GRAiNITA: fine sampling crystal grain calorimetry.

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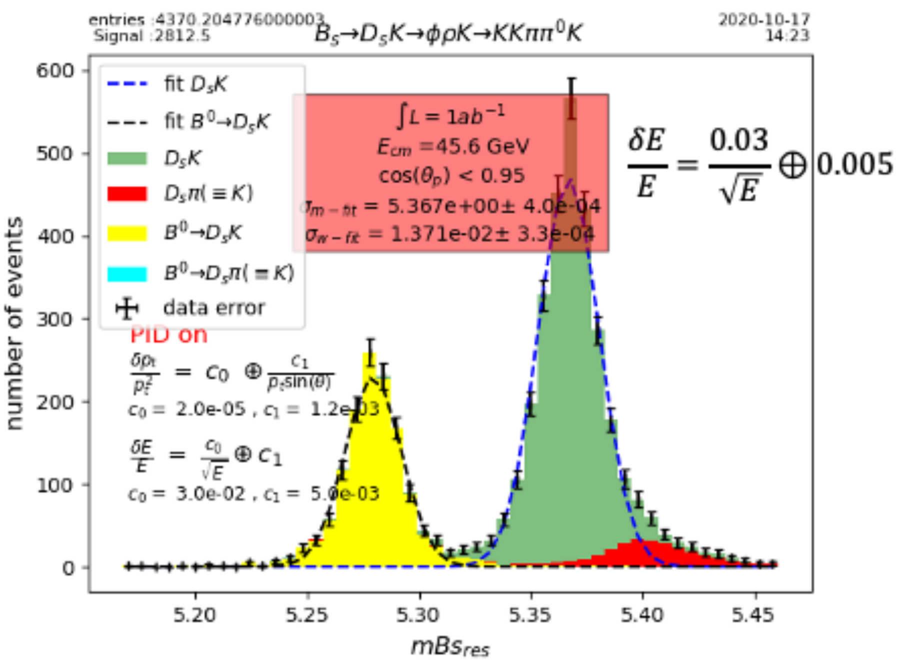
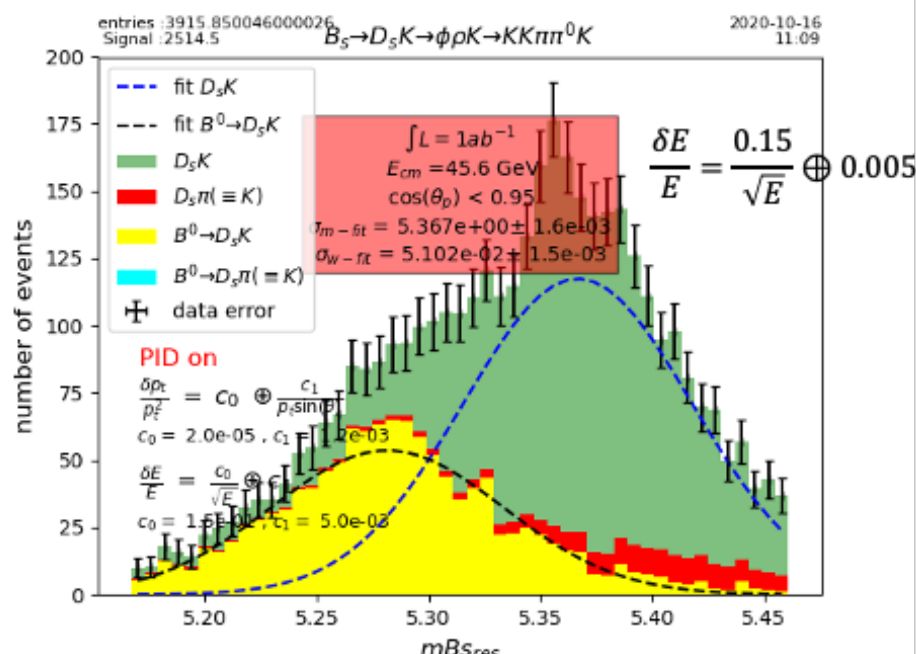
Outline

1. Motivations for FCC-ee and principle of GRAiNITA
2. The grains, the fibres, the liquid, the first prototype
3. Cosmic test bench results: the stochastic term
4. Next steps: the constant term
5. A word (one slide) on Pulse Shape Discrimination [if time allows]
6. Conclusions

1. Motivations for high E-resolution calorimetry

- The *CP*-violation and rare decays programs requires an excellent electromagnetic energy resolution for the reconstruction of *b*-flavoured hadron decays: radiative decays $b \rightarrow s(d)\gamma$ and final states with neutral pions.
- Two illustrations:
  - 1) From R. Aleksan: CKM angle γ (D_sK w/ $D_s \rightarrow \phi\rho\ (\rightarrow \pi\pi^0)$)





- Two illustrations:
  - 2) From radiative decays: separation of $b \to s\gamma$ and $b \to d\gamma$. *Academic exercise w/ $B^0 \to K^*\gamma$.*

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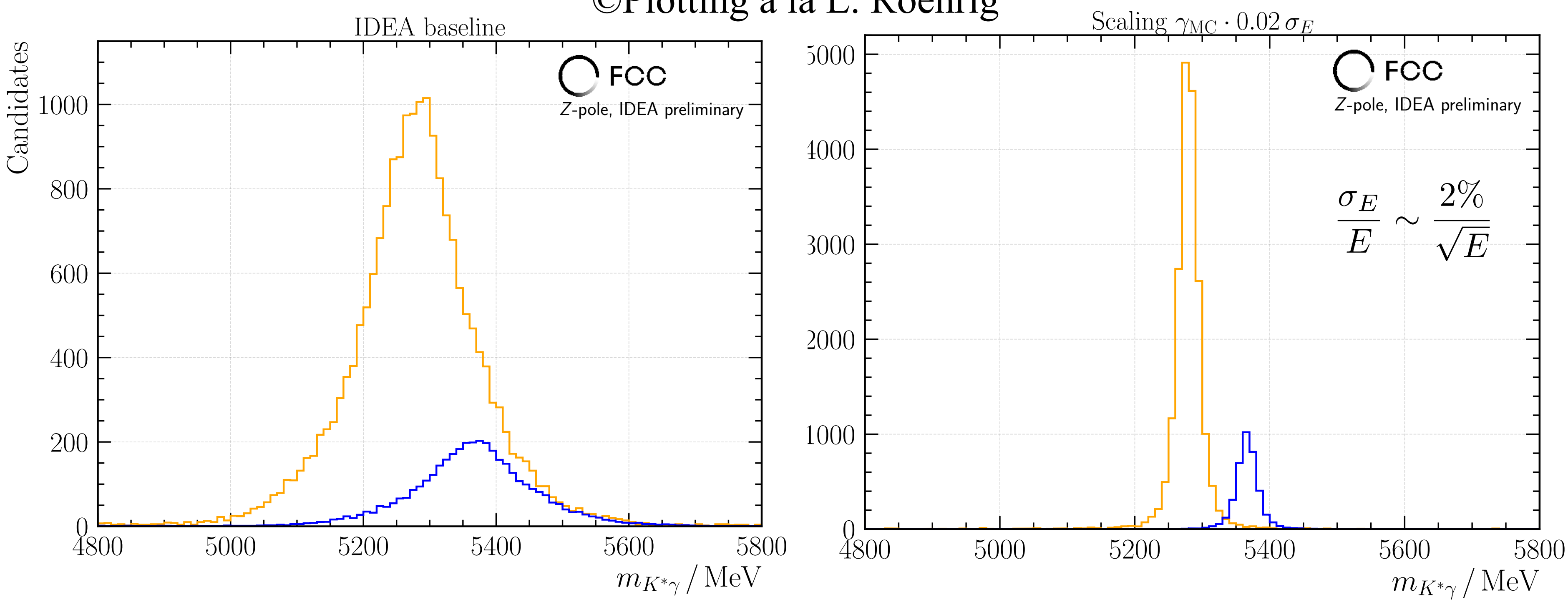
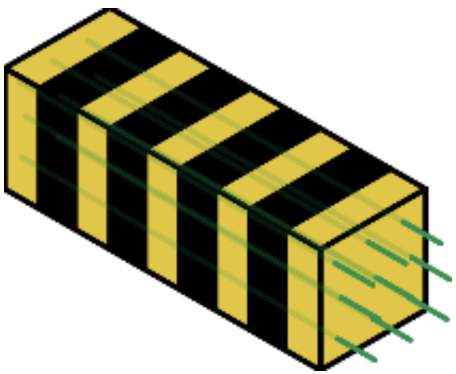


- There's a difference! addressing or not this Physics.

1. Principles of GRAiNITA

- Reaching an exquisite energy resolution while preserving high transverse granularity

Typical sampling calorimeter (e.g. Shashlik)

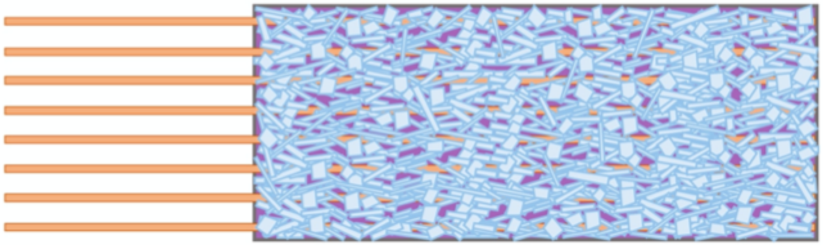


$$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}}$$

Crystal calorimeter

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

- Can we make the best of the two approaches ?
- Fine sampling
- Local containment of the scint.light (inspired by A. Cabrera et al. LiquidO Commun Phys 4, 273 (2021)



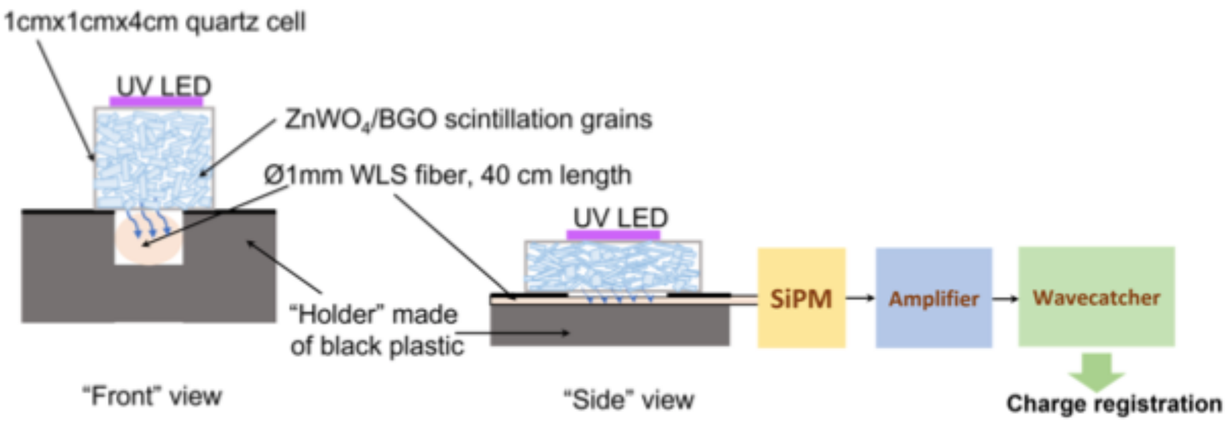
2. The grains, the fibres, the liquid

Table 1. Properties of interest for the GRAiNITA study of the the BGO and $ZnWO_4$ materials.

	BGO	$ZnWO_4$
Effective Z	74	61
Density (g/cm^3)	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

- Possible candidate for the grains: $ZnWO_4$
- ISMA: dedicated R&D to produce $ZnWO_4$ grains with the flux method (inexpensive method). Production technique mastered.
- Scintillation decay time ok for FCC-ee (~75 kHz at the *Z* pole).
- About 1 kg produced.
- Other options under consideration, *e.g.* BGO.

2. The grains, the fibres, the liquid



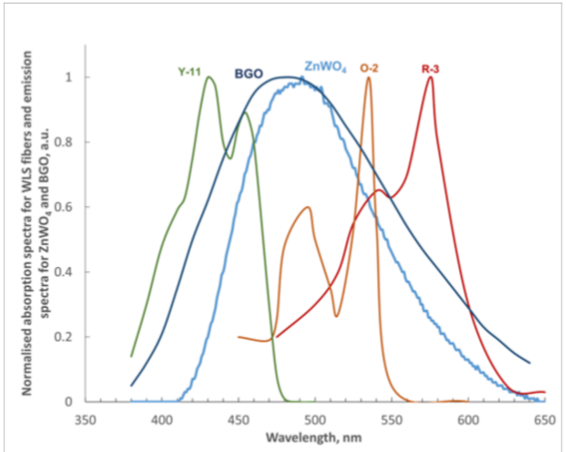


Figure 3. Absorption spectra for Y-11, O-2 and R-3 fibers from Kuraray [9] and emission spectra for BGO [10] and $ZnWO_4$ measured at ISMA for this study.

	Relative efficiency (%)	
Fiber type	$ZnWO_4$ grains	BGO grains
O-2(300)	100	100
O-2(200)	104	104
Y-11(200)	44	98
R-3(100)	60	n.a.

Table 2. Relative efficiencies measured for several grains and WLS fibers pairing.

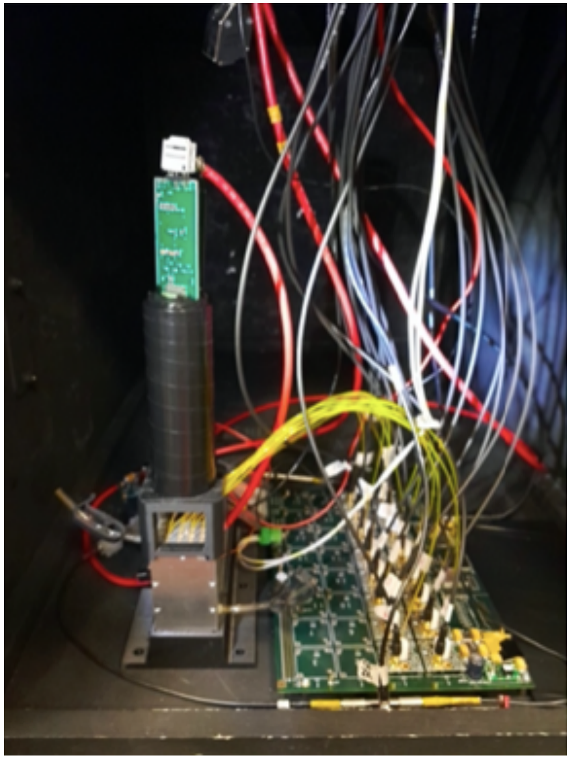
- Preferred choice is the O-2 fibre

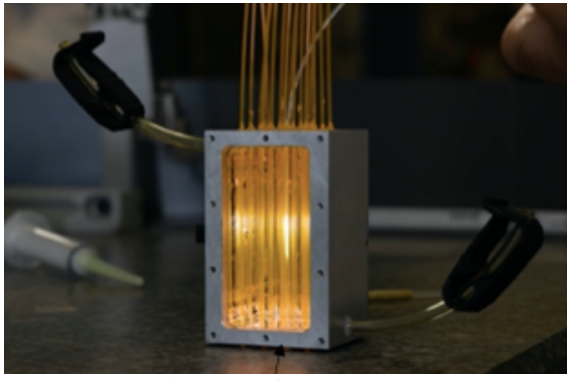
2. The grains, the fibres, the liquid

- Ideally, the calorimeter modules (volume b/w grains) shall be filled with a high-density transparent liquid (maximising the light output and e.m. shower containment).
- A good candidate is identified: Sodium metatungstate with a density of ~ 3 g/cm^3 and a refractive index of ~ 1.85
- Yet, it was impractical to run the preliminary qualifications (light propagation and signal yields) with it.
- Instead, these initial studies were run w/:
    - air
    - water
    - ethylene glycol

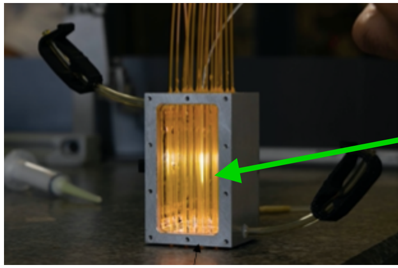
3. Cosmic test bench at Orsay: towards the stochastic term

- Active volume = 2.8 x 2.8 x 6 cm^3 (~200 g of $ZnWO_4$)
- Fibres spacing: 7 mm
- 16 fibres read-out by SiPM
- Possibility to repeat the study with BGO (ongoing)
- Cosmic rays triggering
- Note: no mirror at the end of the fibre
- Blue/Green LED injected in the middle to study propagation of light.





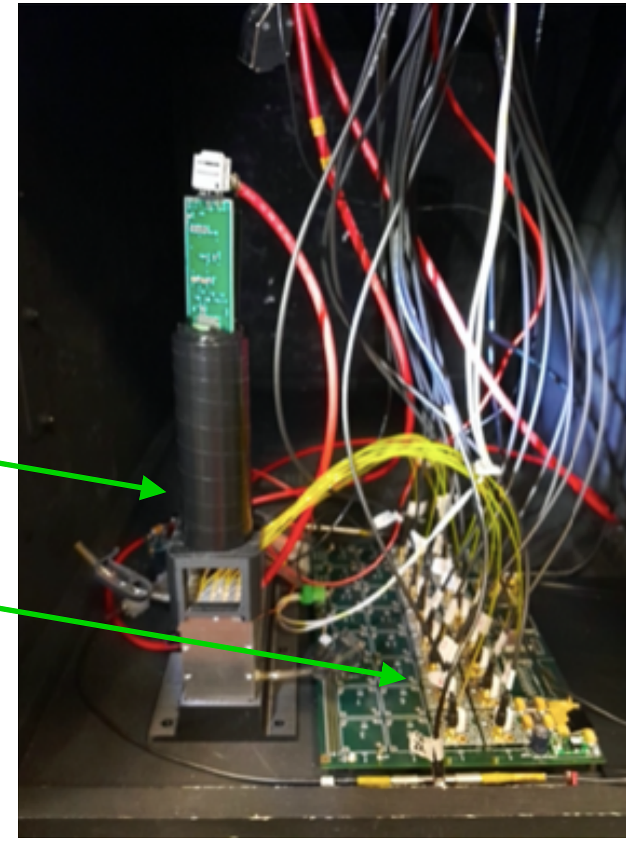
3. Cosmic test bench: the light propagation



Inject green light
in the middle
(depolished fibre)

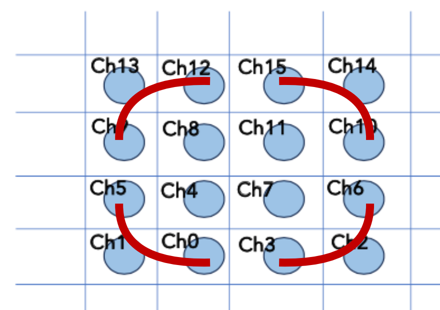
Sc. Coincidences

SiPM towards
Wavecatcher
(counting the p.e)



- Observables used in the following:

$$\text{Sum} = \sum_{i=1}^{i=16} \text{Ch}_\text{i} \qquad \text{Centrality} = \frac{\sum \text{Ch}_{4\text{center}}}{\text{Sum}}$$



Centrality is there to ensure we have the muon candidates fully contained. 8-channels read-out for this test bench.

3. Cosmic test bench: the light propagation / collection

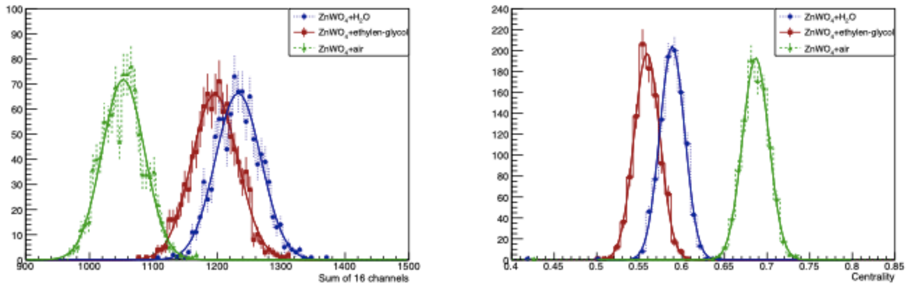


Figure 6. Comparison of the sum of the signals recorded on the 16-channels (left plot) and the ratio of the signal recorded in the 4 more central fibers to the sum of the signal in the 16 fibers (right plot). The three data-taking configurations are shown: $ZnWO_4$ grains only (green dashed line), with $ZnWO_4$ grains immersed in water (blue dotted line) and with $ZnWO_4$ grains immersed in ethylene-glycol (red full line) with a green LED illumination (see text for details).

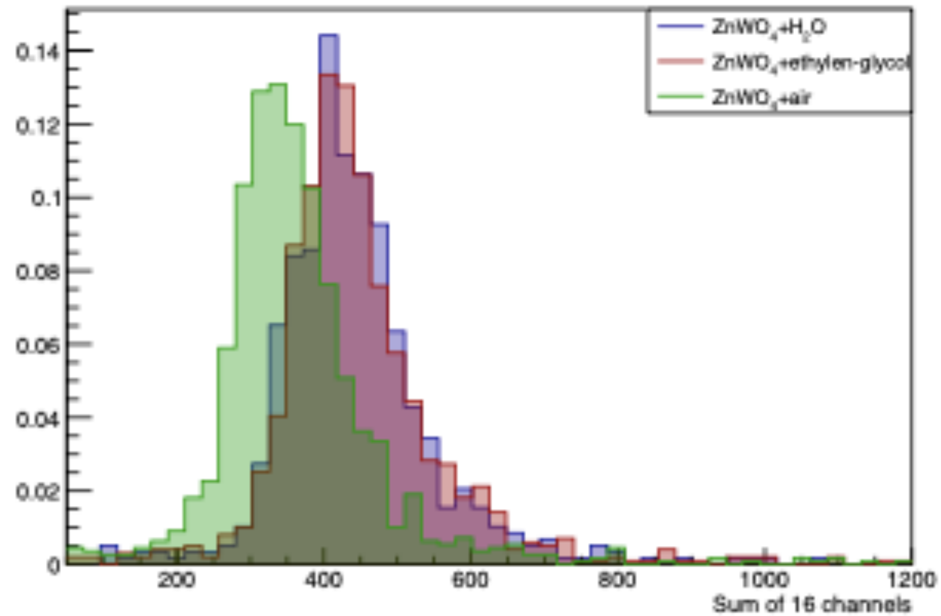
External medium	n($ZnWO_4$)/n(Medium)	Mean (Sum)	Mean (Centrality)
Air (n=1)	2.1	1052.9 ± 1.1	0.6866 ± 0.0005
Water (n=1.33)	1.58	1232.8 ± 1.1	0.5886 ± 0.0005
Ethylene-glycol (n=1.43)	1.47	1196.1 ± 1.1	0.5590 ± 0.0005

Table 3. Measured mean values for the signal obtained from the sum of the 16 channels and for the centrality for the three configurations considered with the green light illumination (see text for details).

- Lessons:
  - light emitted by the depolished fibre measured lower with liquids than in air.
  - better matching b/w the medium and the ZnWO4 indices —> smaller impact of the absorption in the grains
  - efficiency of the WLS fibers for the signal collection varies with the medium refractive index.

3. Cosmic test bench: towards the stochastic term

- The rate is 4 cosmic particles / hour
- Landau density probability function

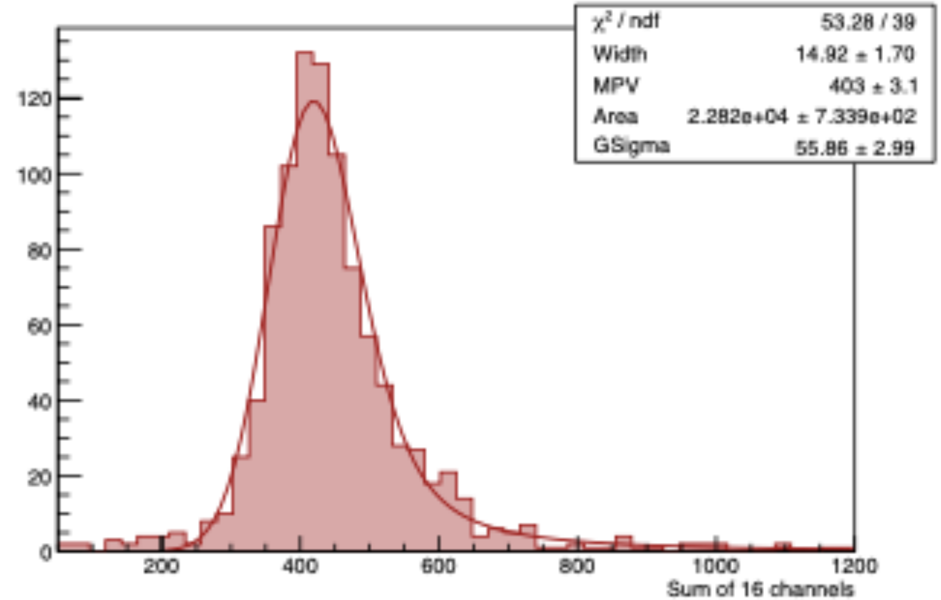


- Lessons:
  - the scintillation light yield gets larger with a better matching of the refractive indices grains / medium.
  - (Very-)high photon yield!!

3. Cosmic test bench: towards the stochastic term

- Average dE/dx for muons in the prototype: ~1.5 MeV / (g.cm^{-2})
- Density of the prototype is about half that of $ZnWO_4$ (~4 g.cm^{-3})
- The length of prototype seen by a muon is about 6 cm
- The energy deposited in the prototype by a cosmic muon is *O*(40 MeV)

- About 400 photo-electrons
- About 10 p.e. per MeV, *e.g.* 10000 p.e. per GeV. !!
- More to study: mirror ends on fibres, heavy liquid …



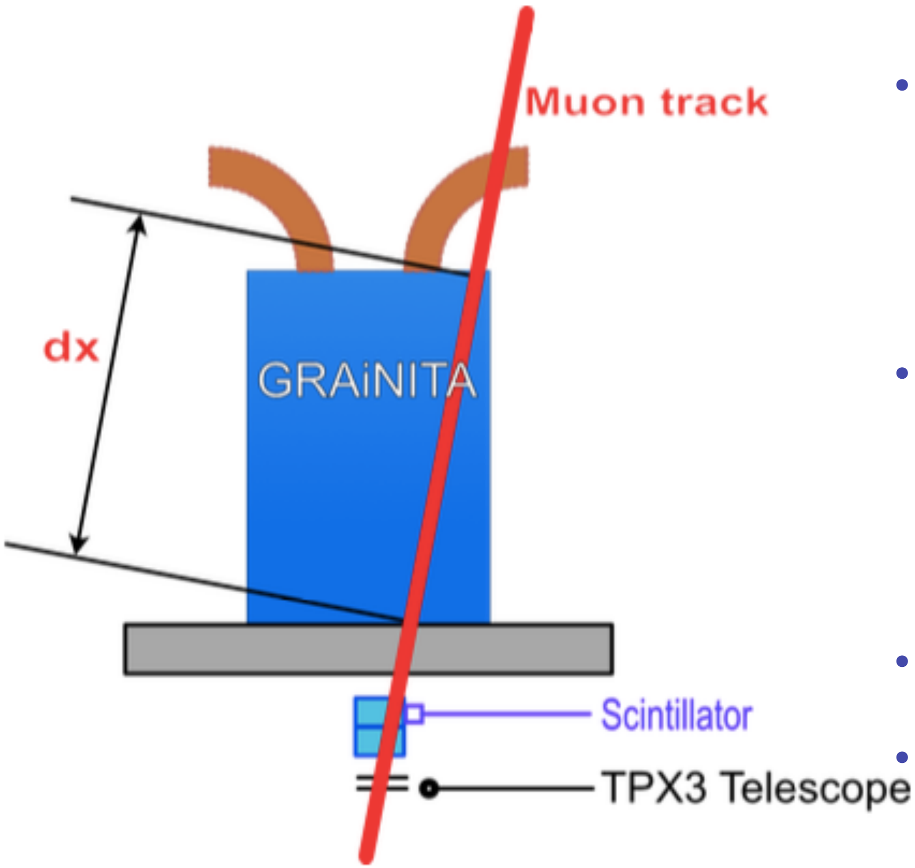
Should these numbers be confirmed, the

1% stochastic target is at reach !

4. Next step(s): the constant term

- Since an exquisite stochastic term is at reach, necessary for the proof of concept to assess the constant term.
- Non-uniformities and escaping energies are among the sources of constant term.
- The latter can be addressed first by simulation studies: an effort in coll. w/ TSNUK has started.
- The former can be determined in *e.g.* muon test beams. We're preparing a new test bench (@Clermont) to identify the trajectory of the muons and measure the responses as a function of their path in the detector.
- This information can in turn be used within the simulations to assess that component of the constant term.

4. Next step(s): the constant term



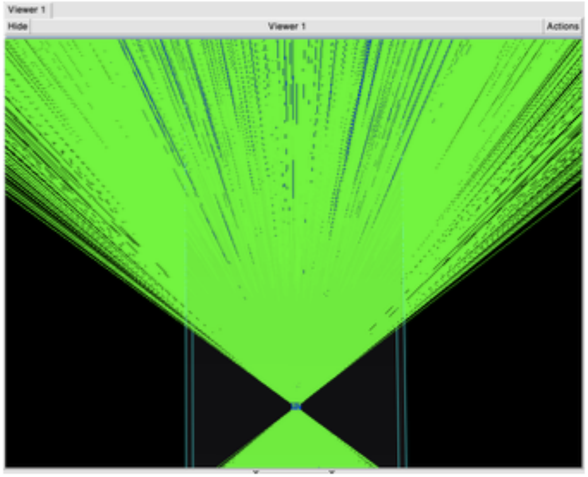
- Accurate (1mm at 15 cm) knowledge of the muon trajectory in the prototype thanks to a Si telescope prototype (TPX3)
- Aim at measuring the response of the GRAiNITA prototype as a function of the actual (length) passage of the particle, the distance to the fibre etc…
- Start to address the non-uniformities.
- To be used further in muon test beam.

4. Next step(s): the constant term

- TPX3 qualification:
  - comparison of the angular distribution of muons (use seven days sent by the manufacturer) with the canonical model

    $I(\theta)=I_0 \cos^{2.22}(\theta)\ \mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$

  - works fine: 0.73 muons /min observed while 0.74 / min were predicted



Event viewer

- Status of the bench:
  - commissioning

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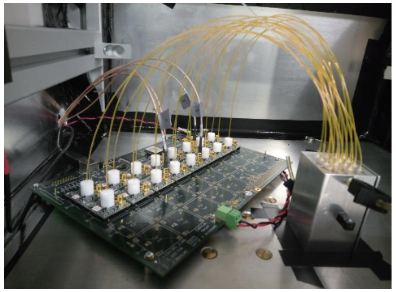
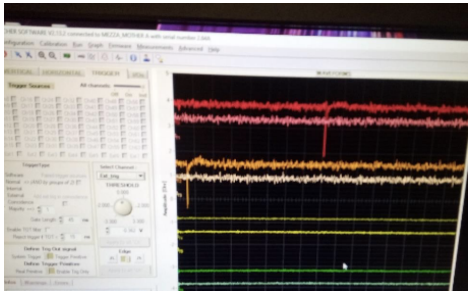
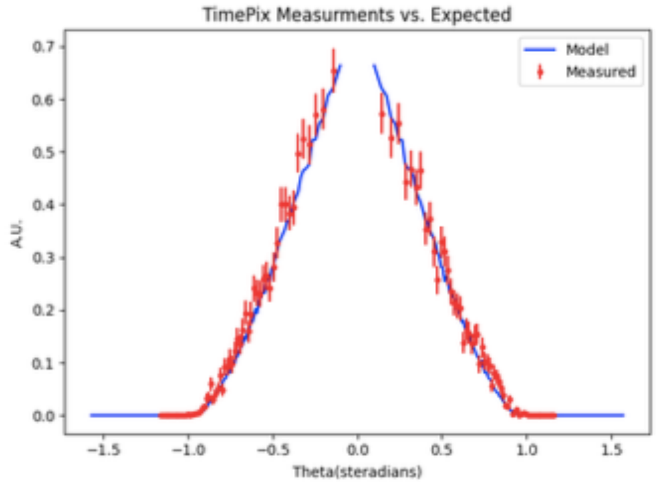


First photon seen yesterday!



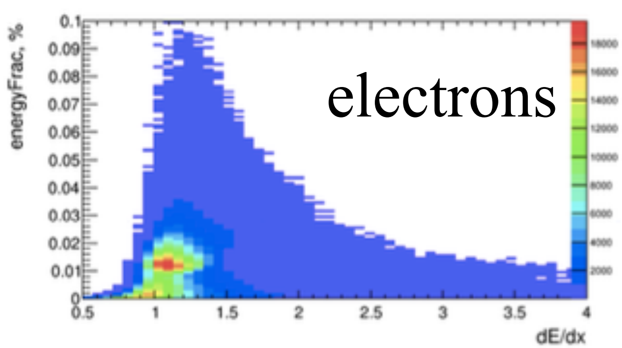


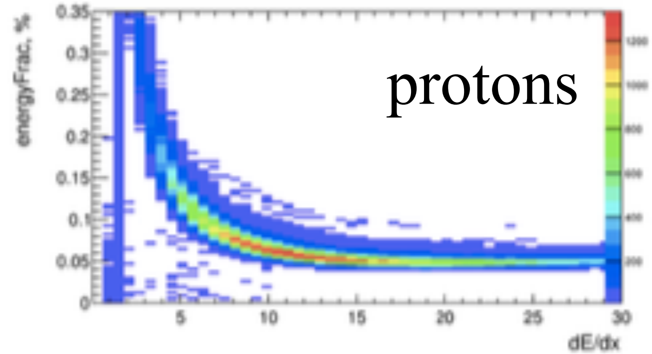
5. A slide on PSD

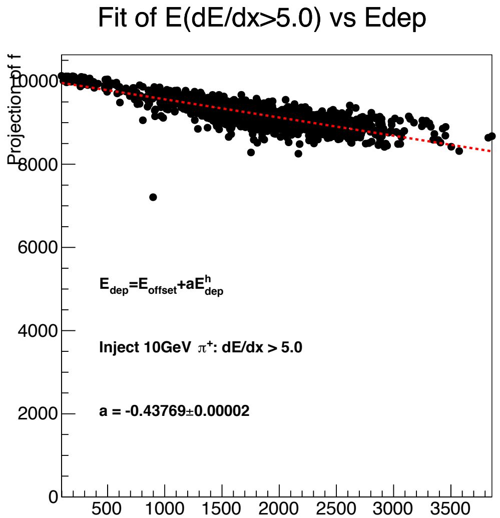
- Not a priori directly related to GRAiNITA but so far brought / studied by the same proponents.
- Pulse Shape Discrimination is a well-known technique used in nuclear and neutrino physics to separate hadronic and electromagnetic scintillation light.
- We think that it can be used in FCC context to separate electromagnetic and hadronic components in a hadron shower. Discrimination based on the scintillation signal development.
- First step consisted in checking the existence of a correlation, at simulation level, b/w the total energy deposit corresponding to an initial charged pion, to the energy deposited by low momenta high dE/dx protons in the cascade (but also deutons, alpha, nuclei).
- The simulation work has been recently restarted.
- See J. Lefrançois's talk (FCC Paris) for more details here

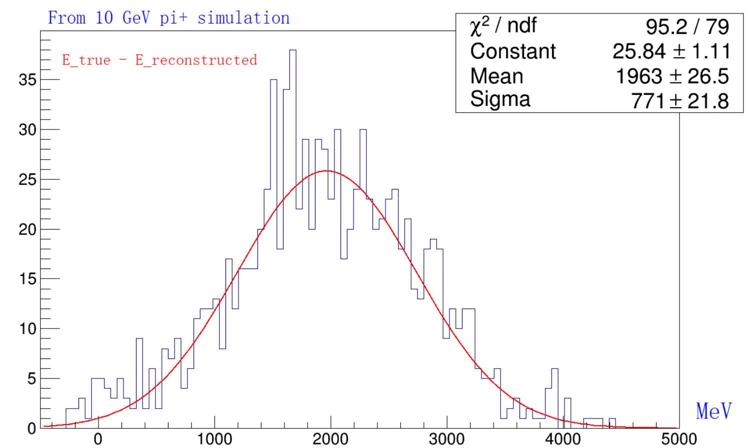
5. A slide (or two) on PSD

- Pulse Shape Discrimination









- Different ways to deposit the energy shall reflect into different scintillation times: next step is to educate an optical model (test beam at low energy first and simulations).

6. Conclusions

- A high energy-resolution electromagnetic calorimeter is desirable at FCC-ee, be it at least for *CP* violation studies and heavy flavoured radiative decays (beauty and charm)
- A prototype featuring $ZnWO_4$ grains, produced by ISMA, has been studied in a dedicated cosmic muons test bench at Orsay
- First results are promising: the stochastic term of 1% is at reach
- Described in the paper arXiv:2312.07365, submitted to JINST
- Next step of the study is to start assessing the constant term
- Pulse Shape Discrimination simulation studies have restarted
- A full-size module demonstrator (17 × 17 × 40 cm3) (25X0 in depth)