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Proof of concept of the GRAiNITA calorimeter

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Detectors for e+e- colliders

For future e+e- colliders: EM calorimeters based on sampling technique (CALICE, Dual Read-out Calorimeter)

- Good granularity at limited cost 😏
- Rather poor photon energy resolution 😒

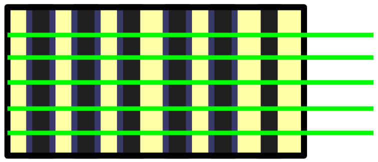
↪ at small energies: $\sigma E/E \sim 10\%/\mathrm{sqrt}(E)$

Proof of concept for a next-generation calorimeter with extremely fine sampling: GRAiNITA

→ For improved photon energy resolution while maintaining a good jet energy resolution using PSD

GRAiNITA concept

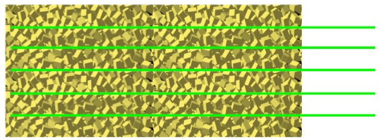
Shashlik calorimeter: alterning layers of scintillator and absorber



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

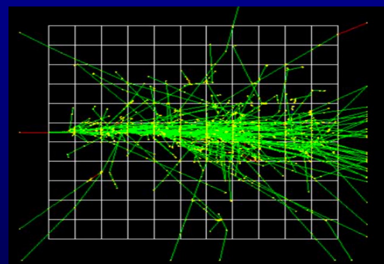
- High granularity
- Modest energy resolution

GRAiNITA: mix of scintillator grains soaked in a high-density liquid



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

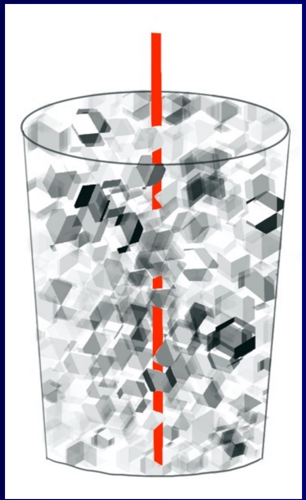
- High granularity
- Good energy resolution



GEANT4 simulation
$ZnWO_4$ 1mm cubes+ CH_2I_2
(random position)

Inspired by LiquidO technique for neutrino detector
(A. Cabrera et al. LiquidO Commun Phys 4, 273 (2021))

GRAiNITA R&D project



- High-Z and high-density grains
- High-density and high-refractive index liquid
- WLS fibers to collect the scintillation light

$ZnWO_4$
- LY= 10 000 ph/MeV
- Z_{eff}=61
- Density 7.62 g/cm^3
- n=2.1-2.3
- τ = 20 μs
- λ_{max}^{em} = 490 nm

$Bi_4Ge_3O_{12}$ (BGO)
- LY= 10 000 ph/MeV
- Z_{eff}=74
- Density 7.13 g/cm^3
- n=2.1
- τ = 300 ns
- λ_{max}^{em} = 480 nm

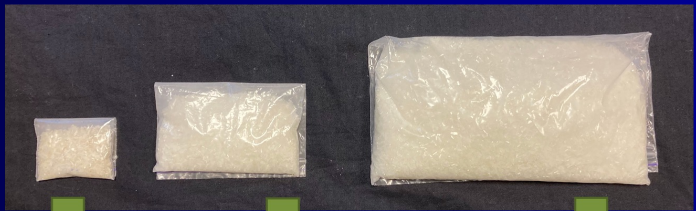
Development of two medium-size GRAiNITA prototypes, employing respectivement BGO and $ZnWO_4$ grains and equipped with 16 WLS fibres and SiPMs for the read-out of the scintillation light

Scintillator grains

Grown in High-melting Scintillation Materials Laboratory
ISMA (Kharkiv, Ukraine)

$ZnWO_4$ grains produced via the flux method

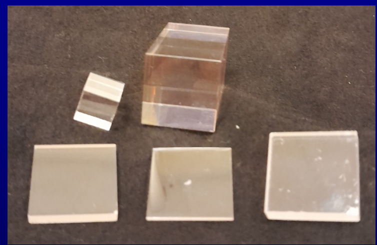
1st batch	2nd batch	3rd batch
40 g	170 g	1380 g
~1-3 mm	~1-2 mm	~1 mm



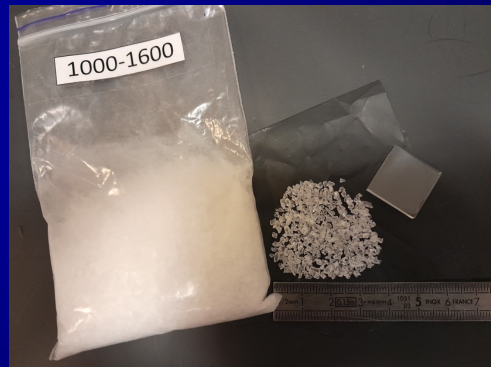


Prix crystal/grains = 2.5

$ZnWO_4$ single crystals



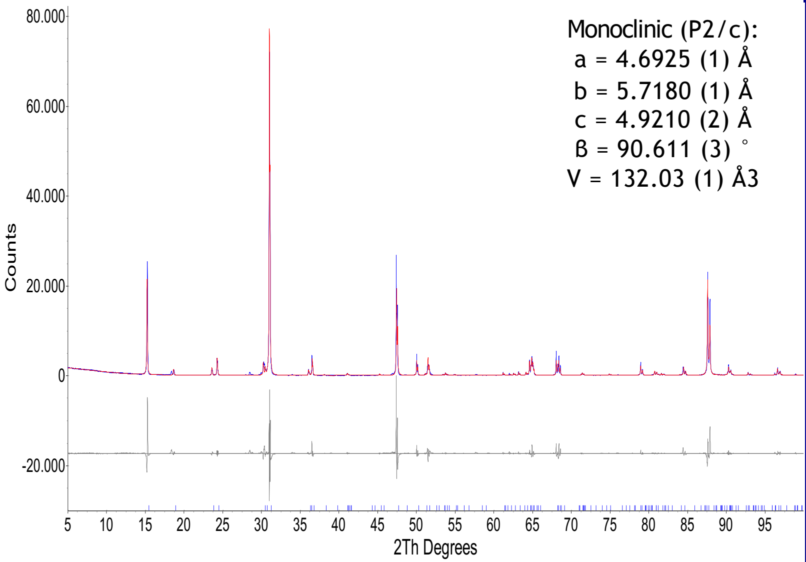
BGO single crystals and grains produced via mechanical crushing



Prix crystal/grains = 1.1

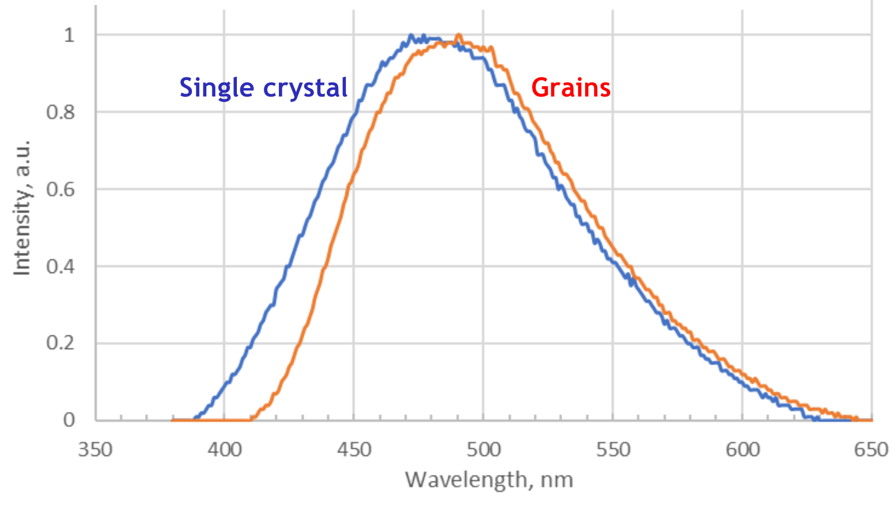
$ZnWO_4$ optical characterization @ ISMA

X-ray powder diffraction analysis



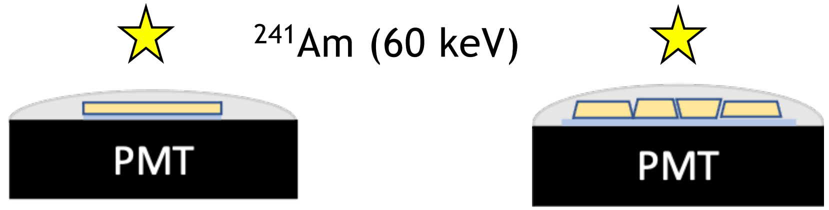
$ZnWO_4$ grains possess the monoclinic wolframite-phase structure as well as single crystals

X-ray excite luminesce spectra

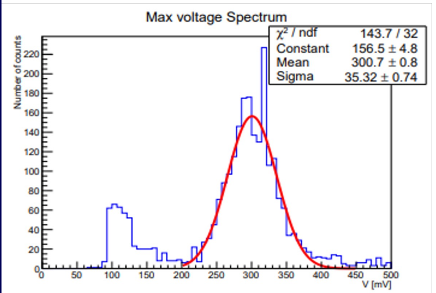


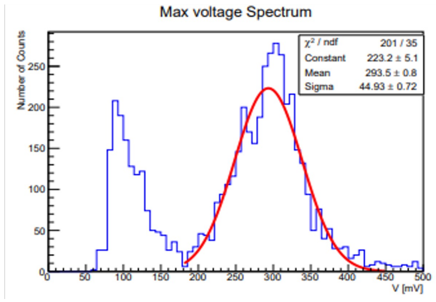
Similar luminescence spectra of $ZnWO_4$ grains and single crystal. The small shift of the luminescence maximum for grains is the result of their increased absorption/scattering of light.

$ZnWO_4$ grains scintillation properties



- High gain PMT Hamamastu R2083, silicon grease, teflon tape
- ^{241}Am (60keV, completely absorbed in one grain
- **RC = 100μs**

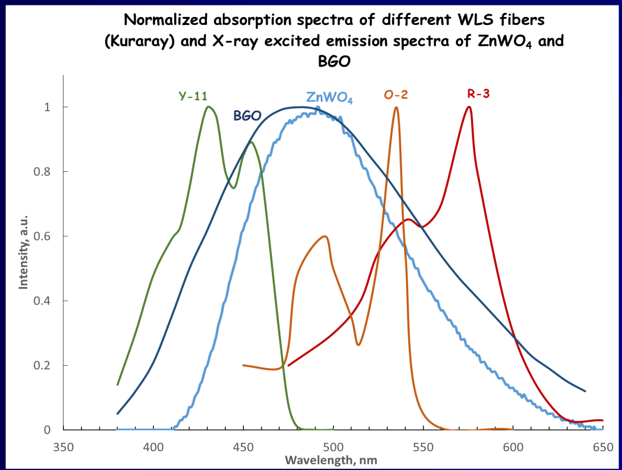


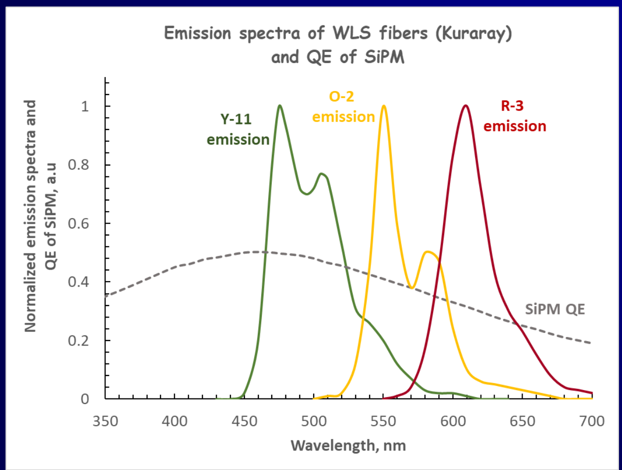


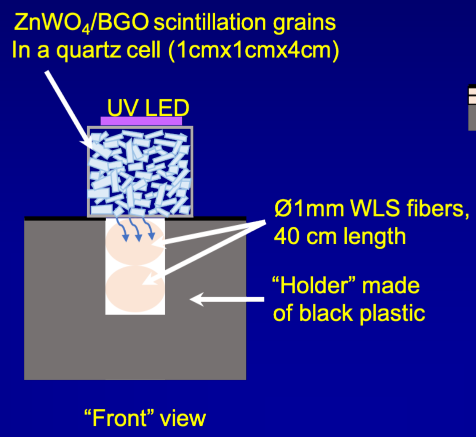
Sample	Mean, mV	Sigma, mV
Grains in the frame 1st batch (40 g)	260.7	59.24
Grains in the frame 2nd batch (170 g)	279.9	43.11
Grains in the frame 3rd batch (1380 g)	293.5	44.93
2x2x0.085 cm^3 plate	296.7 301.9	37.65 36.36
2x2x0.103 cm^3 plate	300.7 298.3	35.32 36.21
2x2x0.214 cm^3 plate	284.7 288.4	35.99 36.91
2x2x0.314 cm^3 plate	265.7 277.2	34.15 30.79
2x2x0.425 cm^3 plate	272.1 268.8	33.39 34.82
1x1x1 cm^3 cube	181.7	26.45

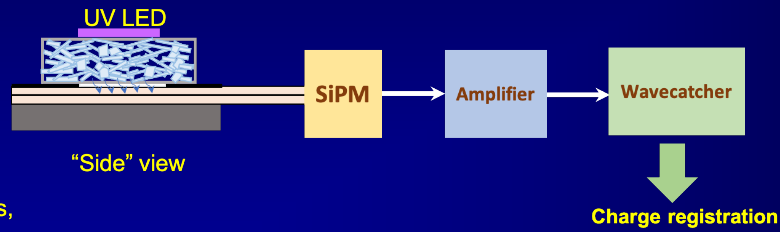
- Good reproducibility for the 2nd and 3rd batches of grains → stable technology for grain production
- The 2nd and 3rd batches of grains show a much smaller variance in the amplitude of the ^{241}Am peak → better homogeneity in the light yield

Selection of the proper WLS fiber





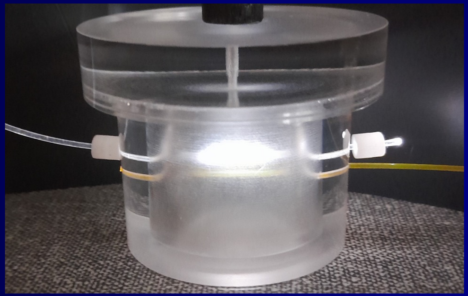




O2(200) and O2(300) are both excellent candidates for $ZnWO_4$ and BGO

WLS fiber	Estimated N_{phe}	Relative efficiency, %
$ZnWO_4$ grains ~9 mm in the quartz cell		
O-2(300)	302.555064	100
O-2(200)	313.631277	104
Y-11(200)	133.50304	44
R-3(100)	181.404855	60
$ZnWO_4$ grains ~5-6 mm in the quartz cell		
O-2(300)	294.391397	100
O-2(200)	304.384926	103
Y-11(200)	215.041589	73
BGO grains ~9 mm in the quartz cell		
O-2(300)	326.1381617	100
O-2(200)	339.2981441	104
Y-11(200)	318.4178521	98
BGO grains ~5-6 mm in the quartz cell		
O-2(300)	471.9886362	100
O-2(200)	549.6132684	116
Y-11(200)	671.9978981	142

Light propagation tests



- Small volume of grains
- Green LED (520nm, 20ns, 30Hz pulses)
- Clear fiber for the light injection (depolished for ~1cm)
- WLS fiber for the light collection (4 mm apart from the clear fiber), coupled to a SiPM
- Container wrapped with specular material (VM2000) and black tissue

	Charge [pC]	RMS [pC]	Fraction of captured light [%]	Propagation time [ns]
Empty	71.938	15.377	100	54.89
$ZnWO_4$	60.591	14.263	84	55.51
$ZnWO_4+H_2O$	67.455	14.938	94	54.91

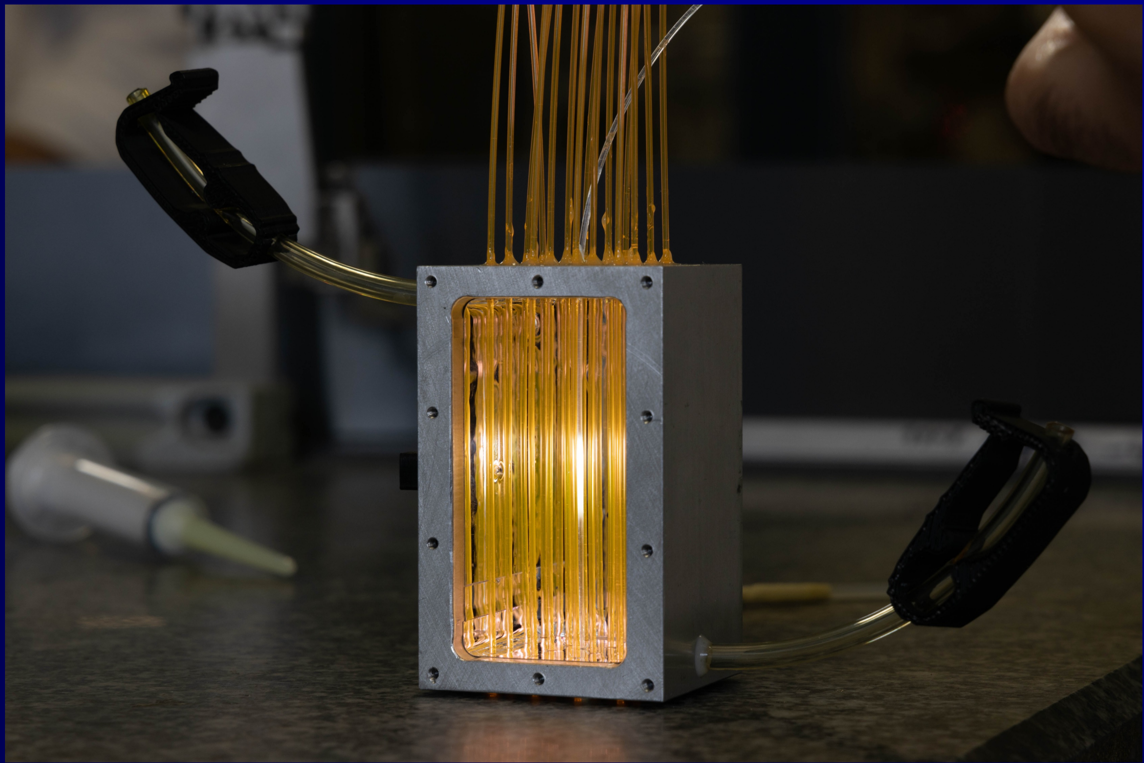
ΔT=0.62 ns
ΔS~12 cm!

✓ Good fraction of the light is captured in the configuration with grains

✓ Adding liquid ($n(H_2O)=1.33$) decreases the light trapping and increases the amount of the light captured by the WLS fiber (liquids with higher n are possible…)

GRAiNITA medium-size prototype

The « Troll »



GRAiNITA medium-size prototype

External dimensions: 4x4x7 cm^3
Internal dimensions: 2.8x2.8x5.5 cm^3

16 WLS fibers placed in square geometry, 7 mm apart to each other

1 clear fiber depolished for 1cm of length and connected to a green LED for the light injection

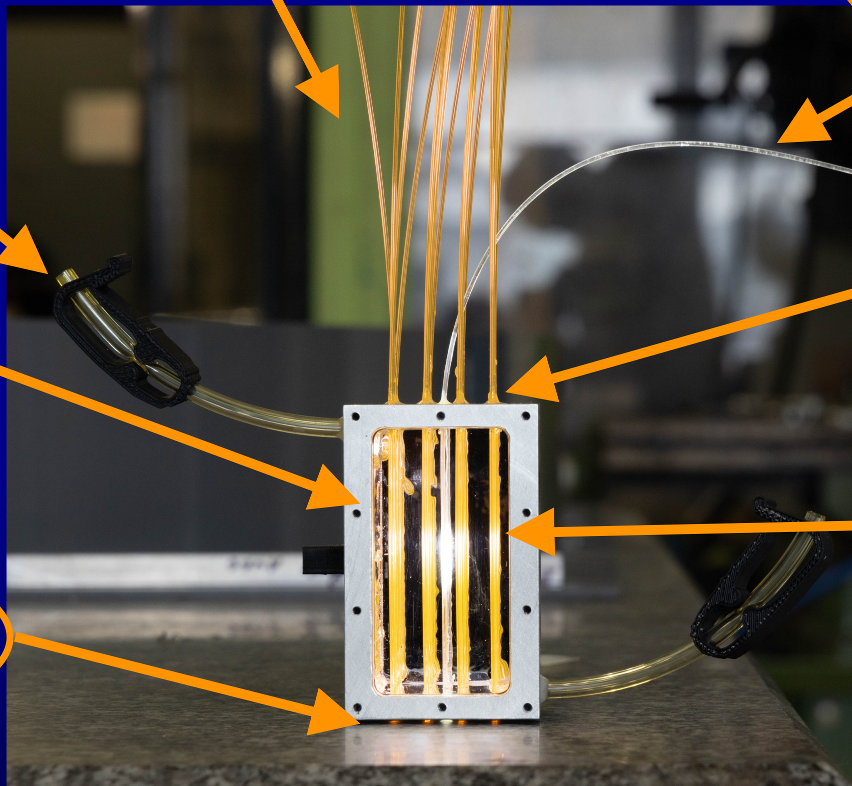
Two pipes to insert the liquid in the volume

Fibers glued to the container

Volume sealed after the grain insertions

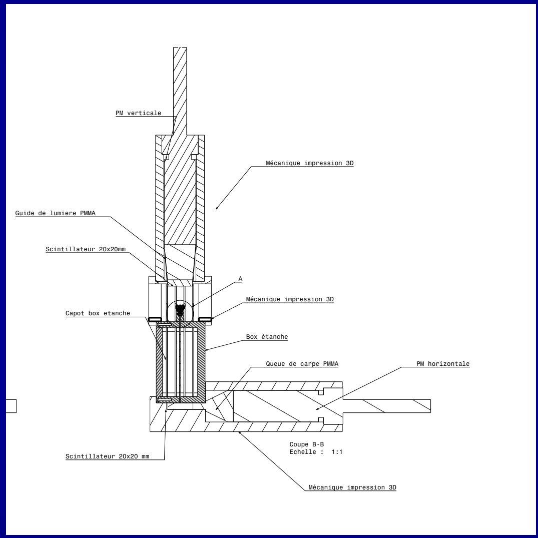
All the internal surfaces of the volume are covered with highly-reflective material (VM2000)

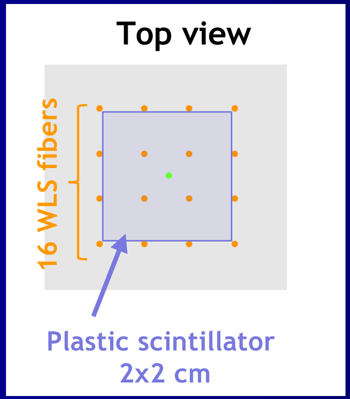
The free fiber ends, at the bottom of the volume not covered with VM2000



GRAiNITA cosmic rays test-bench

Two plastic scintillators coupled to PMTs
→ coincidence for cosmic rays triggering

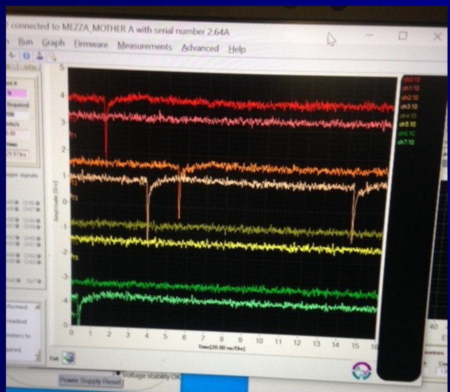


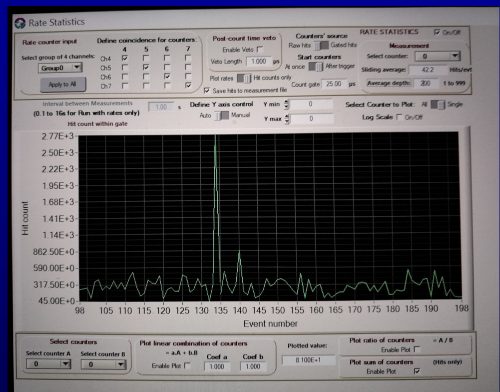


- Number of photoelectrons per MeV
- Study the response uniformity
- Cosmic rays → 1 event every 15 min (roughly 500 ev per run)
  → 40 MeV deposited

GRAiNITA cosmic rays test-bench

- 16 WLS fibers coupled to 16 SiPMs plugged on a PCB to amplify the signals
- Two 8-ch WaveCatchers for the signal readout
- Since $ZnWO_4$ has a long decay time τ≈20 μs, a special program has been implemented allowing to count the number of the single phe pulses on a time scale of 25 μs
- Before and after each run with cosmic rays, we acquire 1000 ev. illuminating the grain volume with the green LED

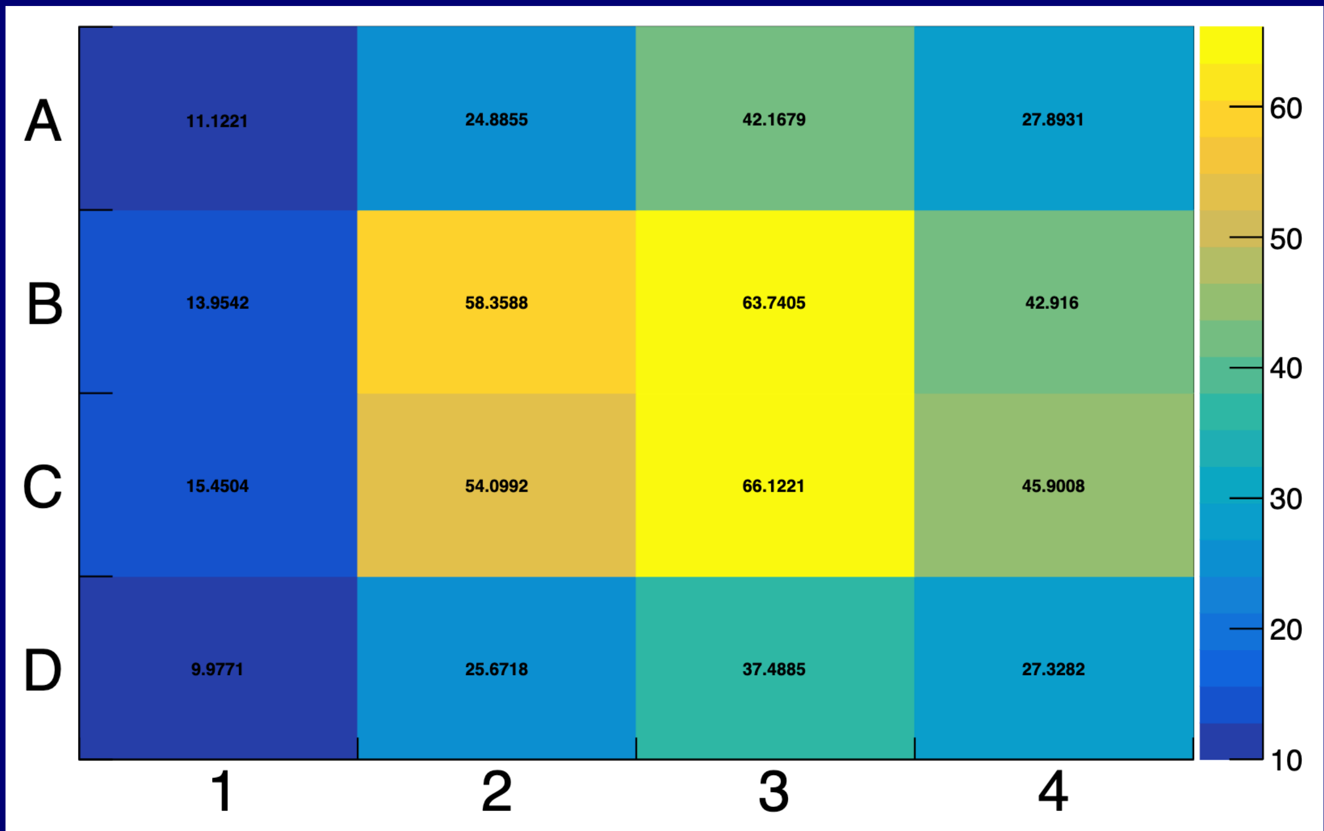




Volume filled with:

- Air
- $ZnWO_4$
- $ZnWO_4$ + water
- $ZnWO_4$ + ethylene glycol

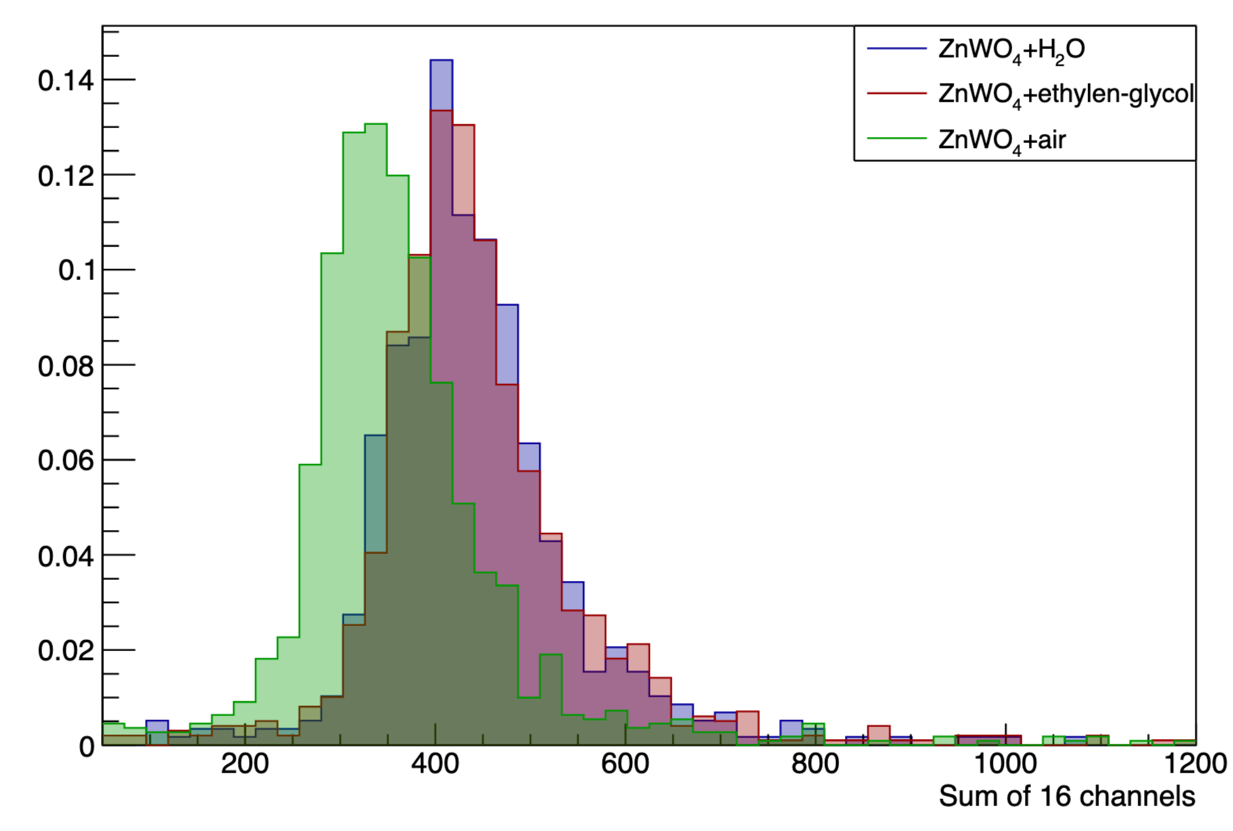
Light distribution



$ZnWO_4 + H_2O$

Light yield

Registered signals from cosmic rays



20-25% more light when we add liquide

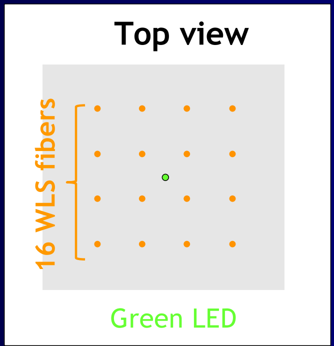
LY = O(400phe/40MeV)

10000 phe/GeV

➔ statistical contribution = 1% for 1 GeV high energy photon

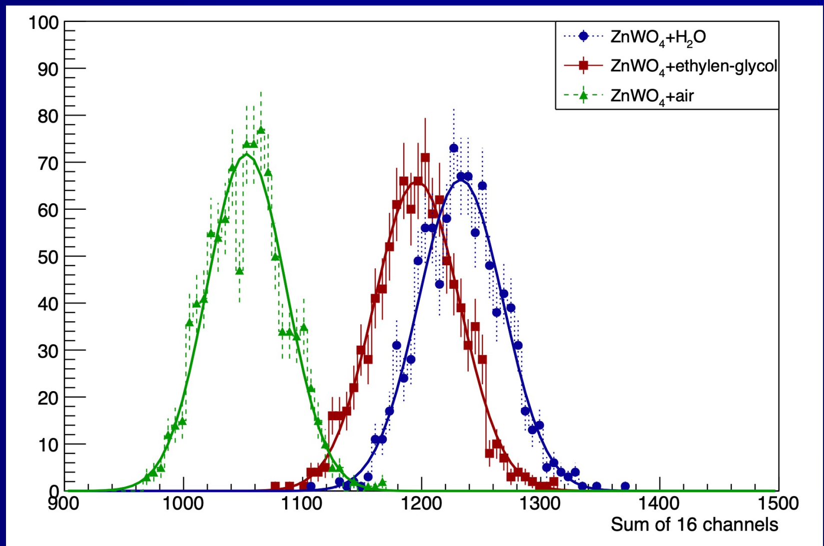
Can be improved as the fiber ends are not covered with reflector

Light confinement

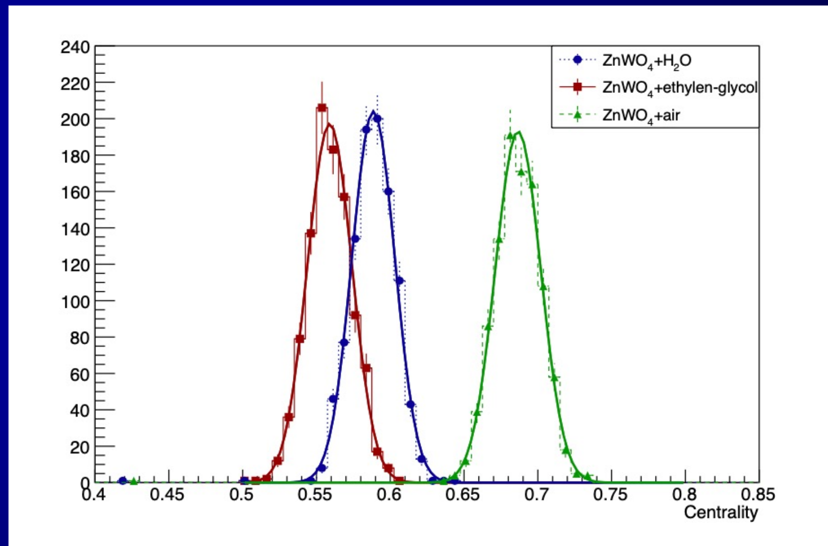


Green LED light injected in the center of the prototype

Sum of the signals in the 16 channels

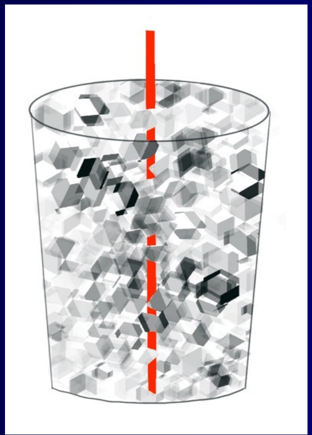


Ratio between the sum of the signal in the 4 central channels and the total



Using just grains in the volume the scintillation light is more confined, this confinement decreases adding liquid with increasing refractive index

Conclusions and Future work



★ We developed a medium size GRAiNITA prototype equipped with $ZnWO_4$ grains, 16 WLS O2(200) fibers and 16 SiPMs.

★ The light yield measured with cosmic rays indicates that a statistical contribution to the energy resolution of 1% at 1 GeV can be achieved

- Continue de tests with $ZnWO_4$ grains in different liquids
- Test the BGO-based GRAiNITA prototype
- Implement the use of 2 layers of TimePix3 in the cosmic rays test-bench in order to study the detector response versus the position and angle of the muon tracks
- Beam test with muons at CERN in 2024

Thank you for your attention!

After a shashlik lets
have a grainita!