Timing Resolution in Aligned PWO Crystal Scintillators

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MOTIVATION

Understanding and correct simulation of electromagnetic showers plays key role when developing HEP experiments. Enhanced radiation and pair production, induced by the crystalline structure of a detector medium, accelerate EM shower development when particle moves at a small angle with respect to crystal axes and comes from its coherent interaction with ordered atoms.

Our recent evaluation of the upper limit of crystal effects in the lead tungstate crystal of the CMS electromagnetic calorimeter showed that the peak of the electromagnetic shower shifts by 2-4 radiation lengths to the entry surface of the crystal [1].

The reduction of effective radiation length in aligned PWO crystal was experimentally observed at CERN SPS [2].

Such shower modification demands **reconsidering** of event reconstruction methods.

References

1. V. Baryshevsky et al., Nucl. Instr. Meth. B 402 (2017) 35.
2. L. Bandiera et al., Strong Reduction of the Effective Radiation Length in an Axially Oriented Scintillator Crystal Physical Review Letters 121, 021603 (2018).

We present timing variations of the EM calorimeter signals from showers in **“crystal” PWO** for ***paraxial*** gamma-quanta, electrons and positrons in comparison with signals from showers in the **“amorphous” PWO**, i.e. when EM shower develops far from directions of main crystal axes and planes.

Current ECAL Timing Performance

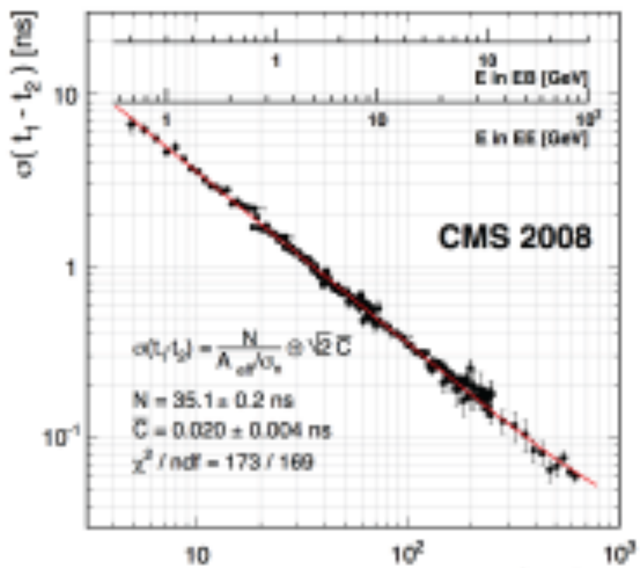
Test beam (2008)

- 2 crystals in the same EM shower: **20 ps constant term**

In-situ (Run1)

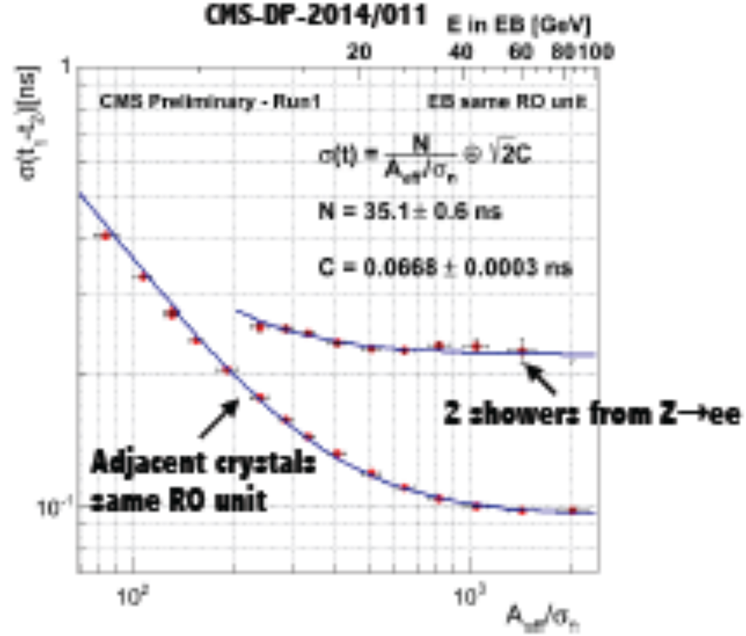
- 2 crystals in the same EM shower & same readout unit: **70 ps constant term**, degradation due to time calibration stability
- 2 crystals in different showers from Z→ee: **150 ps constant term**, additional degradation from clock distribution

JINST 5:T03011,2010



$A_{\rm eff} = A_1 A_2 / \sqrt{A_1^2 + A_2^2}$

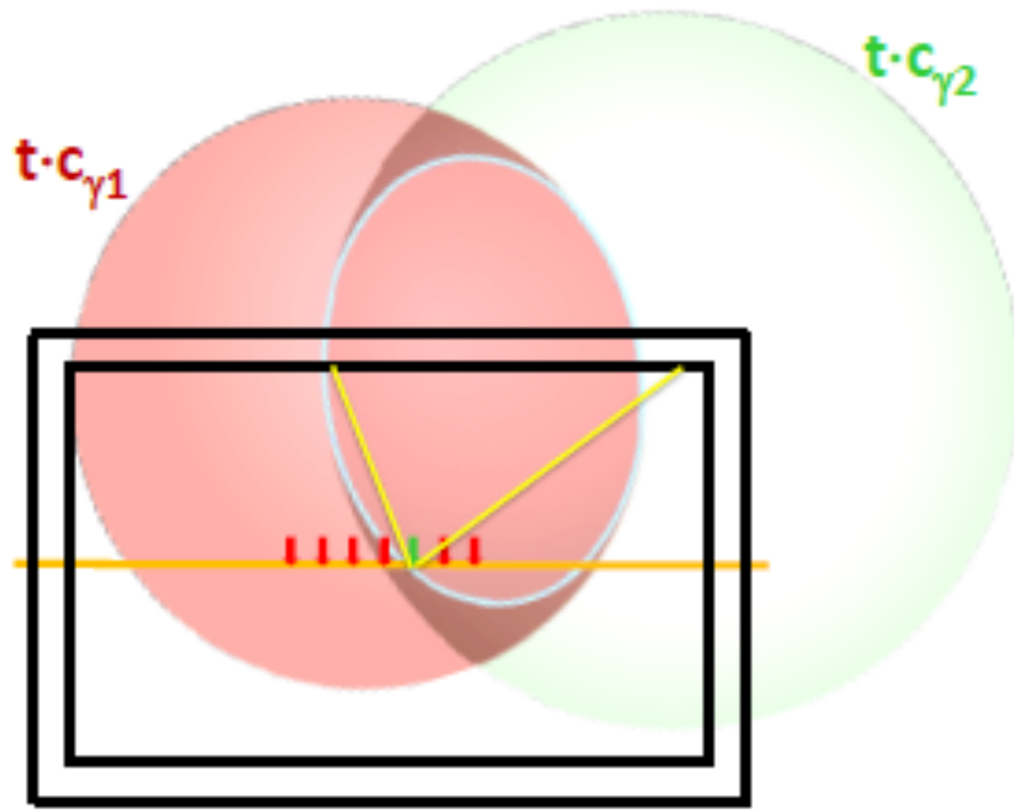
CMS-DP-2014/011



Picture from P. Meridiani talk Precision timing calorimetry with the upgraded CMS ECAL

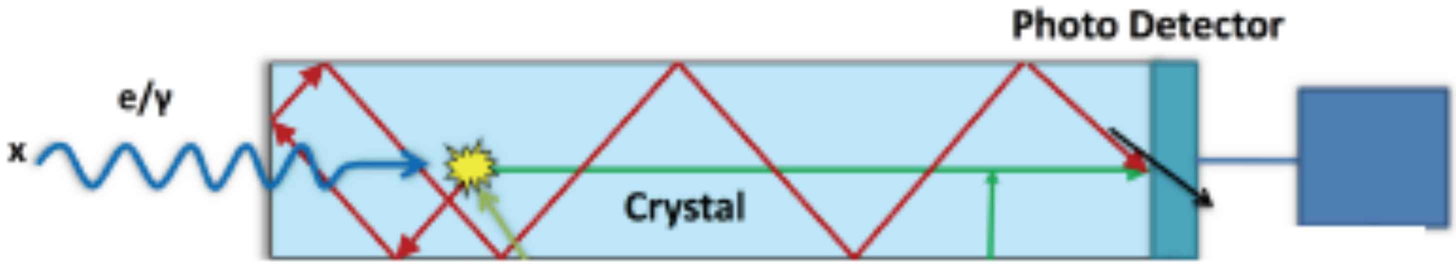
4D Triangulation with Photon Timing

- With two time and position measurements eg. from two photons and with the constraint from the beam axis x and y location, the vertex x and t can be calculated analytically.
- Equivalent to GPS with two satellites.



Picture from A. Bornheim talk Precision Timing Detectors for Particle Physics

Precision Timing with Crystals

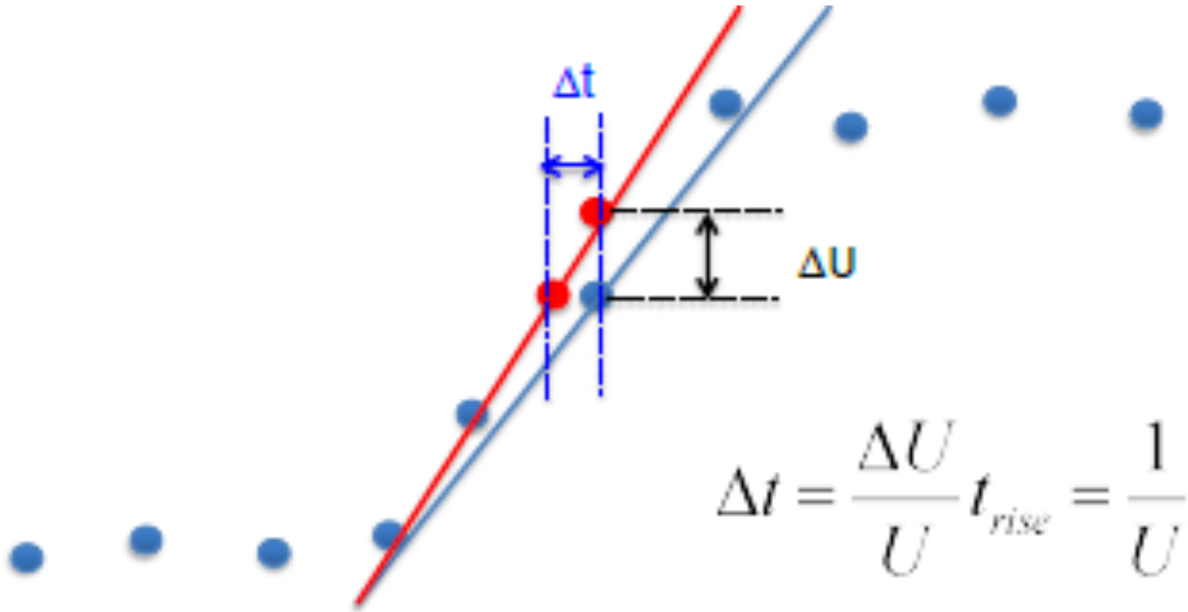


Several ingredients determine the time resolution of an electromagnetic shower in a homogeneous crystal calorimeter

- **Intrinsic EM shower fluctuations**
  longitudinal shower fluctuations
  optical transit time spread: scintillation rise/decay time, light propagation
- **Photodetector + electronics**
  photodetector: rise time, transit time
  noise: dark current, electronic noise
- **DAQ**
  clock distribution

Picture from P. Meridiani talk Precision timing calorimetry with the upgraded CMS ECAL

Fast Timing Fundamentals



$$\Delta t = \frac{\Delta U}{U} t_{rise} = \frac{1}{U} \frac{\Delta U_i}{\sqrt{n_{samples}}} t_{rise}$$

For good time resolution, need:

1. **fast rise time (t_{rise})** ⇒ primary signal rise time (scintillation : LYSO ~30 ps, Si sensors ~1ns)
2. **low Signal-to-Noise ($\Delta U/U$)** ⇒ primary signal amplitude : LYSO ~30k photons/MeV (1.07 MeV/mm MIP) , Si sensors ~30k e/h pairs in 300 µ for a MIP
3. **more time samples ($n_{samples}$)**

Picture from A. Bornheim talk Precision Timing Detectors for Particle Physics

Methodology

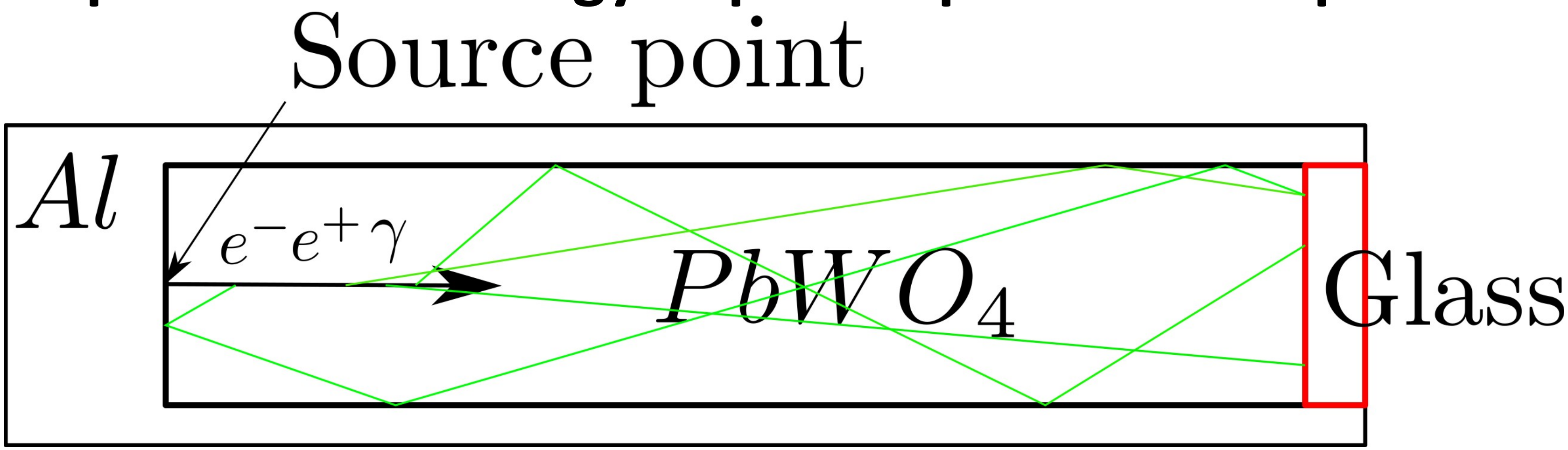
To estimate the PWO crystal structure influence on the energy deposition, the GEANT4 simulation of electromagnetic shower development in a structureless PWO standard sample routinely implemented in GEANT4 was used as a *benchmark*.

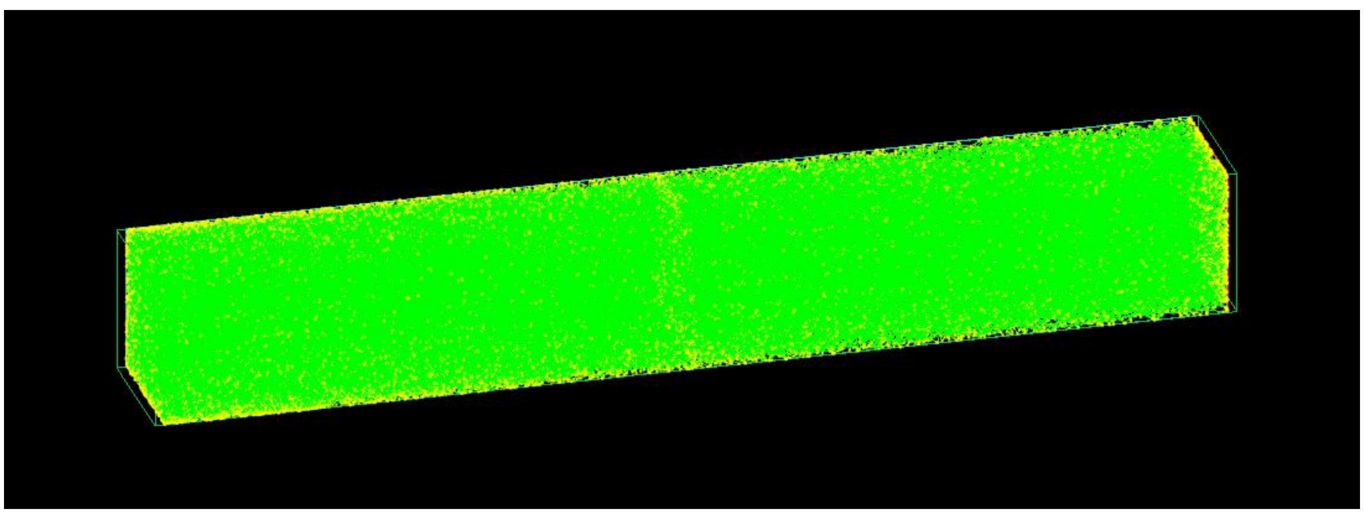
First, the characteristics of both pair production and gamma-quantum emission in the PWO crystal have been evaluated by the method developed earlier for various gamma-quantum and electron (positron) energies.

The obtained pair production probabilities and electron (positron) energy loss lengths, increased due to the influence of the PWO crystal structure, have been introduced into the GEANT4 simulations through the increase of the corresponding values for the structureless PWO.

GEANT4 simulation

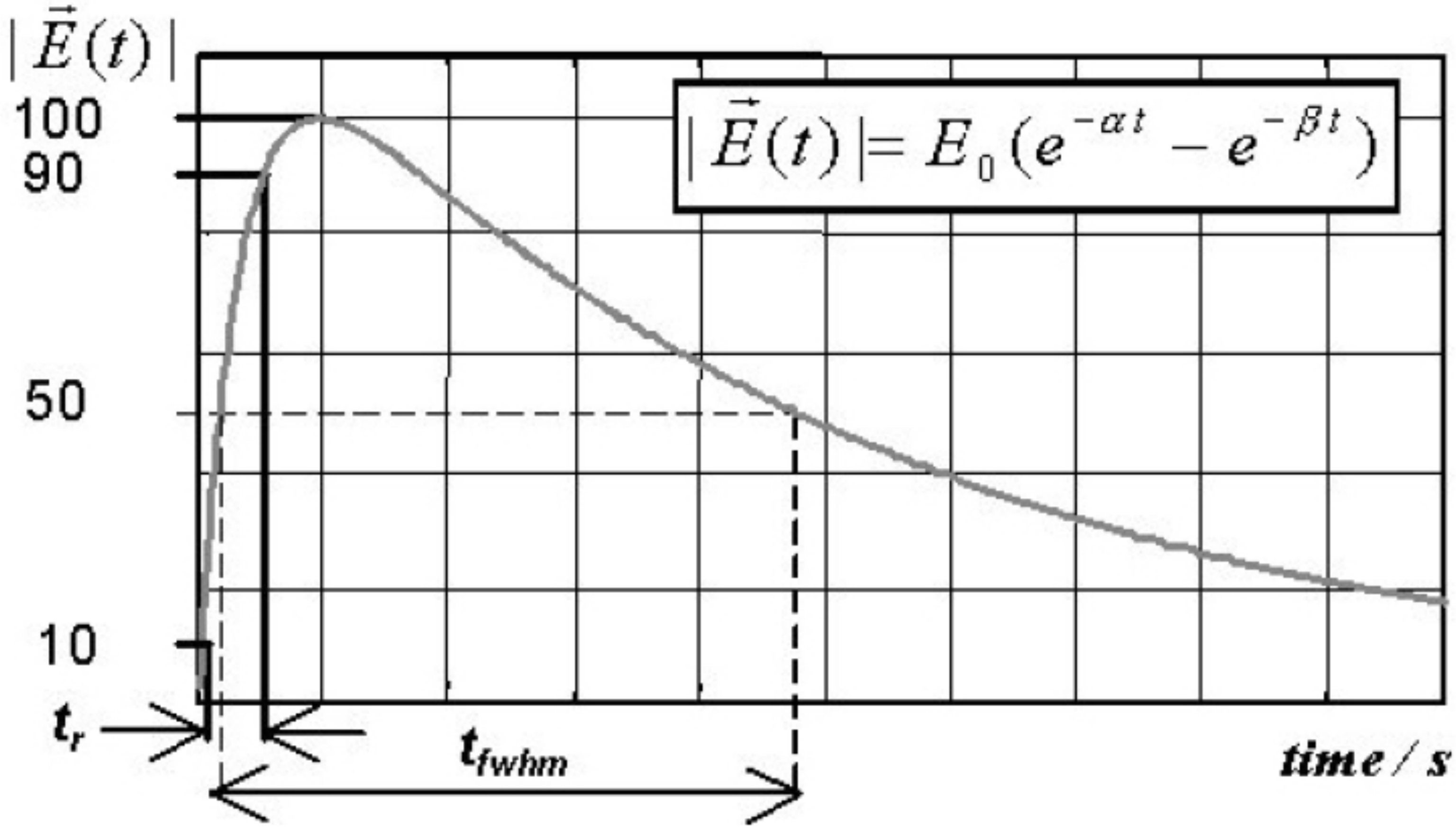
CMS ECAL endcup crystal 30x30x220 mm wrapped with polished Al. Energy deposit + photon transport





Supercomputer MARCONI CINECA, Italy https://www.cineca.it

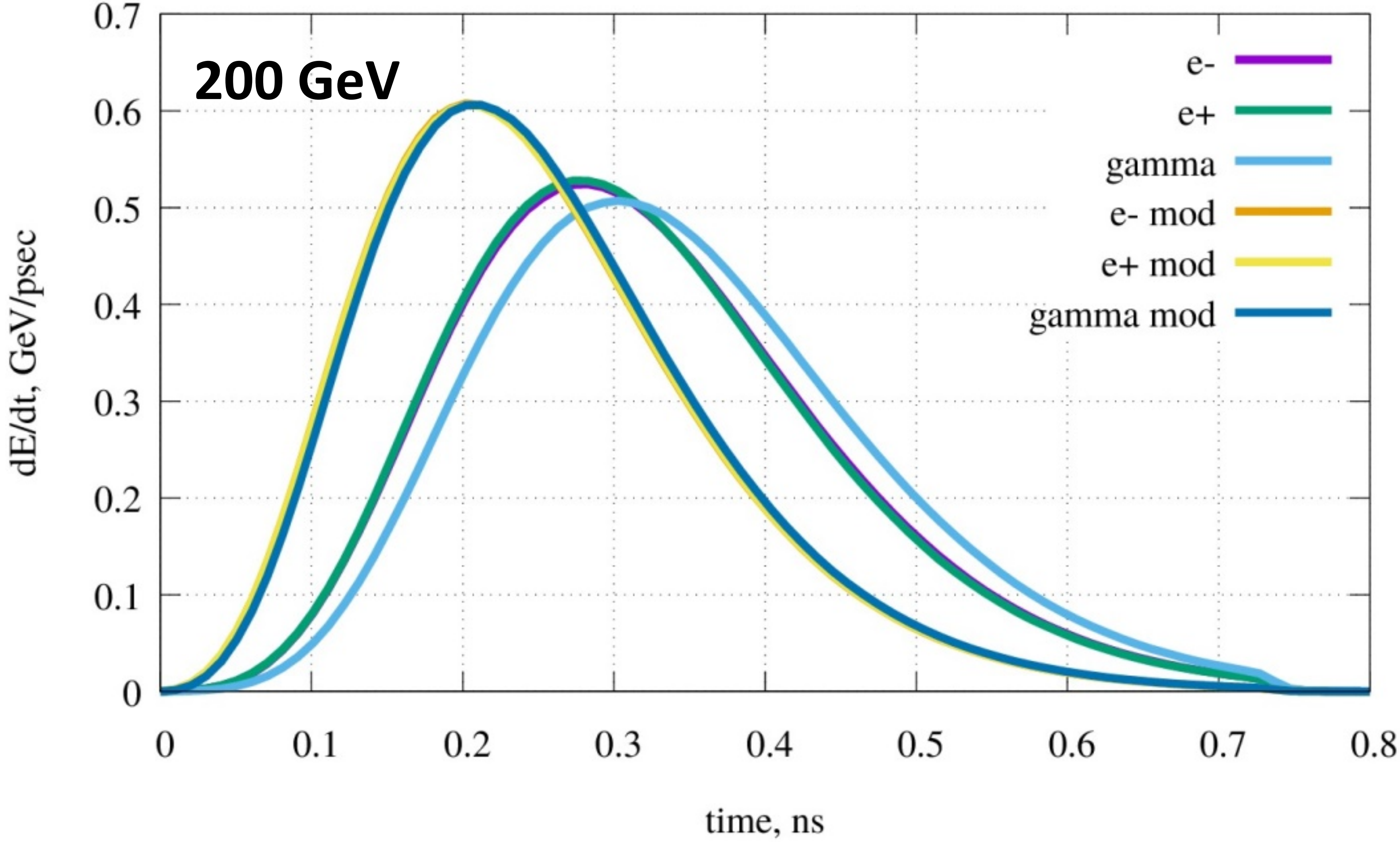
PWO Double Exponential Pulse Shape



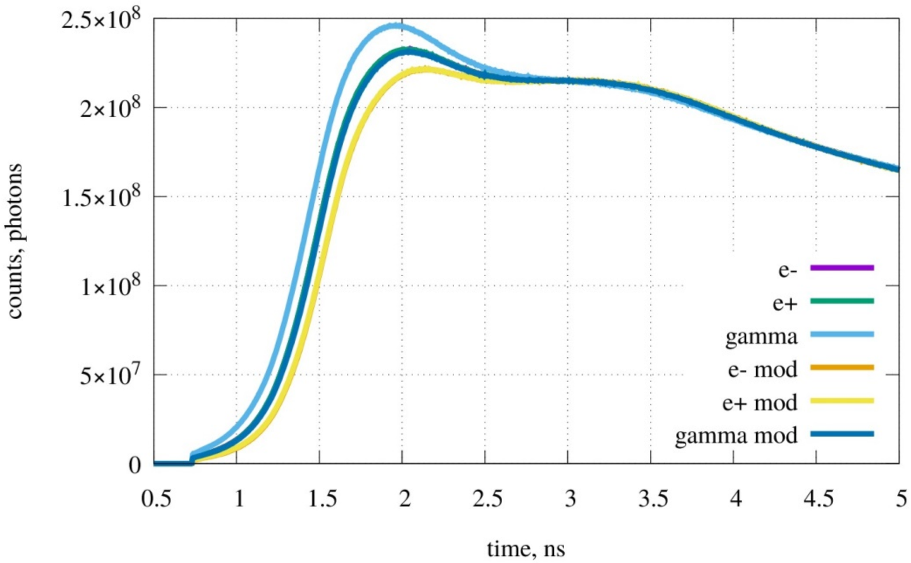
$\alpha = 1/\tau_{rise}$, $\tau_{rise} = \sim 4\ ps$

$\beta = 1/\tau_{decay}$, $\tau_{decay} = \sim 10\ ns$

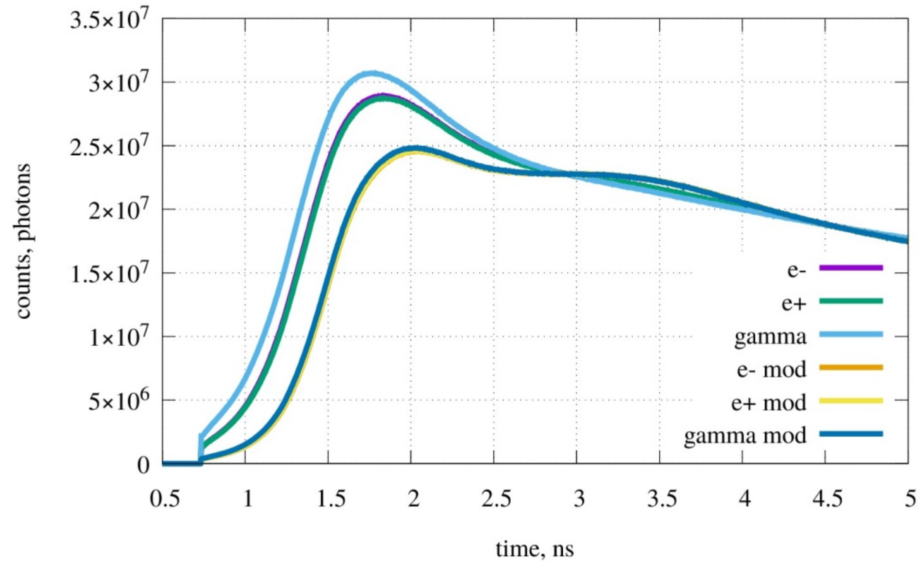
Energy deposition



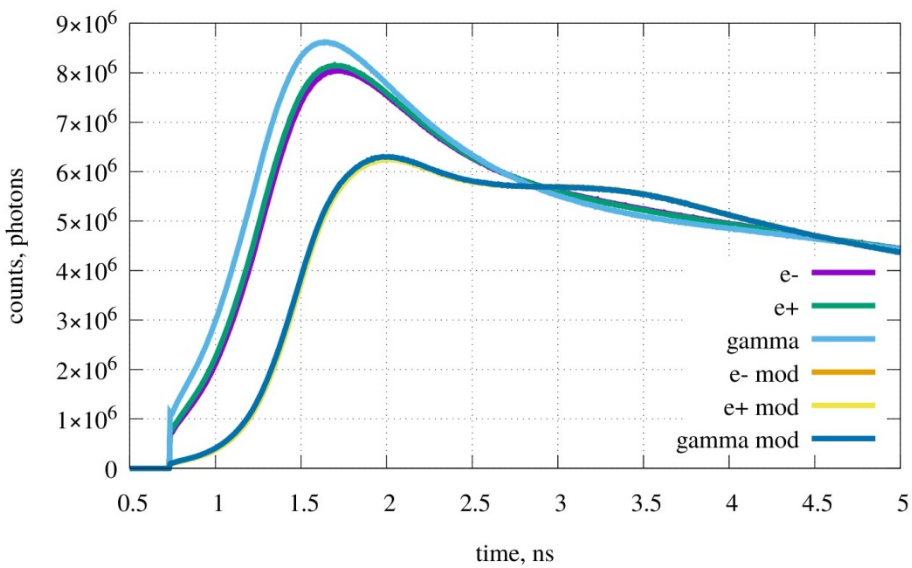
Signal front shape at various energies



20 GeV

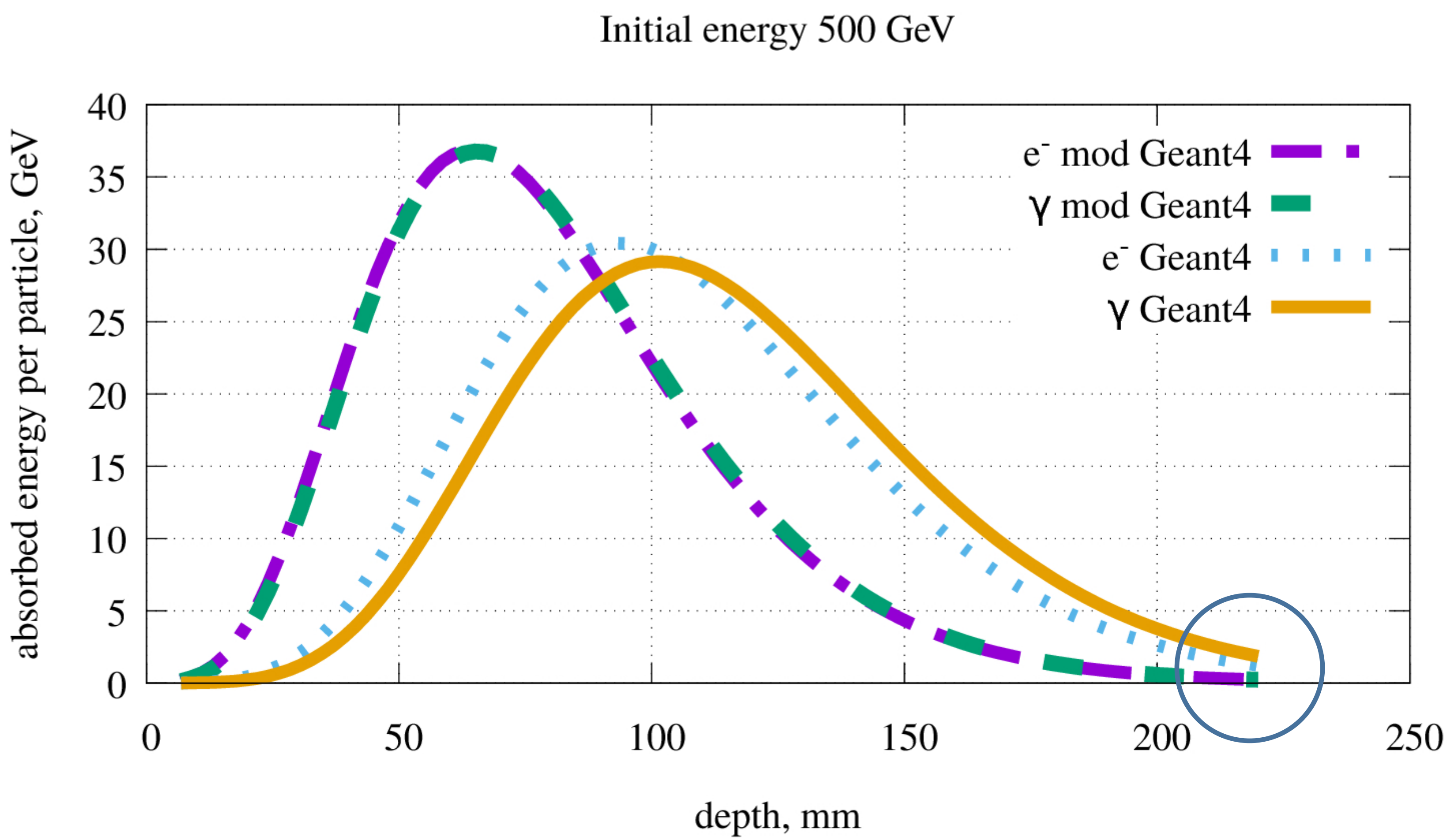


200 GeV



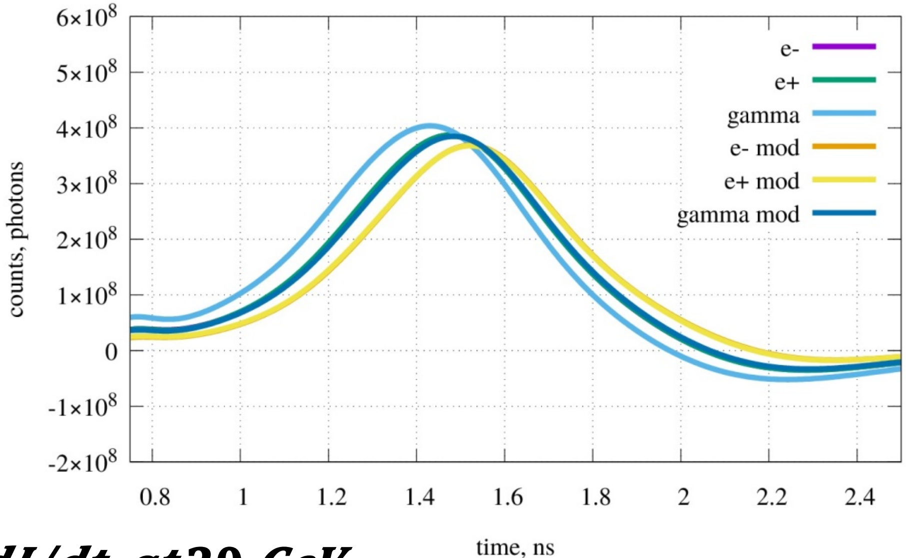
1000 GeV

Results with modified GEANT4 functions

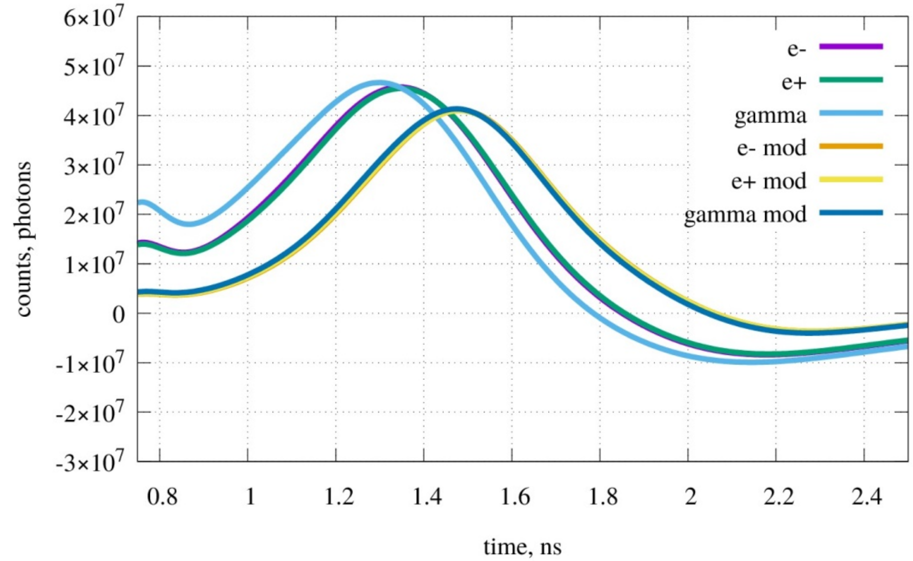


Shower accelerated to approximately 4-5 radiation lengths, thus reducing rear leakage and constant term in the calorimeter energy resolution

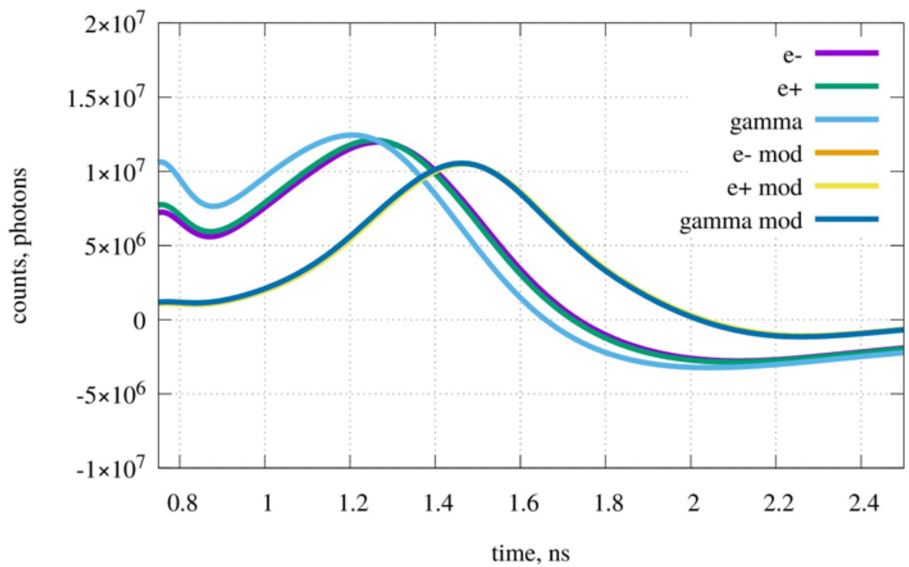
Signal rise time at various energies



$dI/dt\ \ at\, 20\ GeV$



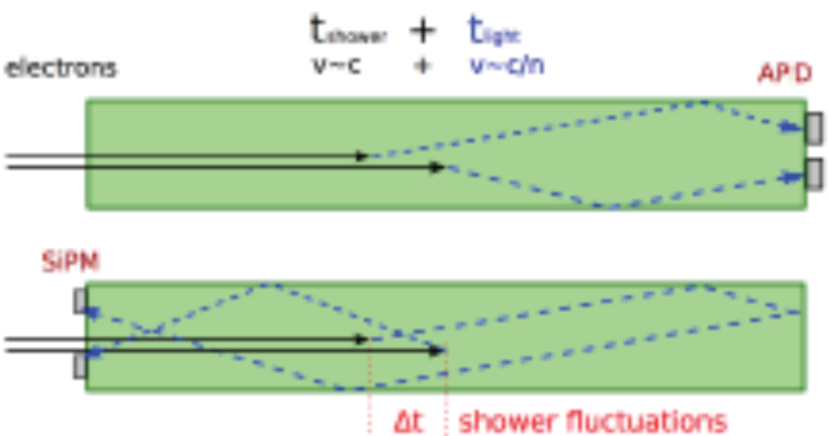
$dI/dt\ \ at\, 200\ GeV$

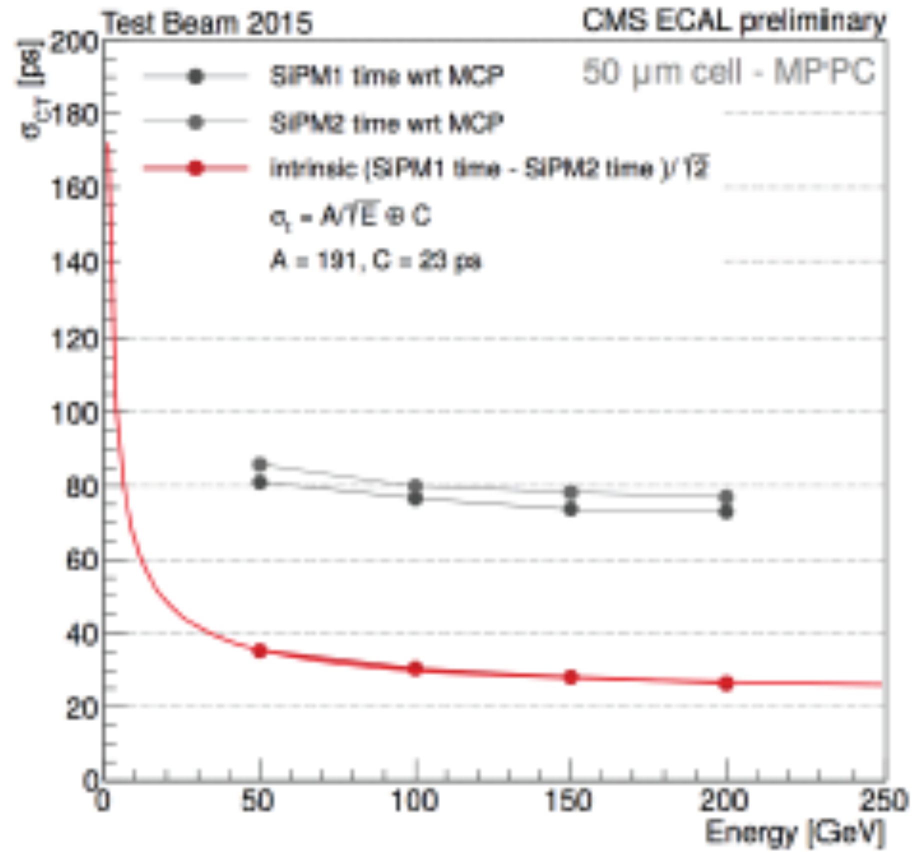


$dI/dt\ \ at\, 1000\ GeV$

Test Beam 2015

Readout using 2 SiPMs from the front face
resolution dominated by longitudinal shower fluctuations (~80 ps constant term)





Picture from P. Meridiani talk Precision timing calorimetry with the upgraded CMS ECAL

Conclusions

- *Results* of simulations of the electromagnetic shower development accelerated by the crystal-assisted processes in the PWO crystals manufactured for the ECAL CMS are reported;
- Obtained results *can be used as an experiment proposal*
- Obtained results *can be used* to refine the methods of a particle reconstruction by Compact Muon Solenoid at LHC (CERN);
- Obtained results *should be used* when performing detector study for Future Circular Colliders and other similar projects at energy frontier (Energy Dependent!);
- Obtained results *should be used* for development of dedicated patches at relevant particle tracking computer toolkits, like GEANT4 and others.

Thank you for attention