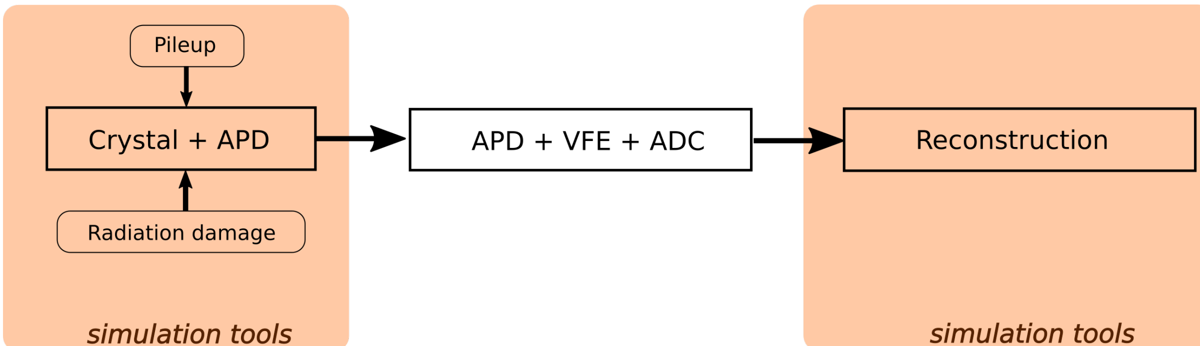
Overview of Simulation Tools

Alexander Ledovskoy
University of Virginia, USA

ECAL VFE Phase II Upgade Workshop at CEA-Saclay INSTN
May 12, 2016

What do we mean by Simulation Tools?



Overview of the presentation

This presentation has four sections

- Radiation damage predictions
- Simulation of photo-current in APD
- Tools for Pulse Reconstruction
- Overview of studies performed at reconstruction level

There will be a list of topics for discussion at the end of each section

Alexander Ledovskoy University of Virginia 2016/05/12

1

Radiation Damage

- $PbWO_4$
- APD

How effects of radiation damage in $PbWO_4$ are simulated?

Model for Light Output (photo-current). Essentially, it follows these steps:

1. Energy depositions from interaction of a particle in active volume of $PbWO_4$ ECAL are simulated by Geant4 to be converted into scintillation photons
2. Cherenkov photons are simulated by Geant4
3. Path of optical photons from emission point to APD is simulated by SLitrani or Geant4
4. Time of emission and path length of detected photons is recorded to form a photo-current pulse
5. Radiation damage → average absorption μ along path length of a photon l
6. Effect of radiation damage → Probability for a photon to be detected

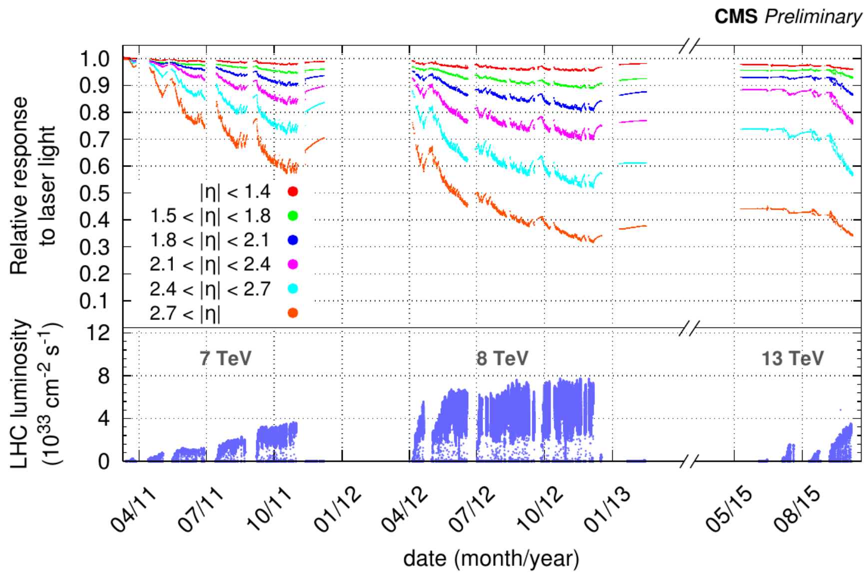
$$p = \exp(-\mu \cdot l)$$

Single most important input parameter for the model is $\mu(\lambda)$

Monitoring at ∼440 nm

Look at average EB degradation. It is pure EM damages so far

L = 3E+33	Equilibrium at 98%	→	μ_{ind} = 0.09 m^{-1}
L = 7E+33	Equilibrium at 96%	→	μ_{ind} = 0.18 m^{-1}



Tuning EM damage model to EB measurements at CMS

Average EB → set $|\eta|$=0.7
Set max EM damage to μ_{max}=2 m^{-1}

Equilibrium between creation of radiation damage and recovery at dose rate R is described by 2 parameters (one type of color centers)

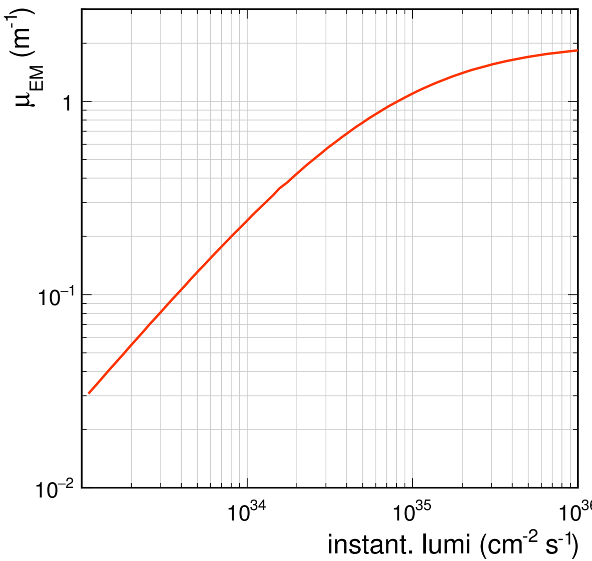
$$\frac{\mu_{EM}}{\mu_{max}} = \frac{b \cdot R}{a + b \cdot R}$$

Recovery parameter has been measured

$$a = 0.054\ h^{-1}$$

Tune remaining parameter to 2 measurements @ λ=440 nm

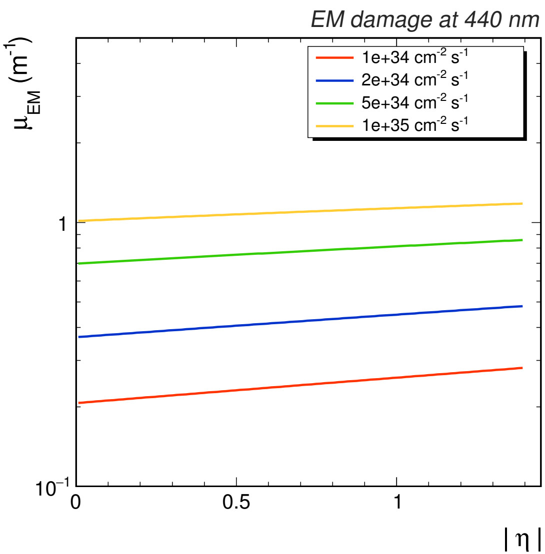
$$b = 0.16\ Gy^{-1}$$

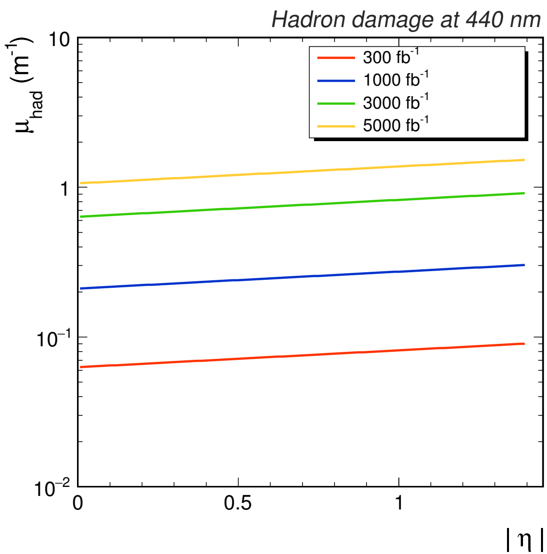


EM and Hadron damage for monitoring light

EM damage at equilibrium is set by instantaneous luminosity
Hadron damage is set by integrated luminosity
Degradation of monitoring transmission

$$LY/LY_0 = \exp\left(-0.23 \cdot (\mu_{EM} + \mu_{had})\right)$$





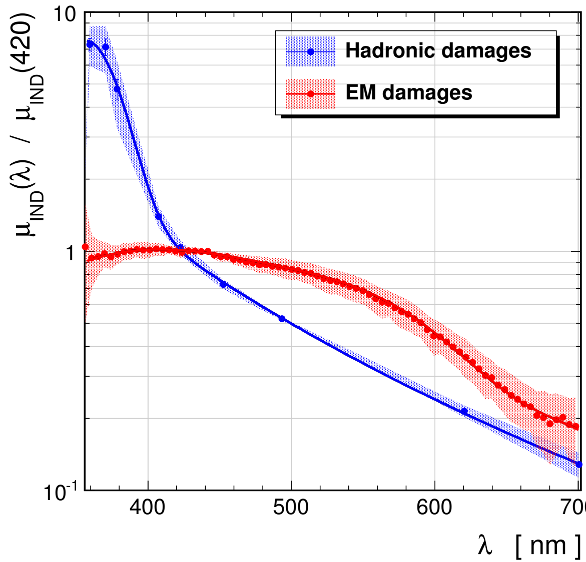
Radiation damage of $PbWO_4$ vs wavelength

Scintillation and Cherenkov photons from EM showers in $PbWO_4$ have a “broad” spectrum.

Radiation damages (induced absorption) has a significant dependence on wavelength and it has to be taken into account

Model has wavelength dependence of radiation damage based on measurements of crystal transmission irradiated by Co-60 or by protons

Error bars are RMS spread between crystals



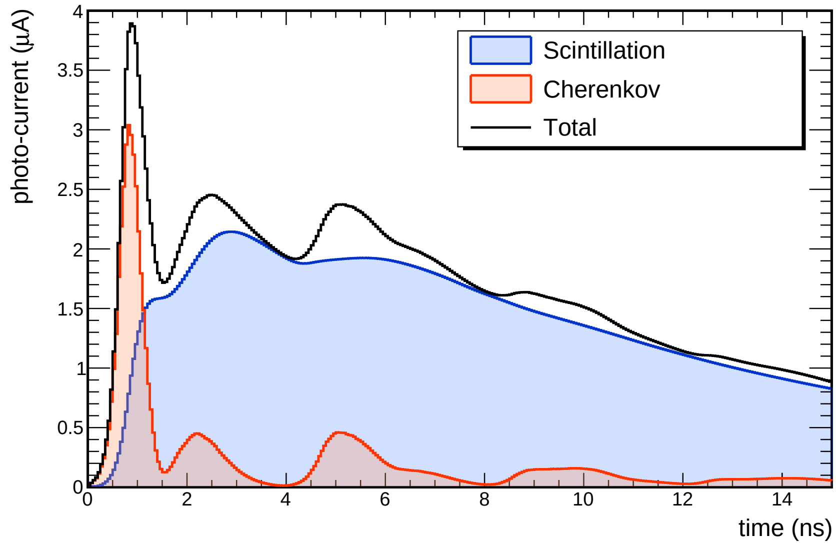
Starting point. Average undamaged crystal.

Photo-current per 1 GeV of EM shower
Apply radiation damage by reweighting each optical photon with

$$w = \exp\left(-\mu(\lambda) \cdot l\right)$$

Assumptions:

4.5 pe/MeV
APD gain 50



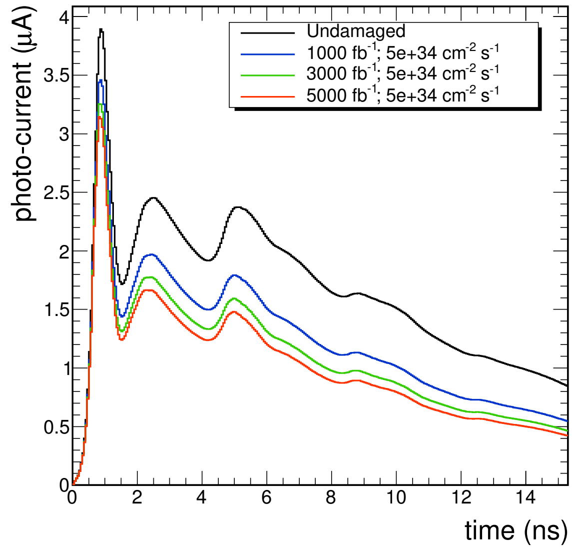
Alexander Ledovskoy UNIVERSITY of VIRGINIA 2016/05/12

Evolution of pulse shape under radiation damage

Model predicts pulse shape and individual contribution from scintillation and Cherenkov processes for any combination of instantaneous and integrated luminosity

Total collected charge (fC) per 1 GeV of EM shower at $L = 5 \times 10^{34}\ cm^{-2} s^{-1}$

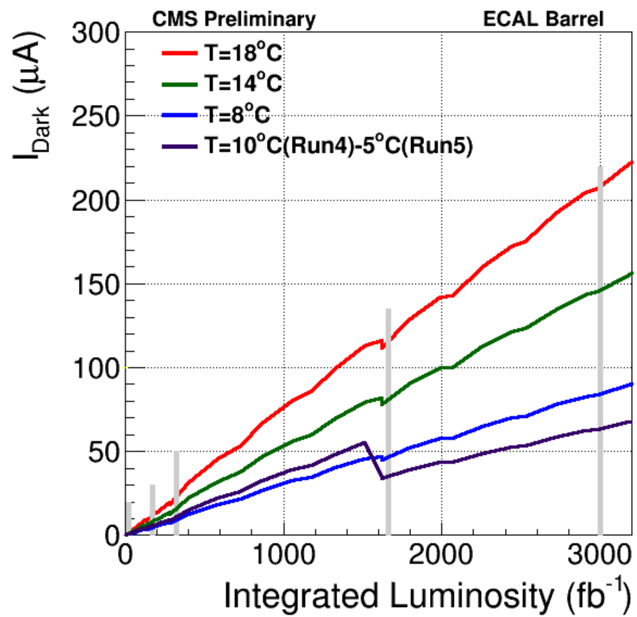
	Scint	Cher	Total
Undamaged	32.0	4.00	36.0
1000 fb^{-1}	22.5	3.21	25.7
3000 fb^{-1}	19.6	2.95	22.5
5000 fb^{-1}	17.9	2.80	20.7



Evolution of APD dark current

Per APD capsule
At $|\eta|$=1.45

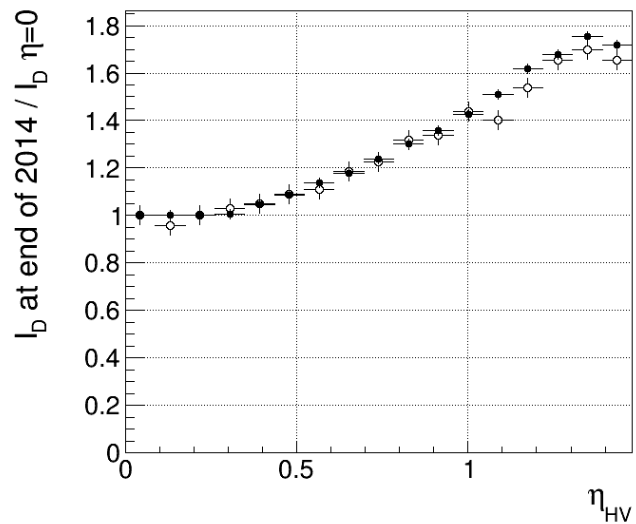
Depends on hadron fluence



Radiation damage in APD vs eta

Measured profile for dark current induced by 8 TeV and 13 TeV collisions

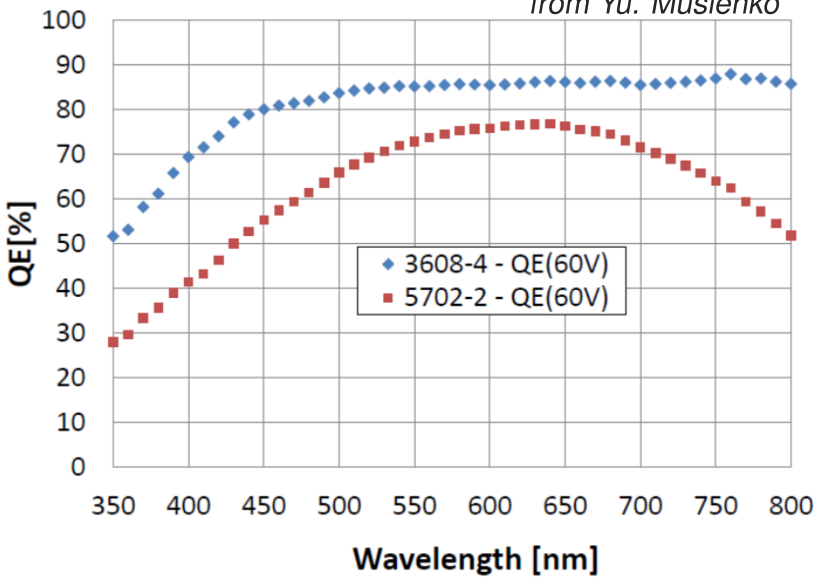
Filled circles: 8 TeV
Open circles: 13 TeV



Loss of QE in APDs

Non-irradiated (blue) and irradiated (red) with 2.5×10^{14} n/cm^2 (1 MeV equivalent)
Difficult measurement but suggest an additional degradation of a signal

from Yu. Musienko



Summary of radiation damage model

- Predicts light losses and pulse shape evolution due to damages in $PbWO_4$ crystals.
  Depends on instantaneous and integrated luminosity
- Predicts APD dark current.
  Depends on history of integrated luminosity and temperature.
- Additional degradation of signal: QE loss, HV sagging etc

Topics for discussion:

- Define few benchmark points: set of conditions for radiation damage
- Everyone should use these benchmark points for easy comparison

2

Photo-Current Simulators

- Pulse Shape
- Pileup

Brief overview of main steps to simulate pulse shape

Energy depositions from EM showers are simulated with Geant4.
Optical photons are simulated with SLitrani and/or Geant4.

"Average" dimensions of ECAL EB crystal:

- Front face = 2.2×2.2 cm^2
- Rear face = 2.5×2.5 cm^2
- Length = 23 cm

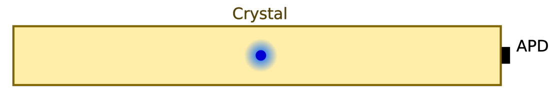
Using measured properties of ECAL crystals and APD as a function of wavelength:

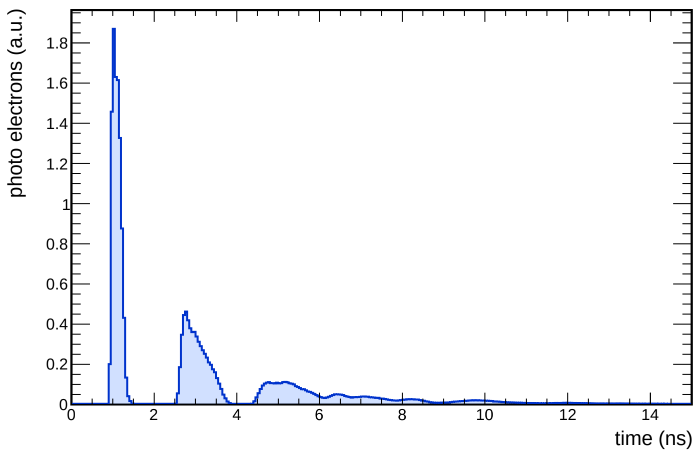
- refractive index (neglecting optical anisotropy of $PbWO_4$)
- transparency without radiation damage
- scintillation spectrum and decay times
- APD quantum efficiency

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 direction

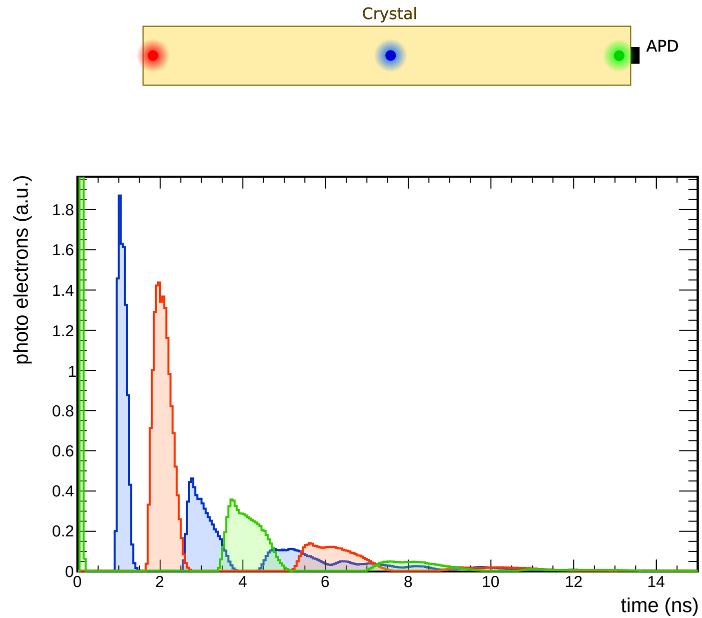
Width of the peaks is due to dispersion and finite size of the photo-detector.





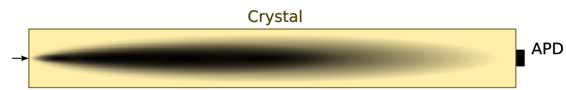
Time distribution depends on emission point of scintillation.

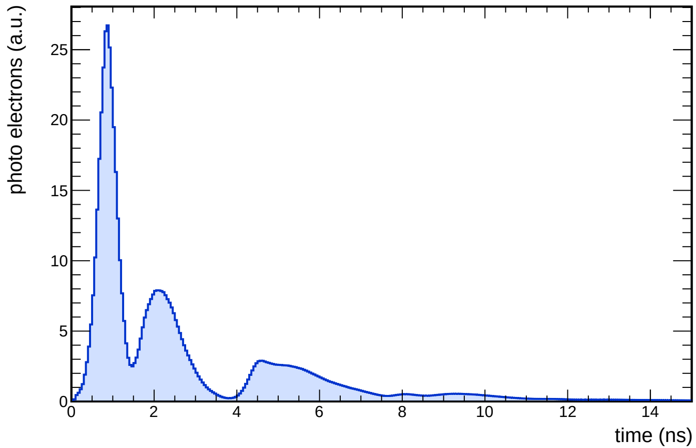
Example of time distribution of detected photons emitted isotropically at t=0 from three different locations



EM shower from 50 GeV electron takes about 1 ns to deposit most of it's energy in a crystal

In case of *instantaneous* scintillation process (hypothetical scenario), the compound effect of finite time of EM shower evolution and travel time of scintillation photons is shown on this time distributioin of detected photons.

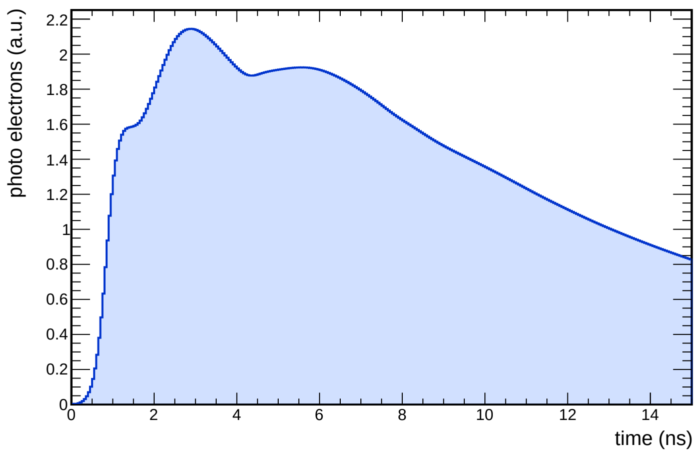




Scintillation emission is not *instantaneous*

$PbWO_4$ scintillation decay time can be described by a sum of three exponentials of typically 5 ns, 15 ns and 100 ns with amplitudes of 39%, 60% and 1% respectively

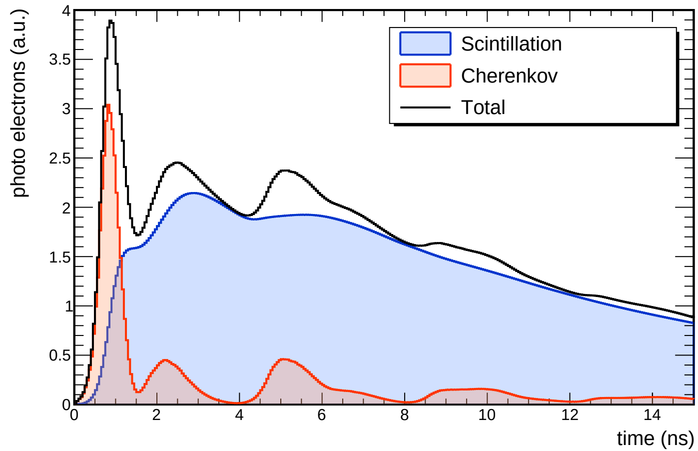
As a result of decay time, the pulse shape of detected photons becomes broader with slower rising edge



Contribution from Cherenkov radiation is estimated to be about 11%
by simulating photons in EM showers within full range of detectable λ = 300 – 1000 nm

Relative light output of Cherenkov and scintillation photons in $PbWO_4$ was determined by simulating experimental results for 150 GeV muons reported in N. Akchurin et al., *"Contributions of Cherenkov light to the signals from lead tungstate crystals"*, NIM A582 (2007) 474-483

Due to *instantaneous* emission of Cherenkov photons, most of them arrive earlier than scintillation photons



Alexander Ledovskoy University of Virginia 2016/05/12

Normalization

We believe that APD sees 4.5 pe/MeV for average undamaged crystals
Using APD gain 50 $\rightarrow$ total charge 36 fC per 1 GeV of EM shower
Previous slide: vertical scale (a.u.) = (μA)

Average Pulse for Undamaged Crystal

Created and available at https://github.com/cms-eb-upgrade/vfe-toymc
Fine steps: 50 ps
See `ExamplePC.C` for instructions

Possibilities

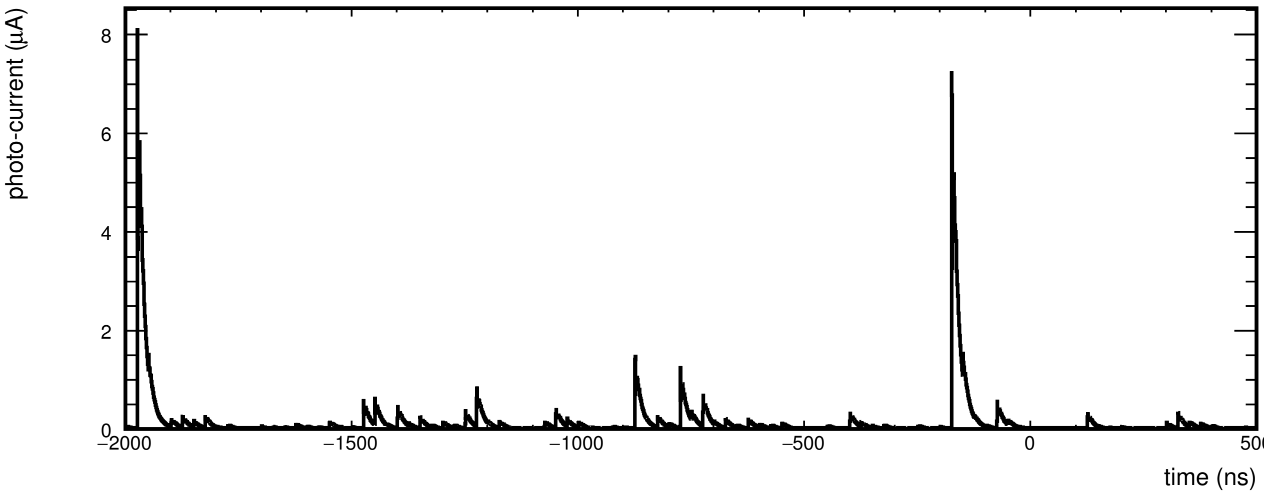
To create average pulse shapes for different levels of radiation damage
To create a library of pulse shapes for individual events to study fluctuations
. . . and make them available for others

Alexander Ledovskoy University of Virginia

Waveforms of Photo-Current with Pileup

See `ExamplePC.C` in https://github.com/cms-eb-upgrade/vfe-toymc

Set average PU rate and generate events. One event = One waveform.
Wide time window (set by user)
Fine time step (set by user; 50 ps here, no reason to go finer)



Topics for discussion

- Are these waveforms and pulse shapes useful?
- Currently, only an average pulse shape for undamaged crystal is available.
- Any requests for other conditions?

3

Pulse Reconstruction

- Digitization
- Amplitude Reco
- Time Reco

Basic Idea

Evaluate performance of calorimeter as a function of noise and pileup

- energy resolution
- timing resolution

Same steps as in CMSSW simulation + reconstruction

1. Input: a pulse shape of VFE
2. Generate an event: a waveform of OOT pileup + signal
3. Apply noise
4. Digitize with a given sampling rate
5. Run reconstruction using our ECAL CMSSW algorithms

Tools are in https://github.com/cms-eb-upgrade/vfe-toymc
Set of examples to be used as a starting point

Reconstruction Algorithms in Standalone

Pulse Shape Fit

- amplitude and time reconstruction
- intuitively, a first choice for reconstruction
- not a default in CMSSW

“Multifit”

- amplitude reconstruction
- pileup mitigation
- default algo in CMSSW

“Ratio”

- time reconstruction
- default algo in CMSSW
- to appear in git soon

Topics for discussion

- It is important to test a VFE scenario with reconstruction algorithms we use. These algos have weaknesses
  - "Multifit" cannot do pedestal subtraction based on pre-samples
  - "Ratio" has no pileup mitigation
- Should we worry about unexpected effects like
  - low frequency noise → affects pedestal subtraction
  - MGPA "slew" effect → degrade timing resolution
- We need VFE scenarios to test
  - pulse shape
  - noise level
  - correlation matrix between time samples

4 Studies So Far

- brief overview
- with conclusions

Pulse Shapes

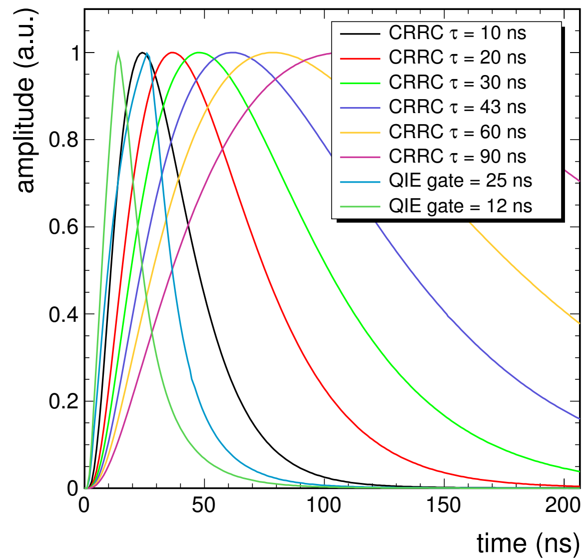
CRRC with τ=10 ns – 90 ns
Three QIE-like scenario

Sampling with

- 40 MHz
- 80 MHz
- 160 MHz

Correlation matrix between time samples

- evaluated
- function of τ

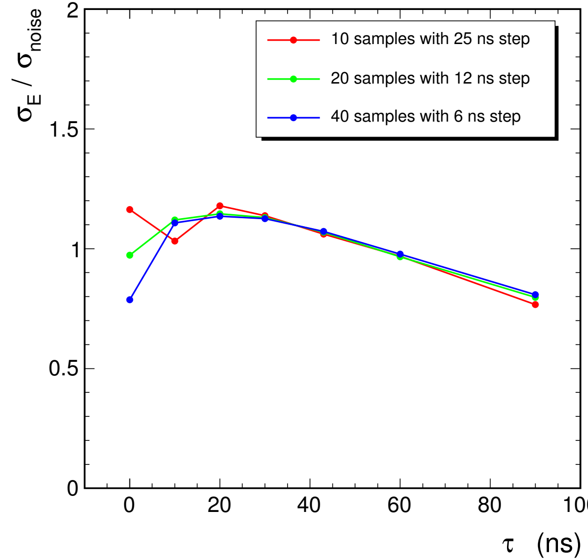


Amplitude resolution vs Noise. Pulse Shape Fit

Linear dependence

$$\sigma_E = N \times \sigma_{noise}$$

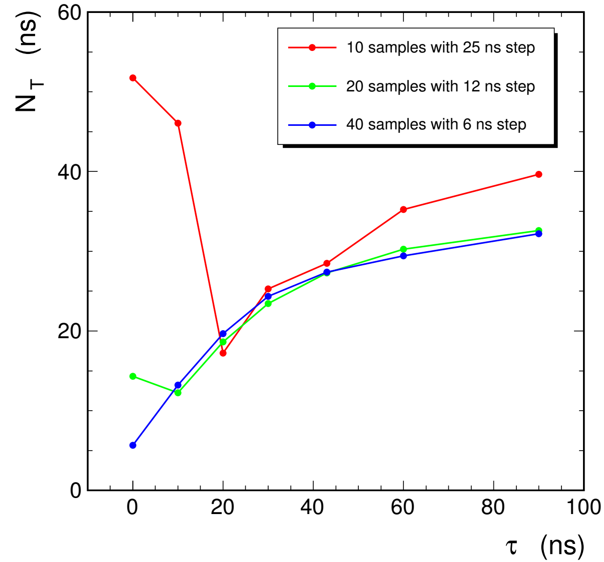
Slope N is a single parameter to describe VFE scenario



Time resolution vs Noise. Pulse Shape Fit

$$\sigma_T = N \times \frac{\sigma_{noise}}{E}$$

Noise term N is a single parameter to describe VFE scenario

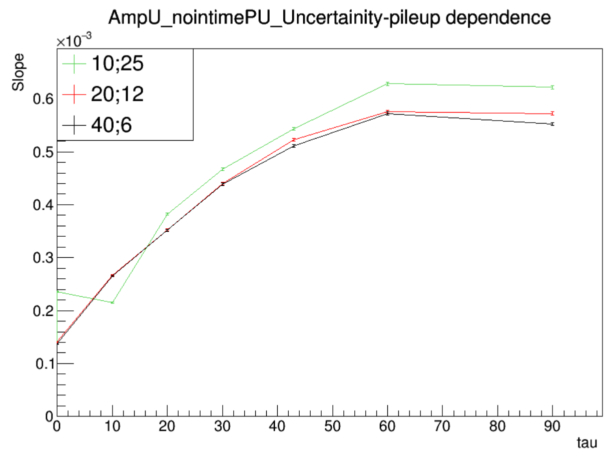


Amplitude resolution vs Pileup. Pulse Shape Fit

Linear dependence

$$\sigma_E = N \times PU$$

Slope N is a single parameter to describe a VFE scenario

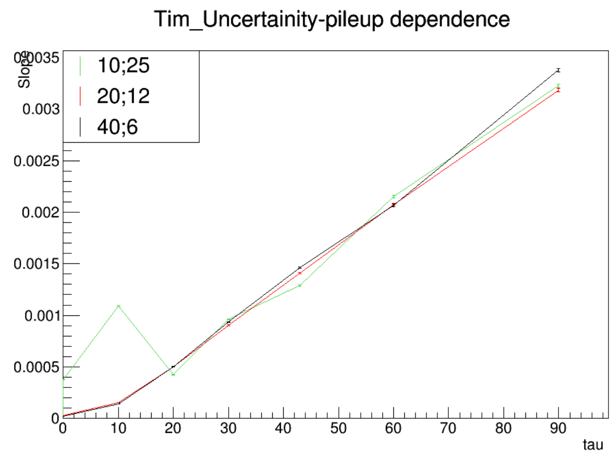


Time resolution vs Pileup. Pulse Shape Fit

Close to linear dependence

$$\sigma_T = N \times PU$$

Slope N is a single parameter to describe a VFE scenario



Amplitude resolution vs Noise. Multifit

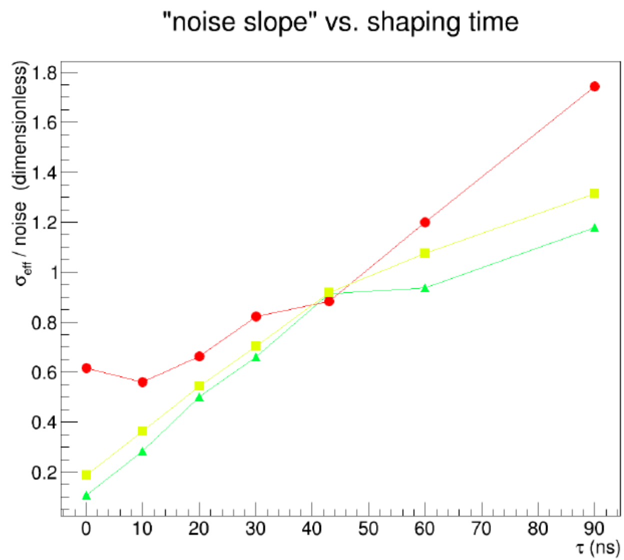


Figure: Here we examine how the dependence of sigma effective on noise (quantified as the slope of the least squares fit line from the above plots) is mediated by pulse shaping time for three sampling periods (red: 25ns; yellow: 12.5ns; green: 6.25ns).

Amplitude resolution vs Pileup. Multifit

- Multifit eliminates OOT pileup to negligible level!
- Performance sees no correlations between noise and pileup

Conclusions so far

- Wide range of pulse shapes and sampling rates testes
- Pulse Shape Fit and Multifit reconstruction algorithms are tested
- Amplitude/Time vs Noise/Pileup
- Singe parameter describes performance for each VFE scenario
- Easy to evaluate performance of VFE for specific noise and pileup levels

Next Steps

Ratio Method for timing resolution vs noise and pileup

Alexander Ledovskoy UNIVERSITY of VIRGINIA 2016/05/12

Topics for discussion

- What do we need to do in a short term (before summer/fall)?
- There is CMS wide campaign for simulation of samples for TDR. New VFE scenario (pulse shape, noise, sampling, reconstruction etc) should be implemented in CMSSW by the end of the year.
- Should we start thinking about strategy/plans for
  - noise measurements
  - pedestal measurements
  - pulse shape measurements (average, individual channels)

  during HL-LHC data taking?