LHCb ECAL upgrade II

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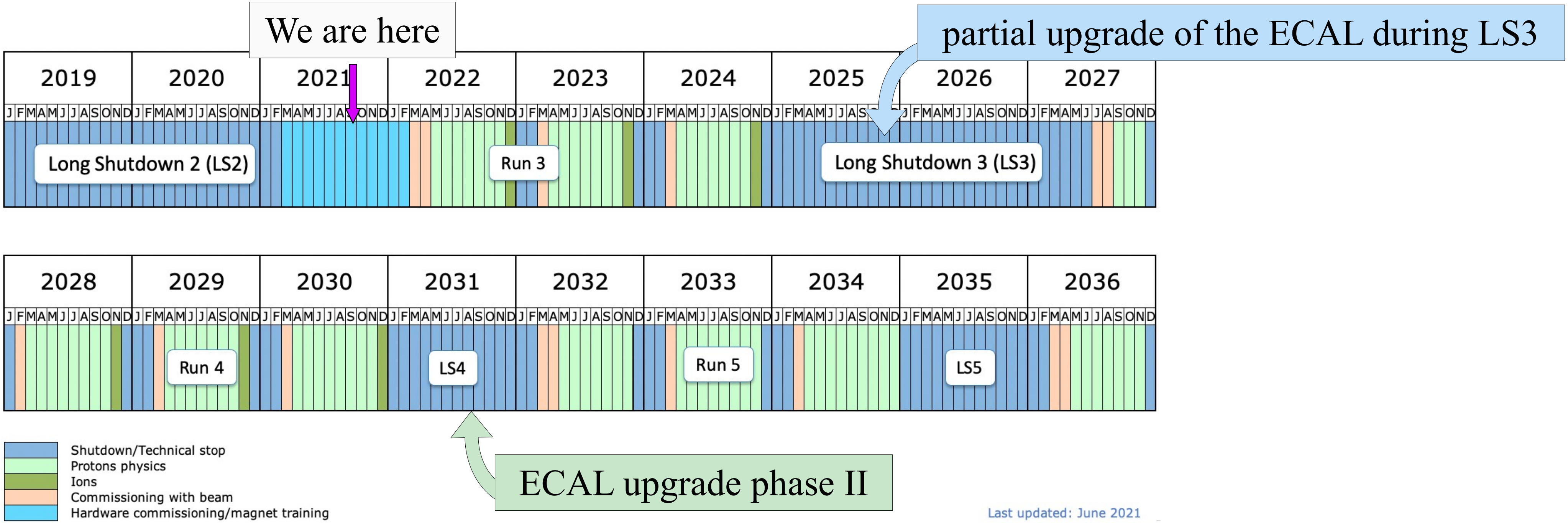
on behalf of the LHCb ECAL Upgrade II R&D group

The LHCb calorimeter Upgrade Phase II



An extensive **upgrade of the calorimeter system** must be prepared **in order to sustain the foreseen instantaneous luminosity of up to 1.5 × 10^{34} cm^{-2} s^{-1}** and the goal of **collecting 300 fb^{-1} after Run 4**. This upgrade will consist replacing a large fraction of the modules of the ECAL detector, and equipping all of the ECAL modules with new front-end and back-end electronics.

The current ECAL was designed with an expected maximum dose of 2.5 kGy/year, equivalent to 2 fb^{-1} /year, and 10 years of operation. For the expected 300 fb^{-1} upto **1 MGy integral dose** estimated in the central region → **central region to be made of radiation hard materials**.

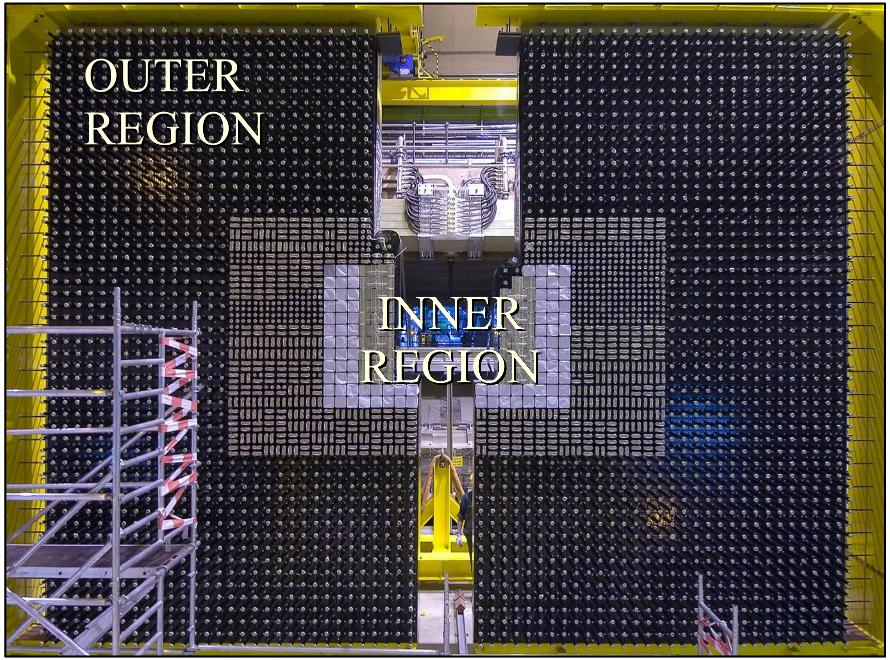
Increased occupancy and pile up requires **better time resolution** (few tens of ps) and **reduced cell sizes.**

Keeping **energy resolution** on the similar level (**stochastic term ~ 10%**)

CURRENT LHCb ECAL

- Shashlik technology: 4 mm scintillator tiles, 2 mm thick lead plates.
- Modules 121.2 x 121.2 mm^2, 66 layers of Pb + 67 scintillator tiles.
- 1.2 mm Kuraray Y11 (250) WLS-fibres.

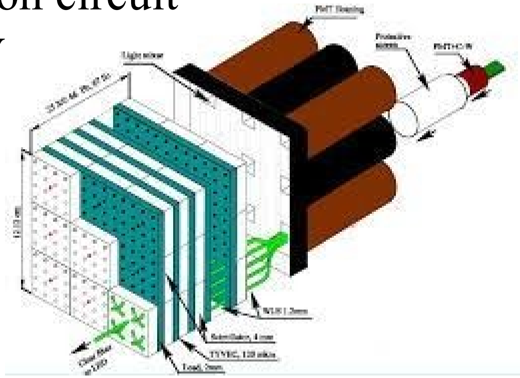
- Segmentation in three zones → Inner (9 cells/module), Middle (4) and Outer (1)



- Total of 3312 modules, 6016 cells, 7.7 x 6.3 m^2.
- Readout PMT R7899-20;
-
- HV: individual Cockcroft-Walton circuit
- Light yield: ~ 3000 ph.e. / GeV

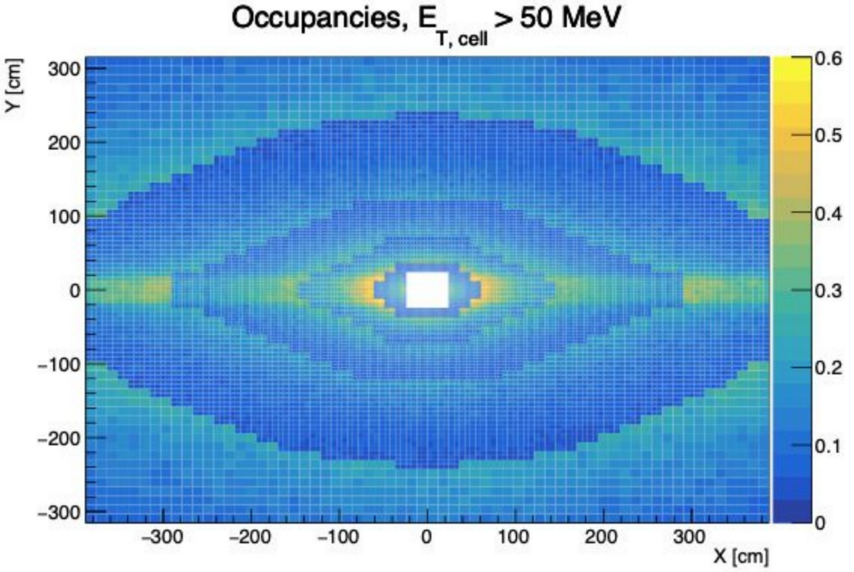
- Energy resolution:

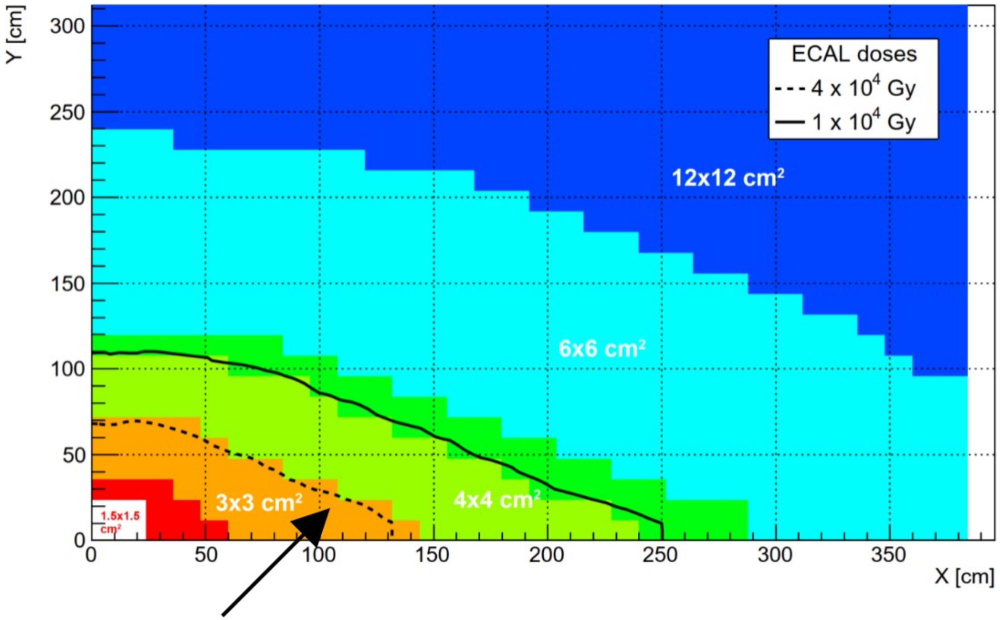
$$\frac{\sigma_E}{E} = \frac{(8.2 \div 9.4)\%}{\sqrt{E}} \oplus 0.9\%$$



R&D strategy for the ECAL Upgrade II

Two technologies, 6 zones with different granularity





Radiation limit of current Shashlik technology

SPACAL technology for inner region:

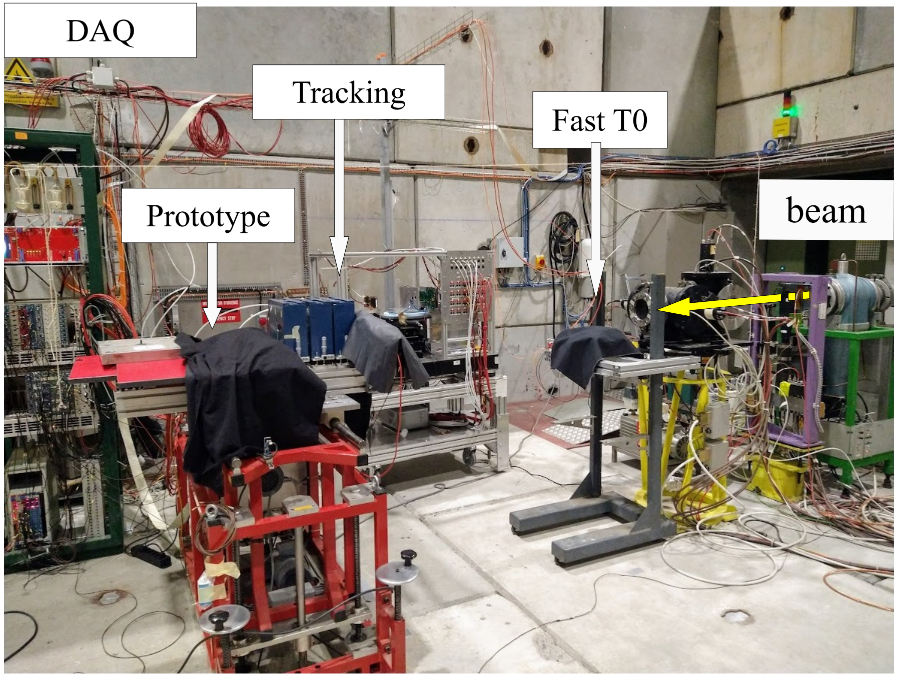
- **32 modules with cell size 15 x 15 mm²** (innermost): radiation hard scintillating crystal fibres and W absorber.
- **144 modules with cell size 30 x 30 mm²** with scintillating plastic fibres and Lead absorber.

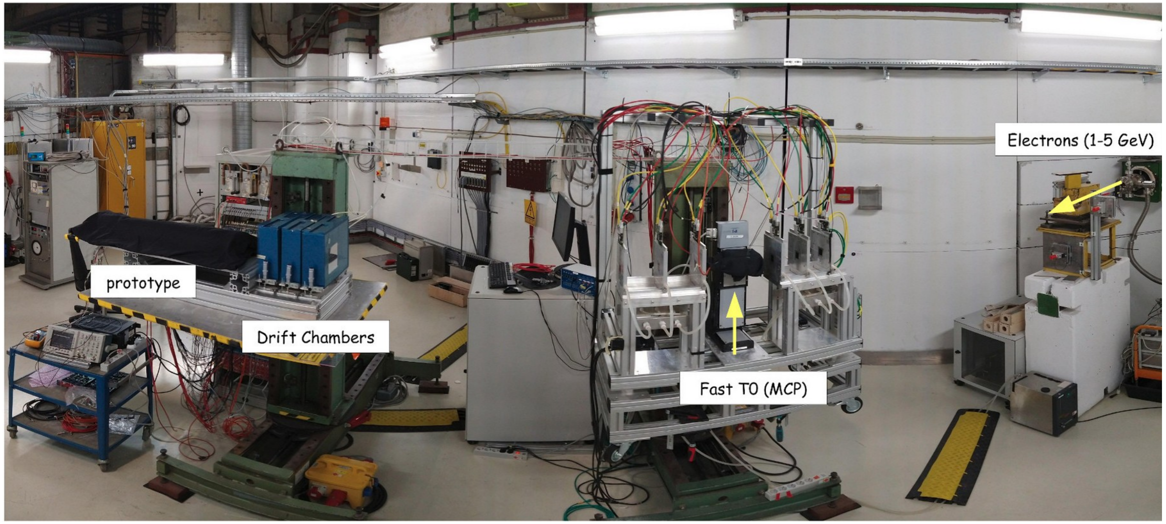
Shashlik technology (Outer regions):

- Improved time resolution with new fast WLS fibres (Kuraray YS2/YS4);
- Double-sided readout;
- Required cell sizes → adding 1300 new modules.

Beamtests: CERN H4 / H8 and DESY T24

CERN H8





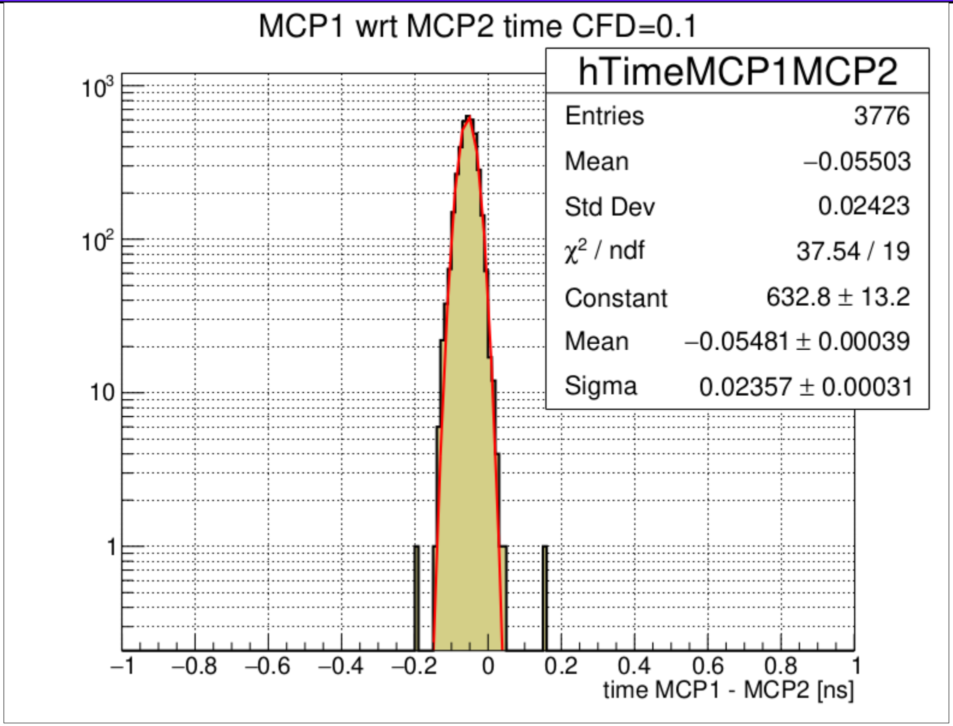
DESY T24: electrons with E = 1 – 5.8 GeV

CERN H4: electrons with E = 20 – 100 GeV

CERN H8: muons and hadrons (p = 150 GeV/c)

Setup:
- tracking system (3 stations of DWC)
- Two scintillation counters for triggering
- Two Fast T0 counters (next slide)
- CAEN digitizers: DT5742 / V1742 (custom calibration)
- TDCs(V1290N), ADCs

Beamtests: T0



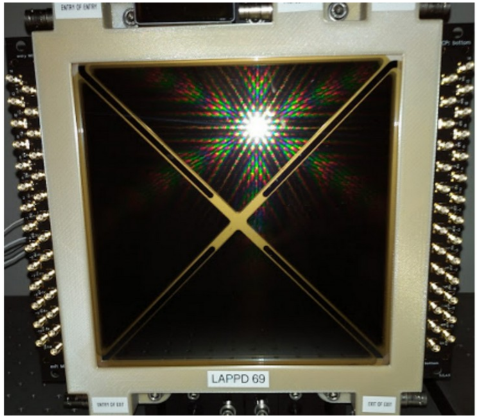
T0: two counters based on MCP-PMT (Ekran FEP, Novosibirsk) **Thanks to A. & M. Barnyakov**

with ⌀18x6 mm cylinder of Plexiglas as a Cherenkov radiator.

Time difference between the two described by Gaussian **σ = 24-28 ps** (beam depended).

Mean (MCP1, MCP2) time → **12 - 14 ps** time resoltuion.

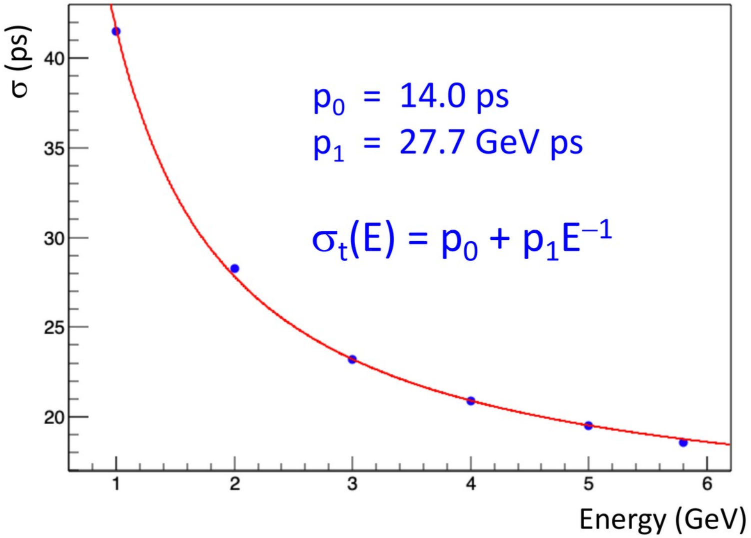
LAPPD: Timing layer placed @ 7X0 to improve shower timing



LAPPD Gen-I

- 20x20 cm 2 active area
- Two MCPs in chevron stack for amplification
- Pore size 20 µm
- Typical gain 10^6 -10^7
- For the beam tests of this prototype, the photocathode was disabled using opposite sign voltage

NOTE:
To sustain required radiation hardness LAPPD would be produced without photocathode.



Timing layer allows to have time resolution (sigma)

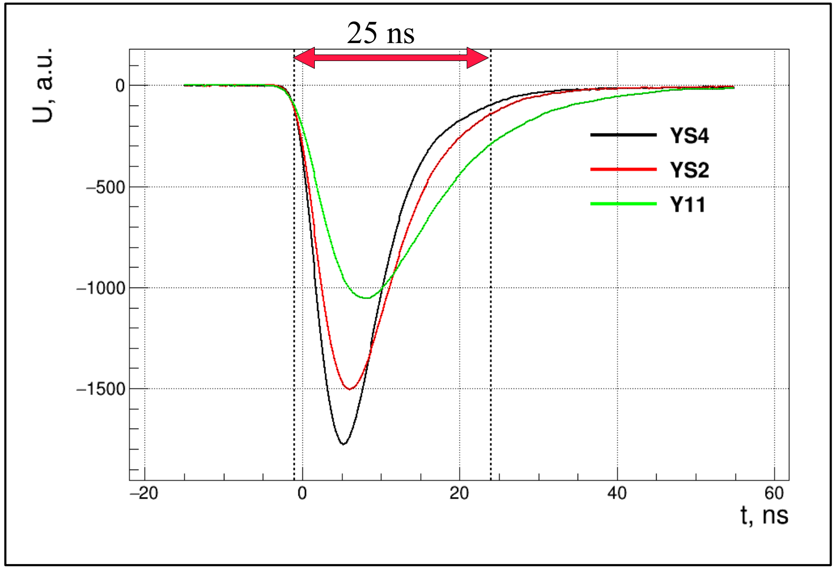
$\sigma < 20$ ps for $E > 5$ GeV

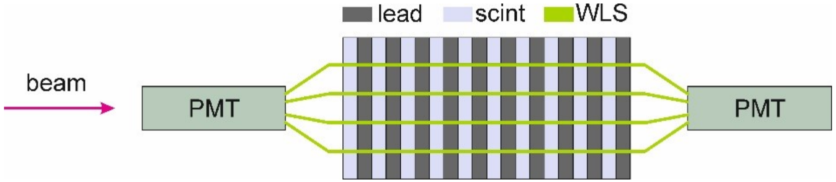
$\sigma < 50$ ps for energies > 1 GeV

The new-generation tiles with pixelated anodes on are becoming available and will be tested next year. Pixel geometries could be customized to match the ECAL layout

SHASHLIK (OUTER REGION)

Pulse shape using different WLS-fibres





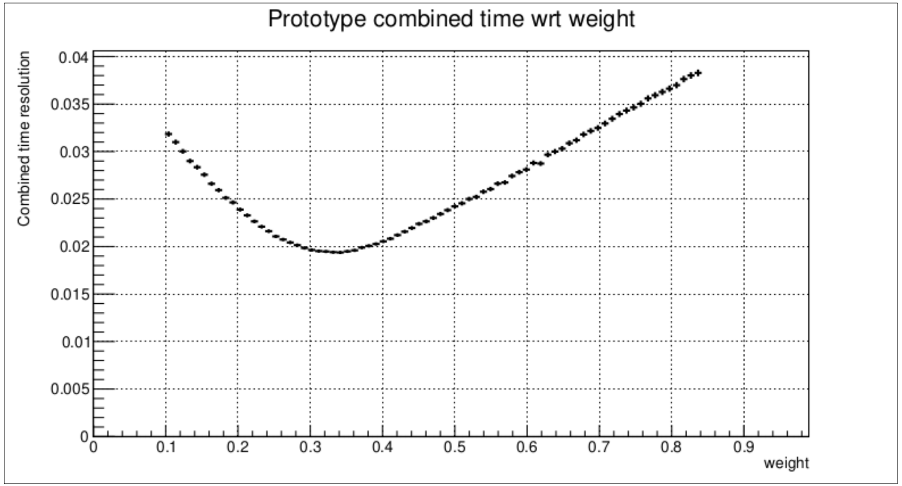
R&D towards better time resolution:

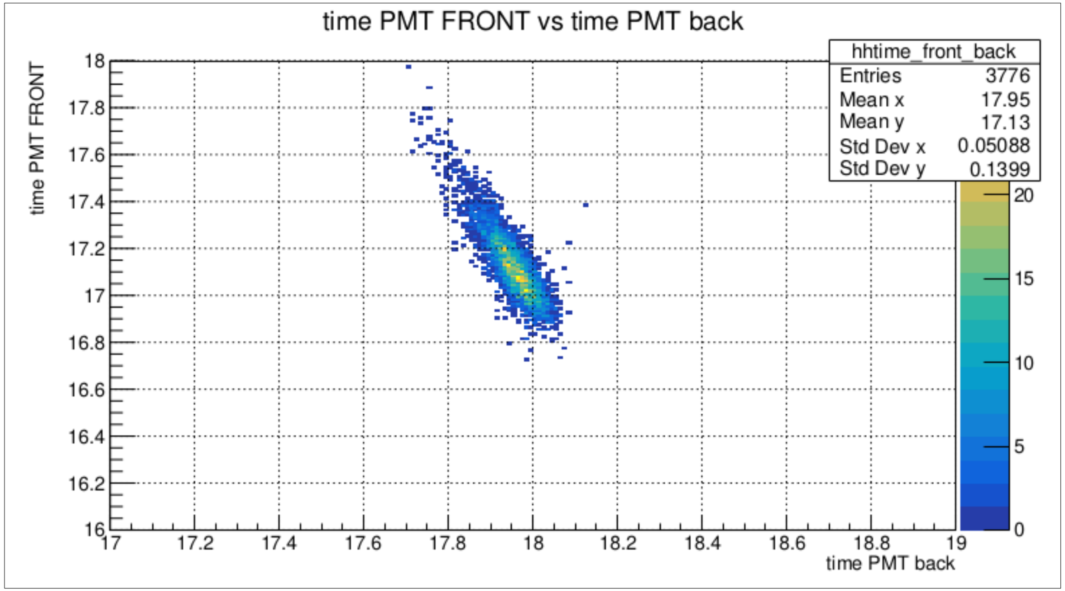
- double-sided readout;
- PMTs with small transit time spread;
- WLS fibres with shorter scintillation decay time:
  Kuraray YS2 and YS4

Many thanks for pre-production sample!

Few spare standard LHCb outer shashlik modules were modified and tested at CERN (H4, H8) and DESY (T24) beamlines

SHASHLIK (OUTER REGION)





Strong anti-correlation between Front and Back PMT time response → combined time (weighted average):

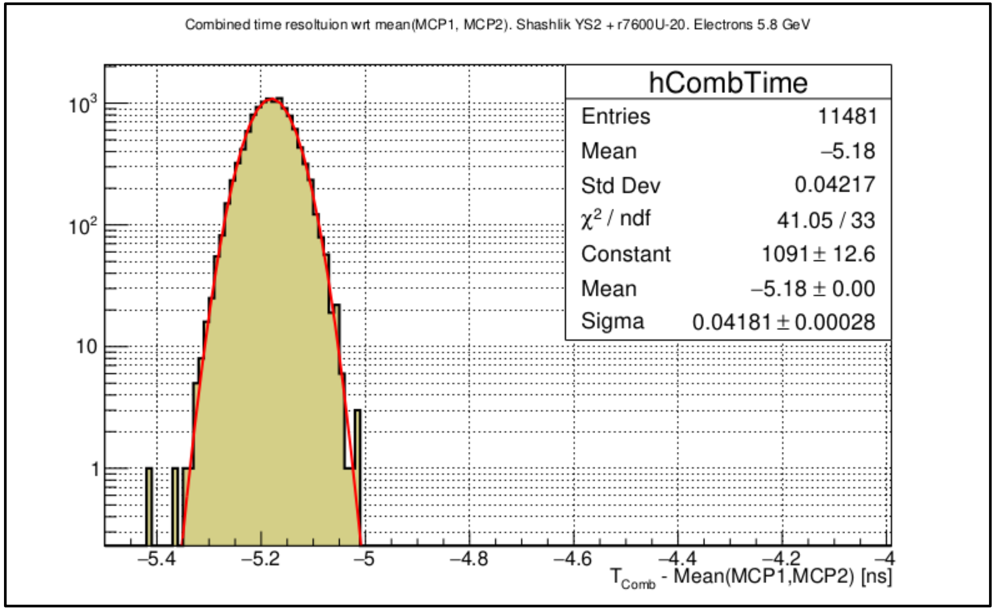
$$T_{comb} = \frac{T_{Back} + \beta \cdot T_{Front}}{1+\beta}$$

Where $\beta \approx 0.33$ gives the best results (doesn't depend on energy).

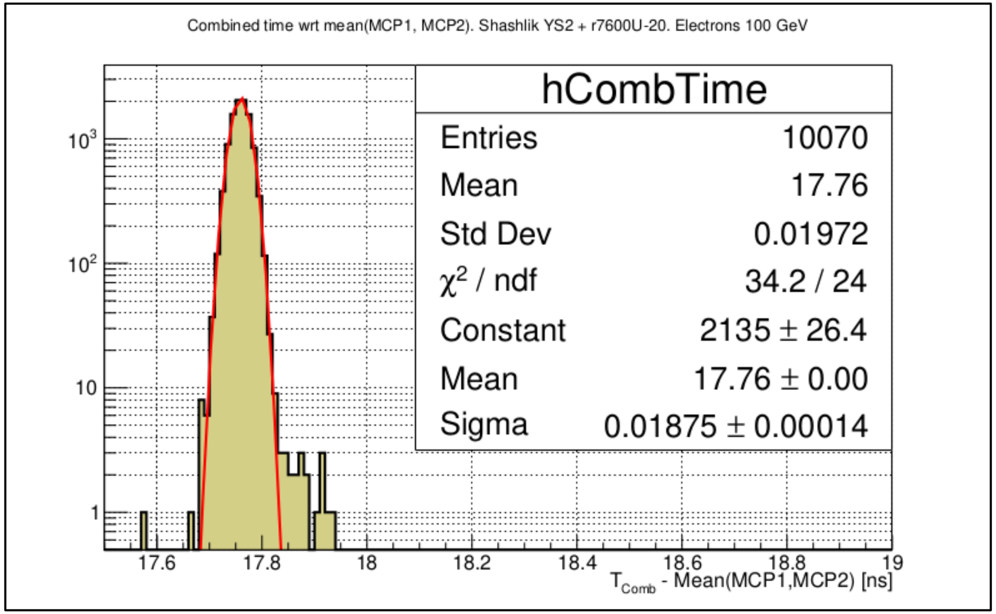
SHASHLIK (OUTER REGION). Electrons 5.8 GeV and 100 GeV

Standard LHCb outer module modified to the double-readout.
using Kuraray YS2 WLS – fibres + R7600U-20 PMTs (front + back).

Electrons 5.8 GeV (DESY T24)

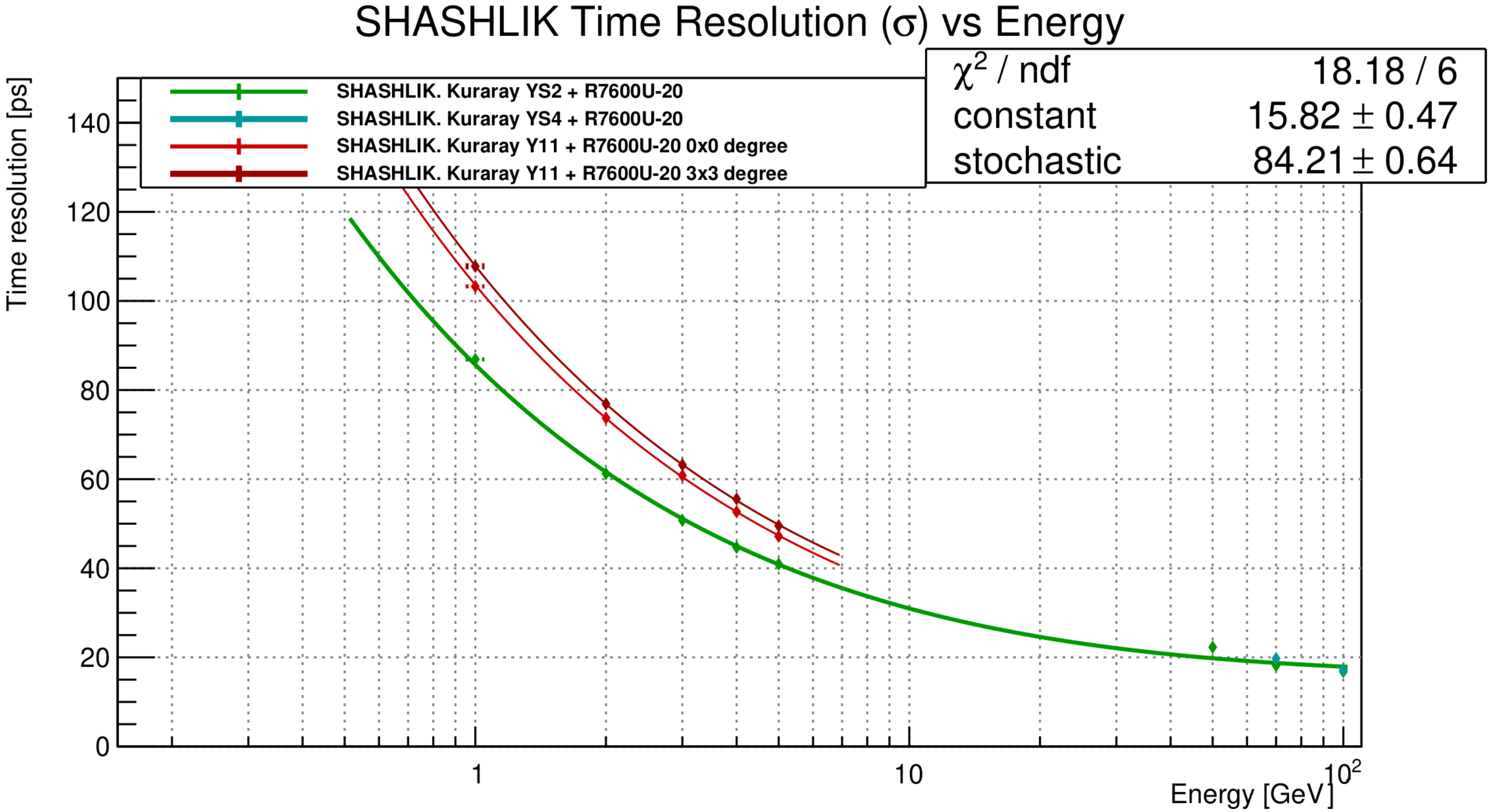


Electrons 100 GeV (CERN H4)



Time resolution below 50 ps achieved for electrons with energies above 5 GeV

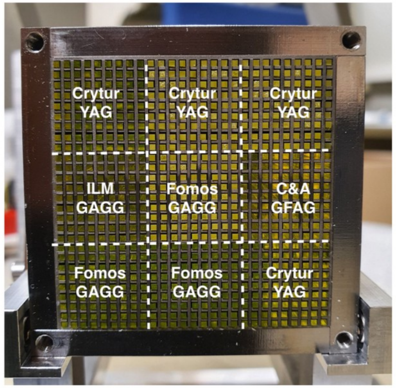
SHASHLIK Time resolution: E = 1 – 100 GeV



Shashlik (YS2 + R7600U-20) as a function of energy could be estimated as

$$\sigma_t(E) = (16 \pm 1)\,ps \oplus \frac{85 \pm 1}{\sqrt{E}}$$

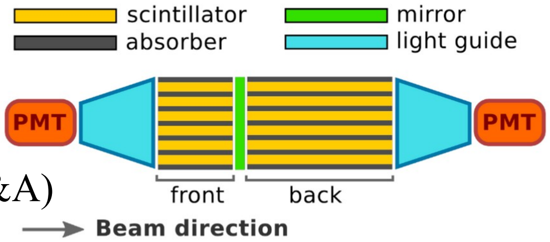
Configuration used at DESY in 2020 and 2021

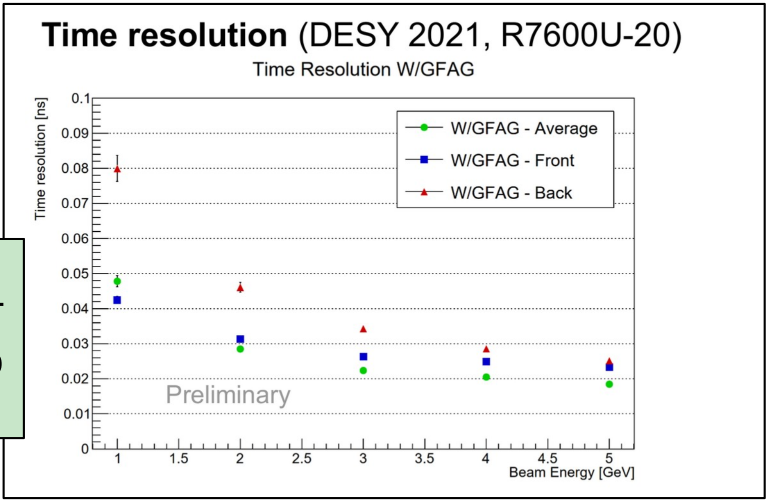


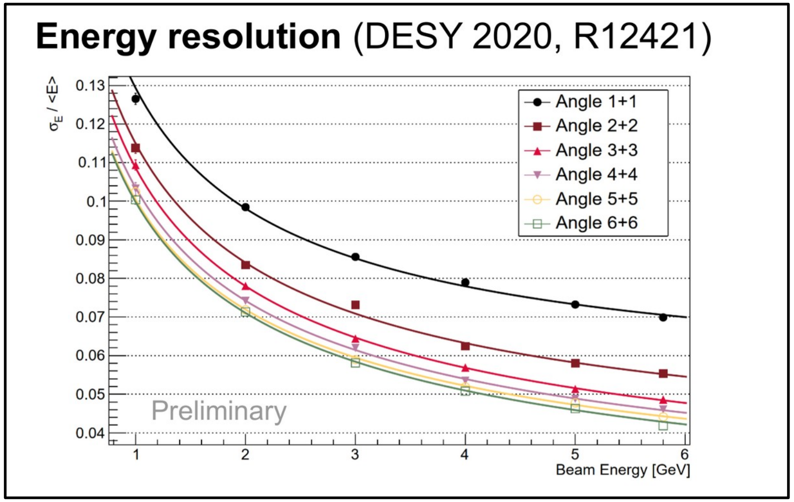
Note:
Achieved with PMT directly coupling to crystal fibres.

SPACAL prototype module with W absorber and garnet crystal fibres:

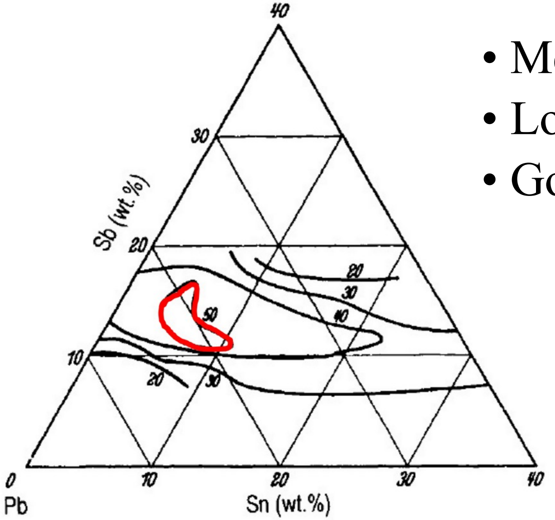
- Pure tungsten absorber with 19 g/cm^3
- 9 cells of 1.5x1.5 cm^2 ($R_M \approx 1.45$ cm)
- 4+10 cm long (7+18 X_0)
- Reflective mirror between sections
- Crystal garnets from several producers (Crytur, Fomos, ILM, C&A)
- Readout with R12421 and R7600U-20 PMTs





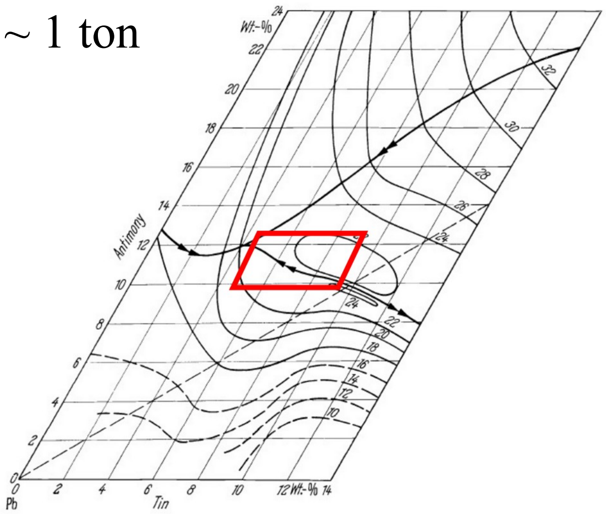


- Preliminary analysis gives energy resolution with **10.6% stochastic term** and **1.9 ± 0.5% constant term.**
- **Time resolution better than 20 ps** @ 5 GeV achieved for GFAG.
- The crystal **scintillation decay time to be improved** to let the signal fit 25 ns period (the fastest [GFAG] t ~ 60 ns)



Fluidity of lead corner of the ternary system lead-antimony-tin

- Mechanical stability under the the loads ~ 1 ton
- Low level of porosity and brittleness
- Good fusibility / fluidity

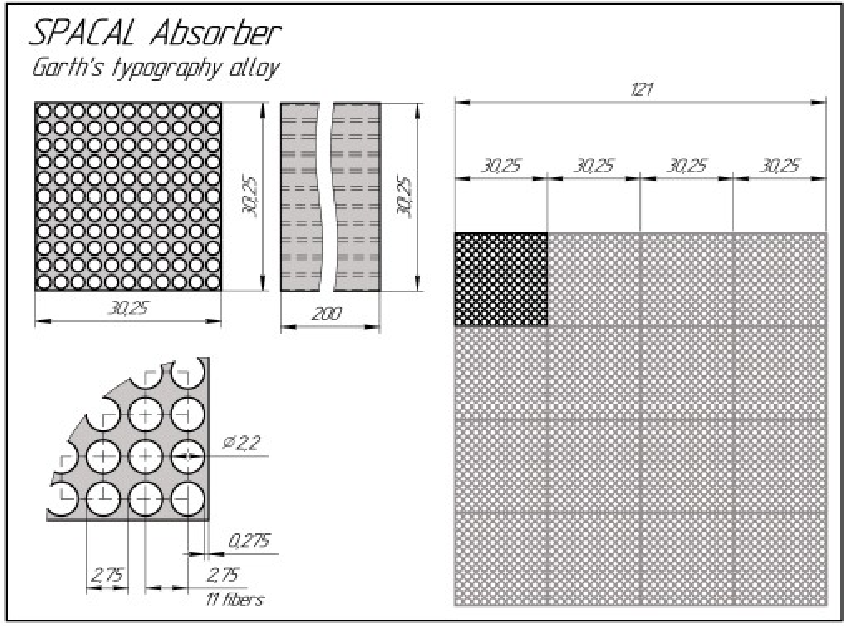


Brinell hardness in the lead corner of the ternary system lead-antimony-tin.

It is known that Pb-Sb-Sn alloys will help meeting this requirement!

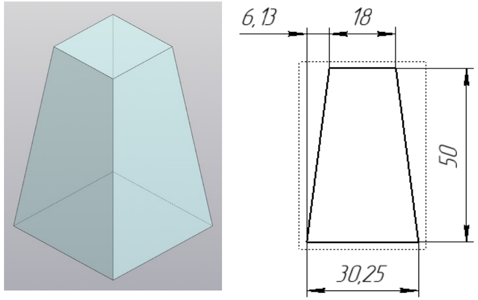
Garth's typography alloy is an available option and has : Pb 84 wt.% - Sb 12 wt.% - 4 wt.% Sn

SPACAL: Molded Lead - polysterene

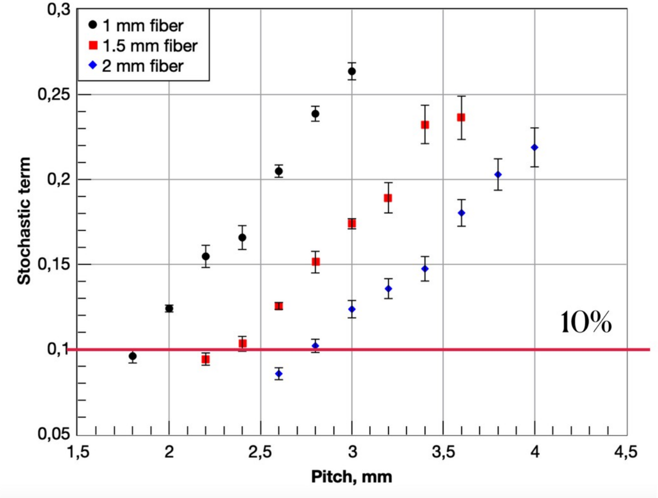


∅ 2 mm scintillating fibres
2.75 mm step between
(0.55 wall thickness)

50 mm long lightguide
(required for fibre equalization)



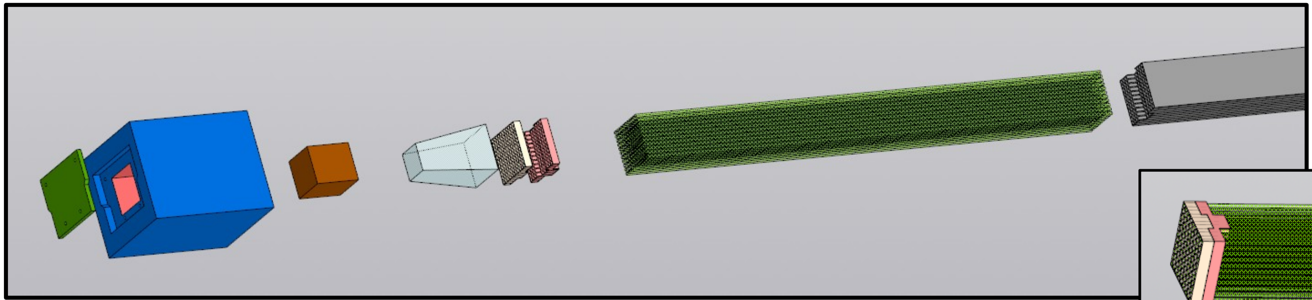
MC: Energy resolution
(sampling term)



- Molded absorber made of Garth's typography allow.
  Suitable for mass production
- 84% Pb alloy for mechanical stability (loads ~ 1 ton)
- Large fibres diameter necessary for fibres changing procedure

SPACAL: Molded lead - polysterene

Due to the high expected radiation doses in the central region, the procedure for ‘fast’ fibres changing (during annual stop) has been implemented in the design.

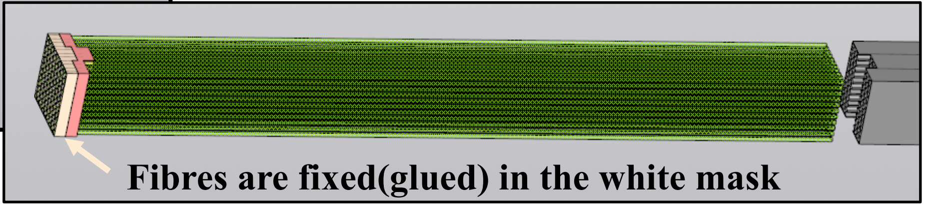


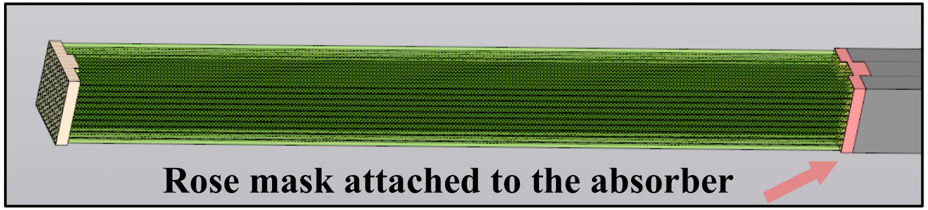
Advantages:

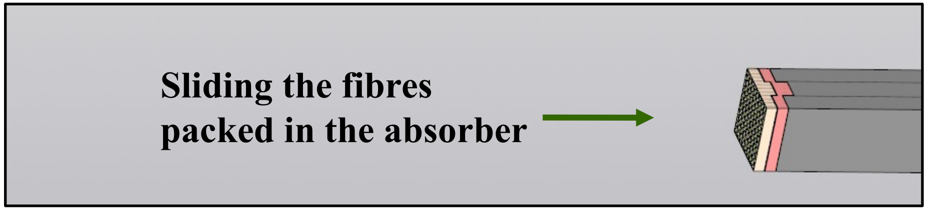
- Possibility to **change fibers in one turn** per cell
- Changing fibers → **polystyrene lightguide** instead of a bundle
- Using masks to fix all **121 fibers** and guide them into absorber
- Adjustable granularity!

To maintain a competitive environment the fibres size fixed to the largest available in the market – 2 mm in diameter.

- Kuraray SCSF-78 ⌀2mm
- Protvino (R&D on fibres production)







SPACAL: Molded lead - polysterene

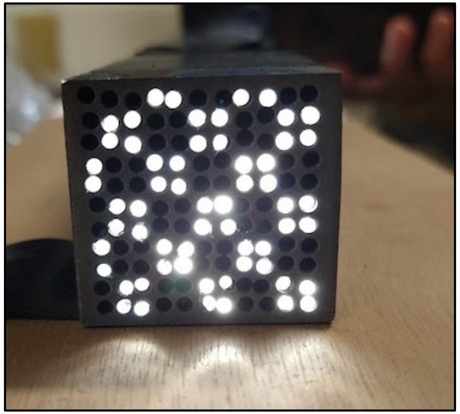
Single-cell prototype produced, assembled and tested at CERN in July 2021

Cell size: 30.25 x 30.25 mm^2

11 x 11 matrix of 2 mm diameter fibres

Double-sided readout with R11187 PMTs through 50 mm long lightguide

fibres “type A” installed

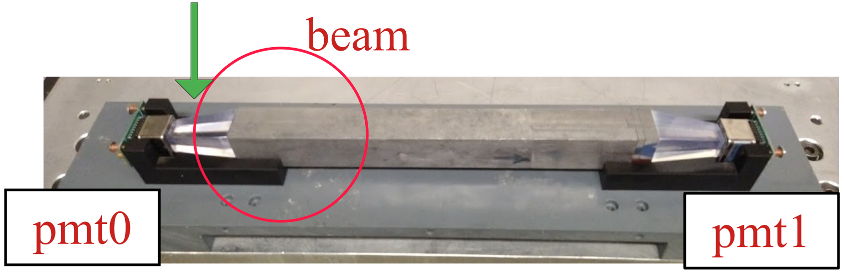


<u>Fibres grouped vertically :</u>

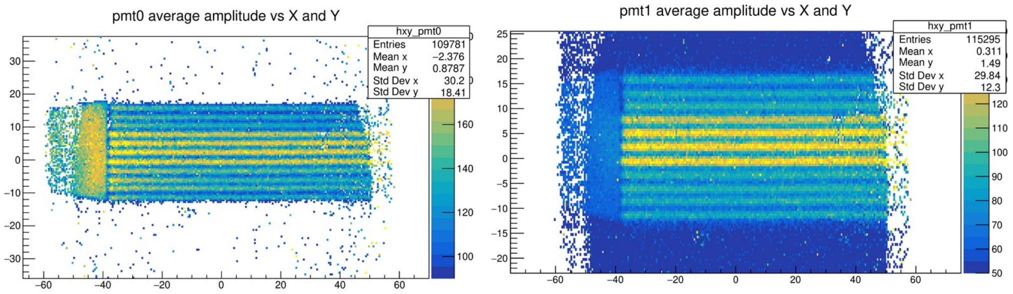
Protvino type 1
Kuraray SCSF-78
Protvino type 2

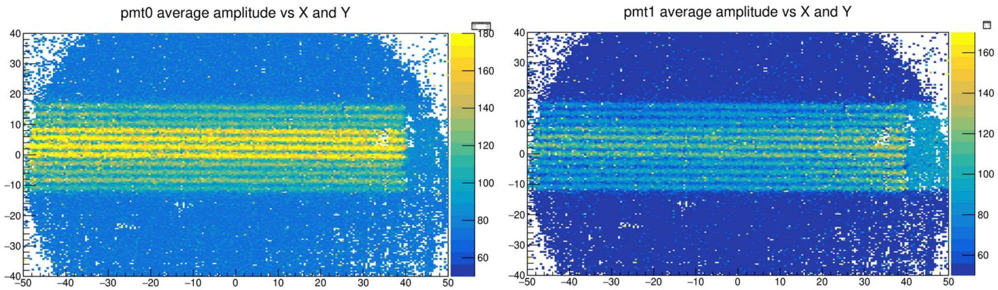
prototype placed perpendicular to the beam

Polysterene lightguide

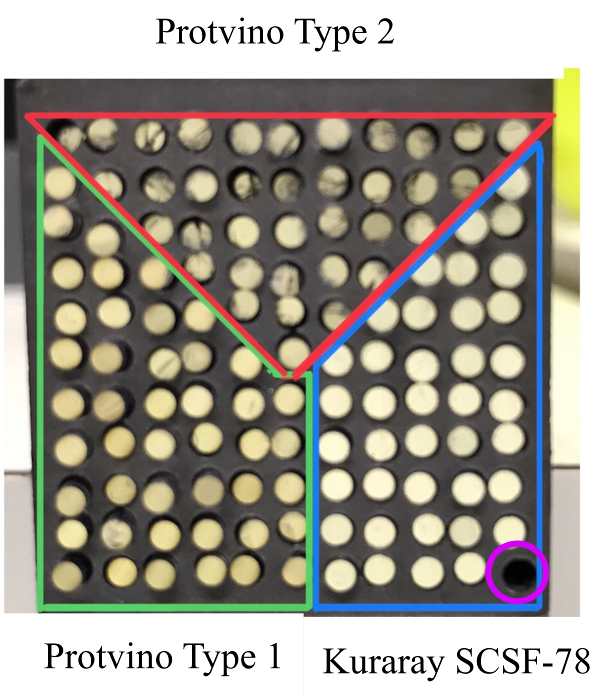


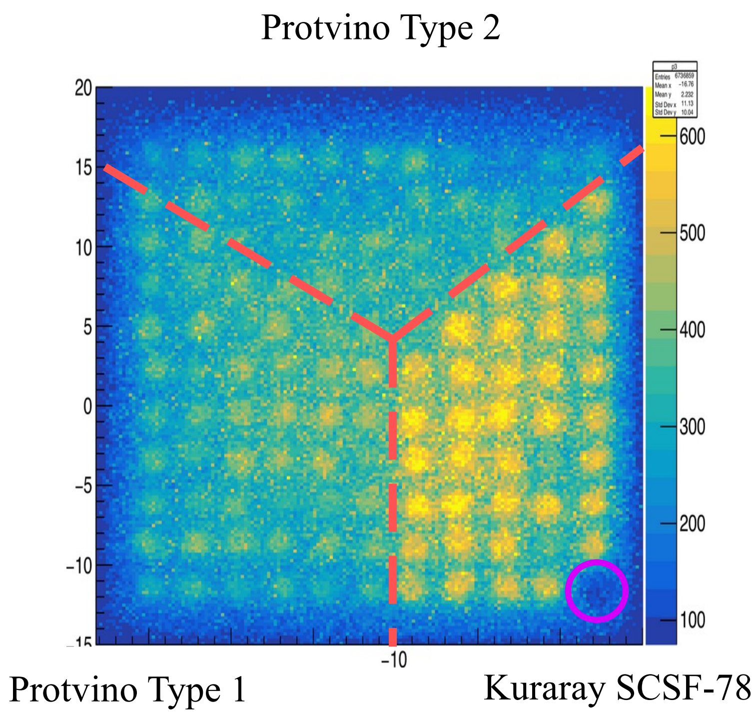
Polysterene lightguide
(doped)





Muonography: Molded lead SPACAL (1)



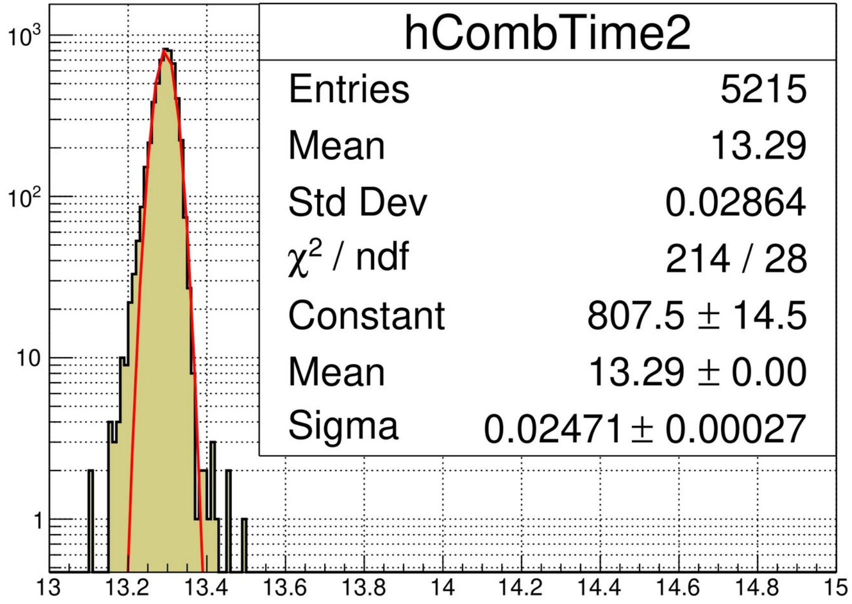


Prototype placed parallel to the beam.

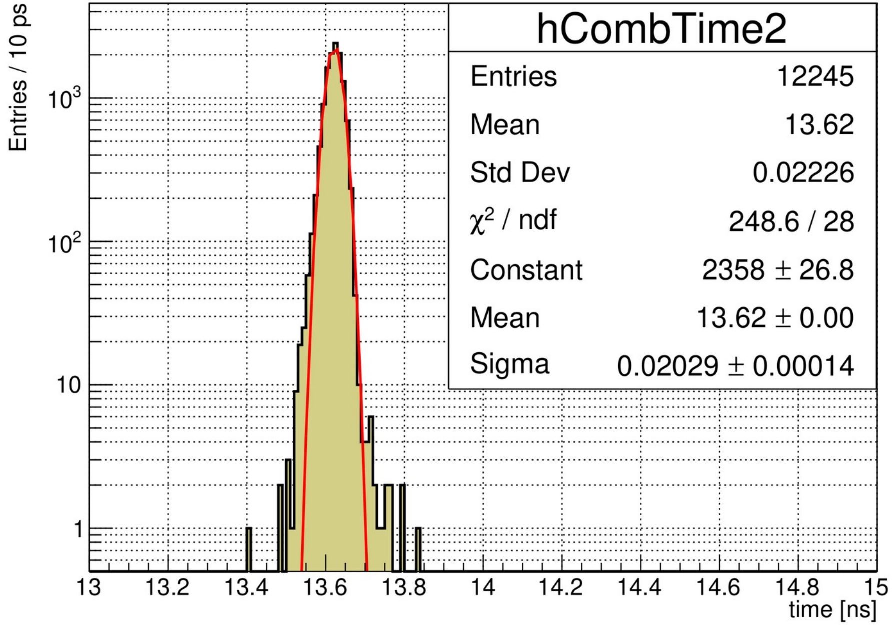
Fibres of both "type 1" and "type 2" were made with smaller diameters (1.8 - 1.9 mm). Plus faced some problems with machining . Both leads to surface imperfection and reduced light-yield

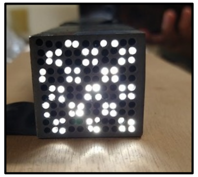
Molded SPACAL Time resolution: E = 100 GeV

Protvino fibres (mixture type1 and type2)



Kuraray SCSF-78 fibres



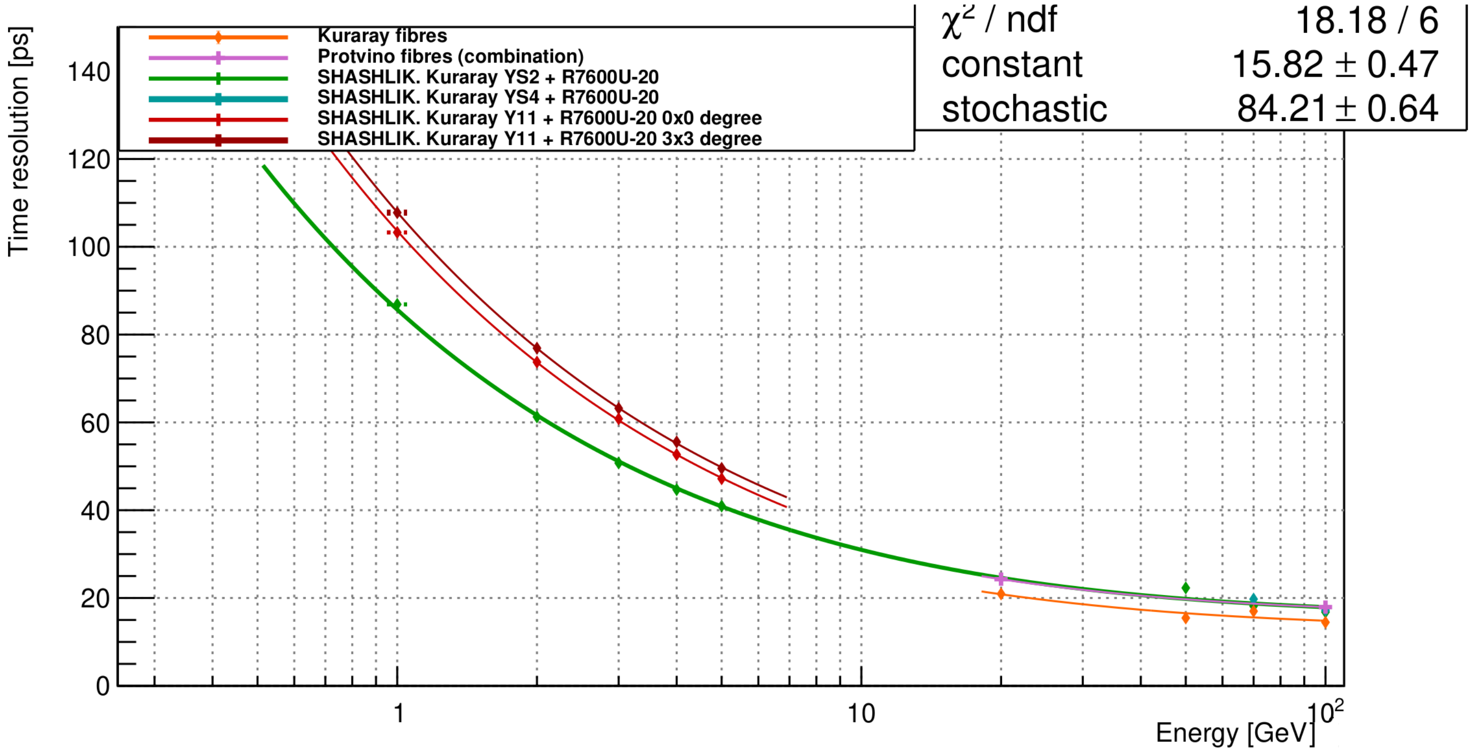


Due to a limited number of fibres, both types were mixed in the prototype in a ‘chessboard sectors’ style (2x2)

Substructing mean time of the two T0 gives time resolution ~20 ps (Protvino) and 17 ps (Kuraray) time resolution for e^- 100 GeV

SHASHLIK + Molded SPACAL Time resolution: E = 100 GeV

Shashlik and spaghetti (molded Lead - polysterene) time resolution



Spaghetti single cell prototype with lead-based molded absorber performs with time resolution better than 20 ps for EM showers with E > 20 GeV.

SUMMARY

For the innermost region:

- Spaghetti calorimeter based on radiation hard crystals **(YAG, GAGG and GFAG)** with combination of W absorber were studied. With **PMTs directly coupled to the crystal fibres** allows to perform with time resolution **(σ) better than 20 ps** for **E > 5 GeV**.

For the outer modules:

- existing **shashlik** modules could be modified to double-readout scheme and equipped with fast WLS-fibres, read by R7600-U20 PMTs. All above allows to performs with t**ime resolution (σ) better than 40 ps** for **E > 5 GeV**.

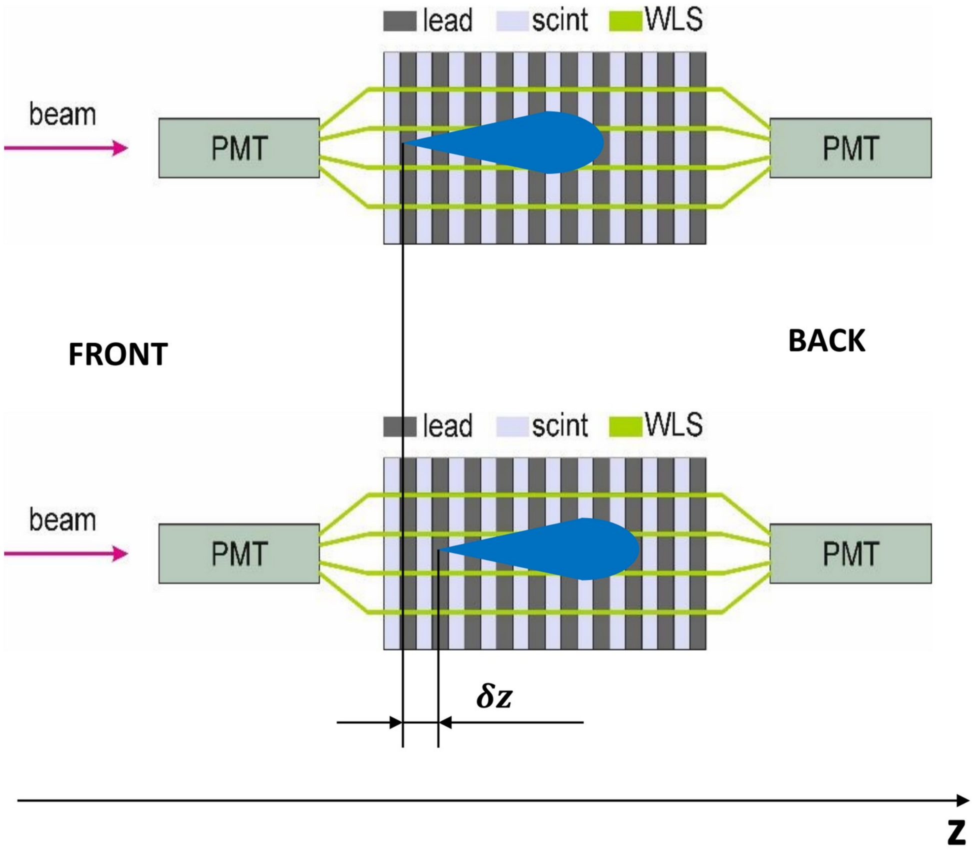
For inner region:

- A new **spaghetti-type** prototype based on a molded technique **suitable for mass production** has been designed, produced and tested with two different sets of fibres (both 2 mm in diameter). Time resolution ≤ 20 ps achieved for energies starting from 20 GeV.

- **To improve time resolution** an option with **Timing layer** placed @ 7 X0 has been tested. LAPPD as a Timing layer allows to register EM showers with time resolution **(σ) <20 ps for E > 5 GeV**.

BACKUP SLIDES

shashlik studies



Let us assume that there are two identical showers which have $\boldsymbol{z}$ positions different by $\boldsymbol{\delta z}$. For the first shower the time measured at front and back are t_{FRONT} and t_{BACK}. Then for the second shower these times will be:

$$t_{FRONT} \rightarrow t_{FRONT} + \frac{\delta z}{c} + \frac{\delta z}{v}$$
$$t_{BACK} \rightarrow t_{BACK} + \frac{\delta z}{c} - \frac{\delta z}{v}$$

, where *c* is speed of light in vacuum and *v* is the *average* speed of propagation of photons along the ***z*** axis.

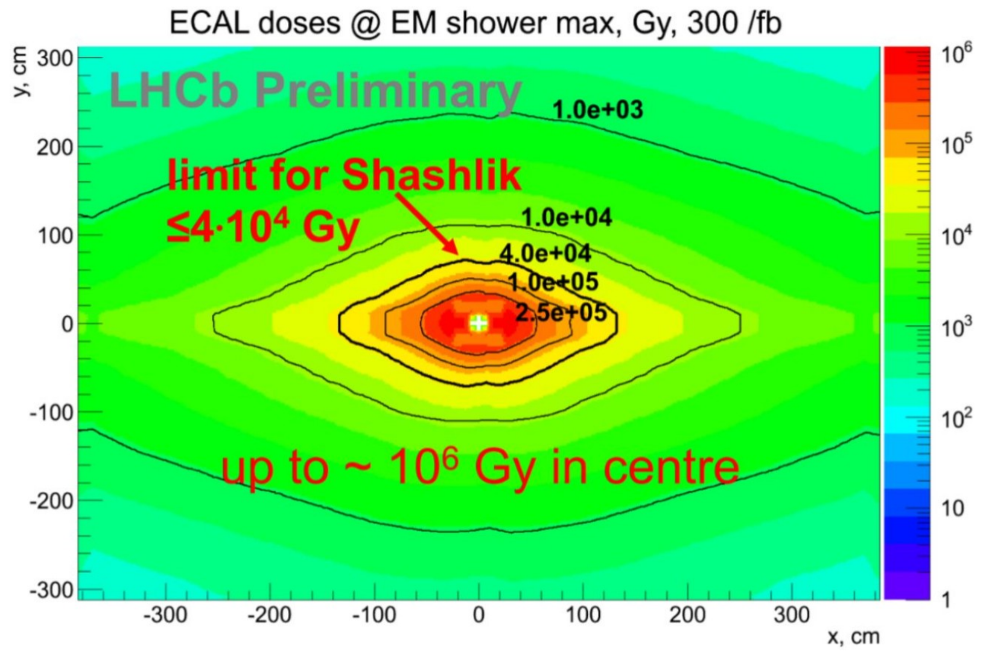
Therefore

$$\Delta t_{FRONT} = \frac{\delta z}{c} + \frac{\delta z}{v}$$
$$\Delta t_{BACK} = \frac{\delta z}{c} - \frac{\delta z}{v}$$

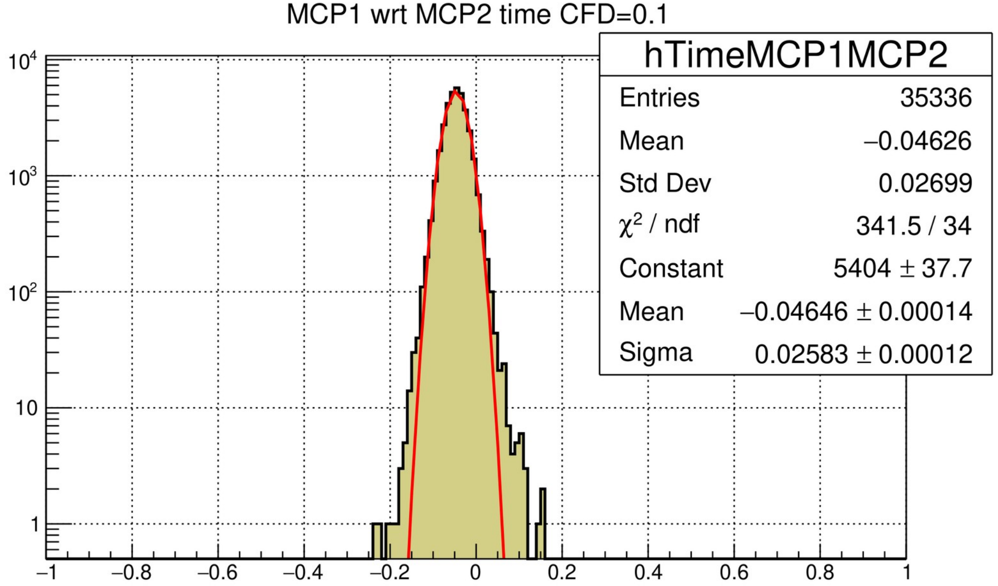
, and

$$\frac{\Delta t_{FRONT}}{\Delta t_{BACK}} = \frac{c+v}{c-v}$$

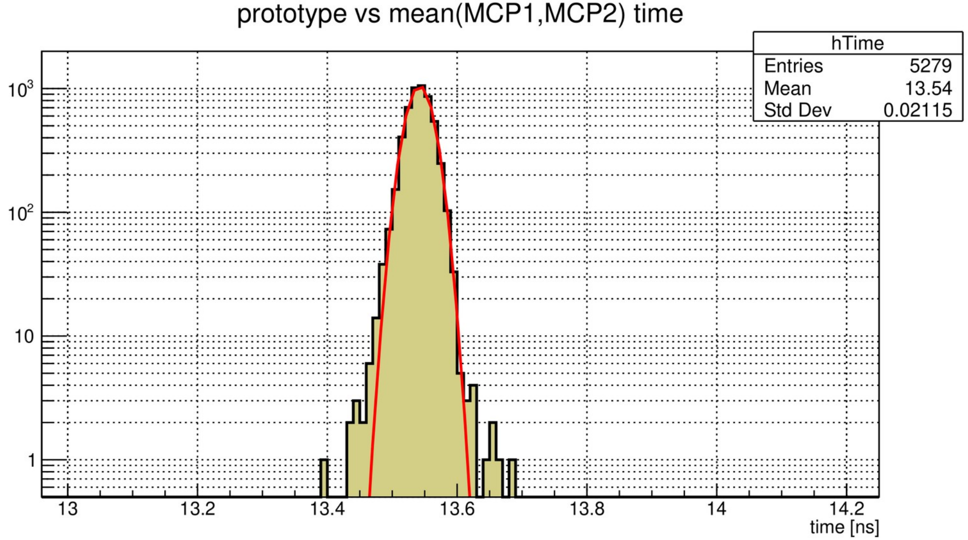
, which determines the slope of the correlation. Obviously this does not depend on energy.


ECAL doses @ EM shower max, Gy, 300 /fb
LHCb Preliminary
limit for Shashlik
≤4·10⁴ Gy
up to ~ 10⁶ Gy in centre
1.0e+03
1.0e+04
4.0e+04
1.0e+05
2.5e+05
y, cm
x, cm
300
200
100
0
-100
-200
-300
10⁶
10⁵
10⁴
10³
10²
10
1

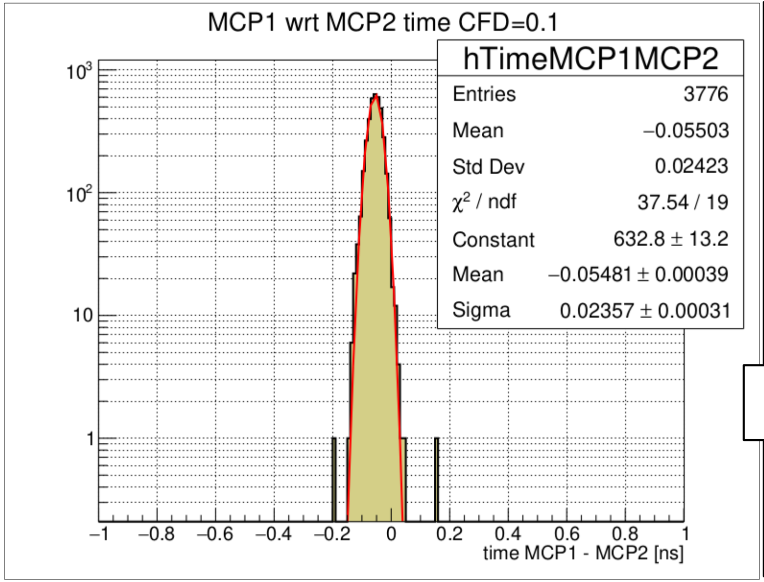
Two counters based on MCP and cylinder made of Plexiglas used as a T0. Time difference between the two gives 27 ps. Using the

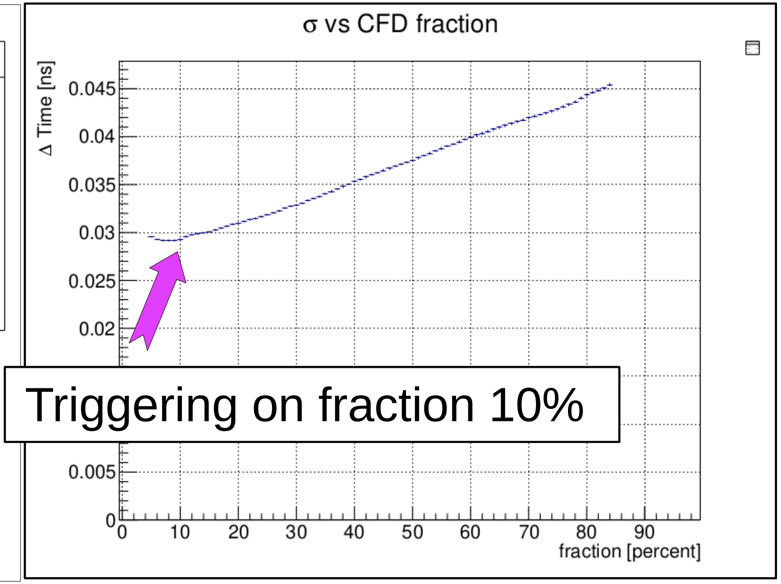


SPACAL (Kuraray) wrt T0 E = 100 GeV



Beamtests: T0





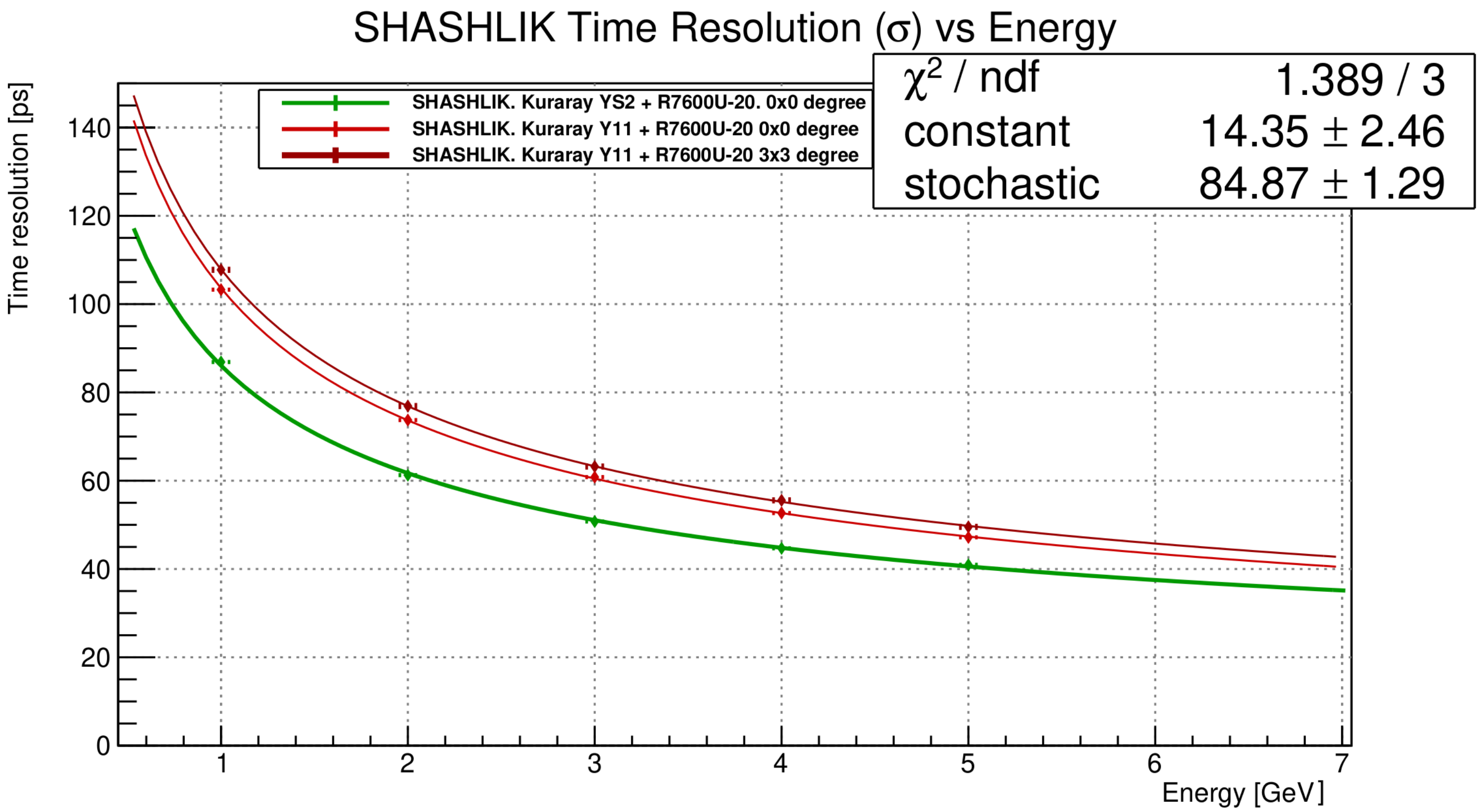
T0: two counters based on MCP-PMT (Ekran FEP, Novosibirsk) **Thanks to A. & M. Barnyakov**

with ⌀18x6 mm cylinder of Plexiglas as a Cherenkov radiator.

Time difference between the two described by Gaussian **σ = 24-28 ps** (beam depended).

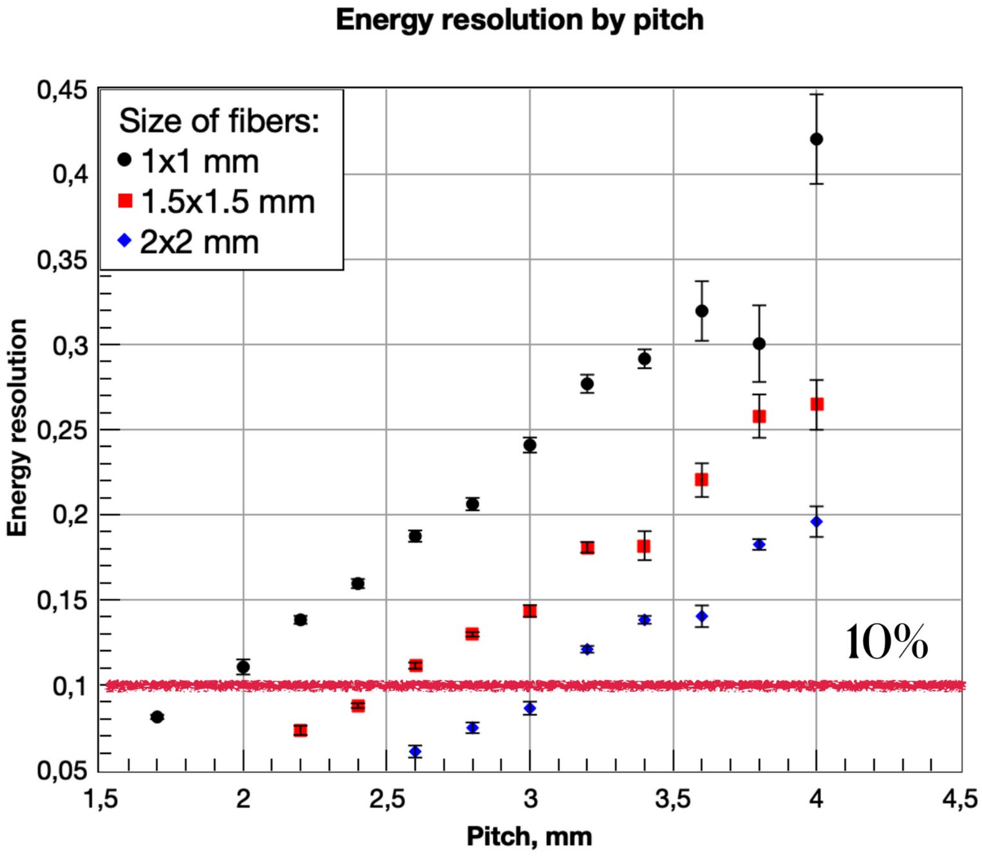
Mean (MCP1, MCP2) time → **12 - 14 ps** time resoltuion.

SHASHLIK Time resolution: E = 1 – 5 GeV



Spacal Lead/Polysterene Energy resolution

Fibres: 1x1 mm^2 (square shape, pure Lead)



Fibres: 1mm diameter (round shape)
Garth typographic alloy (Pb 84%)