Simulation of the CMS Electromagnetic Calorimeter Response at the Energy and Intensity Frontier

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on behalf of the CMS Collaboration

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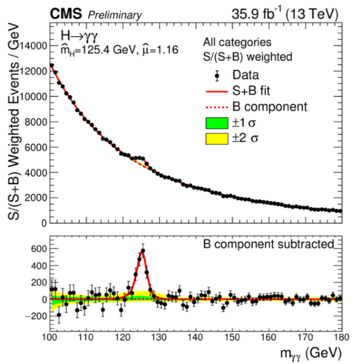
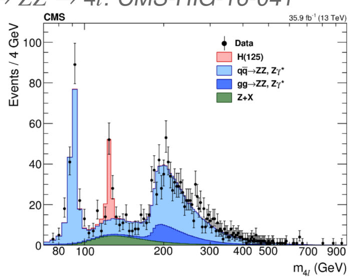
The CMS detector and electromagnetic calorimeter (ECAL)

ECAL is the main component of CMS to *detect and precisely measure* the energies of e/γ

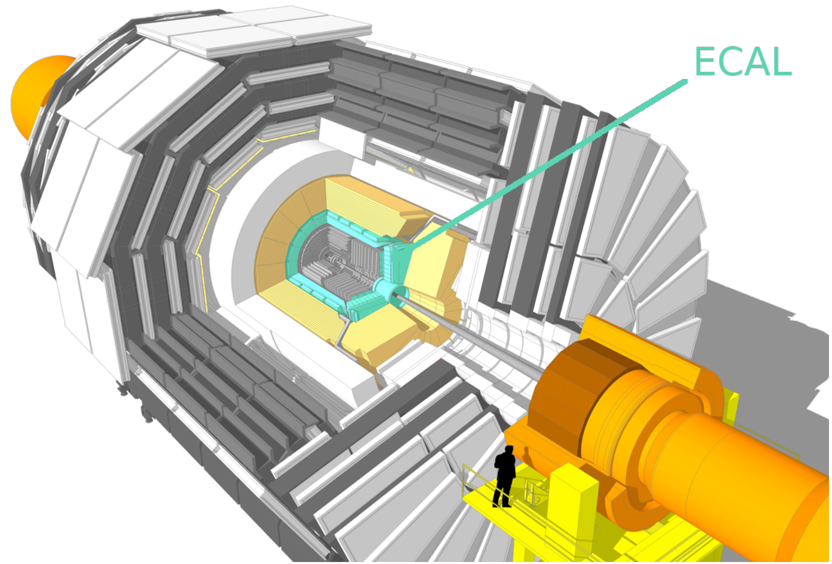
$H \to \gamma\gamma$: CMS-PAS-HIG-16-040



$H \to ZZ \to 4l$: CMS-HIG-16-041



The *excellent resolution and electron/photon ID* of the CMS ECAL was crucial in the *discovery and subsequent characterization* of the **125 GeV Higgs Boson**



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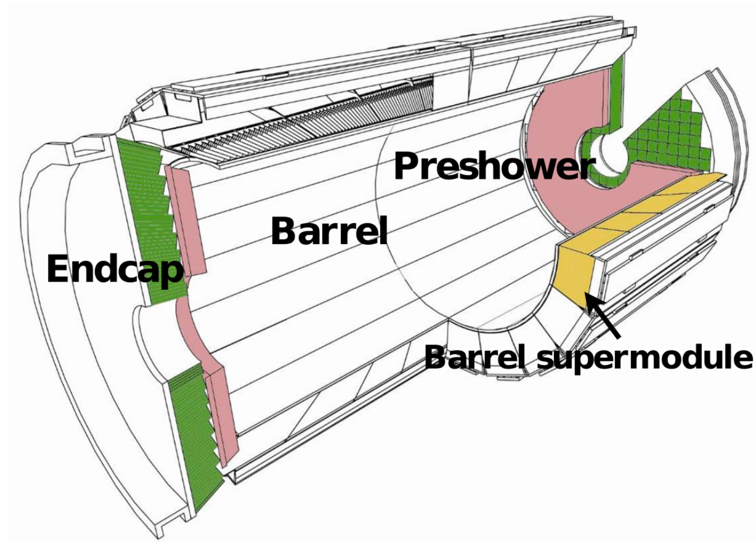
The CMS Electromagnetic Calorimeter

Crystal Barrel and Endcap ($PbWO_4$) + Lead/Si Preshower Endcaps

Barrel (EB):
36 supermodules (1700 channels)
Total of 61200 $PbWO_4$ crystals
Avalanche Photo-Diode readout
Coverage $|\eta| < 1.48$

Endcap (EE):
Four half-disk Dees (3662 channels)
Total of 14648 $PbWO_4$ crystals
Vacuum Photo Triode readout
Coverage: $1.48 < |\eta| < 3.0$

Preshower (ES):
Two Lead/Si planes
137,216 Si strips $(1.8 \times 61\ mm^2)$
Coverage: $1.65 < |\eta| < 2.6$



Simulation of ECAL response

This presentation will focus on simulation of crystal calorimeter response (EB and EE) to EM showers.

Simple approach:

- Simulate energy depositions in crystal volume with GEANT4
- Assume the response of ECAL channel is (almost) proportional to energy depositions
- This approach is used in most of the cases

Detailed Simulations (this presentation):

- Pulse shape formation at the photo-detector stage (photo-current)
- Pulse shape at front-end stage before digitization
- Allows to study sensitivity of ECAL response to
  - loss of transparency in crystals (radiation damage)
  - spatial EM shower fluctuations

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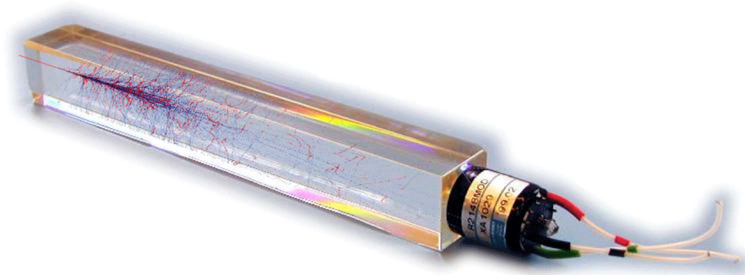
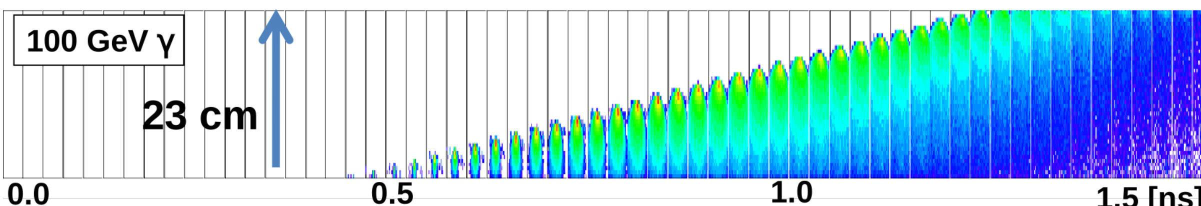
Step I: Energy depositions with GEANT4

Typical step in simulation.
Standard simulation of EM shower in crystal material.
Record energy depositions to be converted into scintillation light.
Simulate Cerenkov radiation



Also: Record time of individual depositions to simulate time evolution of EM shower.
It will be important for pulse shape formation.



Step II: Propagation of Scintillation/Cerenkov photons

Transport of optical photons from emission point to photo-detector. Use SLitrani (1) package. Also can be done with GEANT4.

Parameters to be used at this step:

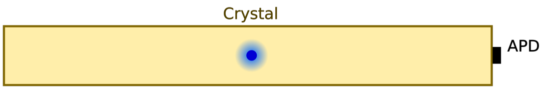
- Geometry of ECAL crystal (trapezoid)
- Geometry of photo-detector
- Quality of surface polishing
- Properties of wrappings
- Decay times of $PbWO_4$ scintillation
- **Wavelength dependence**:
  - Spectrum of emitted photons
  - Absorption of $PbWO_4$
  - Refractive index of crystal, glues, entrance windows
  - Photon-detection efficiency of APDs and VPTs

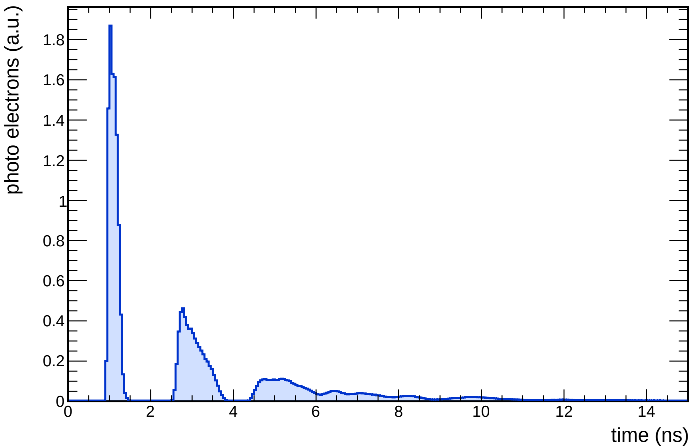
(1) F. X. Gentit, *“Litrani: a general purpose Monte-Carlo program simulating light propagation in isotropic or anisotropic media”*, NIM A 486 (2002) 35-39 https://doi.org/10.1016/S0168-9002(02)00671-X

Time distribution of detected photons emitted isotropically from the center of a crystal at t=0

Discrete structure in time distribution is due to photons in forward and backward directions

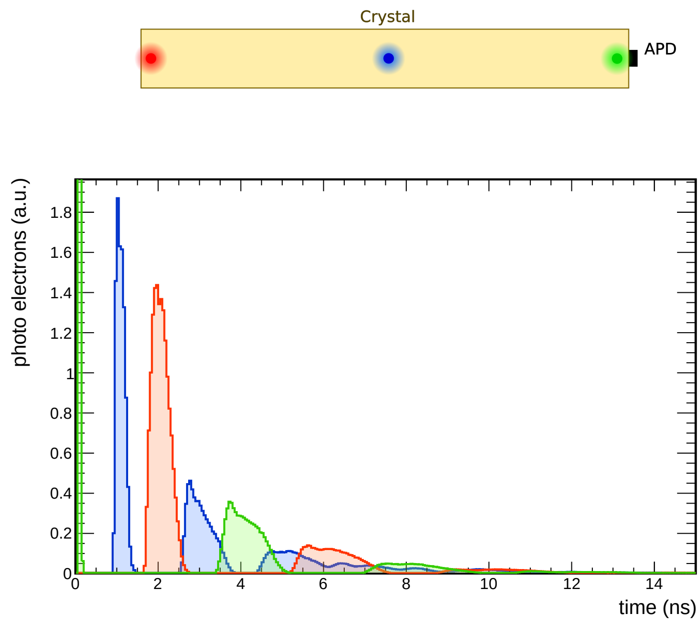
Width of the peaks is due to dispersion and finite size of the photo-detector.





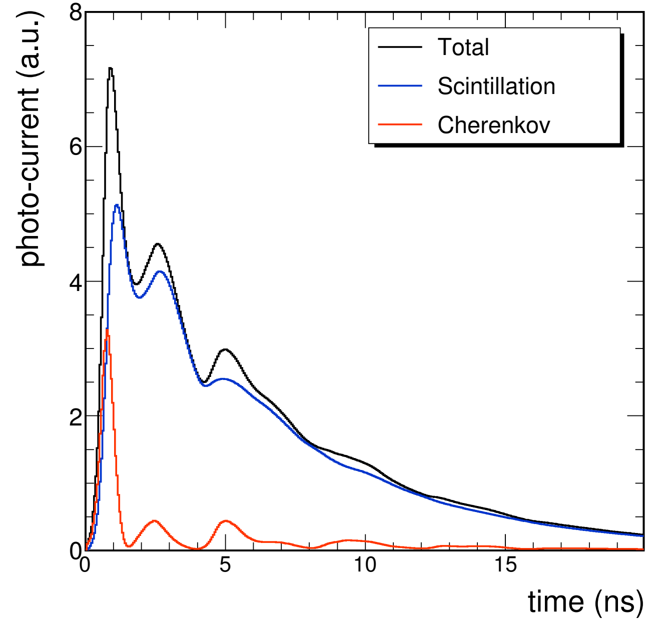
Time distribution depends on emission point of scintillation.

Example of time distribution of detected photons emitted isotropically at t=0 from three different locations



Average pulse shape of photo-current

Simulated average pulse shape from EM shower at the APDs (photocurrent). Contributions from Cherenkov and scintillation emissions are shown separately



Step III: Pulse shape at digitization

Photo-current pulse can be convoluted with single pulse response (SPR) function of front-end to obtain pulse shape at digitization step

SPR:

- Include internal capacitance of APDs, inductance and capacitance of cables etc
- Measured with short laser pulses and nucleon interaction with APDs

Legacy front-end:

- CR-RC shaping
- $\tau = 43\ ns$
- average EM shower pulse shape measured at test beam

Proposed upgrade for HL-LHC:

- Trans-Impedance Amplifier (TIA) architecture
- Minimal pulse shaping
- average EM shower pulse shape measured at test beam

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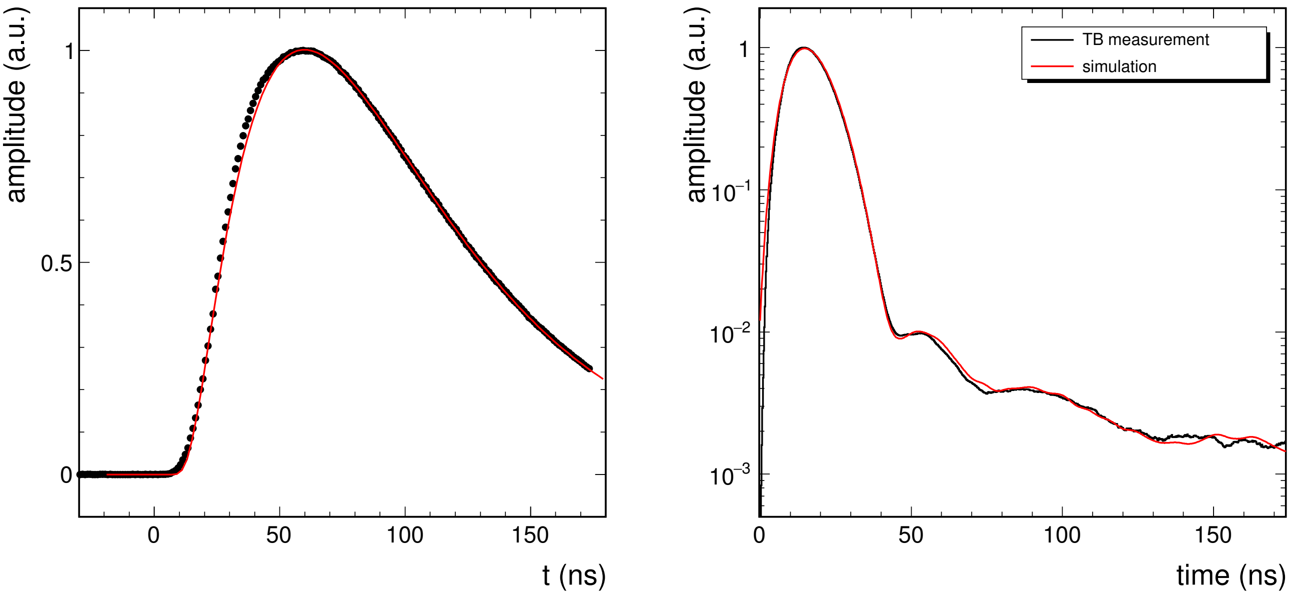
Simulation vs Measurement. Pulse shape at Front-End

Measured (black) and simulated (red) pulse shapes before digitization with the legacy Phase-1 front-end (left) and the TIA HL-LHC front-end (right)



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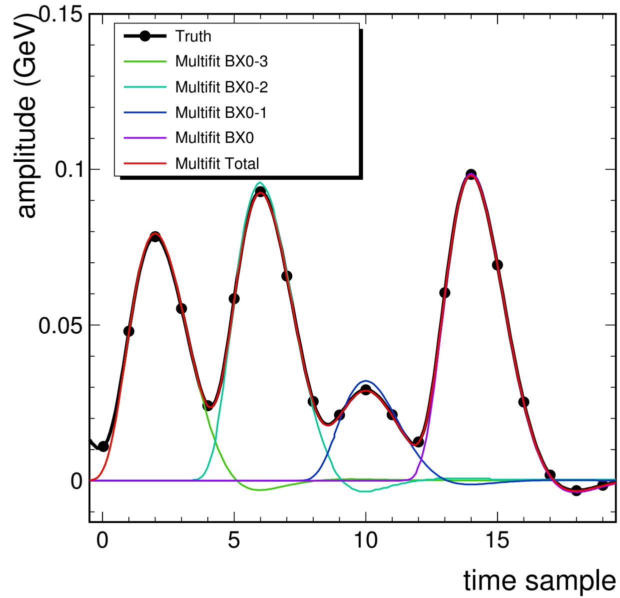
Simulation of readout data frame and reconstruction

Brief summary of other simulation steps towards reconstruction

- Add pulse shapes from all LHC bunch crossings. (The plots shows pulse shapes for TIA architecture front-end)
- Digitize to make amplitude samples (The plots shows 160 MHz sampling frequency)
- Apply noise including correlation between samples (not shown on the plot)
- Use amplitude samples for energy and time reconstruction



Simulation of effects of radiation damage in crystals

Radiation damage results in loss of transparency in crystals due to development of absorption and scattering centers. It can be introduced as index of induced absorption μ_{ind} to describe effective loss of light on a path of length L

$$\frac{LY}{LY_0} = \exp\left(-\mu_{ind} \cdot L\right)$$

Introducing measured or predicted values of $\mu_{ind}(\vec{x}, \lambda)$ into propagation of optical photons from emission point towards photo-detector → effects on pulse shape

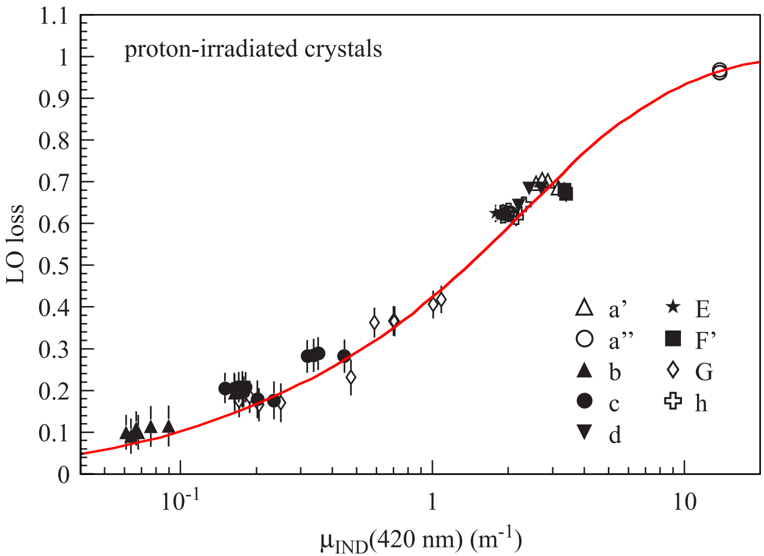
Radiation damage changes pulse shapes and leads to

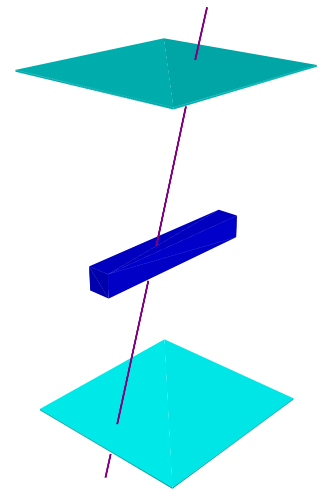
- loss in amplitude
- non-linearity of response
- change in shape → change in average timing of the pulse
- increase in energy resolution due to shower fluctuations and non-uniform light collection

Response to cosmic muons

P. Lecomte et al., NIM A 564 (2006) 164-168

Average light output from a crystal is measured with cosmic muons before and after irradiation. Light loss vs μ_{IND} is plotted.

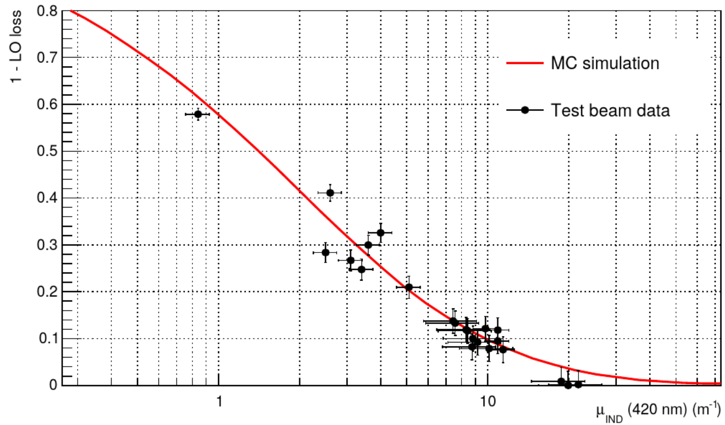




Response to EM showers

CMS: JINST 11 P04012 (2016)

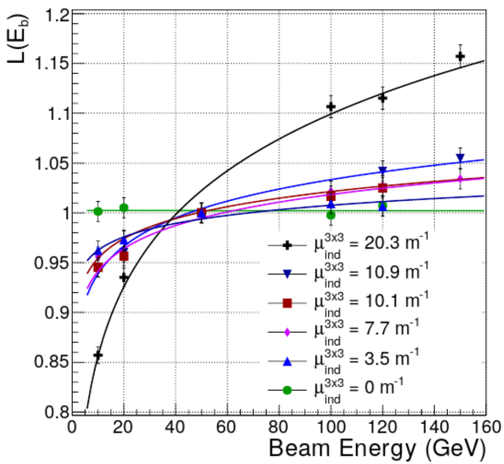
Light output loss as a function of the induced absorption coefficient μ_{ind} for matrices tested in beams in 2012. The red line shows the prediction from the GEANT4+SLitrani simulation.

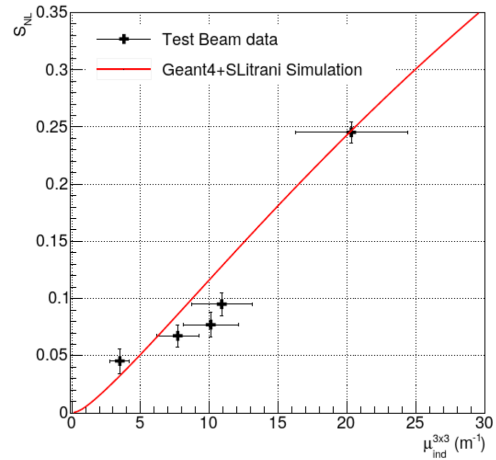


Test non-linearity of EM shower response

CMS: JINST 11 P04012 (2016)

$$L(E_b) = L_0 + \exp\left[S_{NL} \cdot \ln\left(\frac{E_b}{Ec}\right)\right]$$

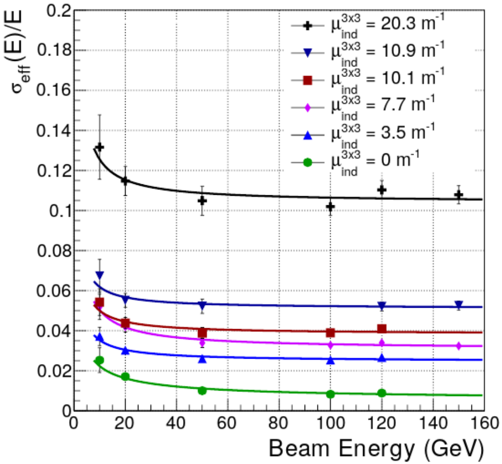


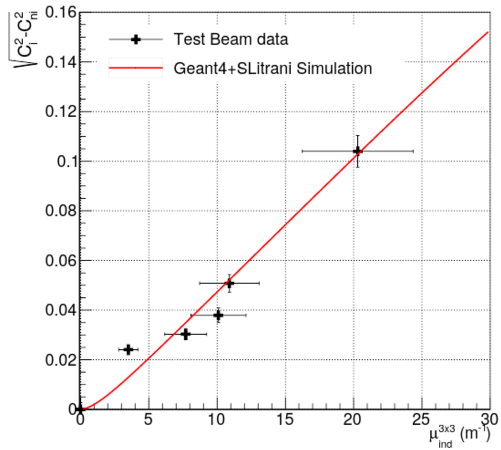


Test of energy resolution degradation

Product of longitudinal shower fluctuations and light collection non-uniformity → increase in constant term of energy resolution (right plot)

CMS: JINST 11 P04012 (2016)

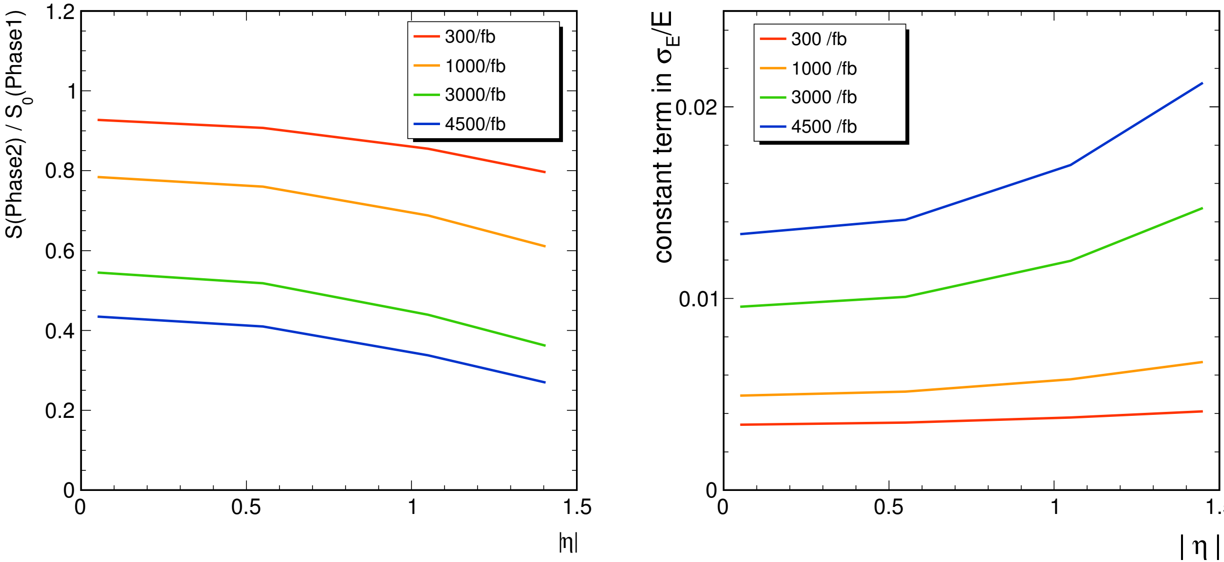




Predicted effects of radiation damage at HL-LHC

We have developed a model to predict $\mu_{ind}(\vec{x}, \lambda)$ during HL-LHC running (not discussed in this talk).

Response degradation (left) and contribution to constant term of energy resolution (right)



Precision timing with ECAL

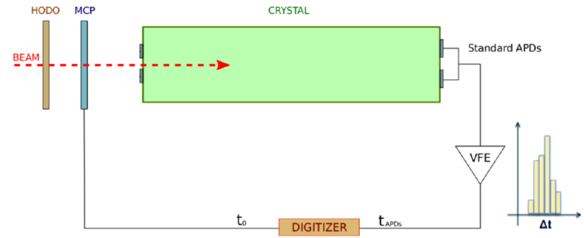
No pulse shaping by TIA → better measurement of pulse timing

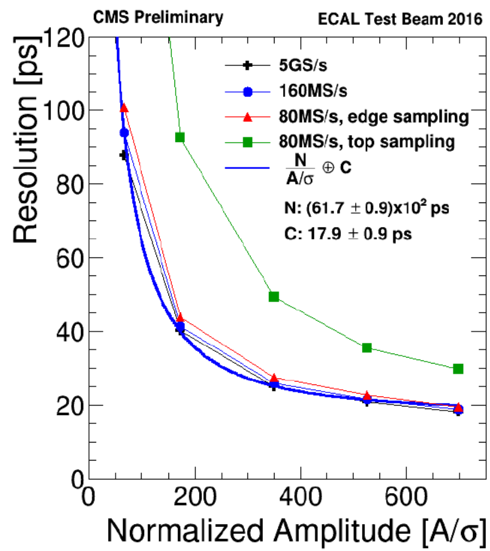
Beam tests achieved $\sigma_t =\sim 20\ ps$

Simulation of individual pulses show that EM shower fluctuations result in $< 20\ ps$ contribution to timing resolution.

The simulation framework has potential to investigate low-level effects on timing and to help identify and reduce systematics

See presentation *"Prospects for a precision timing upgrade of the CMS PbWO crystal electromagnetic calorimeter for the HL-LHC"* by Andrea Massironi on Thursday





Summary

- Method for simulation of response of CMS crystal electromagnetic calorimeter has been described. It includes time evolution of EM showers, propagation of scintillation/Cerenkov photons from emission point towards photo-detectors, measured response of front-end electronics
- Average and individual pulse shapes for photo-current and at digitization step can be simulated at various levels of radiation damage by introducing additional induced absorption. Good agreement between simulations and measurements for overall response degradation, energy non-leariy and energy resolution
- Possibility to simulate precision timing of ECAL pulses and study effects of radiation damage and other systematics that might degrade timing measurements

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