2024 International Workshop on CEPC

PicoCal: fast-timing and radiation-tolerant ECAL for LHCb Upgrade II

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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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   1) SpaCal-W with polystyrene fibers for LS3
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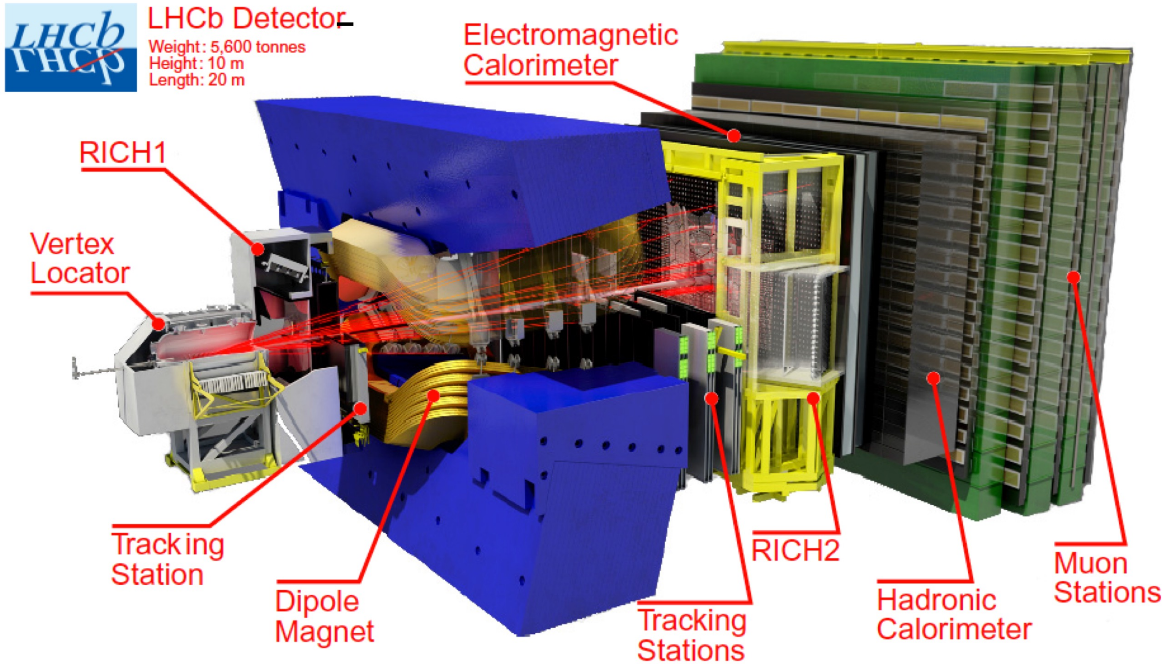
LHCb and physics goal

- **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**
    - **Dark sector**
    - **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:	$\sigma_m = 8$ MeV/c^2 for $B \to J/\psi X$ ($m_{J/\psi}$ 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:	$\Delta E/E = 10\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$

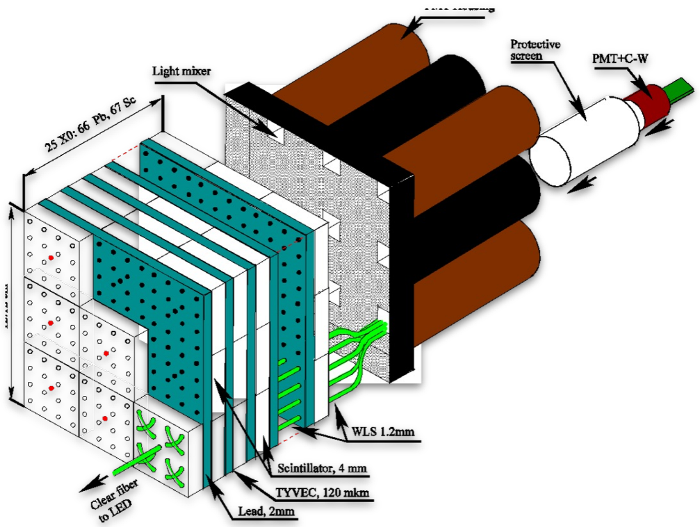


A single-arm forward spectrometer covering $2 < \eta < 5$

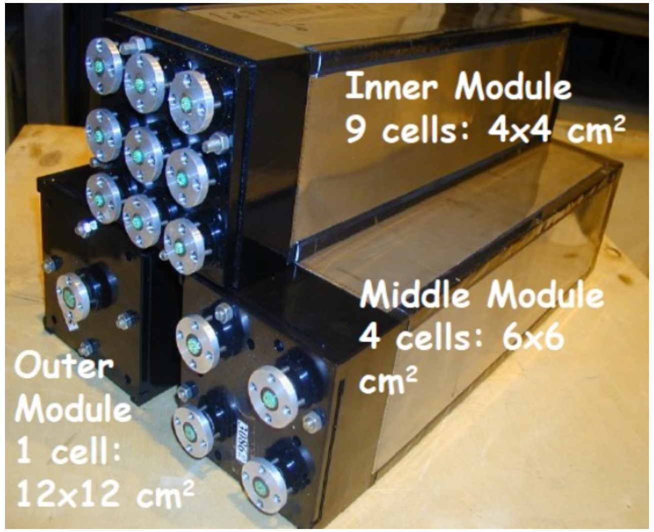
LHCB-TDR-023, LHCB-TDR-024

The Current LHCb ECAL

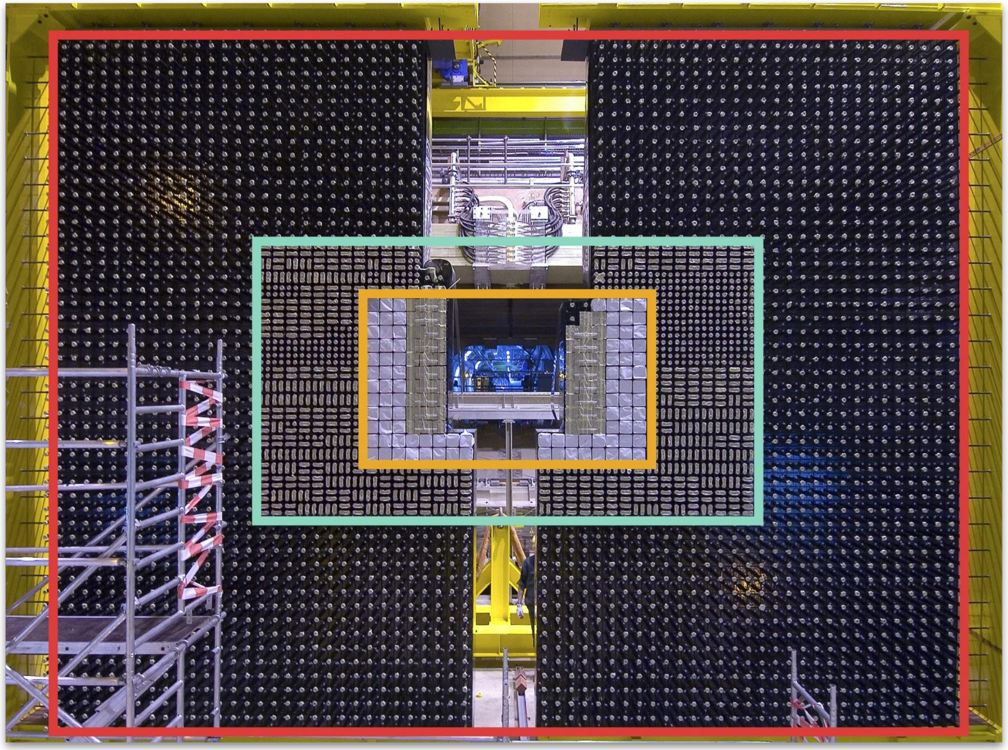
- **ECAL is essential to all measurements involving neutrals and electrons**
- **Optimised for π_0 and γ identification in the few GeV to 100 GeV region at $2 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$**



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



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



View from the back

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

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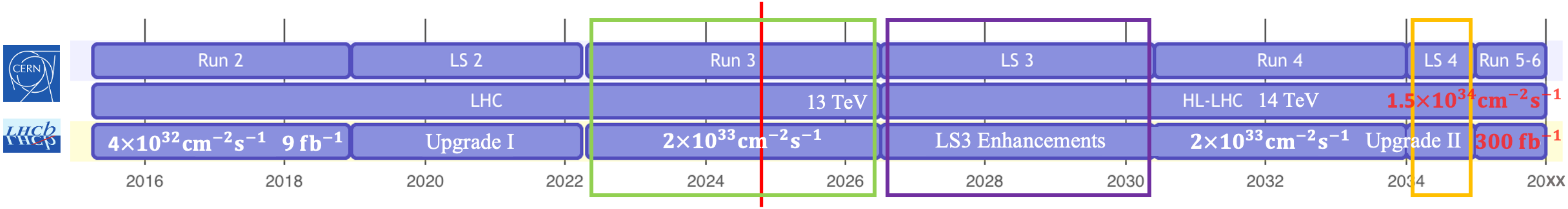
Motivation to upgrade

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



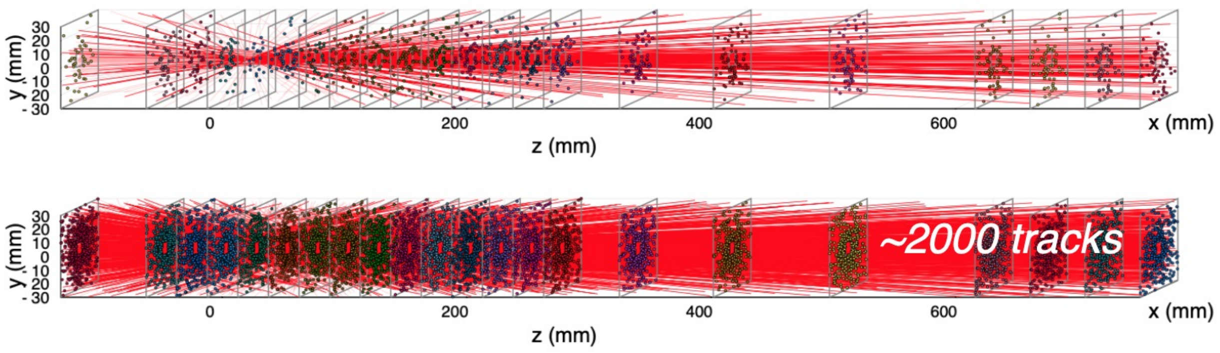
— **Upgrade II to be installed at LS4:** $1.5\times10^{34}cm^{-2}s^{-1}$

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

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

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

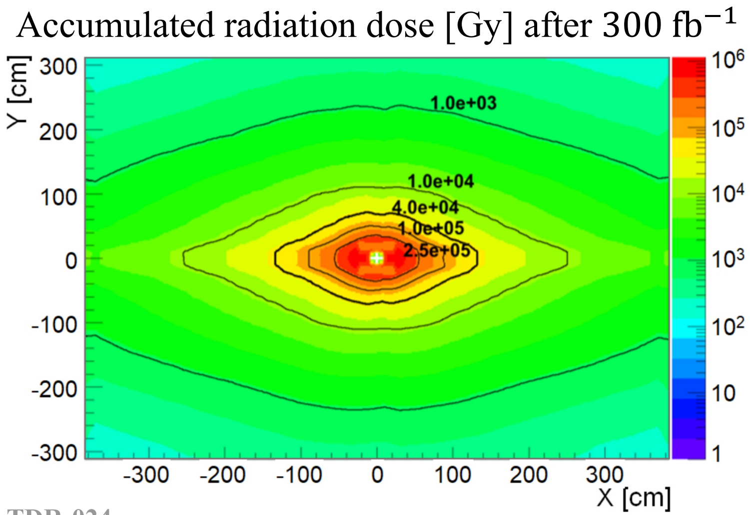
Motivation to upgrade

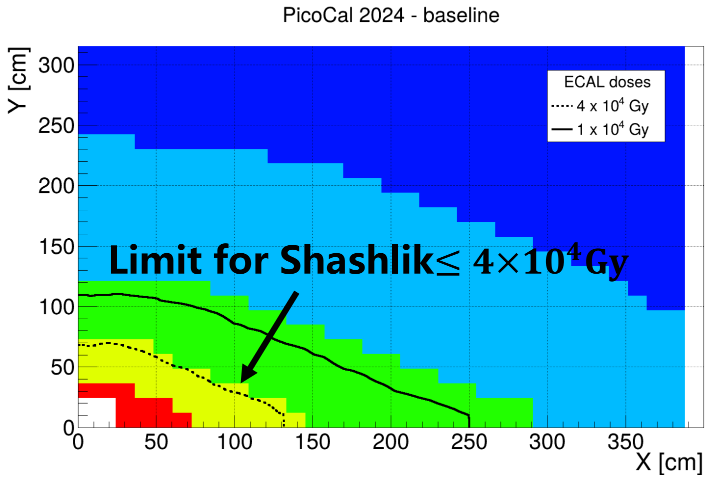
Requirements for the Upgrade II:

- **Radiation doses up to $1\ \mathrm{MGy}$ and $\leq 6\times10^{15}\ 1\ \mathrm{MeV\ neq/cm^2}$ 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 $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$**





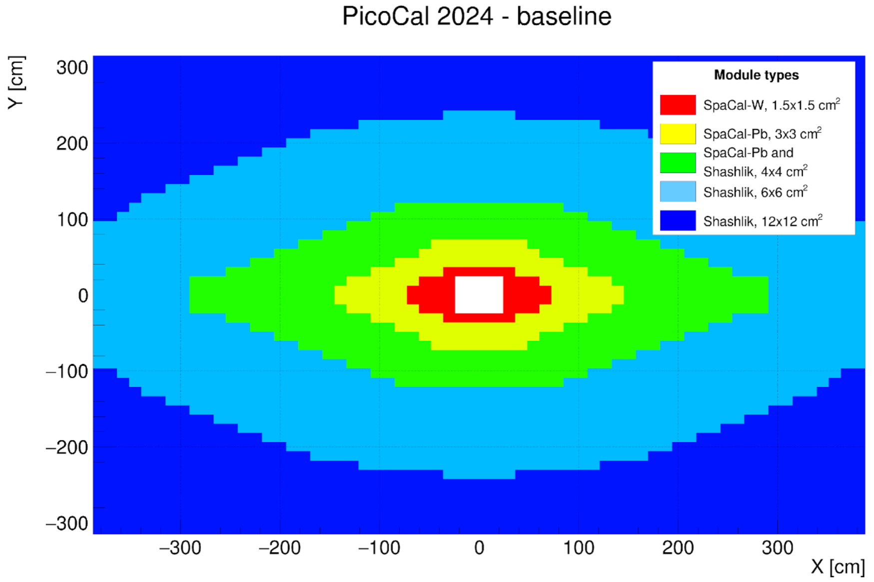
Technologies for ECAL Upgrade II

SPACAL technology for inner region.

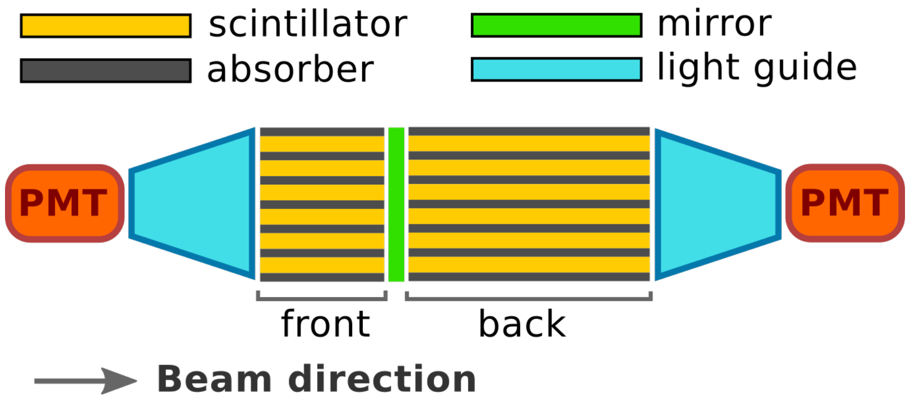
- ➢ 1.5×1.5 cm^2 cell - W absorber and crystal fibres
  - — Development of radiation-hard crystal fibres
  - — Polystyrene fibres for Run 4, then replaced by crystals
- ➢ 3×3, 4×4 cm^2 cell - Pb absorber and plastic fibres:
  - — Need radiation-tolerant plastic fibres

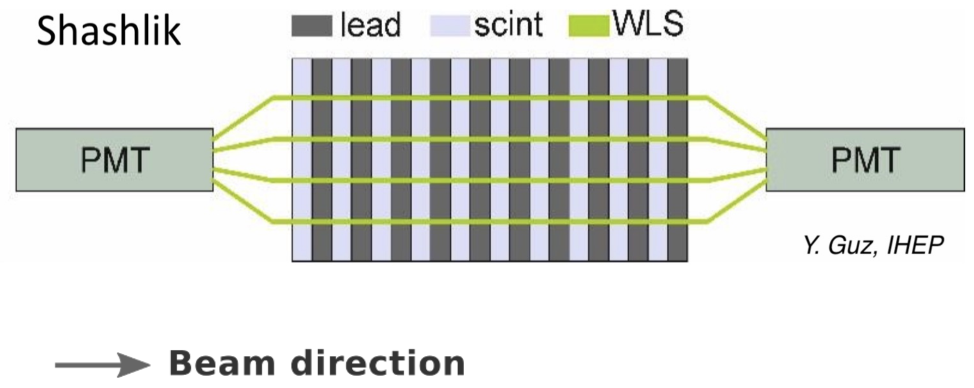
Shashlik technology for outer region

- ➢ 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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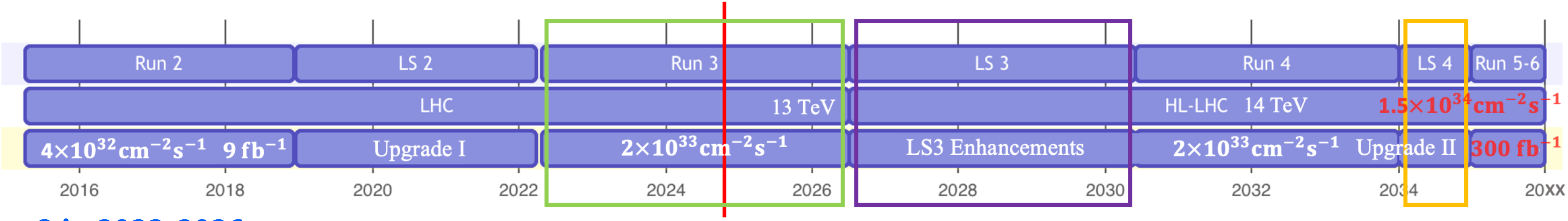
The Upgrade Strategy



Run 3 in 2022-2026:

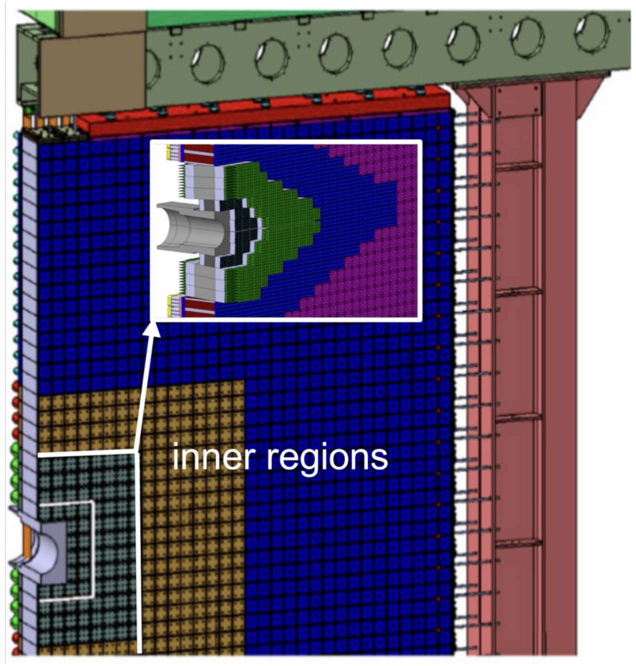
- Run with unmodified ECAL Shashlik modules at $L = 2\times10^{33} cm^{-2}s^{-1}$

LS3 consolidation in 2026-2030:

- 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 $L = 2(4)\times 10^{33} cm^{-2}s^{-1}$
  - 32 SPACAL-W & 144 SPACAL - Pb modules with plastic fibres compliant with Upgrade II conditions

LS4 Upgrade II in 2034-2035:

- 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 $L = 1.5 \times 10^{34} cm^{-2}s^{-1}$
  - Innermost SPACAL-W modules equipped with crystal fibres
  - Include timing information and double-sided readout to full ECAL



LHCB-TDR-023, LHCB-TDR-024

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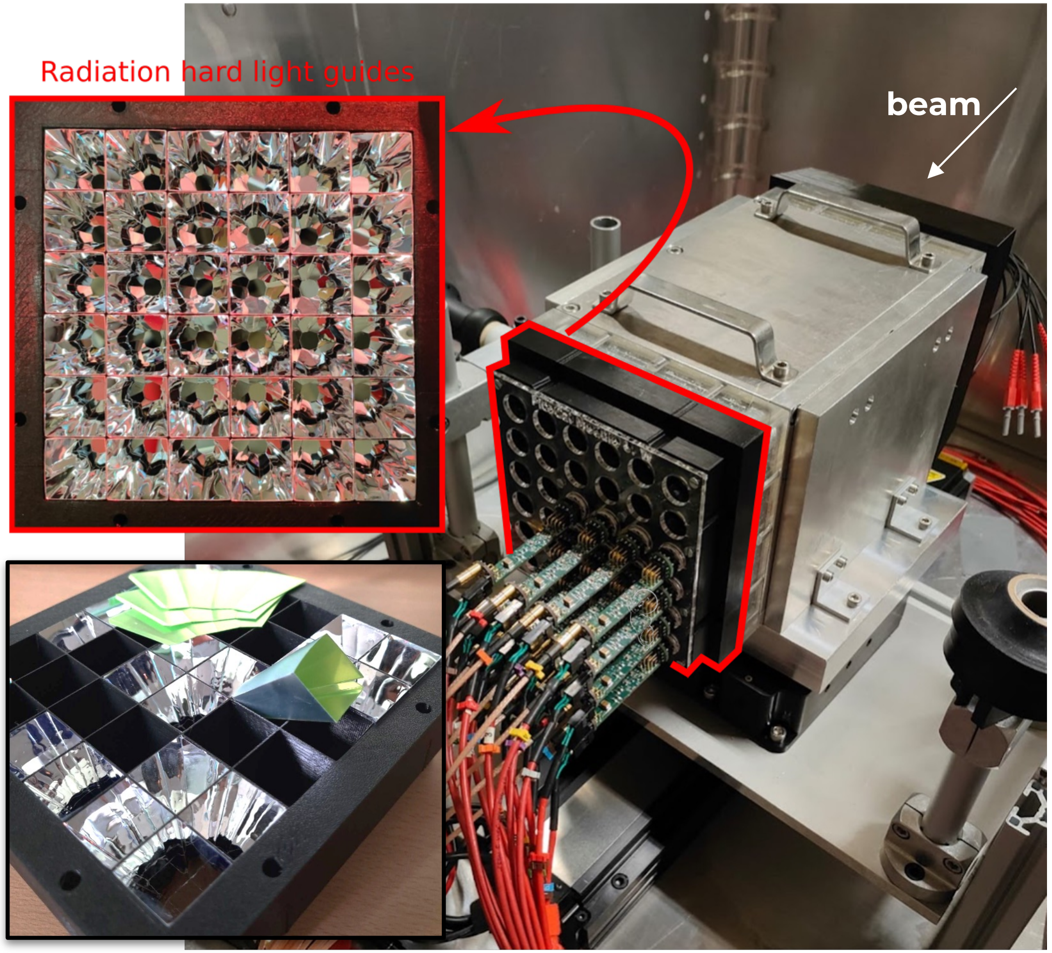
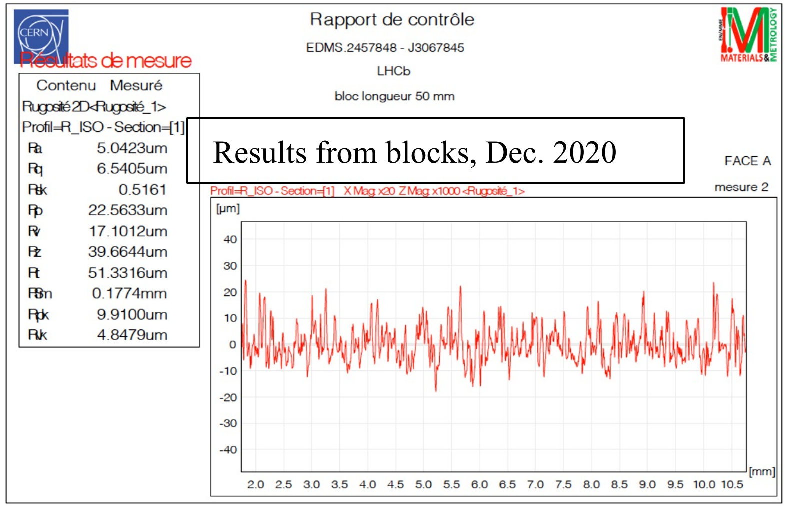
SpaCal - W Absorber - Polystyrene Fibres

- **Full size $121 \times 121\ \mathrm{mm}^2$ *Module 0* assembled at CERN:**
- **Passive materials:**
  - 3D-printed W absorber
    - 3×50 mm + 1×40 mm long blocks
    - R&D performed with EOS, Germany
  - Very good mean roughness $R_a = 5\ \mu m$ 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 $1 \times 1\ \mathrm{mm}^2$

LS3 Enhancement





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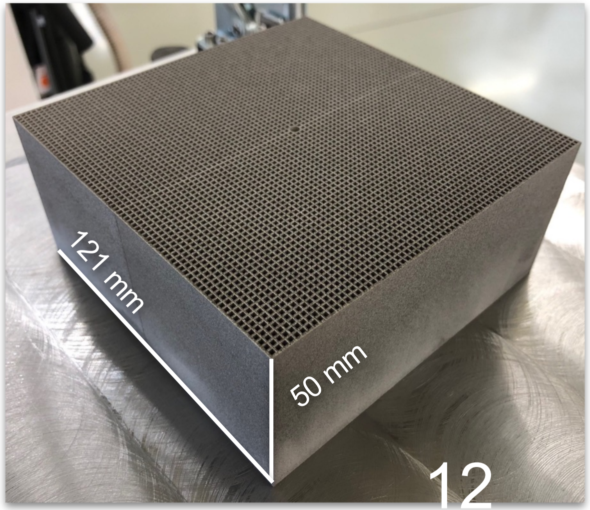
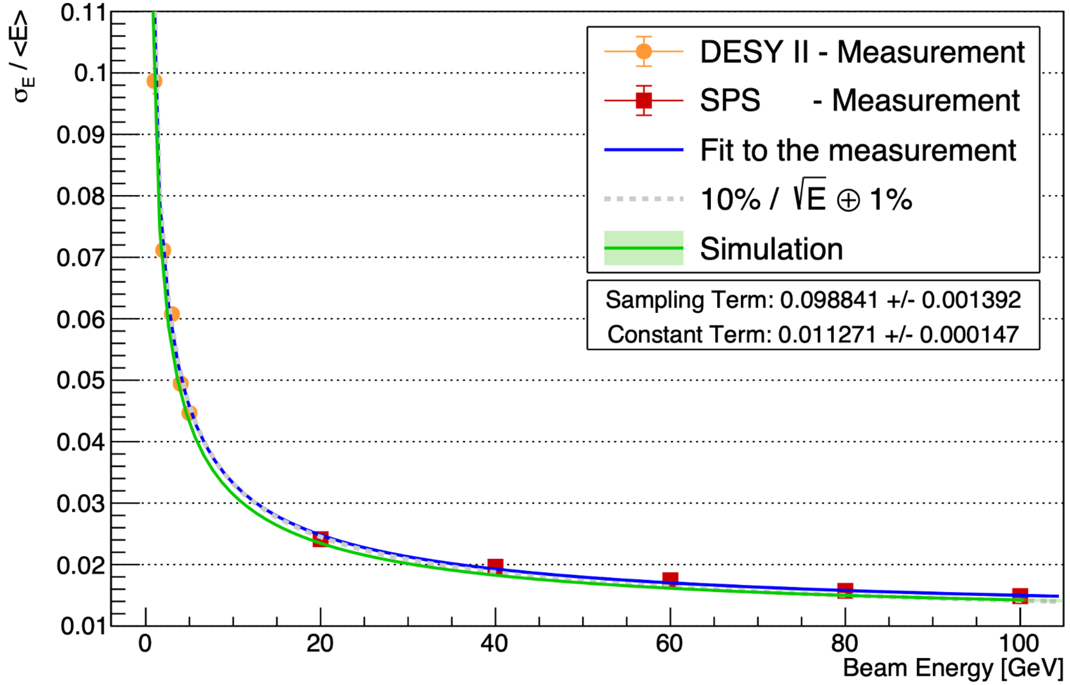
Profil=R_ISO - Section=[1]	
Ra	5.0423um
Rq	6.5405um
Rsk	0.5161
Rp	22.5633um
Rv	17.1012um
Rz	39.6644um
Rt	51.3316um
RSm	0.1774mm
Rpk	9.9100um
Rvk	4.8479um

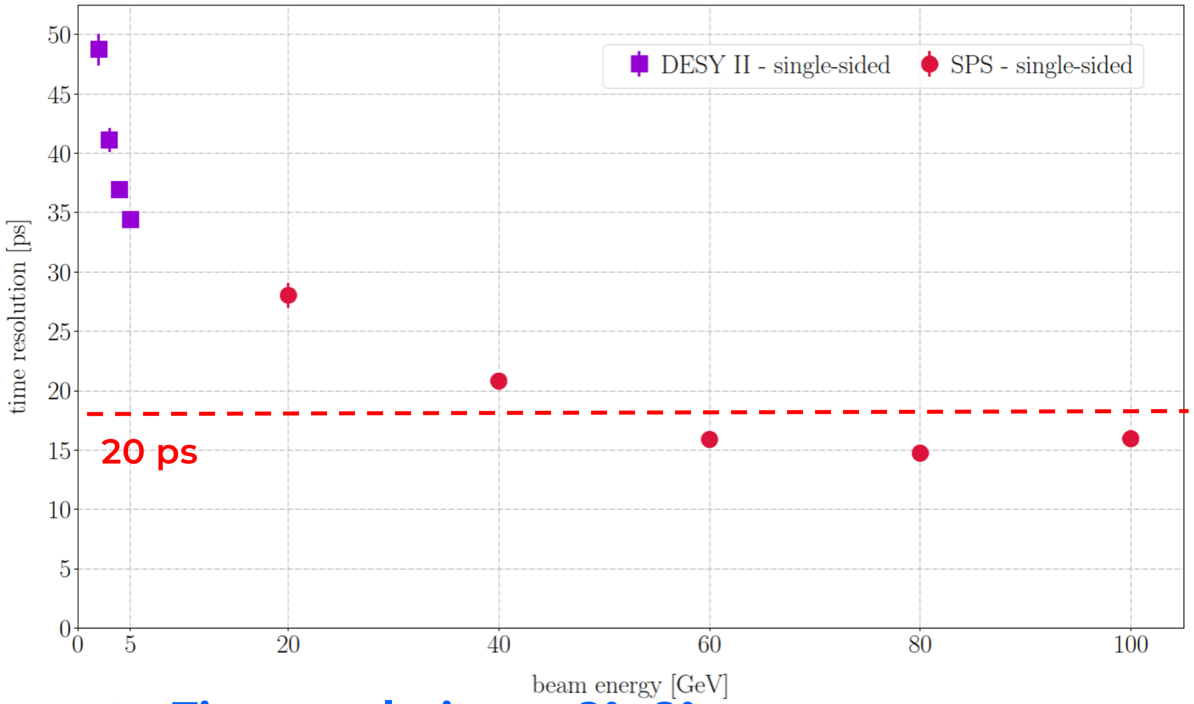


SpaCal - W Absorber - Polystyrene Fibres
- Testbeam Results up to 100 GeV

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

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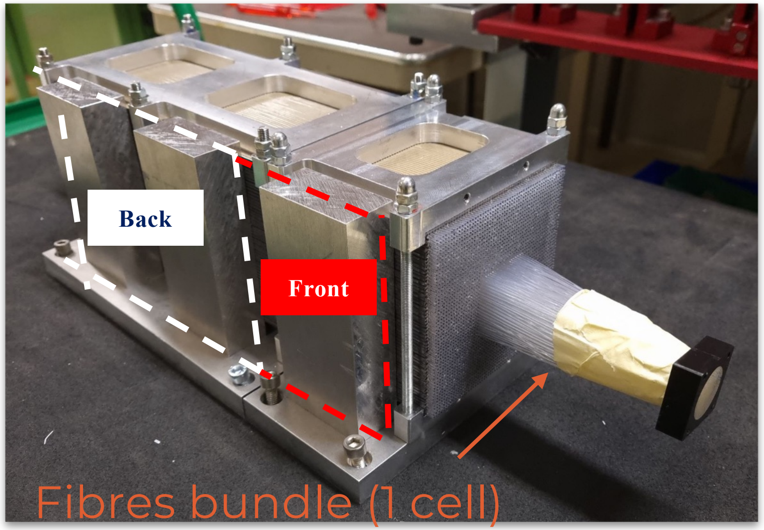
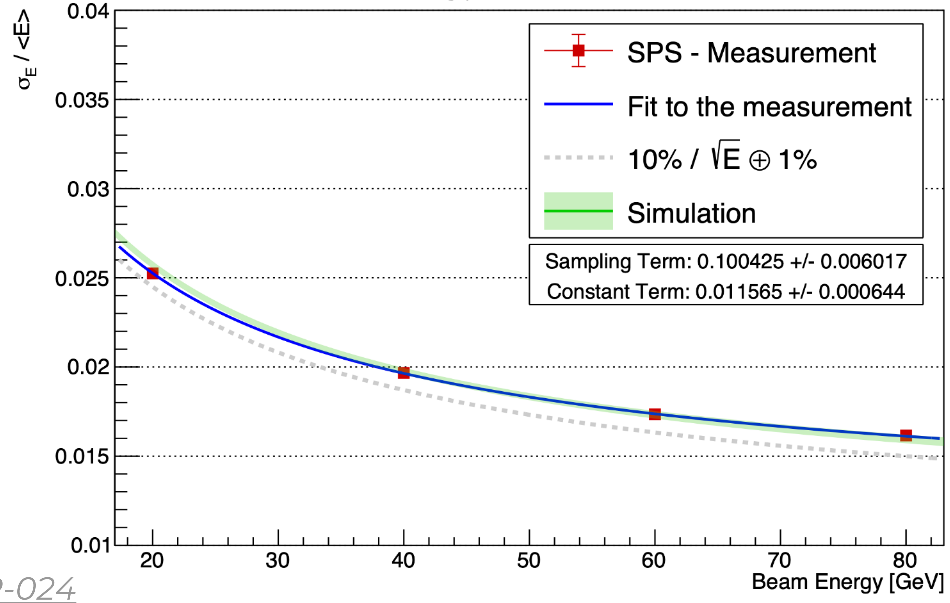
SpaCal - Pb Absorber - Polystyrene Fibres

- Testbeam Results up to 100 GeV at DESY and SPS

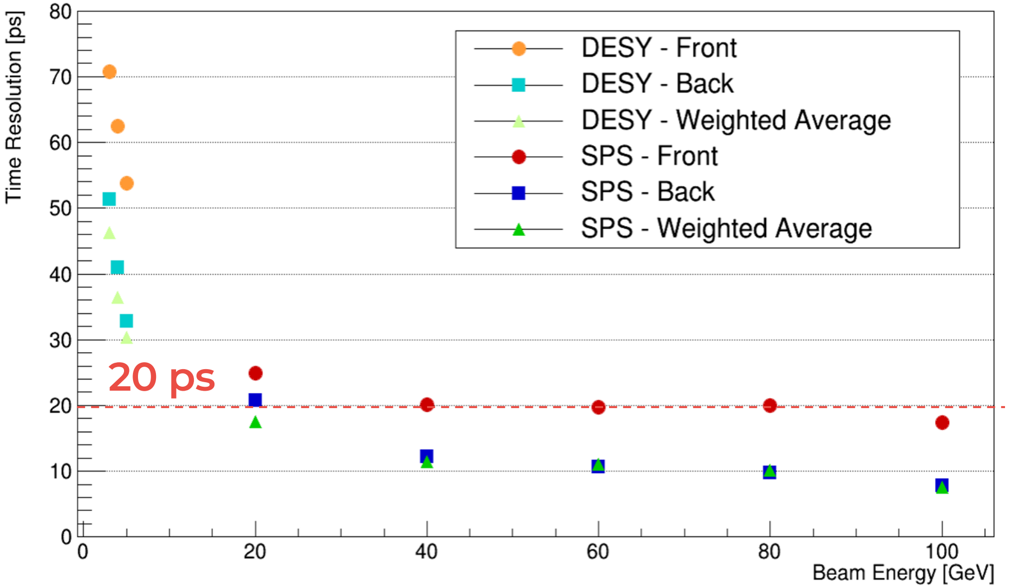
- **Pb absorber and polystyrene fibres:**
  - $8 + 21$ cm long $(7 + 18\ X_0)$
  - Reflective mirror between sections
  - Kuraray SCSF-78 round fibres $\varnothing = 1.0$ mm



Energy resolution



Time resolution



LHCB-TDR-024

SpaCal - Pb Absorber - Polystyrene Fibres
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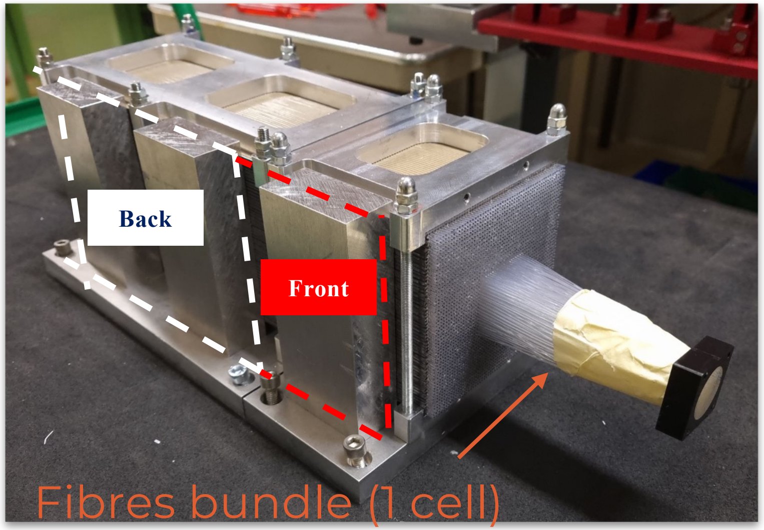
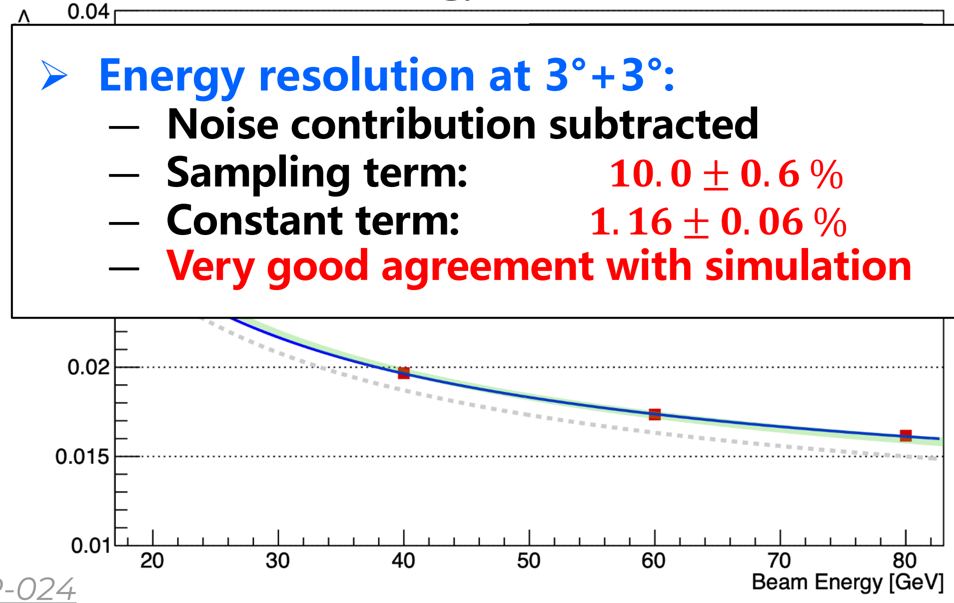


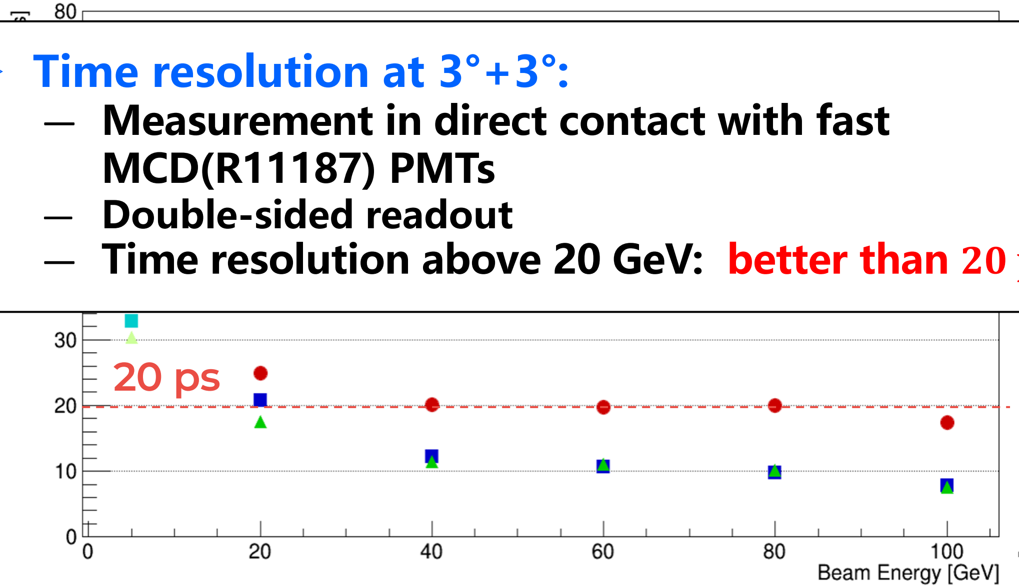
Performance in line with targets

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



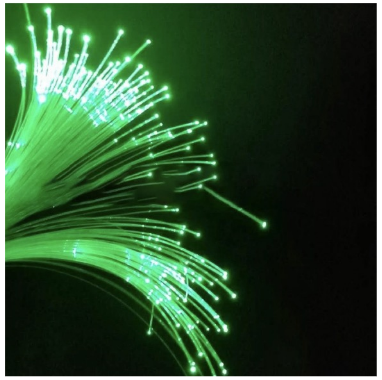
- Time resolution at 3°+3°:
  - Measurement in direct contact with fast MCD(R11187) PMTs
  - Double-sided readout
  - Time resolution above 20 GeV: better than 20 ps

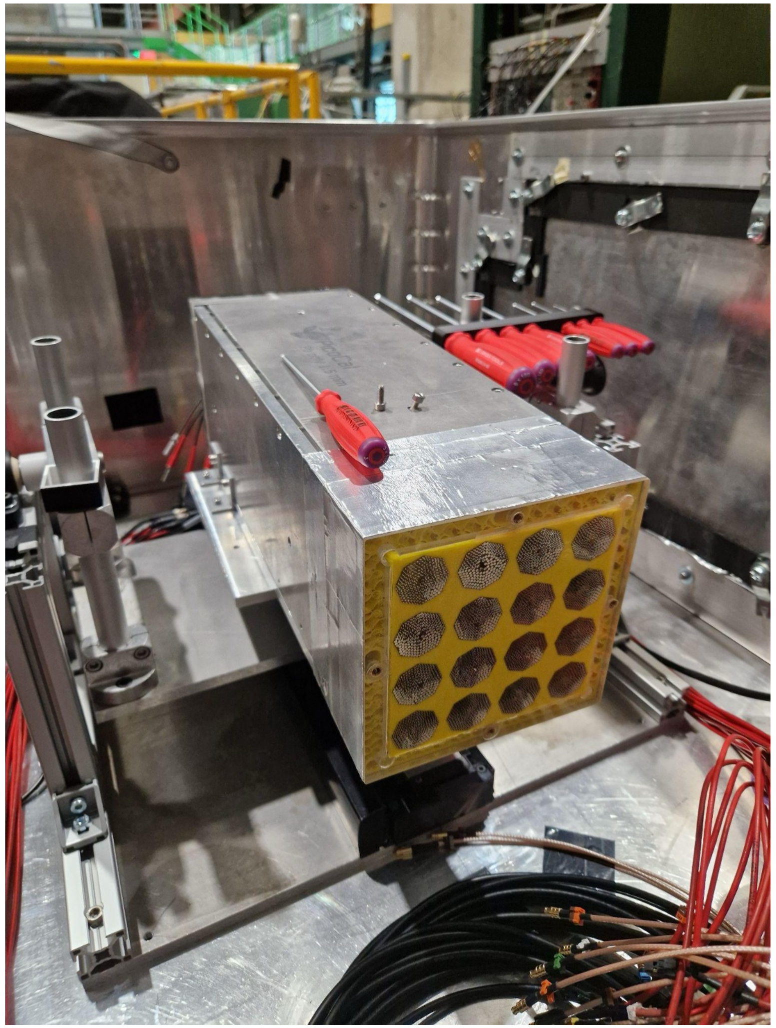
LHCB-TDR-024

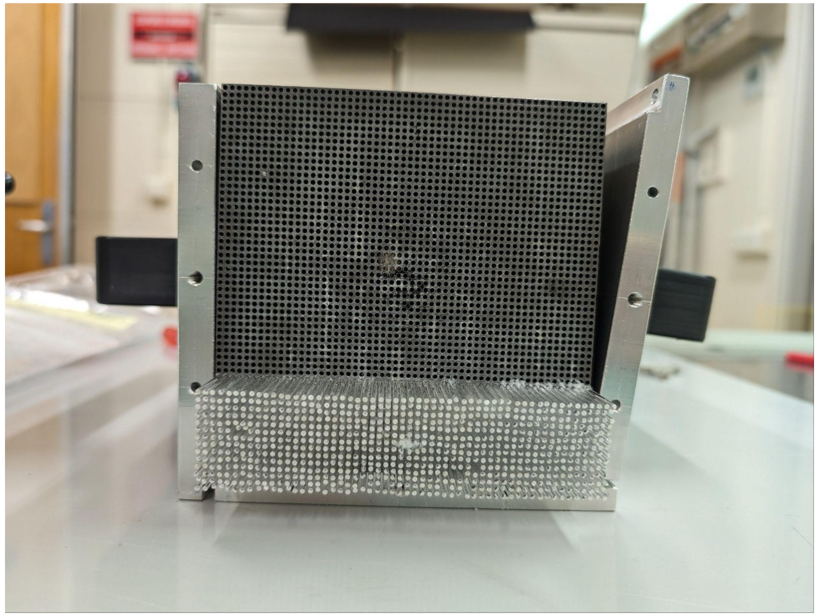
SpaCal - Pb Absorber - Polystyrene Fibres

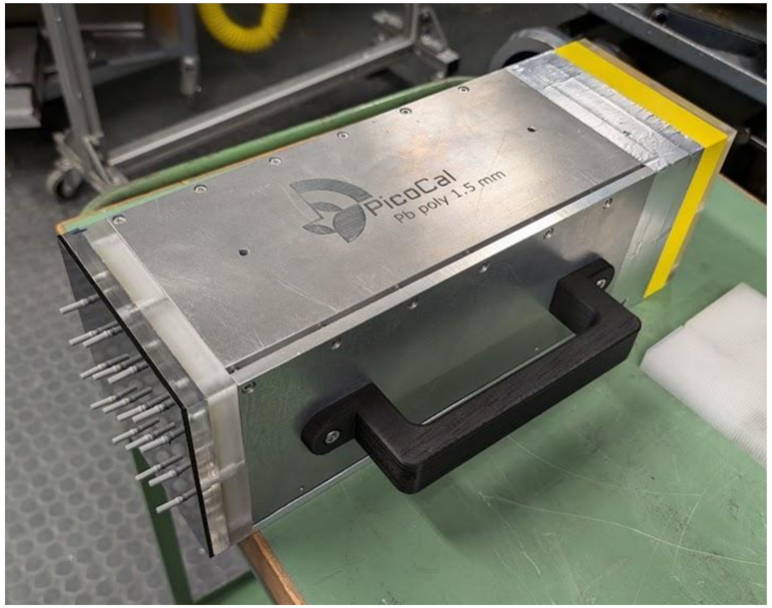
- **New Module 0 prototype assembled in June 2024**
  - **Pb casting technology for absorber production**
  - **Kuraray 3HF green fibres** $\varnothing\, 1.5\ \mathrm{mm}$

- **Under characterisation in testbeam**



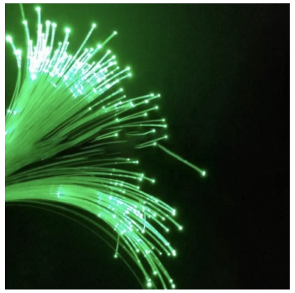






Ongoing R&D: Plastic Scintillator

- **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**



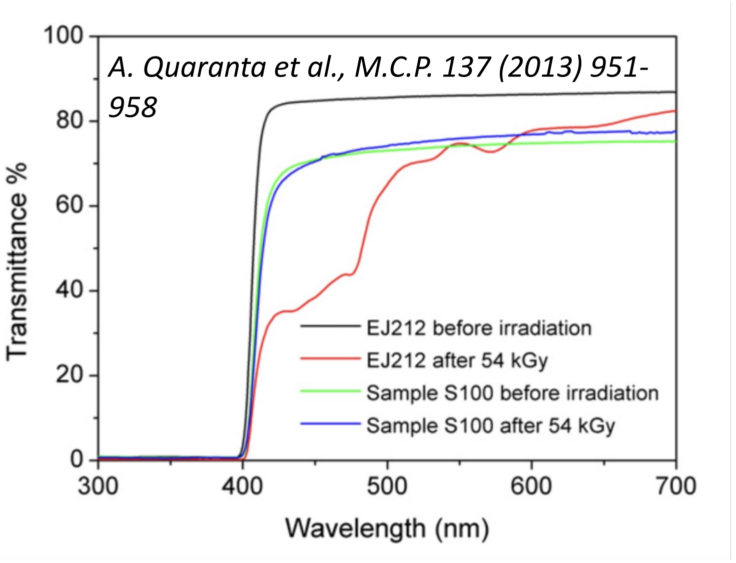
Formulations [1]

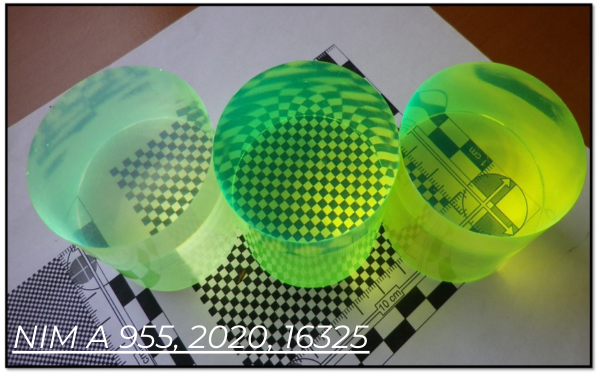
<u>Kuraray Datasheet</u>

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:**
  - **Polysiloxane hosts**
  - **Green emitters**
  - **Scintillating glasses**





<u>NIM A 955, 2020, 16325</u>

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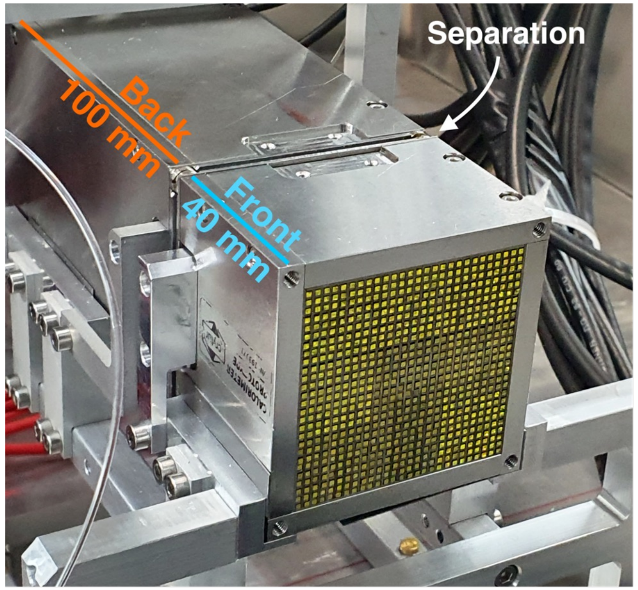
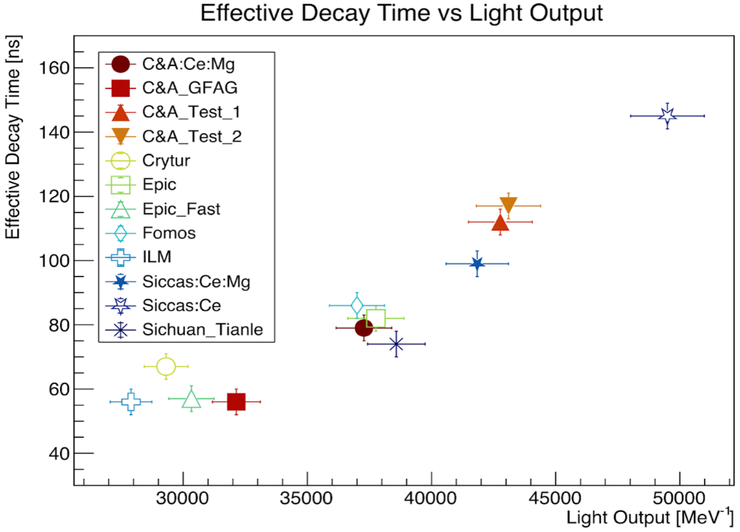
SpaCal - W Absorber - Crystal Fibres

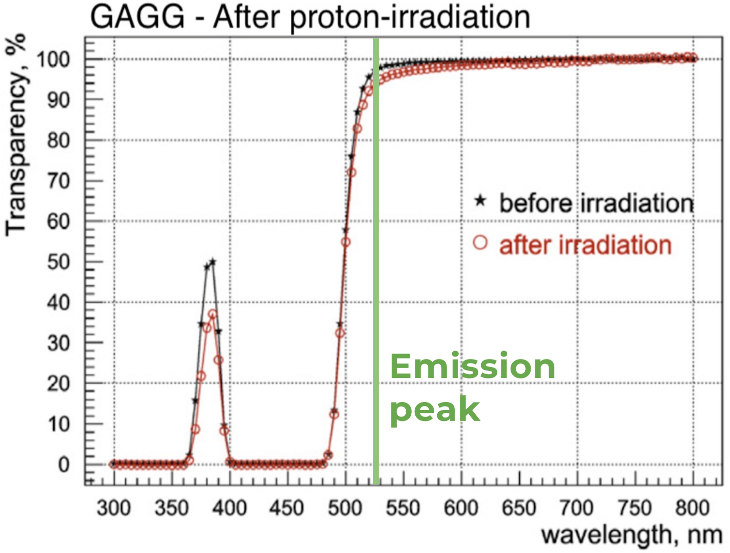
SPACAL prototype with W absorber and garnet crystals

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





NIM A 1000, 165231 (2021)



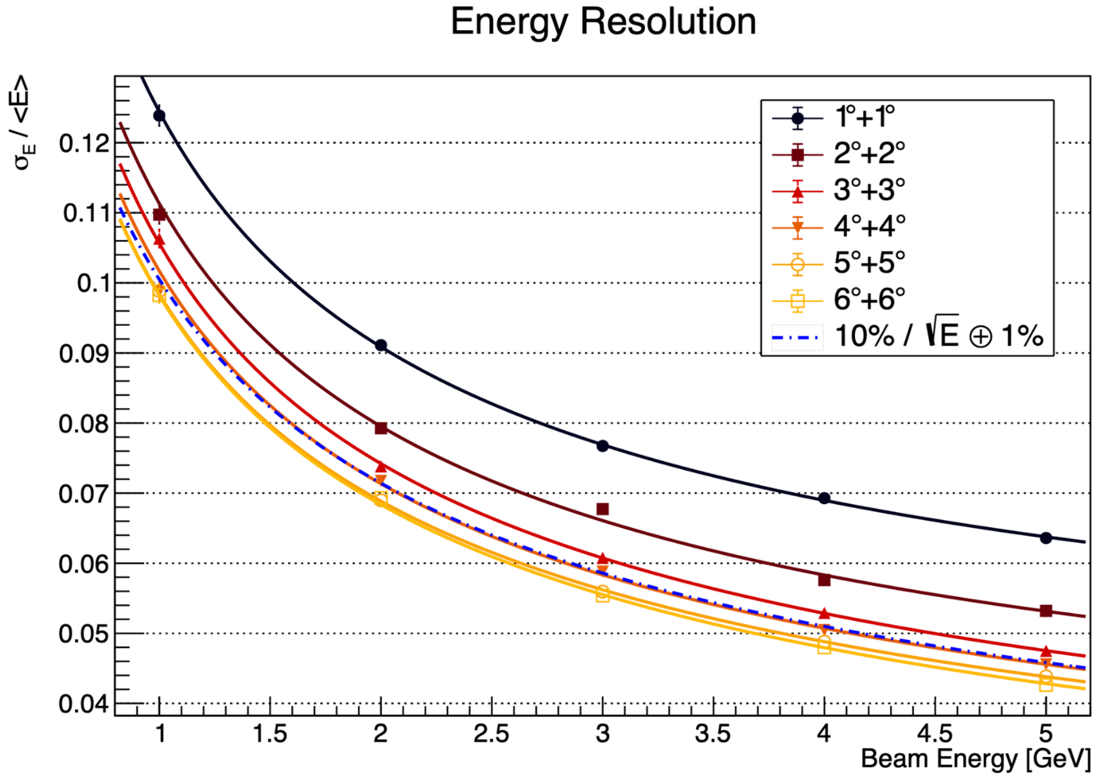
NIM A 816 (2016) 176

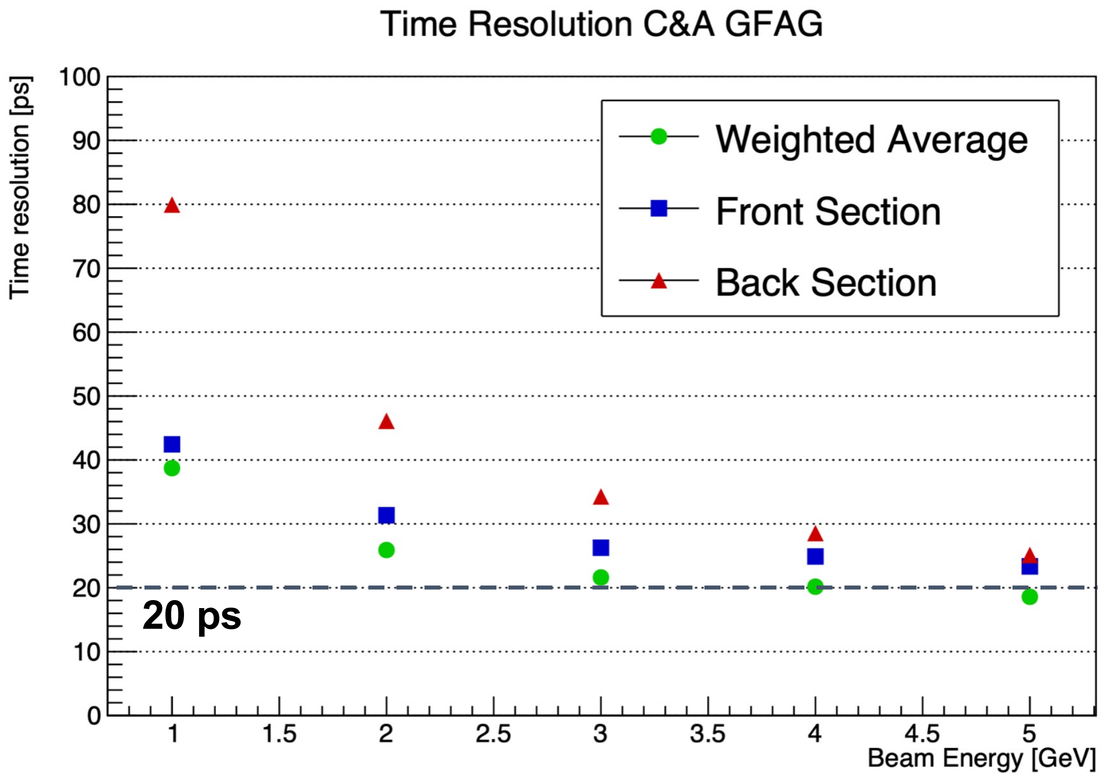
GAGG as scintillating material

- **High light output and relatively fast decay time** $(\sim 50\ \mathrm{ns})$
  - Tunable scintillation properties
- **Radiation hardness tested up to** $1\ \mathrm{MGy}$

SpaCal - W Absorber - Crystal Fibres

- Testbeam Results up to 5 GeV at DESY





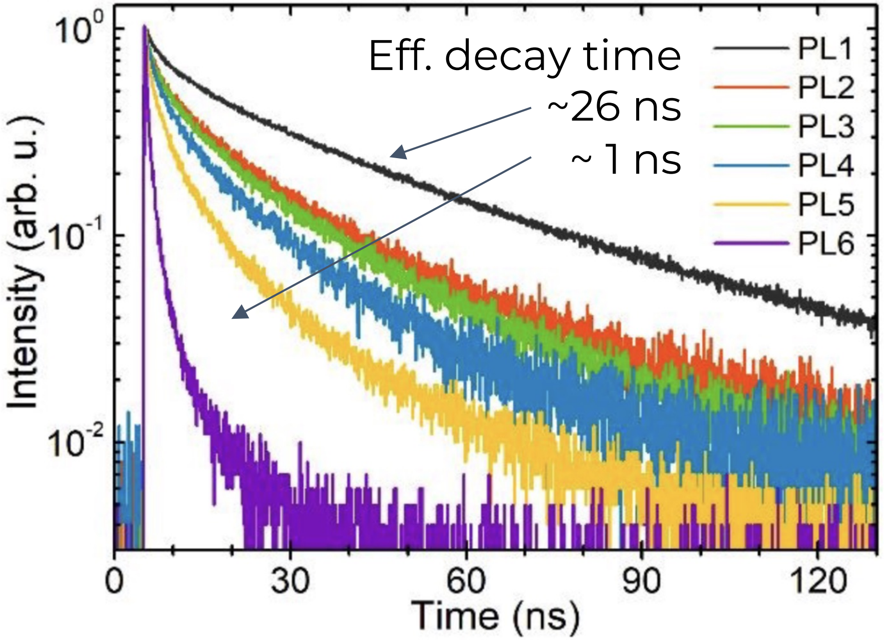
- **Resolution improves increasing the incidence angle**
- **Energy resolution at 3°+3°:**
  - **Sampling term:** $10.2 \pm 0.1\ \%$
  - **Constant term:** $1-2\ \%$

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

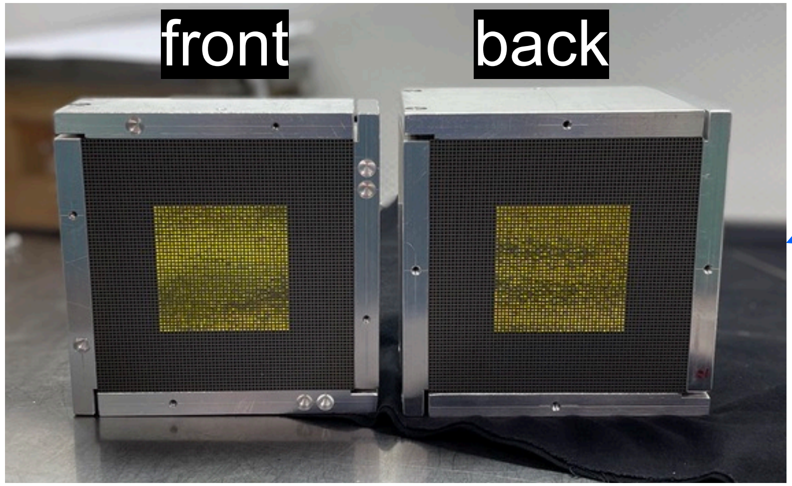
NIM A 1045, 167629 (2022)

Performance in line with targets

Ongoing R&D: Accelerating Scintillation

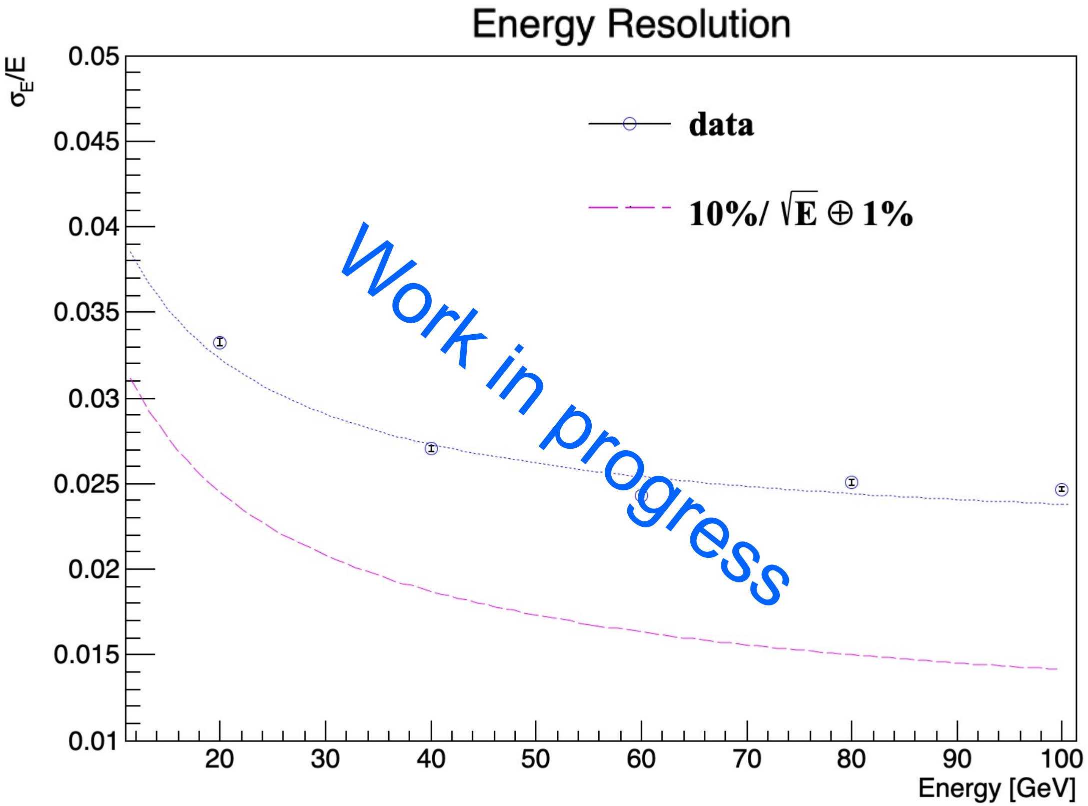


Material Advances, 2022, 3, 6842



- **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**
- **New prototype in June 2024**
  - **SiPAT GAGG with decay time ~ 20 ns**
  - **3D-printed absorber with LaserAdd, China**
  - **Under characterisation in testbeam**

SpaCal - W Absorber - Crystal Fibres
- Testbeam Results from 20 to 100 GeV at SPS



- Resolution improves increasing the incidence angle
- Energy resolution at 3°+3°:
  - Sampling term: $10.9 \pm 0.2\ \%$
  - Constant term: $\sim 2\ \%$

- Time resolution SIPAT GAGG at 3°+3°:
  - Multi-Anode(R7600U-M4) PMT with 4 channels
  - Asymmetric LGs: square to square
  - Double-sided readout
  - Time resolution above 20 GeV: better than 35 ps

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

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

Shashlik R&D

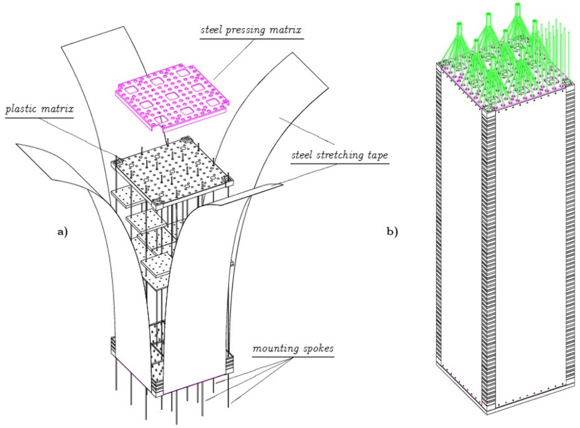
- Current LHCb Shashlik modules have good time properties

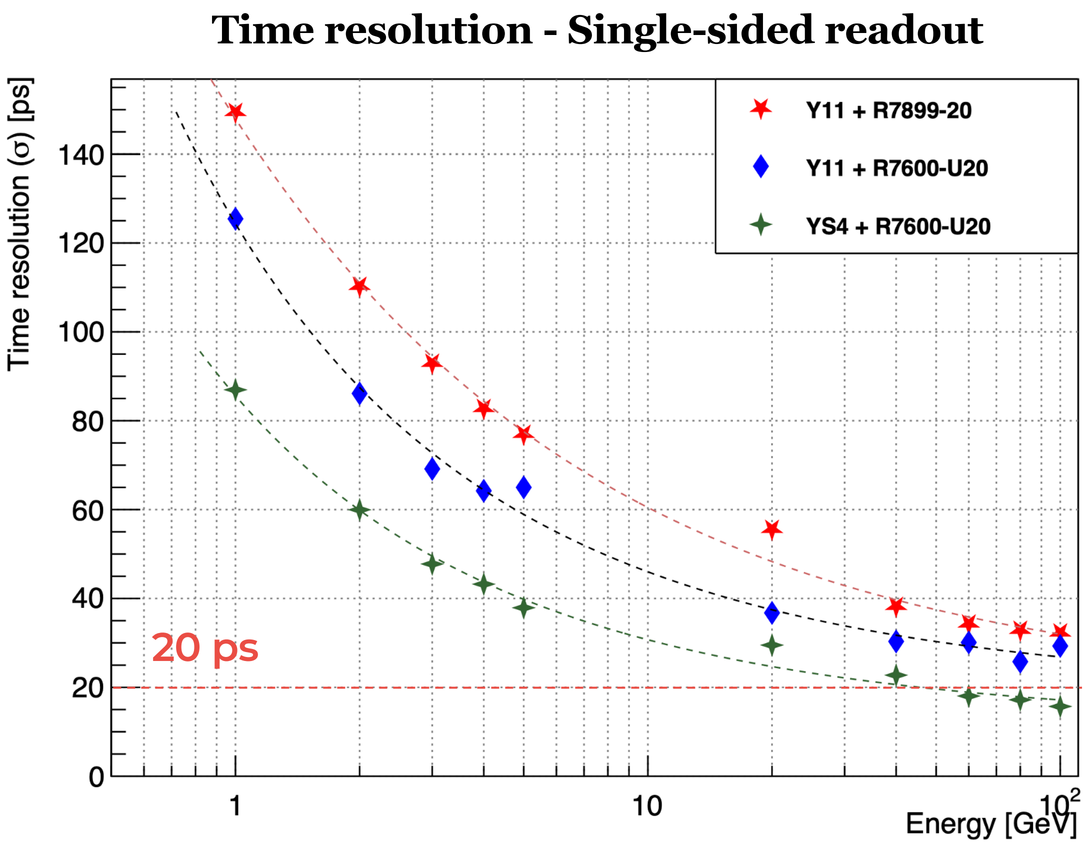
- Improvements:
  - Replacing WLS fibres (Kuraray)

–	Y11	(7 ns decay time) ←	Current LHCb
–	YS2	(3 ns decay time)	
–	YS4	(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)





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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
  - TDR recently approved!

- 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

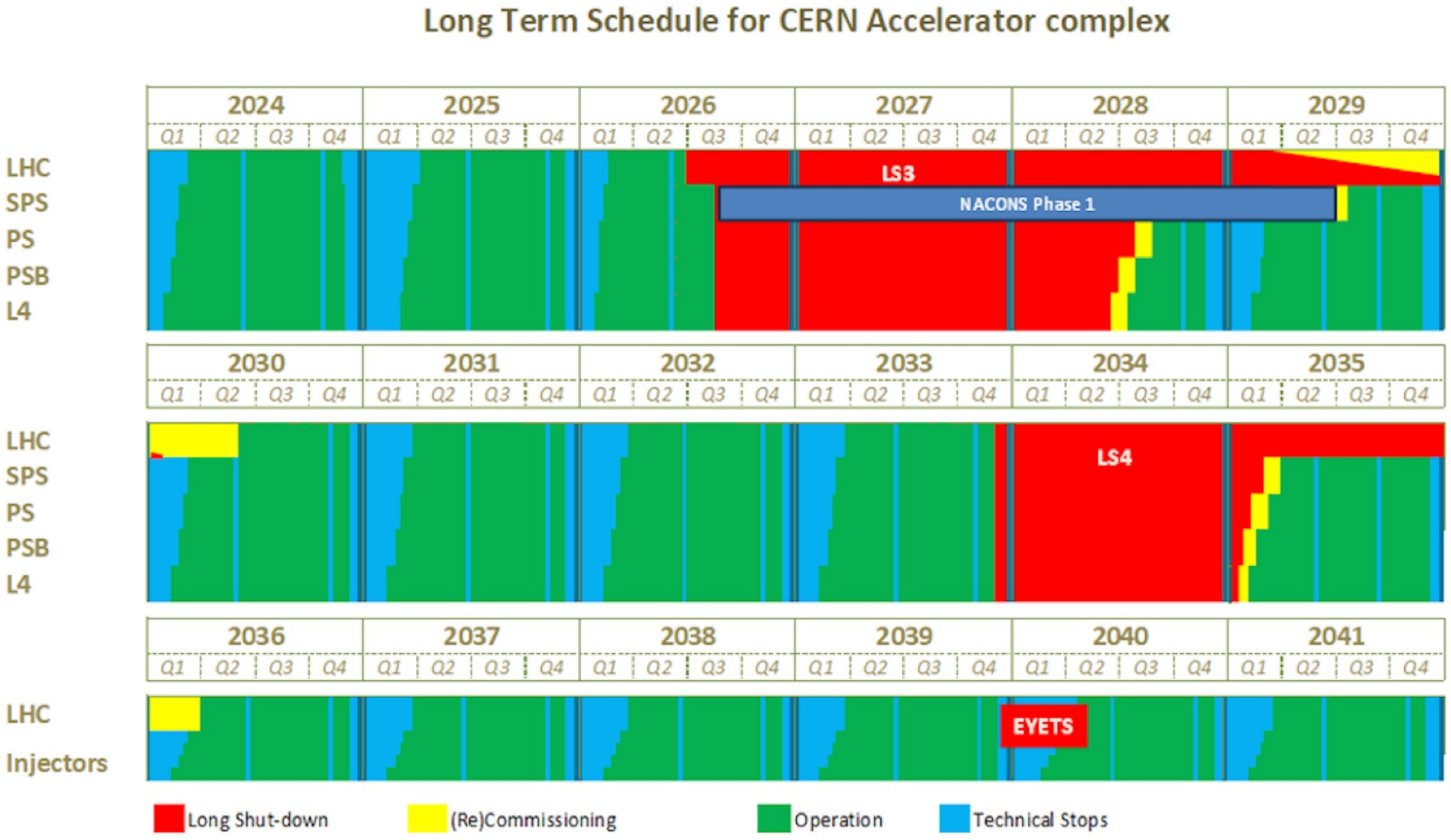
- Comprehensive R&D ongoing (also interesting for other future projects)
  - Test beam measurements with prototypes
  - Detailed Monte Carlo simulations
  - Study of novel absorber production techniques
  - Study of suitable LGs, PMTs and development of readout electronics
  - Investigation of new radiation-hard 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!