AG GDR DI2I - Grenoble - 06/26

Pulse Shape Discrimination in GRAiNITA as a Novel Dual-Readout Method

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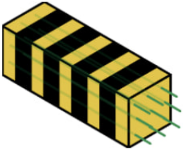
On behalf of the GRAiNITA Group:
CERN; IJClab; ISMA; LPCA; TSNUK.

Setting up the scene [0/4]

1. Principles of GRAiNITA

- The equation: reaching an exquisite cost-effective energy resolution while preserving high transverse granularity for the full FCC physics program.

Typical sampling calorimeter (e.g. Shashlik)

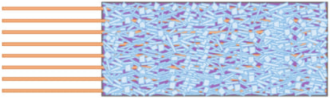


$$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}}$$

Crystal calorimeter

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

- Can we make the best of the two approaches?
  - Fine sampling, scint. light containment
  - Potentially cost-effective: grains can be 2.5 cheaper than homogeneous crystals



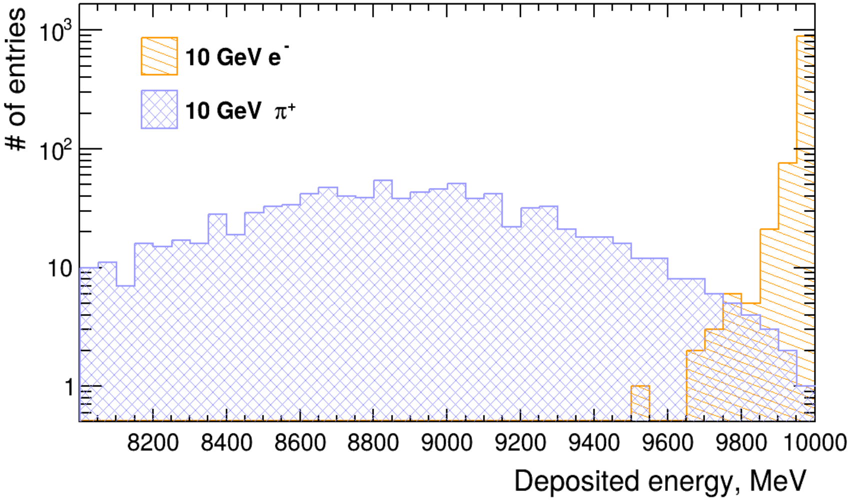
S. Monteil GRAiNITA@ FCC 5

Setting up the scene [1/4]

- Goal: address the energy resolution of the hadronic shower in GRAiNITA-like calorimeter (see the talk from S. Monteil for EM performance details);
- Simplified geometry: 2 m side cube of homogeneous $ZnWO_4$ crystal $\Longrightarrow$ Fully contained showers + no energy leaks;
- Particles at work: e^- (which represents the EM shower) and π^+ (which represents the hadron shower) of various energies [1-35] GeV;
- The Geant4 simulation (with 1k events per particle per energy) reads out the truth level information per interaction step;
- 10 GeV samples are used for illustrative purposes unless otherwise stated.

Setting up the scene [2/4]

An energy response of 10 GeV π^+ (blue cross-hatch) versus e^- (orange diagonal hatch) in a 8 m^3 cube of $ZnWO_4$ homogeneous crystal.



Setting up the scene [3/4]

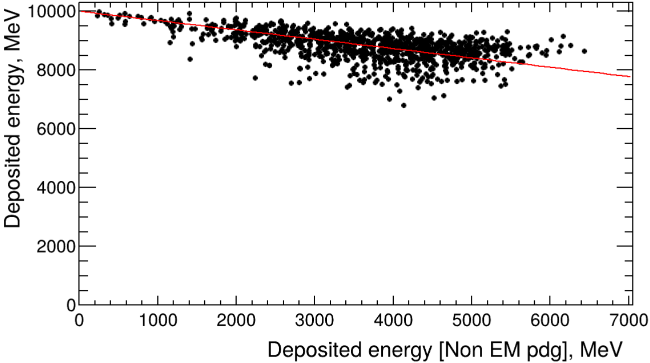
What is the origin of such a difference in response?

Very simplified shower snapshot	e^-	π^+
Particles	$e^{\pm}, \gamma$	Same* + $p, n, \pi^{\pm}, \alpha$, nuclei...
Interactions	Ionisation, bremms, Compton, pair production	Same* + inelastic interactions

- *Hadron showers have an EM part, which comes from π^0s. It is identical to fully EM showers $\Longrightarrow$ it is not the cause of the difference in resolution;
- However, the EM fraction varies a lot event-by-event with the $\pi^0/\pi^{\pm}$ ratio;
- In addition, inelastic interactions are the source of the invisible energy (via nuclei breaking, neutron capture, etc.);
- Is there anything we can do to recover resolution?

Setting up the scene [4/4]

- Yes, BUT the non-EM part of the shower must be measured event-by event;
- Next, the measured hadronic part is correlated with the total deposited energy;

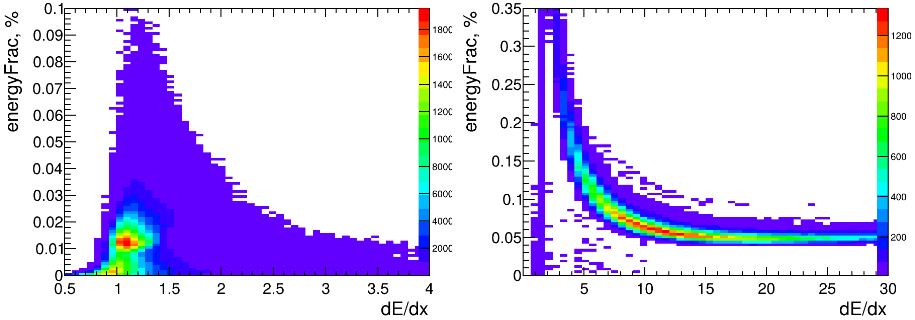


- An anti-correlation is observed $\Rightarrow$ it is (in theory) possible to correct the energy!
- How to convert truth-driven energy deposit into the measurable observable?

Towards the observables [1/2]

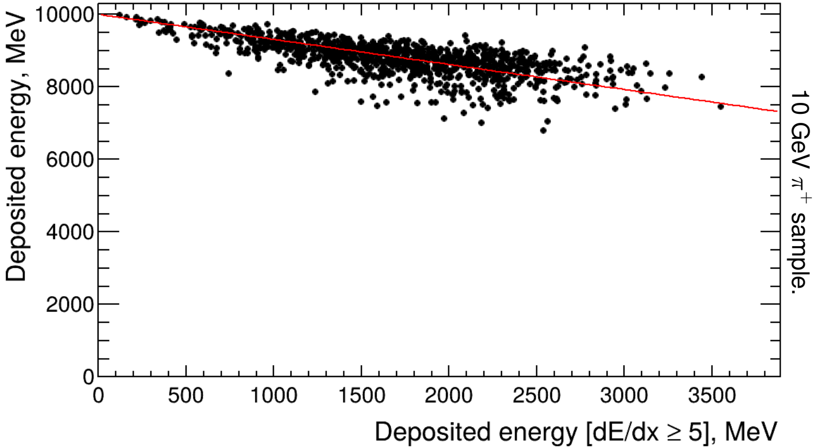
- Several options to discriminate EM component from low p protons, nuclei, α...:
  - Cerenkov light (aka dual readout) [Can be small in some detectors];
  - The difference in the regime of dE/dx;
- A value of 5 MeV·cm^2/g defines the high dE/dx regime by comparing electrons and protons (as highest energy contributors in the respective parts of the shower)

$\Longrightarrow$ the definition of hadronic energy changes from truth to the dE/dx threshold!



dE/dx regimes for e^- (left) and p (right) in the 10 GeV π^+ showers.

Towards the observables [2/2]

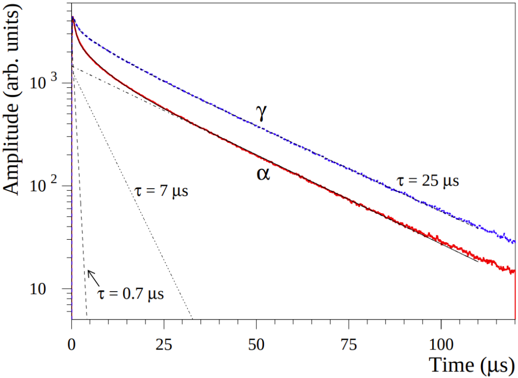


- An anti-correlation remains $\Longrightarrow$ it is still possible to correct the energy!
- However, the dE/dx threshold is still not an observable...

What is PSD? [1/2]

- Pulse Shape Discrimination is a well-known technique used in nuclear and neutrino physics to separate nuclei and EM scintillation light;
- The discrimination is based on the development of the scintillation signal
  - Some inorganic crystal scintillators (e.g. CsI(Tl), $ZnWO_4$) have multiple scintillation decay time components;
  - The values of the time constants, but mostly their relative yields, depend on the type of particle. Higher ionising particles (low-energy protons, α, etc.) have a larger fraction of the fast component;
  - The shapes of the time responses are used to build the PSD parameters to discriminate individual types of particles.

What is PSD? [1/2]



NIM A 544 (2005) 0168-9002

Type of irradiation	Decay constants, μs		
	τ_1 (A_1)	τ_2 (A_2)	τ_3 (A_3)
γ ray	0.7 (2%)	7.5 (9%)	25.9 (89%)
α particles	0.7 (4%)	5.6 (16%)	24.8 (80%)

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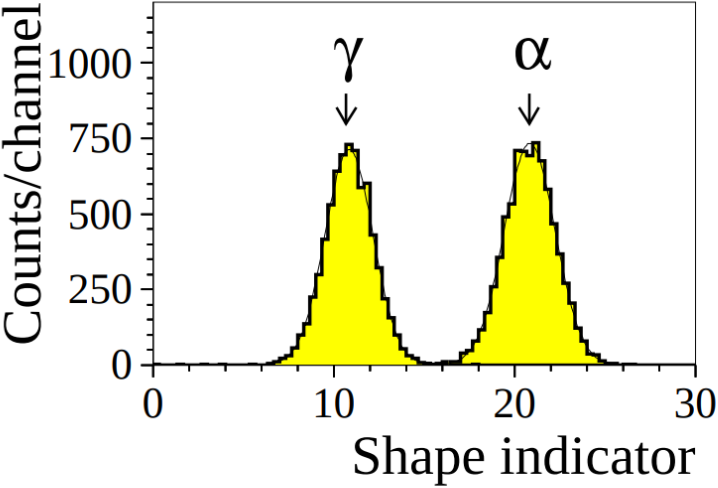

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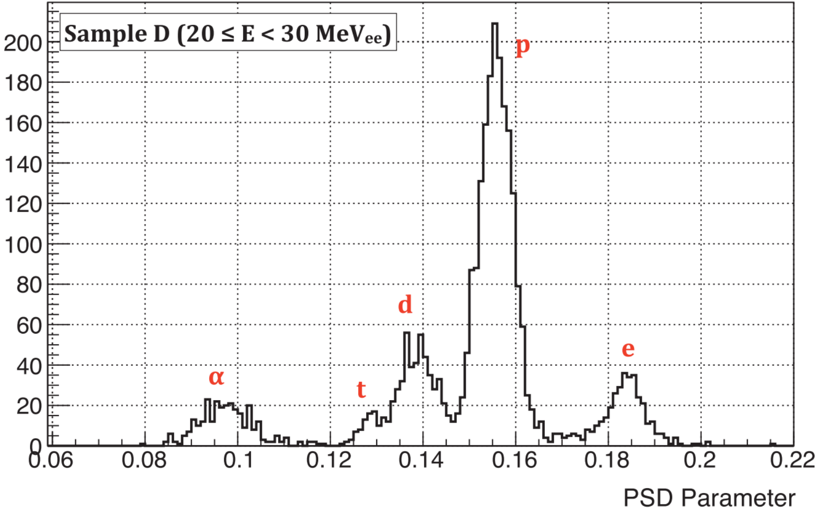
What is PSD? [1/2]

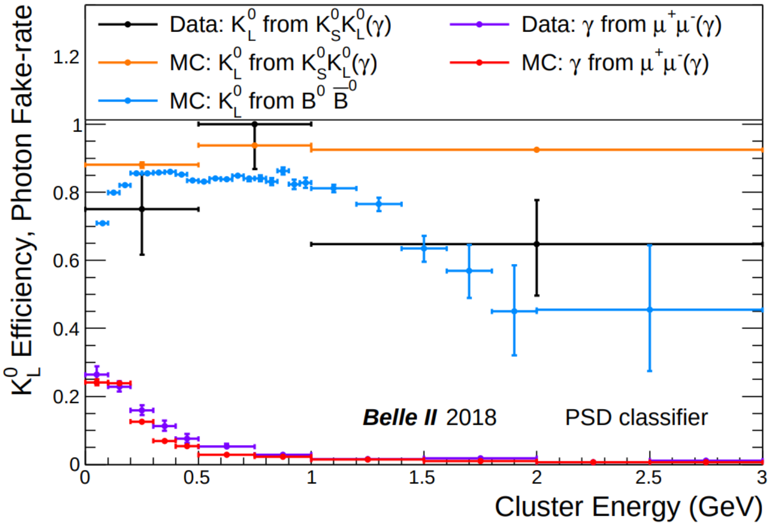


PTEP 4 (2018) 043H01

What is PSD? [2/2]

- To our knowledge, the only example of the use of PSD in particle physics is made by BELLE II experiment to distinguish K_L^0 from γ clusters.
- From the principle of PSD and the observations in BELLE II, we think that PSD can be used in the context of FCC to separate the EM and hadronic components in a hadron shower. See J. Lefrancois' talk in FCC Paris;
- Measurement of the hadronic component allows a correction of the energy of the hadronic shower to compensate for the e/h ratio and thus improve energy resolution. Of course, the representation of the shower requires more than just α and γ [Though, the literature is very scarce!]
- This exploration is not a priori directly related to GRAiNITA. But so far it has been studied by the same proponents in the context of the project.
- The main goal of the study is a **proof of principle** for the PSD technique.

What is PSD? [2/2]



NIM A 982 (2020) 164562

What is PSD? [2/2]

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Towards the PSD correction formula [1/7]

- How to convert the energy deposit of the particles above a given dE/dx threshold into a measurable observable?
- The scintillation physics literature indicates that the increase in dE/dx is reflected in a different time response for different types of particles:
  - A higher probability of the non-radiative processes (aka quenching);
  - An alternation in the time scintillation constants and yields;
- For now, the hadronic shower is approximated with 4 categories:
  - Two categories are defined from the literature (NIM A 544 (2005));
  - Category 1: electromagnetic-like with dE/dx [0,5);
  - Category 4: α-like with dE/dx [60,+∞);
  - The unique time (τ_i) and yields (A_i) provide a template per category ($\Sigma A_i \tau_i$);
- Combination of e^- and α is not enough to describe the hadronic shower!

Towards the PSD correction formula [2/7]

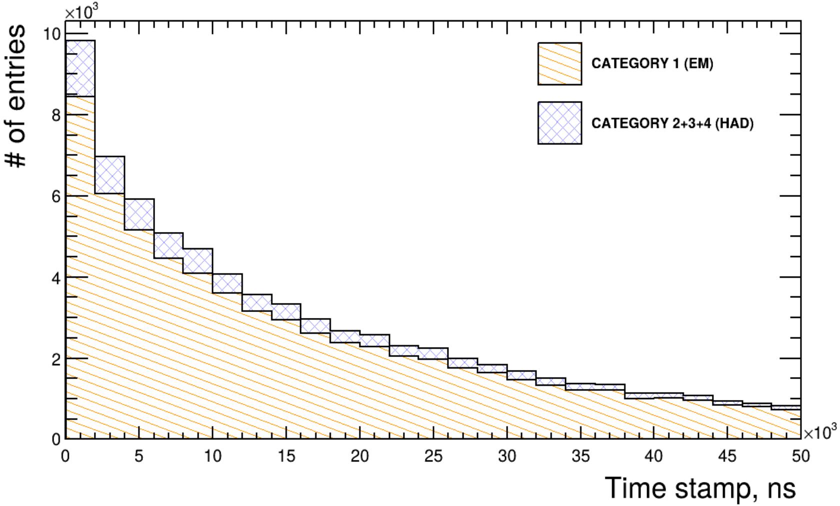
- Test beams are the way to enhance the scarce literature!
- The first test beam with p was performed at the ALTO accelerator in Paris;
- Based on the test beam measurements, 2 more categories were defined:
  - Category 2: Low dE/dx (high E) proton-like category with dE/dx [5,30);
  - Category 3: High dE/dx (low E) proton-like category with dE/dx [30,60);
- Word of caution: these approximated time responses will be refined with the results of the recent low-energy protons test beam at the CYRCE cyclotron in Strasbourg.

Towards the PSD correction formula [3/7]

- All energy deposits in the event are categorised according to dE/dx;
- Each energy deposit is quenched (with Birks' law) and converted to the number of PE with a yield of 10000 PE/GeV (see JINST 19 (2024) P04008);
- Each PE gets the time stamp according to τ_i and A_i of its dE/dx category;

Towards the PSD correction formula [3/7]

An example of the time response of the 10 GeV π^+ shower.



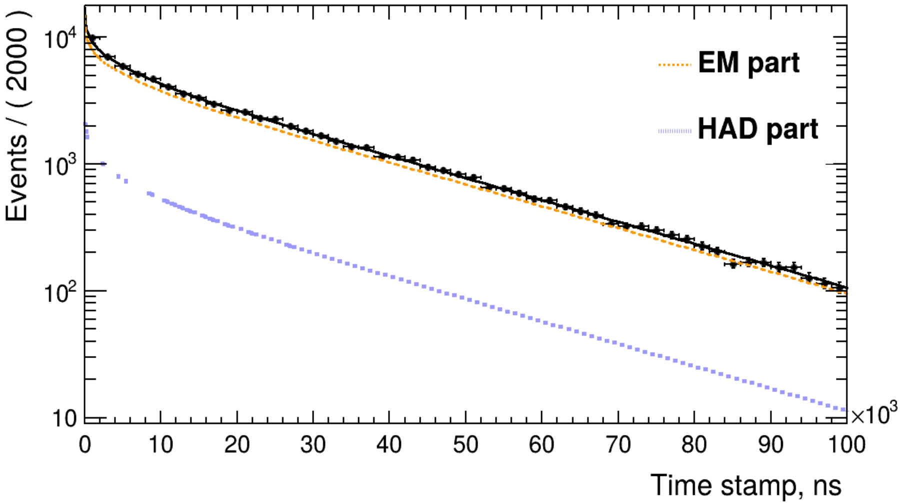
Towards the PSD correction formula [3/7]

- All energy deposits in the event are categorised according to dE/dx;
- Each energy deposit is quenched (with Birks' law) and converted to the number of PE with a yield of 10000 PE/GeV (see JINST 19 (2024) P04008);
- Each PE gets the time stamp according to τ_i and A_i of its dE/dx category;
- The obtained distribution of time stamps is fitted back to check if it is possible to retrieve the fractions of categories:
  - It has been observed that the fractions of Categories 3 and 4 are too small to be properly measured;
  - Currently implemented solution: mix categories 2-4 in a generic hadronic shape in proportions provided by the simulation*;
  - Thus, f_{EM} (Category 1 fraction) is the only free parameter of the fit.

* consistency of proportions is verified in the energy range of [1-35] GeV.

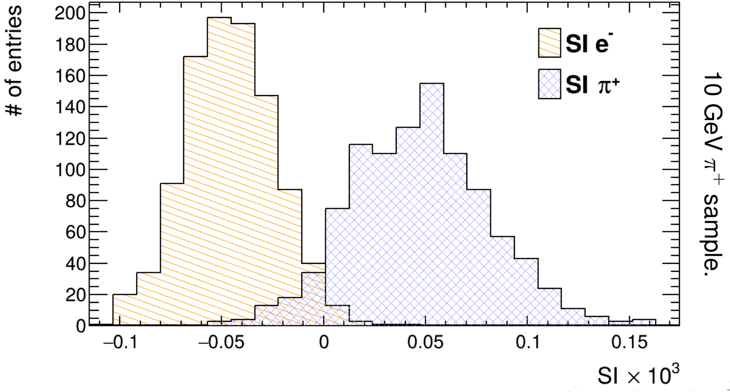
Towards the PSD correction formula [3/7]

An example of the time response fit for the 10 GeV π^+ shower.



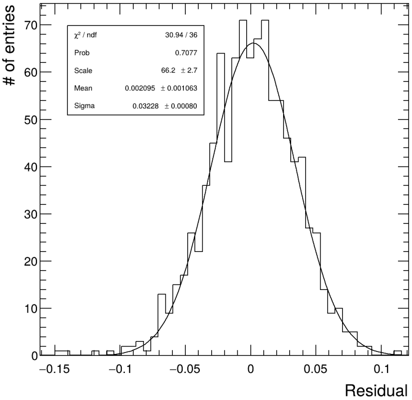
Intermezzo: PSD variable

- The fit of the time response per se does not provide a clear visual separation between the electromagnetic and the hadronic showers;
- A shape indicator (SI), defined as in NIM A 544 (2005) shows that the differences in the time shapes are enough to distinguish the two!

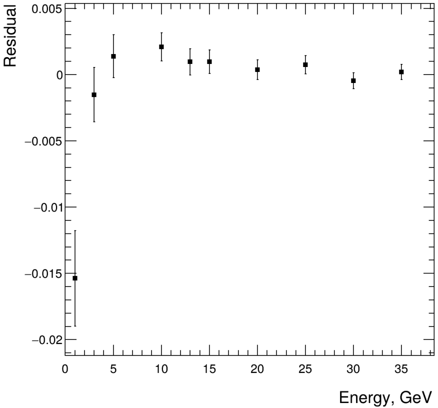


Towards the PSD correction formula [4/7]

- The fits were further studied in terms of pulls and residuals;
- No fit bias observed at high energies $\Longrightarrow$ we can measure f_{EM} correctly!



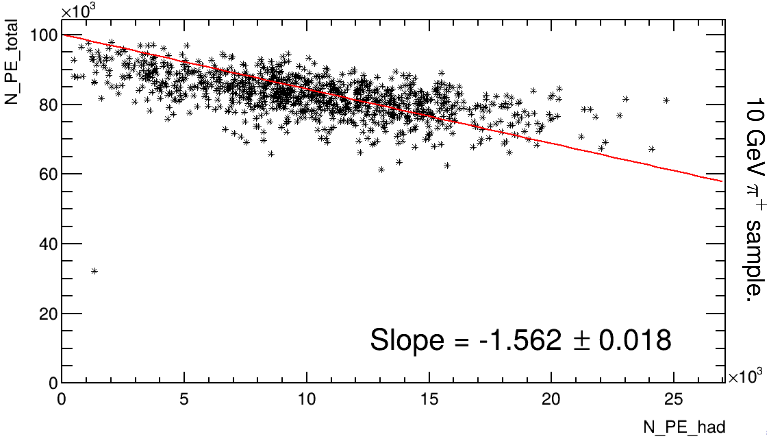
Residuals for 10 GeV π^+ events.



Residuals versus energy.

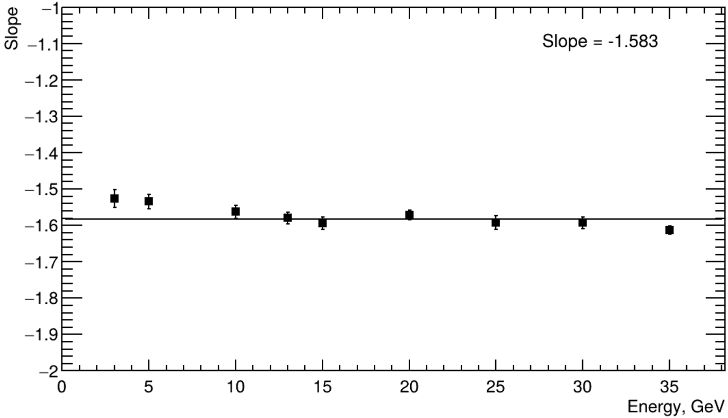
Towards the PSD correction formula [5/7]

- The anti-correlation (visible energy versus high dE/dx) is now measured between the total number of photoelectrons (nPE) and the number of PE from the highly ionising particles (Categories 2 + 3 + 4), denoted nPE_{Had};
- nPE_{Had} can be computed with the knowledge of f_{EM} as $nPE \cdot (1 - f_{EM})$;



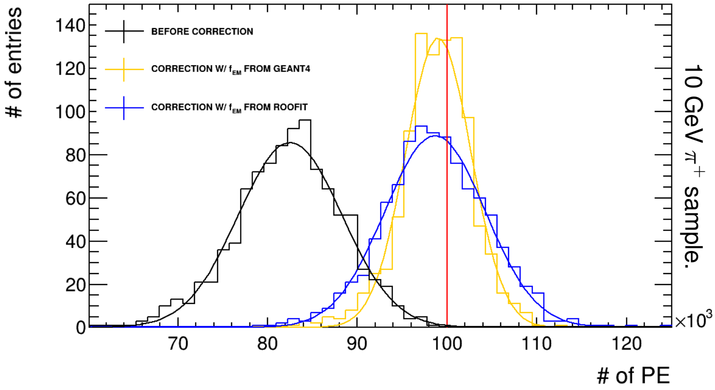
Towards the PSD correction formula [6/7]

- The correlation is obtained by linear fit, in which the intercept is fixed to the incident energy of π^+;
- The slope is independent of the incident hadron energy in the [5-35] GeV range;
- This allows us to define a generalised energy correction!



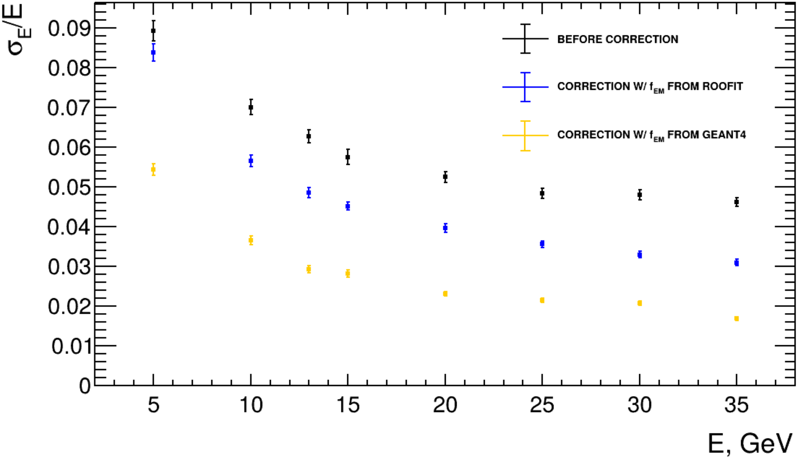
Towards the PSD correction formula [7/7]

- The master formula for the PSD correction is $E_0 = E \cdot [1 - a \cdot (1 - f_{EM})]$;
- The distribution in blue indicates that the technique works by bringing the corrected number of PE to the expected value (red vertical line);
- The distribution in yellow shows the asymptotic performance of the method;



On the energy resolution improvement

- A PSD correction also improves the energy resolution from 23% to 18%;
- Words of caution: these results are obtained with the unrealistic* detector!



* Both due to the size and the pure scintillating crystal nature.

Summary

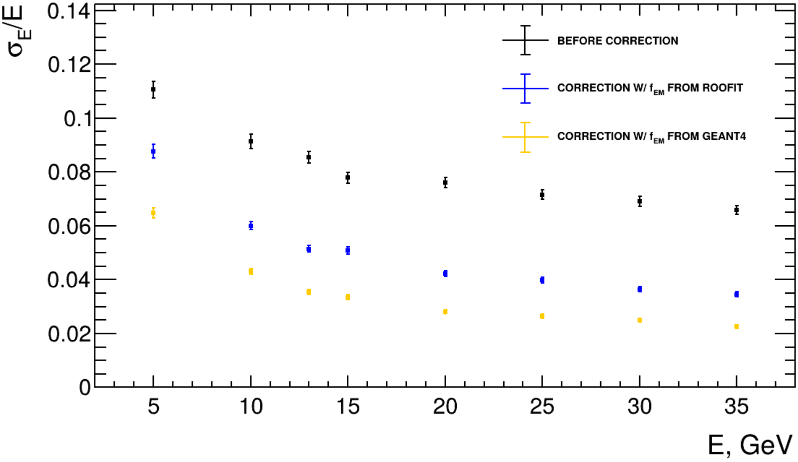
- The PSD correction technique is introduced as a novel dual-readout method to improve the energy resolution of the hadron showers;
- An anti-correlation between the total deposited energy of the shower and the energy deposits from highly ionising particles was established;
- The variation of the time response of different particles in inorganic crystal scintillators allows us to convert the latter into an observable;
- f_{EM} (and hence f_{HAD}) of the shower can be properly measured with a fit;
- The correlation slope does not depend on the incident energy of the π^+;
- In conclusion, the proof of principle for the PSD correction technique is obtained for the unrealistic detector.

Outlook [1/2]

- The publication is on its way [including the quenching determination]!
- GRAiNITA is now a part of the ALFA detector concept for FCC!
- The next stage is to move to the simulation with more realistic detector:
  - Include the heavy liquid;
  - Move to the size of the demonstrator ($17\times17\times40$ cm^3 or $25X_0$);
  - Simulate individual grains (technology is already at hand!);
- Intermediate stage towards a more realistic scenario: $2\times2\times2$ m^3 homogeneous cube of $ZnWO_4$ + heavy liquid mixture;
- The result is fresh out of the press!

Outlook [2/2]

- A heavy liquid degrades the stochastic resolution from 23 to 30%;
- The PSD correction brings the resolution back to 18%!



Backup

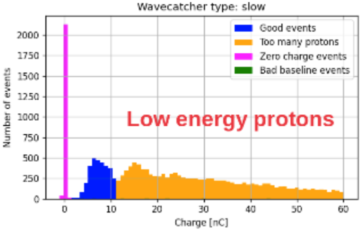
Geant4 simulation description

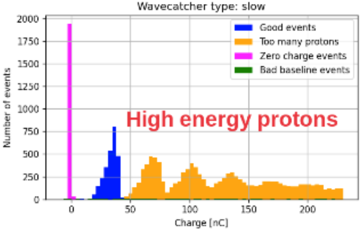
- The simplified geometry of a homogeneous $2m^3$ cube of $ZnWO_4$ is used
  - The hadronic shower is fully contained;
  - The absence of energy leakages is ensured;
- The physics list in use is FTFP_BERT;
- Datasets: 1k π^+ events of [1, 3, 5, 10, 13, 15, 20, 25, 30, 35] GeV;
- The quenching is done according to Birks' law: $E' = E/(1 + k_B \times \frac{dE}{dx})$;
  - k_B value of 0.01181 mm/MeV is from Astroparticle Physics 33 (2010);
- The time stamps for PEs are generated outside of Geant4 using *TRandom*;
- Next stage: geometry with randomly distributed grains is at hand!

Test beam at ALTO [1/3]

Preprocessing setup

- Average pulse curves are calculated for an order of 1000 events.
- The events individually undergo some preprocessing to ensure good quality of events.
- Data measured with fast and slow wavecatchers.
- The events with one proton were selected for analysis. For electrons, it's already one electron.





Test beam at ALTO [2/3]

Normalised average pulse shapes.

❑ Considered the following cases:

- Electrons (measured)
- Protons 6 MeV, low energy (measured)
- Protons 15 MeV, high energy (measured)
- Alphas, pulse builds on values from publication.

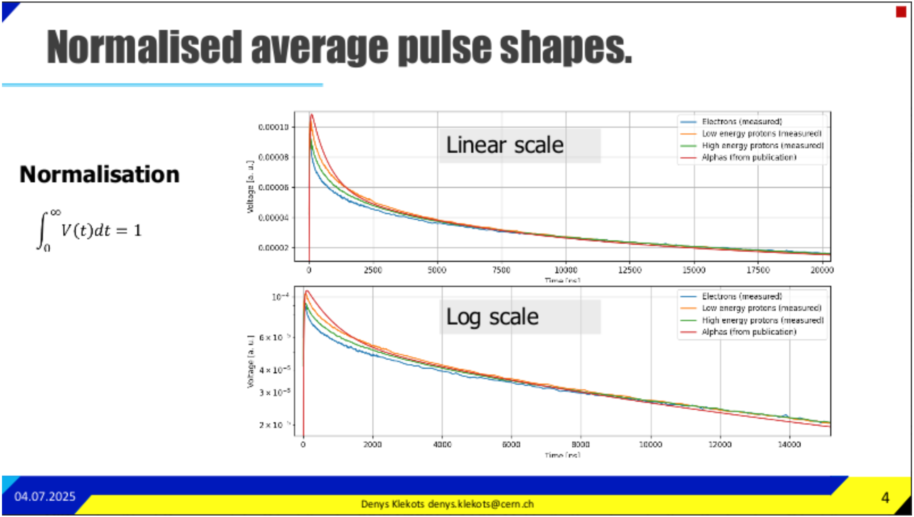
Pulse parameters from publication

Type of irradiation	Decay constants, μs		
	τ_1 (A_1)	τ_2 (A_2)	τ_3 (A_3)
γ ray	0.7 (2%)	7.5 (9%)	25.9 (89%)
α particles	0.7 (4%)	5.6 (16%)	24.8 (80%)

Measured pulses for protons compared against measured electrons.

Built pulses for alphas compared against the built for gammas.

Test beam at ALTO [3/3]



Parameters for the dE/dx categories

Electron	Amplitude [arbitrary units]	time constant [ns]	Charge [arbitrary units]	Charge [%]
	0,338289829	25234,56727	8536,597436	87,96%
	0,187770628	5230,567425	982,1469322	10,12%
	0,207316615	786,2214334	162,9967659	1,68%
	0,266622928	86,3706346	23,02839152	0,24%
Low proton	0,300681592	24304,63789	7307,957216	81,09%
	0,194176587	6617,070077	1284,880084	14,26%
	0,25577449	1412,702447	361,3332478	4,01%
	0,249367331	233,9089103	58,32924063	0,65%
High proton	0,302239168	26575,71835	8032,223001	77,15%
	0,207012683	9113,642178	1886,639521	18,12%
	0,264942118	1627,119436	431,0924698	4,14%
	0,225806031	269,3606679	60,82326327	0,58%
alpha		24800		80,00%
		5600		16,00%
		700		4,00%

PSD variable construction

- Starting point: use an equivalent Shape Indicator (SI) definition as here;
- Idea: SI = $[\Sigma f(t_k) \cdot P(t_k)]/\Sigma f(t_k)$, where $f(t_k)$ is the digitised amplitude;
- $P(t_k) = [\bar{f}_\pi - \bar{f}_e]/[\bar{f}_\pi + \bar{f}_e]$, where $\bar{f}_i$ are reference pulse shapes for π, e;
- Implementation:
  - 1k events for $\pi/e \implies$ provide $\bar{f}_i$;
  - $\bar{f}_i$ are converted to p.d.f.s $\implies$ provide $P(t_k)$;
  - The considered time range is [0, 100]μs, bins are 25 ns;
  - SI_i are computed and compared;
- For now it is tested only for the 10 GeV sample;