Simulation of spillover effects, signal treatment and ideas for improvement

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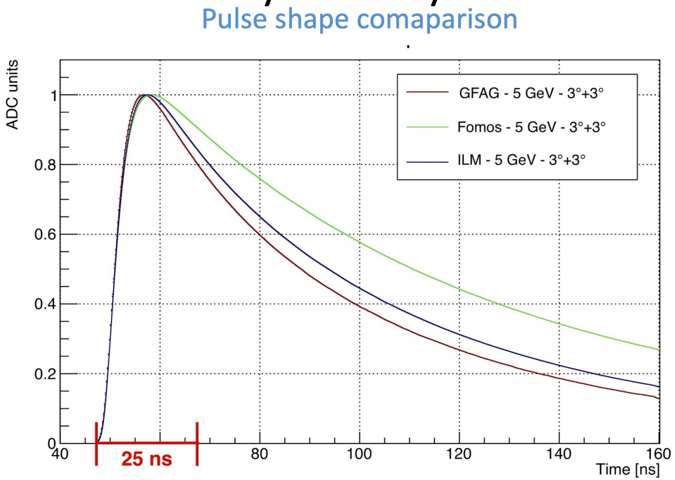
Outline

- Motivations
- Simulation of spillover effects
  - Investigated several crystals with different light-output parameters
- Analysis of simulated data
  - Pulse shaping techniques to analyse and subtract spillover effects
  - Quantification of spillover effects
- Summary and outlook

Motivations

E. Auffray's talk from yesterday

- Garnet crystals are excellent radiators in terms of light output and rising time but have a **slow component with long decay time**
- The long component may cause light to leak in the following events ➔ **spillover**
  - Spillover must be taken into account and subtracted to properly determine energy and time
  - Even if subtracted, statistical fluctuations in the light output can deteriorate performance
- Need to **quantify the potential effects of spillover** to find optimal crystal parameters

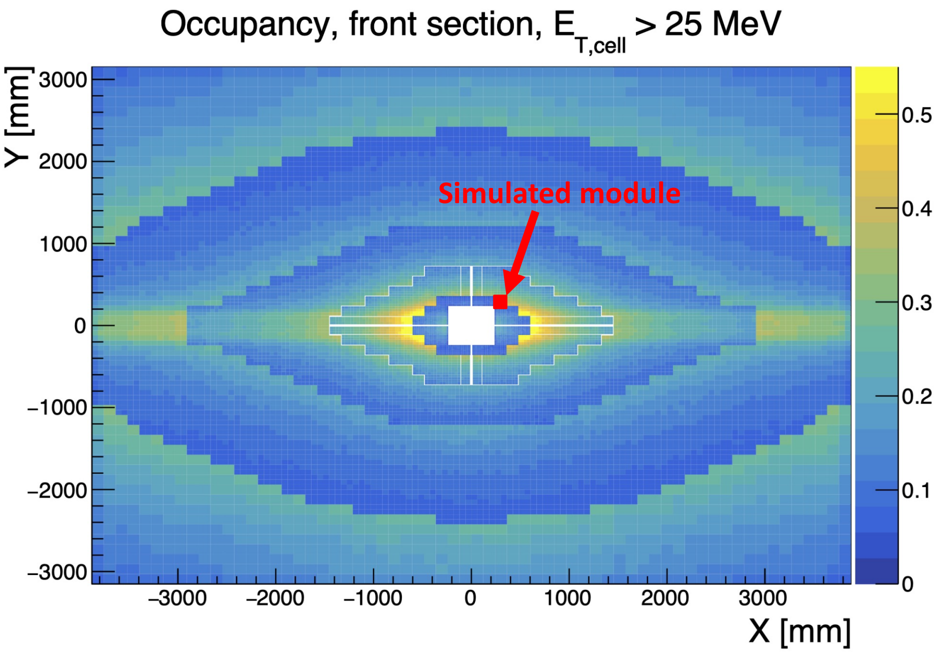


But what will be the impact of pulse shape at HL-LHC ?

Simulation of realistic spillover (I)

- Fully simulated **p-p collisions + full detector** at peak luminosity **$L = 1.5 \times 10^{34}$ cm^{-2}s^{-1}**
- Particle flux is made interact with a SPACAL W/GAGG module (8x8 cells)
  - **SPACAL Hybrid simulation** is used to emulate all the chain up to the pulse shapes in the digitiser (**5 GS/s**) ➔ see M. Pizzichemi's talk from yesterday
  - Important assumptions on PMTs: **no saturation, infinite dynamic range, fully linear, no electronic noise**
- Pulse shapes are linked assuming **25 ns bunch spacing**
  - Every 50 events the pulse shape of an electron (signal) hitting the central cell of the module is added to the chain

P. Roloff's talk from yesterday
LS4 (1.5 x 10^{34} cm^{-2}s^{-1}):



Simulation of realistic spillover (II)

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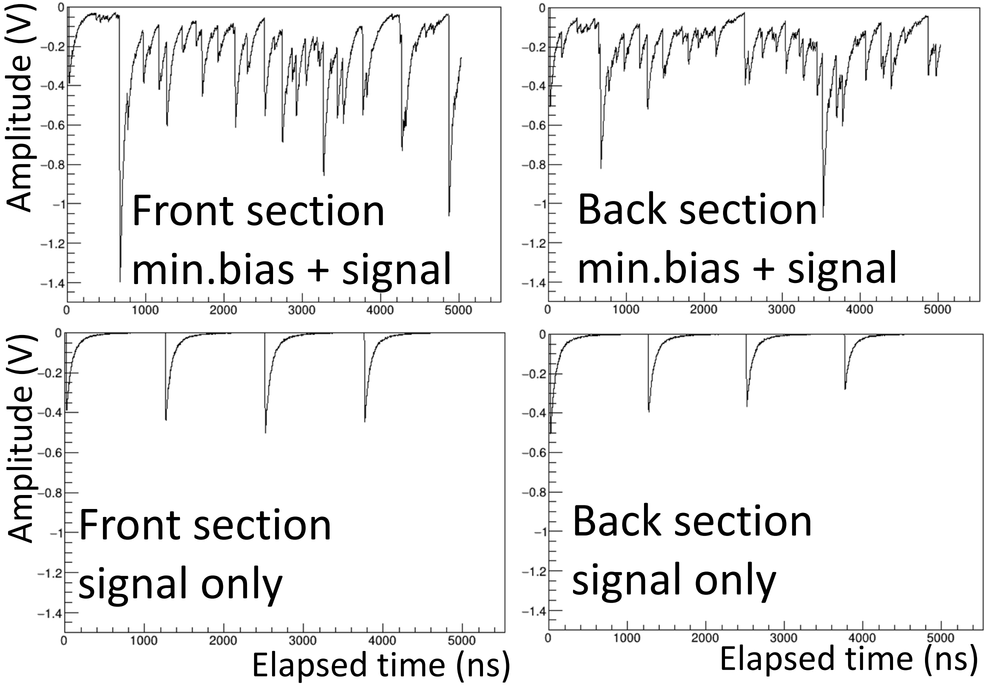
Pulse shapes observed in the digitiser for a cell in the centre of the module

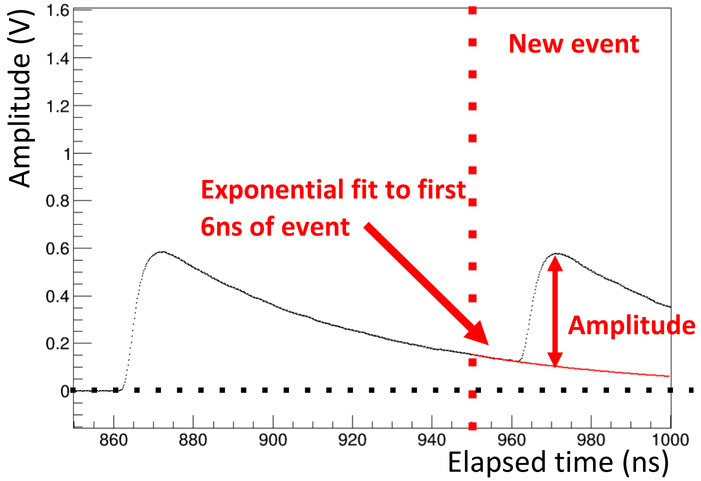


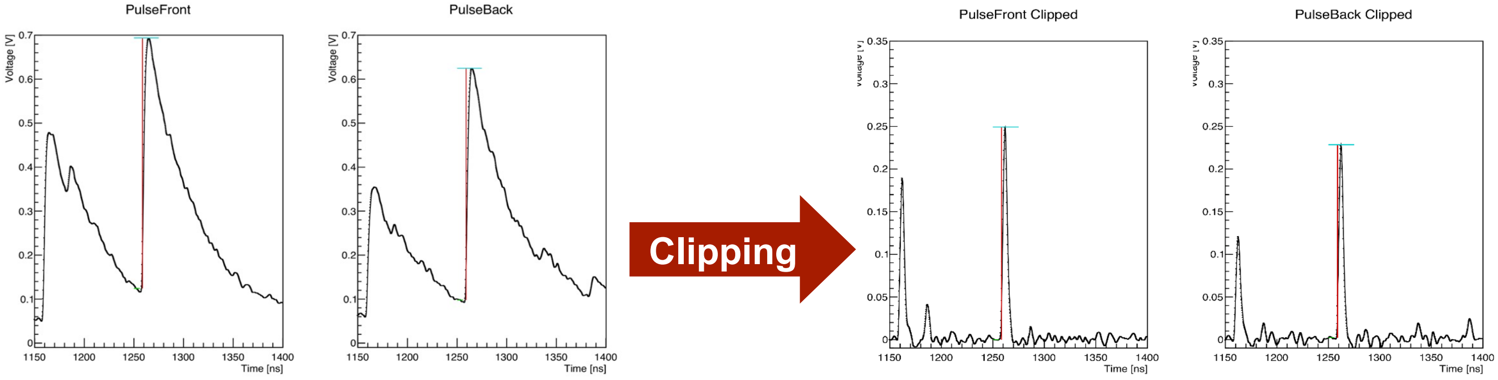
Signal-only chain is used to determine reference performance

Pulse shsaping and determination of time stamp

- Time stamp is measured using a CFD technique
- Two pulse shaping techniques:
  - Exponential fit to the baseline used to subtract spillover
  - Cable clipping:

$$V_{out}(t) = \frac{1}{2}\left(V_{in}(t) - r \cdot V_{in}(t - \delta_t)\right)$$





Simulation of different crystals

- Time resolution is inversely proportional to the **photon time-density**:

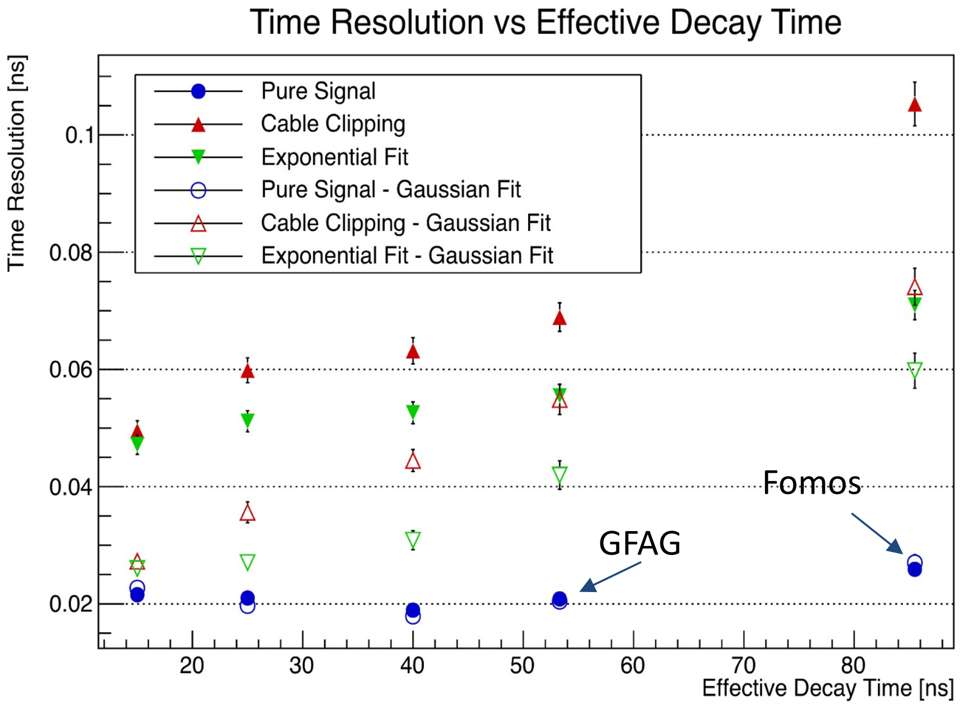
$$\sigma_T \propto \sqrt{\frac{\tau_{d,e} \cdot \tau_r}{LO}}$$

- Note: the formula above does not consider the PMT contribution
- Tested different scintillation decay times and light output but **keeping constant the photon time density**
- Effective decay time defined as: $\frac{1}{\tau_{d,e}} = \frac{A_1}{\tau_{d,1}} + \frac{1 - A_1}{\tau_{d,2}}$

Material	Tau_{d,1} [ns]	Abundance %	Tau_{d,2} [ns]	Tau_{d,e} [ns]	Tau_r [ns]	Light Yield [Ph/MeV]
Fomos	59	56	200	85.5	0.1	40000
GFAG	40	66	150	53.3	0.06	35000
GFAG w/o Tau_{d,2}	40	100		40.0	0.06	26273
25 ns	25	100		25.0	0.06	16421
15 ns	15	100		15.0	0.06	9853

Results for different crystals

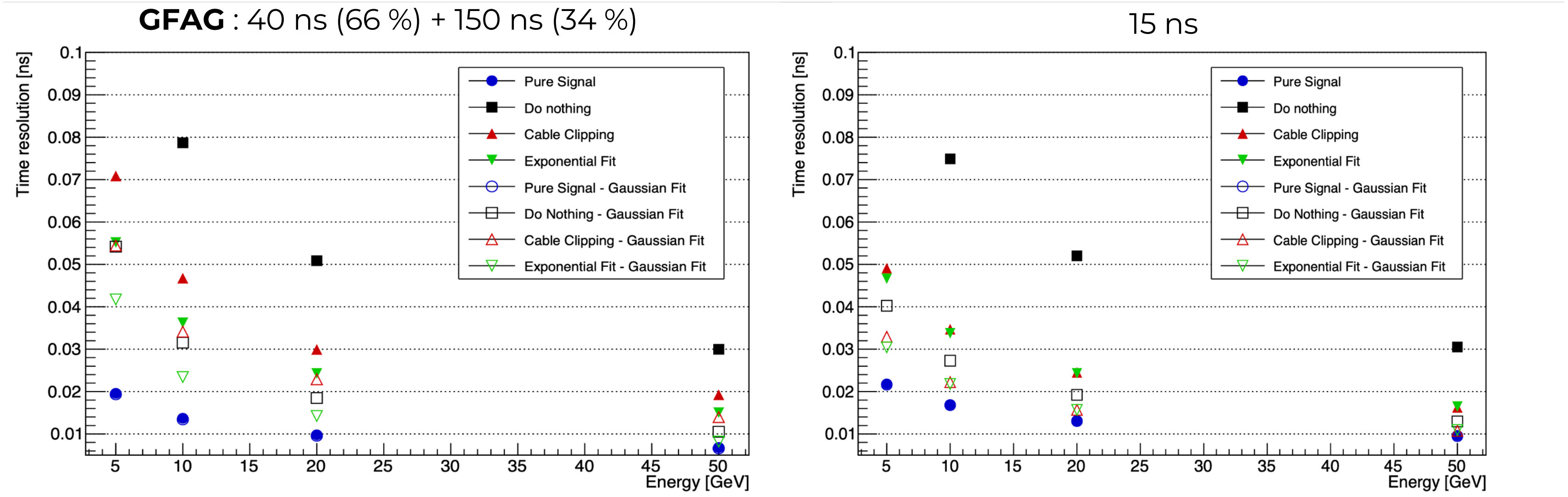
- Time resolution for **pure signal is almost independent** from effective decay time of crystals
- **Spillover effects are mitigated for crystals with faster decay time**
- Pulse shaping with **exponential fit gives better performance with respect to cable clipping**
- Time resolution evaluated with RMS is worse than with gaussian fit
  - **Presence of pile-up**



Here signals are 5-GeV electrons

Spillover for high-energy electrons

- Importance of spillover effects is studied also for signal electrons at higher energies



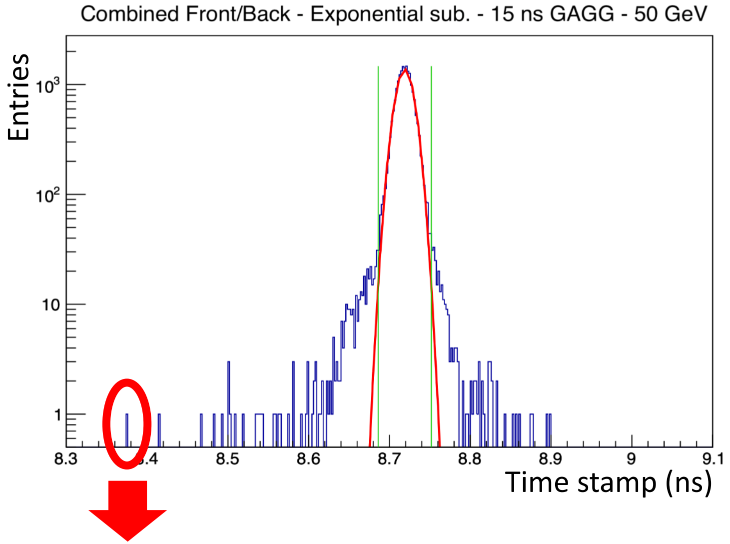
- **Spillover effects are reduced at higher energies**
- **Cable clipping** (triangles) **and exponential fit** (reversed triangles) give same performance **only for fast GAGG**
- Relevant difference between RMS (filled markers) and gaussian fit (hollow markers)

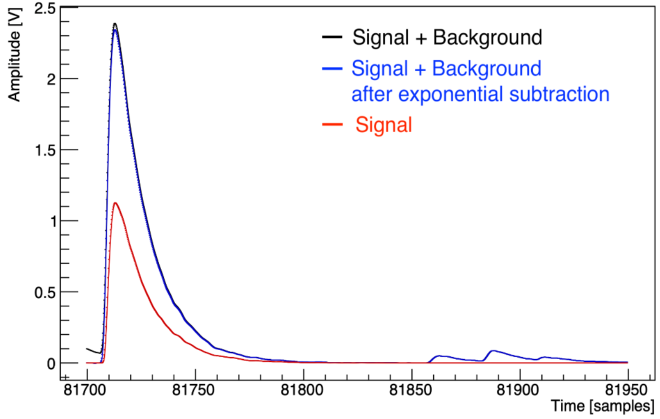
Pile-up

- Distribution of time stamps have outliers far from the core causing large RMS
  - **4.2% @ 5GeV** and **3.1% @ 50 GeV** of events outside ±3σ range
  - Few events already **sufficient to deteriorate time resolution**

- Investigation of outliers evidence that these are **pile-up events with two particles hitting the same cell**
  - Irreducible effect at the moment

Green lines are ± 3σ of gaussian fit



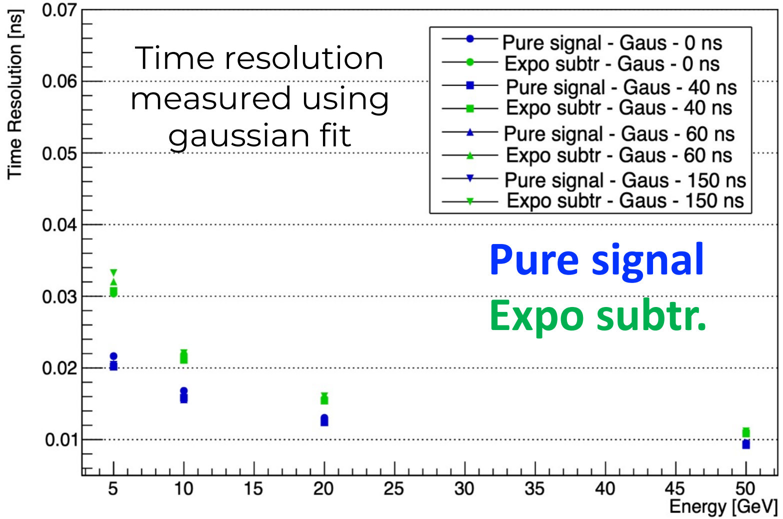


Secondary slow component

- The effect of a secondary slow component for fast GAGG has been investigated
  - On top of quite fast primary component (τ = 15 ns)
  - Constant photon time density

- **If primary component is fast then a slow secondary component has a minimal impact** on time resolution and only at low energies
  - Different markers correspond to different crystals

Material	Light Yield [ph/MeV]	$\tau_{d,1}$ [ns] (%)	$\tau_{d,2}$ [ns] (%)
1	9853	15 (100%)	0 (0%)
2	13137	15 (60%)	40 (40%)
3	14075	15 (60%)	60 (40%)
4	15395	15 (60%)	150 (40%)

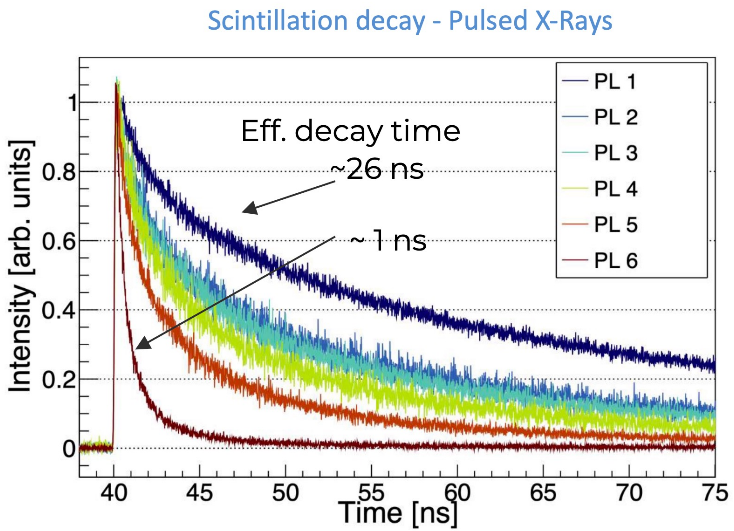


Ultra-accelerated GAGG

- Novel garnet are being studied with ultrafast scintillation
- Concentration of Ce and Mg dopants can be increased to obtain very fast decay time at the cost of less light output
- Simulated an extremely fast GAGG
  - Comparison with not-so-fast GAGG
  - Photon time density kept constant

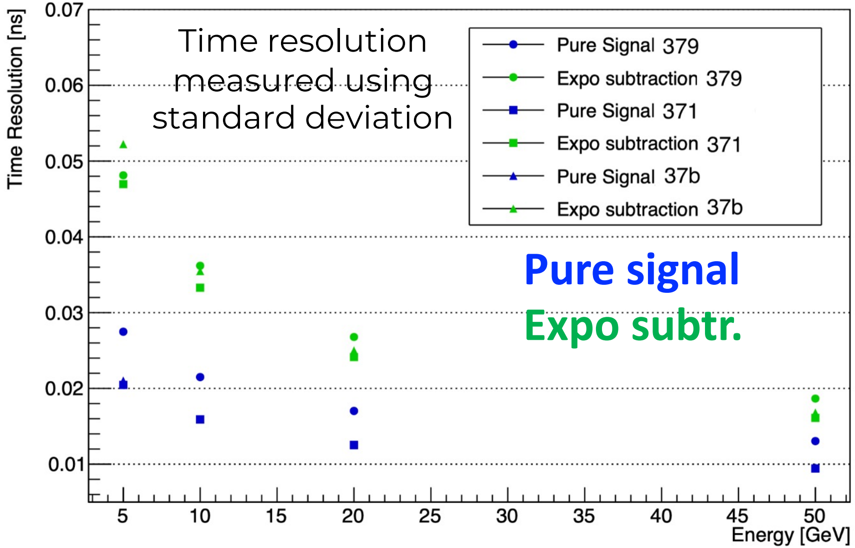
Material	Light Yield [ph/MeV]	$\tau_{d,1}$ [ns] (%)	$\tau_{d,2}$ [ns] (%)
37b	25000	25 (50)	80 (50)
371	13137	15 (60)	40 (40)
379	1000	1.7 (60)	15 (40)

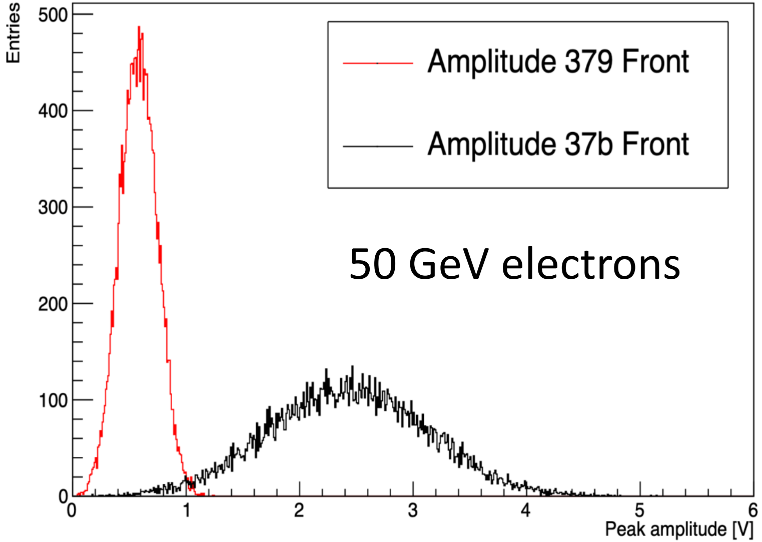
E. Auffray's talk from yesterday



Ultra-accelerated GAGG

- Ultra-accelerated GAGG (circles) does not reach performance of slower but still fast GAGG (squares and triangles)
  - Reason is due to **small signal amplitudes** due to reduced light yield
  - **Optimal balance** between fast decay time and light output **must be found**





Summary and outlook (I)

- Long decay time of GAGG crystals cause spillover effects that deteriorate timing performance of SPACAL
- **Faster GAGG are essential** to mitigate spillover effects
  - R&D samples moving in this direction already present on the market
  - With fast primary component a long secondary component is almost irrelevant
  - Optimal working point requires a **trade off between decay time and light yield**
- **Pulse shaping techniques are important** to mitigate spillover effects
  - Cable clipping and exponential subtraction give similar performance but only for fastest GAGG (τ=15 ns) and using the **full info with 5 GS/s sampling rate**
- Effect of **pile-up** with multiple particles hitting the same cell is an **irreducible effect for now**

Summary and outlook (II)

- Degradation of time resolution is small at higher energies, but not at low energies: **from 20 to 30 ps @ 5 GeV** even for fast GAGG (τ=15 ns)
  - In this study considered a module of SPACAL W/GAGG **not in the hottest region**
  - **Simulated ideal PMTs**: no saturation, infinite dynamic range, fully linear, no electronic noise
  - Simulated the best digitiser available with **full shape at 5 GS/s**
- Next steps (some work already started):
  - Define what can be achieved with **less points at lower sampling rates** ➔ indications from/to electronics
  - Investigate **fancier pulse-shaping techniques** (multivariate algorithms) **to deal with pileup**
  - Find **optimal tradeoff** between decay time and light output for crystals
- Optimisation studies require an holistic approach **taking into account all the components** (crystals, PMTs, electronics…)