GRAiNITA: towards fine sampling crystal grain calorimetry.

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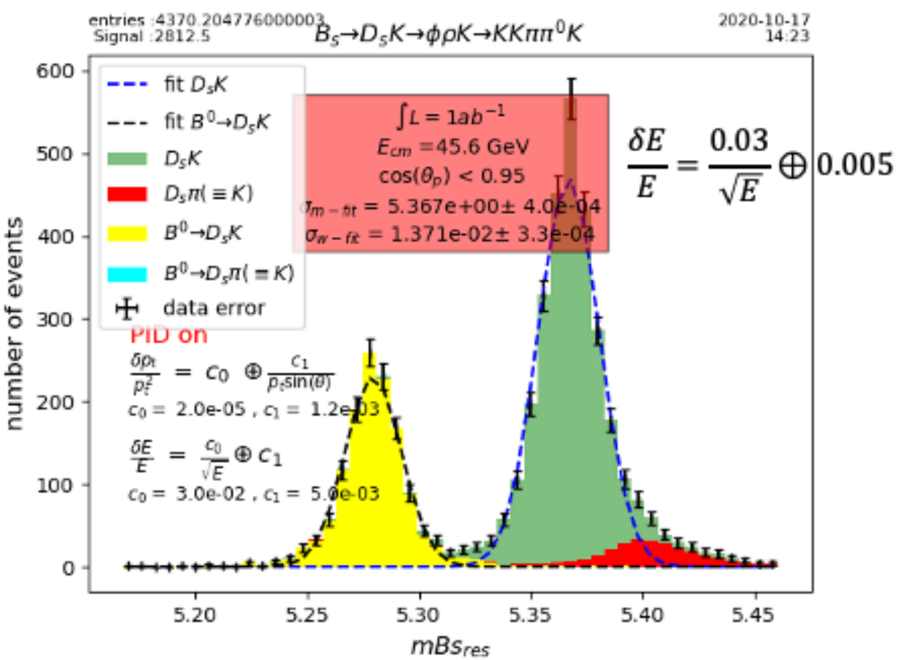
Four institutes: IJCLab, ISMA (Ukraine), LPCA, TSNUK (Ukraine).

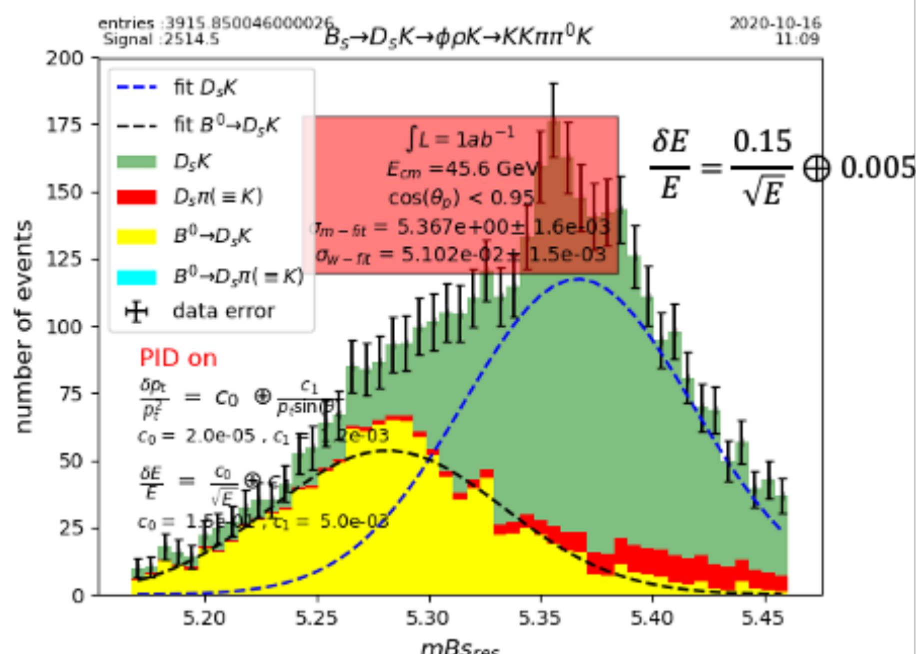
Outline

1. Motivations for FCC-ee and principle of GRAiNITA
2. The grains, the fibres, the liquid, the first proto(s)
3. Cosmic test bench results: the stochastic term
4. Test Beam: towards the constant term
5. Pulse Shape Discrimination
6. The ANR application
7. 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. Does not saturate the requirement: tau, charm, ALPs…
- Two illustrations:
  - 1) From R. Aleksan: CKM angle γ (D_sK w/ $D_s \rightarrow \phi\rho\ (\rightarrow \pi\pi^0)$)





1. Motivations for high *E*-resolution calorimetry

- 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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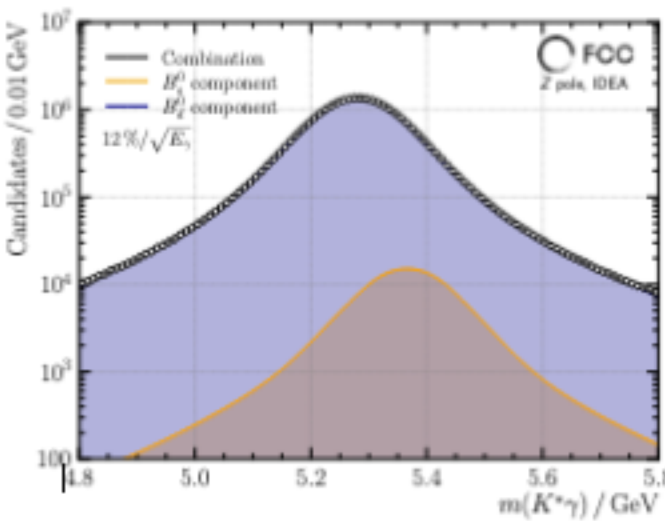
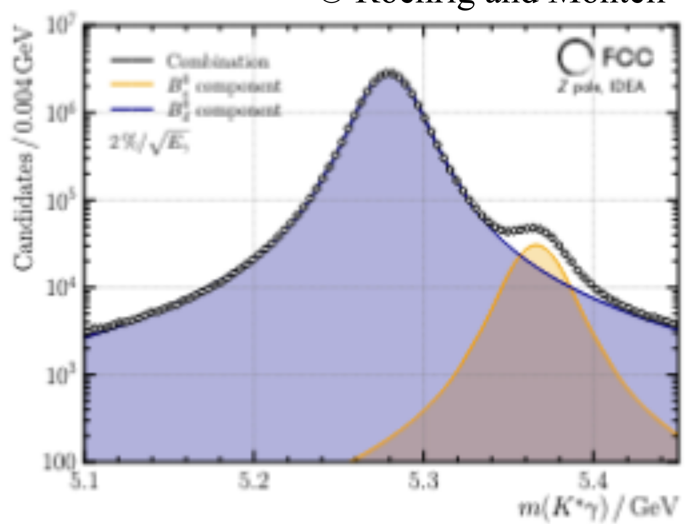
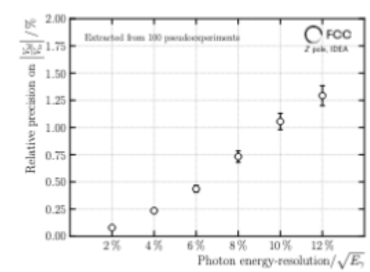


(a) IDEA baseline scenario with a dual-readout calorimeter, $r = 0.12$.



(b) High photon-energy resolution from crystals, $r = 0.02$.



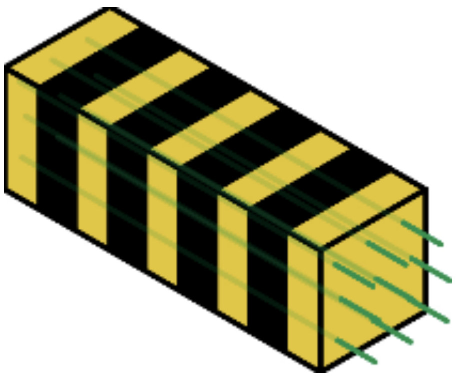
(b) The relative precision as a function of the energy resolution.

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

1. Principles of GRAiNITA

- The equation: reaching an exquisite cost-effective energy resolution while preserving high transverse granularity

Typical sampling calorimeter (e.g. Shashlik)

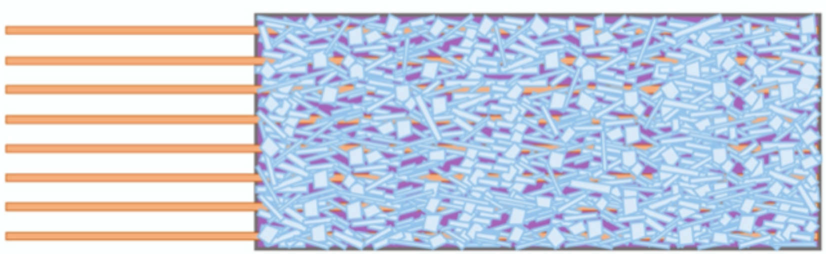


$$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}}$$

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)



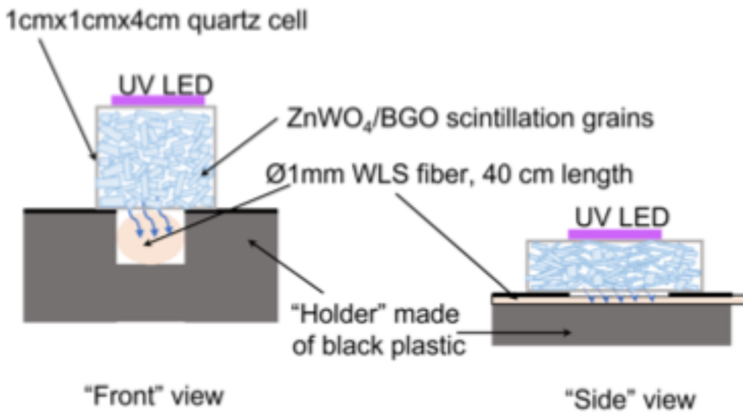
2. The grains, the fibres, the liquid

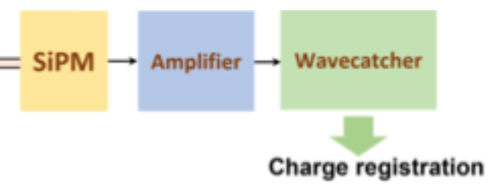
Table 1. Properties of interest for the GRAiNITA study of the the BGO and $ZnWO_4$ materials.

	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 (cost effective). Production technique mastered.
- Scintillation decay time ok for FCC-ee (~50 kHz at the Z pole).
- About 1 kg produced.
- Other options under consideration, *e.g.* CaWO4 (flux method), BGO.

2. The grains, the fibres, the liquid





	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.

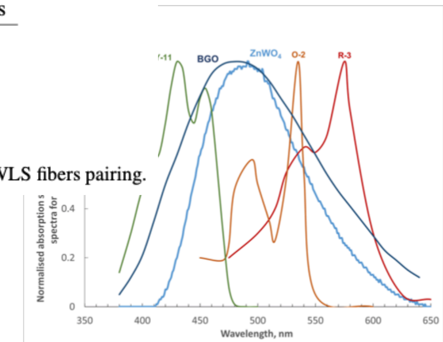
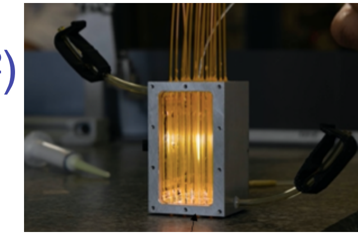


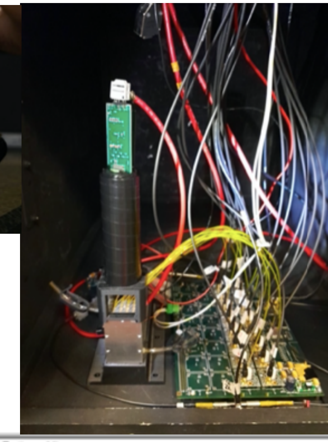
Figure 3. Absorption spectra for Y-11, O-2 and R-3 fibers from Kuraray [9] and emission spectra for BGO [10] and $ZnWO_4$ measured at ISMA for this study.

- Preferred choice is to-date the O-2 fibre
- 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

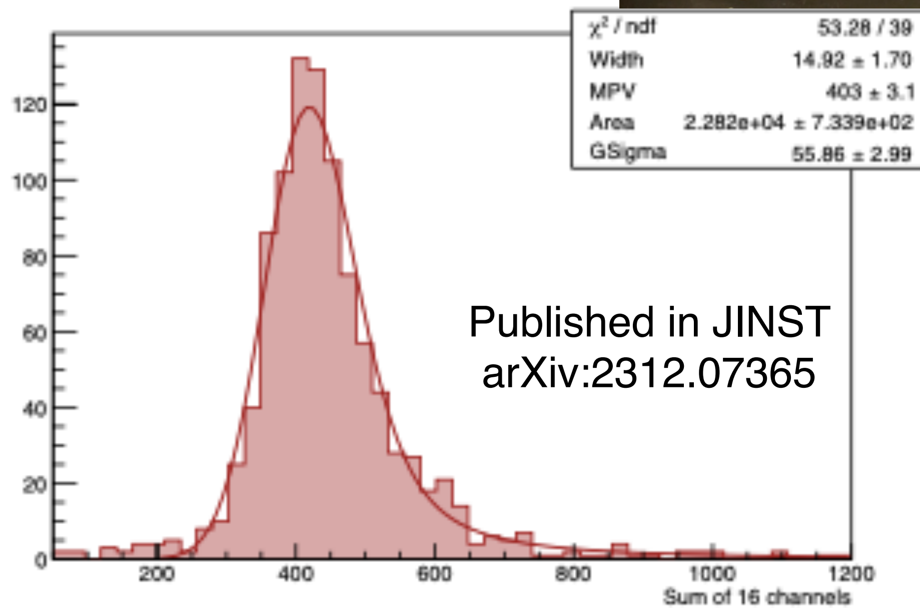
3. Cosmic test bench: towards the stochastic term

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





- Selected "central" muons
- bout 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 …



Published in JINST arXiv:2312.07365

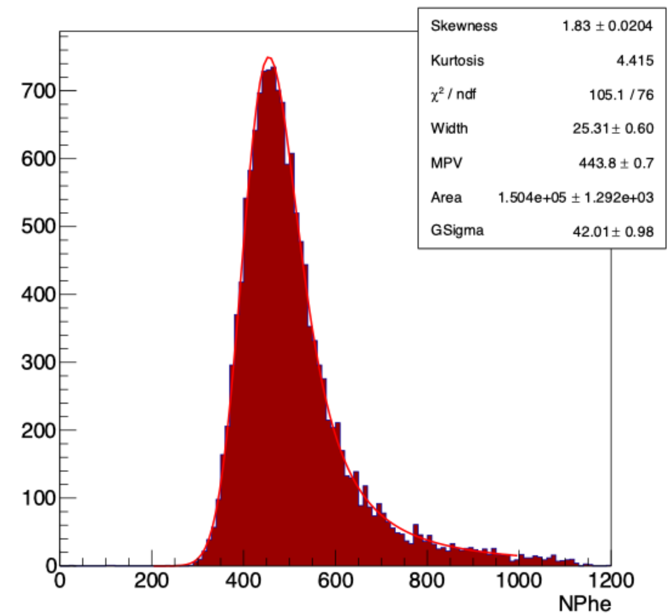
Should these numbers be confirmed, the

1% stochastic target is at reach !

4. Test beam at SPS: in the shadow of LHCb PicoCal

- We got the opportunity to benefit of two days of parasitic testbeam (muons and pions) at CERN SPS.
- Tested two trolls (same small prototypes as in home test bench
- Could check Water and Heavy Liquid
- Objective was to understand if there's not an irremediable constant term.
- Check the non-uniformity of the answer and input the result into simulations (WIP).

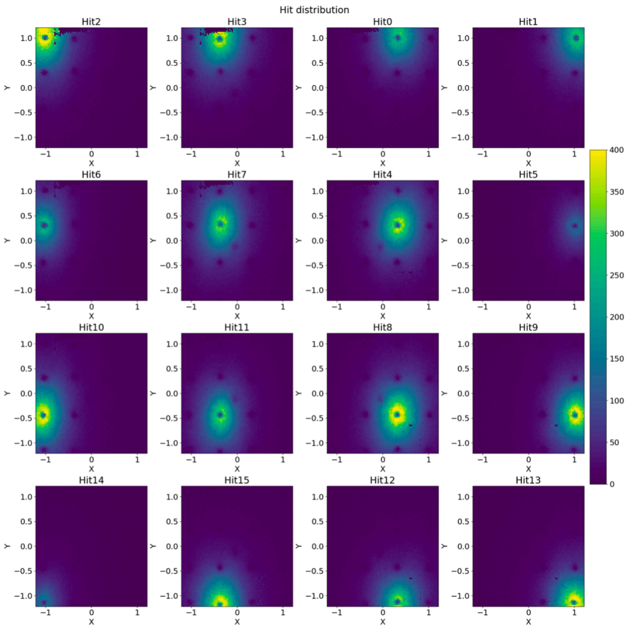
- On the way, one confirms that the 1% stochastic target is at reach.



4. Test beam at SPS: in the shadow of LHCb PicoCal

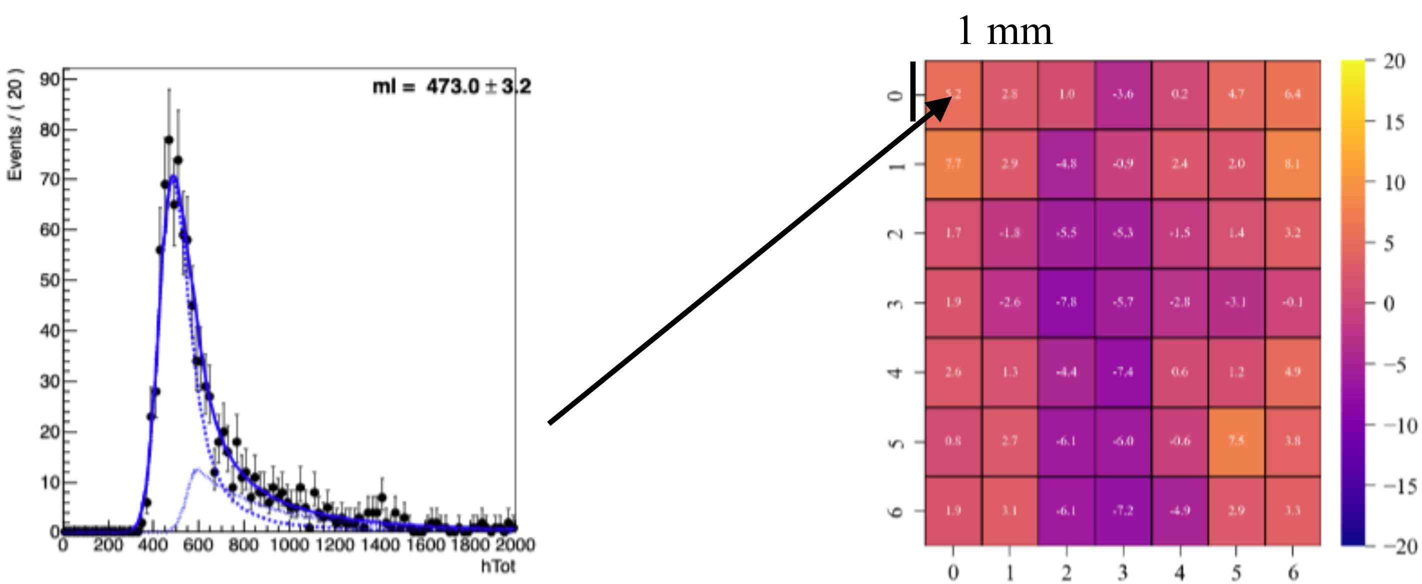
- We got the opportunity to benefit of two days of parasitic testbeam (muons and pions) at CERN SPS. Thanks to out LHCb colleagues for all the help.
- Tested two trolls (same small prototypes as in home test benches)
- Could check Water and Heavy Liquid
- Objective was to understand if there's not an irremediable constant term.
- Check the non-uniformity of the answer and input the result into simulations (WIP).

  - On the way, one confirms that the 1% stochastic target is at reach.
  - Confirms also that the scintillation light is confined close to the fibre.
  - Note to read the plot: the entrance point in (x,y) (2.5 x 2.5) cm² of the beam track is represented here. The colour sketches the response of each of the 16 fibres.



4. Test beam at SPS: in the shadow of LHCb PicoCal

- Scan the GRAiNITA surface by steps of 1mm with pion samples.
- Quantify the non-uniformities (on average smaller than 10%) and input those into ZnWO4 simulations.
- Fluctuations in the response (part of the contant term) is less than 1% of the deposited energy. Promising: publication on the way.
- Difficulties: with such a small prototype, the handling of the border effects is intricate to mitigate. Most of our statistics is coming from pions (that can initiate their hadronic shower in the detector volume, + liquid leakages + electronics configuration problems etc…

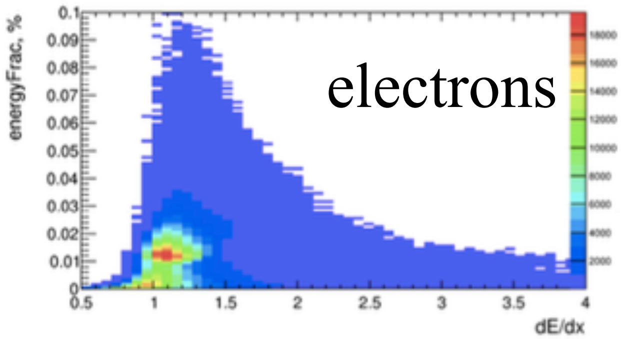


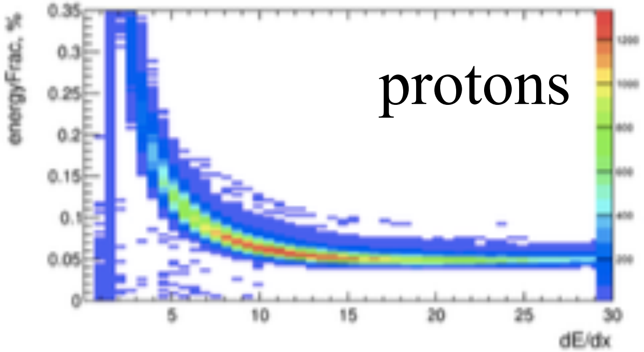
5. Aparté: Pulse Shape Discrimination (PSD)

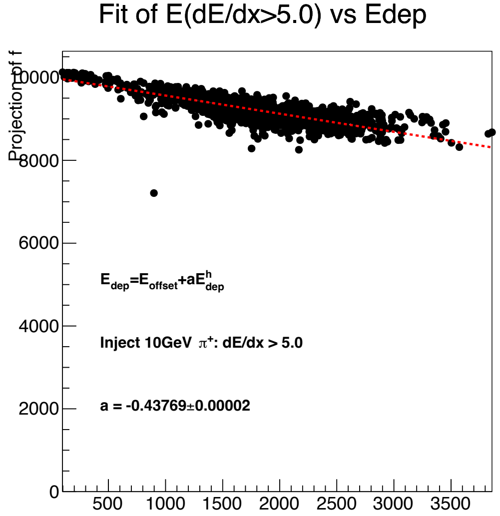
- Not a priori uniquely related to GRAiNITA but brought / studied by the same proponents. All crystals do feature PSD.
- Pulse Shape Discrimination is a well-known technique used in nuclear and neutrino physics to separate hadronic and electromagnetic scintillation light response of individual particles, e.g. photon vs alpha.
- We think that it can be used in FCC context to separate electromagnetic and hadronic components in a hadron shower, as Cherenkov vs scintillation do. Discrimination based on the scintillation signal time 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 (dominant but also deutons, alpha, nuclei).

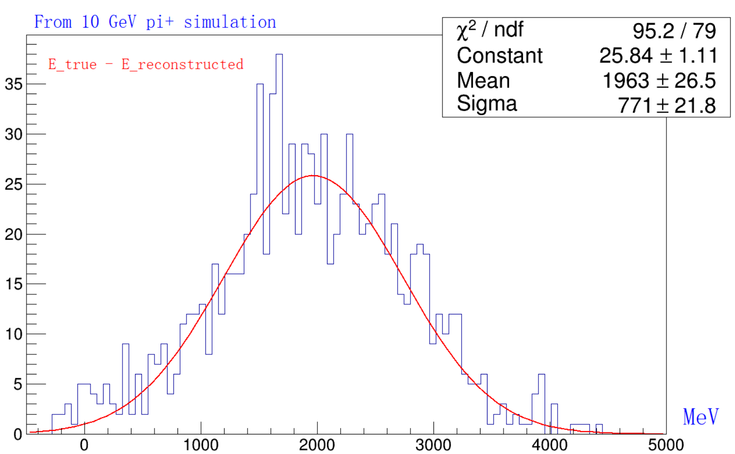
5. Aparté: Pulse Shape Discrimination (PSD)

- Pulse Shape Discrimination





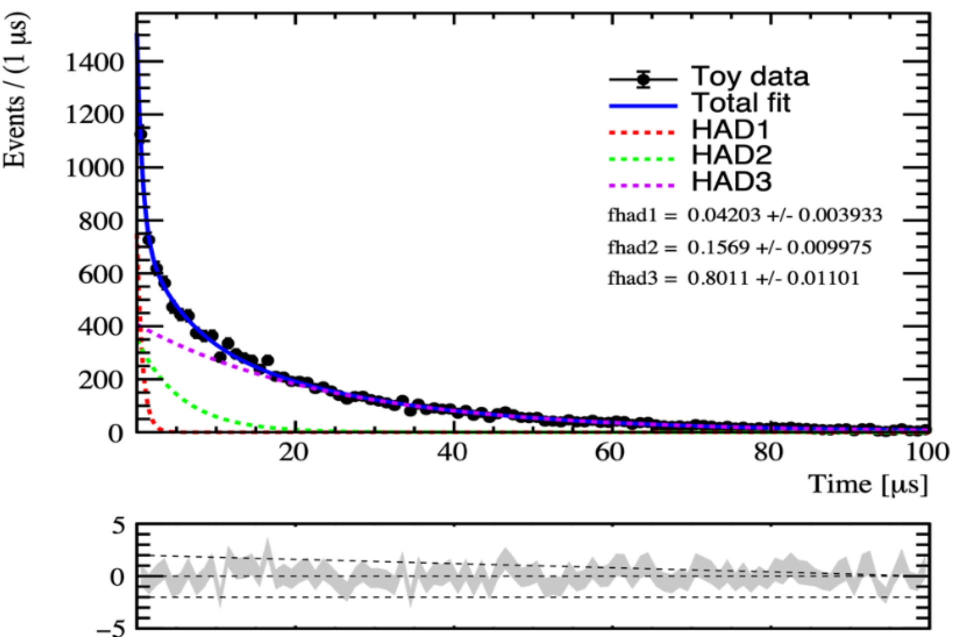


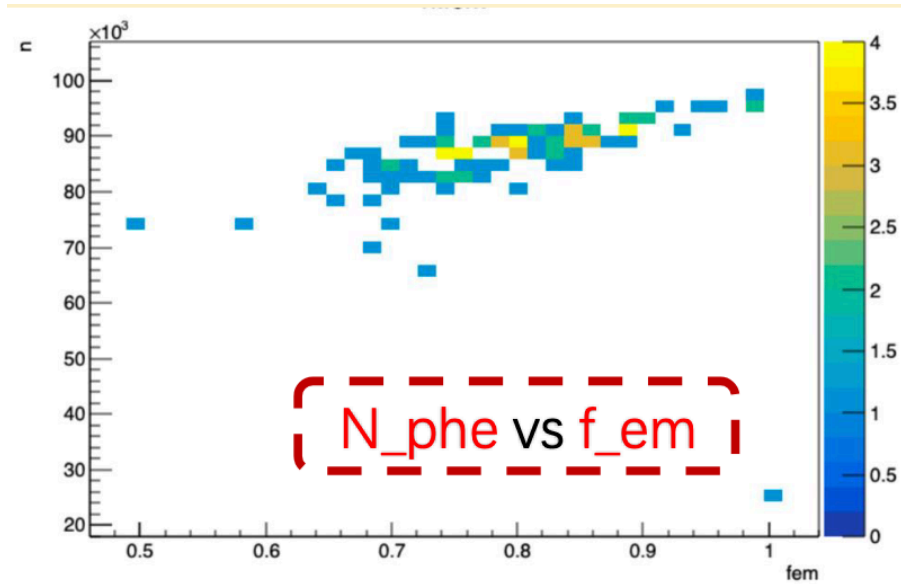


- Different ways to deposit the energy (e.g. breaking nuclei or molecular excitation) shall reflect into different scintillation times: next step is to educate an optical model (test beam at low energy first and simulations).

5. Aparté: Pulse Shape Discrimination (PSD)

- Pulse Shape Discrimination: the optical model is ready. So far, using the value of decay times in literature for alpha particles.





- Next step: use protons at ALTO (energy from 10 to 25 MeV) to feed the simulation.

6. The ANR application

- Important progresses during 2024: stochastic term of 1% is at reach (reported in 2312.07365 — JINST) and the constant term due to non-uniformities is likely < 1% (publication in preparation).
- Engaged studies on the heavy liquid, tests with other crystals ($CaWO_4$, BGO),etc…
- Yet, most of what could have been done with the small prototypes for the proof of concept has been done. A full-size module demonstrator (17 × 17 × 40 cm^3) (25X_0 in depth to contain 25 GeV photons) is in order to assess all components of the resolution.
- Goal: build and characterise the demonstrator to be ready when world beams come back to life.
- Second submission; same proponents. PI: Giulia Hull.

6. The ANR application — Personnel

Partner	Name	First name	Current position	Role & responsibilities in the project (4 lines max)	Involvement (person.month) throughout the project's total duration
CNRS Université Paris-Saclay IJCLab	*Hull*	*Giulia*	*IR - CNRS*	*Scientific coordinator,* *Task leader for WP 3,* *Co-task leader for WP5,* *Partner task for WP 1, 4*	*24 p.month*
	Schune	*Marie-Hélène*	*DR - CNRS*	*Task leader for WP 2.1 and 4.1* *Co-task leader for WP5* *Partner task for WP 3*	*16 p.month*
	Barsuk	*Sergey*	*DR - CNRS*	*Task leader for WP 1* *Partner task for WP 2,3, 4*	*8 p.month*
	Breton	*Dominique*	*IR -CNRS*	*Task leader for WP 3.3* *Partner task for WP 4*	*5 p.month*
	Dominguez-Goncalves	*Carlos*	*AI -CNRS*	*Task leader for WP 3.2* *Partner task for WP 4*	*12 p.month*
	Maalmi	*Jihane*	*IR – CNRS*	*Partner task for WP 3, 4*	*3 p.month*
	XXX	*XXX*	*CDD IR ANR*	*Task leader for WP 3.1* *Partner task for WP 1,3,4*	*12 p.month*
	XXX	*XXX*	*Stagiaire*	*Partner task for WP 1 and 3*	*6 p.month*
CNRS Université Clermont-Auvergne LP-Clermont Auvergne	*Monteil*	*Stephane*	*Professor*	*Scientific coordinator* *Task leader for WP 2.2* *Co-task leader for WP5* *Partner task for WP 4*	*6 p.month*
	Chanal	*Hervé*	*MdC*	*Task leader for WP 4.2* *Partner task for WP 2*	*10 p.month*
	Magne	*Magali*	*IE – CNRS*	*Partner task for WP 3 and 4*	*10 p.month*
	Picard	*David*	*IR – CNRS*	*Partner task for WP 3 and 4*	*14 p.month*
	XXX	*XXX*	*CDD CR ANR*	*Partner task for WP 2, 3, 4*	*24 p.month*
	XXX	*XXX*	*Stagiaire*	*Partner task for WP 2 and 4*	*6 p.month*

6. The ANR application — Work Packages

- WP1: Scintillator production and characterisation
- WP2: Monte-Carlo simulations
- WP3: Demonstrator development
- WP4: Characterisation of the detector

WP 1: Scintillator production and characterization			
Start Month	M1	End Month	M18
Coordinator	Sergey BARSUK	Participants	GH, CDD-IR
Objectives	Characterisation of the crystal grains produced at ISMA: Measure of the grains light yield with an Am241 source Visual check with a digital microscope		
Deliverables	Good quality crystals to be installed in the detector demontrator		
Risks and fall-back solutions	Risk linked to the war in Ukraine (serious but low probability) --> Support to the ISMA institute via an IEEE-NPSS initiative. Research for alternative providers of ZnWO4 grains. Possibility to transport the grains from Ukraine to CERN by a visiting researcher		

WP 2: Monte Carlo simulation			
Start Month	M1	End Month	M24
Coordinator	Marie-Hélène SCHUNE Stephane MONTEIL	Participants	SB, HC, PhD
Objectives	Fully simulate the GRAiNITA detector Study of the PSD to separate the electromagnetic fraction of the hadronic cascades		
Deliverables	Full model of the GRAiNITA detector. Introduction of a novel tool for dual-readout calorimetetry		
Risks and fall-back solutions	The PSD study needs results from proton test beam --> needed to secure the test beam and investigate alternative solutions		

WP 3: Demontrator development			
Start Month	M1	End Month	M30
Coordinator	Giulia HULL	Participants	All
Objectives	Selection of the best suited WLS fiber and dense liquid Design and developemnt of the GRAiNITA mechanics Design and developemnt of the read-out electronics		
Deliverables	GRAiNITA detector ready to be tested		
Risks and fall-back solutions	Risk linked to the procurement of the different detector's elements --> investigate alternative producers		

WP 4: Characterisation of the detector			
Start Month	M10	End Month	M48
Coordinator	Marie-Hélène SCHUNE Stephane MONTEIL	Participants	All
Objectives	Characterisation of the GRAiNITA detector using cosmic rays Characterisation of ZnWO4 grains for PSD at ALTO		
Deliverables	GRAiNITA detector ready to be tested with an eletron beam at CERN		
Risks and fall-back solutions	Risk to access the beam at ALTO (low probability)--> improve the proposal to access the facility, investigate the possibility to perform the study at another facilities		

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7.2.5 Contributions of Participating Institutions and Funding Agencies to the Work Package						
Task 3.2: Innovative Sampling EM calorimeters						
Subtask 3.2.1: GRAiNITA						
	Deliverable					
	D3.6			Total		
Institution / Funding Agency	Material / kCHF	Physicists: FTE months	Engineers and technicians: FTE months	Material / kCHF	Physicists: FTE months	Engineers and technicians: FTE months
FA ANR via IJCLab	295					
FA ANR via LPCA	210					
Total FA A						
FA IN2P3 via IJCLab		0,45	1,2			
FA IN2P3 via LPCA		2,35	0,6			
Total FA B						

7. Conclusions

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- 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 dedicated cosmic muons test benches at Orsay and Clermont as well as in test beams at SPS.
- Very significant (and promising!) progresses since the idea ignition: stochastic term of 1% is at reach (reported in 2312.07365 — JINST) and the constant term due to non-uniformities is likely < 1% (from test beam; publication in preparation).
- Engaged the studies on the heavy liquid, tests with other crystals (CaWO4, BGO),etc…
- Yet, most of what could have been done with the prototypes for the proof of concept has been done. A full-size module demonstrator (17 × 17 × 40 cm3) (25X0 in depth to contain 25 GeV photons) is in order to assess all components of the resolution.

7. Conclusions

- Objective of next years: build and characterise a demonstrator to assess fully the resolution in time to go to beams in 2029.
- Elsewhere:
  - engage with an EoI in FCCee (January). Goal is to reach out to a global calorimetry concept.
  - Connections with Dual-Readout (DR) calorimetry would make sense.
  - Pulse Shape Discrimination technique as another DR studies could be transformative (overcome the $30\,\%/\sqrt{E_{\mathrm{jet}}}$ barrier)… Crystal-agnostic but worth to embody the study within the GRAiNITA project.