# Part I

How to separate good crystals from bad ones based on longitudinal non-uniformity profiles?

# requirement for crystal non-uniformity

1 Mass resolution of $H \to \gamma\gamma$ for $E_\gamma$ from 25 GeV to 500 GeV

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{\sigma_n}{E}\right)^2 + (c)^2$$

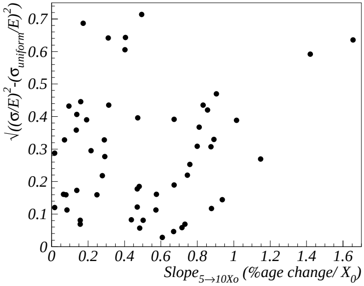
non-uniformity contributes to the constant term and must be less than 0.3% (from ECAL TDR)

2 CMS note 96/002 describes GEANT studies of non-uniformity. Uniformity profile should have slope less than 0.3% per $X_0$ in $5X_0$ to $10X_0$ range

Question: Are items 1 and 2 the same thing?

# cms note 96/002

**Figure:** This is a plot from CMS Note 96/002. Each point represents GEANT estimated contribution to $M_H$ width vs FNUF slope for a crystal. A sample of63 crystals is shown




**Answer:** No!

- many crystals with slope $\leq 0.3\%/X_0$ have $\sigma \geq 0.3\%$
- many crystals with $\sigma \leq 0.3\%$ have slope $\geq 0.3\%/X_0$

# GEANT EM showers in PWO

**Figure:** Sketch of setup geometry for GEANT

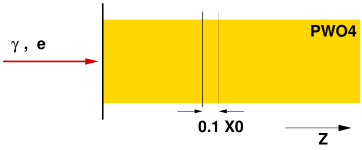
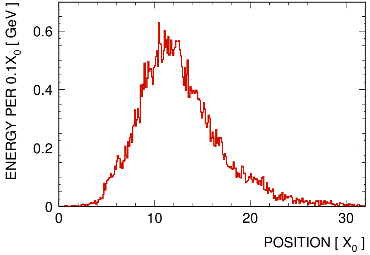



**Figure:** Profile of deposited energy for one shower from $\gamma$ with $E = 50\ GeV$



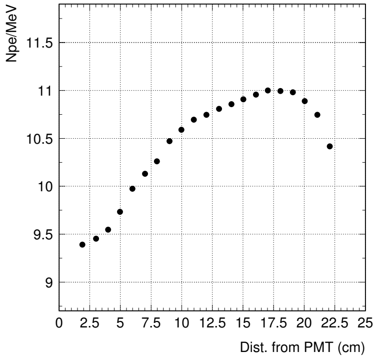

Repeat studies described in CMS Note 96/002 (with some modifications) to get some understanding

## Steps:

- A particle hits a wall of PWO4, $32X_0$ thick. Transverse dimensions - not a factor.
- Record a shower: deposited $\Delta E_i$ in steps $\Delta z = 0.1X_0$ as a function of $z_i$.
- Make a library of 1000 showers for $\gamma$ and $e^-$ with incedent $E = 10, 20, 50, 120$, and $250\ GeV$

# Test one particular crystal with GEANT showers.

**Figure:** Longituinal light yield function for a crystal presented on ECAL DPG meeting in Oct 7, 2005 by R.Paramatti.



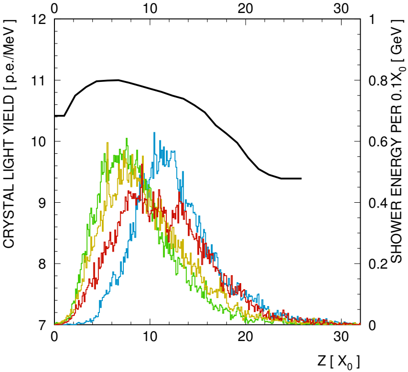

LY function is measured in 21 points, 1 cm apart. Too coarse for these studies.

## Use simple interpolation:

- Linear interpolation between measurements
- At the end points, assume constant LY constant to the edges of the crystal.
- Convert horizontal scale to $X_0$ units, assuming $X_0 = 0.89\ cm$
- Simple linear interpolation can be replaced by polinominal fit

# Resolution due to non-uniformity

**Figure:** Light yield function in $X_0$ units for a crystal (black) and several shower profiles for $\gamma$ with 50 $GeV$ energy.




Steps to determine contribution of longitudinal non-uniformity to energy resolution:

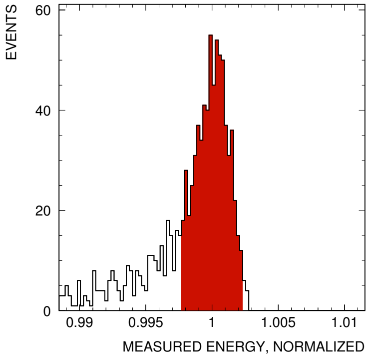
1. Energy of a shower $i$ measured by a crystal, normalized

$$R_i = \frac{\int_0^L E_i(z) \cdot LY(z) dz}{\int_0^L E_i(z) dz}$$

For $LY(z) = const$, every shower will have the same $R_i$. Statistical fluctuations in energy deposited by a particle is taken out by normalization. Fluctuations in $R_i$ are pure non-linearity effect.

# Resolution due to non-uniformity (cont'd)

**Figure:** Distribution of measured energy for photons with $E = 120\ GeV$, normalized to most probable value (black histogram). 68% of events are in region shaded with red color.




2 Obtain a distribution of $R_i, (i = 1, .., 1000)$ for $\gamma$ or $e^-$ with the same incident energy

3 Find shortest interval, $[R_{min}, R_{max}]$, that contains 68.3% of measurements

4 Most probable $R$

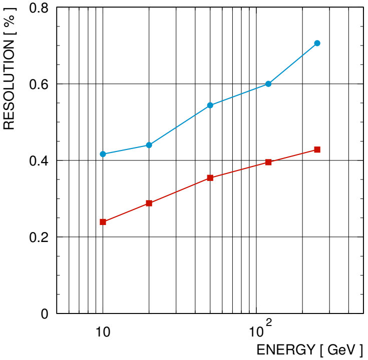
$$R_{peak} = \frac{R_{max} + R_{min}}{2}$$

5 Resolution due to non-uniformity

$$\Delta_{LNU} = \frac{1}{2} \frac{R_{max} - R_{min}}{R_{peak}}$$

# Resolution vs Energy

**Figure:** $\Delta_{LNU}$ vs energy of a particle for $\gamma$ (blue) and $e^-$ (red)

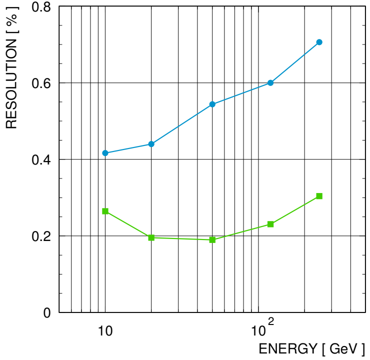



- $\Delta_{LNU}$ is energy dependent. One can use $E_\gamma$ spectrum from $H \longrightarrow \gamma\gamma$ to determine average non-uniformity contribution of this crystal to $M_H$ width.
- Effects of non-linearity from this crystal have differnet magnitude for $\gamma$ and $e^-$.

This crystal has $FNUF = 0.31\%$ per $X_0$ which is considered almost good enough to provide less than 0.3% to $M_H$ resolution due to non-uniformity. But it contributes $\sim 0.5\%$ to $M_H$ width.

# Effects of preshower detector

**Figure:** $\Delta_{LNU}$ vs $\gamma$ energy for the crystal with (green) and without (blue) preshower detector in front of it




Preshower detector in front of endcap ECAL has $3X_0$ total. $2.5X_0$ of it comes from lead convertors. To estimate preshower effects, energy of a shower $i$ measured by a crystal, normalized

$$R_i = \frac{\int_0^L E_i(z - 3X_0) \cdot LY(z)dz}{\int_0^L E_i(z - 3X_0)dz}$$

This crystal's contribution to $M_H$ width is $\sim 0.2\%$ if there is a preshower detector in front of it.

# So, what about this crystal?

1. This crystal will contribute $\sim 0.5\%$ to $M_H$ resolution if it is in the barrel (no preshower). So, this crystal is "bad".

2. This crystal will contribute $\sim 0.2\%$ to $M_H$ resolution if it is in endcap, behind the preshower detector. So, this crystal is "good".

3. This crystal has $FNUF = 0.31\%$ per $X_0$. In this case, $FNUF$ value does not help us to make a fair judgement about this crystal.

# Status. Summary. Next steps

- Need to introduce $E(\gamma)$ from $H \to \gamma\gamma$. It will allow to calculate one number per crystal: an average contribution to $M_H$ resolution

- Get a sample of non-uniformity profiles for $\sim 100$ crystals and compare GEANT approach vs FNUF slope values.

  Suspision: Two approaches of crystal evaluation give different results:
  - with GEANT shower libraries
  - with a simple slope in $5X_0 - 10X_0$ range

- The "slope" approach is based on conclusions from "GEANT" approach.

  Why not to use the GEANT showers in a first place? It is as simple and quick as the linear fit.

# Part II

Is it possible to measure longitudinal non-uniformity profile of a crystal with required accuracy using conventional PMT (not an HPMT)?

# Simulations of longitudinal LY scans

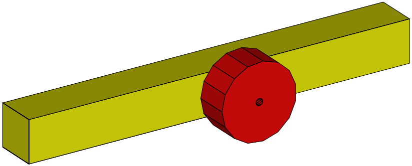
## Objectives

1. Undestanding of PWO responce to Co-60 photons
2. Optimizing PMT running conditions wrt scan accuracy
3. Identifying best fit function for ADC spectrum
4. Understanding accuracy of the fit and optimization of the fit
5. Optimization of collimator for Co-60
6. Other

This is ongoning study.

# GEANT setup

**Figure:** sketch of GEANT geometry: PWO crystal (yello) and Co-60 source assembly (red).



- PWO4 crystal:
  - $2.5 \times 2.5 \times 23.0\ cm^3$
  - Density is $8.30\ g/cm^3$
  - $X_0 = 0.841\ cm$ (GEANT)
    CMS crystals $X_0 = 0.89\ cm$
- Source assembly:
  - Co-60 source
  - Collimator
- Cutoff energy for photons and electrons in PWO is set to minimum ($10\ keV$)
- Output deposited $E(x, y, z)$ to next step in these simulations.

# Source assembly

**Figure:** sketch of source geometry: Co-60 source (yellow); Collimator (blue) and PWO crystal (red).

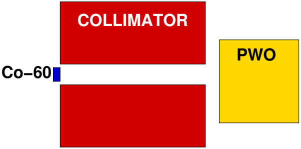
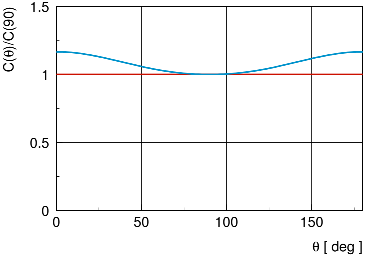



**Figure:** Correlation in angle between photons: isotropic (red) and Co-60 (blue)




- Source is 3 *mm* in diameter and emits 2 photons:
  - $E_1 = 1.173\ MeV$
  - $E_2 = 1.333\ MeV$.
  - same origin
  - anisotropical distribution

$$C(\theta) = C_0 \left(1 + \frac{cos^2\theta}{8} + \frac{cos^4\theta}{24}\right)$$

- Collimator - TUBE geometry
  - Outer diameter: 4.4 *cm*
  - Inner diameter: 0.4 *cm*
  - Length: 2 *cm*.
  - Material: ???
  - Collimator-crystal gap is 2 *mm*

No collimator right now, L=0

# Cross Sections for $\gamma$ and $e^-$ Interactions with PWO

Co-60 $\gamma$ in PWO: compton scattering (photo electrons rarely); electon loose all energy immediatly via ionization but sometime produce brem $\gamma$. Low energy $\gamma$ are absorbed in PWO. Some $\gamma$ escape PWO

**Figure:** Photon cross section in PWO vs energy

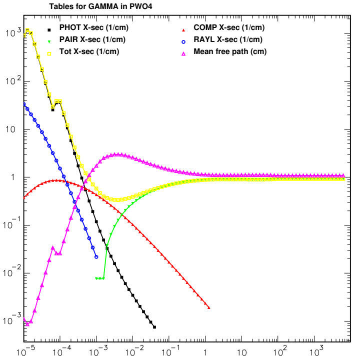
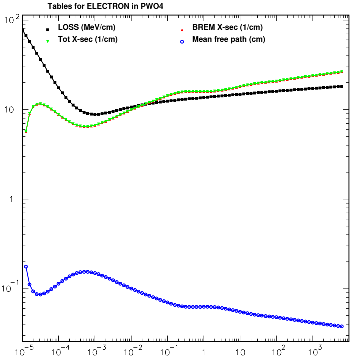
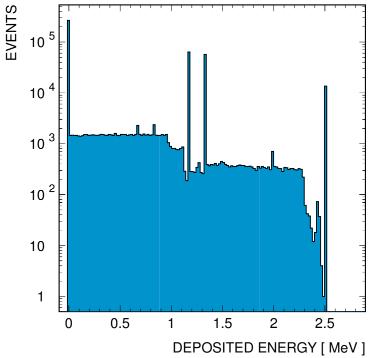



**Figure:** Electron cross section in PWO vs energy



# Energy Deposition in PWO per Co-60 Disintegration

**Figure:** Energy deposited by Co-60 disintegration in PWO crystal (GEANT)




This spectrum is GEANT simulated when the source has no collimator and positioned 2 mm away from the side of the crystal.

Visible energy in PWO ($E > 0$):

| | |
|---|---|
| 1.173 *MeV* | 28.06% |
| 1.133 *MeV* | 24.54% |
| 2.306 *MeV* | 6.89% |
| continuum | 40.51% |

This composition should go into ADC fit function. The effects of uncertainty in cross sections and geometry have to be studied.

# Average number of photo-electrons per event

$$n_{pe} = \int_V P(x,y,z) \frac{E(x,y,z)}{\epsilon_0} dv$$

| | |
|---|---|
| $E(x,y,z)dv$ | energy deposited in volume $dv$ at $(x,y,z)$ |
| $\epsilon_0$ | average deposited energy to make one scintillator photon |
| $P(x,y,z)$ | probability for scint. photon emitted from $(x,y,z)$ to produce a photo-electron in the PMT cathode (integrated over several variable: direction, energy etc.) |

$$P(x,y,z) = C_0 \cdot F_{nuf}(x,y,z)$$

| | |
|---|---|
| $C_0$ | some constant |
| $F_{nuf}(x,y,z)$ | Non-uniformity function, $= 1$ for perfectly uniform crystal |

$$\frac{1}{V} \int_V F_{nuf}(x,y,z) dv = 1$$

# Average number of photo-electrons per event (cont'd)

$$n_{pe} = \frac{C_0}{\epsilon_0} \int_V F_{nuf}(x,y,z)E(x,y,z)dv$$

For perfectly uniform cystal, $F_{nuf}(x,y,z) = 1$,

$$n_{pe} = \frac{C_0}{\epsilon_0} \int_V E(x,y,z)dv = \frac{C_0}{\epsilon_0} E_{tot}$$

$$\frac{C_0}{\epsilon_0} = \frac{n_{pe}}{E_{tot}} = LY_0$$

$LY_0$ Light Yield of the crystal

$$n_{pe} = LY_0 \int_V F_{nuf}(x,y,z)E(x,y,z)dv$$

To generate $n_{pe}$, use $E(x,y,z)$ from GEANT, adjust with introduced non-linearity function $F_{nuf}$, and multiply by measured $LY_0$ for the crystal.

# Simulation of ADC spectrum

Actual number of photo-electrons is random generated,

$$P(N) = \frac{n_{pe}^{N}}{N!} e^{-n_{pe}}$$

ADC channel is random generated according to Gaussian with mean and sigma

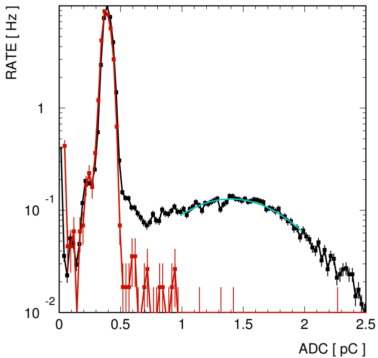
$$m_N = N \cdot m_{1pe} + m_{PED}$$

$$\sigma_N^2 = N \cdot \sigma_{1pe}^2 + \sigma_{PED}^2$$

where $m_{1pe}$ and $\sigma_{1pe}$ are Gaussian parameters of single photo-electron ADC spectrum; $m_{PED}$ and $\sigma_{PED}$ are Gaussian parameters for pedestal.

# Measuring $m_{1pe}$ and $\sigma_{1pe}$.

**Figure:** ADC spectrum of blue LED at HV=1800 V (black dots). Noise ADC is also shown (red dots)




- Blue LED shines through PWO crystal
- LED is driven with a pulser
- LED pulse duration is $\sim 50$ *nsec*
- ADC gate is 100 *nsec*
- LED pulser amplitude is adjusted to get $\sim 20\%$ efficiency for LED (single photo-electron mode)
- DAQ trigger is LED pulser output
- Noise spectrum is taken with LED unplugged
- Tip of the 1 p.e. peak is fitted with Gaussian

# $m_{1pe}$ and $\sigma_{1pe}$ vs PMT voltage

**Figure:** Measured position of 1 p.e. peak vs PMT voltage

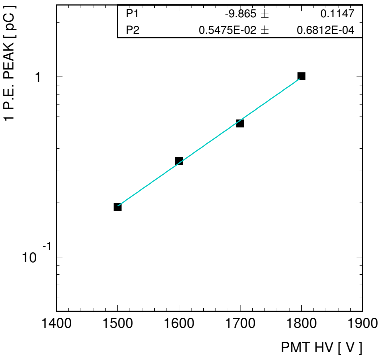
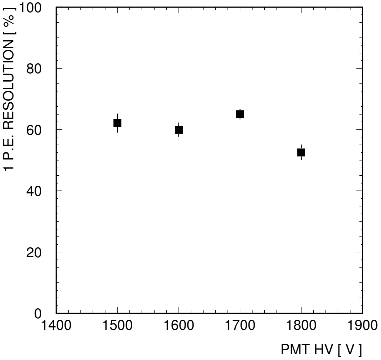



**Figure:** Measured resolution of 1 p.e. peak vs PMT voltage



# Steps to generate ADC spectrum

1. Generate map of deposited energies, $E(x,y,z)$, and apply non-uniformity function, $F_{nuf}(x,y,z)$, using GEANT
2. Random number of photo-electrons, $N$, according to Poisson with average rate of $LY \cdot E$, where $LY$ is light yield (input parameter) and $E$ is random number according to distribution from Step 1.
3. ADC is a random number according to Gaussian distribution with mean of

$$N \cdot m_{1pe} + m_{PED}$$

and width

$$\sigma^2 = N \cdot \sigma_{1pe}^2 + \sigma_{PED}^2$$

where $m_{1pe}$ and $m_{PED}$ are positions of 1 photo-electron and pedestal peaks respectively; $\sigma_{1pe}$ and $\sigma_{PED}$ are widths of one photo-electron and pedestal distributions respectively (all four are input parameters)

# DATA vs MC. Co-60 rate in PWO at HV=1800 V

- Our source had 379.1 kHz rate of disintegrations on Oct 1, 2005 (according to it's certificate)
- Nov 20, 2005: Our source has rate 369.0 kHz
- According to MC simulations, 43.6% of disintegrations leave at least 1 p.e. signal in PMT. Therefore, the predicted rate is 160.9 kHz.
- On Nov 20, I measured rate of 174 kHz with estimated background rate of 5.2 kHz.
- DATA=168.8 kHz vs MC=160.9 kHz

MC predicts rate of CO-60 signals in PWO crystal to better than 5% accuracy. Reminder: GEANT predicts $X_0 = 0.84\ cm$ and CMS quotes $X_0 = 0.89\ cm$

# ADC fit function

$$F(x) = \int_{E>0} dE \left( \sum_{N=1}^{\infty} \frac{A}{\sigma\sqrt{2\pi}} exp\left[ -\frac{(x-m)^2}{2\sigma^2} \right] \frac{\mu^N}{N!} e^{-\mu} \right)$$

$$m = N \cdot m_{1pe} + m_{ped}$$

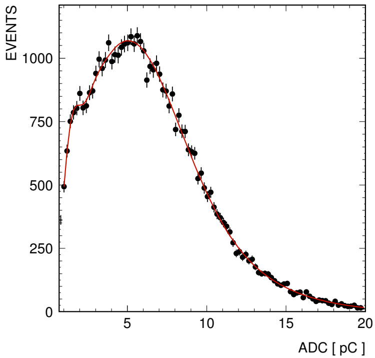
$$\sigma^2 = N \cdot {\sigma_{1pe}}^2 + {\sigma_{ped}}^2$$

$$\mu = g(E) \cdot LY$$

| | |
|---|---|
| $x$ | ADC channel in pC |
| $A$ | Amplitude |
| $m_{1pe}$ | position of a photo-electron peak in pC |
| $\sigma_{1pe}$ | resolution of a photo-electron peak in pC |
| $m_{ped}$ | position of a pedestal peak in pC |
| $\sigma_{ped}$ | resolution of a pedestal peak in pC |
| $LY$ | light yield in photo-electrons |
| $g(E)$ | spectrum of energy deposition by Co-60 photons in a uniform crystal as calculated in GEANT simulations |

# fit is working

**Figure:** MC generated ADC spectrum of Co-60 source (black dots) and it's fit (red)




ADC was generated with

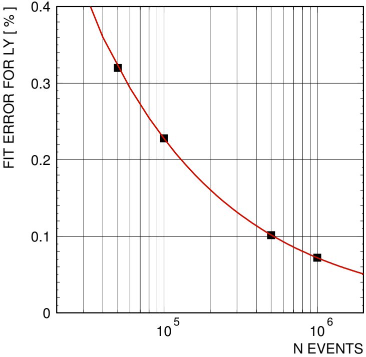
- $LY = 5.00\ p.e.$
- $m_{1pe} = 1.0\ pC$
- $\sigma_{1pe} = 0.55\ pC$
- $m_{ped} = 0.395\ pC$
- $\sigma_{ped} = 0.0335\ pC$
- 50,000 events were generated

ADC was fitted with $LY$ and $A$ floating. Other parameters were fixed to it's true values. MINUIT returned:

- $LY = 5.0033 \pm 0.0160\ p.e.$
- $\chi^2 = 91.07$ based on 95 points.

# fit errors vs number of events

**Figure:** Fit error on $LY$ parameter vs number of events in ADC spectrum (black dots). A general $\sim 1/\sqrt(N)$ function is also shown (red line)




Two-parameter fit: $LY$ and amplitude.
Errors on $LY$ are MINUIT errors.
They follow general dependence:

$$\Delta = \frac{C_0}{\sqrt{N}}$$

# fit sensitivity vs light yield

Fit errors depend on shape of ADC spectrum. This dependence is small and it can be compensated with total number of events in a spectrum.

Co-60 ADC spectra are generated for crystals with total $LY$ in $1 - 20\ p.e.$ range. Each spectrum is fitted with two floating parameters: $LY$ and amplitude. Each spectrum has the same 1) number of events and 2) fitted range of ADC

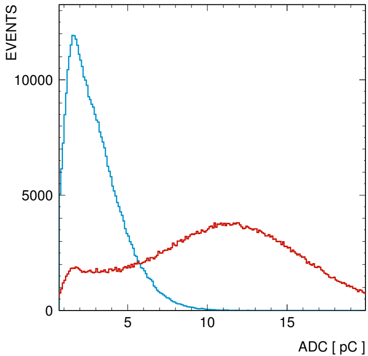



**Figure:** Co-60 ADC spectra for two crystals: a dim crystal with $LY = 2\ p.e.$ (blue) and a bright crystal with $LY = 10\ p.e.$ (red)

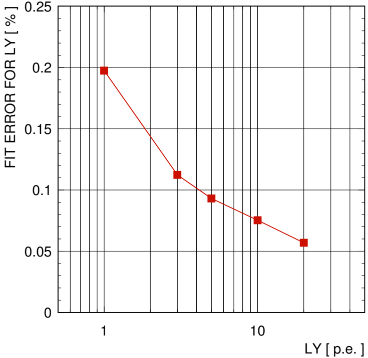



**Figure:** Fit sensitivity for $LY$ parameter vs $LY$ if ADC spectra has 500K events

# fit errors vs number of parameters

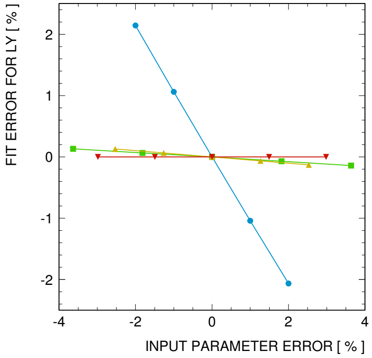
Errors on fit parameters as calculated by MINUIT.

| | fit #1 | fit #2 | fit #3 | fit #4 | fit #5 |
|---|---|---|---|---|---|
| $LY$ | .072% | .56% | .092% | .56% | .074% |
| $m_{1pe}$ | FIXED | .52% | FIXED | .54% | FIXED |
| $\sigma_{1pe}$ | FIXED | .71% | FIXED | FIXED | .64% |
| $m_{ped}$ | FIXED | FIXED | 1.04% | FIXED | FIXED |
| $\sigma_{ped}$ | FIXED | FIXED | $> 100\%$ | FIXED | FIXED |

It seems important to know the position of 1 p.e. peak for precision measurement of light yield

# LY bias due to input parameter uncertainty

**Figure:** Bias in fit result for *LY* if one of the input parameters is fixed to wrong value: mean value for 1 p.e. peak (blue), width of 1 p.e. peak (green), mean value for pedestal peak (yellow), width of pedestal peak (red)




So far, fit had two floating parameters (light yield and amplitude) and other four paramters were fixed to it's true values. What happens if one of the four parameters is fixed to the wrong value?

Position of 1 p.e. peak is a single most important input parameter for the fit. Fluctuations in position of 1 p.e. peak result in *LY* fluctuations of the same magnitude.

What are the implications for our experimental setup?

# Two scenarios

1 Mean value of 1 p.e. peak fluctuates during LY non-uniformity scan significantly (more than 0.5%)

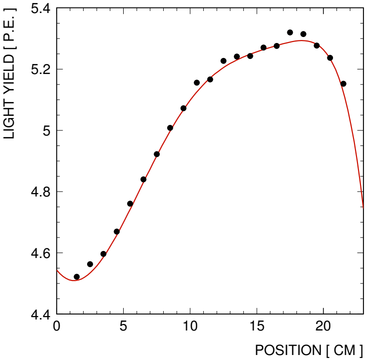
Need to determine the average position of 1 p.e. peak during each measurement with $< 0.1\%$ accuracy. Take Co-60 and LED triggers at the same time. Need to simulate effects of fluctuations on fit and non-uniformity measurements. (ToDo)

2 Mean value of 1 p.e. peak is stable during LY non-uniformity scan (fluctuations are less than 0.1%).

Use the same value of 1 p.e. peak position in a fit function for all ADC spectra. The discrepancy between true value of this parameter and value used in the fit function will result in *LY* error of the same magnitude. What are the effects on non-uniformity measurements?

# Simulation and Measurement on Non-uniformity

**Figure:** Crystal non-uniformity function used during GEANT simulations (red line) and fit results for $LY$ (black dots)




1. Use an arbitrary non-uniformity curve in GEANT simulations.
2. Simulate ADC spectrum using point-like beam of photons from Co-60 (ideal collimator)
3. Fit ADC spectrum and find $LY$
4. Repeat 2 and 3 for 21 positions of Co-60 along the crystal

Measurements are not exactly on the line due to finite bin size of $g(E)$ distribution used in simulations (easy to improve, ToDo)

# Bias in non-uniformity vs error in 1 p.e. peak

In the second scenario, it is possible to measure non-uniformity accurately even if we make an error in 1 p.e. peak position of few %. Realistic error is $< 1\%$.

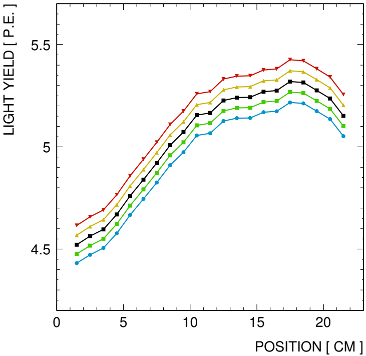



**Figure:** Measured non-uniformity profile using different values for position of 1 p.e. peak: nominal is 1.00 p.e (black), 1.02 p.e. (red), 1.01 p.e.(yellow), 0.99 p.e. (green), and 0.98 p.e. (blue)

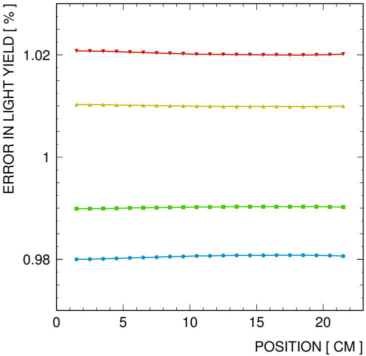



**Figure:** Ratio of nouniformity profiles: measured with error over correct one. The error is in input position of 1 p.e. peak: 2% (red), 1% (yellow), -1% (green), -2% (red)

# Status. Summary. Next steps

- Theoretically, it is possible to make precision measurement of $LY$ with conventional PMT
- Position of 1 p.e. peak should be stabe within 0.1%. Is it possible?
  - PMT
  - HV poswer supply
  - Temperature
- Make simultaneous measurements of 1 p.e. peak with LED
- Need to simulate fluctuations of 1 p.e. peak and its implications
- There is a long list of GEANT studies to optimize the experimental setup, running conditions and fitting procedure