Geant4-based simulation studies

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UIb/II ECAL Upgrade Meeting
23rd of November 2018

Outline of the Talk

1) Introduction to the Geant4-based upgrade studies of the ECAL

2) Setup for the standalone Geant4-based simulations

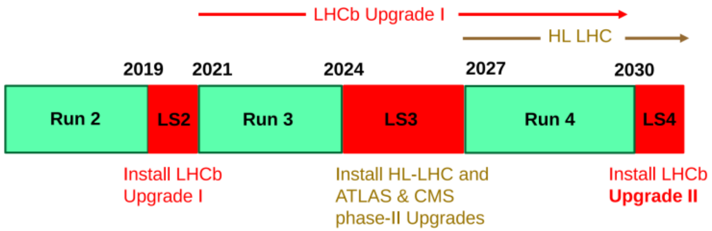
3) Preliminary results for shashlik-type sampling and single crystal calorimeters

4) Summary

Motivation for the Geant4-based simulation studies

- The HL upgrade of the LHC will require operation of the ECAL of LHCb in extreme conditions.

- An upgrade of the ECAL during LS3 can (ideally) provide:
  - Radiation hardness
  - Better energy and spatial resolution
  - Fast timing



- Opportunity to improve on ECAL-related physics:
  - Final states with π^0, soft and hard γ, and electrons

- The following upgrade options are to be studied using the Geant4-based simulations:

  1. “Shashlik”-type sampling calorimeter
  2. Single large scintillating crystals
  3. “SpaCal”-type sampling calorimeter (fibers of scintillating crystals in absorber)

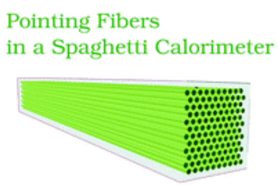
The aim of the Geant4-based simulations studies is to estimate the ECAL performance for various detector options and physics cases at the upgrade conditions.

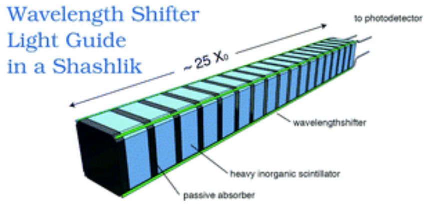
Effects to be considered for a potential ECAL upgrade

Scintillator:
- Light yield
- Energy& time resolution
- Radiation hardness, …

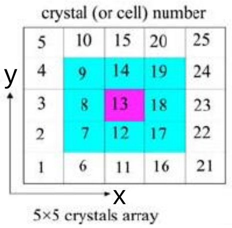
Absorber:
- Molière radius
- Sampling & resolution
- Size of the ECAL modules

Single modules:
- Choice of geometry:
  Single crystal, Shashlik, SPACAL, ACAL, …
- Light propagation and readout
- Lateral and longitudinal shower shape, energy, and time resolution

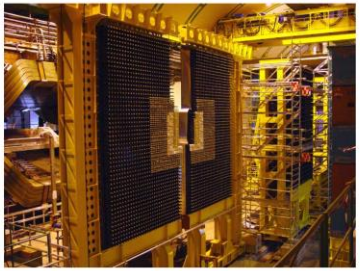




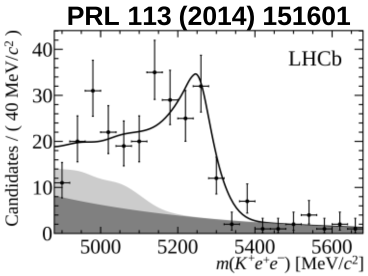
Array of modules:
- Reconstruction of energy of primary particles from clusters of detected scintillation light
- Backgrounds, occupancies, …



The ECAL:
- Interplay with other detectors
- PID, Trigger, …



Physics:
- Performance in physics analyses
- Decay mode specific



Complexity

→ The simulation and optimization studies require to account for various physics processes and a complex configuration space (nothing above is fixed)

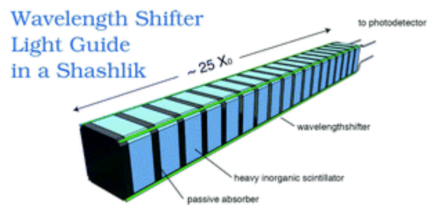
Potential options for the ECAL modules

- <u>Topologies</u>:

Single scintillating crystals:

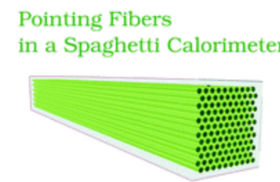
- Very good energy resolution
- Bulky, not compact
- Might be expensive

Shaslik-type sampling:



- Yet unsolved problem of radiation hard WLS fibres for light transport

SPACAL:



- Scintillating fibres can be directly read out at the ECAL front and rear faces.

- <u>Scintillator materials</u>:
  - LYSO (rad. hard, much light, fast decay time)
  - GAGG-Ce (properties similar to LYSO, but experimental)
  - BaF_2, CsI (fast timing, excellent energy resolution for single crystal options, inexpensive)
  - …

- <u>Absorber materials</u>:
  - Lead
  - Tungsten
  - Addition of Cu
  - …

Setup for the standalone Geant4 simulations

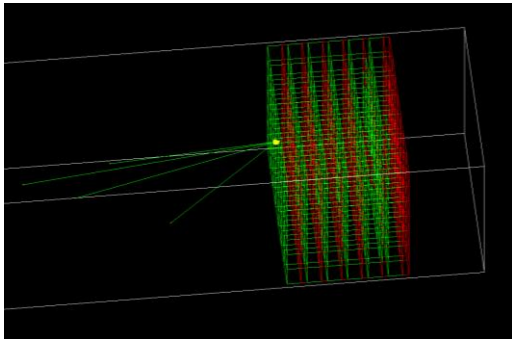
A setup has been developed to perform the simulations directly in Geant4, some features:

- Able to define arbitrary shashlik-type sampling or single crystal modules.
- Sensitive volumes are not replicated layers in 2D (xy-plane), but in 3D.

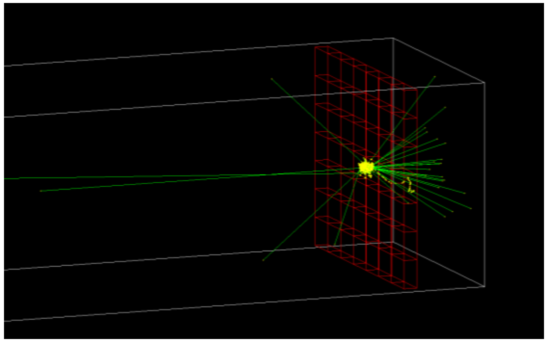
  This allows the access to the lateral+longitudinal shower development, e.g. important for the timing studies. (Not implemented in current LHC-CaloHit objects.)
- A modified event generator gun is used to create primary signal particles together with background particles randomly sampled from Gauss simulations.
- Simulations use very small cell sizes, and can be reclustered later on analysis level to larger cells (i.e. it is not necessary to redo simulations for different cell sizes, but can be optimized at a later step)
- All info of the simulated electromagnetic showers can be written out to ntuples (e.g. momenta, hits, energy deposits and timing information of any secondary particles.)
- Text file steering, runs on CERN’s HTCondor cluster
- Started working using the multithreading option in Geant 4.10 to use several CPUs.

Setup for the standalone Geant4 simulations

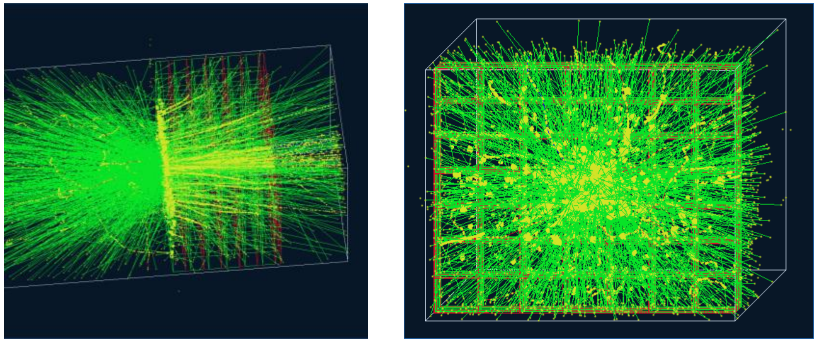
Some visual examples of the simulations:



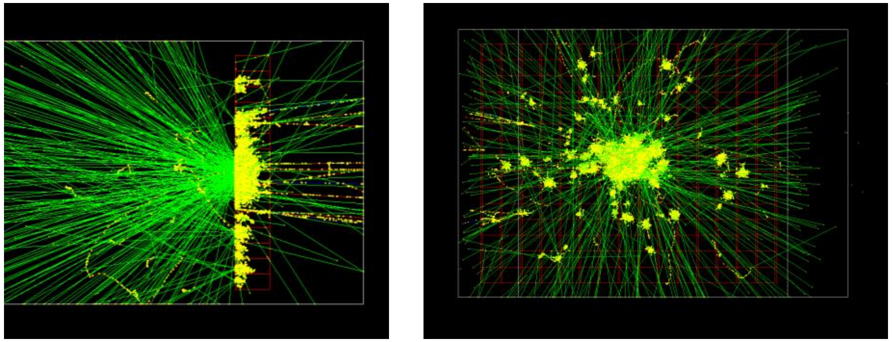
Lead (green) + GAGG (red) shashlik,
50 GeV signal photon at 5°, wo/ background



Bariumflourid single crystal modules,
100 GeV photon at 0°, wo/ backogrund



Same as above w/ background



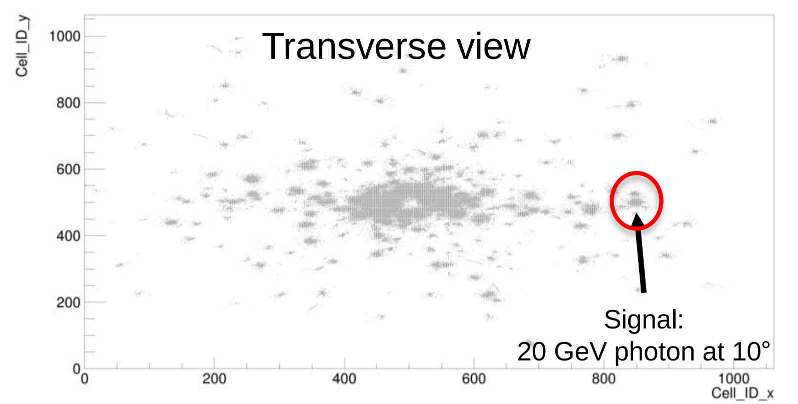
Same as above w/ background

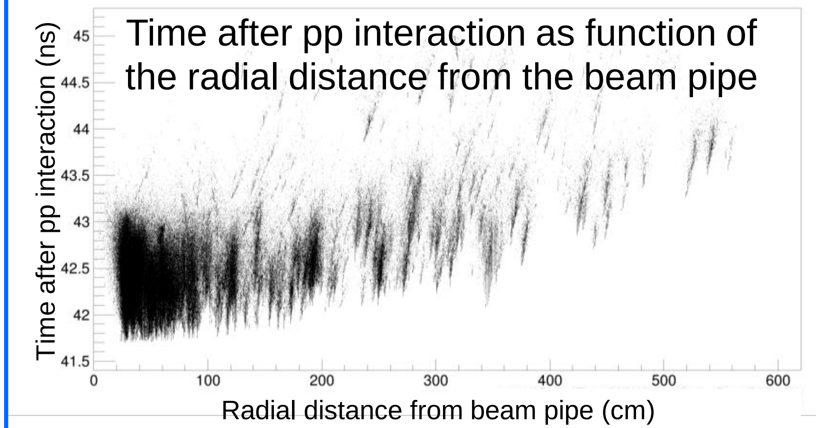
[Above used ECAL geometry parameters are not in scale to improve visibility.]

Setup for the standalone Geant4 simulations

```
# LHCB Ecal model, called: ./create_mac_file.py 30 Lead 4 GAGG 2 gamma 100 0 1 0 1500

/control/verbose 2
/run/verbose 2

# set to default ECAL geometry using 1cm cell sizes
/LHCb_Ecal/det/setEcalBeginZ 12530.0 mm
/LHCb_Ecal/det/setEcalOutXSize 779 cm
/LHCb_Ecal/det/setEcalOutYSize 633 cm
/LHCb_Ecal/det/setNHalfCellsX 389
/LHCb_Ecal/det/setNHalfCellsY 316

# define modules for shashlik type sampling calorimeter
# or single crystal calorimter
/LHCb_Ecal/det/setNbOfLayers 30
/LHCb_Ecal/det/setNbOfAbsor  2
/LHCb_Ecal/det/setAbsor 1 Lead 4 mm
/LHCb_Ecal/det/setAbsor 2 GAGG 2 mm

# define CaloHit writeout mode, i.e. write out any hit,
# or accumulate hits per cell
/LHCb_Ecal/det/CaloHit_writeout_mode 0

# optionally range cuts, useful to speed up simulations
#/run/setCut 100 um

# define name of output root file
/analysis/setFileName lhcb_ECAL_module_NbOfAbsor_2_NbOfLayers_30_Absor1_Lead_4_mm_Absor2_GAGG_2_mm_P

/run/initialize

# define an active region, for example to ignore background
# events far from the signal region.
/LHCb_Ecal/det/defineCaloActiveRegion 1

# An area of 240cm x 240cm will be simulated around theta,
# if defineCaloActiveRegion is set to 1
/LHCb_Ecal/det/defineCaloActiveRegion_at_theta 0

# define primary particle and energy
/gun/particle gamma
/gun/energy 100 GeV

# choose gun option
/LHCb_Ecal/gun_control/selectGunAction 0 # signal only
#/LHCb_Ecal/gun_control/selectGunAction 1 # background only
#/LHCb_Ecal/gun_control/selectGunAction 2 # signal+background

# define theta and phi angles
/LHCb_Ecal/gun_control/setGunSignal_theta 0
/LHCb_Ecal/gun_control/setGunSignal_phi 0

/run/printProgress 100

# generate N events
/run/beamOn 1500
```

Example of the simulation macro steering





Some ntuple examples for 1 event with any hits writtten out.

Treatment of the background

- The large background levels expected at high instantaneous luminosities are the main challenge for the design of the ECAL upgrade. Therefore, a detailed understanding and proper treatment of the background the simulations studies are important.

- Gauss can run the full event simulations from the creation of the primary particles in the pp collision (event generators, e.g. Pythia, EvtGen,…) up to the detector response (Geant4) for various upgrade conditions (lumi, new detectors, …).

→ The Gauss simulations of the full LHCb events are computationally very intensive and cannot carried out for each ECAL configuration.

- To include the background in the ECAL upgrade studies, we use Gauss to “measure” the background hitting the ECAL front face, and then include these backgroundsas input to the standalone Geant4 simulations.

[Idea by Vanya Belyaev, realized by Zhihong Shen (Tsinghua University)]

→ This allows to estimate the performance of the ECAL upgrade options with realistic background and occupancy conditions.

Treatment of the background

- Scheme for the treatment of the background:

1) In Gauss, a transverse plane is placed on the front face of the ECAL and defined as a sensitive detector in Geant4.

2) In Gauss, particles from minimal-biased events are propagated through the upgraded LHCb detector. All information of the primary and secondary particles hitting the sensitive detector plane upstream is written to ntuples.

3) The composition and properties of the background hitting the ECAL are analyzed in detail for instantaneous luminosities up to $\mathcal{L} = 2 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$.

4) In the standalone Geant4 simulations, the background events are used as input in addition to the signal. This is done by randomly sampling from the background ntuples produced in Gauss and using a modified primary particle generator class in Geant4.

- Zhihong Shen analyzed in detail the background conditions at the ECAL front face and produced high statistics background ntuples.

→ Please see also the presentation by Zhihong Shen.

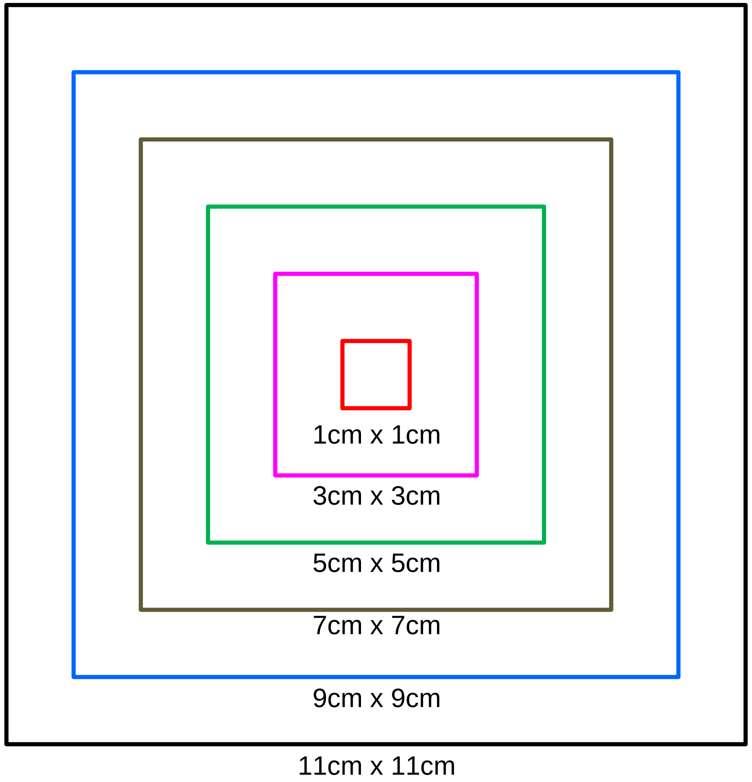
Treatment of the cell size

- In the simulations, very small transverse cluster sizes of 1cm x 1cm are used. This cluster size is small compared to the Mollière radii of the absorber and scintillator ECAL materials, and allows for an an adaptive simulation scheme wo/ rerunning each simulation for each cluster size (significant performance and bookkeeping benefit).

- In the analysis, we study the effect of the cell size by reclustering the original 1cm x 1cm cells in 2cm steps up to a cell size of 11 cm x 11 cm.

- This range covers various Mollière radii (e.g. ≈1cm for Tungsten or 3cm for CsI).

- It also covers approx. the cell sizes of the current ECAL (about 4cm x 4cm in the inner region and 12cm x 12cm in the outer region).



→ For the resolution studies, we give all results as a function of above cell sizes.

Overview of performed simulations to test the simulation scheme

- To test the simulation scheme and to obtain starting working points for further studies, we've chosen the following configurations:

Shashlik configurations:

GaGG + Lead : 30 + 60 layers
GaGG + Tungsten: 30 + 60 layers

→ Chosen to probe for effects due to different Mollière radii and sampling fractions.

Single crystal configurations:

Bariumflourid (BaF2)
Pure CsI

→ Radiation hard inorganic scintillators with very fast timing capability.

- The simulations are performed for pure signal events and for events including the background expected at $\mathcal{L} = 1.5 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$.

- Each simulation set is performed for primary photons generated at:
  Incident angles θ=0 (for reference), 3, 4, 5, 6, 7, 8, 9, 10, and 11 degrees
  Photon nergies at 10, 25, 50, 75, 100, 125, 150 and 175 GeV

- Each simulation "point" consists of 1500 events.

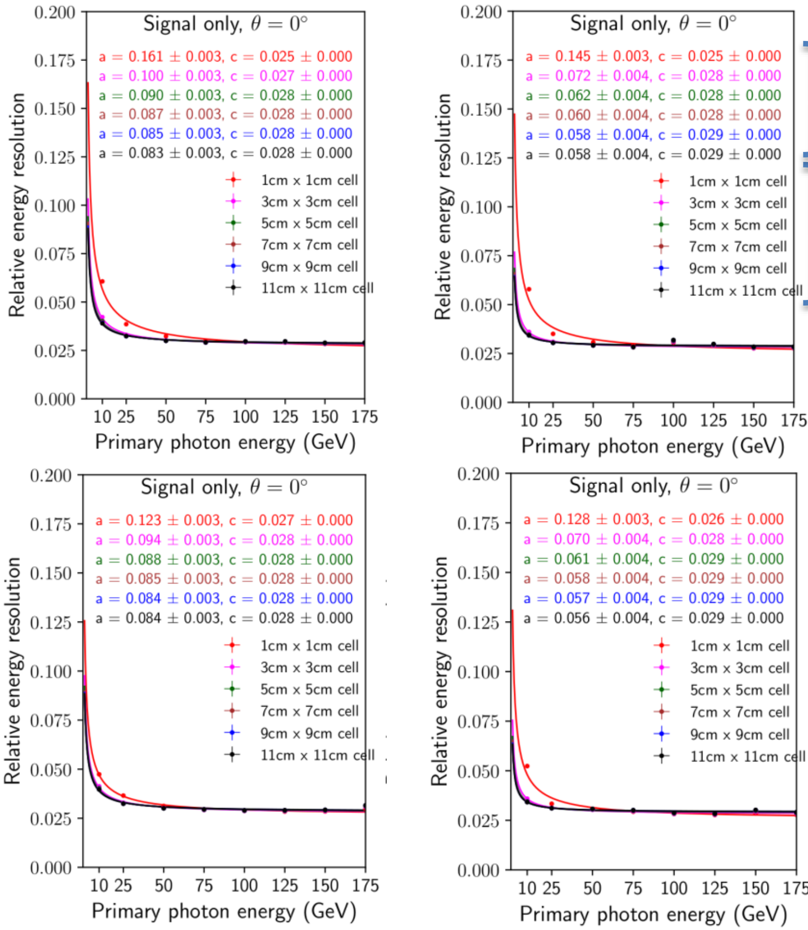
Preliminary results

Comparison GAGG-lead and GAGG-tungsten, for signal only at 0 degrees:

30 layers | **60 layers**

GAGG-lead

GAGG-tungsten



Result of fit for stochastic term a, and constant term c

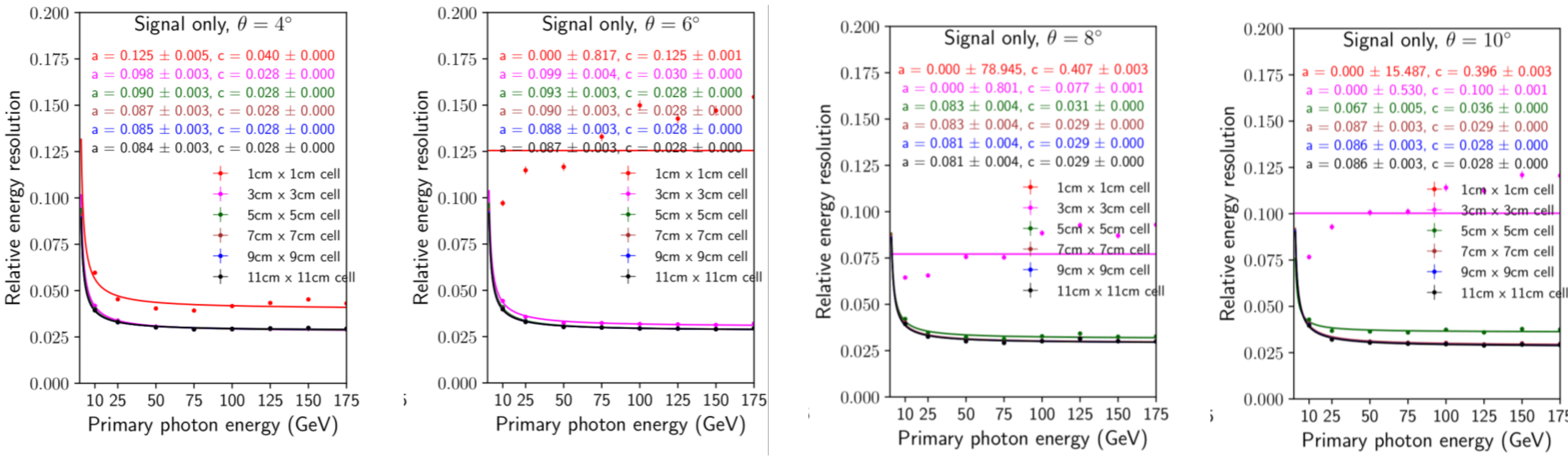
Color code for cell sizes

[Unrealistic case, but allows to probe intrinsic properties and provides a reference.]

Preliminary results

Effect of variation of the angle as function of cluster size:

Inner region — In between — Outer region

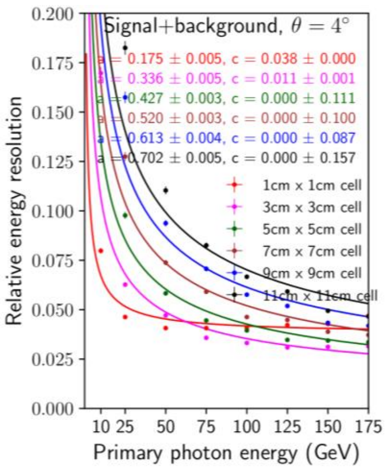


Example: GAGG-lead 30 layers
Signal only

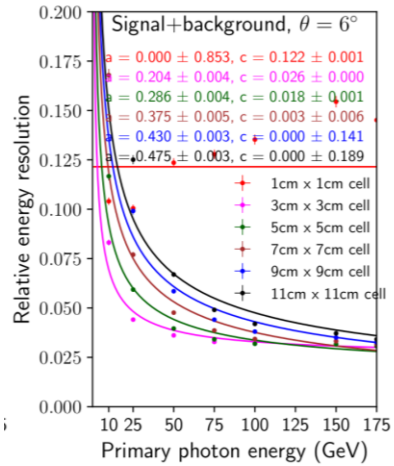
Preliminary results

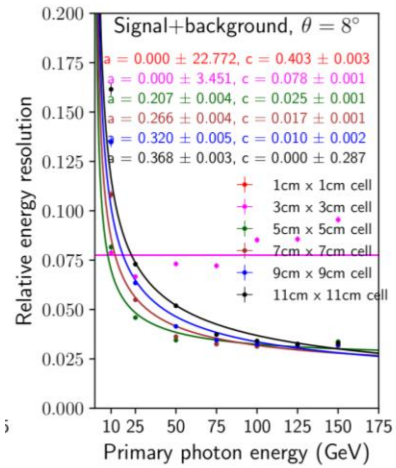
Effect of variation of the angle as function of cluster size and including background:

Inner region

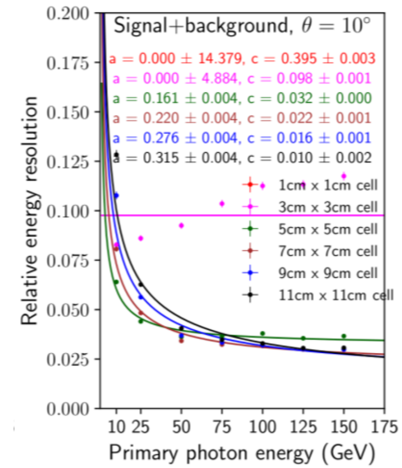


In between





Outer region



Example: GAGG-lead 30 layers

Signal + background

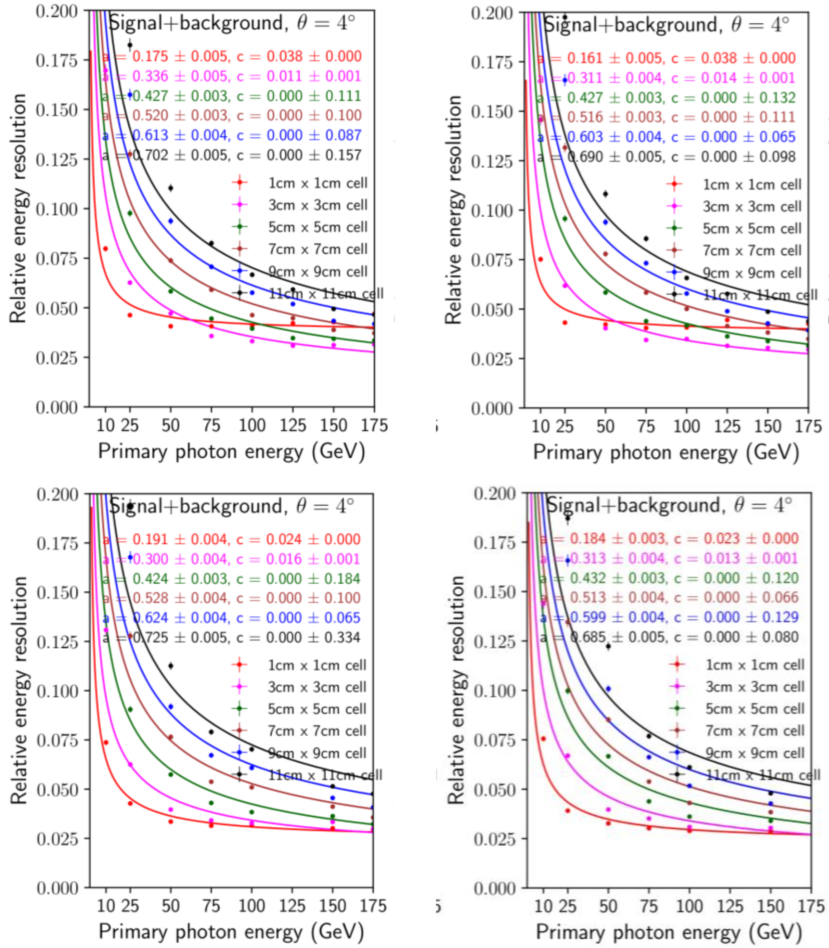
Preliminary results

Comparison GAGG-lead and GAGG-tungsten, for signal+background in inner region:

30 layers | **60 layers**

GAGG-lead

GAGG-tungsten

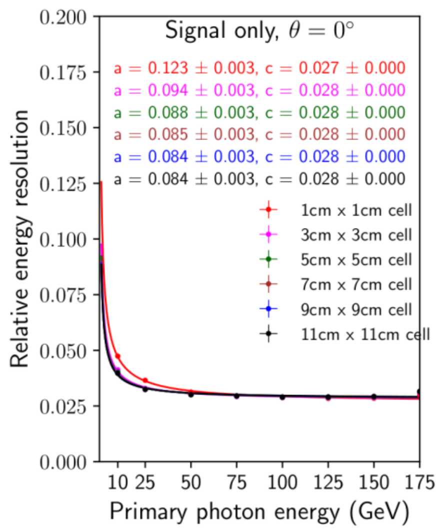


4 degrees (inner region)
Signal + background

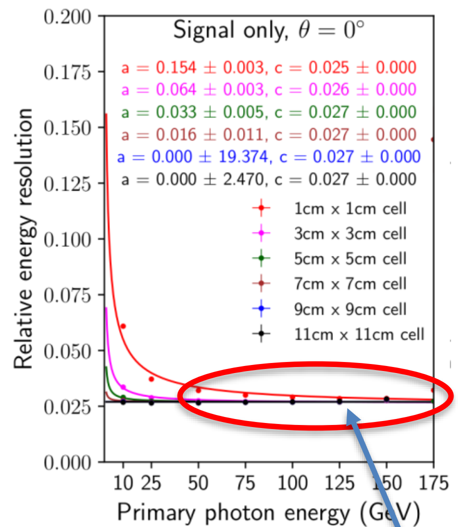
Preliminary results

Comparison of shashlik to the single crystal option:

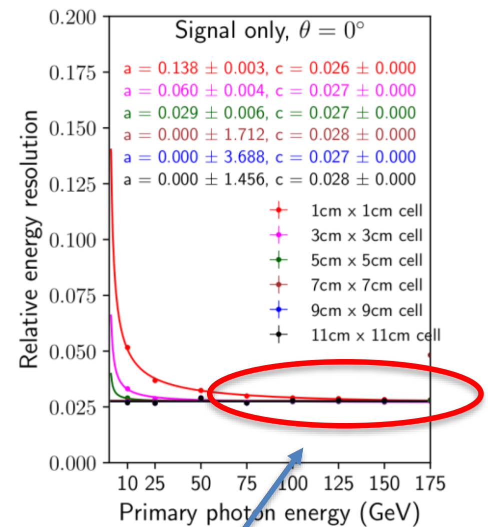
GAGG-tungsten 30 layers



BaF2



CsI

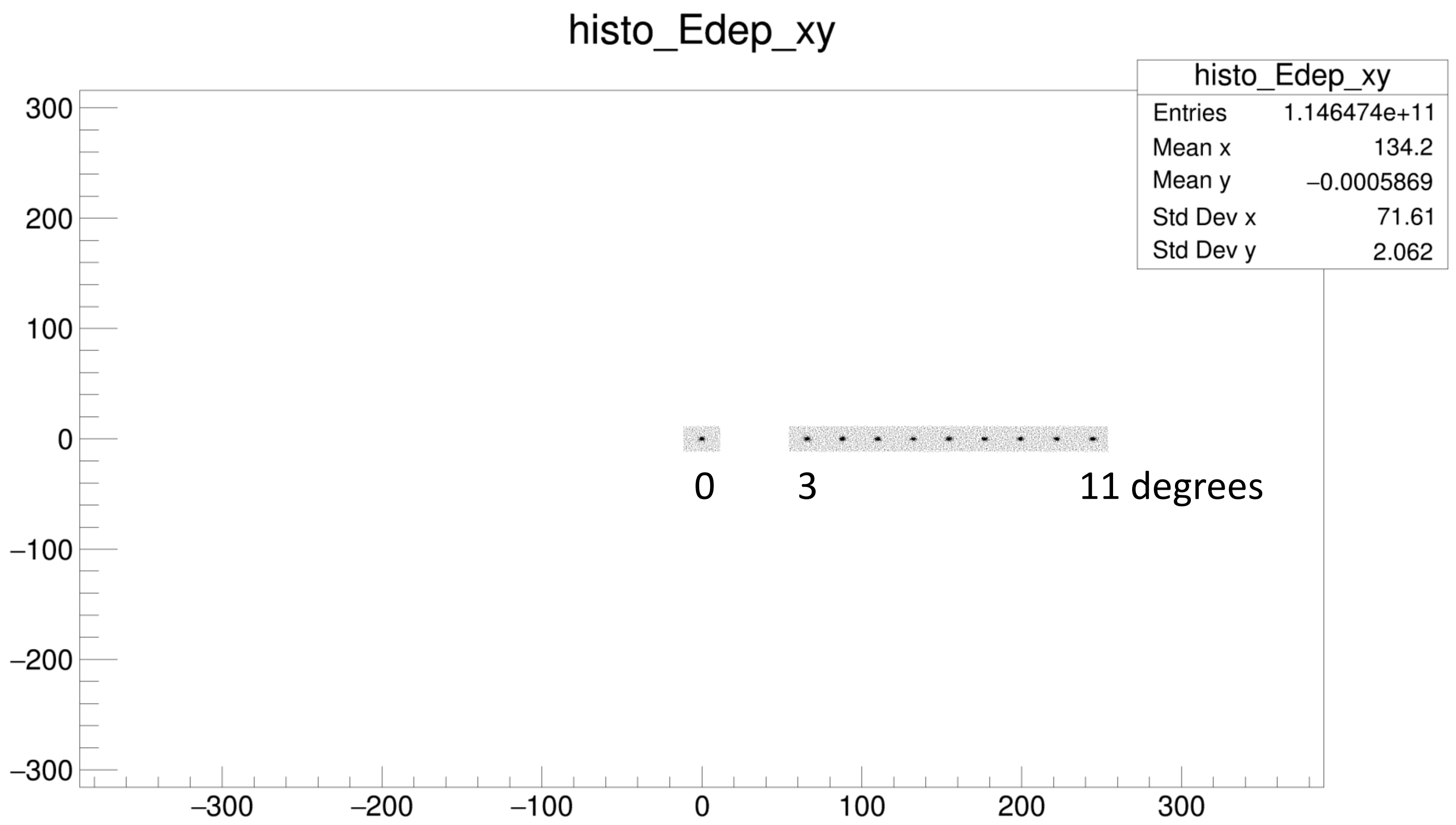


Single crystal simulation finished very late.
Found resolution width overestimated in this region,
and constant term is wrong (factor 10 too large).

Summary

- The progress on the Geant4-based simulation studies has been reported.
- A framework to perform standalone simulations for arbitrary ECAL configurations has been developed, and some features have been presented.
- First preliminary results of shashlik-type and single crystal configurations performed at realistic background levels has been reported.
- Next steps are:
  - Further cross-checking and extension of the simulations and analysis.
  - Applying scheme to more ECAL configurations.
  - Work out of a light transport model. This requires dedicated simulations of optical photons and/or raytracing.

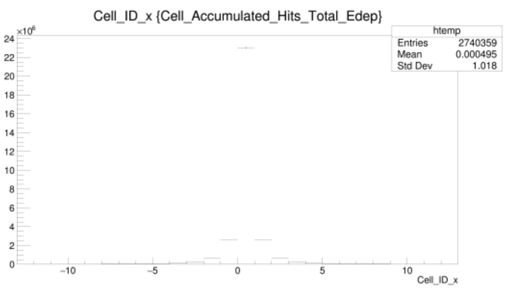
Some example plots

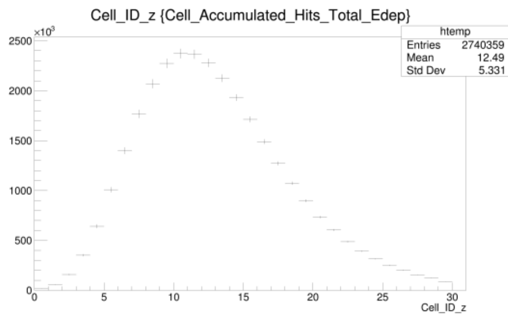


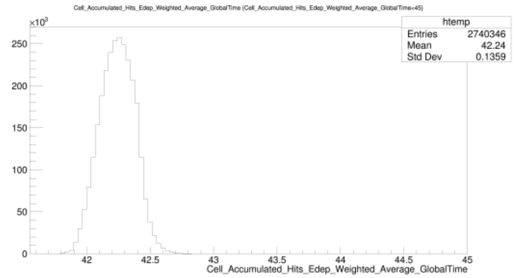
Some example plots

100 GeV photon wo/ background

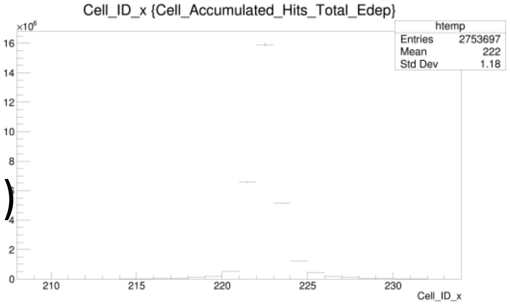
Central

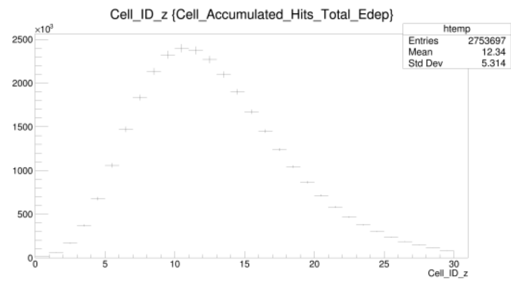


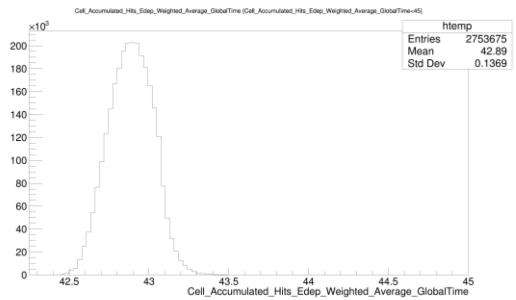




Large angle
(10 degrees)





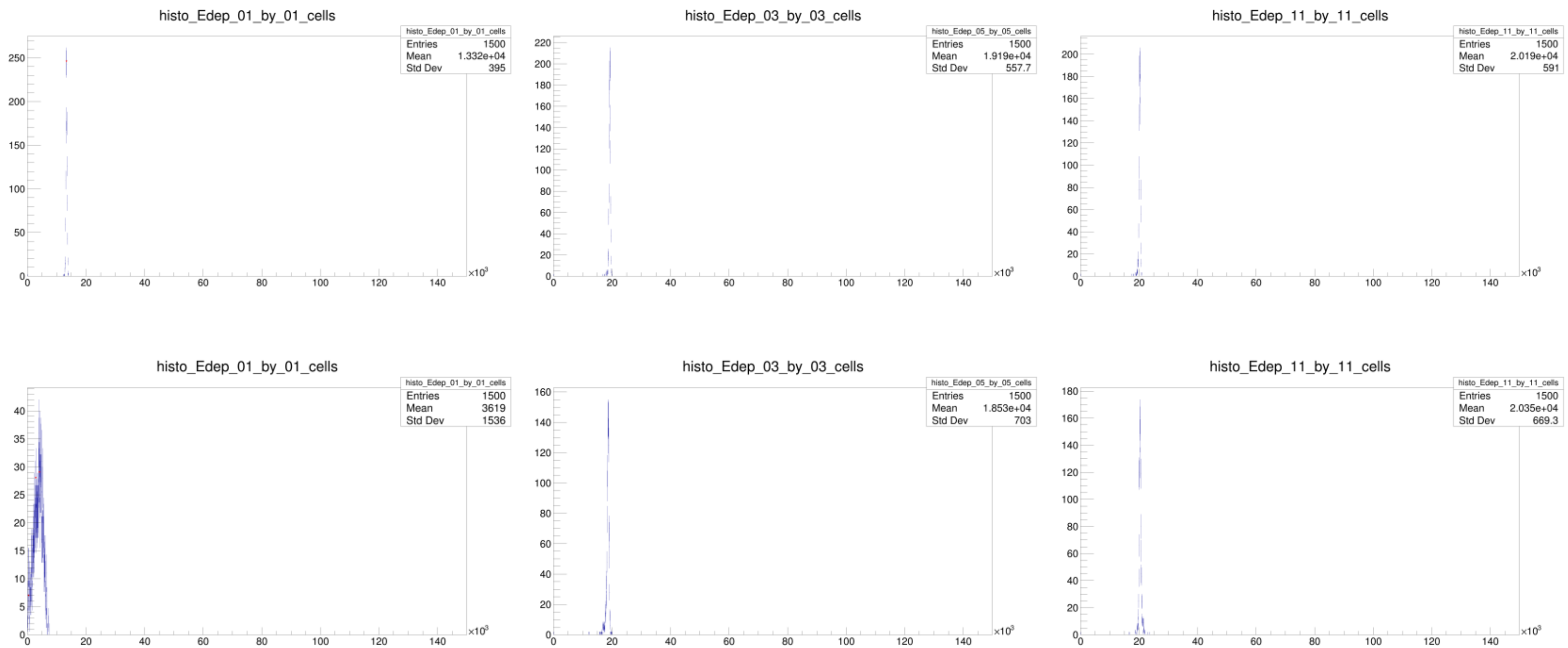


Example of spectra for different angles and cluster sizes

100 GeV photon w/ background

Central

Large angle
(10 degrees)



1 cm x 1 cm

5 cm x 5 cm

11 cm x 11 cm

Cluster size

Time resolution, choice of single crystal options

16th International Conference on Calorimetry in High Energy Physics (CALOR 2014) IOP Publishing
Journal of Physics: Conference Series **587** (2015) 012055 doi:10.1088/1742-6596/587/1/012055

Table 3 lists the values of the figure of merit for time resolution for various crystal detectors, which is defined as the light output in the 1st, or the 1st 0.1, ns [25]. It is clear that the best crystal scintillators for ultra-fast timing are BaF_2, LSO:Ca,Ce and LSO/LYSO:Ce. $LaBr_3$ is a material with high potential theoretically, but suffers from scattering centers in the crystal as well as its intrinsic hygroscopicity.

Table 3 Figure of Merit for Time Resolution for Various Crystal Scintillators

Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	53.8	5.4	75.3
CeF_3	7.3	100	30			208	6.8	0.7	8.6
BGO	21	100	300			350	1.2	0.1	2.5
PWO	0.377	80	30	20	10	9.2	0.42	0.04	0.4
$LaBr_3$:Ce	130	100	20			3810	185.8	19.0	229.9
$LaCl_3$:Ce	55	24	570	76	24	1570	49.36	5.03	62.5
NaI:Tl	100	100	245			2604	10.6	1.1	14.5
CsI	4.7	77	30	23	6	131	7.9	0.8	10.6
CsI:Tl	165	100	1220			2093	1.7	0.2	4.8
CsI:Na	88	100	690			2274	3.3	0.3	4.5