A BaF2 calorimeter for Mu2e-II

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Proposal (1)

- ❑ This technological development is driven by the **aim of improving the state-of-the-art calorimetry in search for the conversion of a muon into an electron**.

- ✓ The conversion process is forbidden in the Standard Model of Particle Physics and its observation will be a clear evidence for new physics.

- ✓ Two international experiments are already in construction for this search, one in Japan (COMET at JParc) and one in USA (Mu2e at Fermilab), with the goal of improving the previously reached sensitivity by four orders of magnitude.

Proposal (2)

- Our proposal finds a natural framework and timeline in the upgrade of the Mu2e experiment, Mu2e-II, that will increase of a factor of 10 the sensitivity allowing to observe signals with a branching fraction as small as 6×10^{-18}.

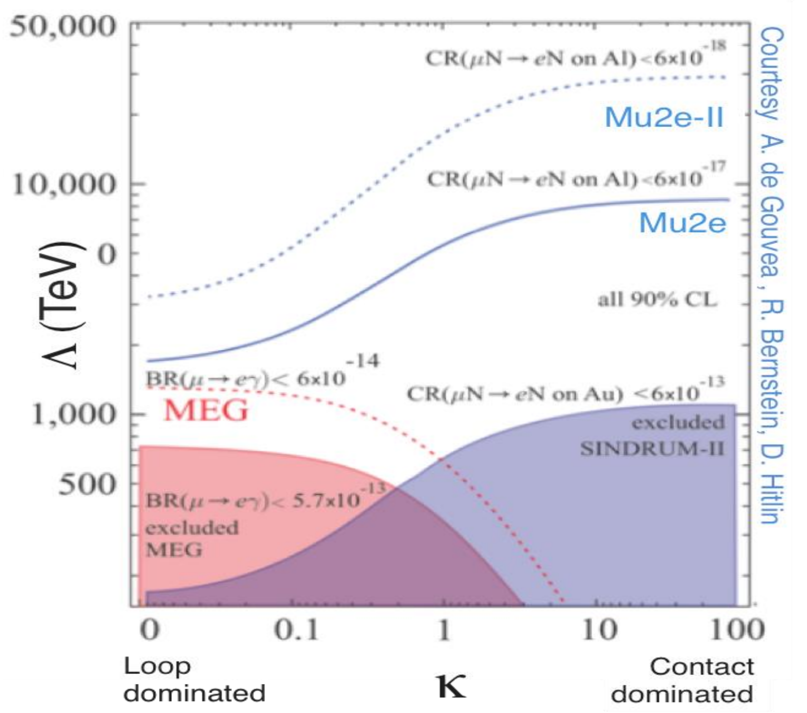


Figure 1: Λ versus κ sensitivity plots for the CLFV muon channels. Mu2e is a potential discovery experiment that is relevant in all possible scenarios.

Proposal (3)

- ❑ To achieve this goal, a very intense, "pure" negative muon beam has to be stopped on a thin target, at the high rate of 30 GHz, inside an evacuated detector region and in presence of 1 T axial magnetic field.

- ✓ A very fast calorimeter, with high timing resolution and extremely high rate capability, can be achieved by optically connecting the extremely fast barium fluoride (BaF_2) crystals to our proposal of a new generation UV extended Silicon Photomultipliers.

- ✓ To do this, we will take full advantage of the fast 220 nm scintillation component (τ = 0.9 ns) strongly reducing the larger slow component at 300 nm (τ = 650 ns) while preserving high gain, low noise and radiation hardness.

State of the art

- The existence of the very fast scintillation component in BaF_2 makes this crystal an attractive, if not the best, candidate for high-rate applications to the upgrade phase of Mu2e calorimeter.

✓ A lot of research and development on UV extended, solar blind, Avalanche Photodiodes (SB-APD) has been carried out from a consortium of Caltech/JPL/RMD in USA.

✓ **The SB-APD works in the proportional regime** (gain between 100-1000), it is a really promising technology and will work properly in magnetic field **but presents three disadvantages that we can overcome with our proposal**:

- **(i)** **the gain is too low** thus requiring a high amplification in the front-end stage;
- (ii) the **signal has** a rise-time of 15 ns but **a quenching time of about 30 ns**;
- (iii) the related **noise is too high to operate at room temperature**.

R&D Approach

❑ **The R&D approach is to transform a standard large-area (6×6 mm²) SensL J-series SiPM into a UV device using a thin layer of nanoparticles.**

✓ The possibility of wavelength shifting using nanoparticles was first tested by ANL in collaboration with the University of Illinois at Urbana-Champaign investigating the properties of Si nanoparticles.

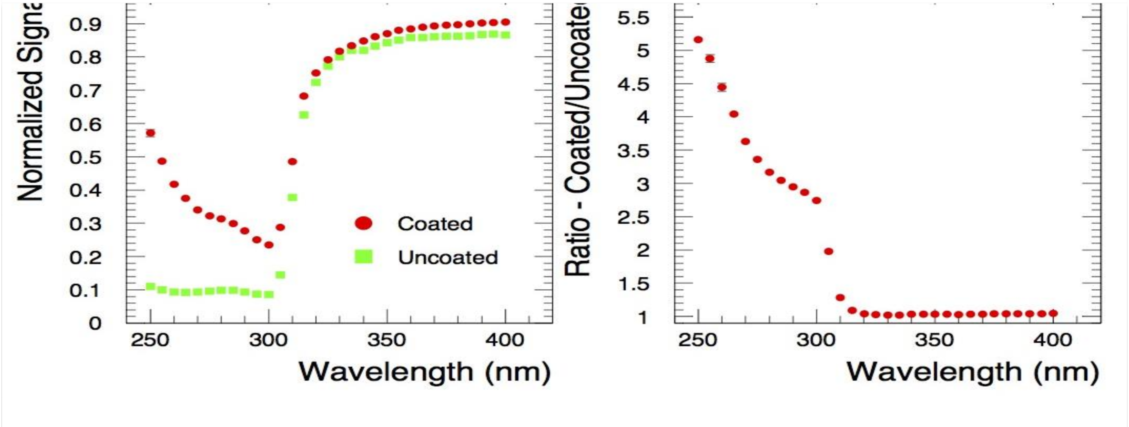


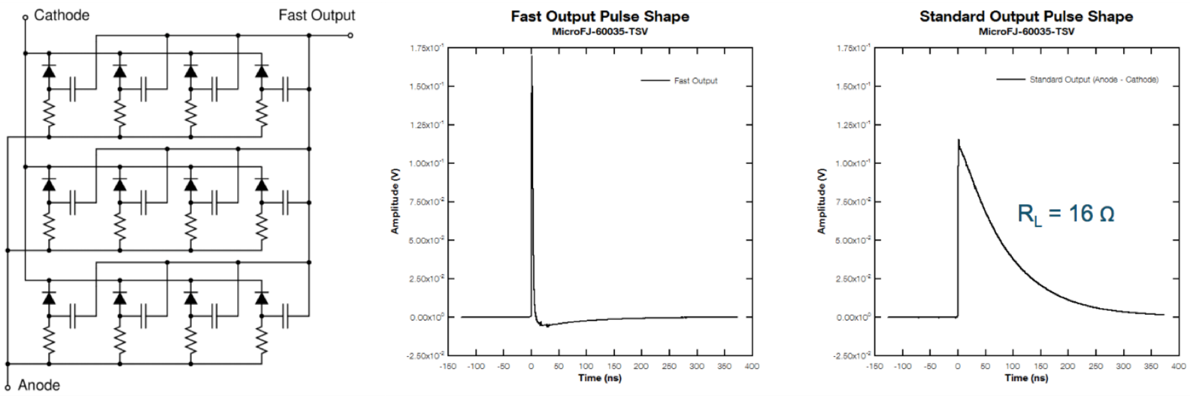
Figure 2: (Left) Response of SiPM through uncoated plastic film (squares), and through plastic film with Si nanoparticle coating (dots). (Right) Ratio between the response of the coated/uncoated configurations.

SensL's J-Series with fast output

The decay time, τ_{SPE}, of a SiPM is determined by the quench resistor values and the total capacitance of the microcells, is typically in the range of tens of nanoseconds:

$$\tau_{SPE} = C_d \cdot \left(R_q + R_{Input} \cdot N_{microcells}\right)$$

- SensL has developed a SiPM with a third electrode coupled to individual diodes through low capacitance. As a result, the response signal has a very short pulse width. The capacitance of the third electrode toward the other SiPM electrodes is ~10% of C_{SiPM}

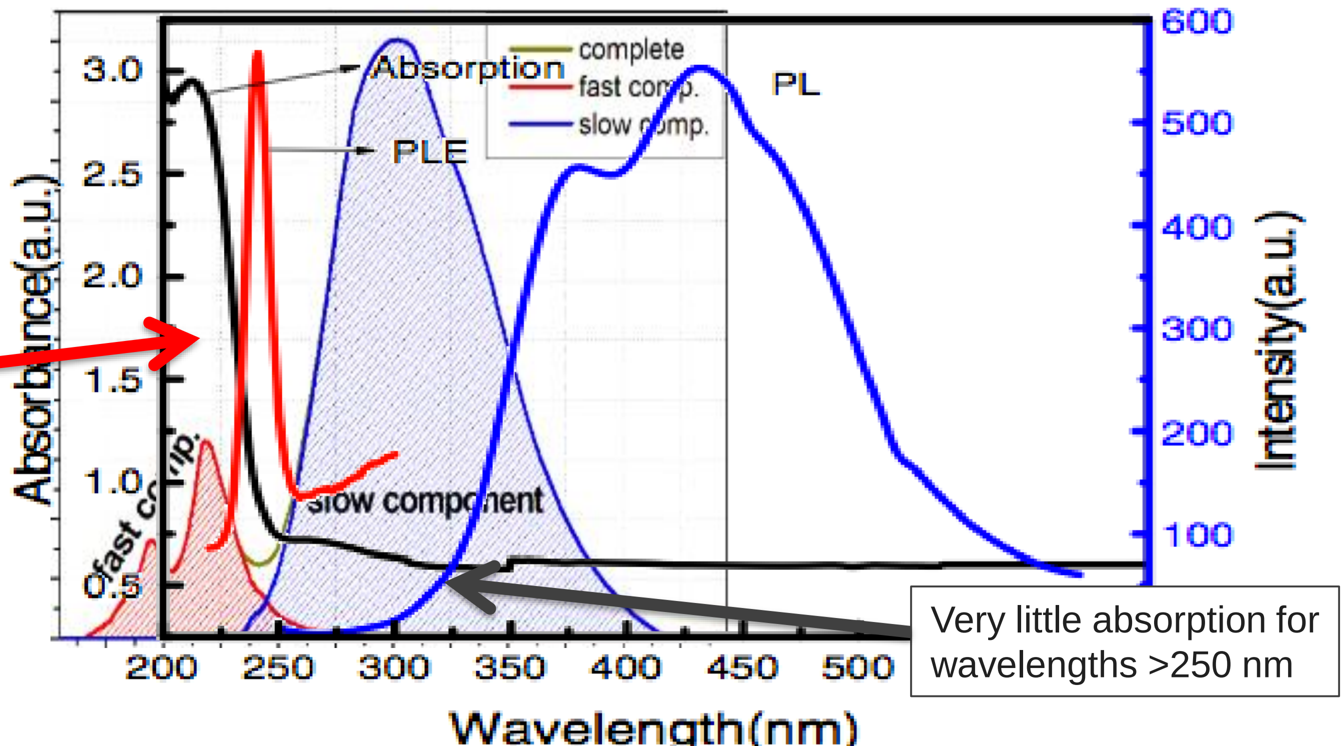


Nanoparticle Type – LaYO

- The constraint for the Mu2e-II experiment is to discriminate between the 220 nm (fast emission) and the above 300 nm (slow emission) components of the BaF_2 emission spectra.

➢ **LaYO nanoparticle is a good candidate for BaF2 Readout**

Note that the 220 nm emission of BaF2 is contained in the absorption peak of the LaYO nanoparticles



Fermilab

Working progress

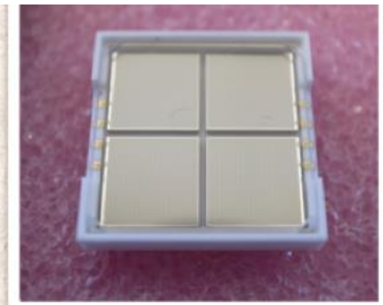
- **The major foreseen risk is to not reach an appropriate level of filtering for the BaF_2 slow component.** Nonetheless, should this case occur, the lesson learned with the first prototypes will suggest us what to improve in order to produce a better filter in short time. The backup plan is to apply another level of filtering to the our device.

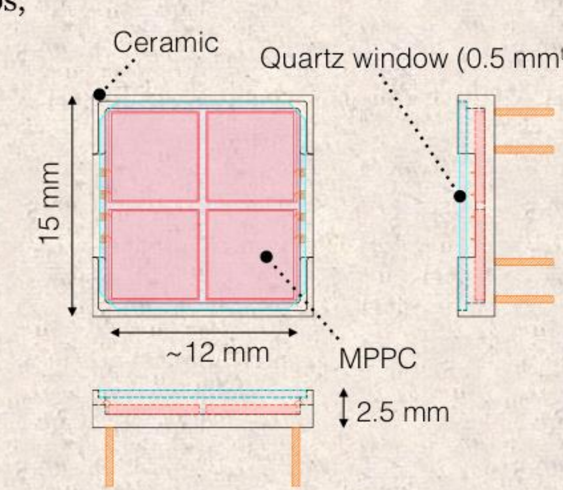
- **A lower technical risk is related to the difference between the emission and the absorption times of the WLS process**. Indeed the procedure must preserve the fast emission time of UV light from crystals (0.9 ns for the barium fluoride). Our goal is to keep this time difference below few ns.

First test with BaF2 and SiPM at LNF

To evaluate the time resolution of the complex BaF2 crystal + SiPM, we have used an UV-sensitive MPPC from Meg.

- **First production model delivered** in March 2014
  - S10943-3186(X)
  - 600 sensors produced for prototype LXe detector
- Active area **~12×12mm²**
  - Discrete array of four independent sensor chips, ~6×6mm² each)
  - **To be operated as a single sensor by connecting 4 chips in series** in external assembly PCB.
- **50μm pixel pitch**
- **Metal quench resistor** (only 20% change at LXe temp)
- **After-pulse suppression**
- VUV-transparent thin quartz window for protection (non-hermetic)





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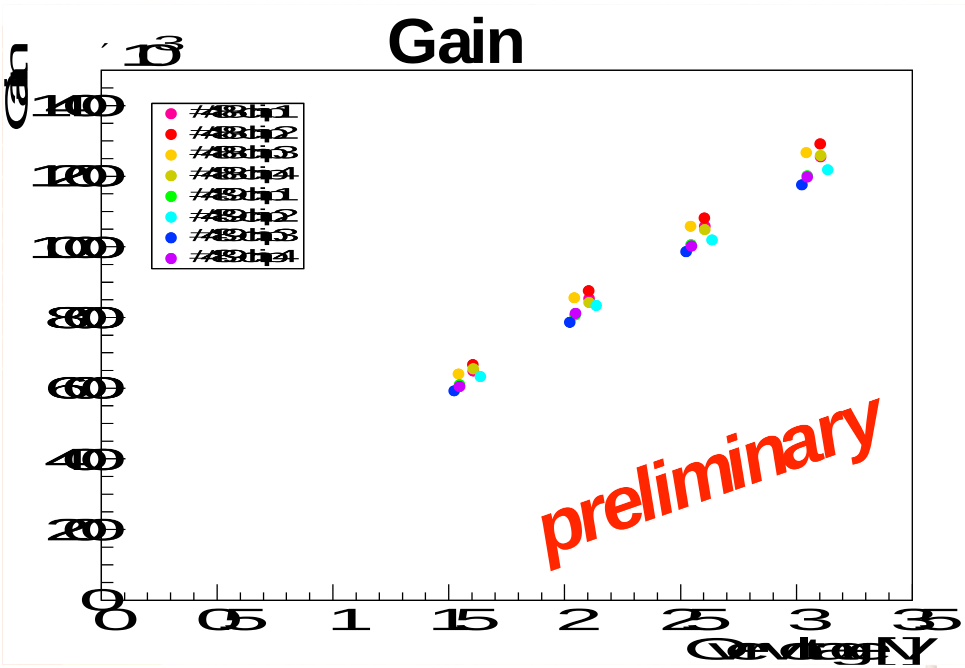
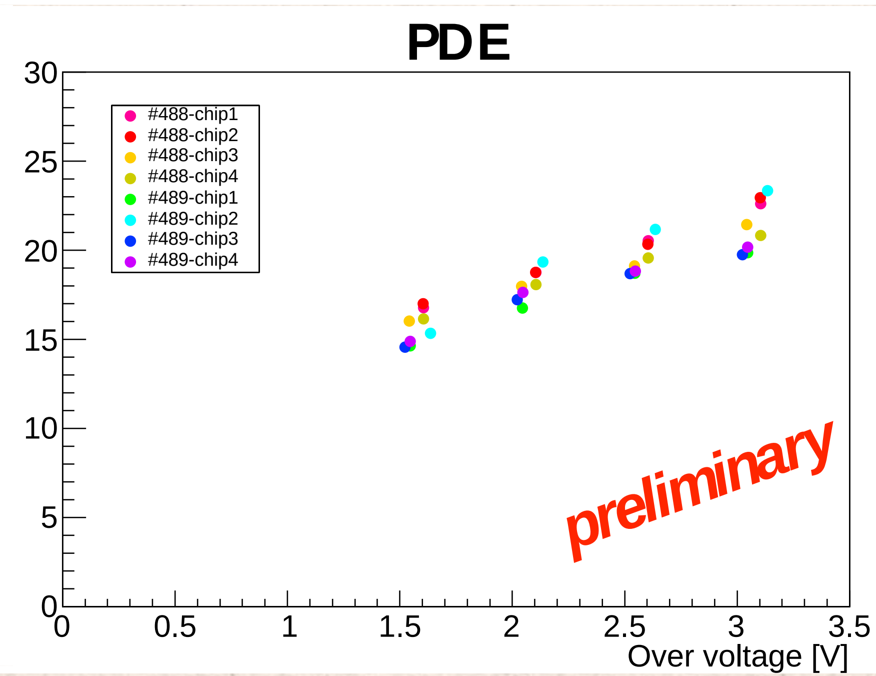
Measured performances for single cell

Voltage = Vbr+2.5, G = 8 x 10^5 PDE = 20%





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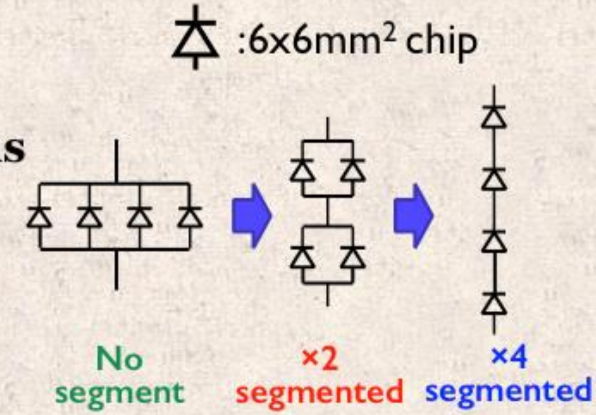
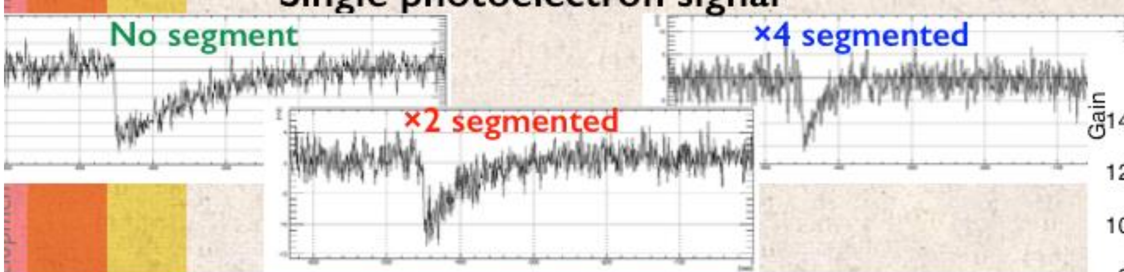
Measured performance for series

- Performance compared bw/ different segmentations.
- **Signal fall time reduced down to 25-50ns with series connection**
- Still reasonably high gain ($>2\times10^5$)

→ **We decided to have 4 segments.**



Single photoelectron signal



	Non-segmented	×2 segmented	×4 segmented
Fall time	135ns ⇒	49ns	25ns

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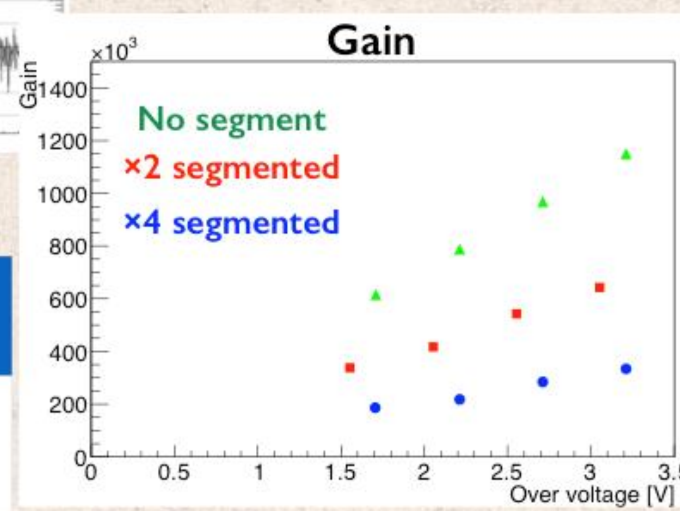
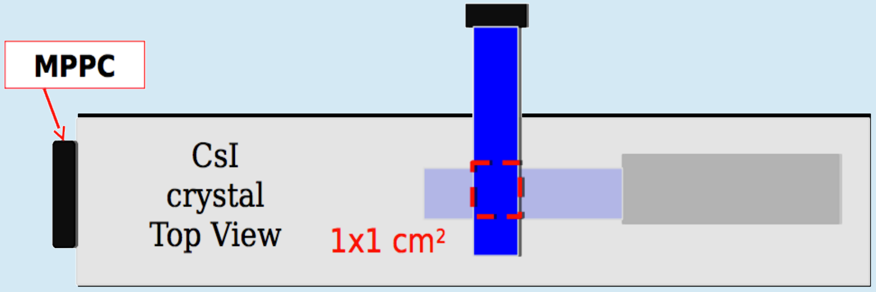


Test of CsI/BaF2 + Meg MPPC with CR

Then we have setup a cosmic rays test station and made the comparison between the performance of the CsI crystals (used in Mu2e) and the BaF2 crystals (proposed for Mu2e-II).

Experimental setup

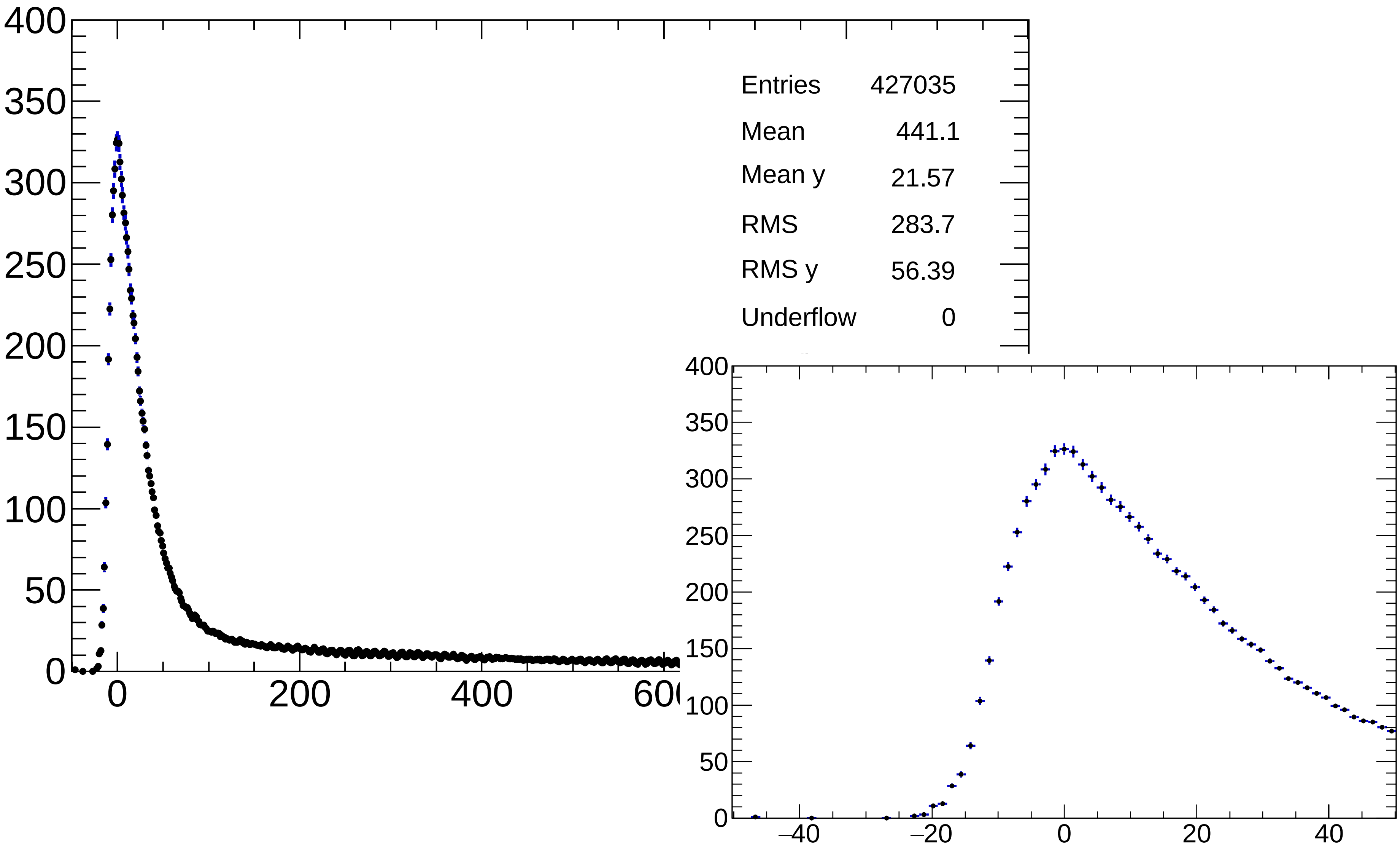
- Crystals between two scintillation counters
- MPPC readout



Analysis thecnique

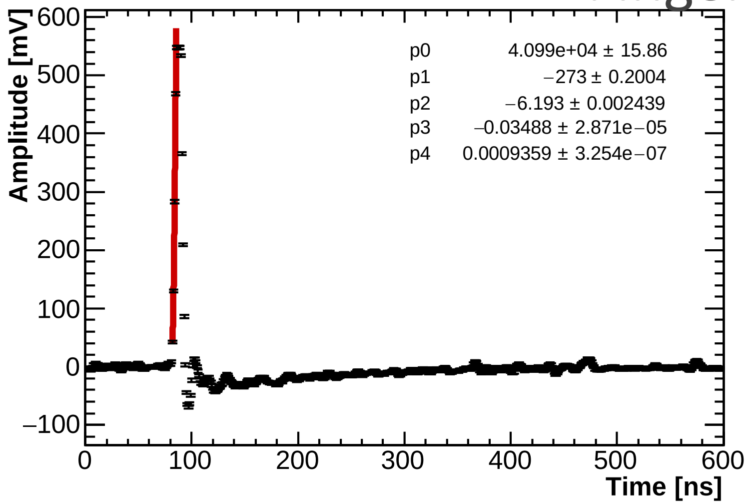
- Fit function -> pol4
- Fit range: (0.1 – 85)% of the max amplitude
- Constant fraction method

Signals shape - CsI

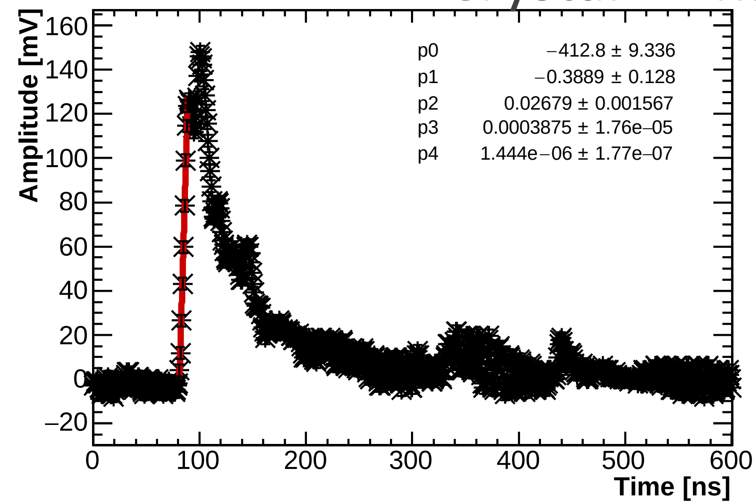


Waveform – CsI

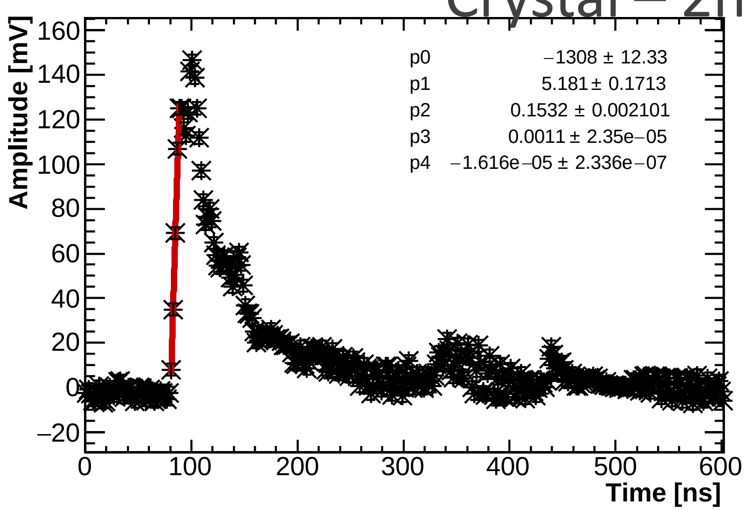
Finger



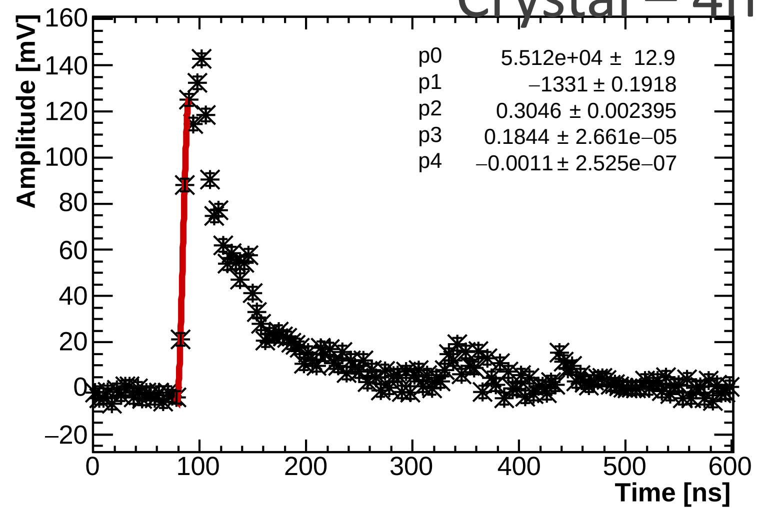
Crystal – 1ns



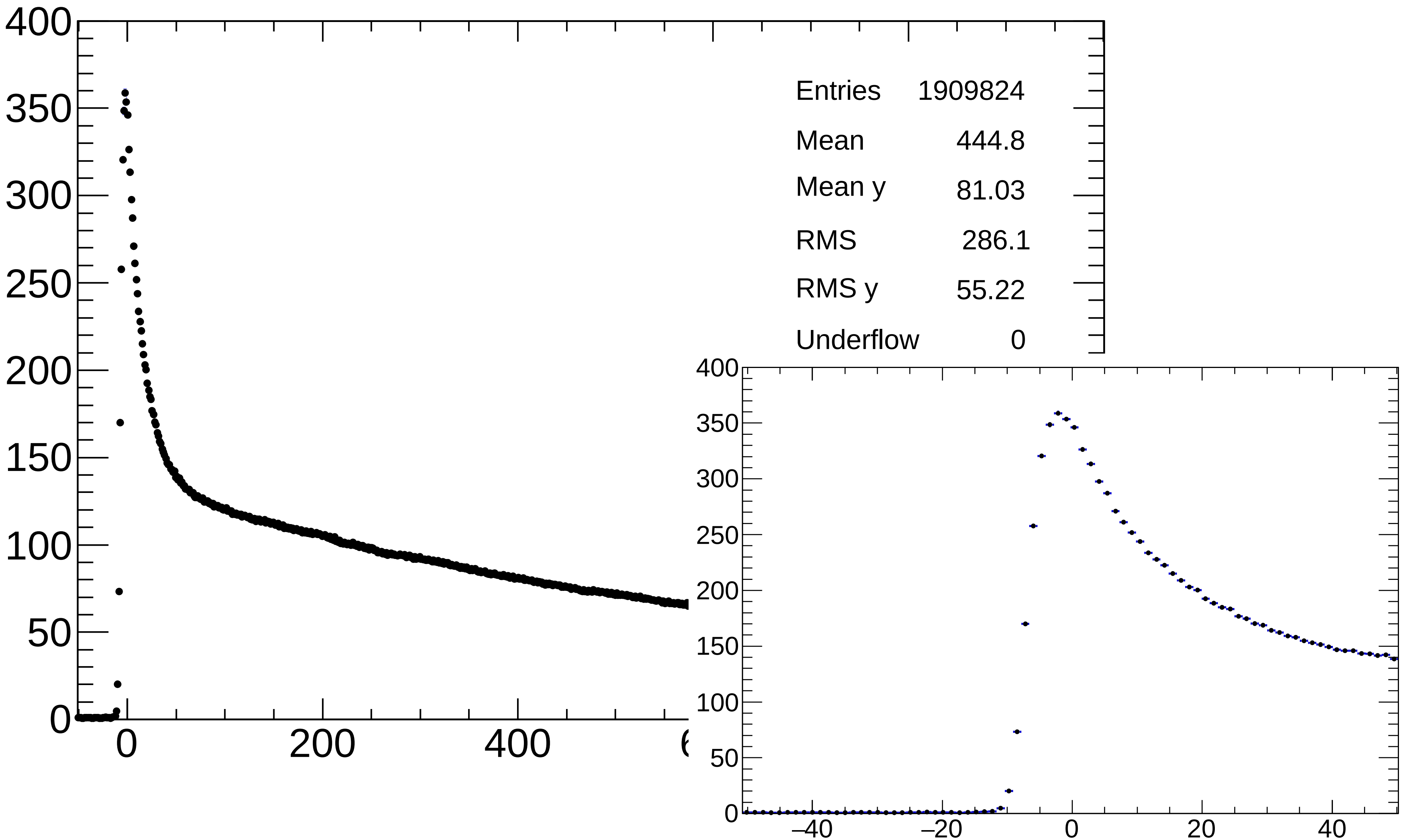
Crystal – 2ns



Crystal – 4ns

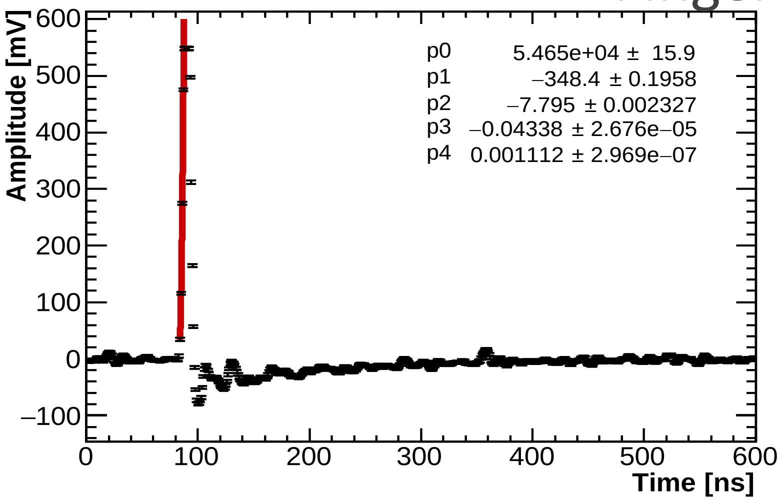


Signals shape - BaF2

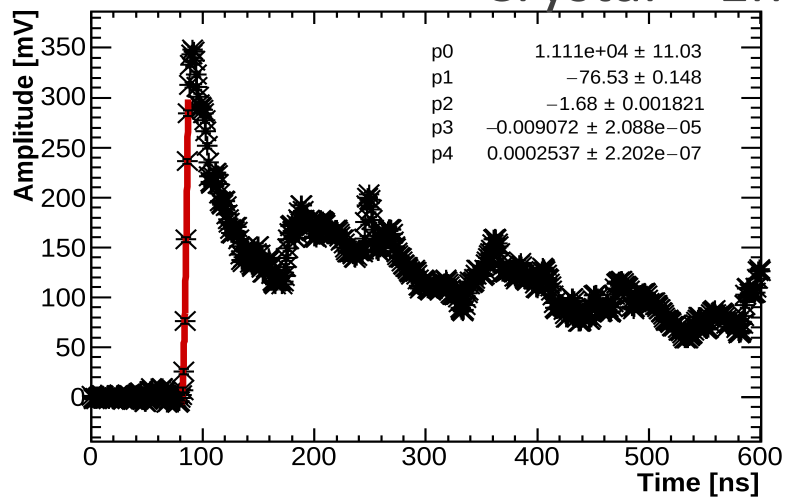


Waveform – BaF_2

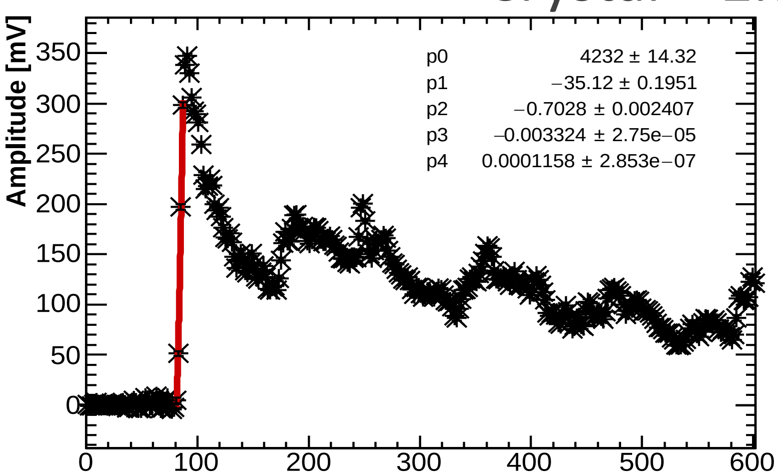
Finger



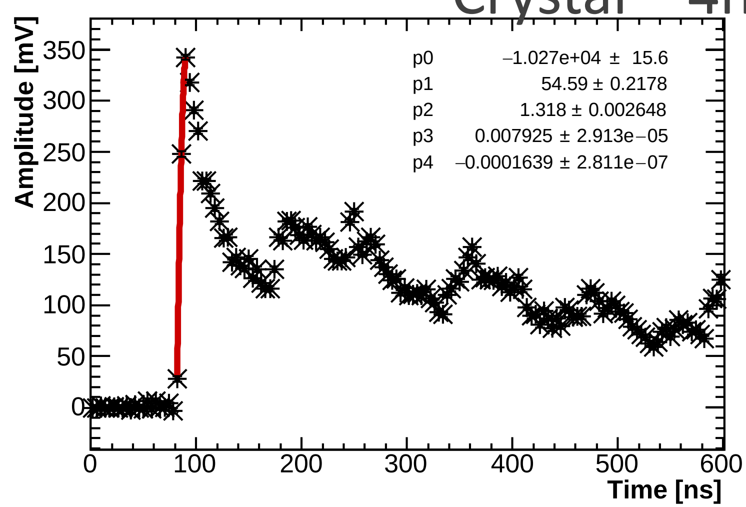
Crystal – 1ns



Crystal – 2ns

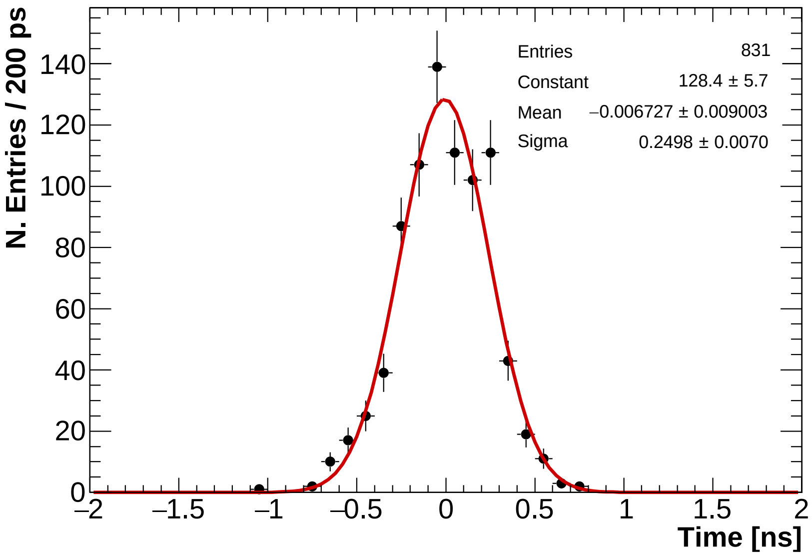


Crystal – 4ns

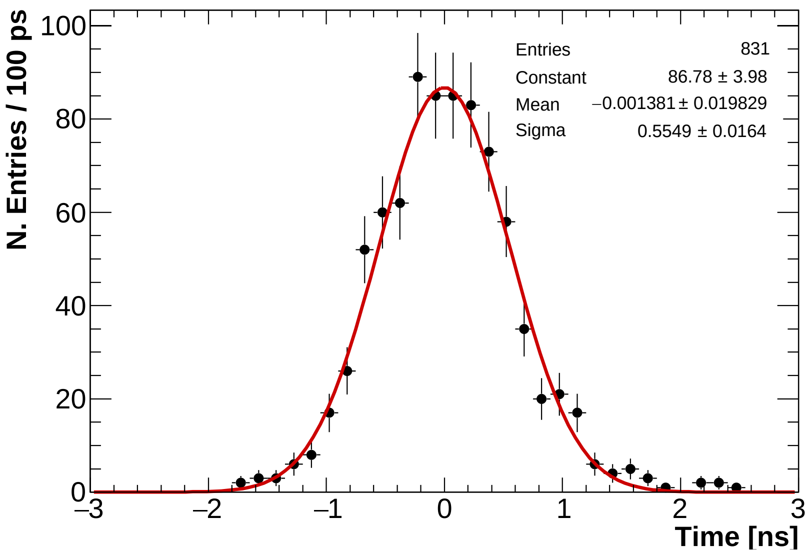


CsI Time Resolution – 1 Gsps/s

Fingers Time resoltion



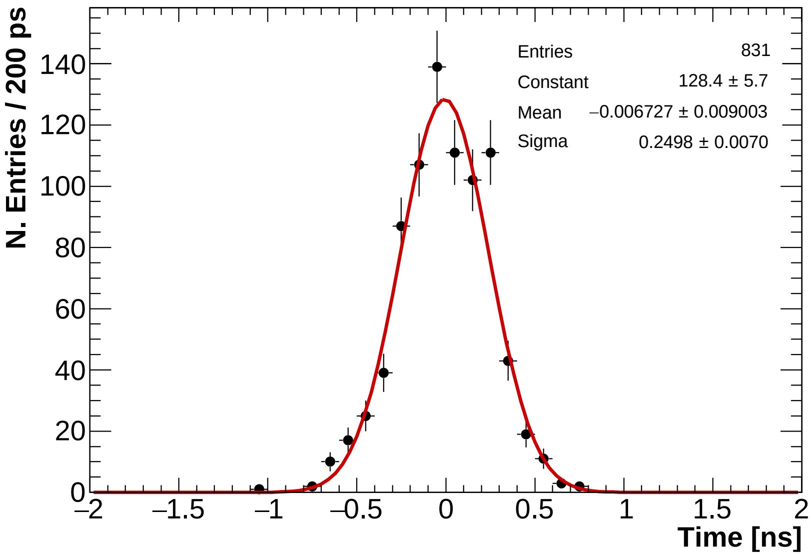
CsI + MPPC time resolution



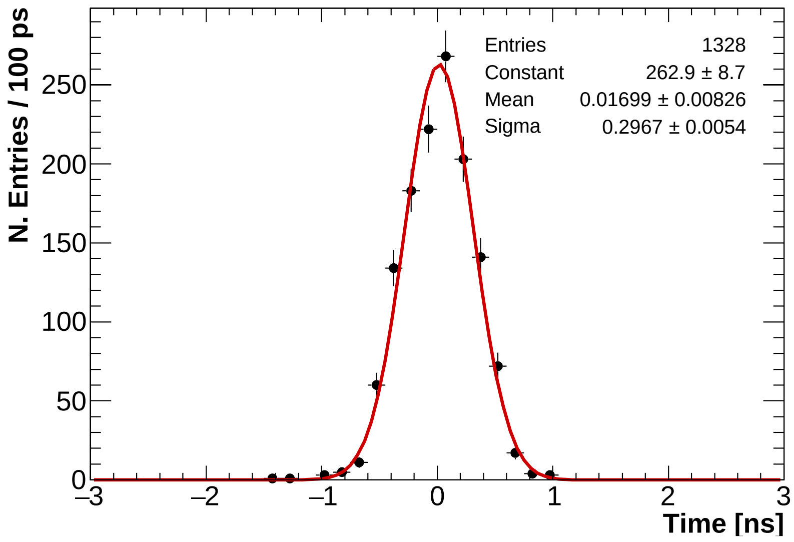
BaF2 Time Resolution – 1 Gsps/s

✓ **The first results are really encouraging**

Fingers Time resoltion



BaF2 + MPPC time



Conclusions

- The framework and timeline of the project find a natural application in the calorimeter upgrade for the phase-II of the Mu2e experiment (Mu2e-II) at Fermilab.
- The requirement for this innovative silicon photosensor is that of being able to readout the fast component (220 nm) of the light emitted by the BaF2 crystals while achieving practical blindness to the slow component (> 300 nm).
- Using these sensors and the BaF2 crystals, we aim to build a radiation hard calorimeter with good energy resolution and extremely high performance in timing resolution, rate capability and pileup discrimination power for 100 MeV electrons. All of the above has to be achieved in the presence of a strong magnetic field (1 T), in a radiation hard environment and with 10 GHz muon beam impinging on a thin target.