

# The GRAiNITA calorimeter

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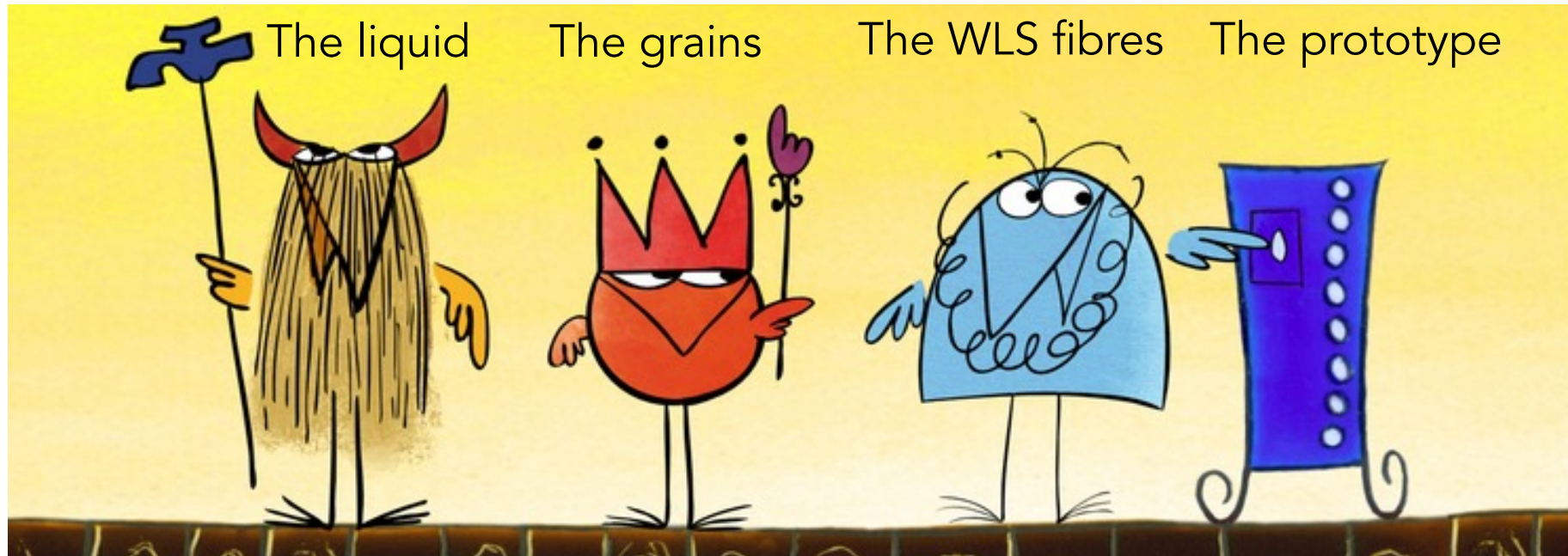
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- The concept, the small prototype and the very first measurements
- First test beam results
- A word on pulse shape discrimination

# The concept and the small prototype and the very first results



Ethylene glycol

- refractive index ~ 1.4
- LST FastFloat
- density ~ 2.85 g/cm<sup>3</sup>
  - refractive index ~ 1.5

ZnWO<sub>4</sub>

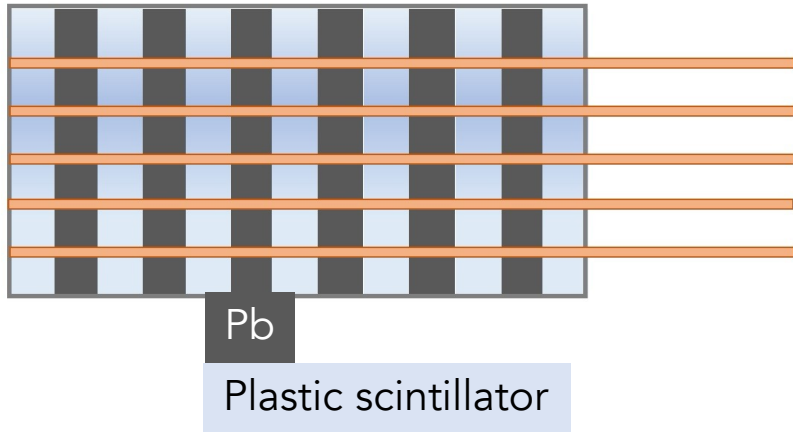
O2-(200) from Kuraray

# The overall idea (in a nutshell)

Typical sampling calorimeters:

$$\frac{\sigma_E}{E} \sim \frac{10\% - 15\%}{\sqrt{E}}$$

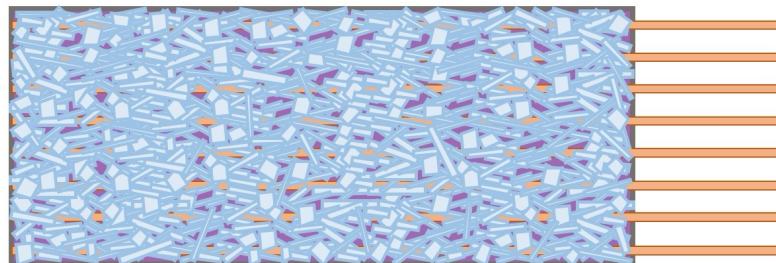
Shashlyk-type calorimeter



Requirements:

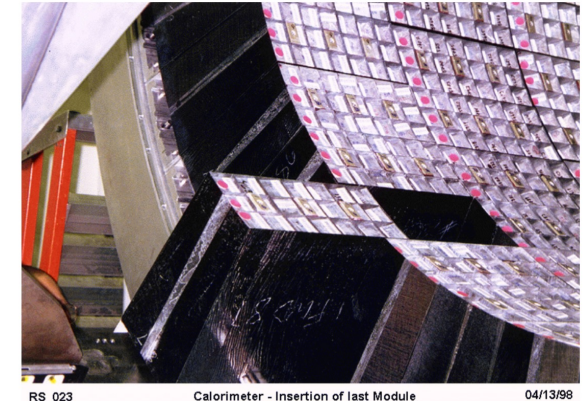
- Good energy resolution
- fine sampling
- scintillation light locally contained

GRAINITA



Crystal calorimeters :

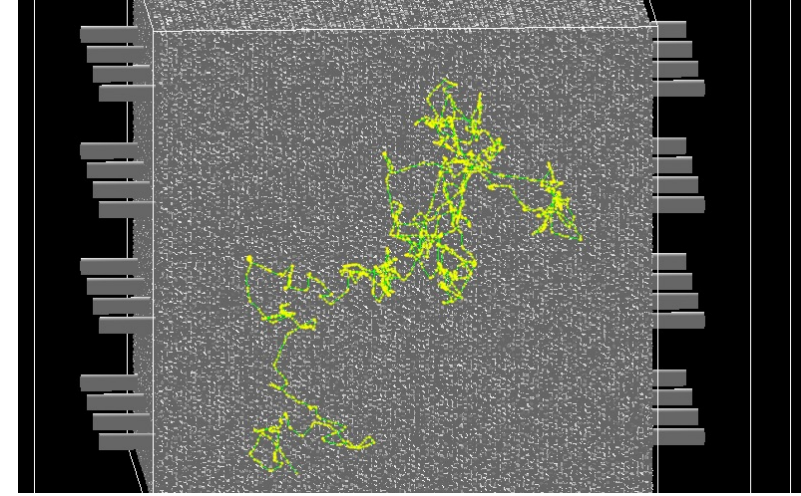
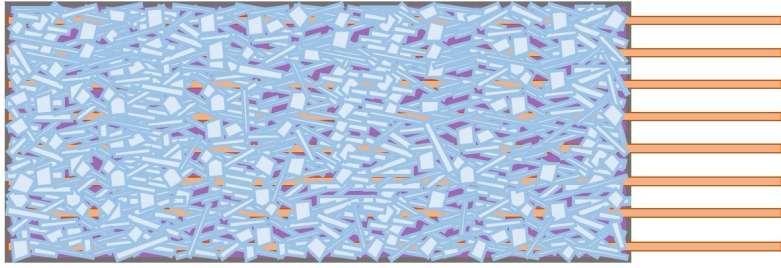
$$\frac{\sigma_E}{E} \sim \frac{1\% - 2\%}{\sqrt{E}}$$



Main components :

- Scintillating grains
- WLS fibers
- Heavy liquid

## GRAiNITA



Light is produced in the grains and collected by the WLS fibres

Choice of grains driven by number of photo-electrons and the production technique

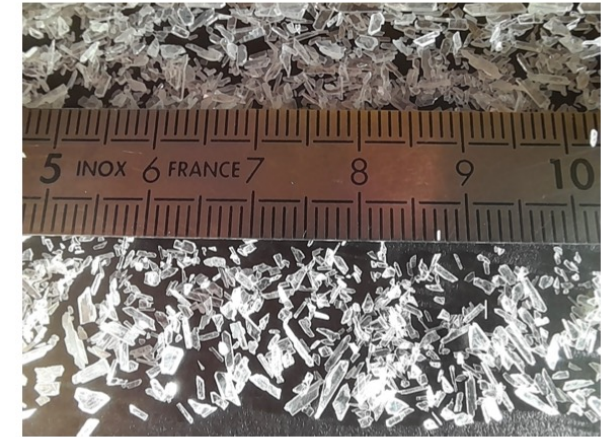
The heavy liquid:

- increases the density and thus reduce the size of the calorimeter
- the 1.5 refractive index of HL: reasonable compromise to have light confinement and not too long path before reaching the WLS fibres

ZnWO<sub>4</sub> has been identified as a promising candidate

	BGO	ZnWO <sub>4</sub>
Effective Z	74	61
Density (g/cm <sup>3</sup> )	7.13	7.87
Refractive index	2.15	2.0 - 2.3
Light yield (photons/MeV)	~ 9000	~ 9000
Peak emission wavelength (nm)	480	480
Decay time (μs)	0.3	20
Radiation length (cm)	1.12	1.20
Molière radius (cm)	2.26	1.98

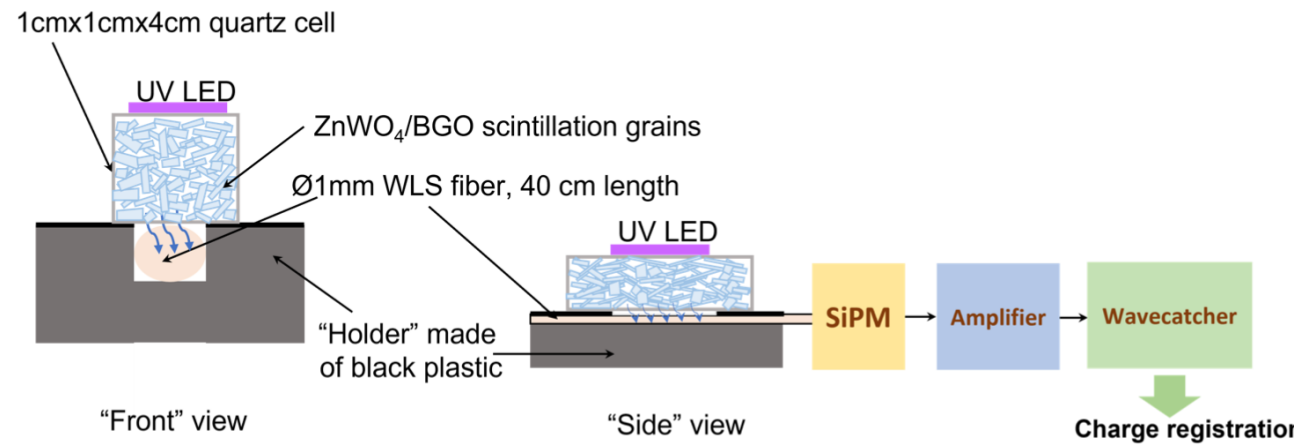
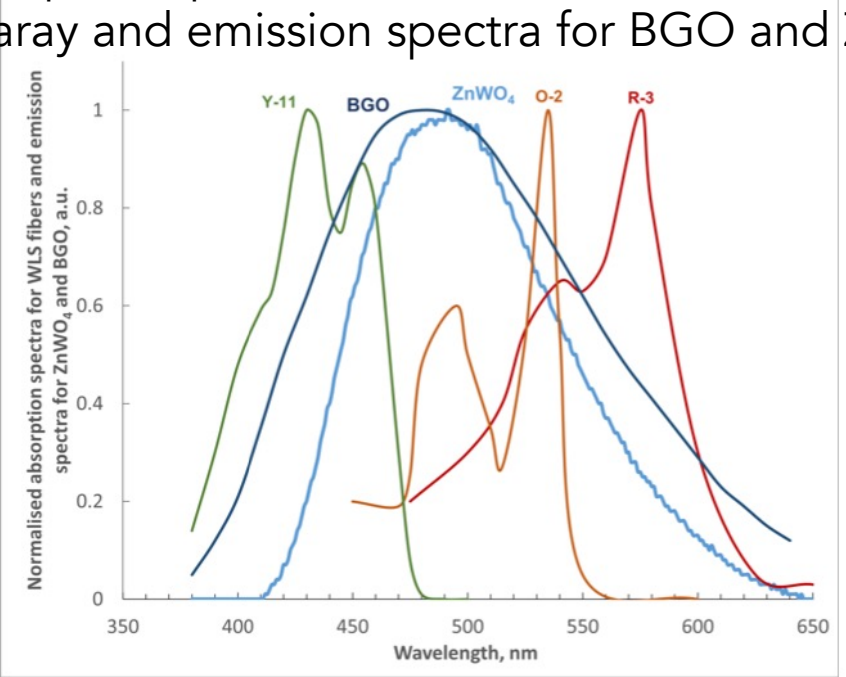
Scintillation decay time ok for FCC-ee (~50 kHz at the Z pole).



**ISMA:** dedicated R&D to produce ZnWO<sub>4</sub> grains with the flux method (cost effective). Production technique mastered.

~ 1 kg of high-quality ZnWO<sub>4</sub> grains produced

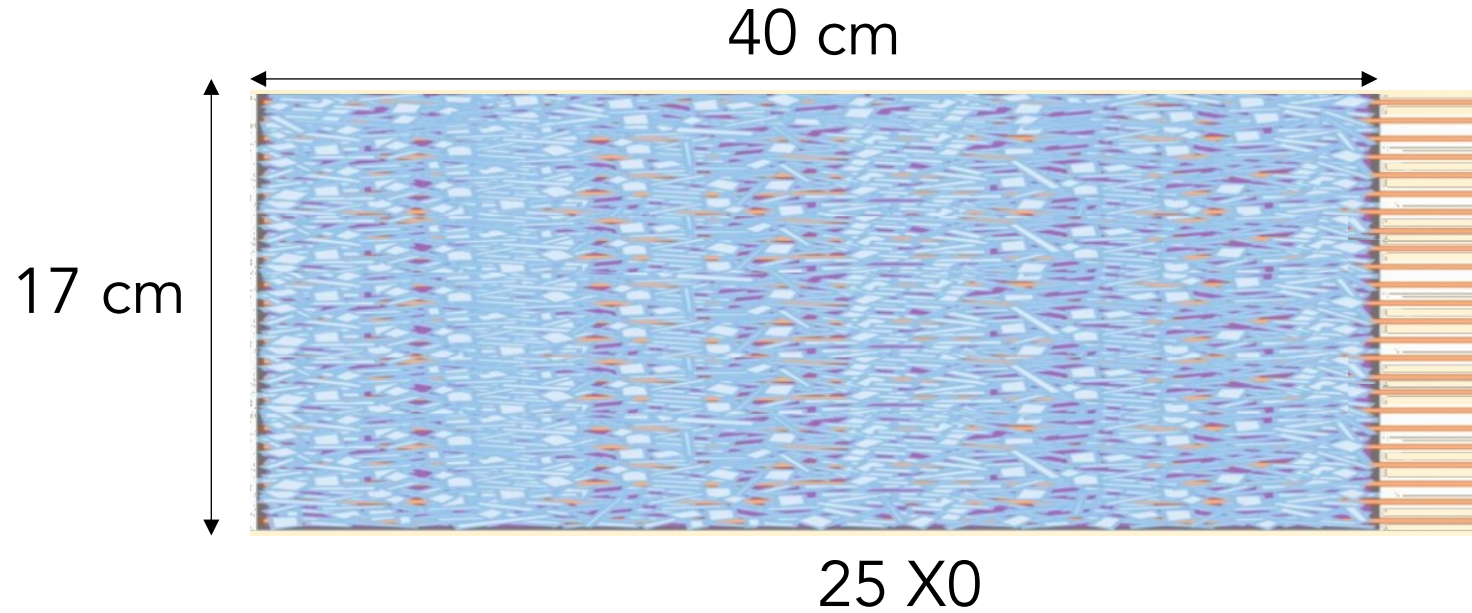
Absorption spectra for Y-11, O-2 and R-3 fibers from Kuraray and emission spectra for BGO and ZnWO<sub>4</sub>



Fiber type	Relative efficiency (%)	
	ZnWO <sub>4</sub> grains (~ 9 mm)	BGO grains (~ 9 mm)
O-3(300)	100	100
O-2(200)	104	104
Y-11(200)	44	98
R-3(100)	60	n.a.

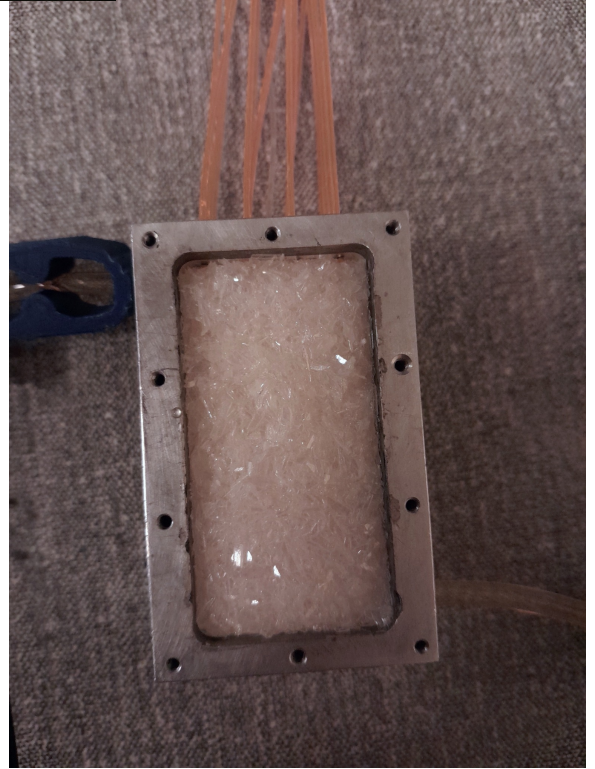
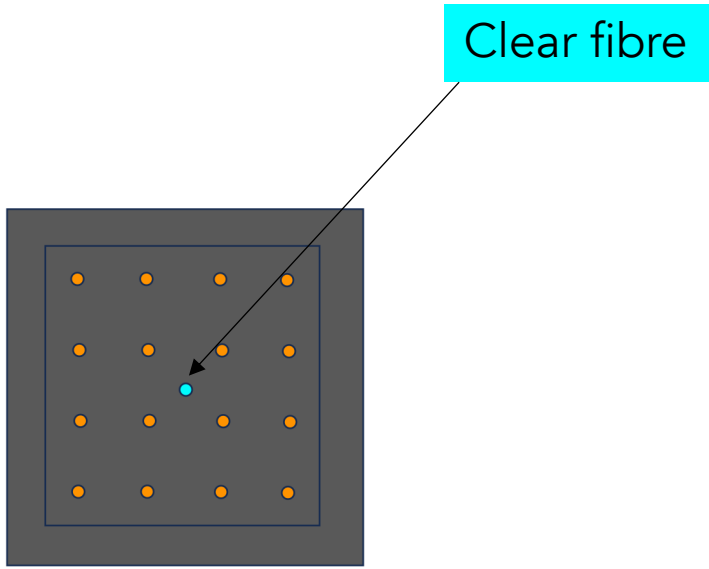
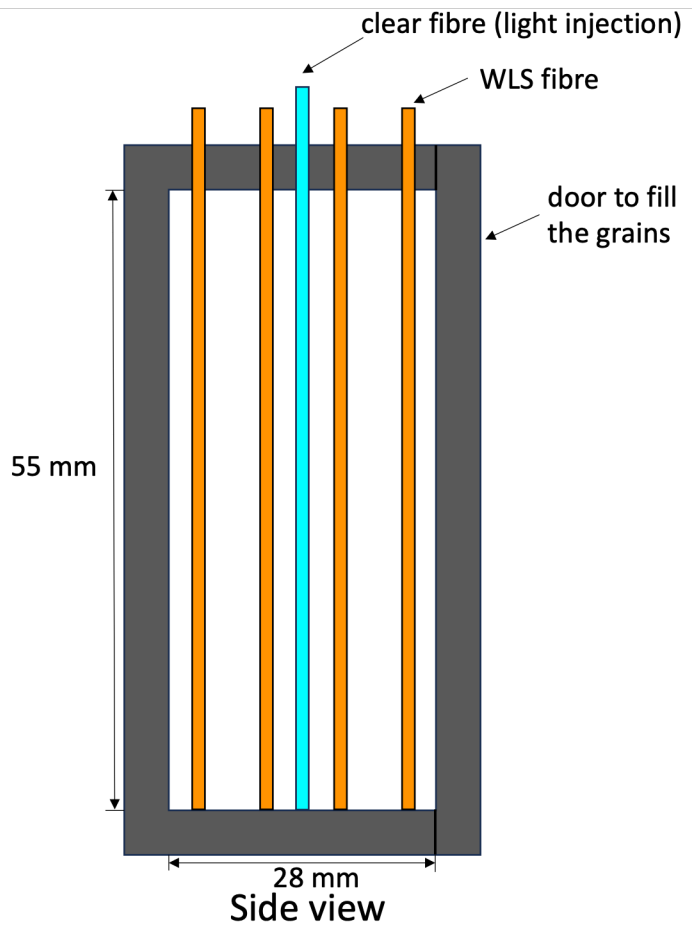
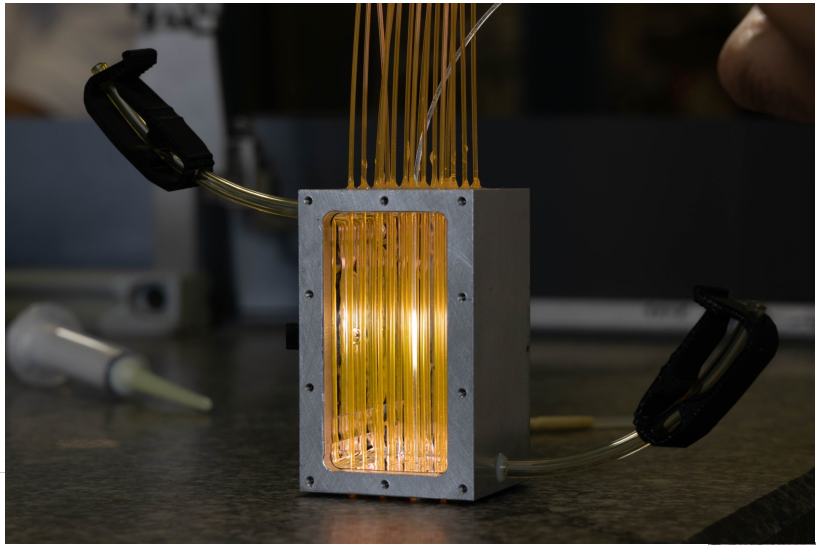
ref  
preferred choice

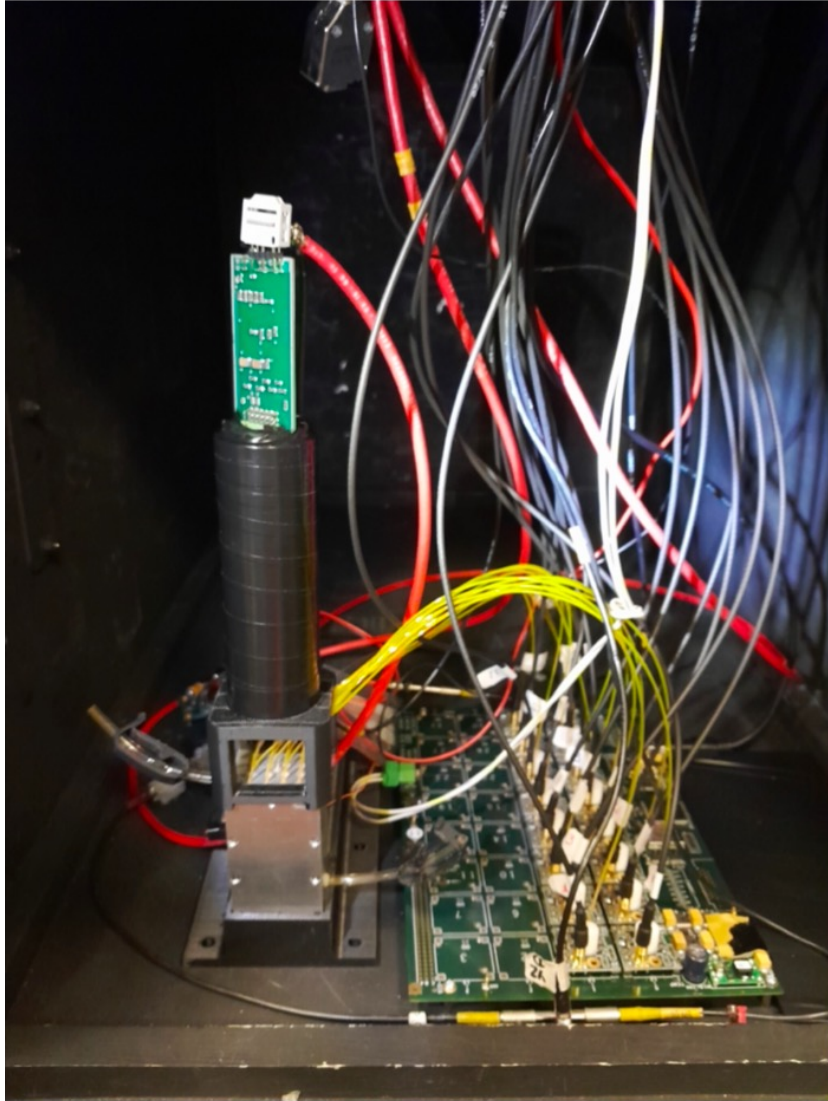
Goal: scale one module to contain the shower of a 25 GeV photon



~50 kg of grains

But it started small !





16 WLS fibres couples to a SiPM mounted on a PCB for amplification.

Signals are digitized at 3.2 GHz with a Wave Catcher.

The photo-electrons are identified and counted in a  $25 \mu\text{s}$  window.

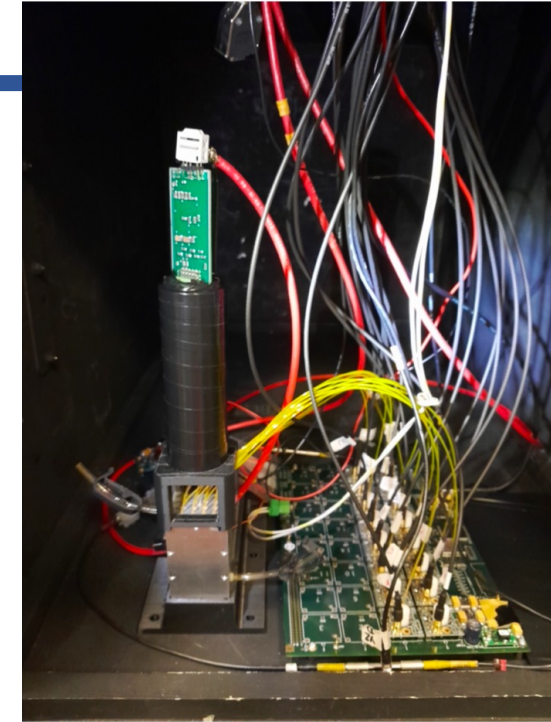
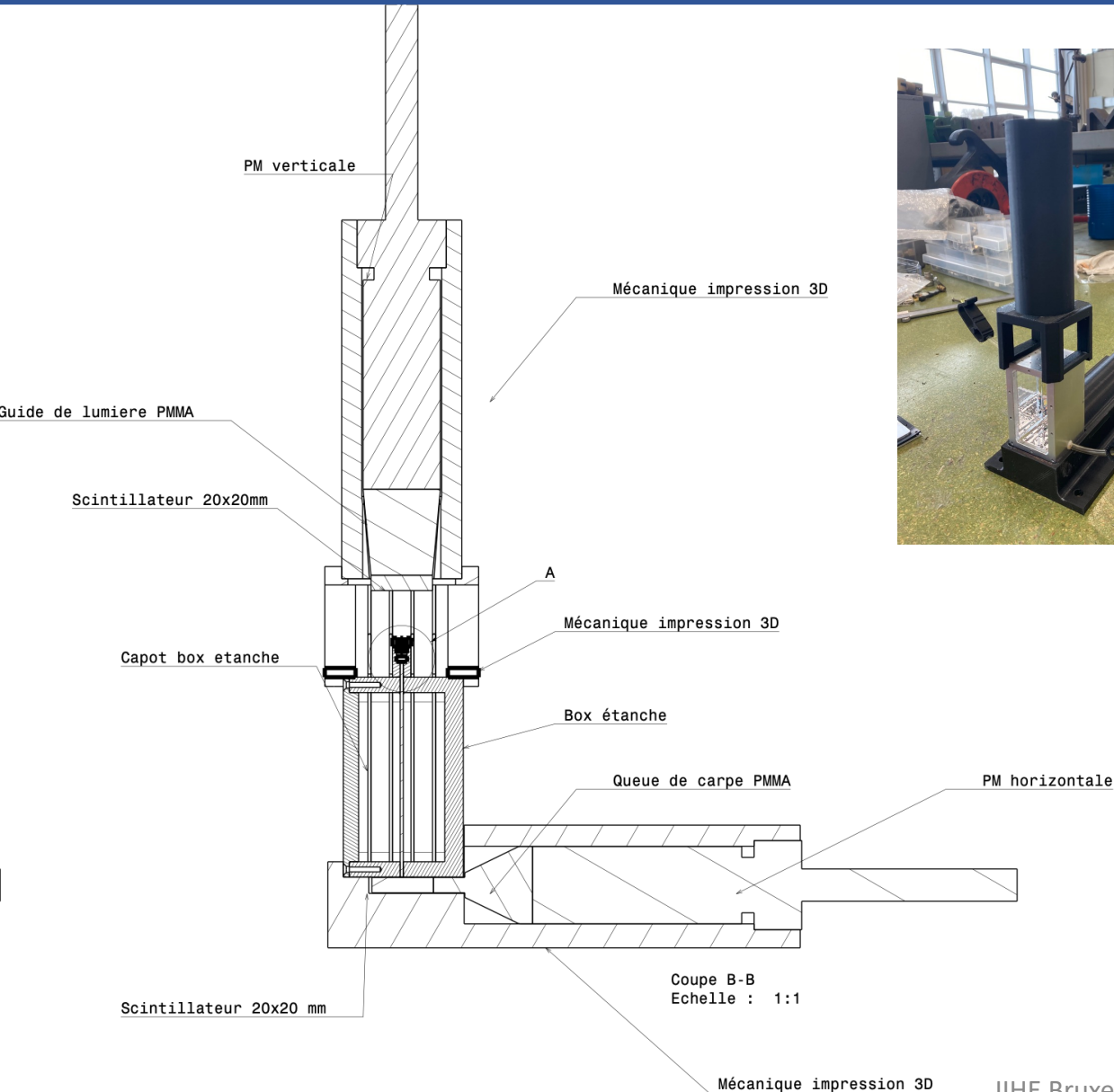
# First measurements

stochastic  
(dom. at high E)

calib.,  
non uniformity

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

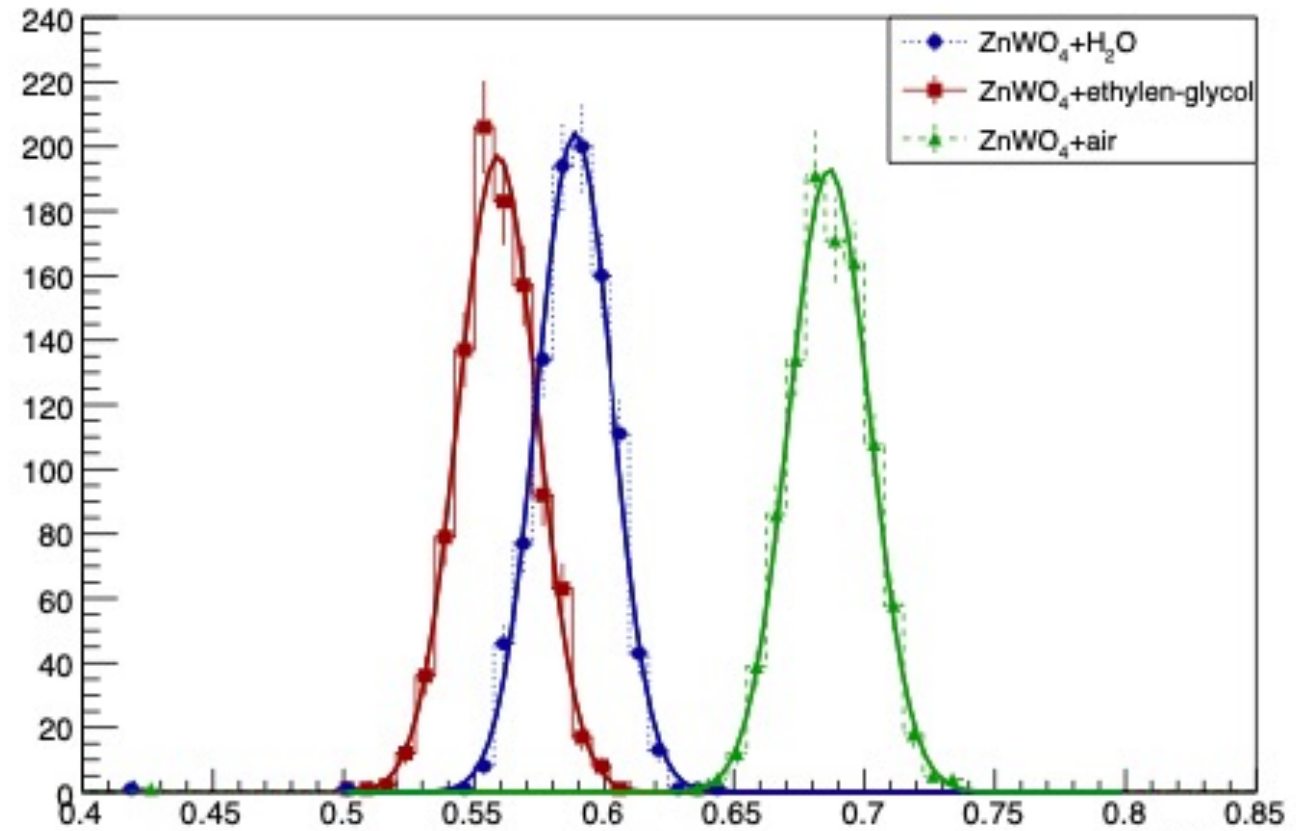
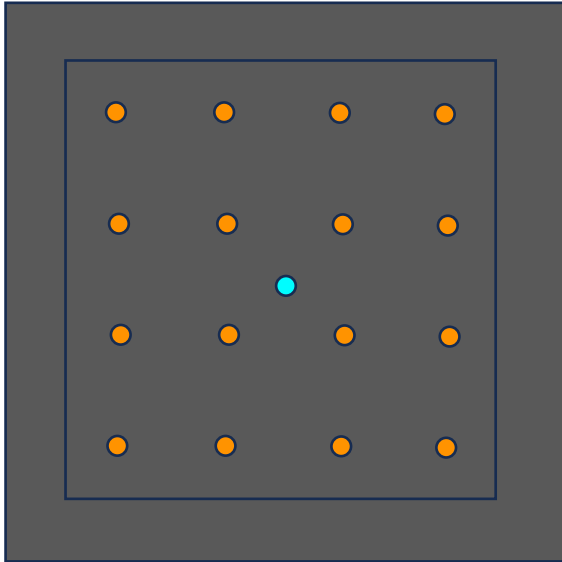
# Cosmic rays test bench



Small ( $2 \times 2 \times 5.5 \text{ cm}^3$ ) prototype

~ 1 week to record 500 events  
Energy deposit ~ 40 MeV

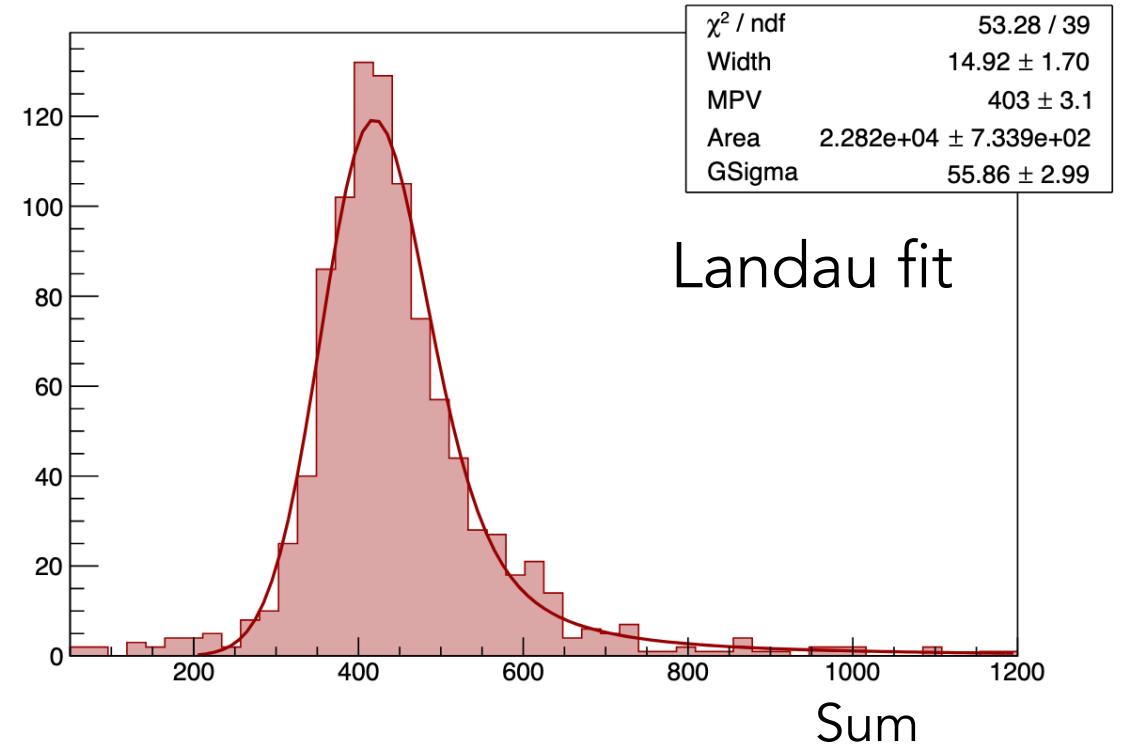
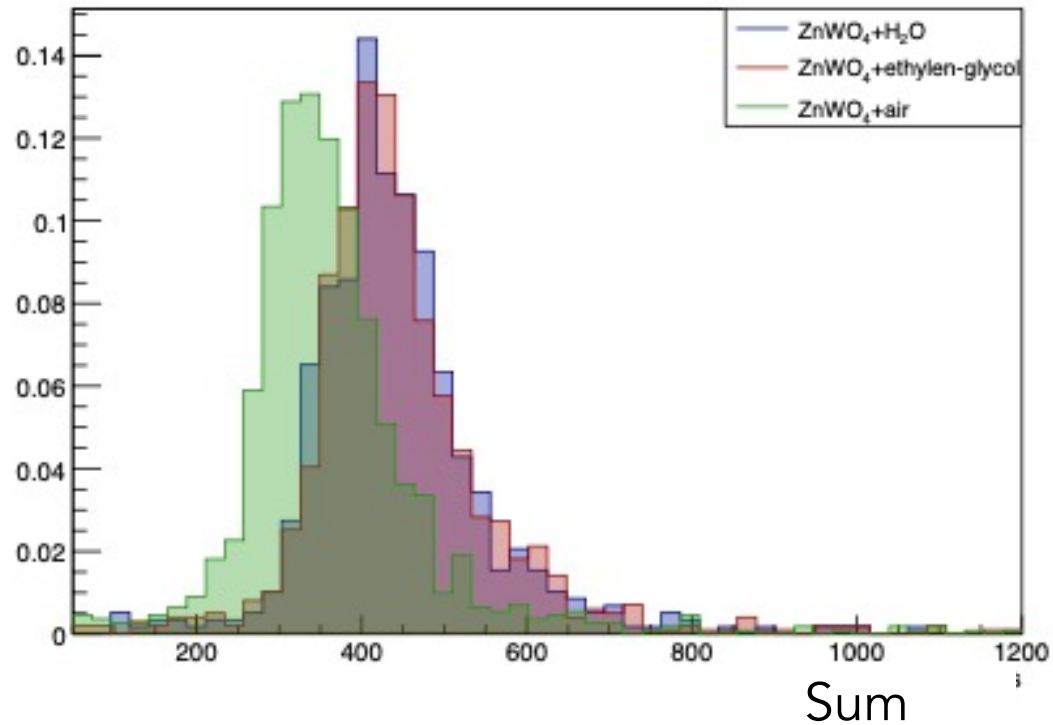
# First results using the green LED light injection

ZnWO<sub>4</sub>ZnWO<sub>4</sub> +  
H<sub>2</sub>OZnWO<sub>4</sub> +  
EGL

$$\text{Centrality} = \frac{4 \text{ central channels}}{\text{Sum}}$$

## Light is confined

With cosmic muons:



⇒ ~ 10 000 photo-electrons/GeV

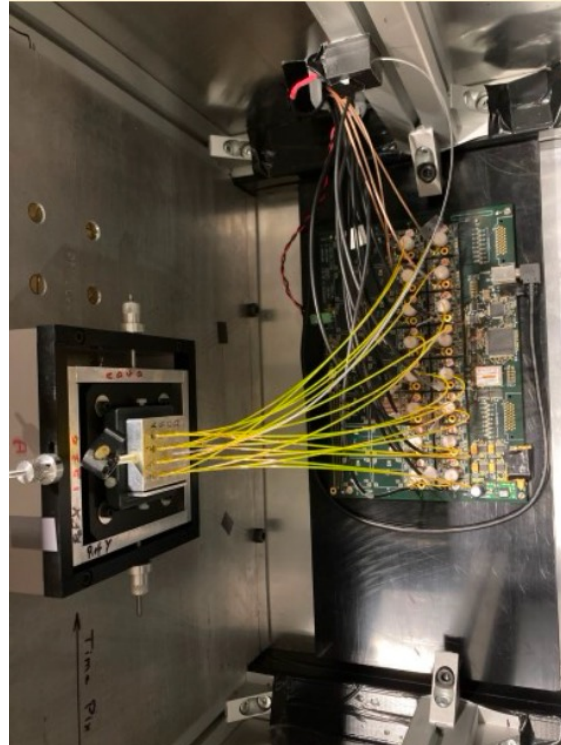
⇒ opens the road to a statistical fluctuation of  $\frac{\sim 1\%}{\sqrt{E}}$  due to photon statistics

G4 simulation of cubic (for now) small grains and heavy liquid ⇒ sampling energy fluctuation of  $\frac{\sim 2\%}{\sqrt{E}}$

Term smaller than usual sampling calorimeter because of small grains and high density of scintillator

# First test beam results

[arxiv:2512.03811](https://arxiv.org/abs/2512.03811) (accepted by JINST)



Main objective: investigate the uniformity response (constant term in the energy resolution)

# Which data ?

2 days of data-taking (in the shadow of LHCb PicoCal test in June 2024):

- ~ 2 millions of muons events
- ~ 48 millions of pions events (small prototype: only 20% of pions are interacting)

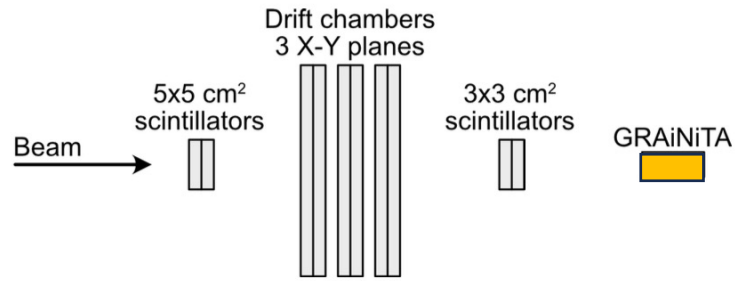
Energy ~ few 10 GeV

2 data-taking periods:

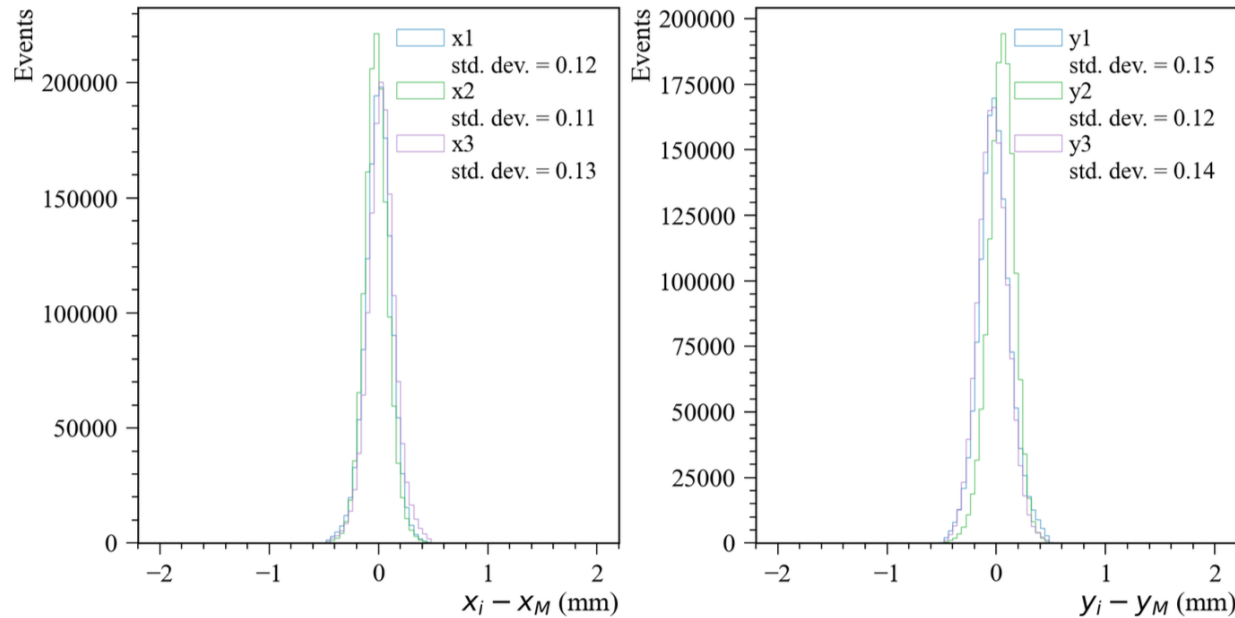
- $\text{ZnWO}_4$  grains in water
- $\text{ZnWO}_4$  grains in water-based sodium polytungstate solution (*Fastfloat*)

(refractive index = 1.5,  
density =  $2.85 \text{ g.cm}^{-3}$ )

# Set-up



GRAiNiTA read-out triggered by the drift chamber + scintillators

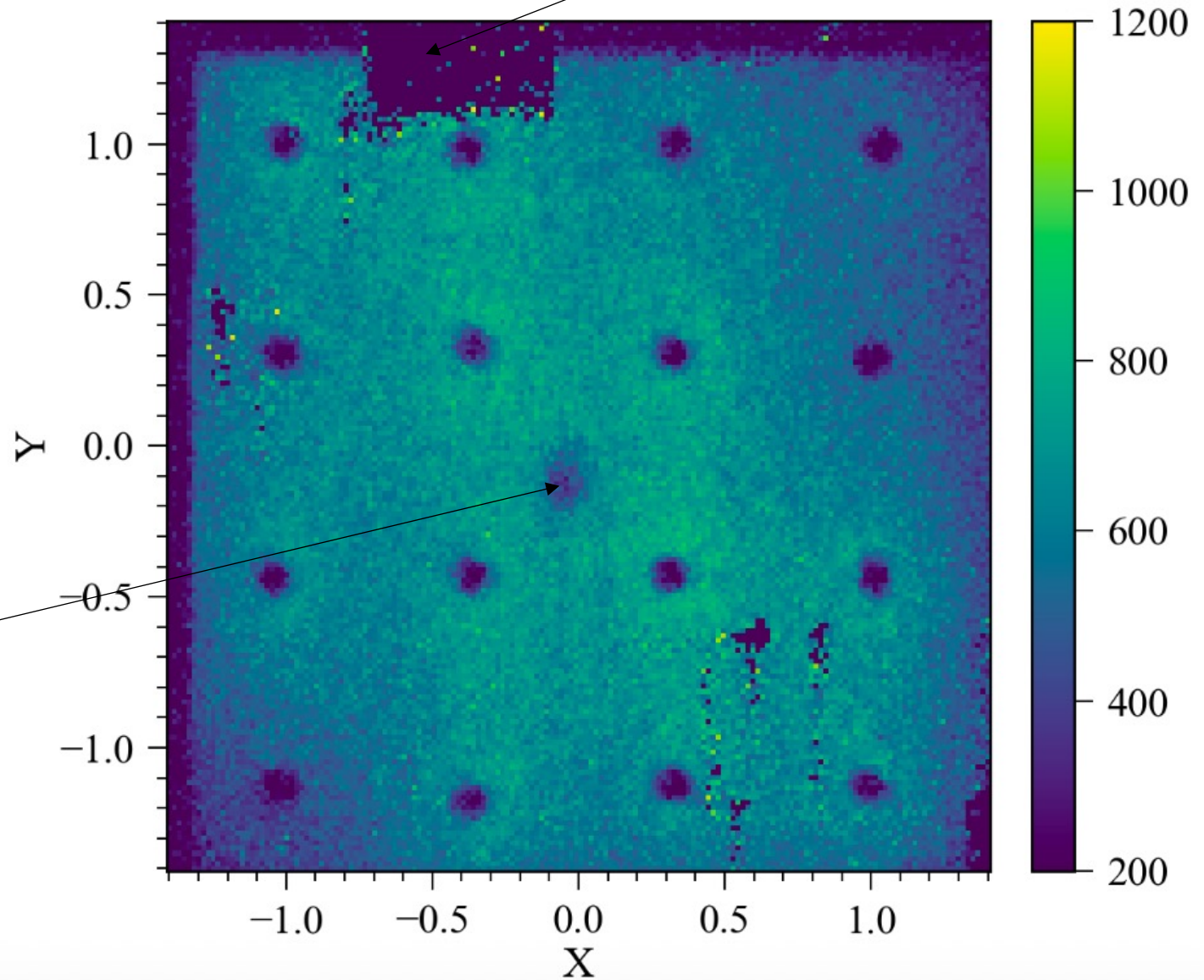


Resolution on the track position  $\sim 170 \mu\text{m}$

A very first look in  $170 \times 170 \mu\text{m}^2$  bins

DWC not fully functional

for muon tracks in each bin:  
mean value of  $N_{\text{PHE}}$  from the sum  
of the 16 WLS fibres



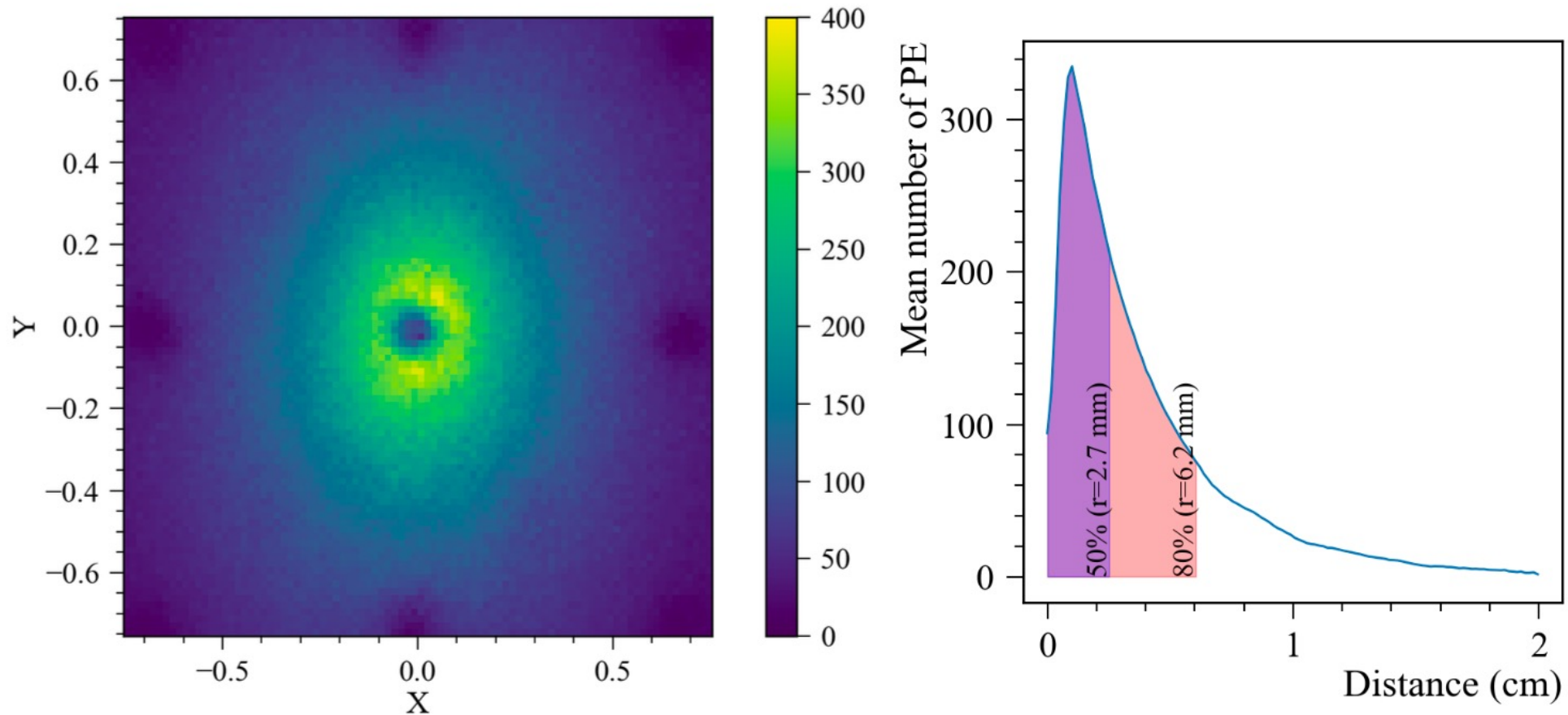
Clear fibre is bent

# Light confinement

confirmed

Using muons and the 4 more central fibres

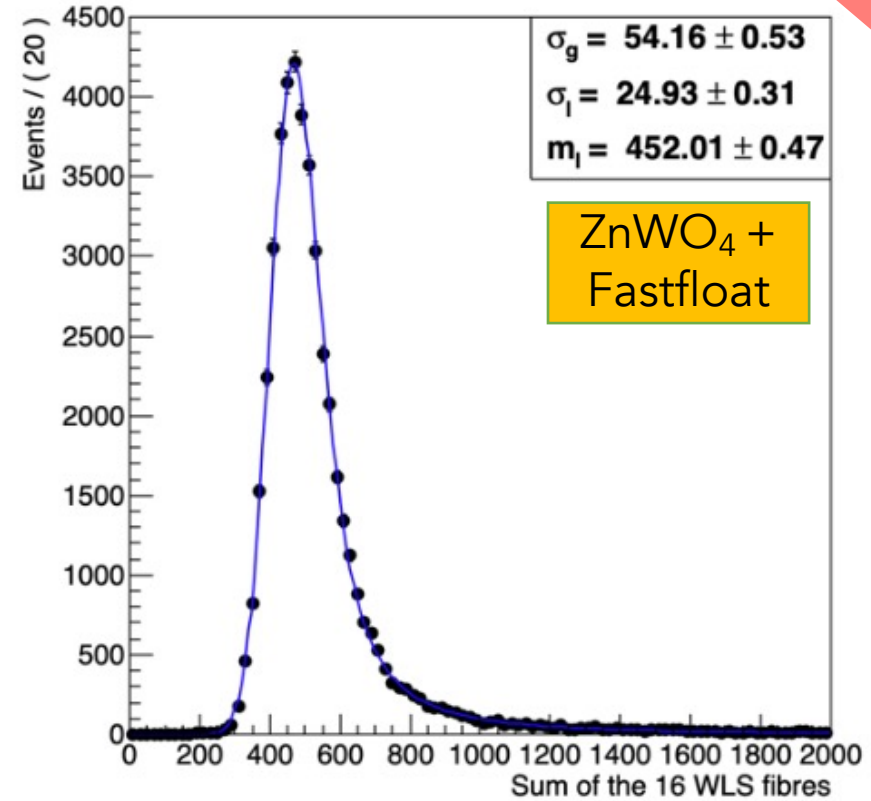
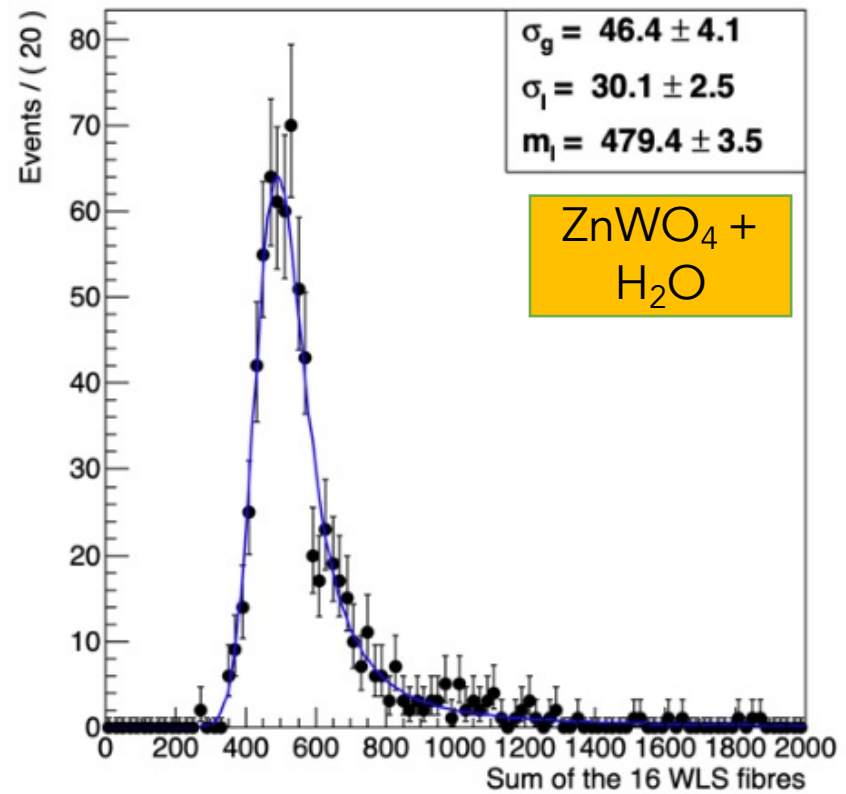
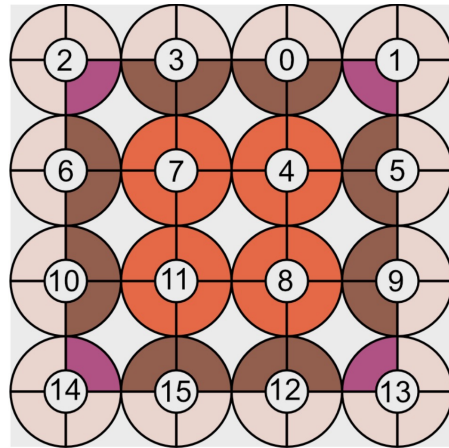
Signal on a given fibre as a function of the position of the track



# Stochastic term

confirmed

Use muon tracks close to the centre (orange zone)

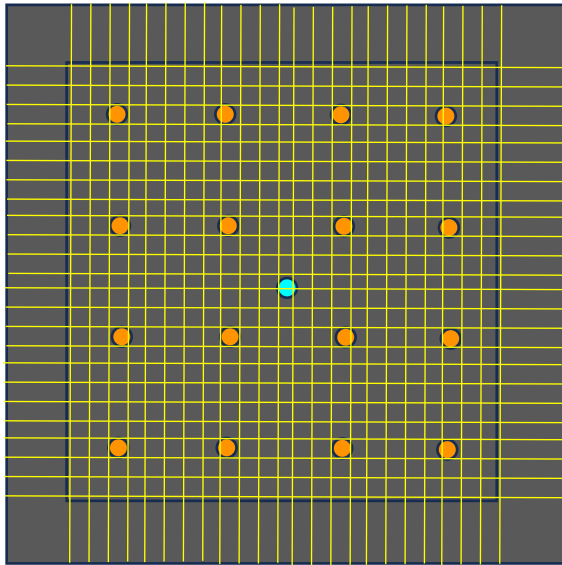


# Test of the uniformity

Pave the prototype surface by bins of  $1 \text{ mm}^2$   
Measure the sum of the 16 WLS signals for each bin  
Fit the integral to extract the most probable value



©Britannica Dictionnary



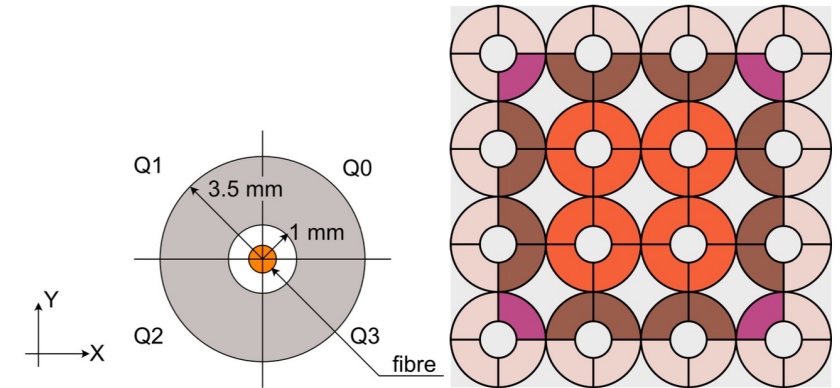
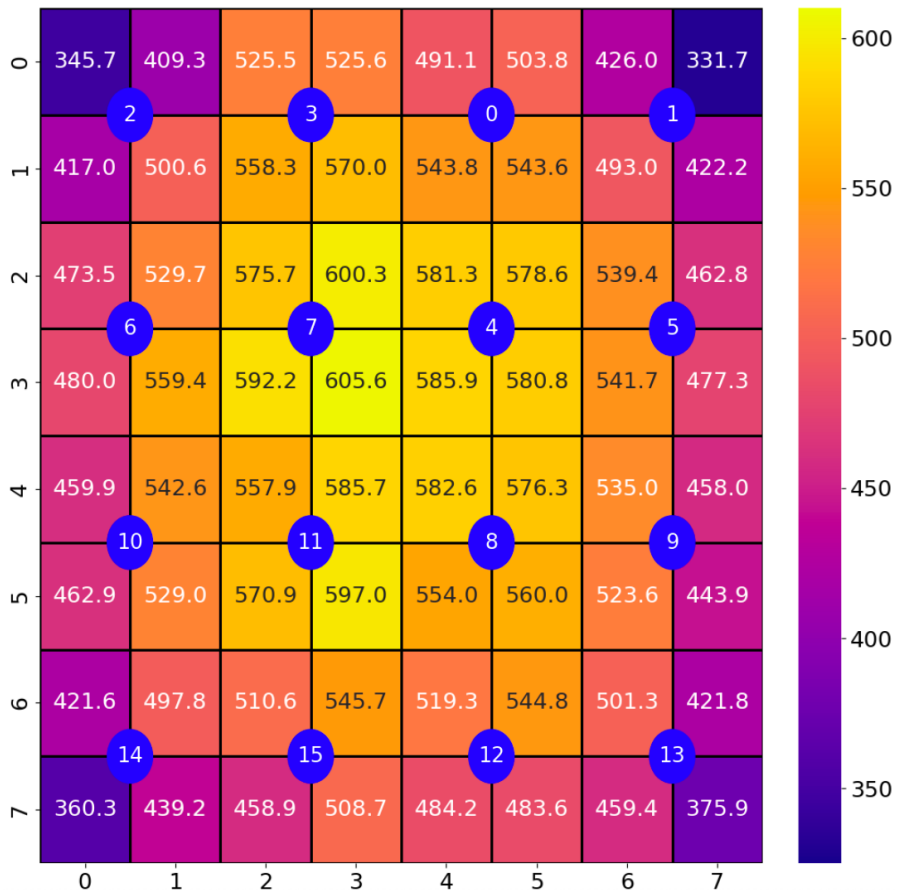
## Challenges:

- very large data samples required
- with such a small prototype, the handling of the border effects is intricate to mitigate.
- data-taking issues (liquid leakages + electronics configuration problems etc... )

# Data processing for non-uniformity assessment

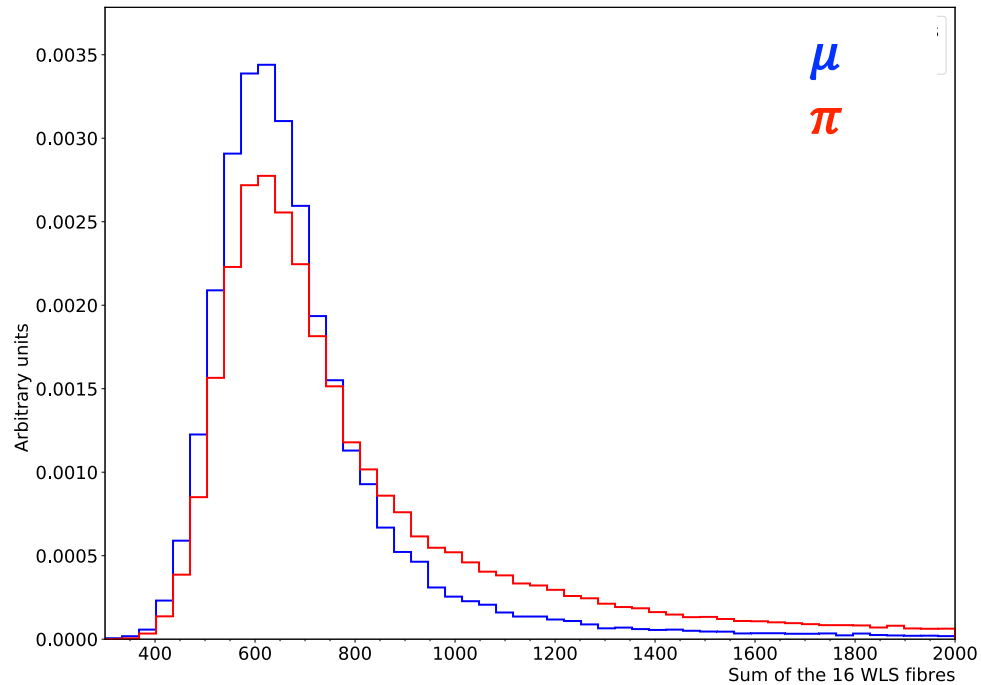
Prototype plugged and un-plugged many times during the beam test period  
→ need for homogenised responses

Muon hit map after the homogenisation:



- Fiducial cuts to be applied despite the VM2000 on the walls.
- Pion runs to be used (larger stat)

# Pion fitting model



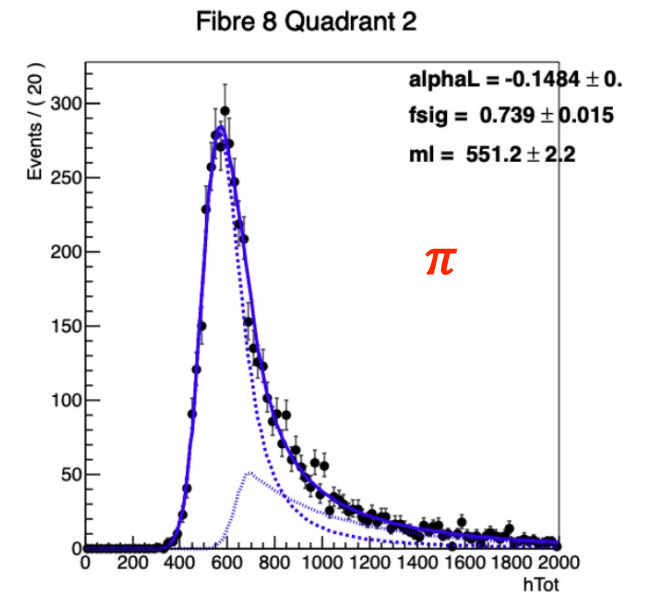
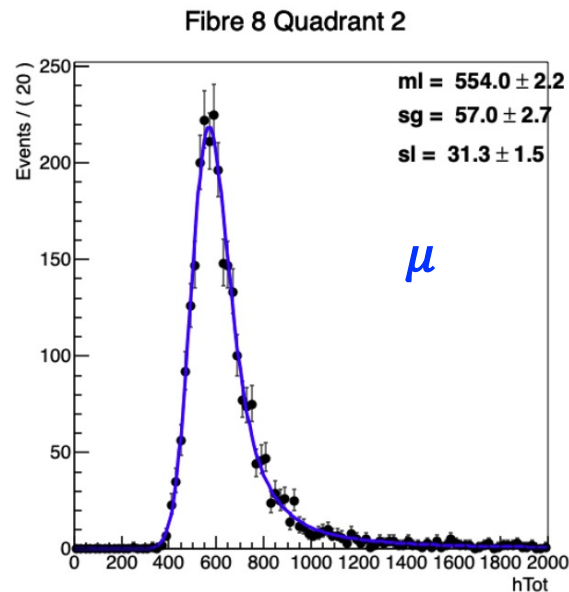
**Muon** signal : Landau  $\otimes$  Gauss ( $M(s)$ )

**Pion** Signal  $P(s) = f_{\text{sig}} M(s) + (1 - f_{\text{sig}}) \text{CB}(s)$

$$\sigma_{\text{CB}} = \sigma_G$$

$$n_L = 6$$

$$x_{0\text{CB}} = 8/9 \sqrt{2} m_L$$



Fit all fibres separately and extract all nuisance parameters

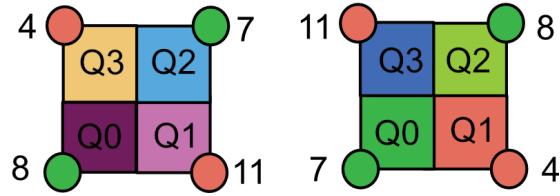
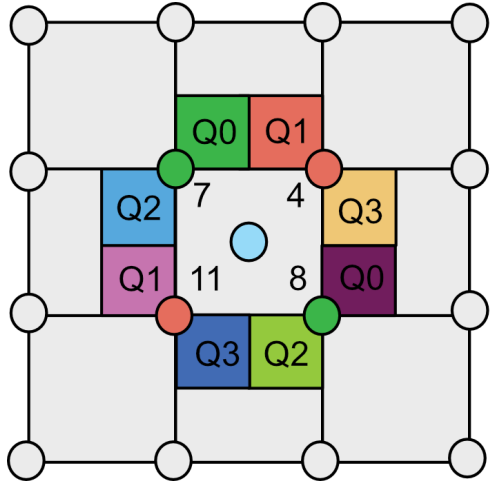
Fix to the mean value of the nuisances parameters

→ one free parameter : the Landau mean

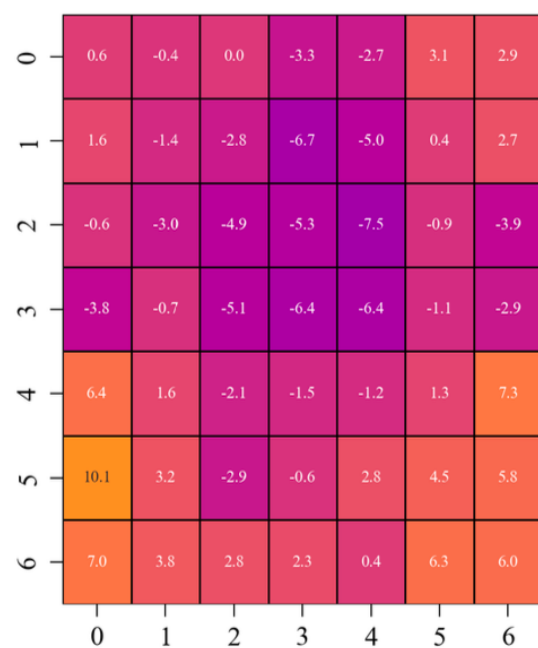
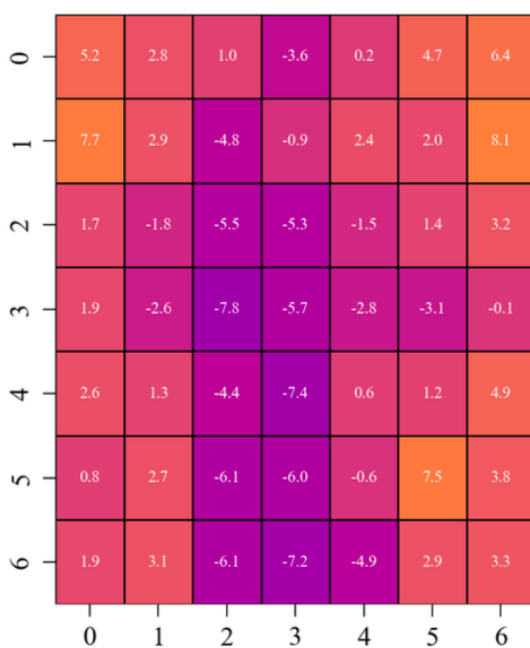
$\sigma_l$	$\sigma_g$	$f_{\text{sig}}$	$\alpha_L$
19.7	49.6	0.736	-0.126

Method tested one and applied to the 15 others!

# Avoiding the walls and the clear fibre

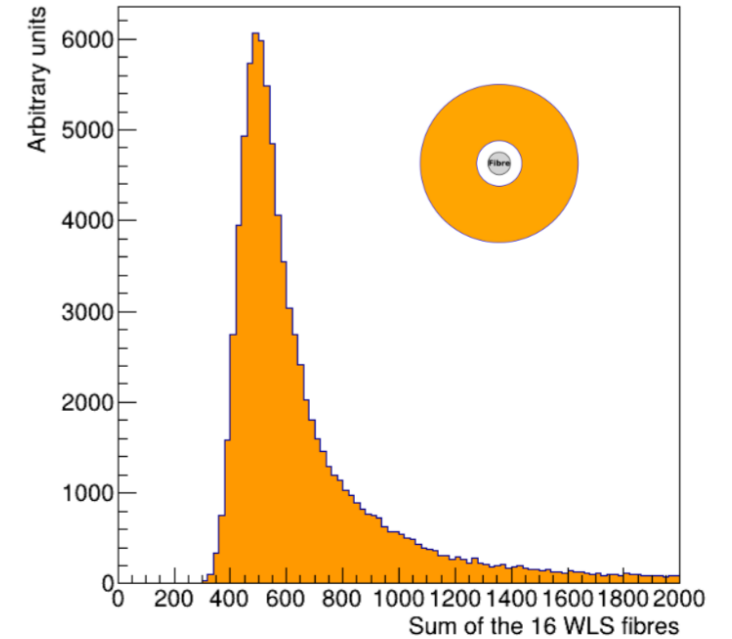
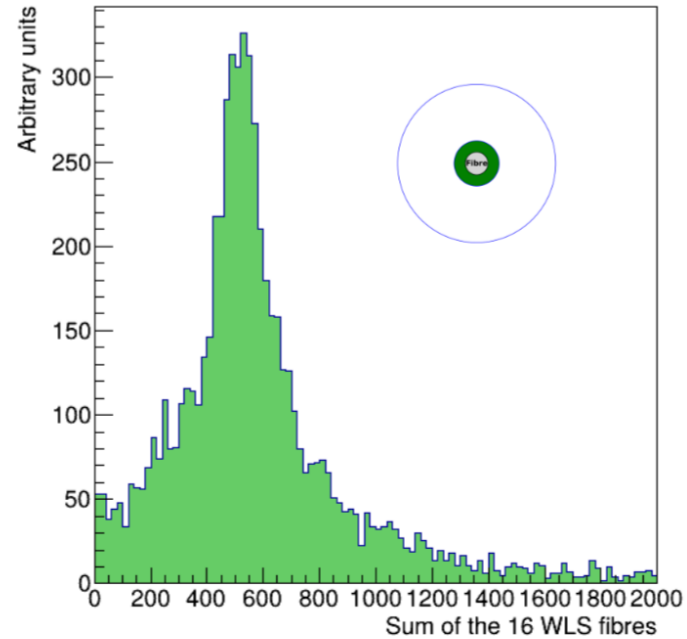
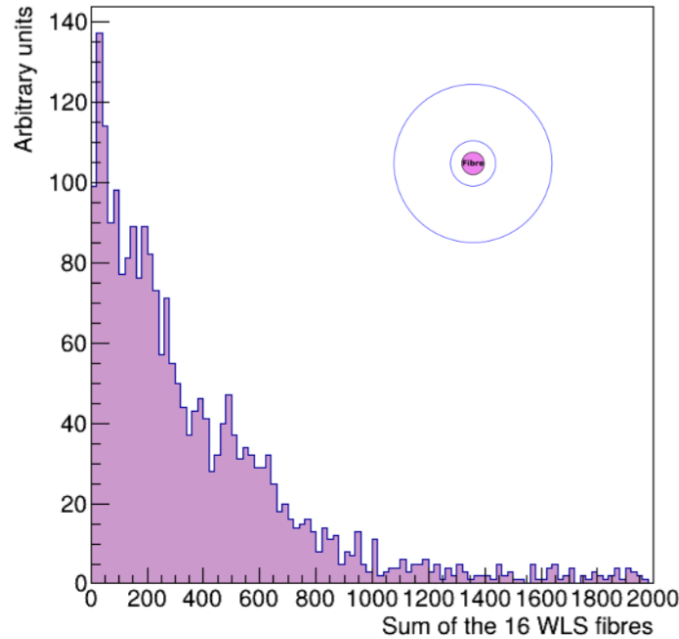


Pions hit map (1 mm<sup>2</sup>) on the virtual units  
fractional values (%)



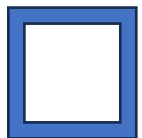
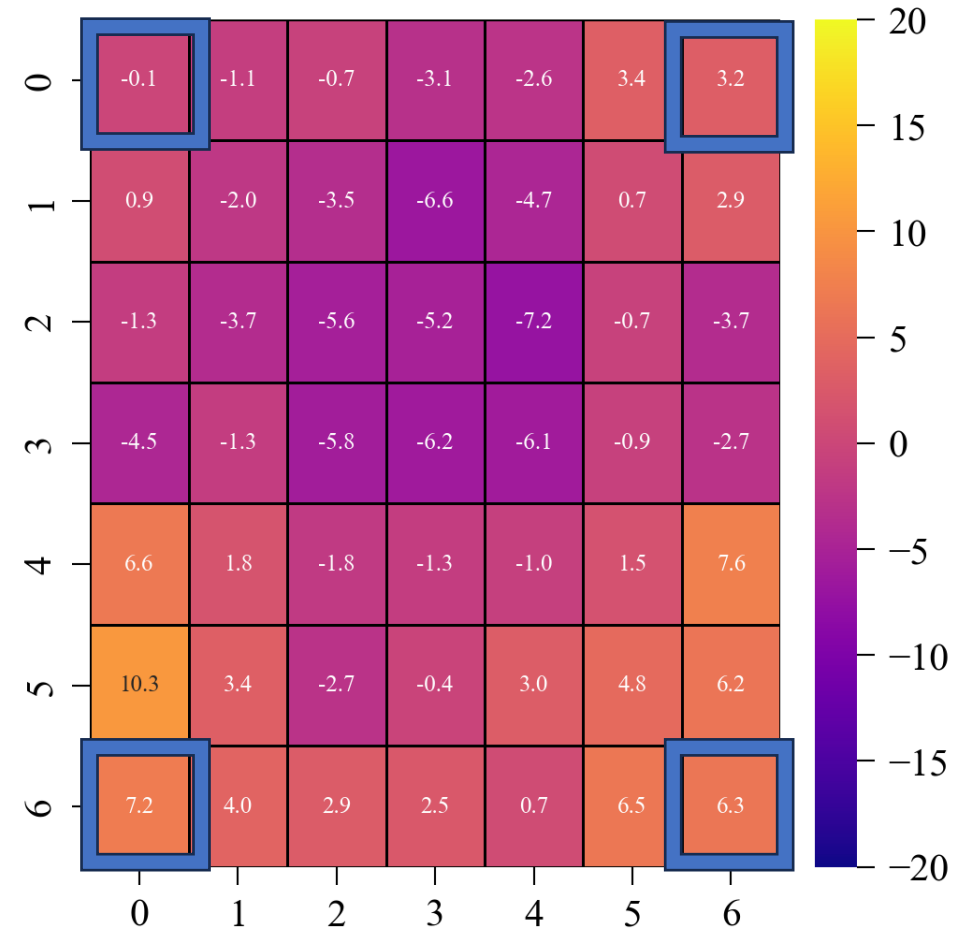
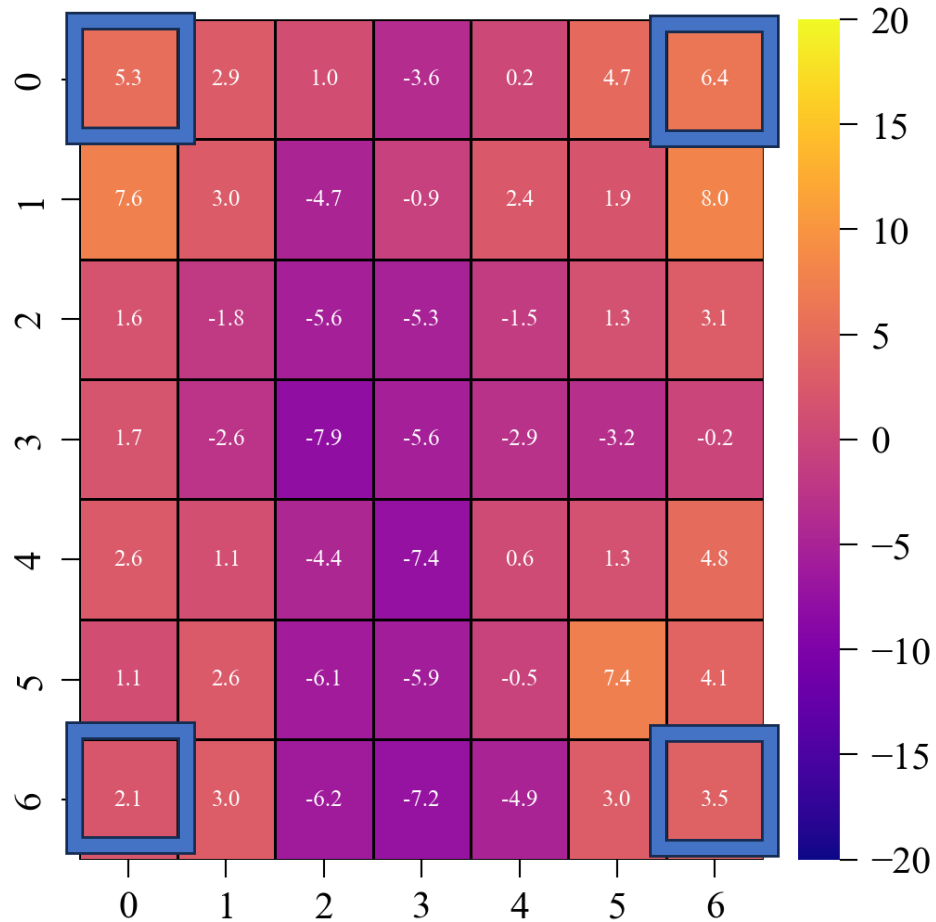
Rms variation of signal over  
different positions less than 10%

As expected signal varies a lot if the track hits the fibre



In the simulation when a track hits a fibre, no scintillation light is emitted

# Hitmaps for the 2 virtual units (in %)

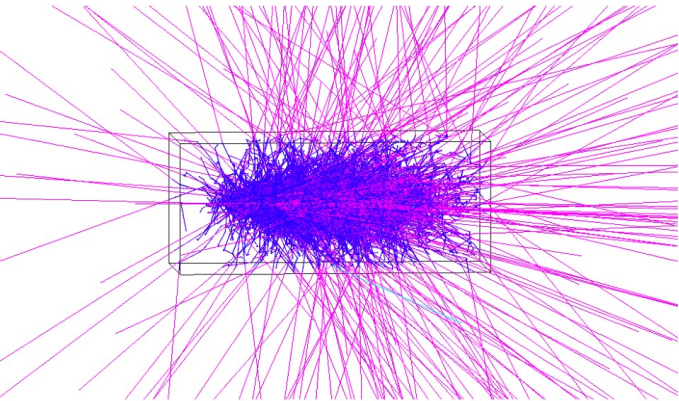


Bin where there is a fibre. Mean replaced by average of adjacent bins.  
 In the simulation when a track hits a fibre, no scintillation light is emitted

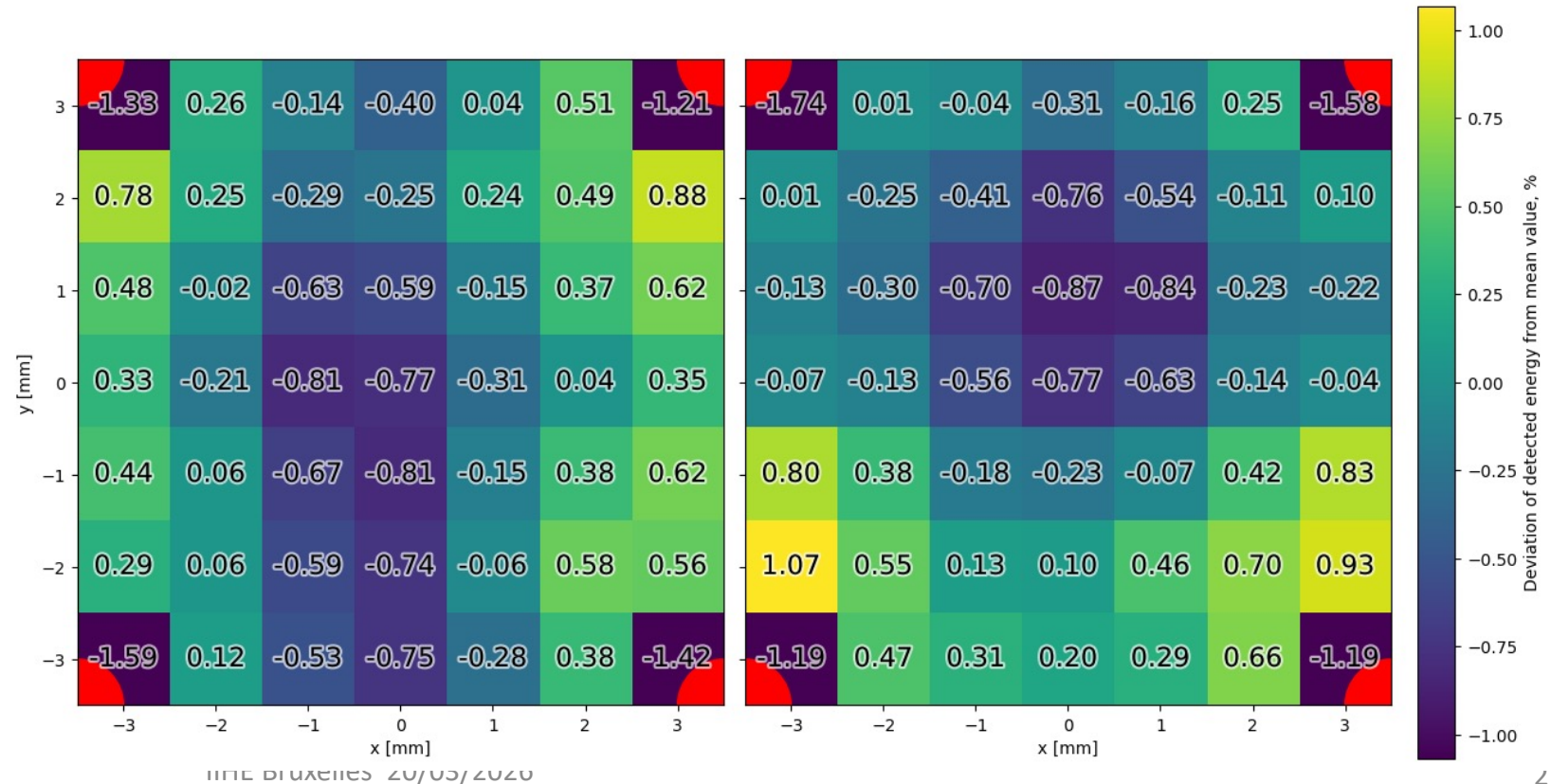
# Impact on the constant term

Geant4 simulation of a full-size prototype (17 x 17 x 40 cm<sup>3</sup>) with a mixture of ZnWO<sub>4</sub> (no grains) and sodium polytungstate

25 GeV  $\gamma$

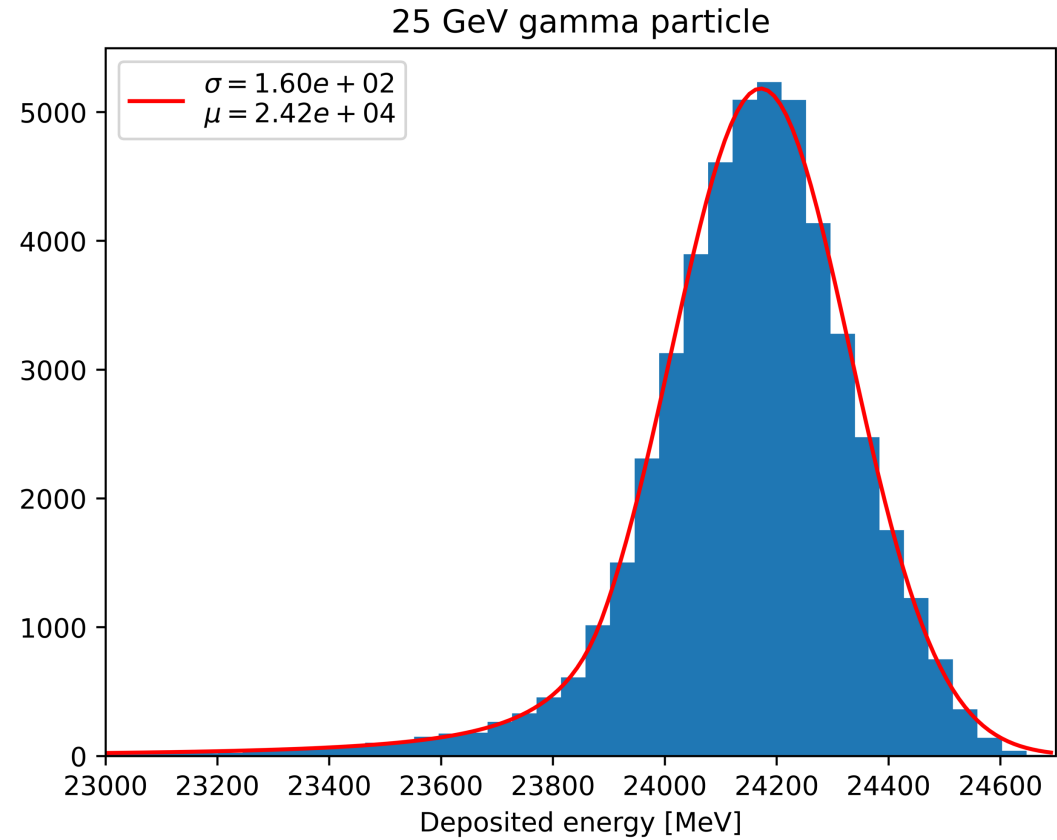
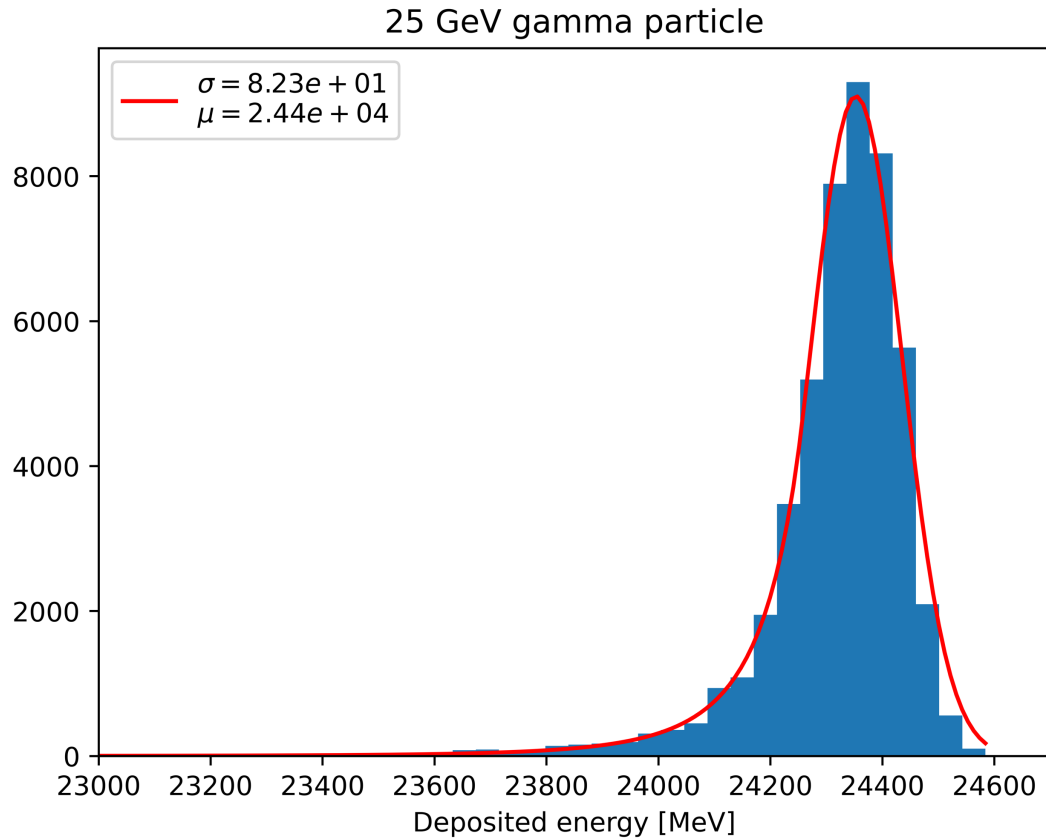


Deviation of the detected energy from mean value (%)



No uniformity simulated

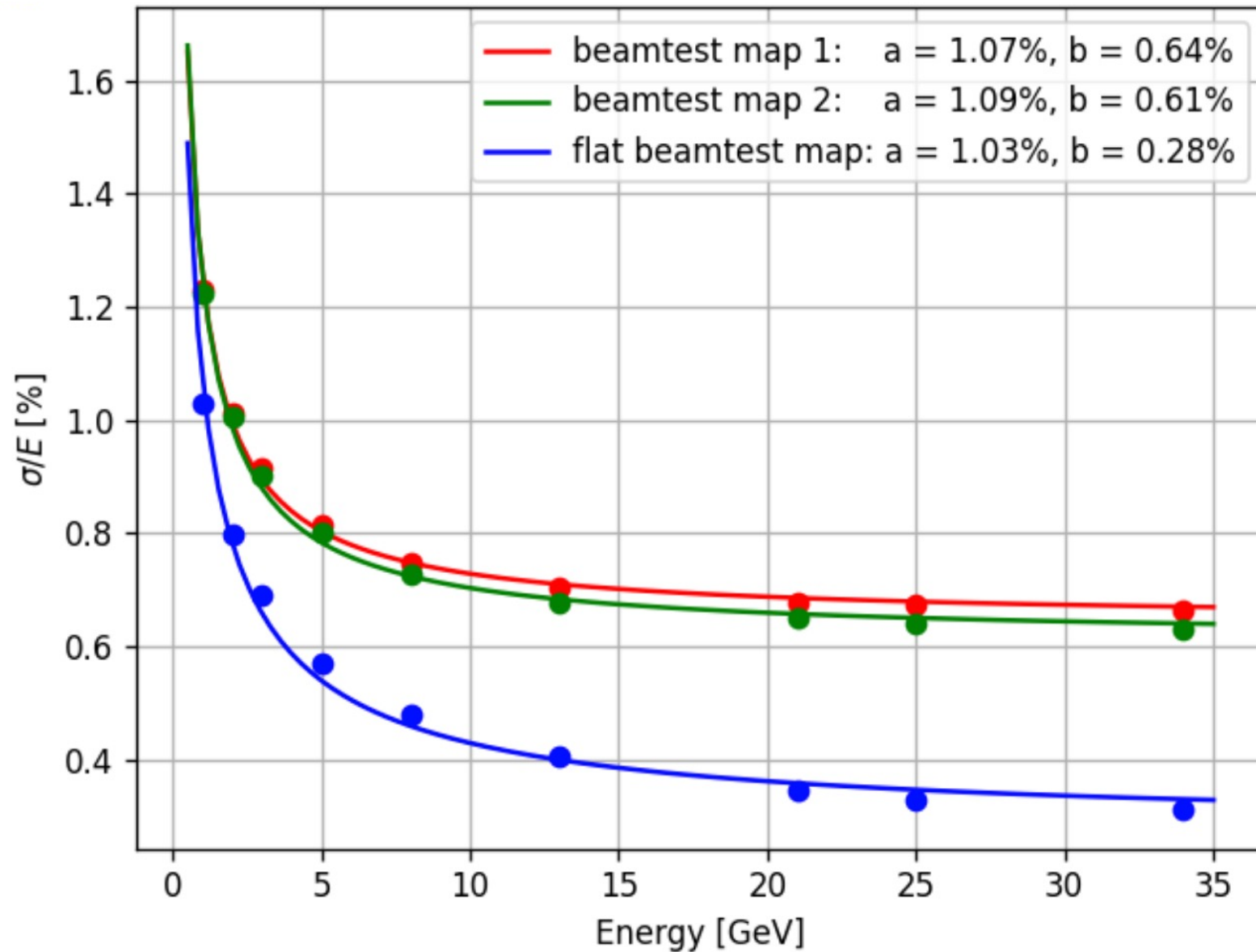
With map from the test beam



Constant term  $\sim 0.7\%$  (including the systematics from the pion model)

# Energy resolution

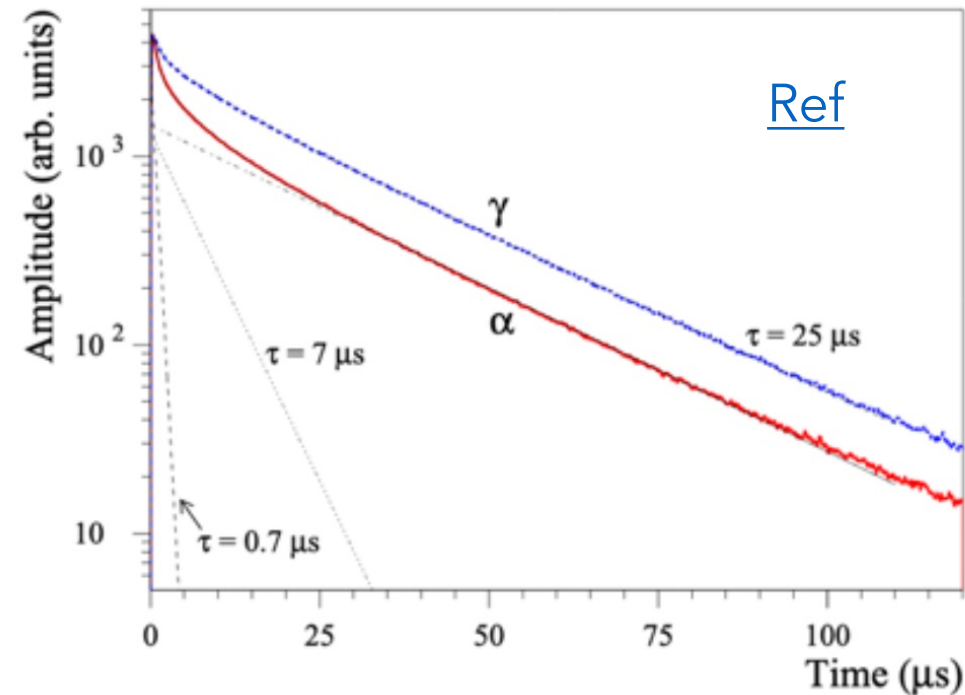
GRAiNITA internal



# A word about pulse shape discrimination

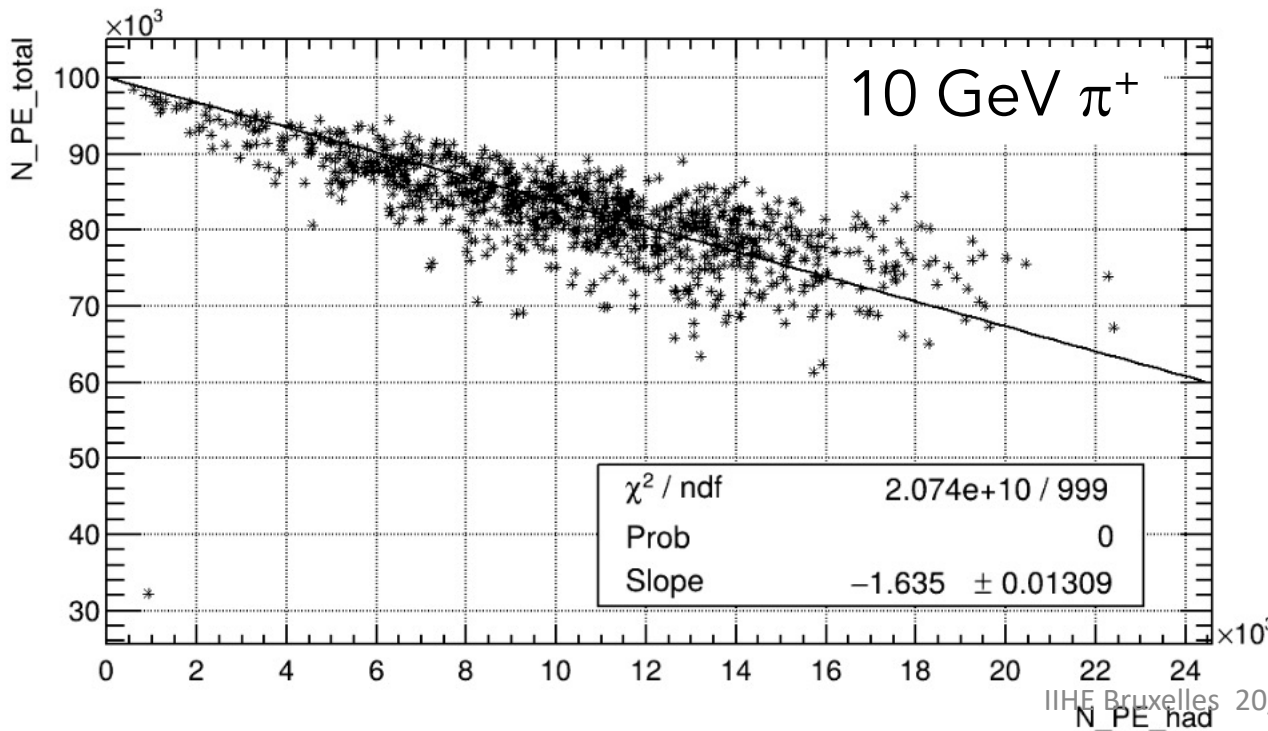
ZnWO<sub>4</sub>: clear difference between  $\gamma$  and  $\alpha$  ()

Type of irradiation	Decay constants, $\mu\text{s}$		
	$\tau_1$ ( $A_1$ )	$\tau_2$ ( $A_2$ )	$\tau_3$ ( $A_3$ )
$\gamma$ ray	0.7 (2%)	7.5 (9%)	25.9 (89%)
$\alpha$ particles	0.7 (4%)	5.6 (16%)	24.8 (80%)



Can it be used to separate electromagnetic and hadronic components in a hadron shower ? (as Cerenkov vs scintillation do).

- Data taken with protons at the ALTO accelerator (energy from 10 to 20 MeV)
- 4 sets of lifetime (electrons, low E protons, 'high' E proton,  $\alpha$ ), inputs to G4 optical model
- Demonstrated the ability to extract the electromagnetic fraction of the shower
- → possibility to correct and thus improvement in the hadronic energy resolution

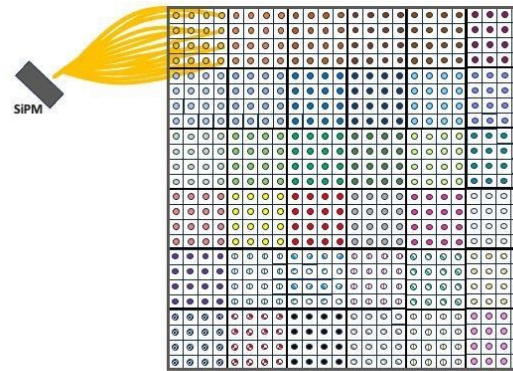
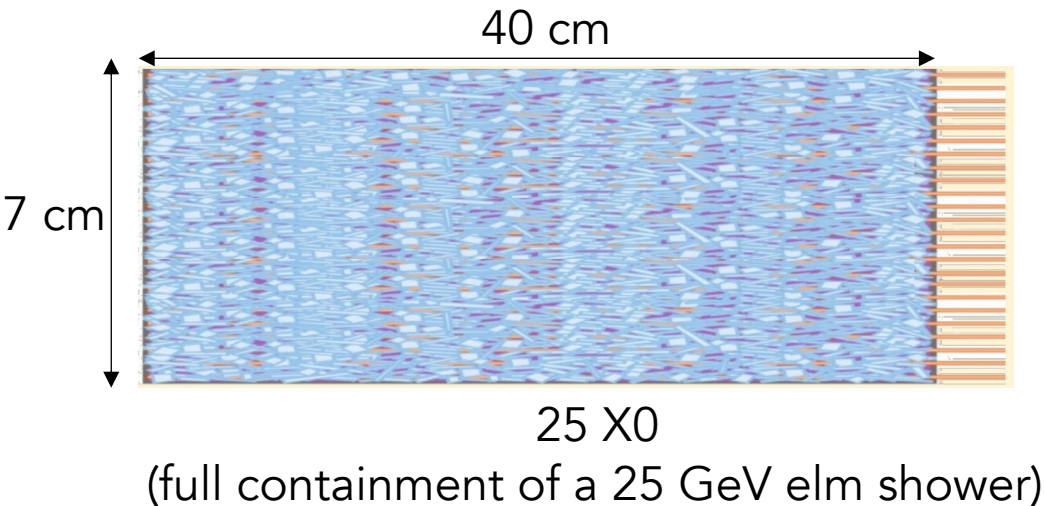


WIP

More precise measurements at the CYRCE cyclotron at the end of April.

# Towards a scale-one calorimeter module

Got a grant to build a full-size module demonstrator to assess all the components of the resolution

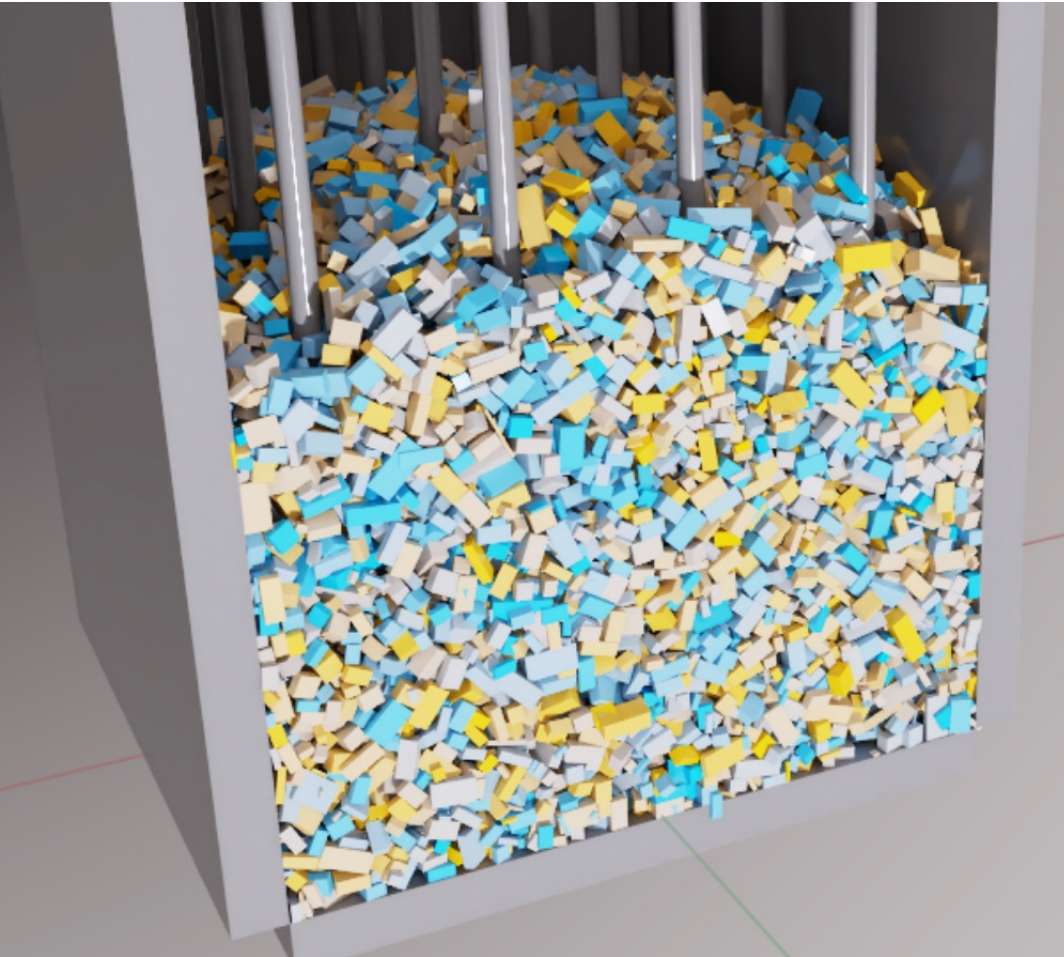


576 WLS fibres separated by 7mm  
(as in the small prototype) grouped  
in 16 fibres bundle  
coupled to 36 large-area SiPMs

Goal is to have a prototype built in 2028  
→ test with cosmics and beams

*Stay tuned*

Quantify with a realistic simulation the effect of the grains.



# GRAiNITA is young !

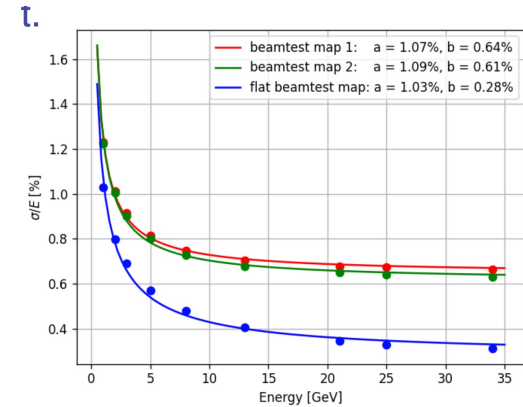
Feb 2020, just before COVID



- **End of 2019, beg of 2020:** first G4 simulations
- **Spring 2021:** First test bench measurements with salt & comparison with G4 simulations
- **2022:**
  - very first measurements with  $\text{ZnWO}_4$ , WLS identification
  - start a collaboration with LPC-Clermont (Pulse Shape Discrimination , cosmic test bench)
  - Funding from IN2P3 for a small prototype
- **2023:** building the 16-channels prototype & cosmics rays test
- **2024:** test of the 16-channels prototype at CERN on  $\mu/\pi$  test beam
- **2025:** ANR grant to build a scale-one module
- **2026:** start of the collaboration with CERN for the design of a calorimeter for FCCee

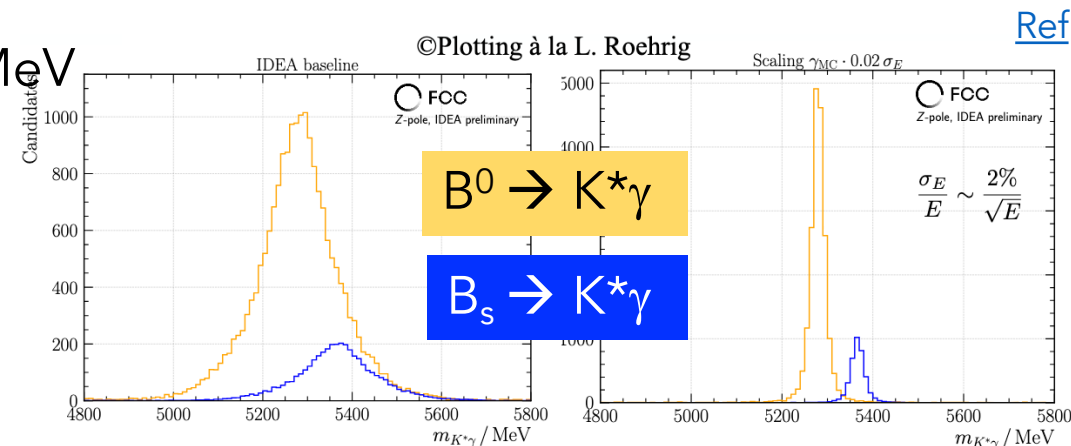
# Conclusion and future

- Analysis of the test beam data:
  - confirms  $N_{\text{PHE}}$  value
  - constant term from non-uniformity  $\sim 0.7\%$  (limitations due to the prototype size)
- Other (on-going) studies and tests:
  - heavy liquid
  - other crystals ( $\text{CaWO}_4$ ,  $\text{Ca/PbWO}_4$ , ...)
  - Mirror at the ends of the fibres
- Pulse Shape Discrimination:
  - data with electrons and p (at ALTO@IJCLab : 10-20 MeV proton beam) recorded
  - Inputs to Geant4 has started
- Collaboration with CERN for the design of a calorimeter for FCCee



$$\frac{\sigma_E}{E} \sim \frac{12\%}{\sqrt{E}}$$

$$\frac{\sigma_E}{E} \sim \frac{2\%}{\sqrt{E}}$$



# Backup slides

# ZnWO<sub>4</sub> or CaWO<sub>4</sub> ?

We also have an alternative candidate: CaWO<sub>4</sub>

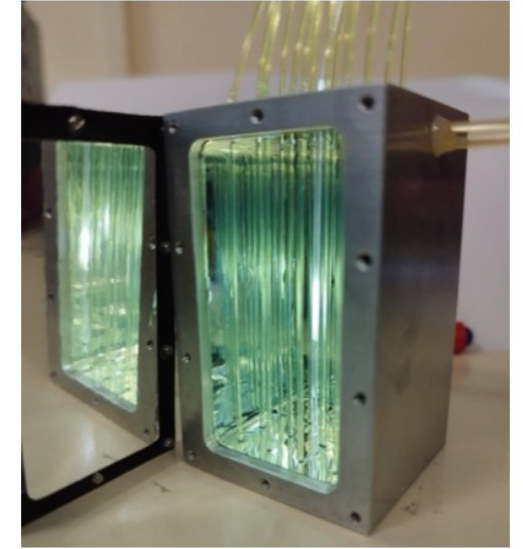
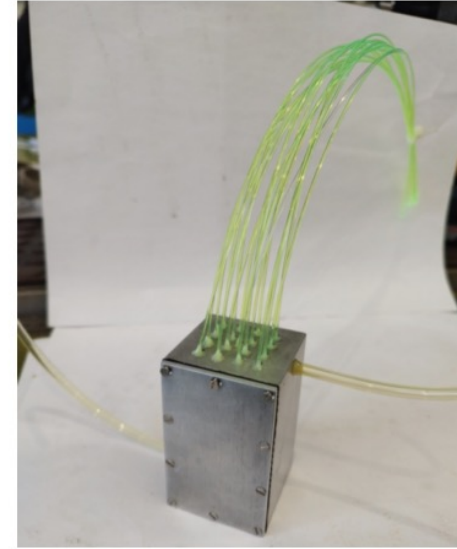
Same production technique (flux method)

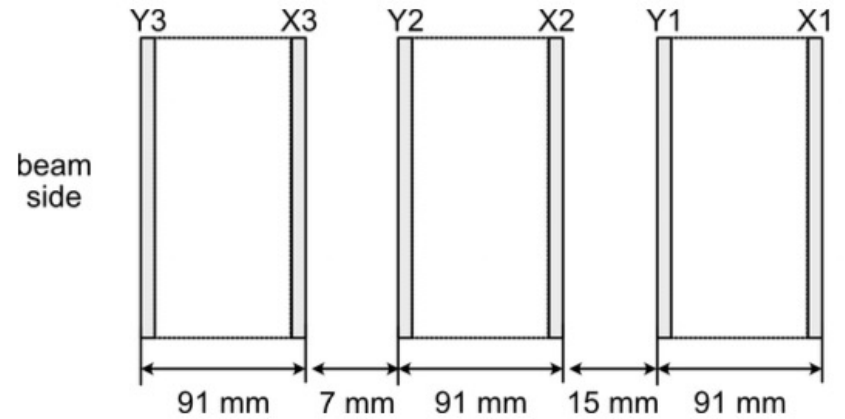
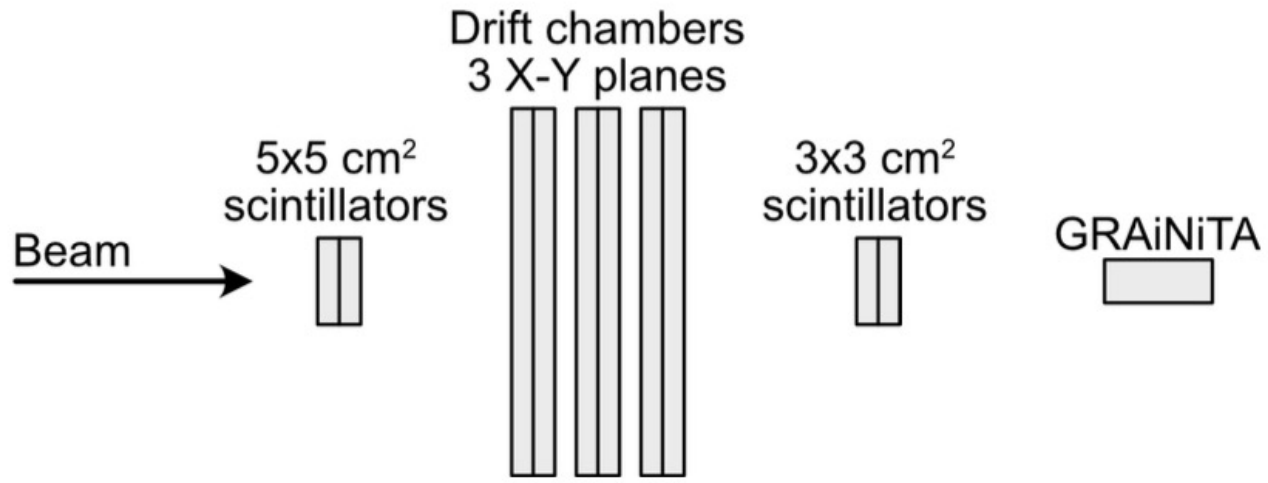
Faster signal : 12.5  $\mu$ s instead of 25  $\mu$ s

Expect a good light yield, shifted to green  $\rightarrow$  use Y11

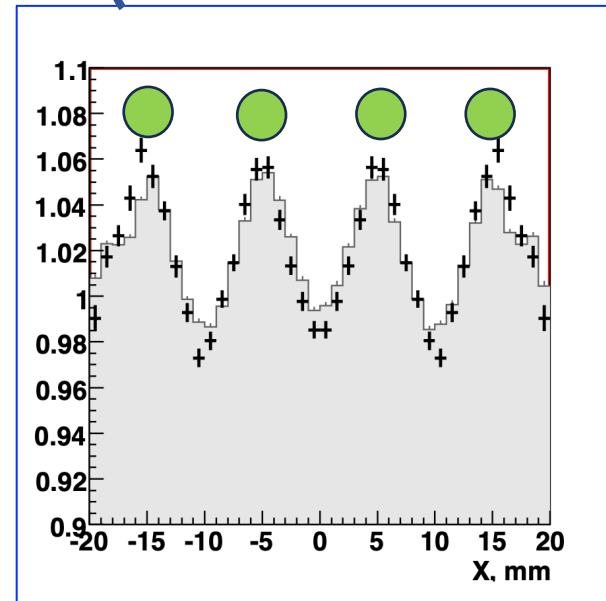
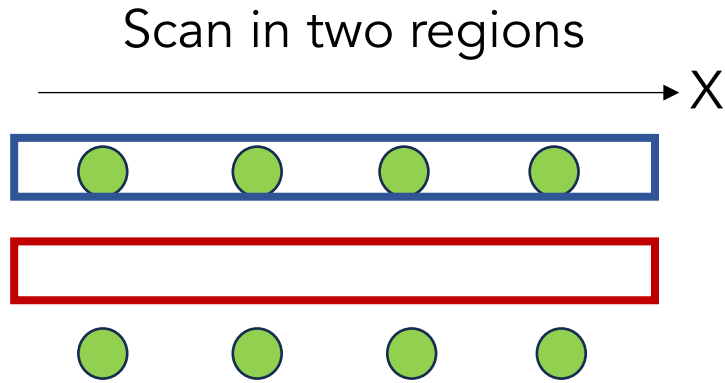
Measured number of photo-electrons  $\sim 1.7 \times$  ZnWO<sub>4</sub>  
using cosmics ...

...but density significantly lower (6.1 vs 7.6)

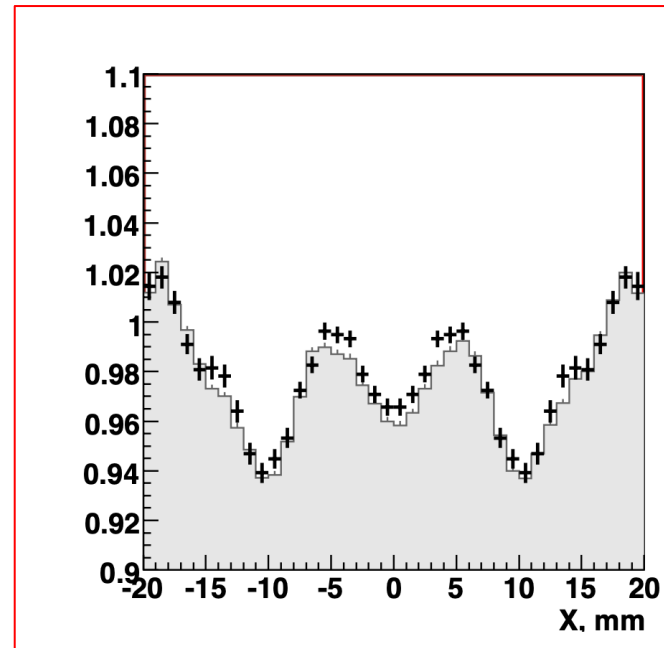




# Principle of the method (LHCb calorimeter)



Grey = simulation



~0.8% constant term for LHCb  
calorimeter