LHCb Upgrade II
Plans for the RICH, TORCH and CALO projects

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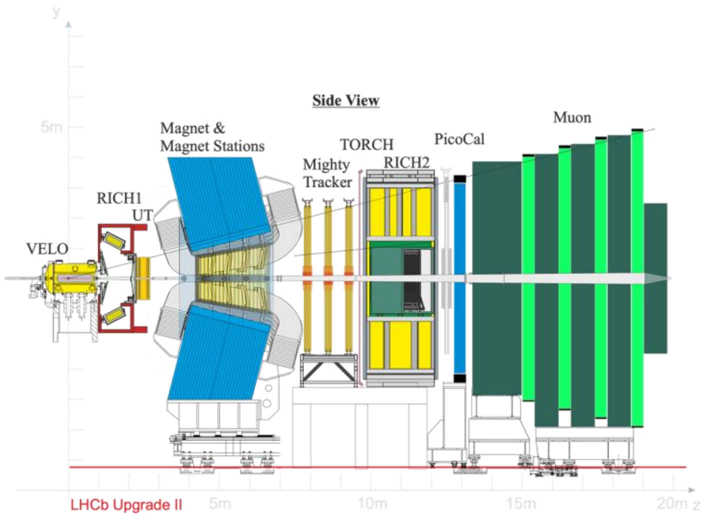
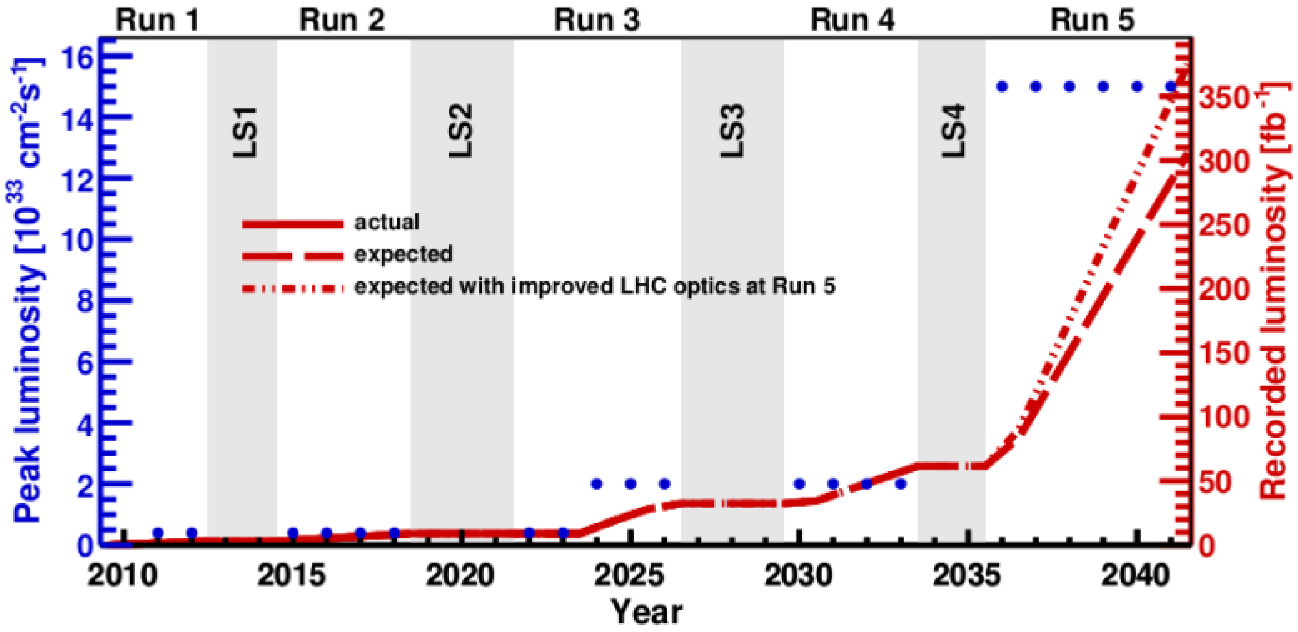
On behalf of the LHCb RICH/TORCH/CALO collaborations
(with slides from Philipp Roloff and Thomas Blake)

17th Terascale Detector Workshop, Bonn

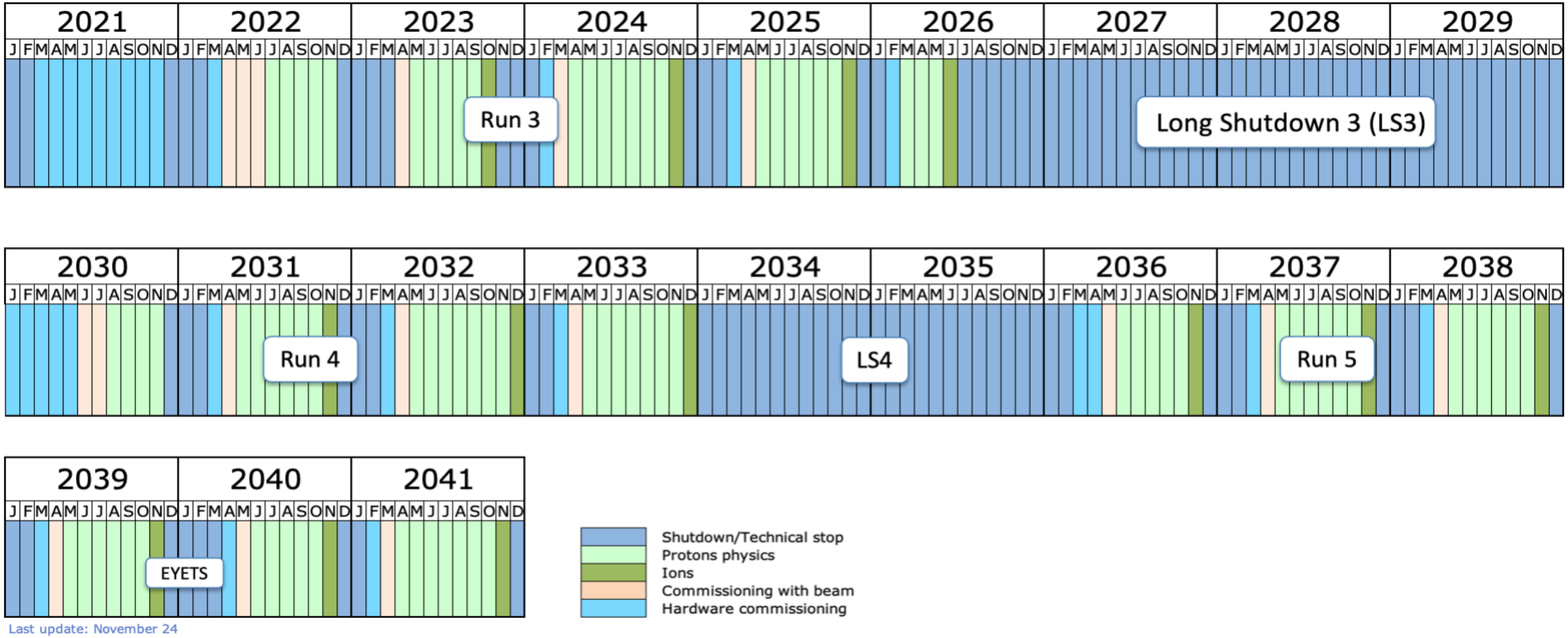
LHCb Upgrade II

- Upgrade the LHCb detector to operate at an instantaneous luminosity of 1 to 1.5 x 10^{34} $cm^{-2}s^{-1}$ and collect a dataset that corresponds to more than 300 fb^{-1}





LHC Schedule



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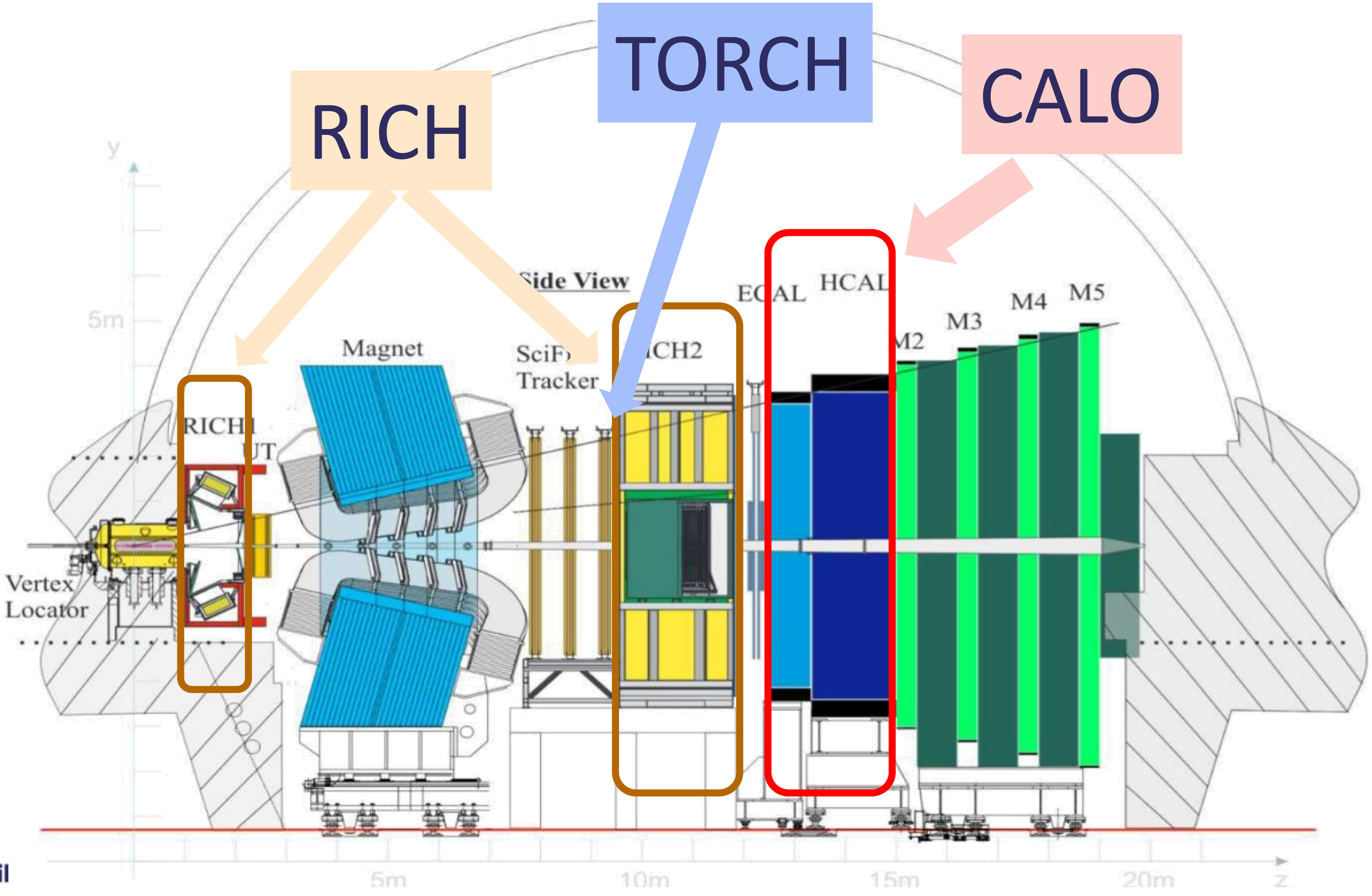
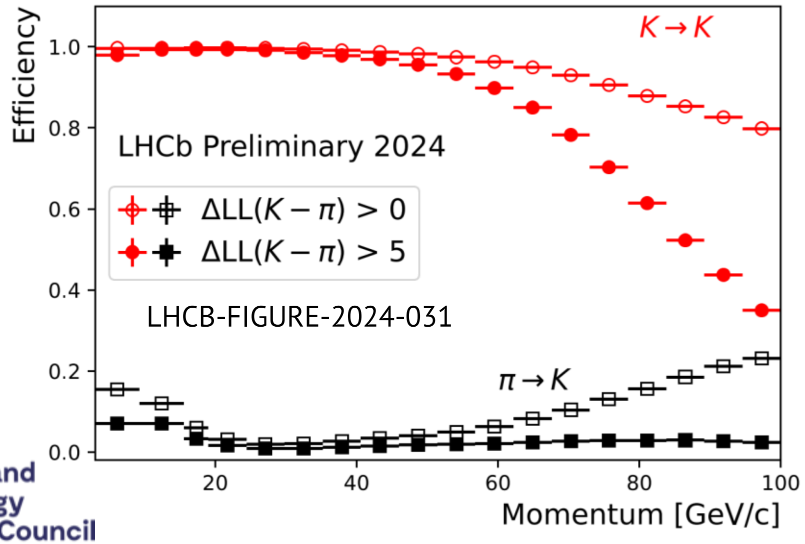
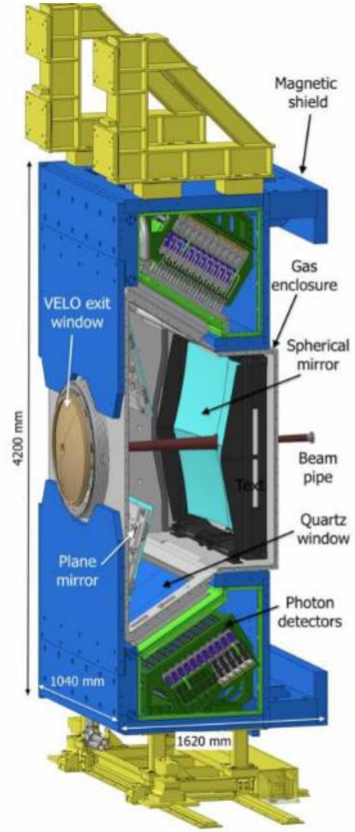
The (Upgraded) LHCb detector

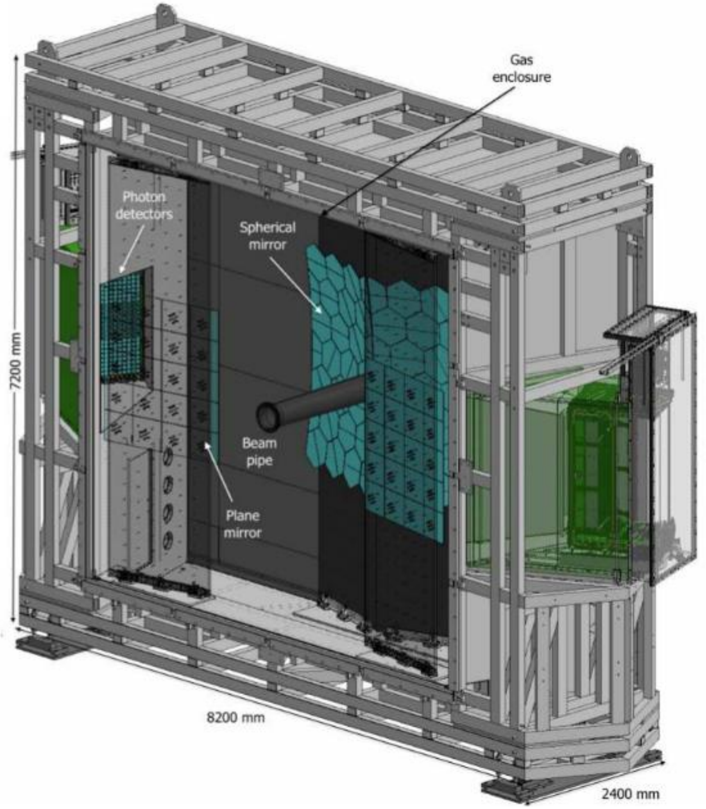


The LHCb RICH system

- Two RICH detectors to cover momentum 2 – 100 GeV/c
- Radiators: C_4F_{10}, CF_4
- Current photon detectors:
  - MaPMTs, pixel size 3x3 and 6x6 mm^2







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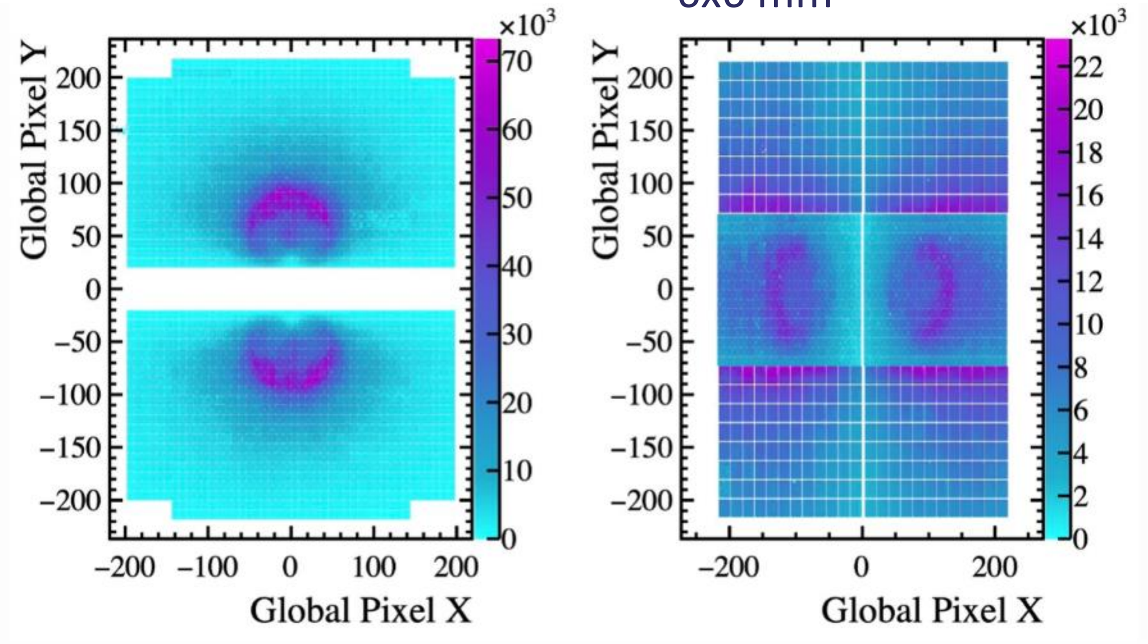
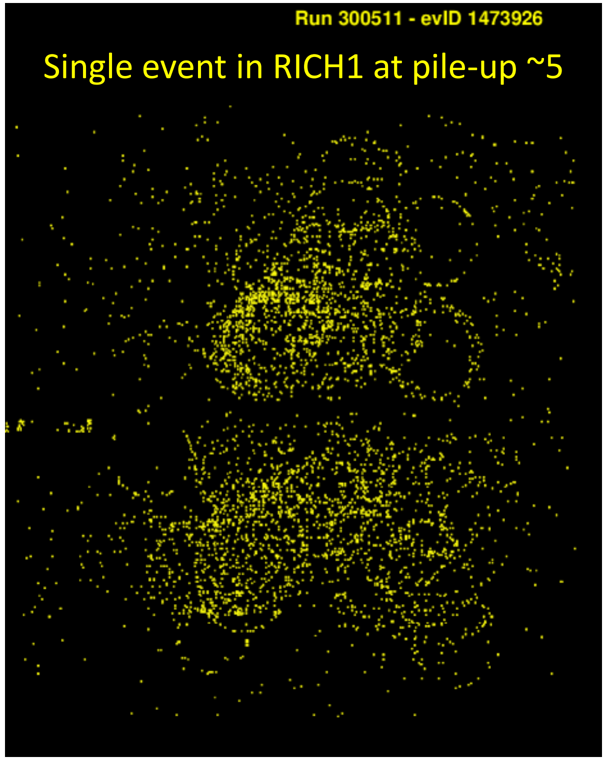
The RICH challenge

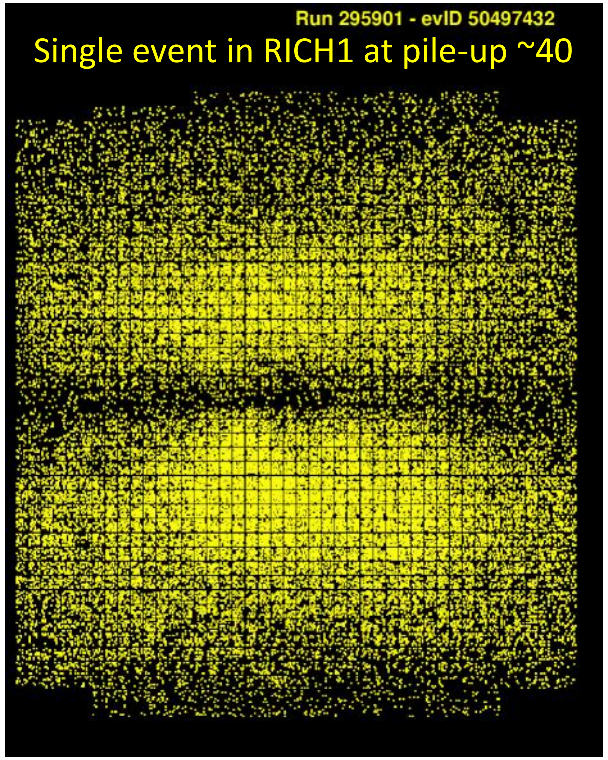
Pixel size 3x3 mm^2

Pixel size 3x3 mm^2 and 6x6 mm^2



Current hitmap for RICH1 and RICH2





Required improvements in Cherenkov angle resolution and inclusion of timing information

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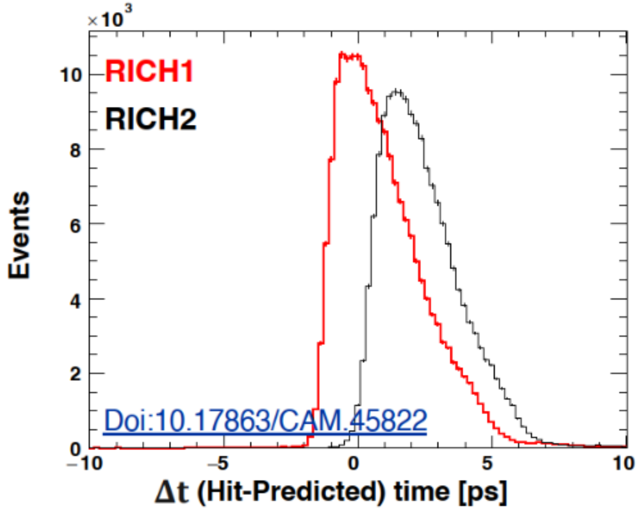
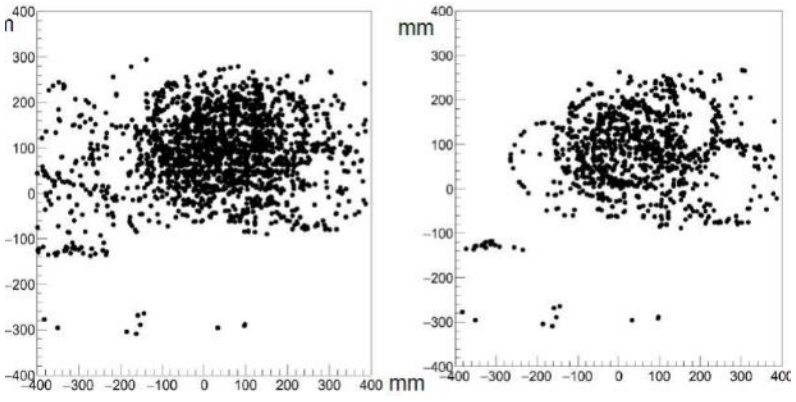
Use of timing in a RICH detector

- Prompt Cherenkov radiation and use of focusing optics means that the time of arrival of photons is highly predictable (for a particle of known momentum and t_0).
- Front-end electronics time stamp photons.
- Using only detected hits close to the predicted time of arrival can strongly enhance the particle ID performance (by reducing the event complexity)

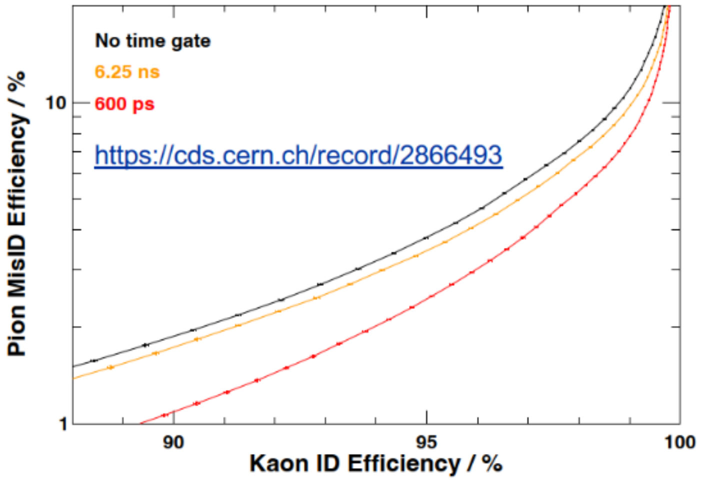


3 ns gate

100 ps gate



Run 3 simulation



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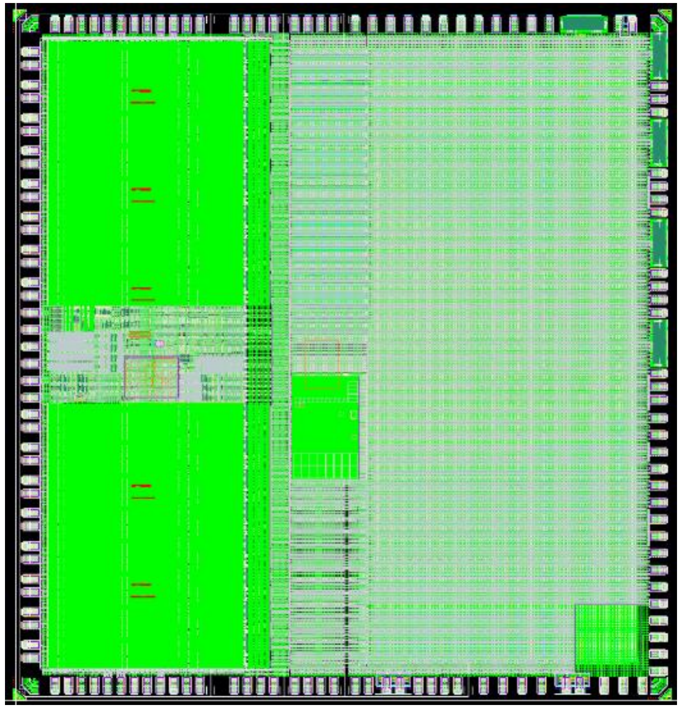
FastRICH

Key analogue features:

- Input signal dynamic range: 5μA to a few mA
- Better than 10 ns recovery time
- Constant-Fraction Discrimination or Leading Edge

- Key digital features:
  - 25 ps timestamp
  - Configurable internal shutter
  - Data compression
  - Radiation hard
    - Up to $2x10^{13}$ n_{eq}/cm^2



16-channel ASIC in 65 nm technology
Submitted on 5th February

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Photon detectors: SiPMs

Measurements performed at -30°

SiPMs have attractive properties:

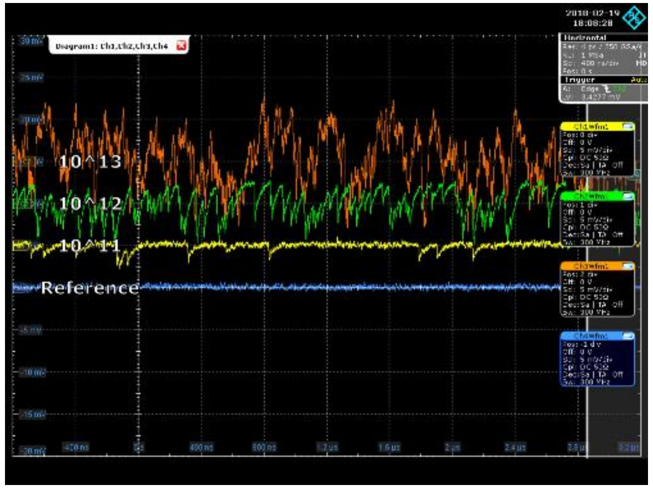
- Small pixel size
- Resilience to magnetic fields
- High detection efficiency for single photons
- Good time resolution (<100 ps)

Main drawback:

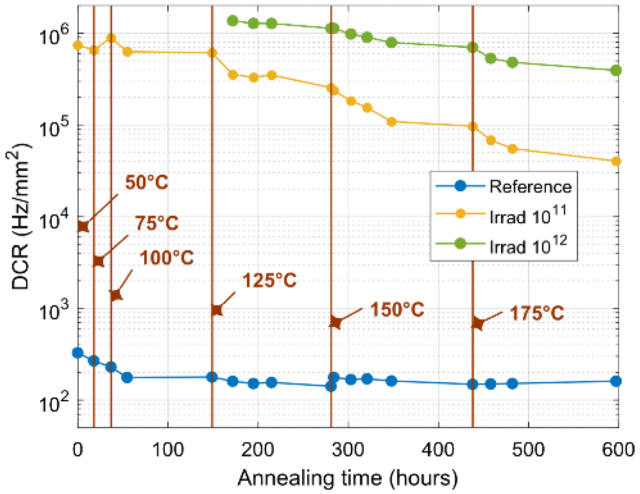
- High dark count rate after irradiation

Possible solutions:

- Cooling at very low temperatures
- Annealing (with heat)



10^{13}
10^{12} n_{eq}
10^{11}
Reference



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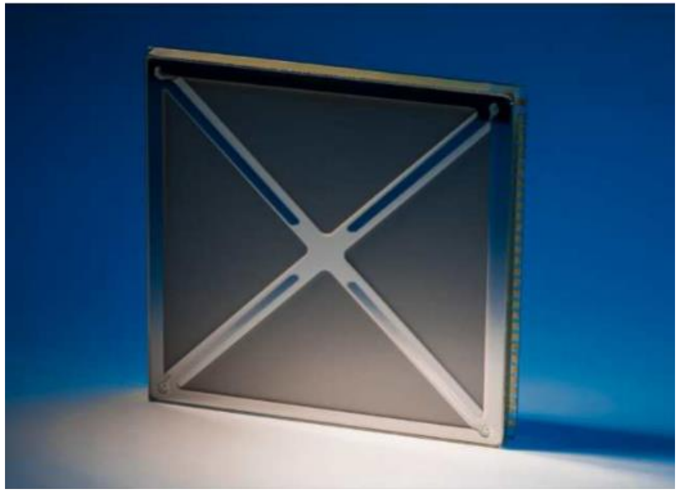
Photon Detectors: MCP

- Main advantages:
  - Very good time resolution (~40 ps)
  - Radiation hard
- Drawbacks:
  - Limited lifetime (collected charge)
  - Loss of gain at high rates
  - QE not as well tuned as SiPMs

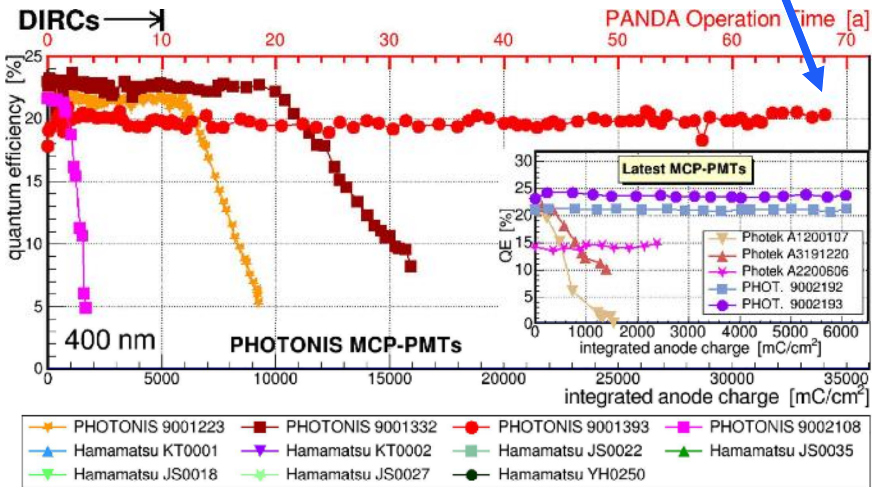


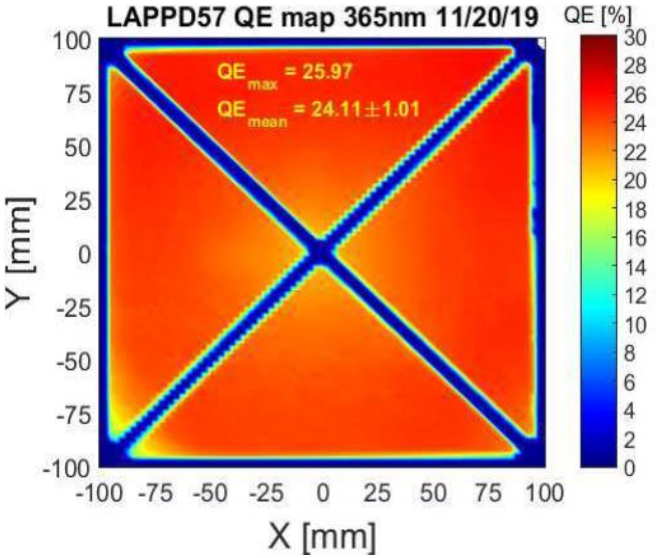
Large Area Picosecond Photon Detector

Photonis Planacon XP85112

Hamamatsu R10754-07-M16

34 C/cm²





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Improvements to Cherenkov angle reconstruction

- Geometry
  - Emission point error, aberrations
  - Restrictions from experimental layout
- Detector pixel size
  - The smaller the better, but could end up with too many channels
- Chromatic dispersion
  - Restrict spectrum, but reduce number of photons

Configuration		Overall [mrad]	Chromatic [mrad]	Emission pt. [mrad]	Pixel [mrad]	Yield
RICH1	MaPMT (Run 3)	0.82	0.59	0.38	0.46	62
	SiPM	0.51	0.28	0.37	0.22	65
	SiPM & geometry	0.38	0.28	0.13	0.22	52
RICH2	MaPMT (Run 3)	0.50	0.33	0.37	0.20	39
	SiPM	0.42	0.19	0.36	0.10	33
	SiPM & geometry	0.22	0.19	0.05	0.10	25

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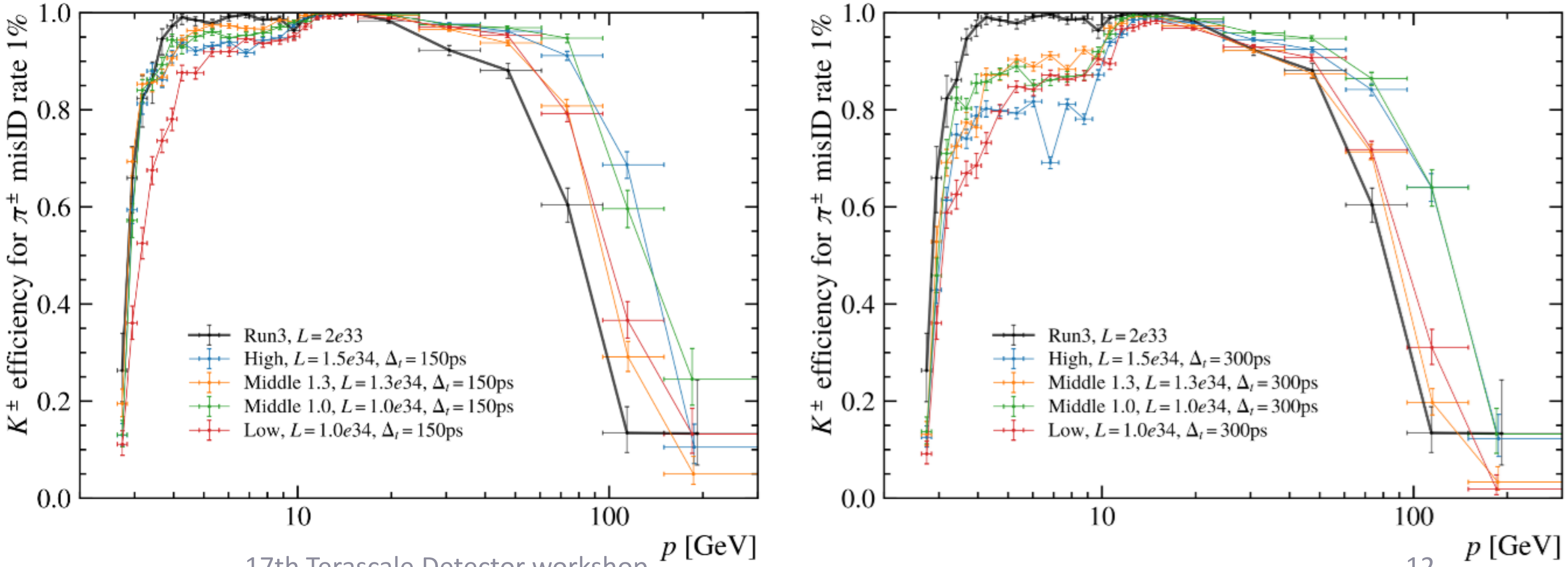
PID performance studies

Using simulation and emulation (where simulation output is modified according to the scenario under study) we can compare the PID performance of different combinations with:

- Different peak luminosity
- Different timing capabilities for the photon detectors
- Different optical designs
- Different pixel sizes

150 ps Time window 300 ps



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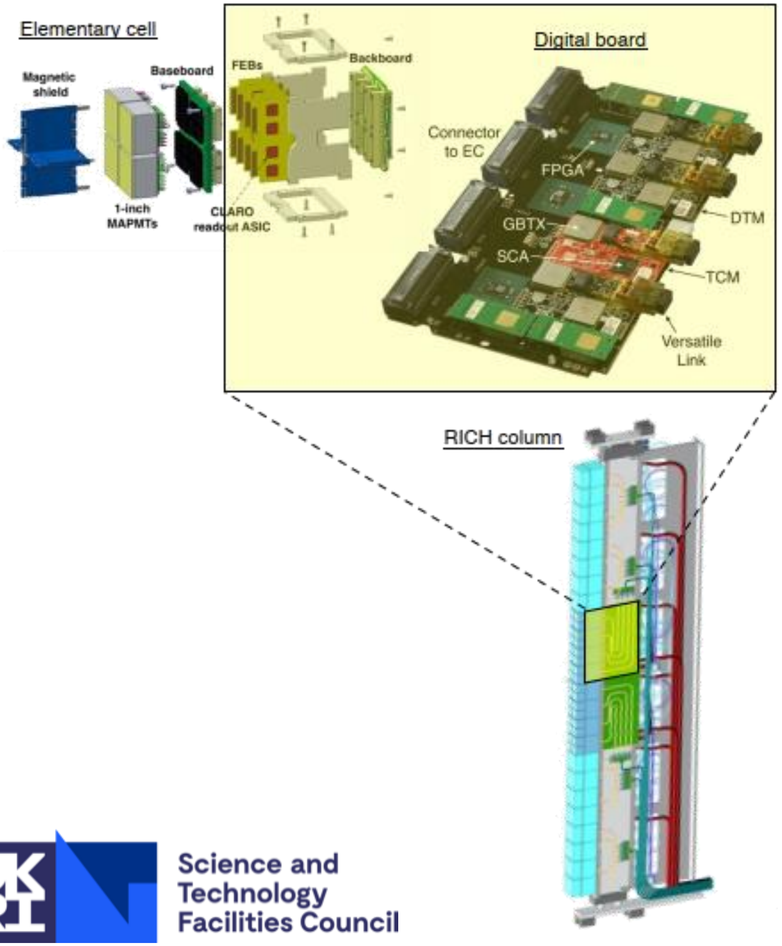
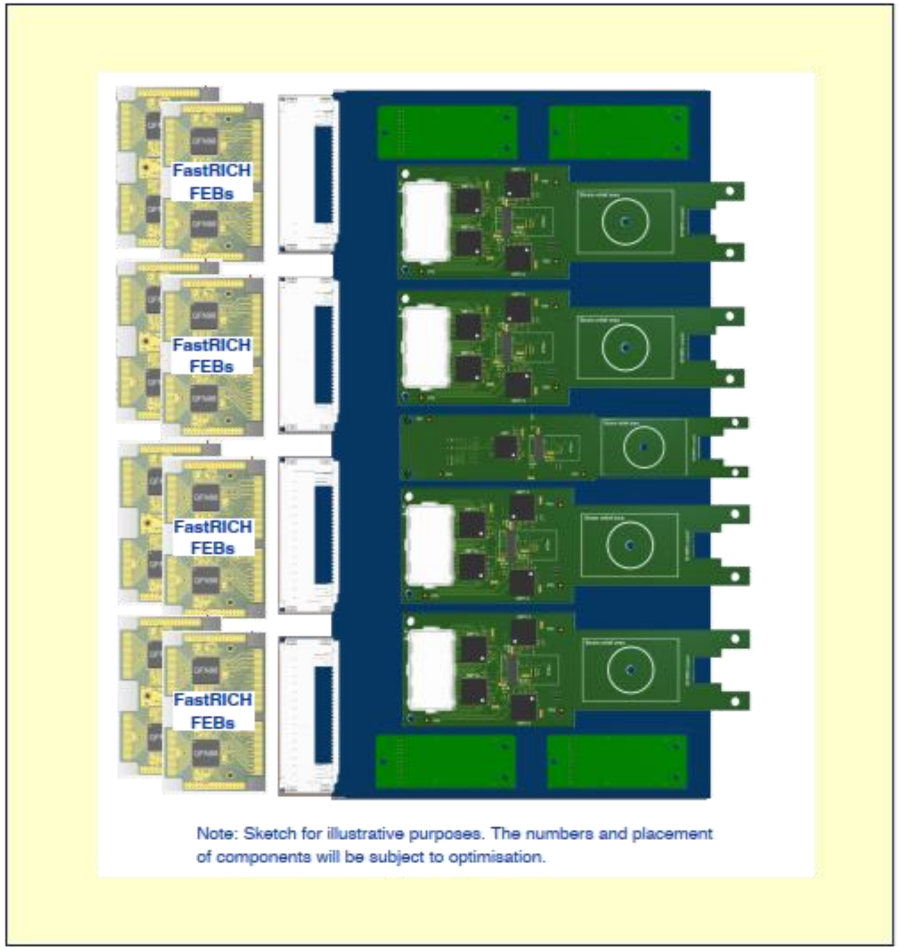
LS3 Enhancements



LS3 Enhancement

Introducing before Upgrade II:

- FastRICH ASIC.
- lpGBT & VTRX+ next generation optical links (for data transmission DTM and controls TCM).
- bPOL12V regulators.



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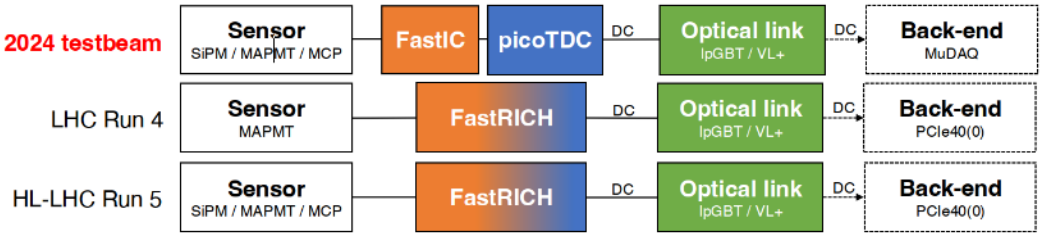
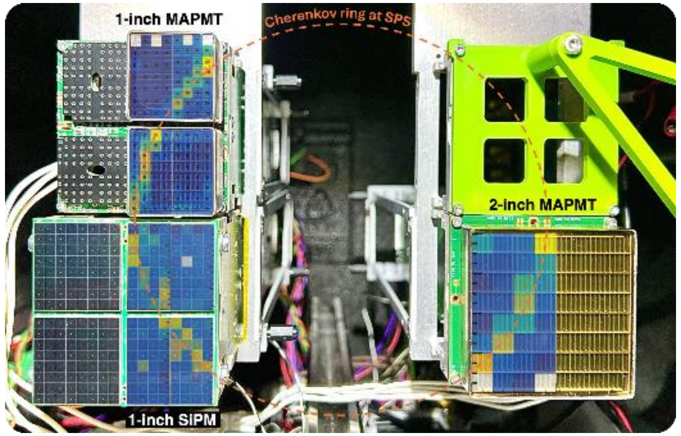
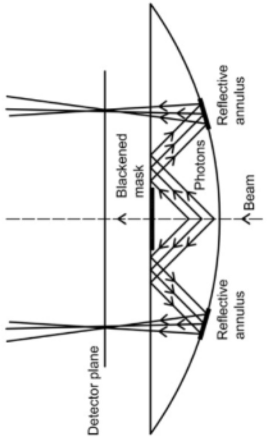
Prototype testing

- Prototype based on FastIC+picoTDC to be replaced by the FastRICH
- 7 readout chains with ~500 channels coupled to MaPMTs, SiPM and LAPPD sensors
- Readout with prototype lbGBT plugins with VTRX+
- Tested at the SPC facility at CERN







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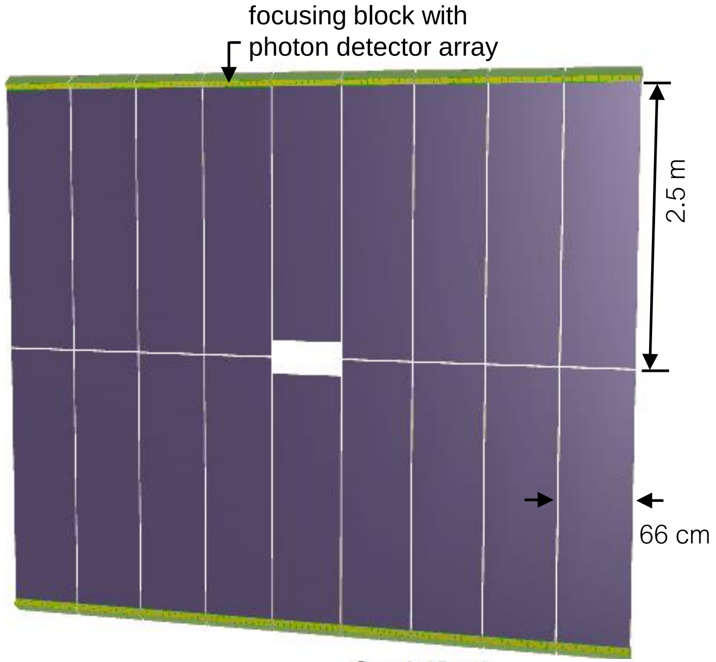
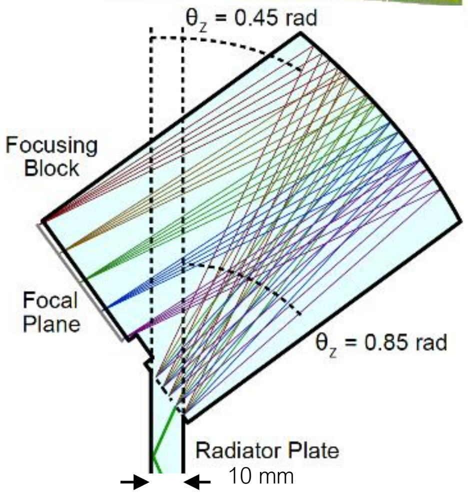
TORCH concept

- Exploit prompt production of Cherenkov light in an array of fused-silica bars to provide timing.
- Cherenkov photons are propagated to detector plane via total internal reflection from the quartz surfaces.
- Cylindrical focusing block, focusses the image onto a detector plane with highly segmented photon detectors.
    - Used to correct for chromatic dispersion.
- Large area detector required to cover the full LHCb acceptance ($5 \times 6 m^2$).
- Provide PID in the momentum range 2-15 GeV/c.
- Requires 70 ps time resolution per photon.



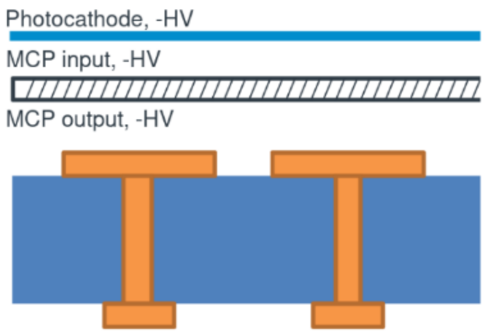


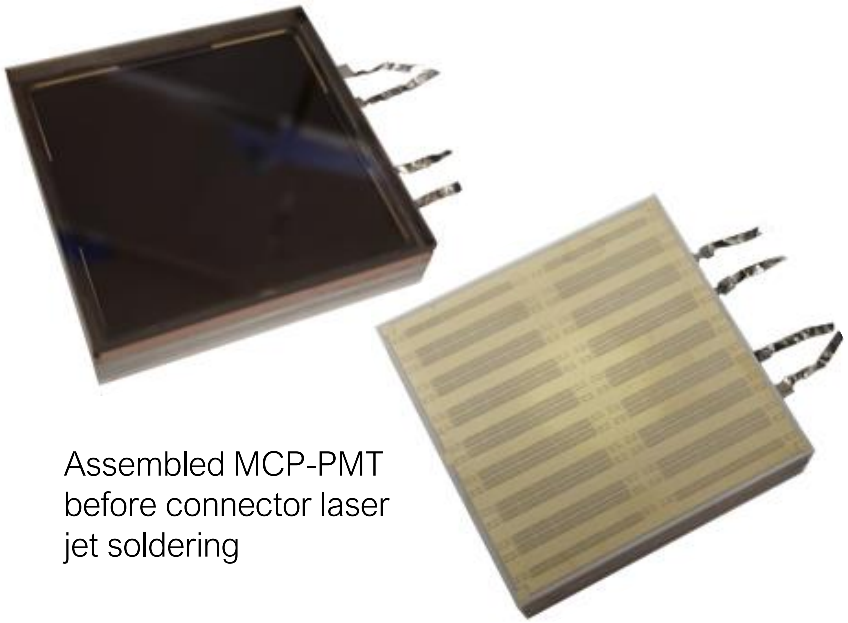
For more details on the TORCH concept see **[NIM A 639 (1) (2011) 173]**

Photon detectors

PHOTEK
ENVISAGE THE FUTURE

- Recent R&D effort to produce a 16-by-96 pixel MCP-PMT using direct rather than capacitive coupling.
  - New tube is currently under test at Photek.
- Aim to reduce charge-sharing and per-pixel occupancies.
  - 8-by-64 prototype exploits charge-sharing to achieve 8-by-128 effective resolution.
- Work ongoing in context of DRD4 to improve rate capability and lifetime (ideally well beyond 10C/cm^2).



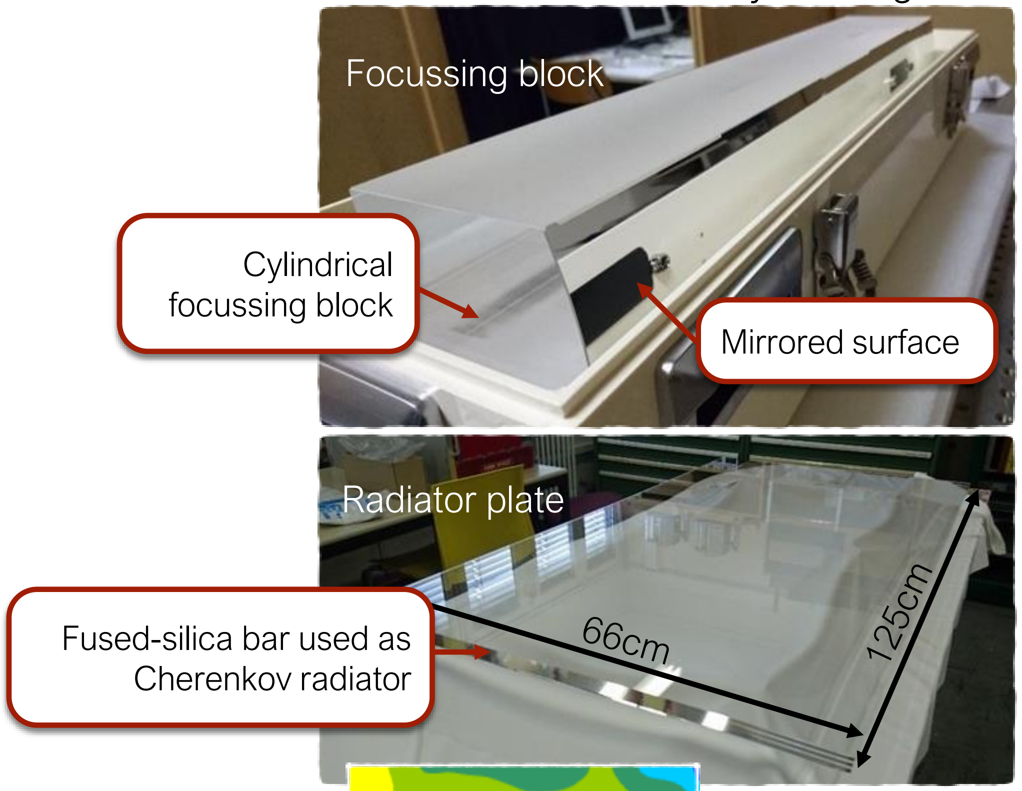


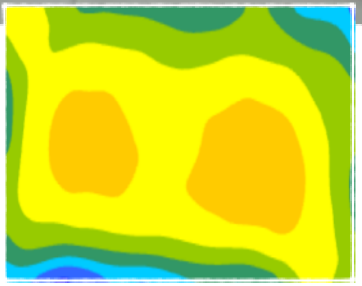
Assembled MCP-PMT before connector laser jet soldering

Fused-silica pieces

- Optics formed from multiple pieces of synthetic fused-silica that are bonded.
  - Pactan 8030 used with existing prototype but a structural epoxy will be used for final detector.
- Require high-quality surface on front and rear faces (flatness variation$\leq 3\mu\mathrm{m}$ and surface roughness 5Å).
- Two 66x62.5x1cm^3 radiator plates have recently been acquired to equip a full-sized module.

Produced by Nikon glass

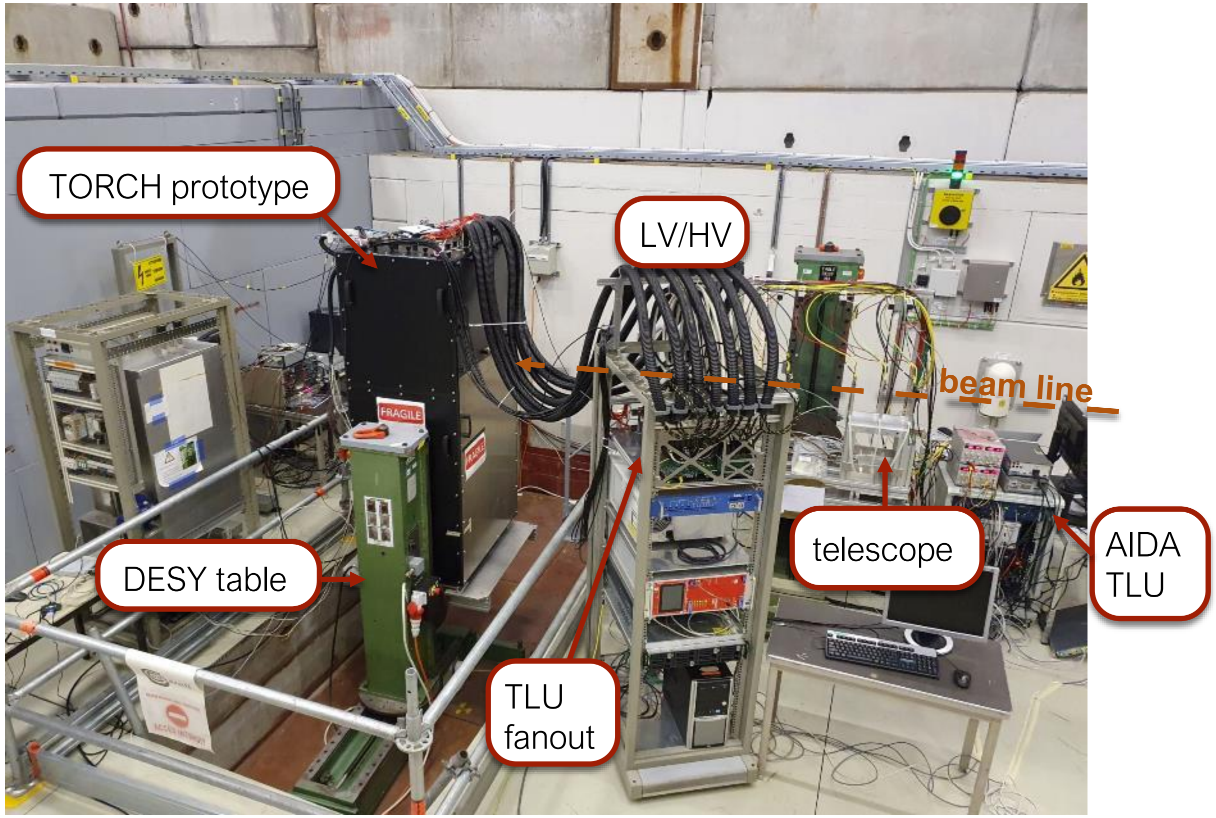




Measured flatness variation in 1 $\mu\mathrm{m}$ contours

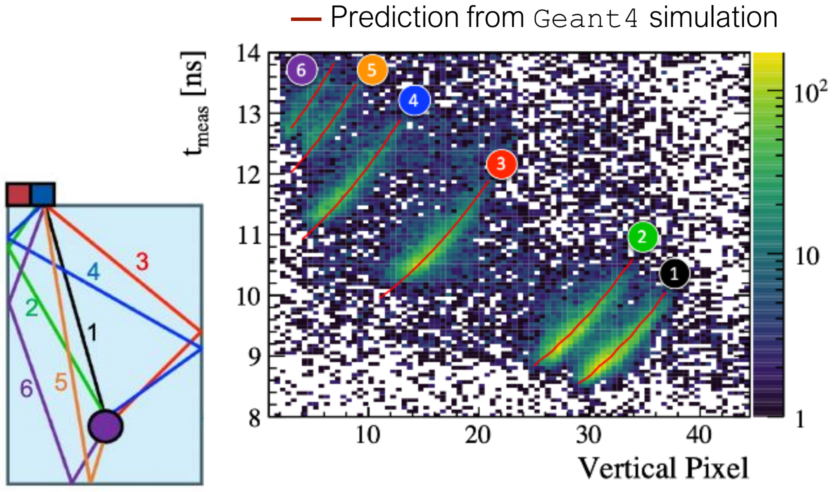
Beam test experimental area

- Already a large scale prototype requiring significant infrastructure.
  - We are equipping 3072 channels with 6 MCP-PMTs.



Performance in 2018 beam test

- Observed pattern is consistent with `Geant4` simulations of the prototype.
  - Form image in space time that is folded by reflections from the sides of the radiator.
- Studies indicate that time resolution can meet the needs of TORCH.



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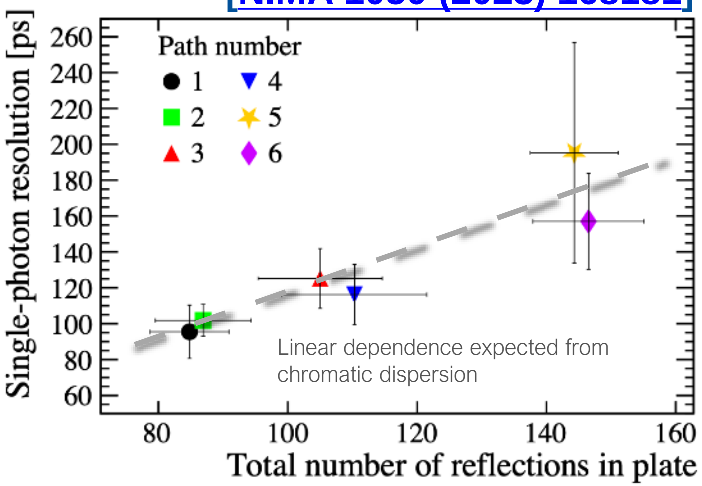
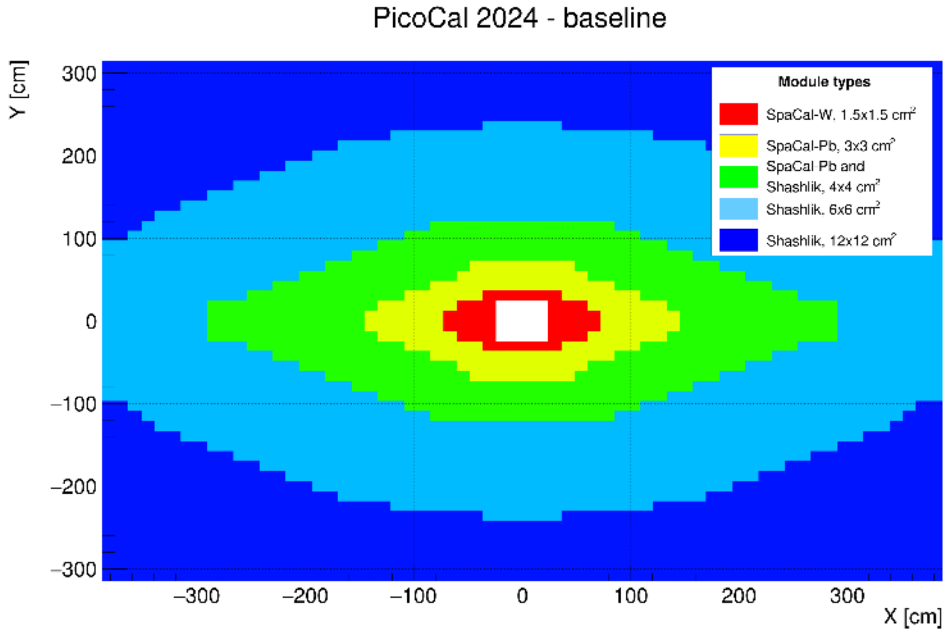


The LHCb PicoCal (= ECAL after Upgrade II)

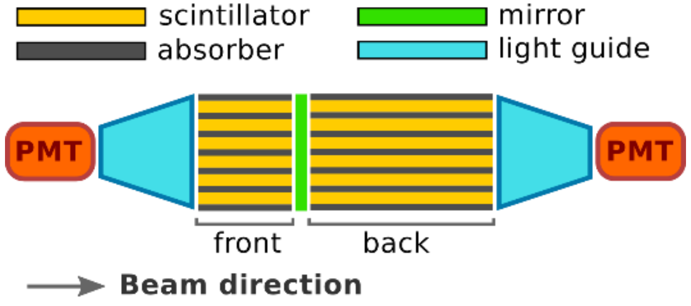


SpaCal technology for inner region:
- Innermost modules with scintillating crystal fibres and W absorber
→ Development of radiation-hard scintillating crystals
→ 1.5x1.5 cm^2 cell size
- Intermediate region with scintillating plastic fibres and Pb absorber
→ Need radiation-tolerant organic scintillators
→ 3x3 cm^2 and 4x4 cm^2 cell size

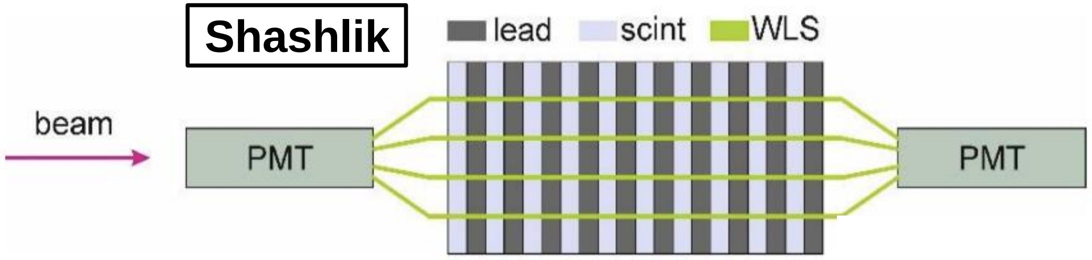
Shashlik technology:
- About 2900 Shashlik modules with improved timing capability and double-sided readout
→ WLS fibres replaced in all modules, about 900 modules modified for smaller cell size

- **LS3 enhancement:** W absorber for innermost modules equipped with scintillating plastic fibres for 2x2 cm^2 cell size, single-sided readout
- All SpaCal modules tiled by 3°+3°

SpaCal

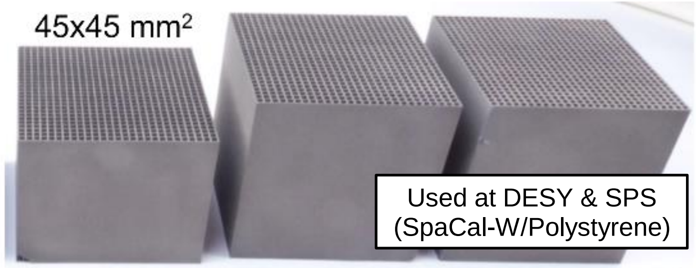


Shashlik

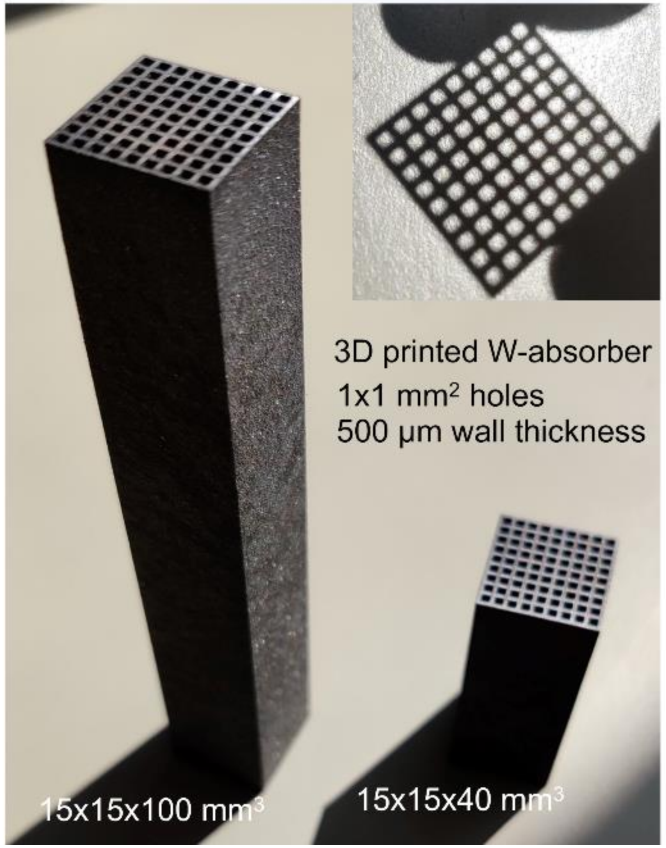


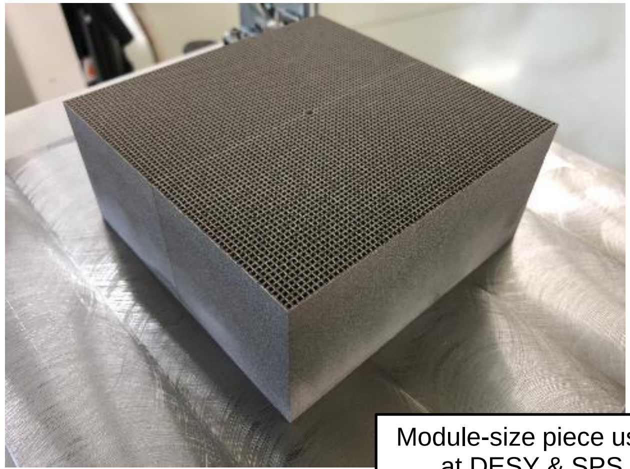
R&D example: 3D printing of tungsten absorber

- 3D printing using pure tungsten powder found to be a scalable technology for absorber production
- Smooth surface mandatory to avoid damaging the fibres during insertion
→ Very good mean roughness of $R_a = 5\ \mu m$
(average profile height deviations from mean) achieved
- Based on R&D campaign with EOS (Germany)
- Module-size pieces also produced by Laser Add Technology Co. in China with similar precision

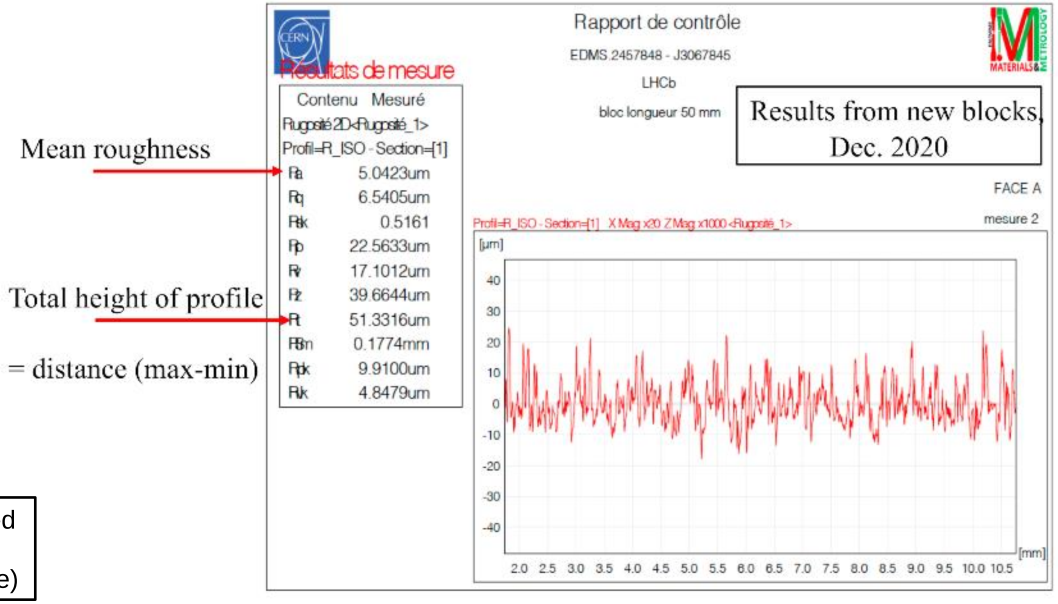


Used at DESY & SPS (SpaCal-W/Polystyrene)



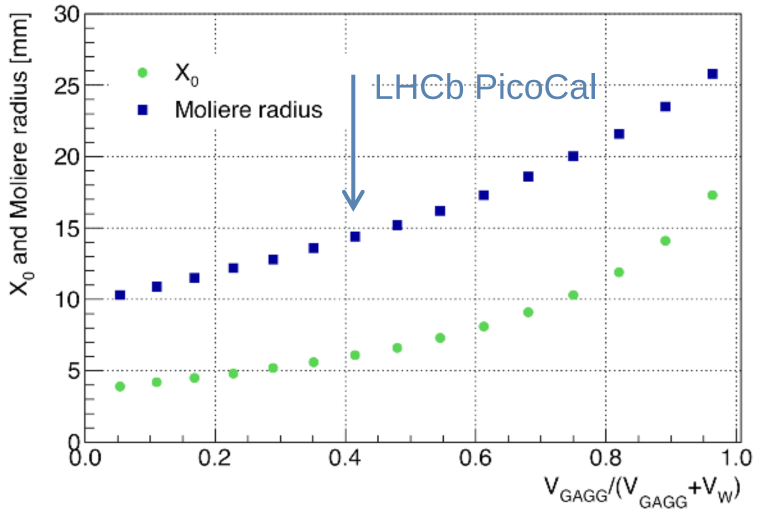


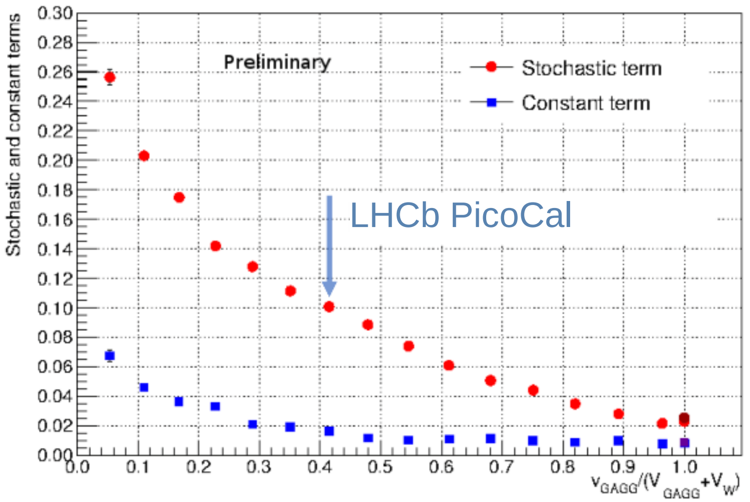
Module-size piece used at DESY & SPS (SpaCal-W/Polystyrene)

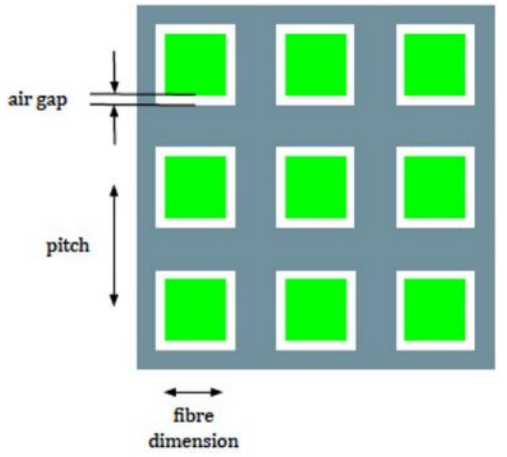


SpaCal: tuning of X_0, R_M and energy resolution

Example: Variation of fibre size with constant pitch in SpaCal with crystal fibres and tungsten absorber







GAGG fibers/W absorber

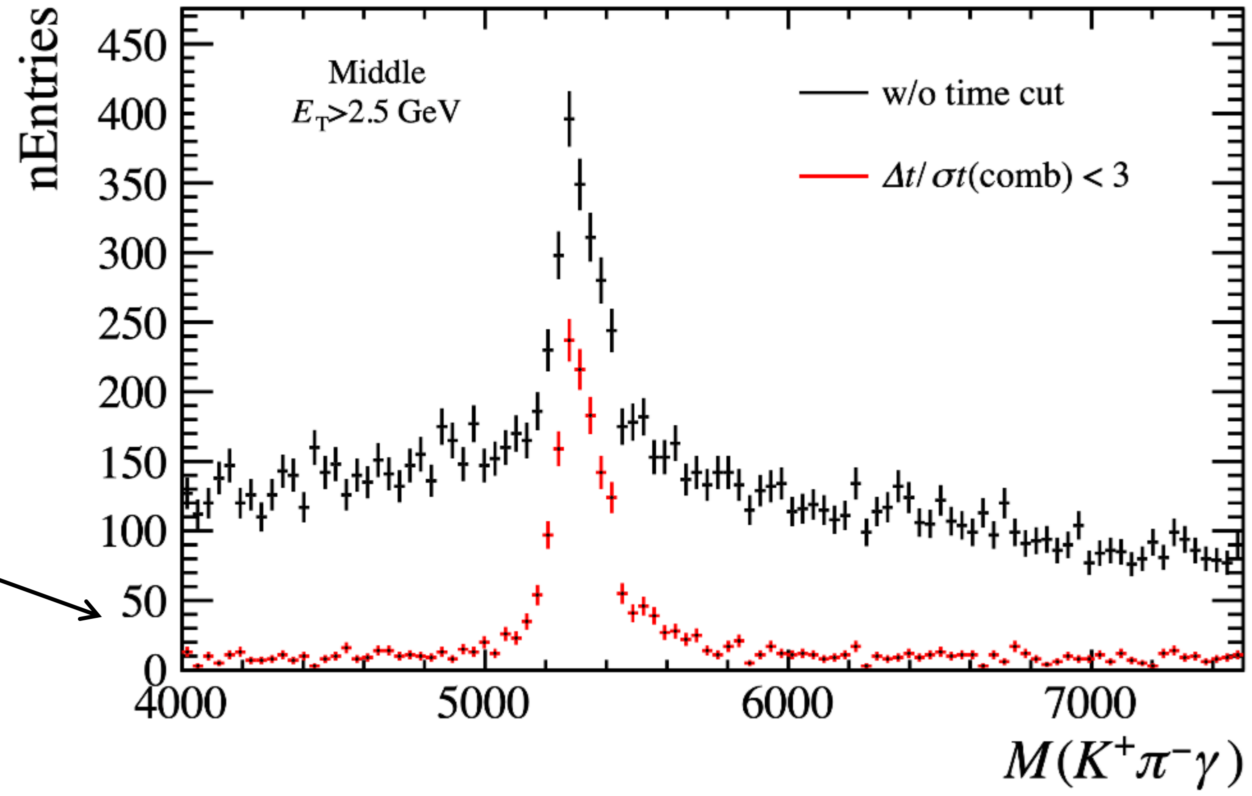
- Similar variations also possible for organic fibres or Shashlik modules
- Very flexible technology, can be adapted for LHCb PicoCal, Higgs factories, FCC-hh, fixed-target experiments at the intensity frontier, ...

Why picosecond-level time resolutions?

Example: $B^0 \rightarrow K^{*0}\gamma$

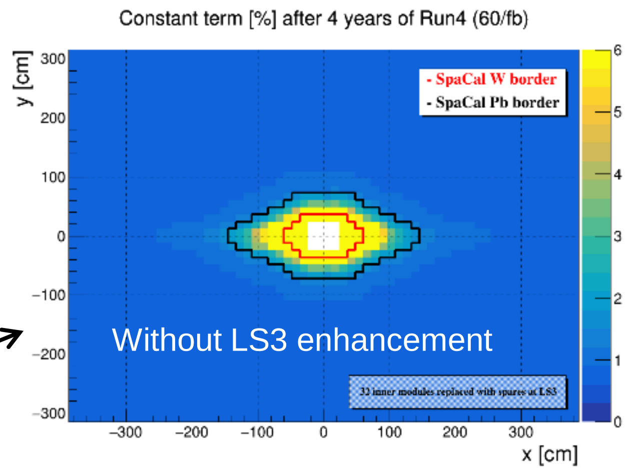
- Time of $K^{*0}\rightarrow K^+\pi^-$ from vertex detector
→ Allows to predict photon arrival time in ECAL
→ Comparison with measurement in ECAL allows to suppress background (distributed typically over a few hundred picoseconds)

PicoCal simulation



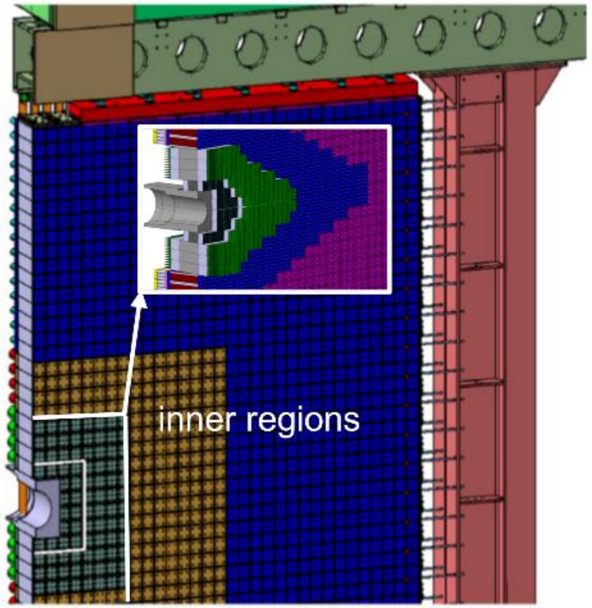
LHCb ECAL upgrade strategy

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 $L = 2 \times 10^{33}\ cm^{-2}s^{-1}$
(new 40 MHz readout)

LS3 enhancement in Q3/2026 - 2029:
Introduce single-section rad. tolerant SpaCal (2x2 and 3x3 cm^2 cells) in inner regions and rebuilt 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
No timing info



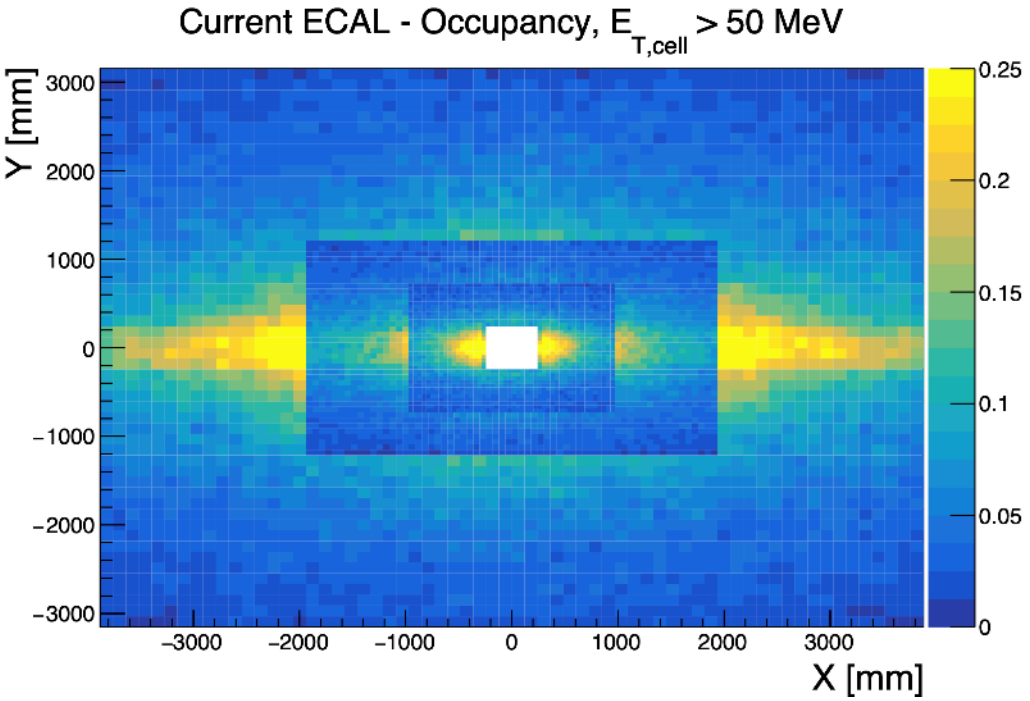
LS4 Upgrade II in 2033/2034:
Introduce double-section radiation hard SpaCal (1.5x1.5, 3x3 and 4x4 cm^2 cells) and improve timing of Shashlik modules for a luminosity of $L = 1.0$ or $1.5 \times 10^{34}\ cm^{-2}s^{-1}$
→ Innermost SpaCal-W modules equipped with crystal fibres
→ Include timing information and double-sided readout to full ECAL for pile-up mitigation

LHCb-TDR-023, LHCb-TDR-024

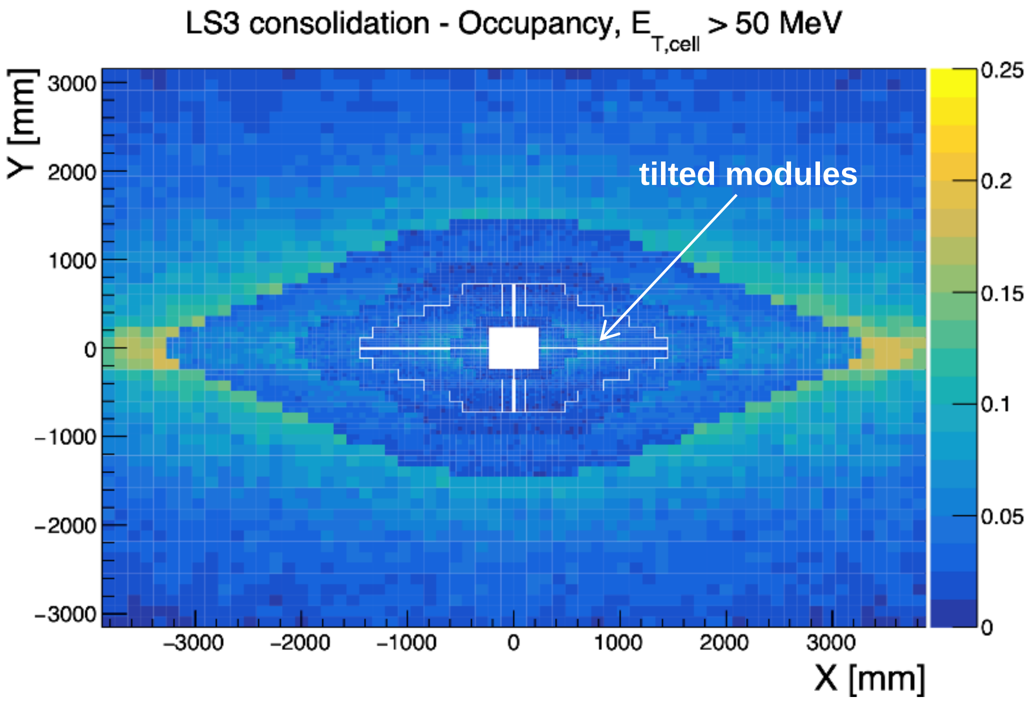
LS3 enhancement: impact of improved granularity

- Occupancies from detailed simulation, also including the hadronic component!
- Assumed luminosity: $L = 2 \times 10^{33}\ cm^{-2}s^{-1}$

Current ECAL:



With LS3 enhancement:



- Sizeable occupancy in large regions before LS3 enhancement (e.g. challenge for neutral pion reconstruction)
- Occupancy map after LS3 enhancement reasonably flat

Outline: R&D and test beam results

SpaCal with tungsten absorber:

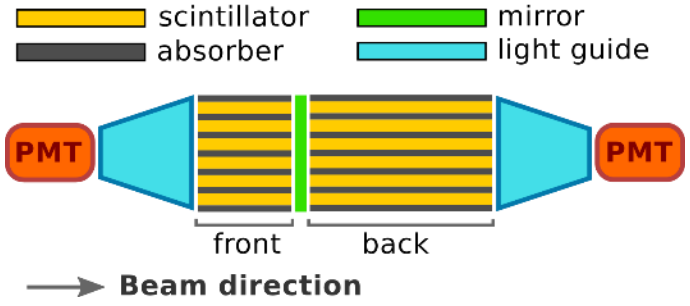
- SpaCal-W with crystal fibres for LS4
- SpaCal-W with polystyrene fibres for LS3

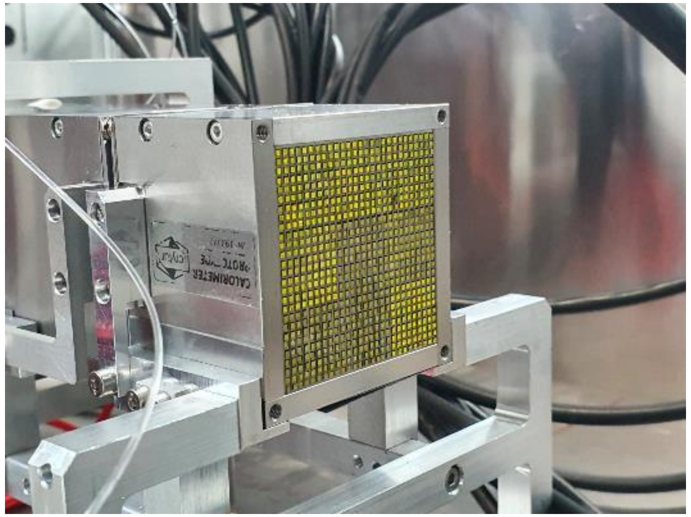
SpaCal with lead absorber

Shashlik with fast WLS fibres

First step: tungsten absorber and garnet crystals

SpaCal prototype module with W absorber and garnet crystal fibres:
- Pure tungsten absorber with 19 g/cm^3
- 9 cells of 1.5x1.5 cm^2 ($R_M \approx$ 1.45 cm)
- 4+10 cm long (7+18 X_0)
- Reflective mirror between sections



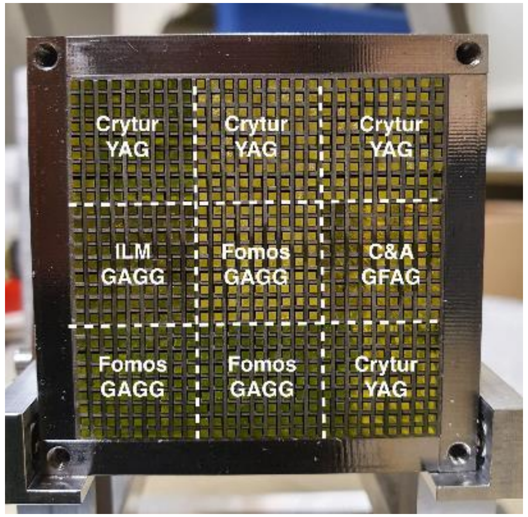


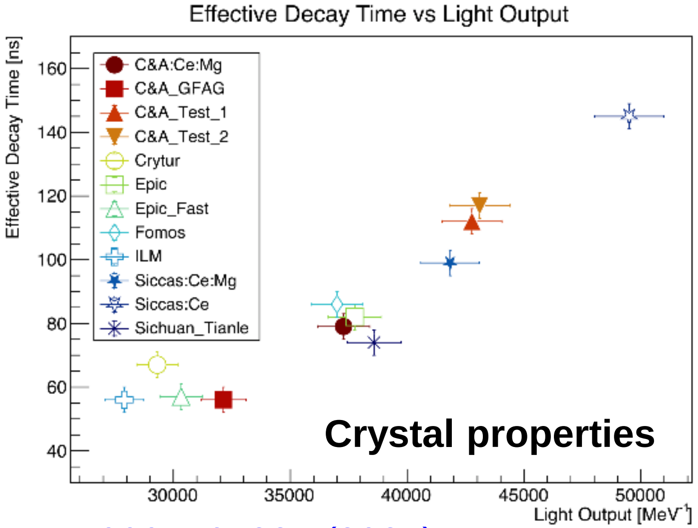
Crystal garnets from several producers:
- Crytur - YAG
- Fomos - GAGG
- ILM - GAGG
- C&A - GFAG

→ Characterised with laboratory measurements

Photon detectors used:
- Hamamatsu R12421 for energy resolution
- Hamamatsu R7600U-20 metal channel dynode (MCD) PMT for timing for better time resolution

Configuration used at DESY in 2020 and 2021

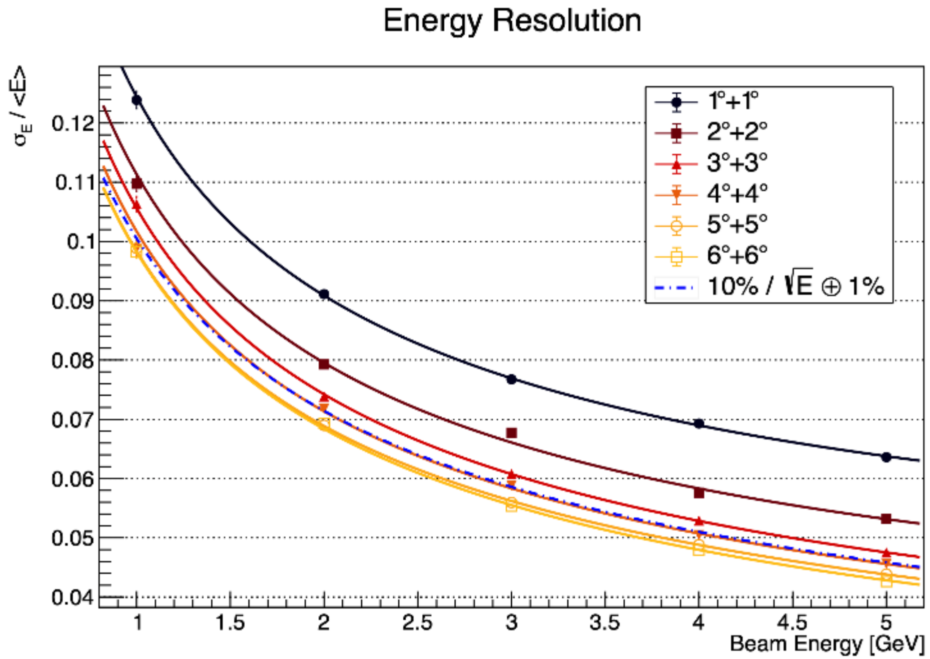




NIM A 1000, 165231 (2021)

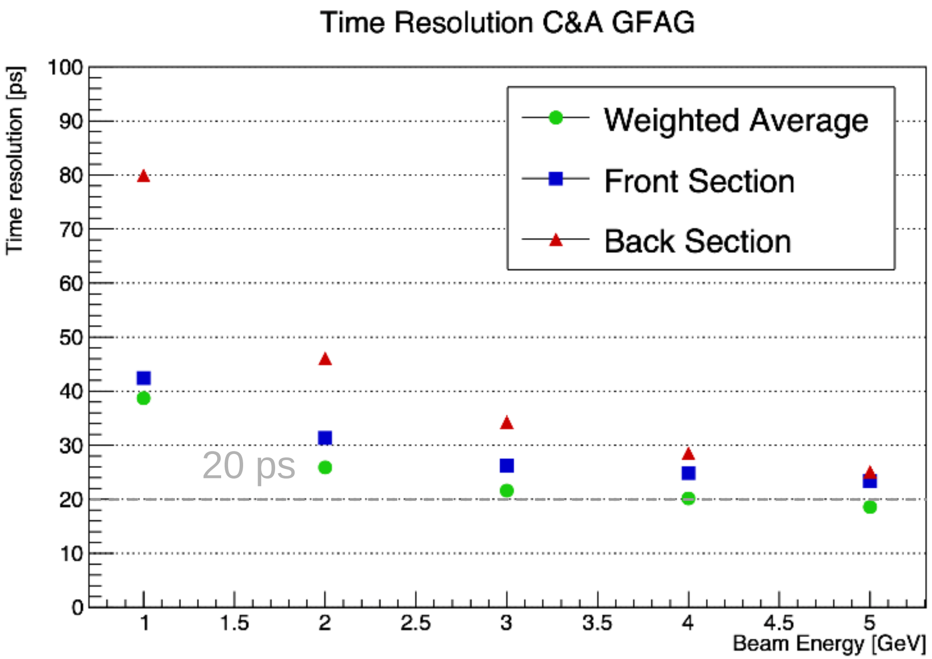
SpaCal-W with crystal fibres: test beam results

Energy resolution (DESY 2020, R12421)



- Better energy resolution with larger incidence angles
- Data up to 5 GeV give (10.2 ± 0.1)% sampling term and 1-2% constant term for $\theta_X = \theta_Y = 3°$

Time resolution (DESY 2021, R7600U-20)



- Incidence angles: $\theta_X = \theta_Y = 3°$, double-sided readout
- Time stamps in front and back obtained using constant fraction discrimination (CFD)
- Time resolution at 5 GeV for GFAG: better than 20 ps

NIM A 1045, 167629 (2022)

Outline: R&D and test beam results

SpaCal with tungsten absorber:

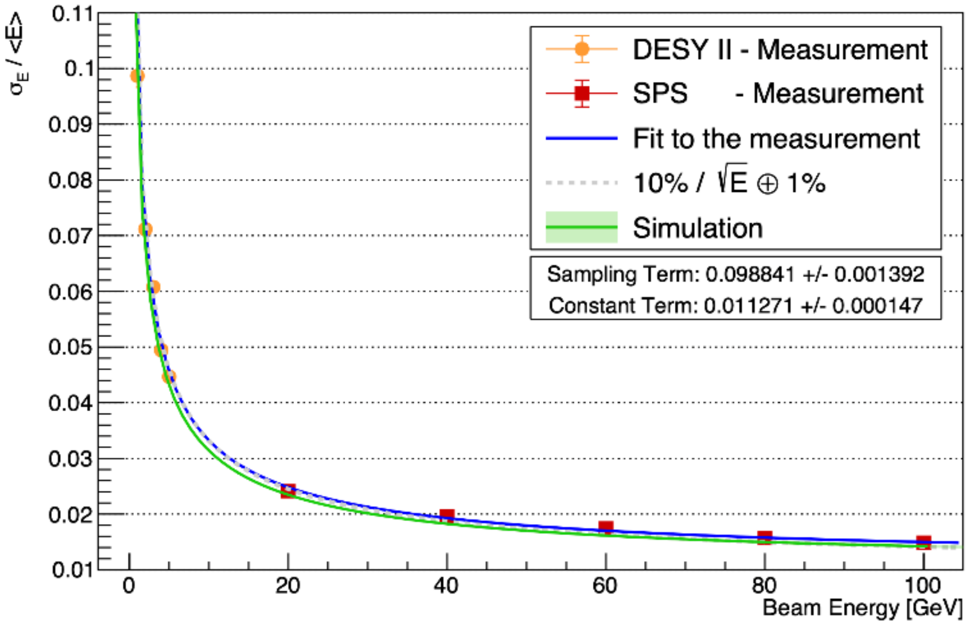
- SpaCal-W with crystal fibres for LS4
- SpaCal-W with polystyrene fibres for LS3

SpaCal with lead absorber

Shashlik with fast WLS fibres

SpaCal-W with polystyrene fibres: test beam results

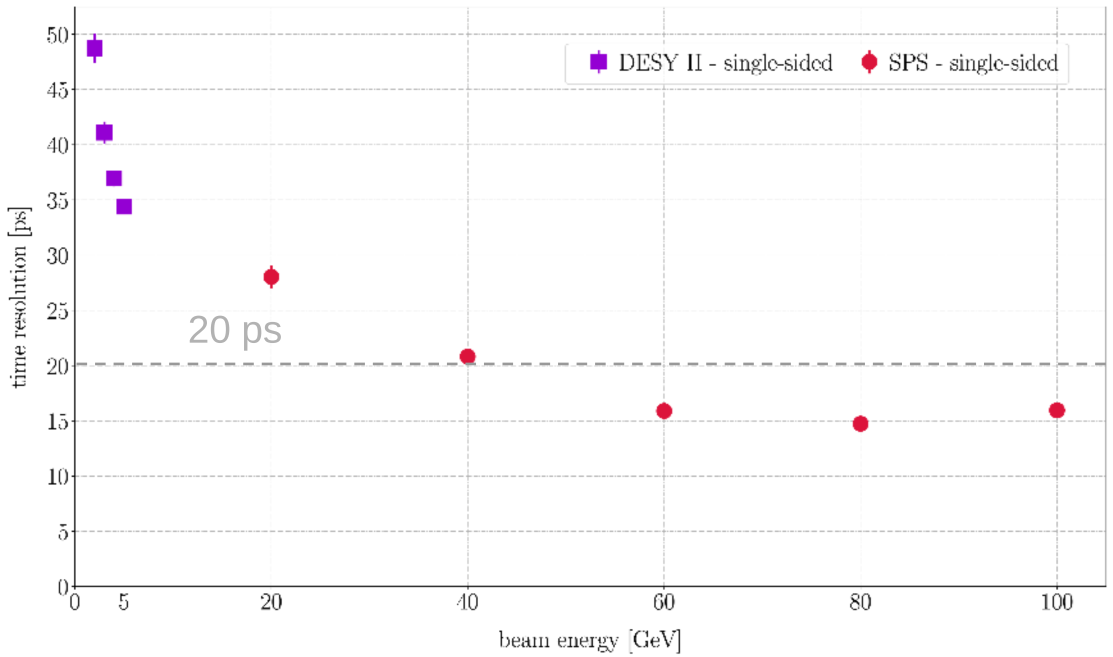
Energy resolution (DESY & SPS, R14755U-100)



- Incidence angles: $\theta_X = \theta_Y = 3°$, single-sided readout
- Module-size prototype
- Noise contribution subtracted
- Sampling term: 9.9%, constant term: 1.1%

→ Very good agreement with simulation

Time resolution (DESY & SPS, R7600U-M4)



- Incidence angles: $\theta_X = \theta_Y = 3°$, single-sided readout
- Prototype with 2x2 cells
- Optical coupling with “hollow” light guide
- Multi-anode PMT with 4 channels
- Time resolution above 40 GeV: better than 20 ps

LHCb-TDR-024

Outline: R&D and test beam results

SpaCal with tungsten absorber:

- SpaCal-W with crystal fibres for LS4
- SpaCal-W with polystyrene fibres for LS3

SpaCal with lead absorber

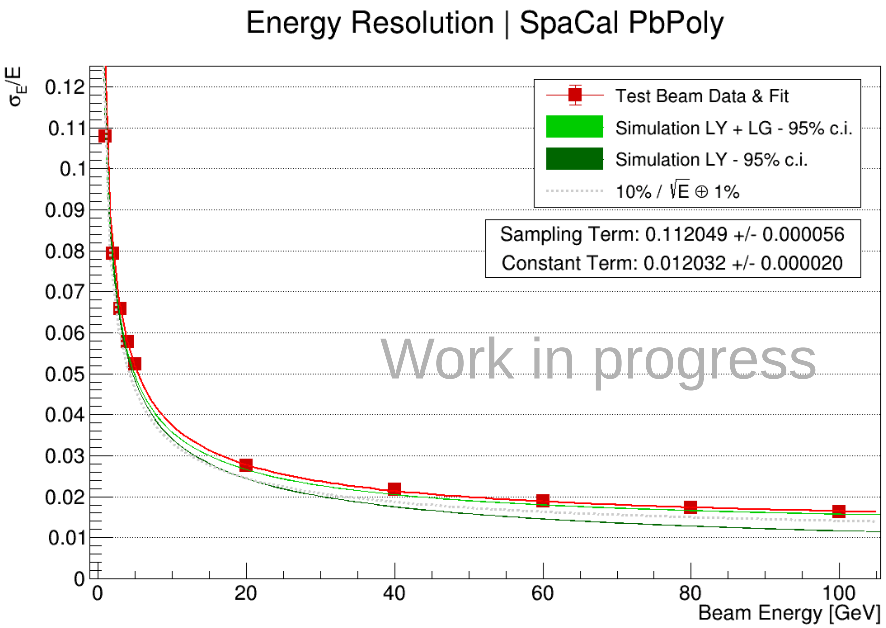
Shashlik with fast WLS fibres

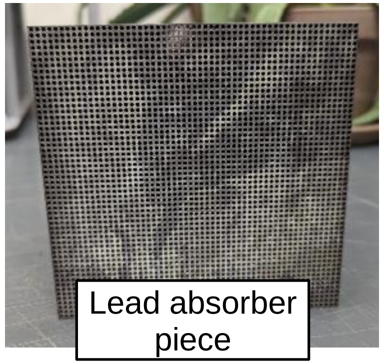
Module-size prototype with lead absorber

- 12.1 x 12.1 x 30 cm^3 absorber produced by ICM & MTH (Germany) using novel low-pressure casting approach in 2024
- Filled with green 3HF fibres (better radiation hardness than SCSF-78), 1.5 mm diameter
- Light yield: ≈ 1500 ph.e. / GeV
- Two-staged optical coupling: fibre bundle + hollow light guides

→ More uniform spacial homogeneity

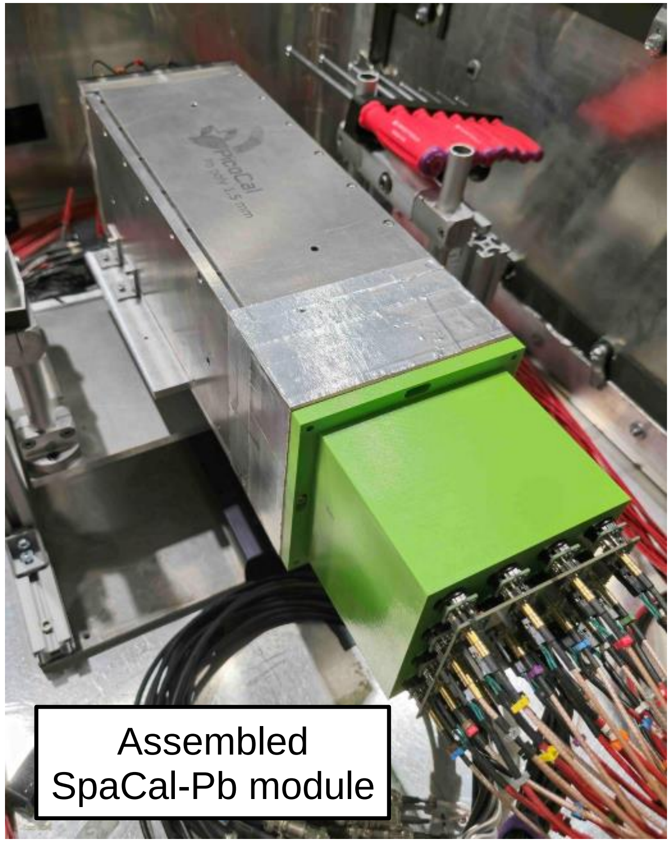
→ Better constant term of energy resolution





Lead absorber piece

Module with fibre bundles



Assembled SpaCal-Pb module

Outline: R&D and test beam results

SpaCal with tungsten absorber:
- SpaCal-W with crystal fibres for LS4
- SpaCal-W with polystyrene fibres for LS3

SpaCal with lead absorber

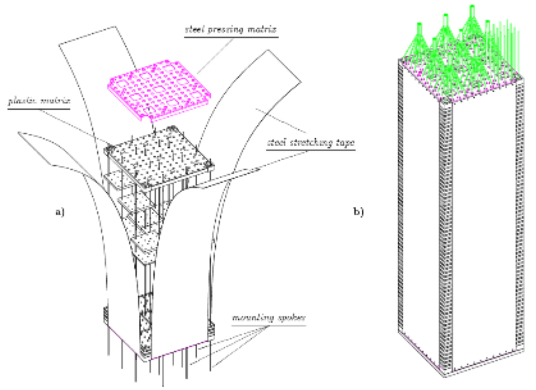
Shashlik with fast WLS fibres

What about the Shashlik modules for LS4?

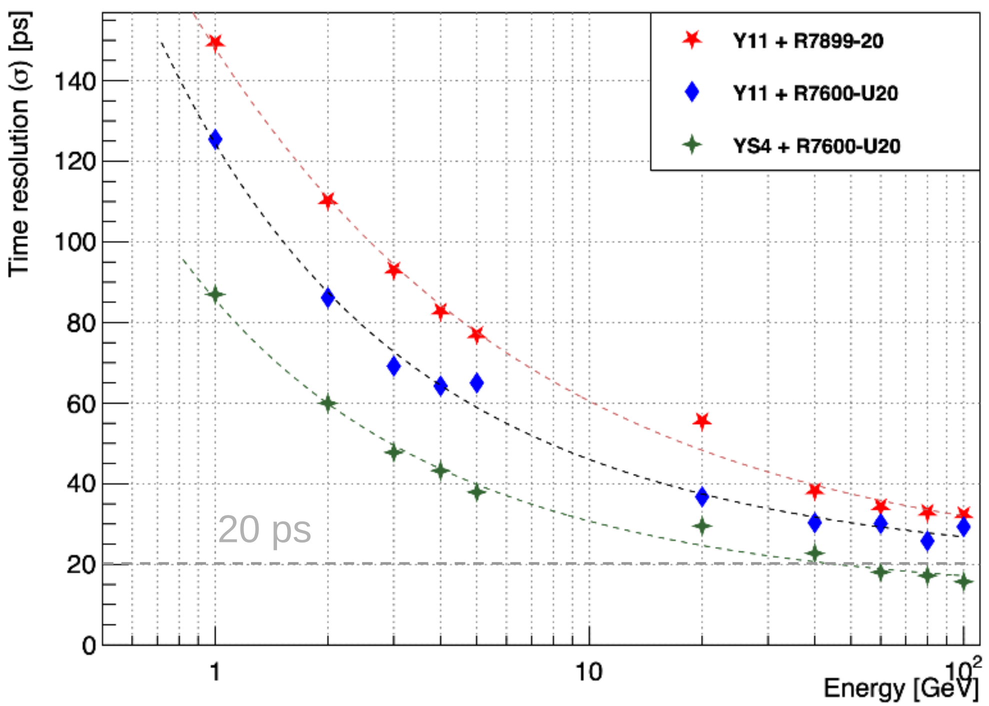
• Current LHCb Shashlik modules have good time properties, further improvement by replacing WLS fibres by faster ones:

- Y11 (7 ns decay time) → current LHCb
- YS2 (3 ns decay time)
- YS4 (1.1 ns decay time)

• Measurements at DESY and SPS with current (R7899-20) and faster (R7600-20) PMT, single-sided readout, $\theta_X = \theta_Y = 3°$



Time resolution (DESY and SPS)



• Better than 20 ps achieved above 40 GeV
(even slightly better with double-sided readout)

LHCb-TDR-024

Summary

- There is extensive R&D for all projects involved in the LHCb Upgrade II with very promising results
  - Timing is the new dimension used by most sub-systems to allow better association of particles to primary vertices as the geometry of the spectrometer makes it challenging if only spatial information is used
- The requirements for the photon detectors of the RICH and TORCH are difficult to meet at this point in time
  - However, SiPMs cooled at very low temperatures appear promising
- There are significant upgrades for LS3 that will demonstrate some of the Upgrade II technologies