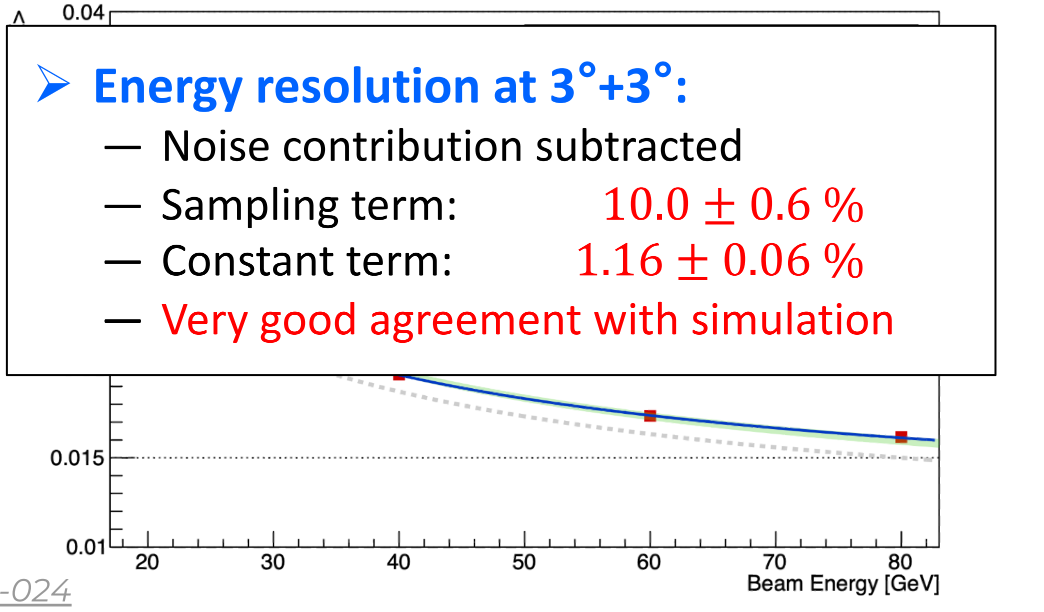
  - Kuraray SCSF-78 round fibres $Ø = 1.0$ mm



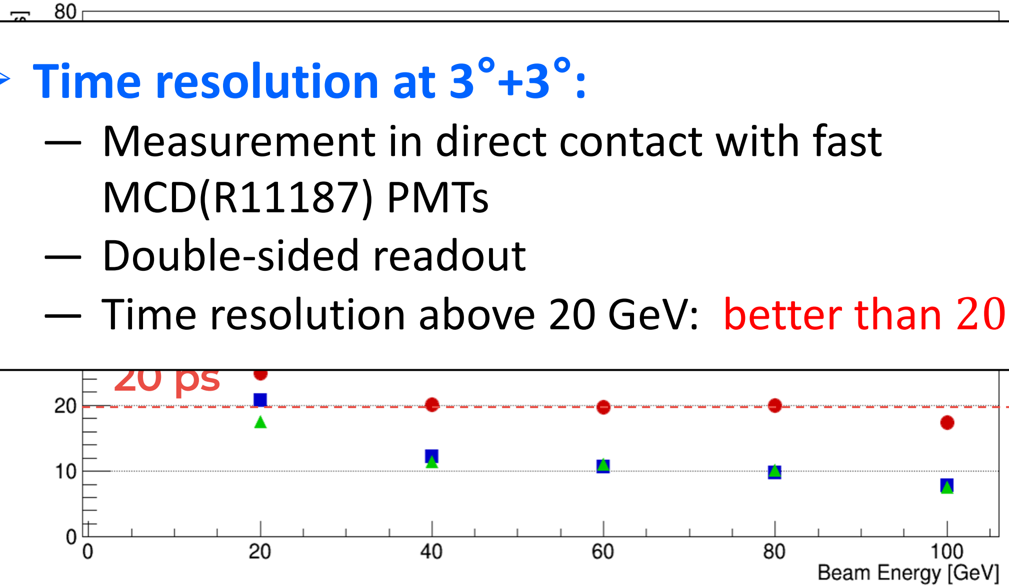

**Performance in line with targets**

Energy resolution




- **Energy resolution at 3°+3°:**
  - Noise contribution subtracted
  - Sampling term: $10.0 \pm 0.6\ \%$
  - Constant term: $1.16 \pm 0.06\ \%$
  - 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