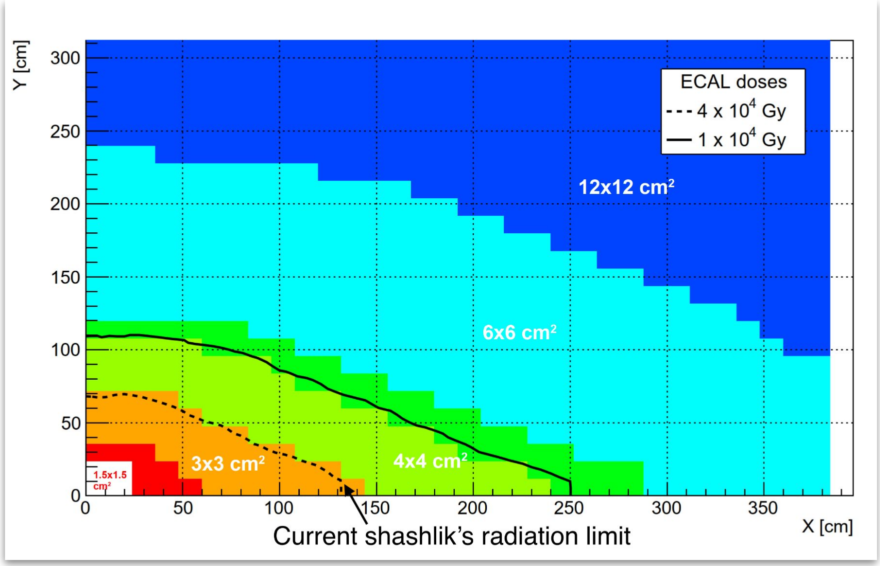
# SPACAL W-GAGG Performance


Loris Martinazzoli[1,2]
on behalf of the LHCb ECAL Upgrade II R&D Group

[1] CERN, Geneva, Switzerland
[2] Università degli Studi di Milano-Bicocca, Milan, Italy

# Upgrade Strategy




**1.5 x 1.5 cm$^2$ cell** region - **SPACAL W**

- 32 modules - Tungsten absorber

- Plastic fibres (LS3)
- Garnet crystal fibres (LS4)

**3 x 3 cm$^2$ cell** region - **SPACAL Pb**

- 144 modules - Lead absorber
- Plastic fibres

**4x4**, **6x6**, **12x12 cm$^2$ cell** regions - **Shashlik**:

- refurbished and upgraded with faster WLS fibres

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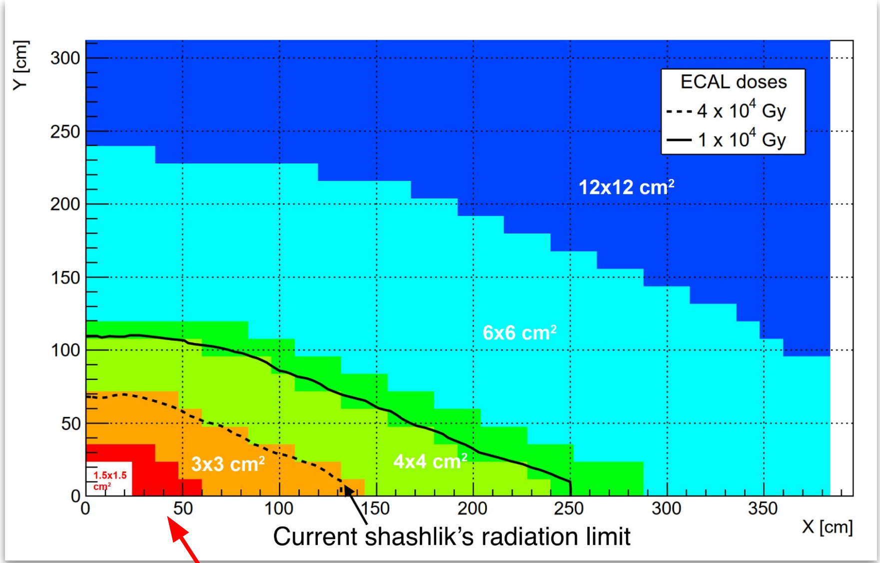


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- 144 modules - Lead absorber
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**4x4, 6x6, 12x12 cm² cell** regions - **Shashlik**:

- refurbished and upgraded with faster WLS fibres

Radiation doses up to **1 MGy and 6x10$^{15}$ 1 MeV neq/cm²** for 300 fb$^{-1}$

# GAGG

| | light yield (photons/MeV) | first decay time (ns) | second decay time (ns) |
|---|---|---|---|
| $Gd_3Al_4Ga_1O_{12}$ | 15 895 | 316 (100%) | |
| $Gd_3Al_3Ga_2O_{12}$ | **45 931** | **221** (100%) | |
| $Gd_3Al_2Ga_3O_{12}$ | **42 217** | **52.8** (73%) | 282 (27%) |
| $Gd_3Al_1Ga_4O_{12}$ | 17 912 | 42.2 (34%) | 90.5 (66%) |
| $Gd_3Al_0Ga_5O_{12}$ | 0 | *ND | *ND |

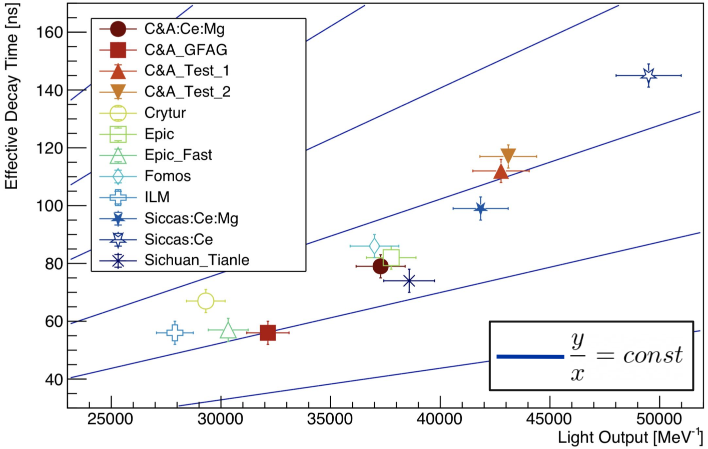
*K. Kamada et al., Cryst. Growth Des. 2011, 11, 10, 4484–4490*

Ce-doped multi-component garnets discovered in 2011.

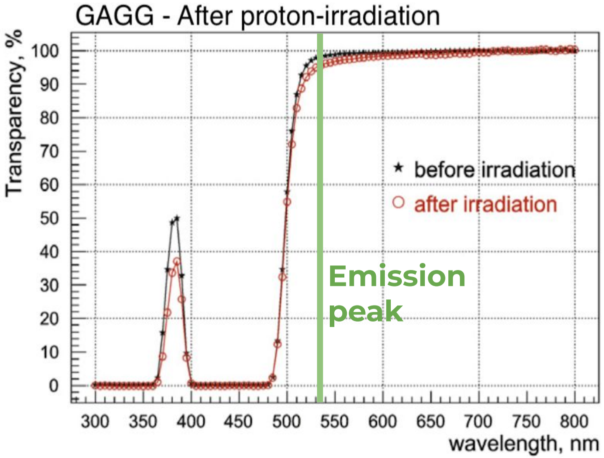
Gadolinium Gallium Aluminium Garnet $Gd_3Al_2Ga_3O_{12}$ (GAGG):

- **High light output** and relatively **fast decay time (~50 ns)**
- **Tunable composition**
  - *K.Kamada, Optical Materials 36 (2014) 1942–1945*
  - *K. Kamada, Optical Materials 41 (2015) 63–66*
- **Excellent time resolution** close to LYSO:Ce
- **Radiation hard** tested up to 1 MGy

Courtesy of K. Lebbou, ILM

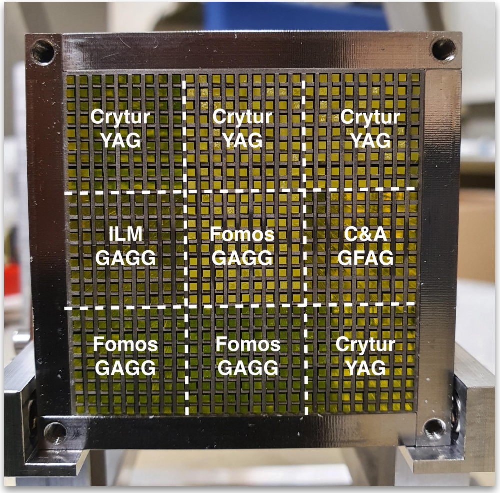


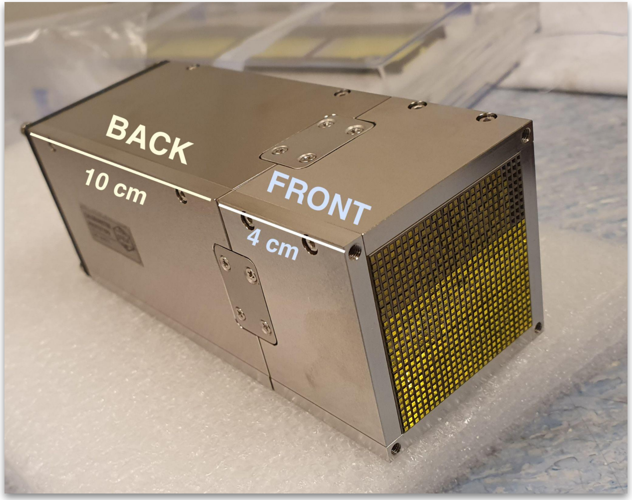

L. Martinazzoli et al., NIM A, 2021, 165231

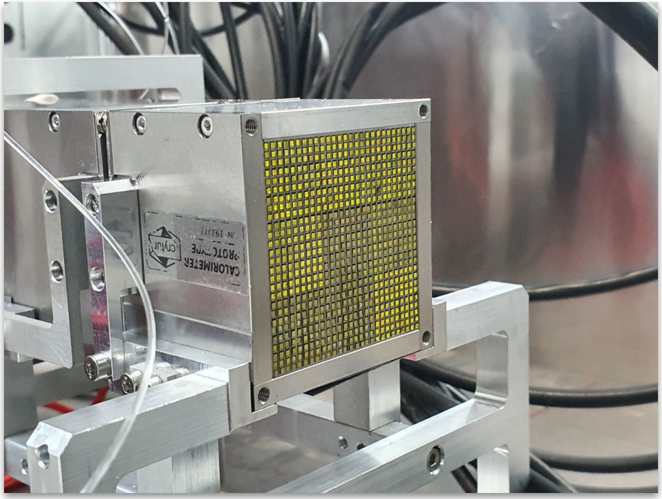



*V. Alenkov et al., NIM A 816 (2016) 176*

# The Prototype



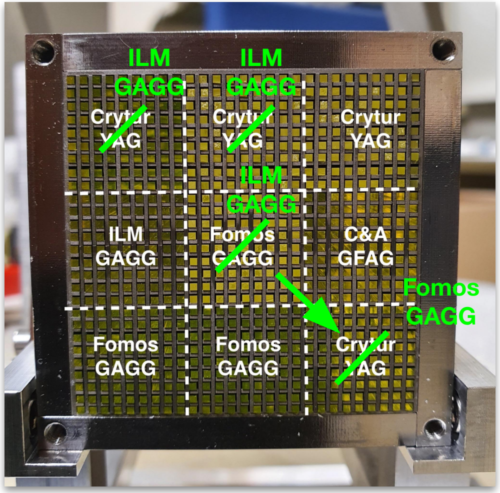



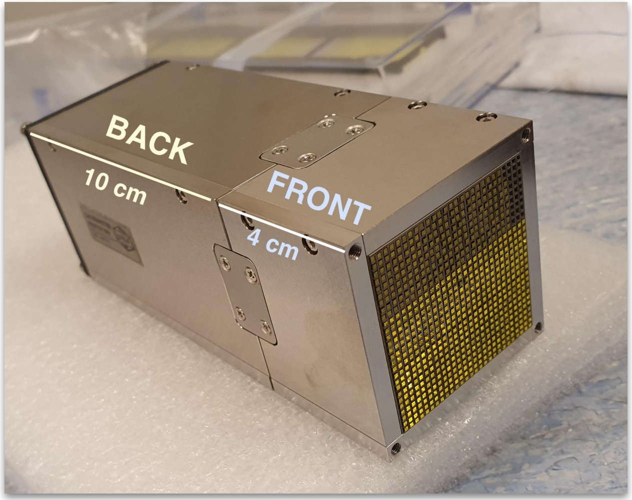



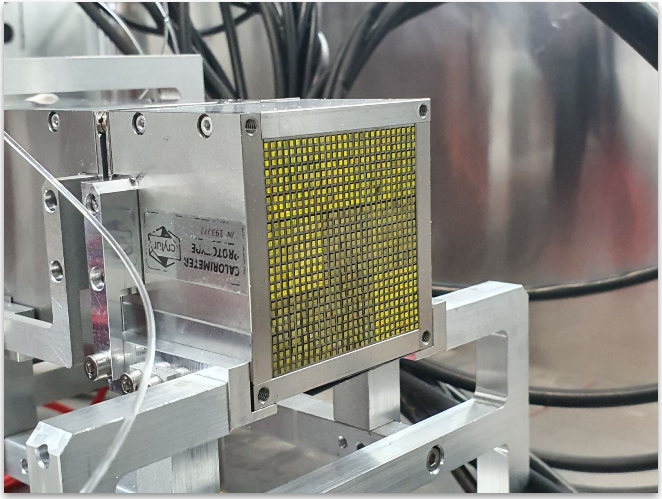
SPACAL prototype with **W absorber** and **garnet crystals**.

- Absorber in pure tungsten 19 g/cm$^3$
- 9 cells of 1.5x1.5 cm$^2$ (Molière radius: ~ 1.5 cm)
- 4+10 cm long (~ 7+18 $X_0$)
- ESR mirror between sections
- 1x1 mm$^2$ garnet crystal fibres

# The Prototype



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Mix of YAG and GAGG upgraded to pure GAGG in 2021

1. **DESY 2020-2021**
2. SPS 2022

# 1. DESY 2020-2021
2. SPS 2022

Nuclear Inst. and Methods in Physics Research, A 1045 (2023) 167629

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

## Performance of a spaghetti calorimeter prototype with tungsten absorber and garnet crystal fibres

L. An [a], E. Auffray [a], F. Betti [a], F. Dall'Omo [a], D. Gascon [i], A. Golutvin [b], Y. Guz [c], S. Kholodenko [c,f], L. Martinazzoli [a,h,*], J. Mazorra De Cos [e], E. Picatoste [i], M. Pizzichemi [a,h], P. Roloff [a], M. Salomoni [a], D. Sanchez [i], A. Schopper [a], A. Semennikov [d], P. Shatalov [d], E. Shmanin [f], D. Strekalina [f], Y. Zhang [g]

[a] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[b] *Imperial College London, London, United Kingdom*
[c] *Institute for High Energy Physics NRC Kurchatov Institute (IHEP NRC KI), Protvino, Russia*
[d] *Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia*
[e] *Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia CSIC, Valencia, Spain*
[f] *National University of Science and Technology "MISIS", Moscow, Russia*
[g] *School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[h] *Universitá degli Studi di Milano-Bicocca, Milano, Italy*
[i] *Universitat de Barcelona (ICCUB), Barcelona, Spain*

A R T I C L E   I N F O

*Keywords:*
Calorimetry
High energy physics (HEP)
Particle detectors
Spaghetti calorimeter (SPACAL)
Fibres
Scintillating crystals

A B S T R A C T

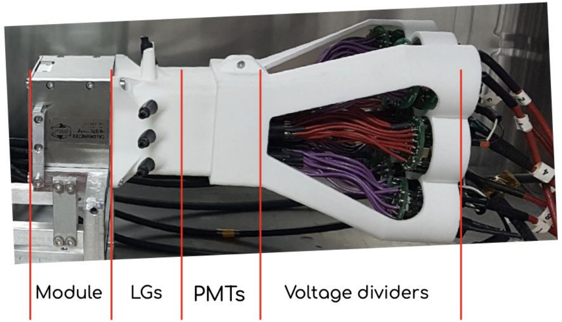
A spaghetti calorimeter (SPACAL) prototype with scintillating crystal fibres was assembled and tested with electron beams of energy from 1 to 5 GeV. The prototype comprised radiation-hard Cerium-doped $Gd_3Al_2Ga_3O_{12}$ (GAGG:Ce) and $Y_3Al_5O_{12}$ (YAG:Ce) embedded in a pure tungsten absorber. The energy resolution was studied as a function of the incidence angle of the beam and found to be of the order of $10\%/\sqrt{E} \oplus 1\%$, in line with the LHCb Shashlik technology. The time resolution was measured with metal channel dynode photomultipliers placed in contact with the fibres or coupled via a light guide, additionally testing an optical tape to glue the components. Time resolution of a few tens of picosecond was achieved for all the energies reaching down to $(18.5 \pm 0.2)$ ps at 5 GeV.

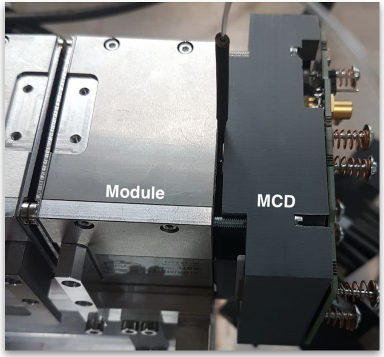
https://doi.org/10.1016/j.nima.2022.167629

# Readout

Cells read out in 2 ways:

- Hamamatsu **R12421** + PMMA light guides (LGs)
  - Small size to **equip all the cells for energy measurements**
- Hamamatsu **R7600U-20** (MCD) in direct contact
  - Low TTS **for timing** (only 1 cell equipped - front and back)



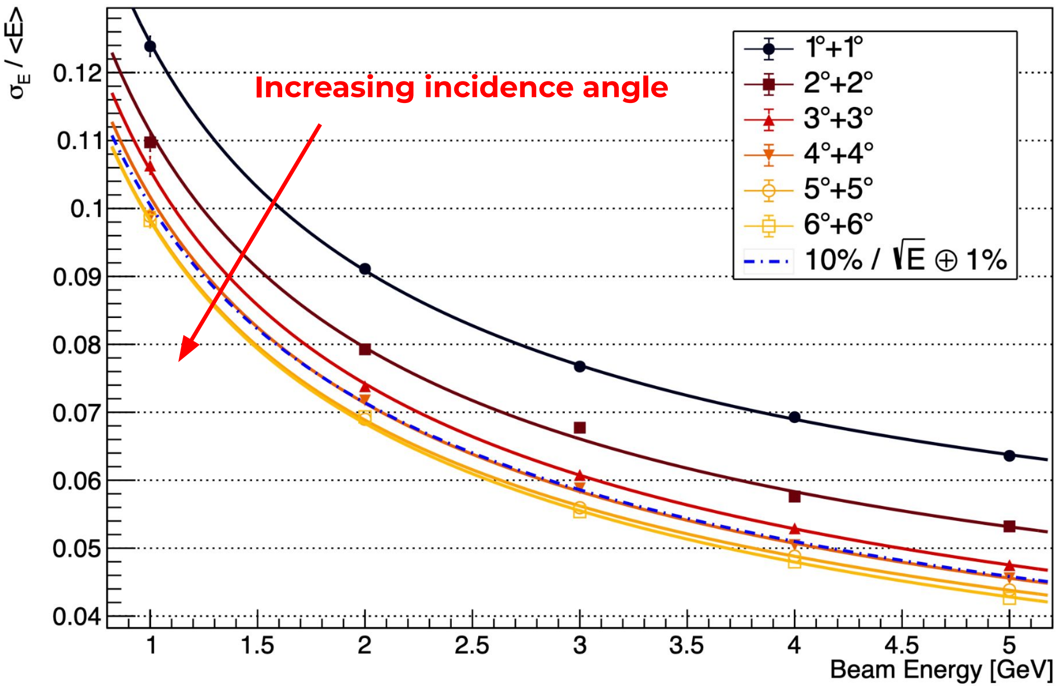

| Model | Size [mm] | Time Transit Spread [ns] |
|---|---|---|
| R12421 | 13.5 ø | 1.4 |
| R7600U-20 | 30 x 30 | 0.35 |

**Hamamatsu R7600U-20**

**Hamamatsu R12421**

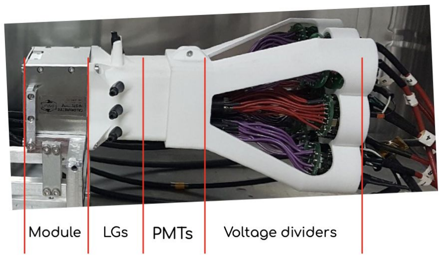
- No optical glue or grease was employed (unless otherwise specified)
- R7600U-20 active area reduced with black mask to match the cell size

# Energy Resolution



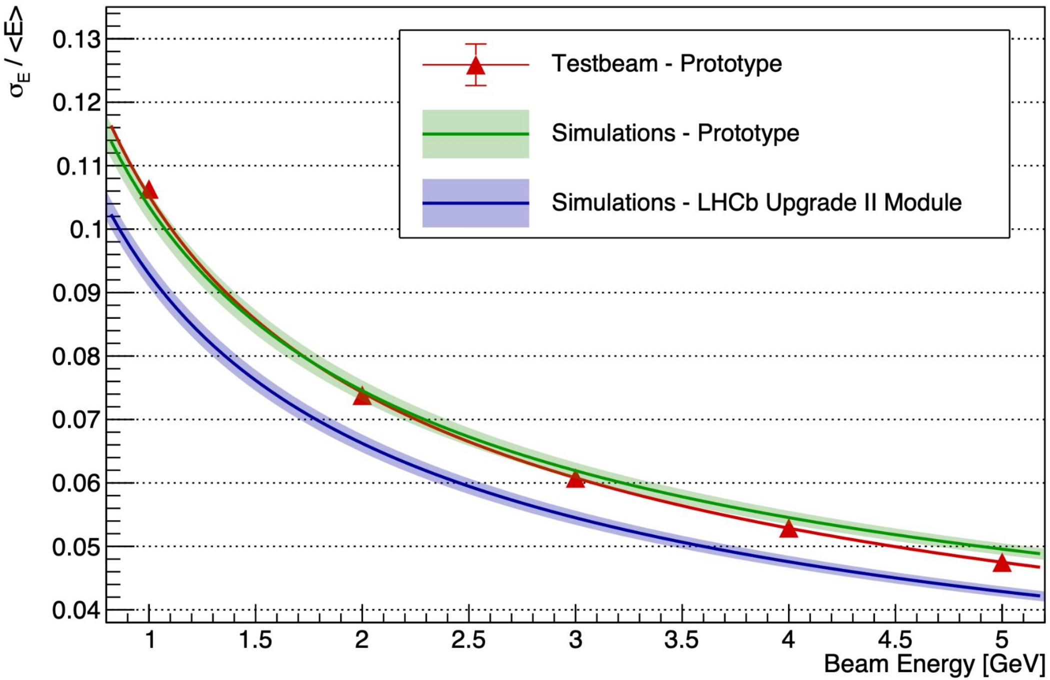

- Resolution improves increasing the incidence angle

- **Energy resolution at 3°+3°:**
  **Sampling term: 10.2%**
  **Constant term: 1-2%***
  *Higher-energy data needed to measure the constant term




**Hamamatsu R12421**

# Energy Resolution

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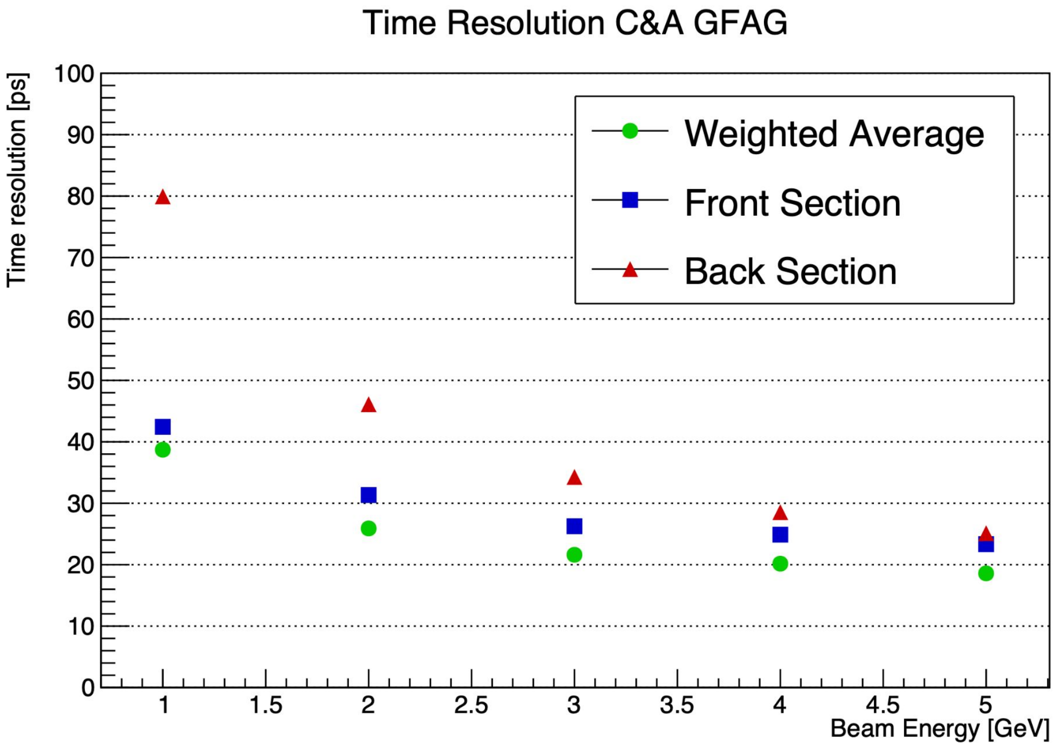
- **Energy resolution at 3°+3°:**
  **Sampling term: 10.2%**
  **Constant term: 1-2%***
  *Higher-energy data needed to measure the constant term

- Satisfying match with simulations

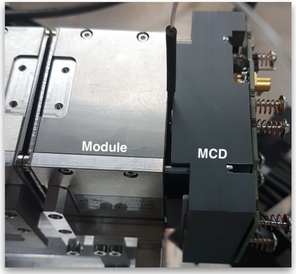
- Improvement expected from final design
  - Reduced material budget between front and back
  - Smaller pitch
  - Slightly longer sections

# Time Resolution



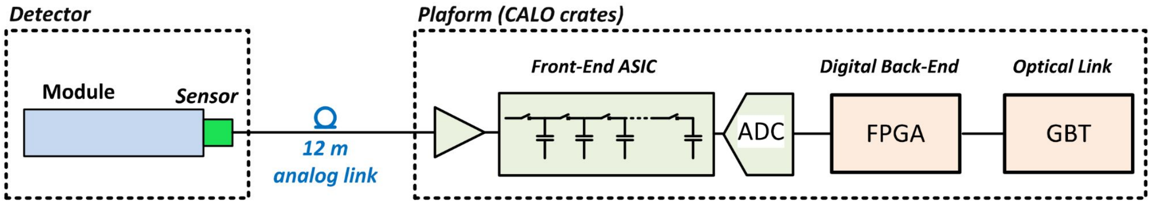

- Direct contact
- Front performs better than back at low energies

**Time resolution < 20 ps @ 5 GeV**




**Hamamatsu R7600U-20**

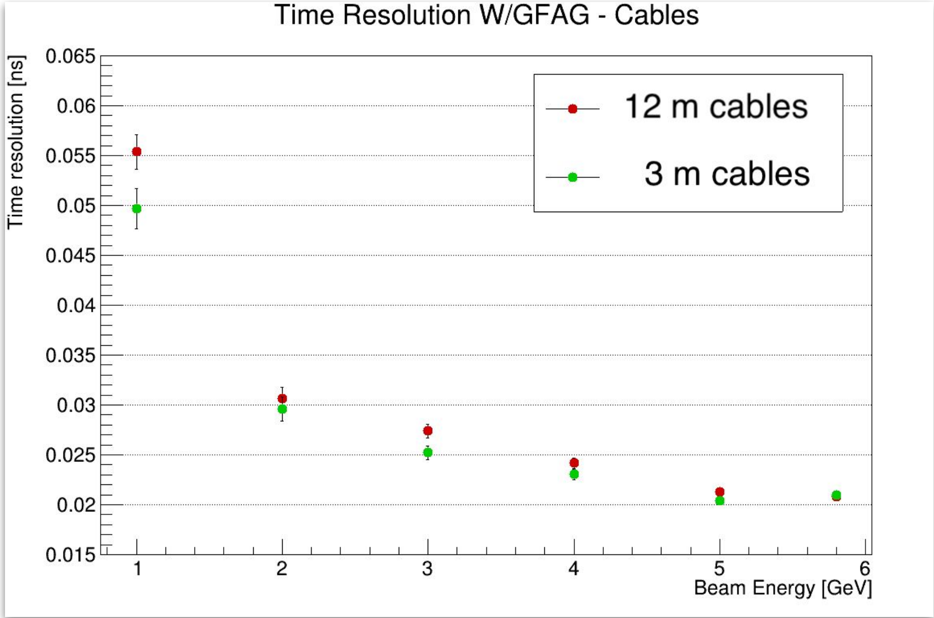
# Time Resolution with Long Cables




The baseline approach for the calorimeter architecture is to move the Front-End board to the ECAL platforms (lower radiation dose area)

Tested the **present 12 m long cables.**

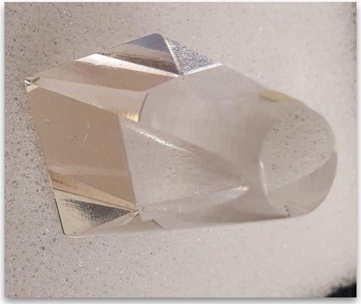
**No major degradation with 12 m long cables**

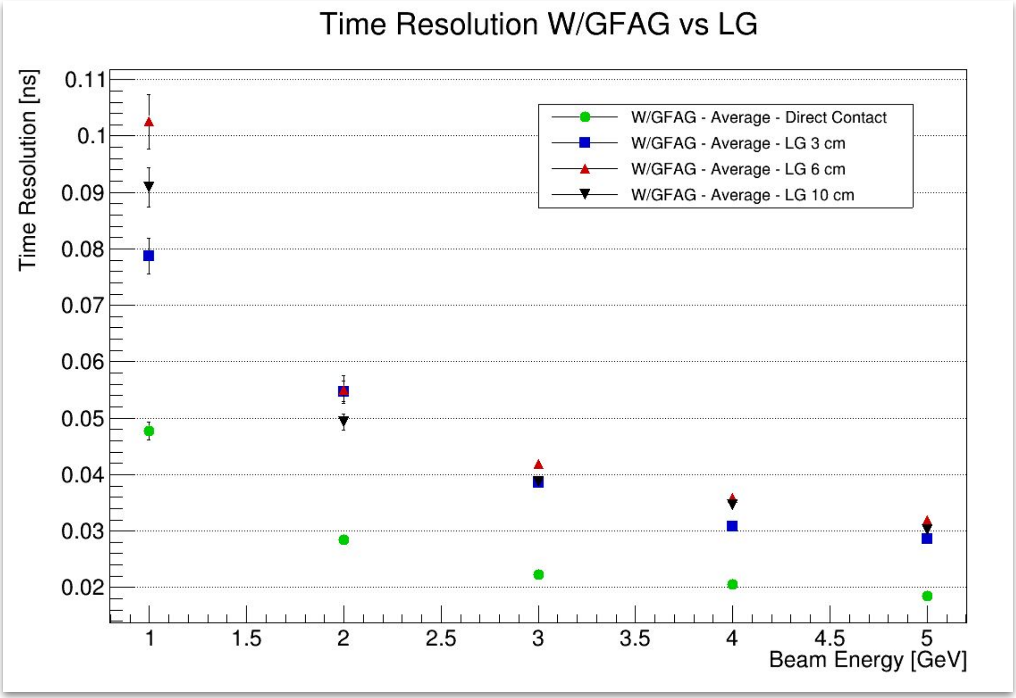



N.B. plot not comparable to previous slide due to different settings

# Time Resolution with Light Guides

- Time resolution with dry coupling and different light guides length
- >50% worse time resolution @ 5 GeV due to light losses
- No major difference with length
  - Loss due to the **additional optical interfaces** between fibres, light guide, and PMT



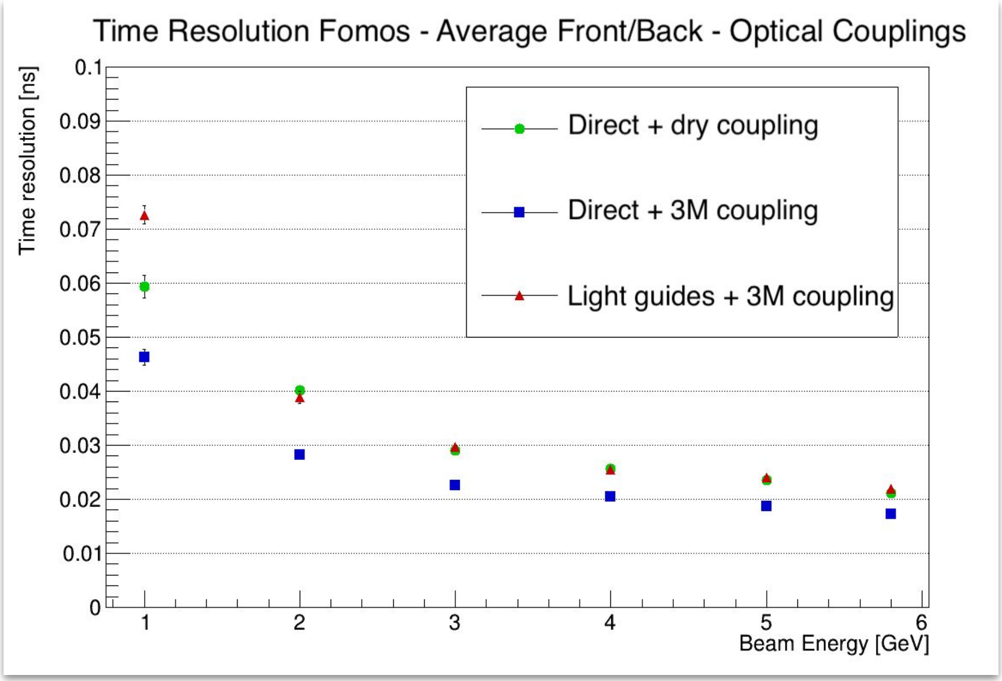


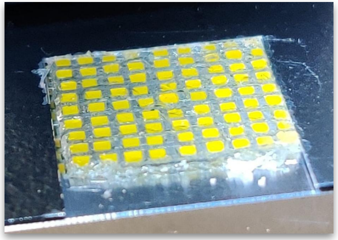
# Time Resolution with Optical Couplings

- Fomos GAGG cells with 3M optical coupling
  - Direct contact + **dry (air)** coupling
  - Direct contact + **optical** coupling
  - **Light guide + optical** coupling on both sides

- Optical coupling improves light extraction
  - GAGG n = 1.9
  - Air n = 1
  - 3M coupling n = 1.5

Time resolution with **light guides and optical coupling** comparable with **direct dry contact**



1. DESY 2020-2021
2. **SPS 2022**

# New Photomultipliers

R&D to identify candidate PMTs based on:

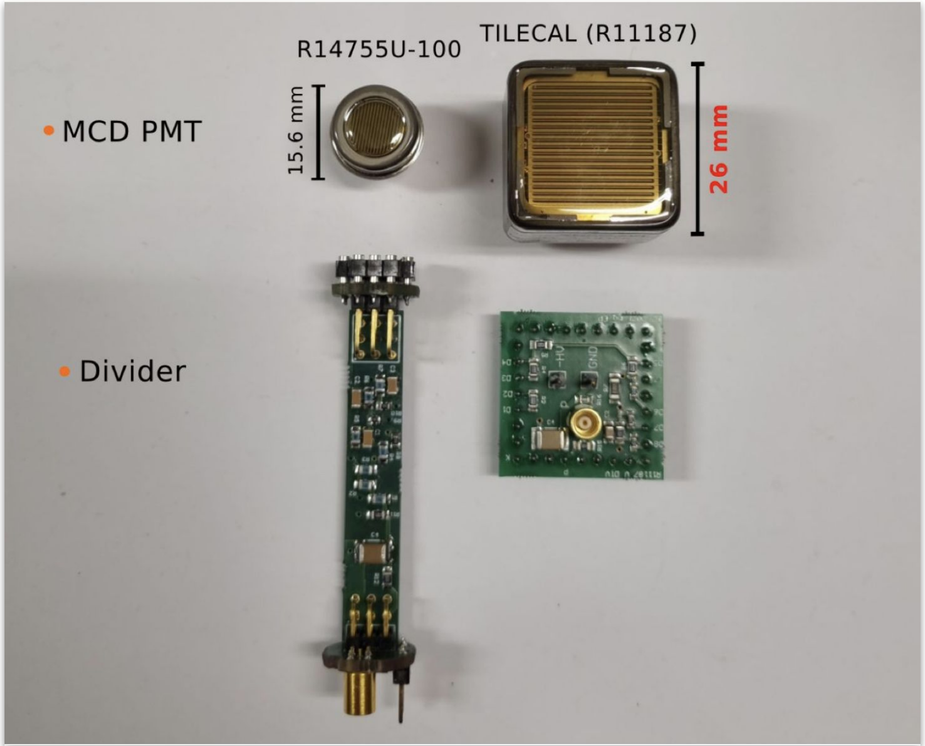
- Time transit uniformity and spread
- Signal linearity
- Geometry fitting the cell size

**R11187 (TileCal) PMTs** for the **SPACAL Pb**:

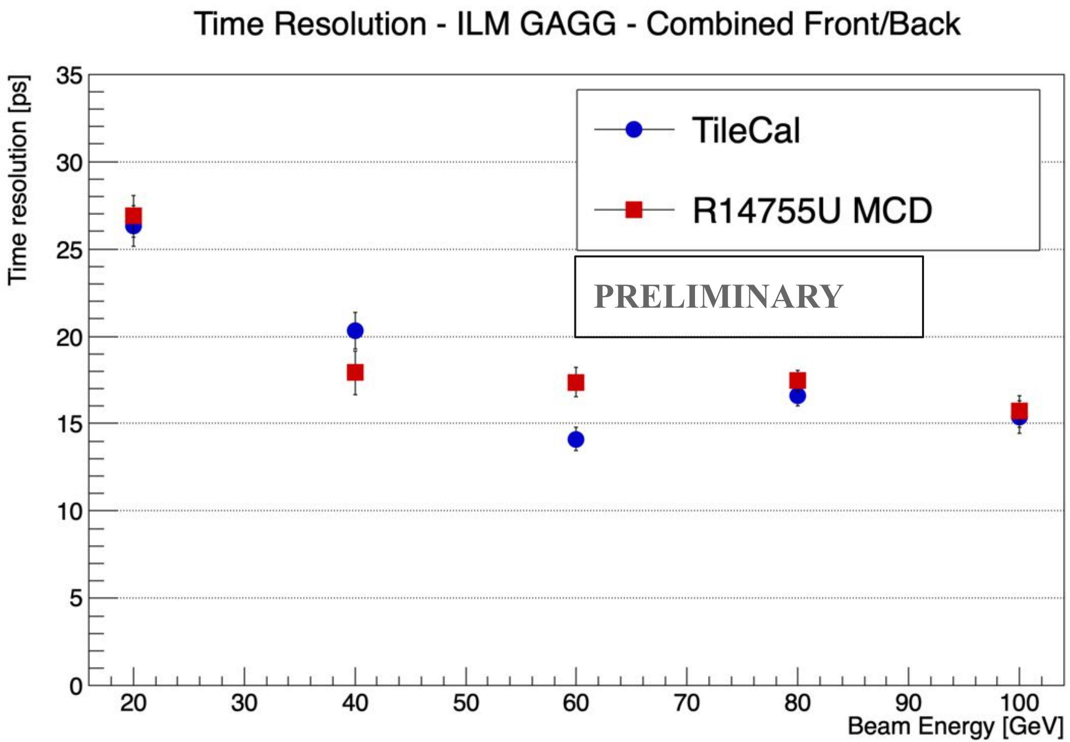
- Section of ~2.5x2.5 $cm^2$ fits the 3x3 $cm^2$ cells.
- Large set of R11187 PMTs soon purchased by ATLAS for their TileCal

**R14755U-100 PMTs** for the **SPACAL W**:

- Issues with linearity! Probably due to voltage divider
  **Lab measurements to be done**



# Time Resolution




- Light guides
- Incidence angle 3°+3°
- Results very preliminary, analysis ongoing

**Time resolution < 20 ps @ high energies**

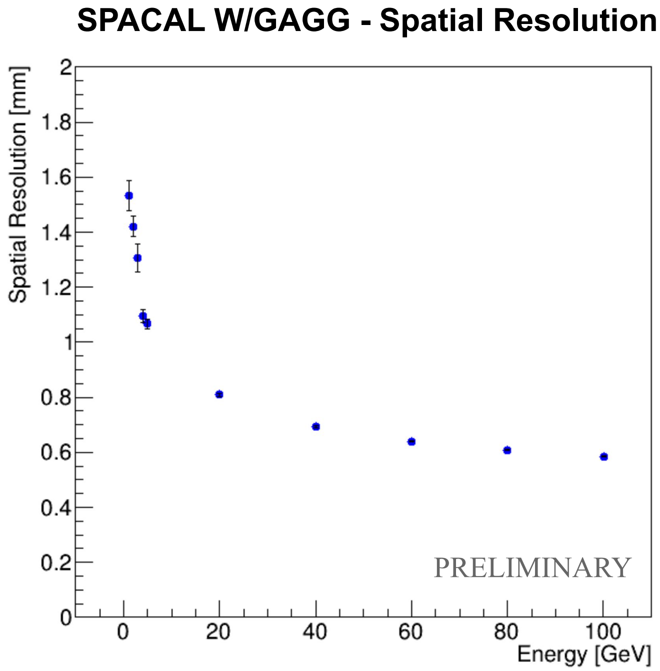
# Spatial and Angular Resolution

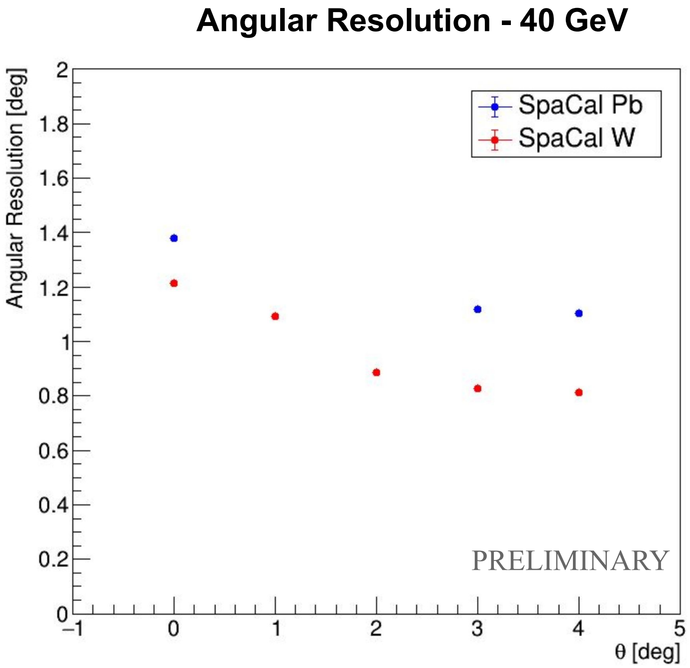
Measured spatial resolution of SPACAL **W-GAGG** with 3x3 cluster @ 3°+3°:

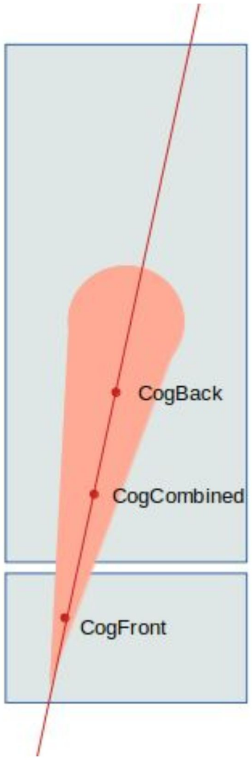
- **<1 mm above 20 GeV** combining the front and back sections

**Longitudinal segmentation** is a handle **to measure the incidence angle** of the particles:

- Angular **resolution ~1°** at 40 GeV




CERN-THESIS-2022-087

# Conclusions

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SPACAL W-GAGG is the baseline solution for the innermost region (1.5x1.5 $cm^2$) in LS4

- **Energy resolution** of **$\sigma(E) / E \approx 10\% / \sqrt{E} + 1\%$** for the optimised configuration
- **Time resolution** above 20 GeV < **20 ps**
- **Spatial resolution** of **~ 1 mm** above 20 GeV

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**R&D ongoing:**

**Scintillating materials**

- Too large light output reduces PMTs lifetime
- Long decay time:
  - Spillover
  - Pulse integration in the electronics

**Photomultipliers:**

- Finding a candidate with the right size matching the performance requirements.

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**R&D ongoing:**

**Scintillating materials** → see E. Auffray in Detector R&D session

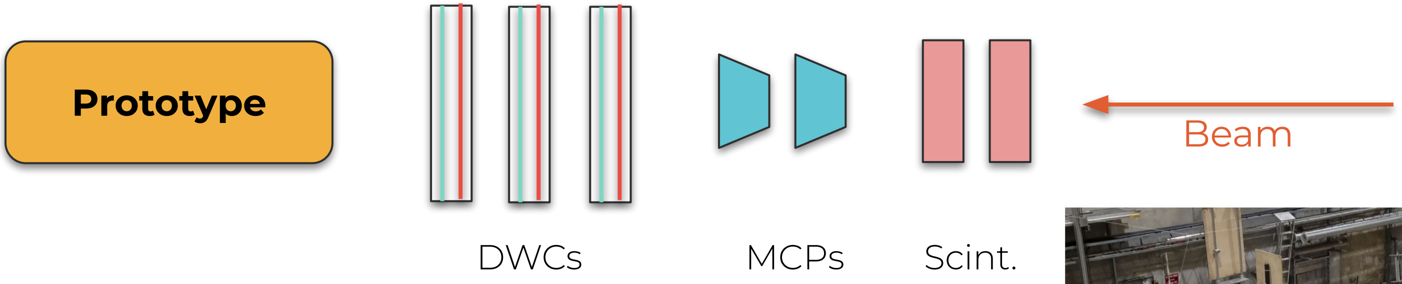
- Too large light output reduces PMTs lifetime
- Long decay time:
  - Spillover → see S. Perazzini in Electronics I session
  - Pulse integration in the electronics

**Photomultipliers:** → see E. Picatoste in Electronics II session

- Finding a candidate with the right size matching the performance requirements.

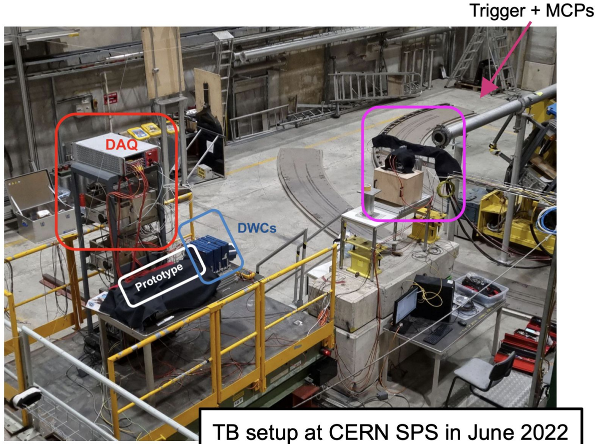
# Back-up

# Testbeam Set-up




Set-up from the beam:

- **2 scintillating pads** for trigger
- **2 MCP-PMTs** in combination as time reference ($T_0$)
  - Intrinsic time resolution of **15 ps**
- **3 Delay Wire Chambers** for tracking
- Prototype enclosed in a dark box
  on a stage with 2 rotating axes (azimuth + altitude)



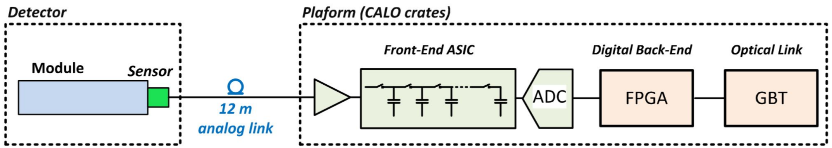

TB setup at CERN SPS in June 2022

Pulses recorded with V1742 CAEN digitizer (DRS4-based), 5 Gs/s, bandwidth 500 MHz

**Data from Testbeams at:**

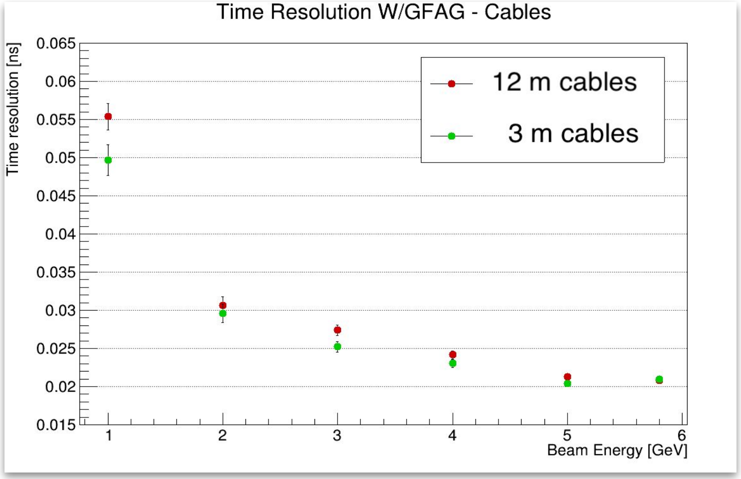
- DESY II May 2021-2022
- SPS November 2021 + June 2022

# Time Resolution - Extra




Tested the **current** 12 m long cables at the front and the back instead of 3 m long ones

- **No major degradation of time resolution observed**
- Low-attenuation cables to be studied

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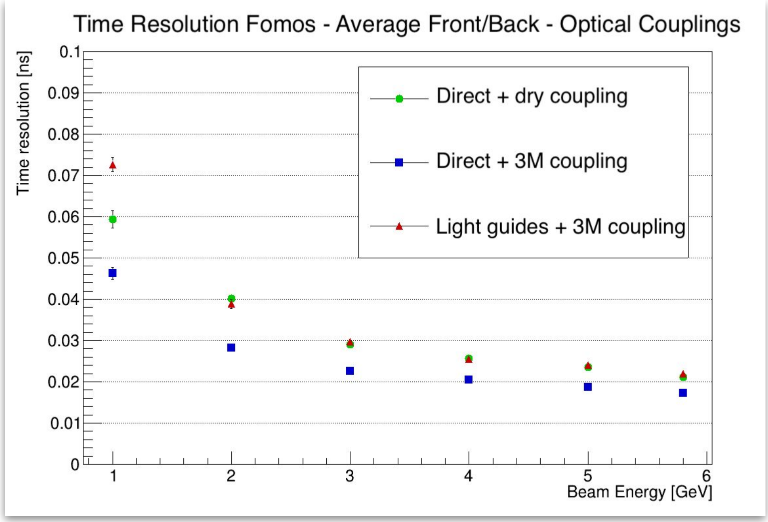


- Fomos GAGG cells with 3M optical coupling
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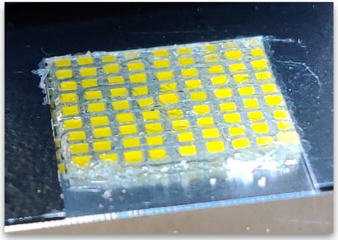
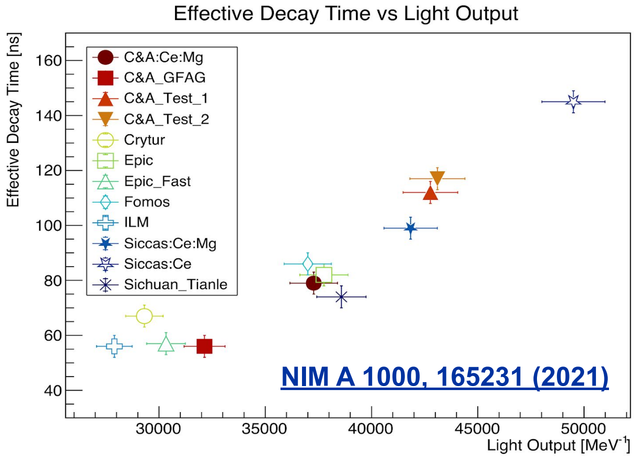


# New GAGG Compositions

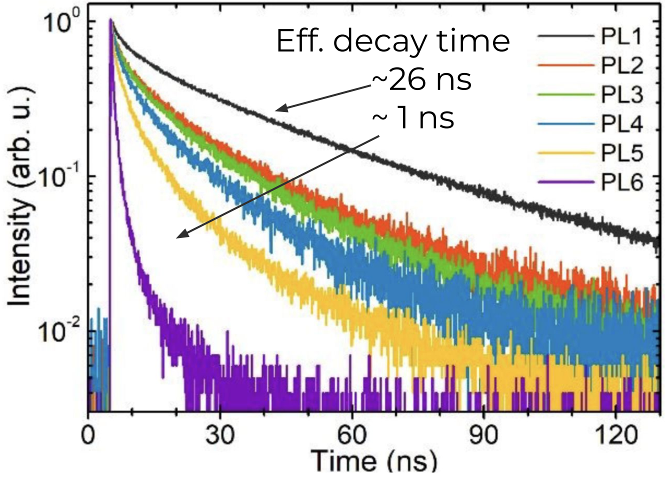



- Current GAGG have scintillation decay time >40 ns
  - Time resolution degradation due to spill-over
  - Pulse shaping techniques (e.g. cable clipping) can recover partially the performance

- Too large light yield can reduce lifetime of the PMTs

**Novel GAGG compositions developed** to quench scintillation

- Light yield reduced
- Decay time accelerated
- Time resolution kept competitive




*Material Advances, 2022, 3, 6842*

See presentation on Thursday 22, Session 12,
*"Acceleration of the scintillation response in garnet-type multicomponent scintillators"*

# Gadolinium Gallium Aluminium Garnet (GAGG)

Courtesy of K. Lebbou, ILM

Ce-doped multi-component garnets discovered in 2011.
Amongst them is Gadolinium Gallium Aluminium Garnet $Gd_3Al_2Ga_3O_{12}$:

- **High light yield** and **fast scintillation**
  *K. Kamada et al., Cryst. Growth Des. 2011, 11, 10, 4484–4490*
- **Tunable composition**
  *K. Kamada et al., Optical Materials 36 (2014) 1942–1945*
- **Acceleration** of scintillation **via divalent ions codoping** (e.g. Magnesium)
  *K. Kamada et al., Optical Materials 41 (2015) 63–66*

| | light yield (photons/MeV) | first decay time (ns) | second decay time (ns) |
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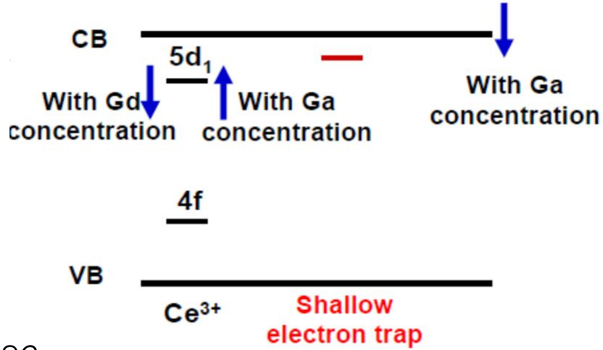
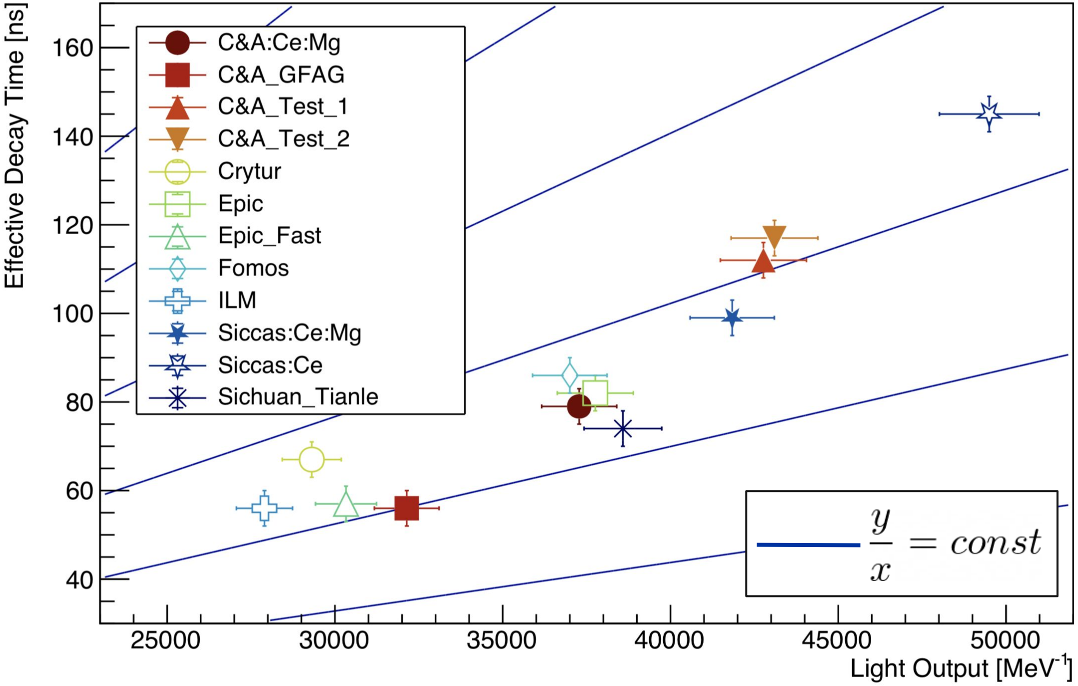


# Search for the Candidates



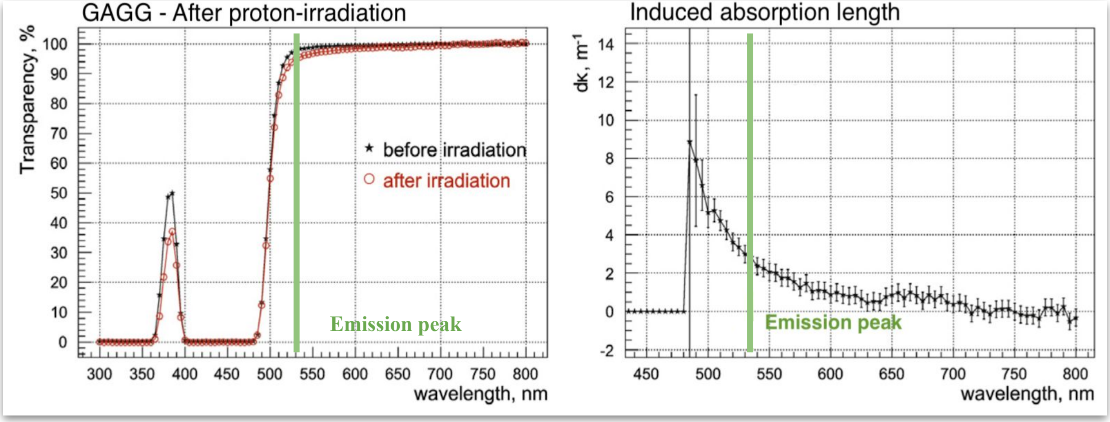

*L. Martinazzoli et al., NIM A 1000 (2021), 165231*

- Samples tested spanning a factor 2 in light output and 3 in decay time
- **High light output <--> slow decay time**
- Scintillation is sped up at the expense of light yield with Mg codoping

Blue lines are constant light output/decay time ratios

**Faster samples have also better light output/decay time ratio (better time resolution!)**

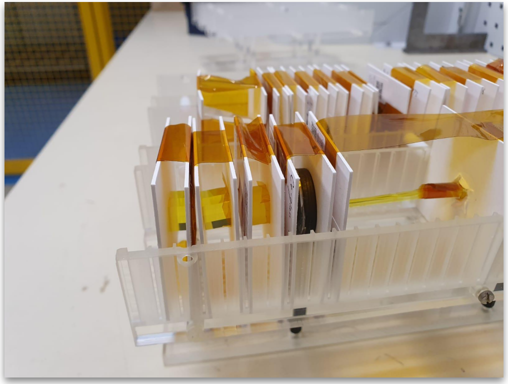
# Radiation Hardness



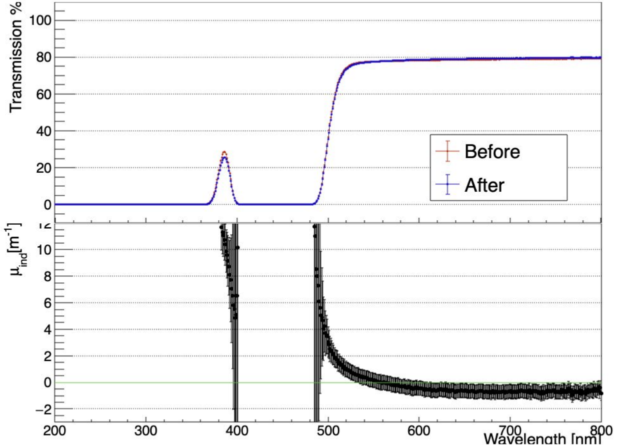

Garnet crystals are **radiation hard**

- Irradiated with protons of 24 GeV/c up to 910 kGy ($3.1 \times 10^{15}$ p/cm$^{-2}$)
  - Induced absorption below 4m$^{-1}$ at the emission peak

*V. Alenkov et al., NIM A 816 (2016) 176*



**C&A GFAG**




**Samples irradiated to $1 \times 10^{15}$ p/cm$^{-2}$**

**Induced absorption below 2m$^{-1}$ at the emission peak**