Monte Carlo Simulation of SAC

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Based on arXiv:1809.10840

GOAL

- Study of geometry dependence of the properties of the distribution of Cherenkov photons produced in PbF_2 crystals and converted into photo-electrons through PMT photocathode:
  - Distribution of number of collected photons
  - Distribution of arrival times
  - Containment of Cherenkov light
  - Energy resolution

Implementation on Geant4

Construction of PbF_2 crystal:

- Configuration of geometric properties:
  - Rectangular parallelepiped of dimensions *30x30xL mm*
  - Different lengths considered: *L=10, 12, 14, 16, 18, 20 cm*
- Configuration of optical properties:
  - All optical properties are specified as a function of the photon energy
  - Energy spectrum of interest: from 1.6 eV to 5.0 eV with bin width of 0.02 eV
  - Computation of refractive index through the dispersion formula:

$$n^2 - 1 = \frac{0.66959342\,\lambda^2}{\lambda^2 - 0.00034911^{\,2}} + \frac{1.3086319\,\lambda^2}{\lambda^2 - 0.17144455^{\,2}} + \frac{0.01670641\,\lambda^2}{\lambda^2 - 0.28125513^{\,2}} + \frac{2007.8865\,\lambda^2}{\lambda^2 - 796.67469^2}$$

*Reference: I. H. Malitson and M. J. Dodge. Refraction and dispersion of lead fluoride, J. Opt. Soc. Am. **59**, 500A (1969)*

  - Computation of absorption length from PbF_2 transparency
  - Application of overall scale factor to absorption length spectrum of 1.0, 2.0, 5.0, 10.0

- Configuration of surfaces:
  - Ideally planar surfaces:

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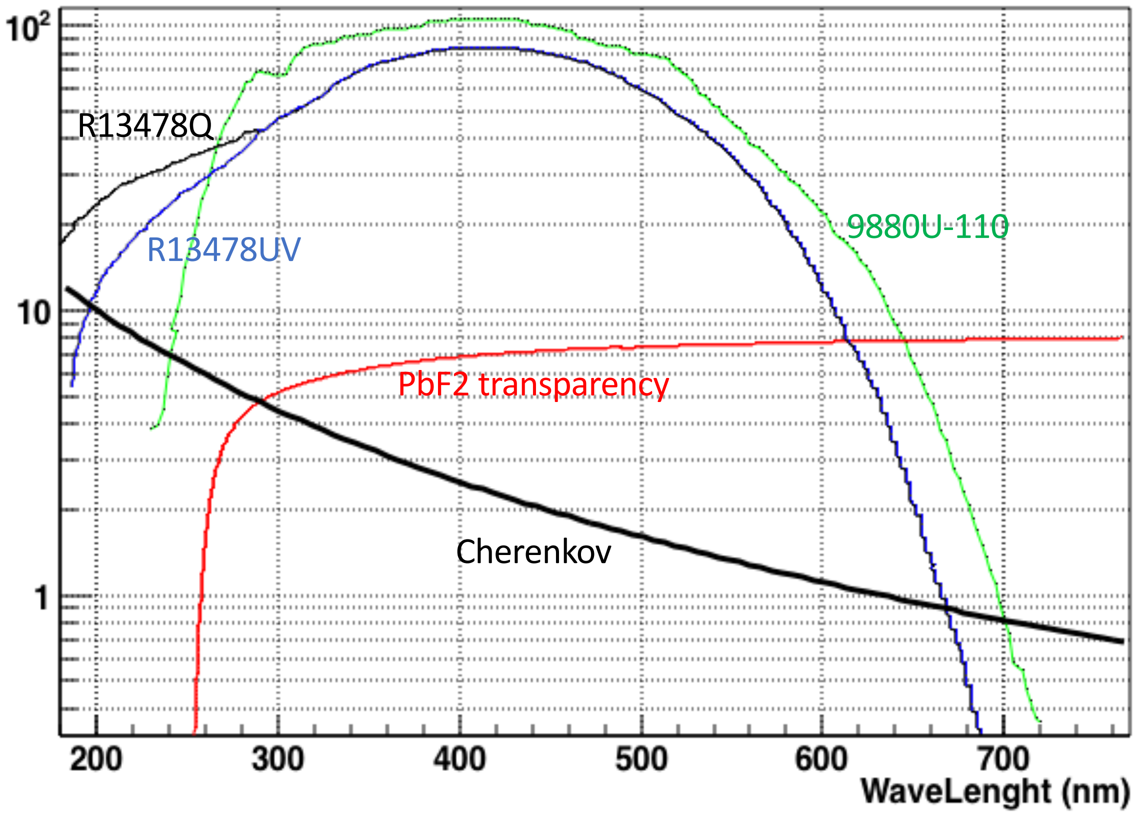
opPbF2Surface->SetType(dielectric_dielectric);
opPbF2Surface->SetModel(glisur);
opPbF2Surface->SetFinish(polished);
```



Construction of glue cylinder:

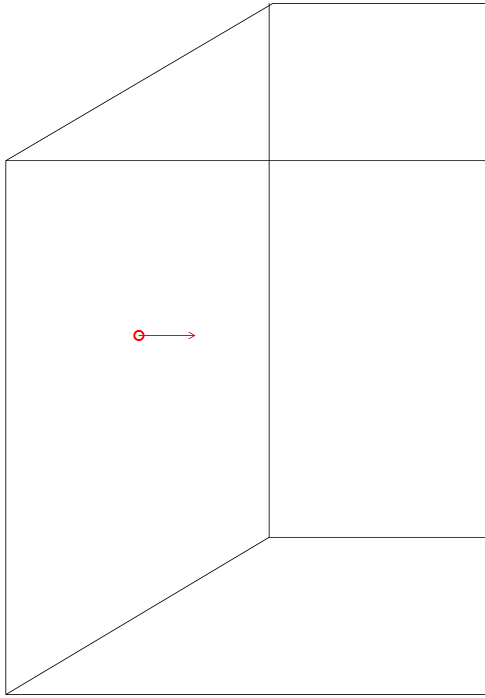
- Epoxy EJ-500 (CMS IN1999/026)
- Dimensions:
  - Radius of *1.27 cm*
  - Thickness of *0.1 cm*
- Refractive index of 1.57

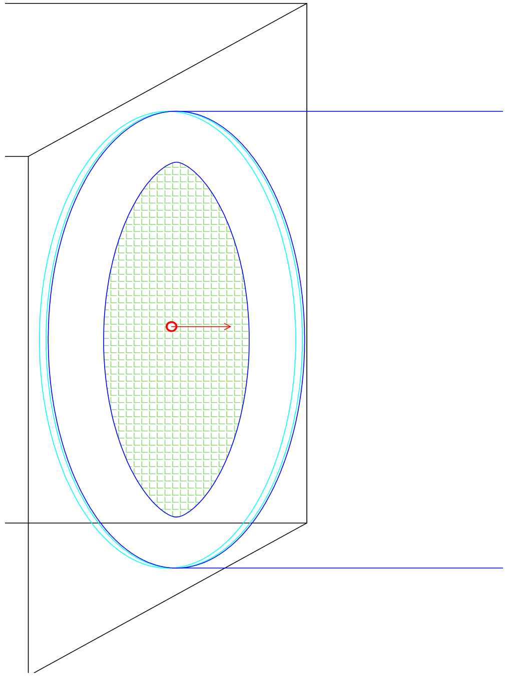
Implementation of PMT R13478UV Quantum Efficiency as function of photon energy

Different energies of the incident photon were considered: *10, 50, 100, 200, 500, 1000 MeV*

Single optical event

- One beam of a single photon with energy fixed is fired at a distance of *1 mm* from the crystal’s surface along the direction of the major axis
- Production of about 3000 optical photons by Cherenkov effect inside the crystal
- Simulation step by step of the optical path followed by each photon





- Analysis of the photons satisfying the following conditions:
  - Survived to get to the opposite face of the crystal
  - Hit the surface inside the area covered by the glue circle
  - Was refracted through the resin and got to PMT surface
  - Passed selection due to PMT quantum efficiency

```
### Run 0 start.
OpNoviceEventAction - Event 0 Begin

*********************************************************************************
* G4Track Information:   Particle = gamma,   Track ID = 1,   Parent ID = 0
*********************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0        0        0      -71       200        0        0         0       World initStep
    1        0        0      -70       200        0        1         1 PbF2_Crystal Transportation
    2        0        0    -61.1         0        0     8.91      9.91 PbF2_Crystal conv

*********************************************************************************
* G4Track Information:   Particle = e-,   Track ID = 2,   Parent ID = 1
*********************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0        0        0    -61.1        65        0        0         0 PbF2_Crystal initStep
    1   0.0118 1.44e-05    -60.9      64.8    0.171    0.222     0.222 PbF2_Crystal Cerenkov

*********************************************************************************
* G4Track Information:   Particle = opticalphoton,   Track ID = 109,   Parent ID = 2
*********************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0   0.0562   0.0375    -60.1  4.63e-06        0        0         0 PbF2_Crystal initStep
    1       15      1.6    -53.2  4.63e-06        0     16.5      16.5       World Transportation
    2      291      127      500  4.63e-06        0      631       647  OutOfWorld Transportation
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*******************************************************************************************************
* G4Track Information:   Particle = opticalphoton,   Track ID = 107,   Parent ID = 2
*******************************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0   0.0688   0.0513    -59.9  3.86e-06         0        0         0 PbF2_Crystal initStep
    1      -15    -4.85    -48.2  3.86e-06         0     19.7      19.7        World Transportation
    2      -15    -4.85    -48.2  3.86e-06         0        0      19.7 PbF2_Crystal Transportation
    3       15    -14.6    -24.9  3.86e-06         0     39.2      58.9        World Transportation
    4       15    -14.6    -24.9  3.86e-06         0        0      58.9 PbF2_Crystal Transportation
    5     13.8      -15      -24  3.86e-06         0      1.6      60.5        World Transportation
    6     13.8      -15      -24  3.86e-06         0        0      60.5 PbF2_Crystal Transportation
    7      -15    -5.65     -1.7  3.86e-06         0     37.6        98        World Transportation
    8      -15    -5.65     -1.7  3.86e-06         0        0        98 PbF2_Crystal Transportation
    9       15     4.11     21.5  3.86e-06         0     39.2       137        World Transportation
   10       15     4.11     21.5  3.86e-06         0        0       137 PbF2_Crystal Transportation
   11     13.7     4.53     22.6  3.86e-06  3.86e-06     1.69       139 PbF2_Crystal OpAbsorption

*******************************************************************************************************
* G4Track Information:   Particle = opticalphoton,   Track ID = 104,   Parent ID = 2
*******************************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0   0.0595    0.041      -60  1.62e-06         0        0         0 PbF2_Crystal initStep
    1      -15    -9.99      -45  1.62e-06         0     23.5      23.5        World Transportation
    2      -15    -9.99      -45  1.62e-06         0        0      23.5 PbF2_Crystal Transportation
    3    -7.48      -15    -37.4  1.62e-06         0     11.7      35.3        World Transportation
    4    -7.48      -15    -37.4  1.62e-06         0        0      35.3 PbF2_Crystal Transportation
    5       15  -0.0216      -15  1.62e-06         0     35.1      70.4        World Transportation
    6       15  -0.0216      -15  1.62e-06         0        0      70.4 PbF2_Crystal Transportation
    7    -7.55       15     7.56  1.62e-06         0     35.2       106        World Transportation
    8    -7.55       15     7.56  1.62e-06         0        0       106 PbF2_Crystal Transportation
    9      -15       10       15  1.62e-06         0     11.6       117        World Transportation
   10      -15       10       15  1.62e-06         0        0       117 PbF2_Crystal Transportation
   11       15    -9.95       45  1.62e-06         0     46.9       164        World Transportation
   12       15    -9.95       45  1.62e-06         0        0       164 PbF2_Crystal Transportation
   13     7.42      -15     52.6  1.62e-06         0     11.8       176        World Transportation
   14     7.42      -15     52.6  1.62e-06         0        0       176 PbF2_Crystal Transportation
   15      -10    -3.38       70  1.62e-06         0     27.3       203 Epoxy_Resin Transportation
*** Killing Photon Event 0 N 1 P = -10.019 -3.380 70.000 mm T = 1.255 ns E = 1.618 eV ***
```

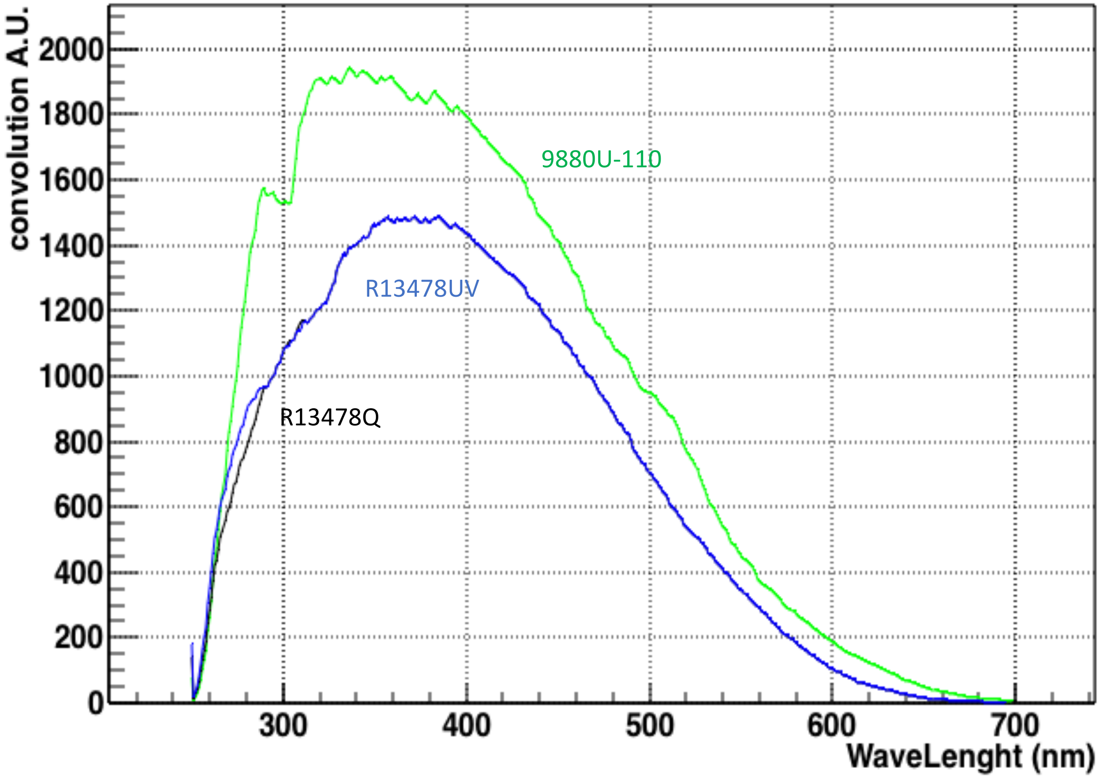
Control Check: distribution of wavelengths

Simulation of 100 events of single *200 MeV* photon, absorption length scale of 10.0

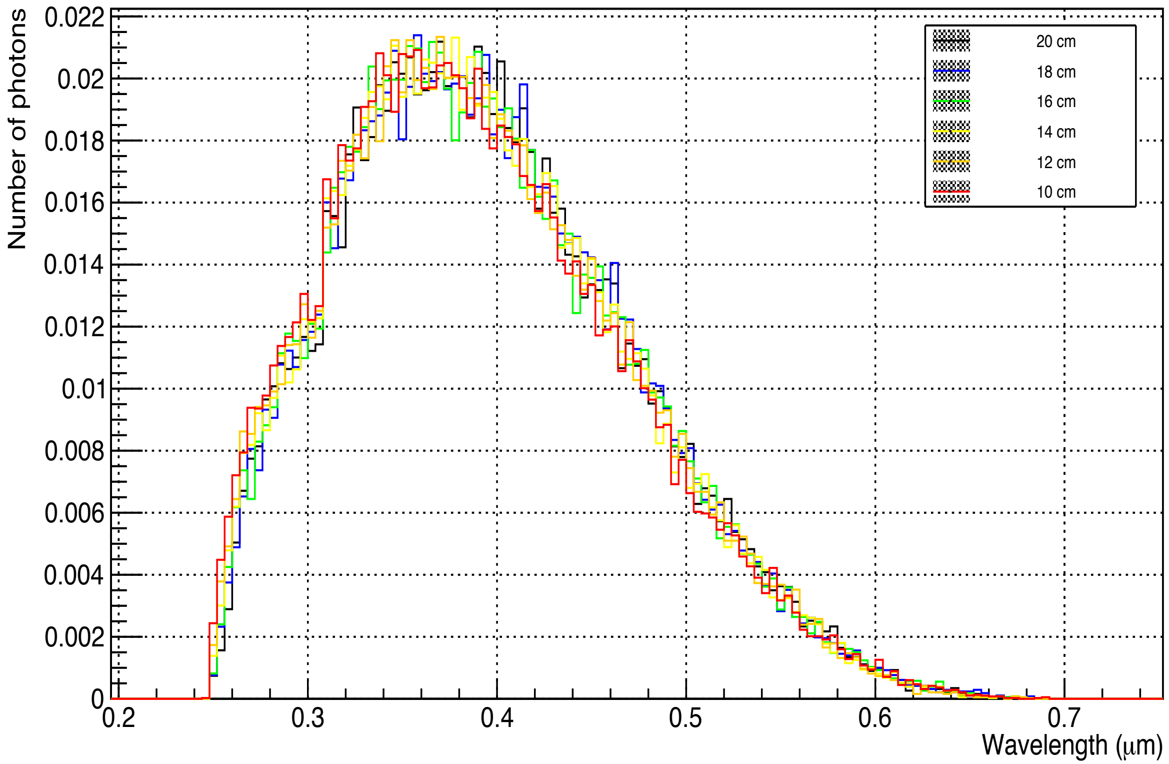
Normalized histogram of wavelengths of collected photo-electrons

- Invariance under change of crystal's length
- Consistency with expected distribution profile

Expected distribution



MC distribution

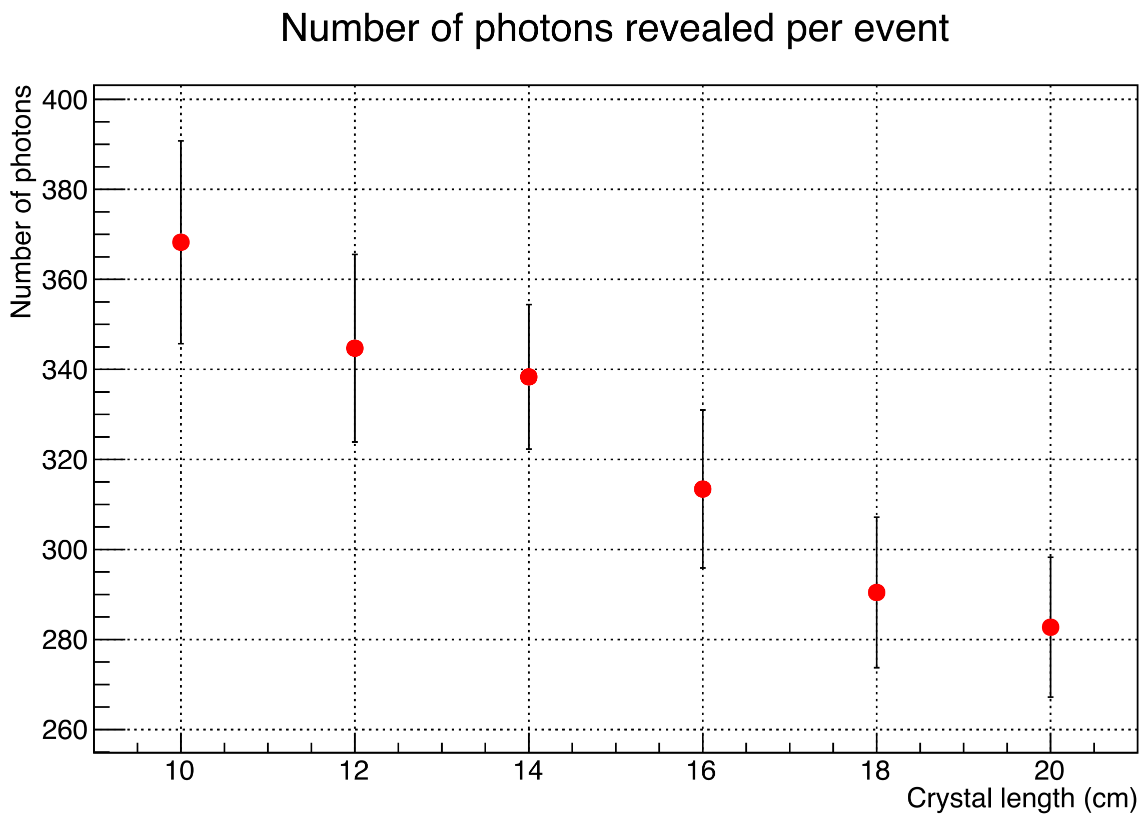


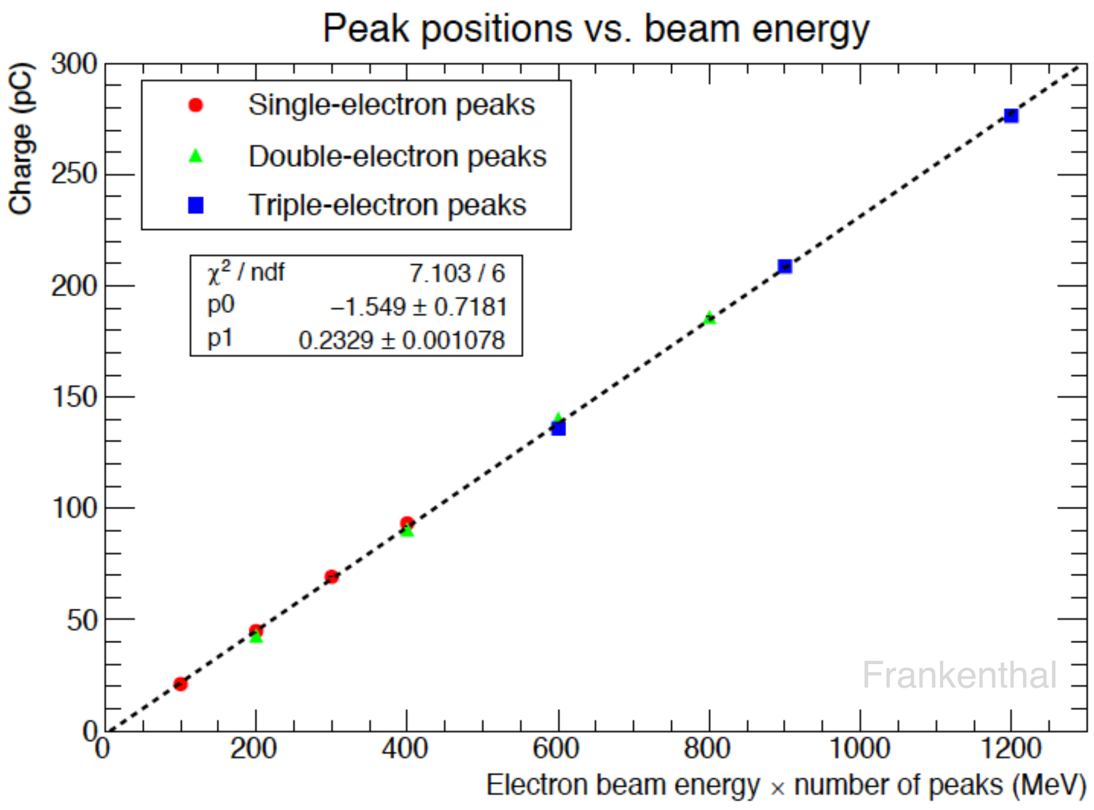
Control Check: number of p.e. per MeV

Simulation of 100 events of single *200 MeV* photon, absorption length scale of 10.0

Graph of number of p.e. collected per event as function of crystal's length

- Crystal length of *14 cm*: $338.34 \pm 32.12\ p.e.$ → $1.69 \pm 0.16\ \frac{p.e.}{MeV}$
- Expected value from experimental data (Test Beam): $\frac{Q}{e \cdot G} = \frac{0.23\ pC}{(1.602 \cdot 10^{-19}\ C)\ (8 \cdot 10^{5})} \approx 1.64\ \frac{p.e.}{MeV}$



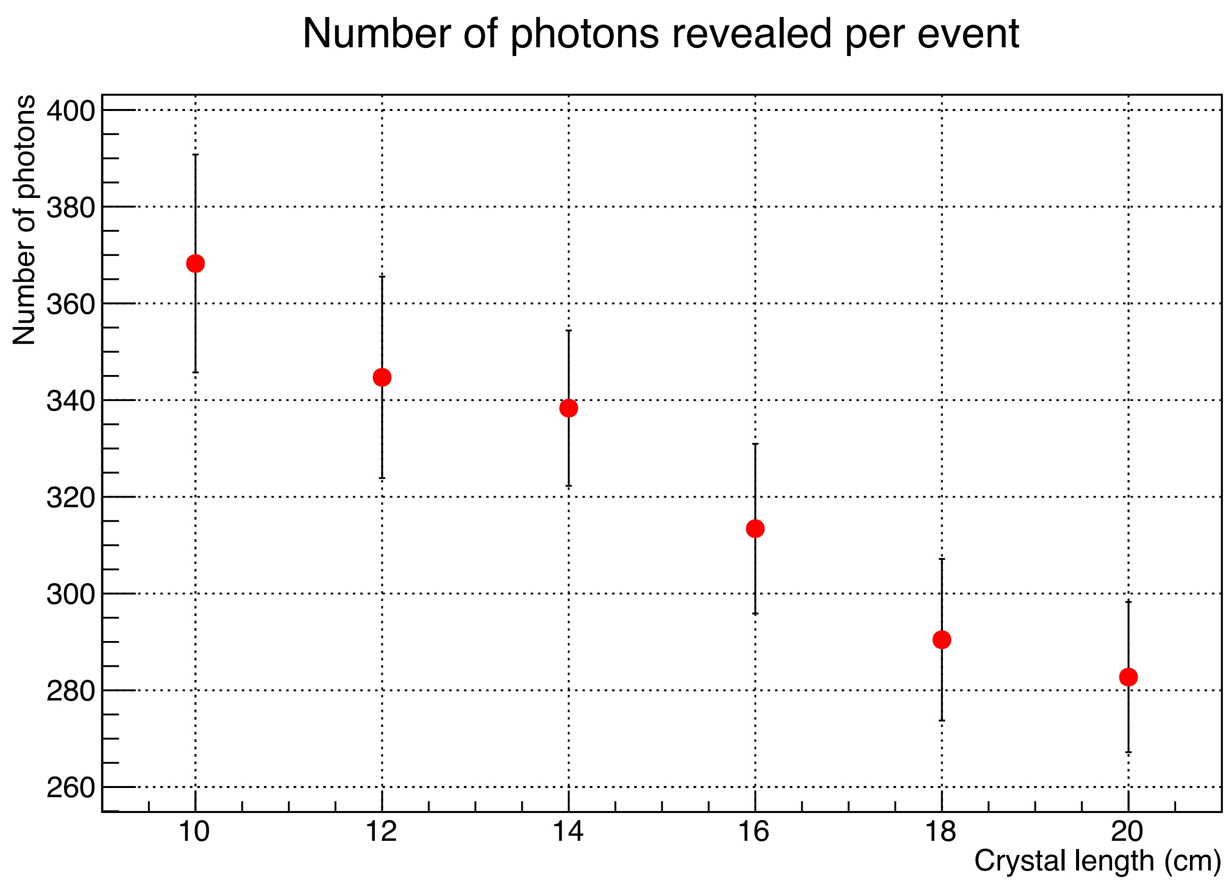


Number of p.e. with different crystal's geometries

Simulation of 100 events of single *200 MeV* photon, absorption length scale of 10.0

Graph of number of p.e. collected per event as function of crystal's length

- Crystal length of *14 cm*: $338.34 \pm 32.12\ \ p.e.$
- Crystal length of *18 cm*: $290.45 \pm 33.42\ \ p.e.$
- Drop of about 14.2% of collected light
- Advantage of shorter lengths

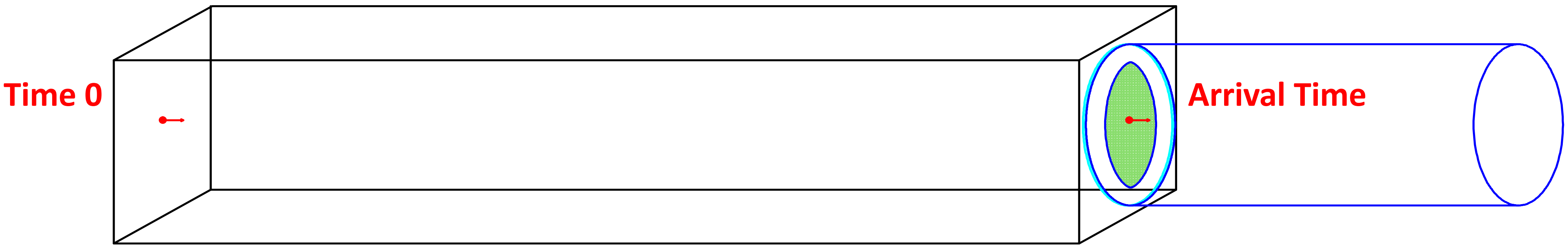


Arrival Times

Simulation of 100 events of single *200 MeV* photon, absorption length scale of 10.0

Analysis of the distribution of arrival times of successful optical photons:

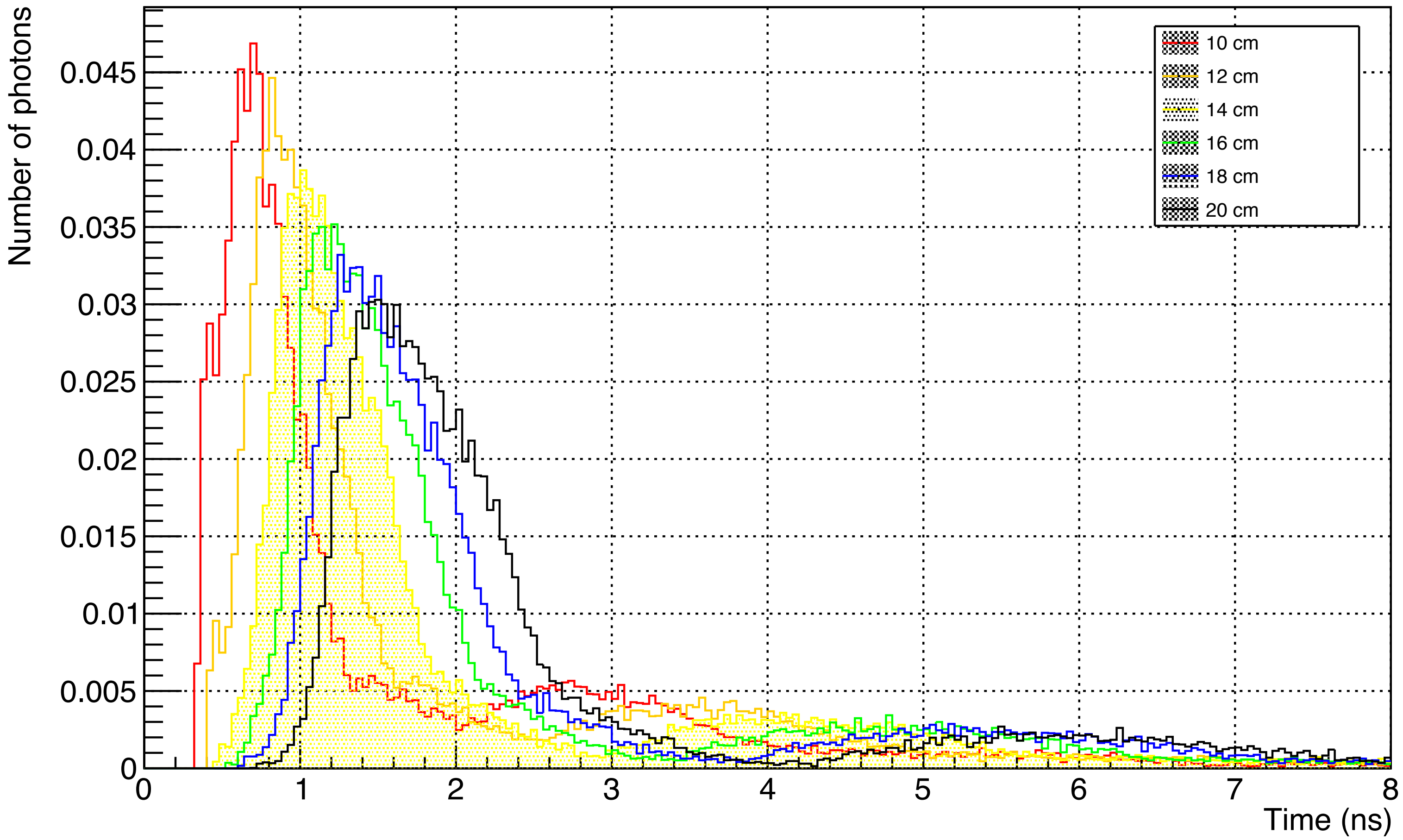
- Time 0: incident 200 MeV photon hits the surface of crystal and refracts inside ≈ start of the simulation
  - Negligibility of time taken to get to the surface (order of $10^{-3}\ ns$) compared to typical times of simulation (order of ns)
- Arrival Time: optical photon survives to PMT photocathode's quantum efficiency selection and is converted into photo-electron



Arrival Times with different crystal's geometries

Normalized histograms of the distribution with two distinguishable peaks

- First peak significantly higher than second one
- Changes in function of crystal length of the absolute and relative proportions of peaks
    - Global translation to right
    - Absolute lowering and widening of peaks
    - Relative departure of peaks

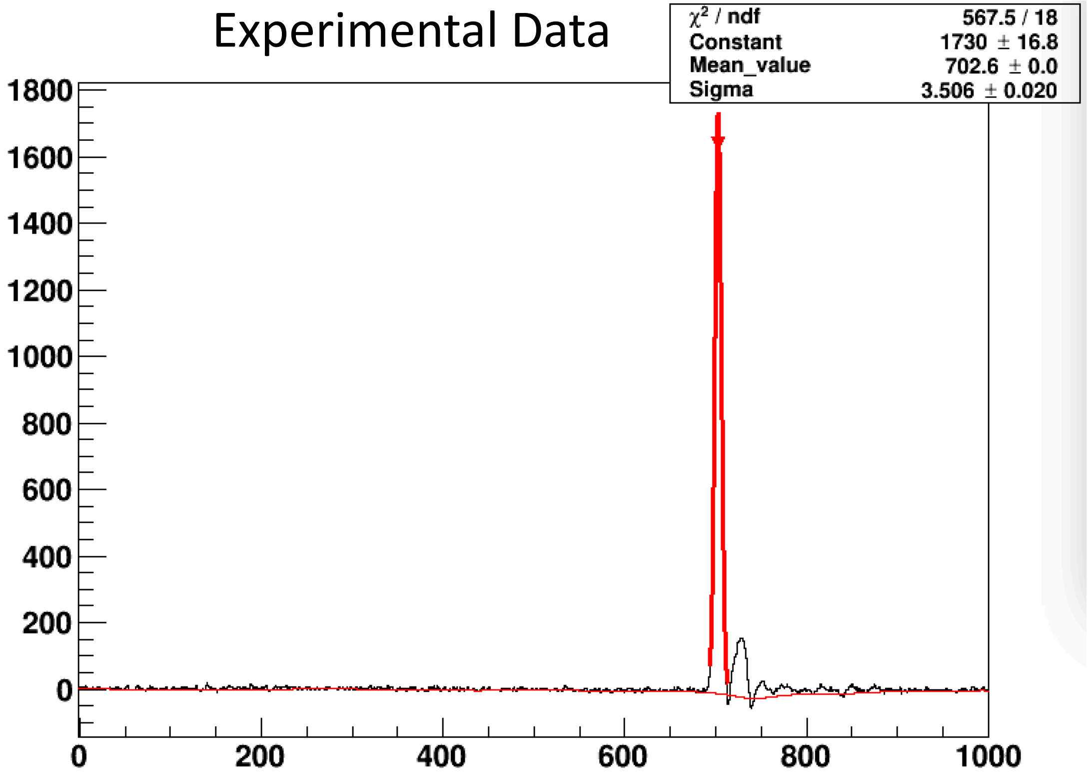


Double Peak on Arrival Times distribution

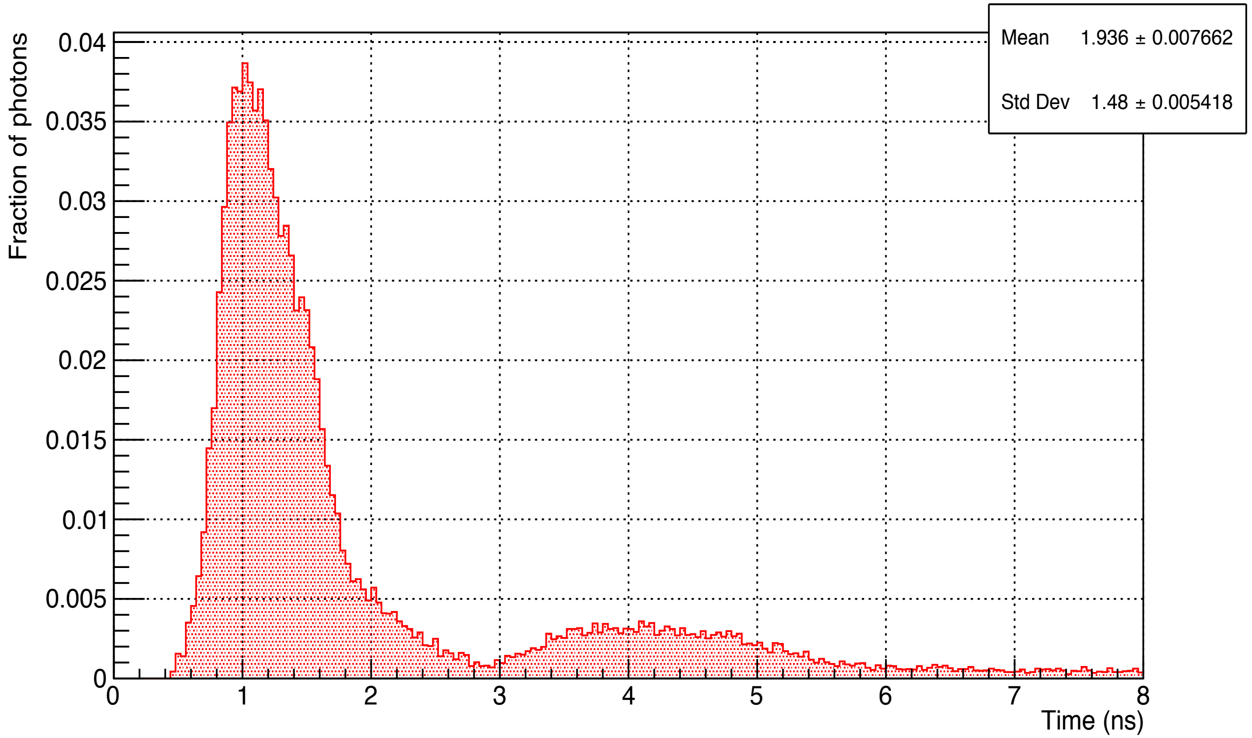
Explanation of the doubly-peaked distribution profile experimentally observed:

- Unavoidable optical effect
- Evident electronic contribution

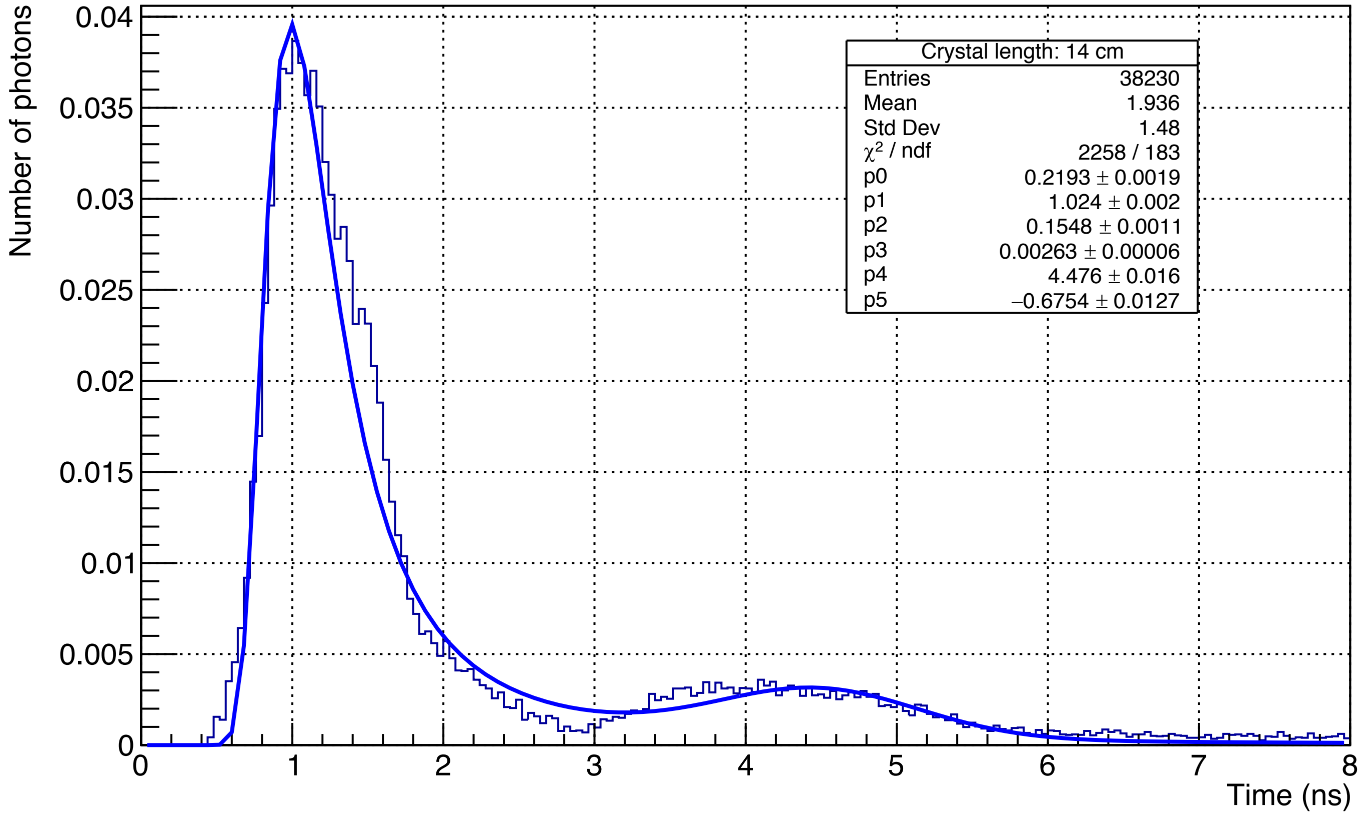
Experimental Data



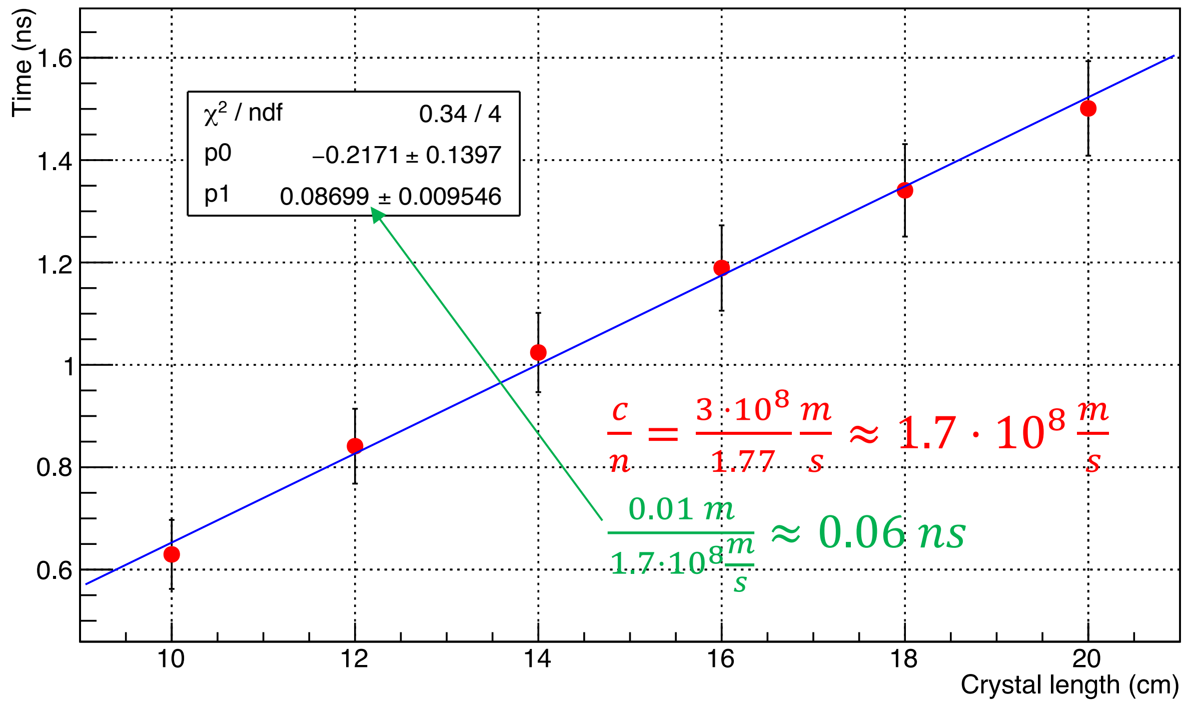
Monte Carlo Data



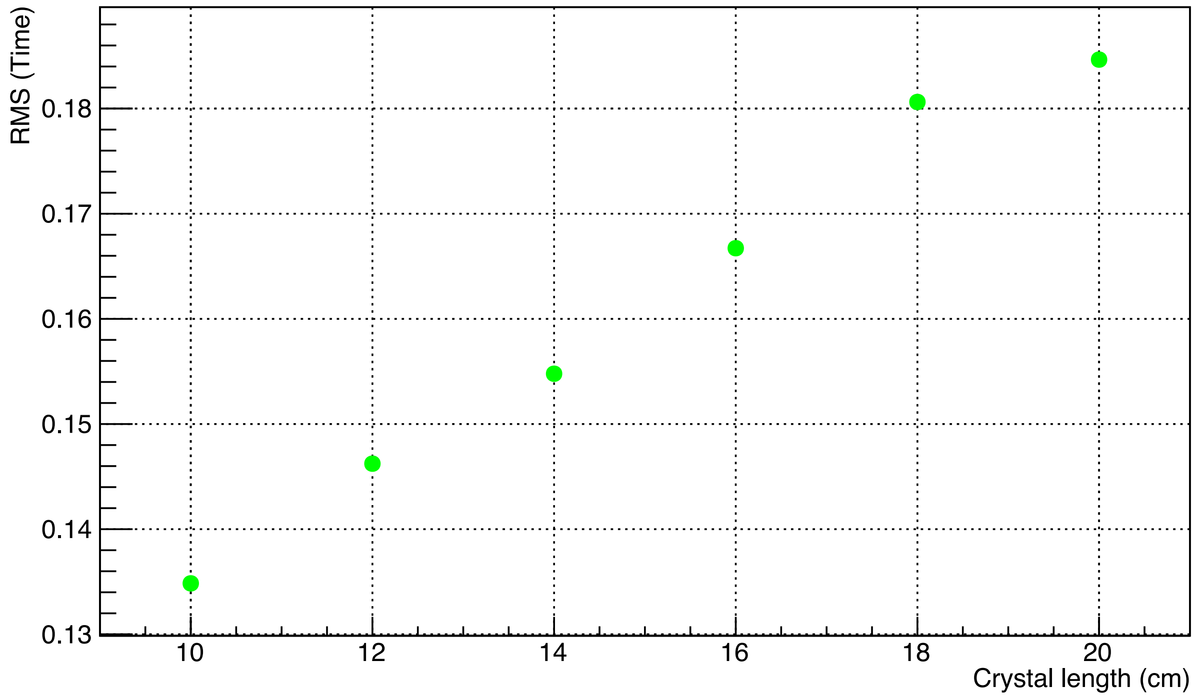
- Fit of the distribution performed using a 6 parameter function given by a Landau function convoluted with a Gaussian function
  - Landau centred at higher peak
  - Gaussian centred at lower peak
- Aim of realizing a tight and high first peak localized at small delay times and a broad, low and distant second peak: quick process and small dispersion in time (purpose of SAC)
  - Selection of the first peak from relative fitting via Landau
  - Graph of Mean Arrival Time as function of crystal length
  - Graph of Arrival Time RMS as function of crystal length



Mean Arrival Time vs. Crystal length



Arrival Time RMS vs. Crystal length



- Linear interpolation partially satisfying
- Absolute delay can easily be managed by a translation of the origin of time
- No real contribution to our previous knowledge

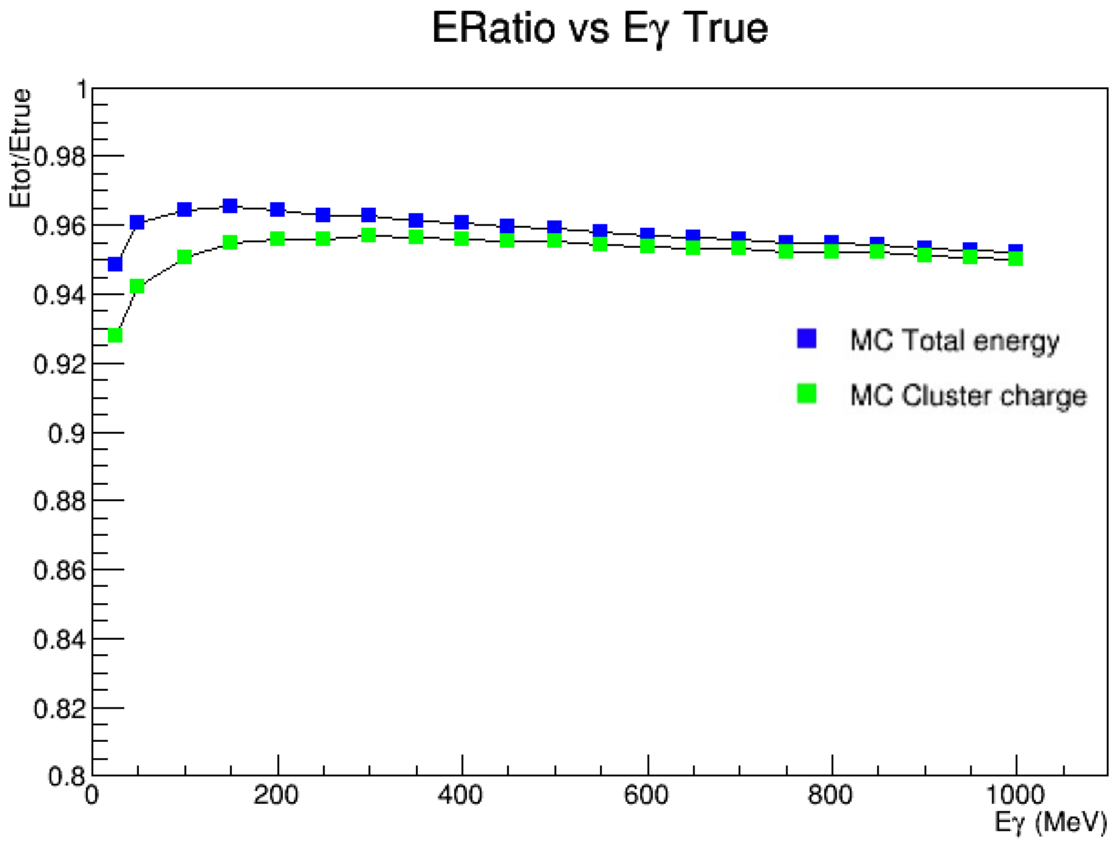
- Quantification of the broadening of time distribution as a consequence of crystal's length increasing
- Bigger lengths involve a lost in time resolution

Containment of Cherenkov light

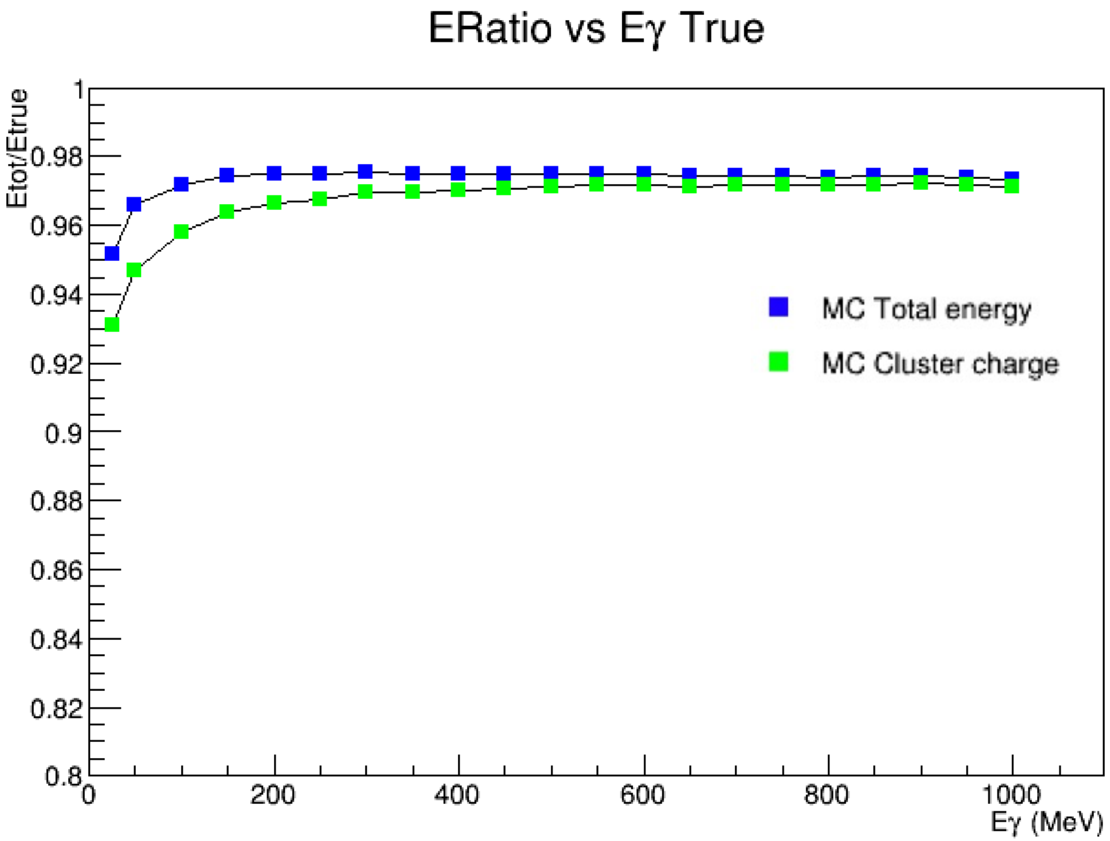
Quantitative analysis of the containment of optical photons by crystals of different lengths:

- Graph of $\mathrm{E}_{\mathrm{ratio}} = \frac{E_{tot}}{E_{true}}$ as function of E_γ
- At higher energies, bigger lengths show a greater stability

Crystal length: 14 cm



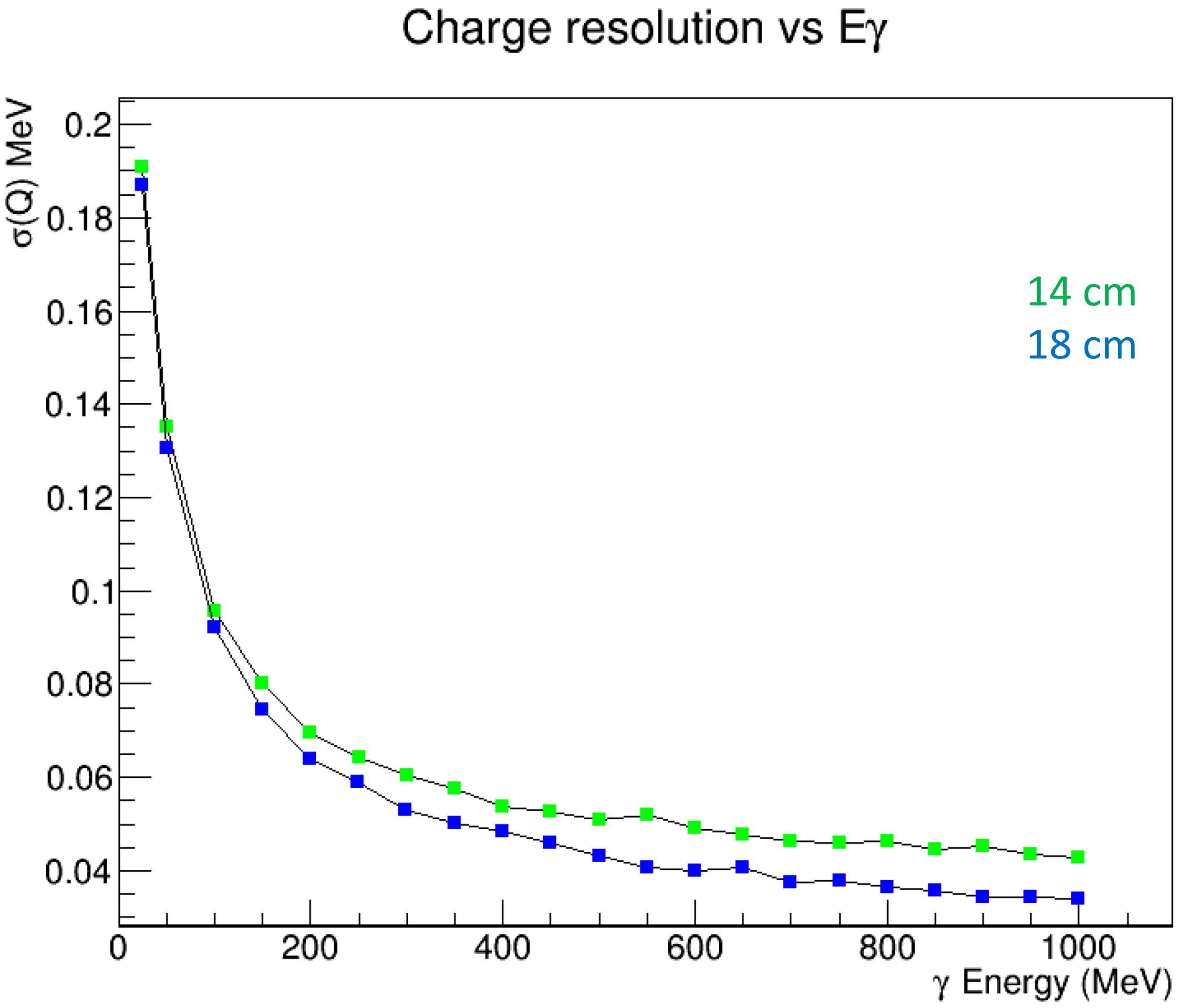
Crystal length: 18 cm



Energy resolution

Analysis of energy resolution as function of crystal's length:

- Graph of $\sigma(Q)$ as function of E_γ
- Difference in resolution is quite moderate if $E_\gamma < 500\ MeV$ (region of interest for PADME)
- This analysis does not consider the decreasing collected light as the crystal's length increases
- Advantage of bigger lengths seems unsubstantial



Conclusions

- MC simulation provides a valid estimates of the PbF_2 photo-electron yield, given the reasonable configuration of the optical system
- Study of different crystal's geometries shows a drop of the number of p.e. collected per event of about 15% going from 14 cm to 18 cm of length
- Study of arrival times:
  - Partially explain double peak behaviour observed in experimental data
  - Time arrival distribution RMS increases with crystal length
- Energy resolution is only slightly dependent on crystal's length
- 14 cm seems to be an adequate choice