ECAL Simulation

Patrick Robbe, IJCLab Orsay + LNF Frascati, for the LHCb Calo Group,31 Mar 2020

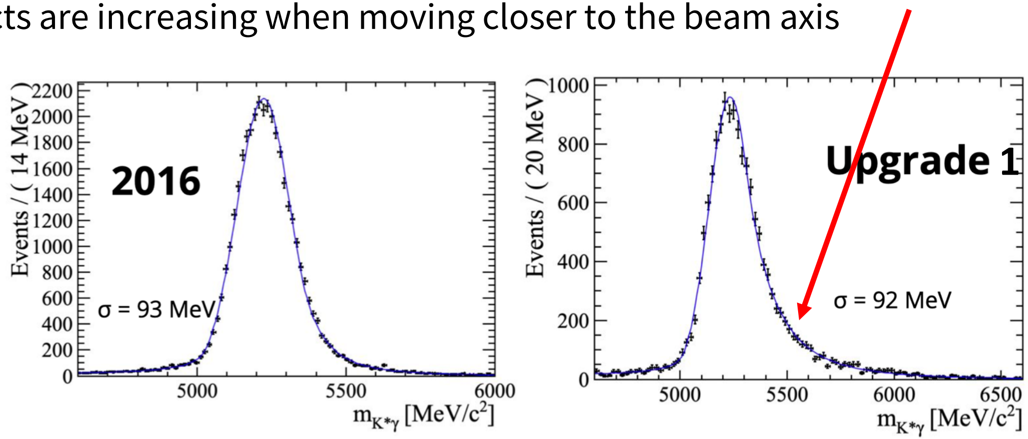
Introduction

- Need to have a simulation setup to test the various options for the ECAL modules and optimize their parameters (granularity, time resolution, Moliere radius, ...) in order to recover Run 1/2 ECAL performances to reconstruct the physics channels of interest.
- Full simulation based on Geant4 for example is too CPU intensive to scan efficiently the various parameters.
- Strategy:
  - Develop fast simulation for signal only
  - Increase realism by adding inputs from full simulation or test beams:
    - Sizes of showers
    - Measurement of time
    - Backgrounds from particles coming from pile-up and from interactions with material in front of ECAL
    - ...

Conditions

- Run 1/2: 4×10^{32} cm^{-2}.s^{-1}, Upgrade I: 2×10^{33} cm^{-2}.s^{-1}, Upgrade II: 1.5×10^{34} cm^{-2}.s^{-1}
- Effect of increase of pile-up:
  - Background increase
  - Candidate photon clusters are rejected when charged tracks point to them: efficiency decreases in reconstruction of photons due to more frequent random track-cluster mis-associations
  - Energies of particles overestimated: efficiency loss when applying mass cuts.
  - These effects are increasing when moving closer to the beam axis

Full simulation,
Signal $B^0 \rightarrow K^* \gamma$



Carla Marin,
Yasmine Amhis

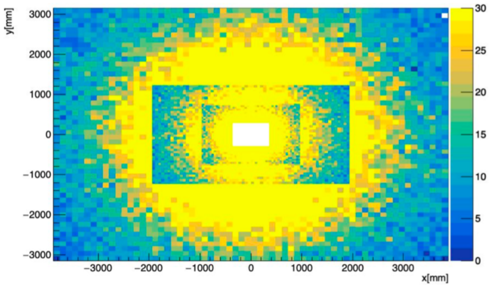
Upgrade I

Carla Marin,
Yasmine Amhis

- ECAL in upgrade I is identical to Run1/2 (same granularity and no timing measurement): expect degradation of performances for Upgrade I compared to Run1/2 because of occupancy.

Decay	$B^0 \to K^*\gamma$	$B^0 \to K^* e^+ e^-$
2016	22.43	12.92
Upgrade	18.84	8.88

Generator level
Signal $B^0 \to K^* \gamma$

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in InMost ECAL: 6.26 %
in Inner  ECAL: 33.69 %
in Middle ECAL: 27.54 %
in Outer  ECAL: 38.77 %
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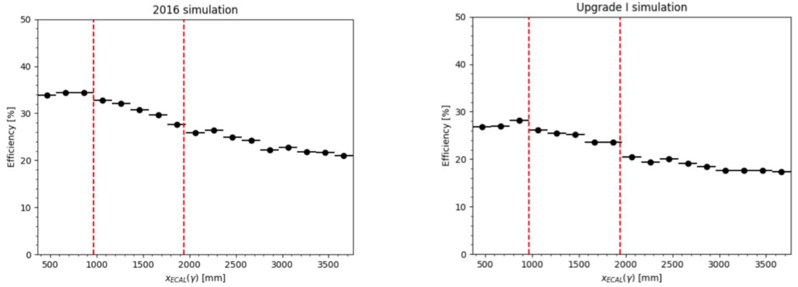
InMost = rectangle of 2 inner cells around the beam hole

Full simulation,
Signal $B^0 \to K^* \gamma$

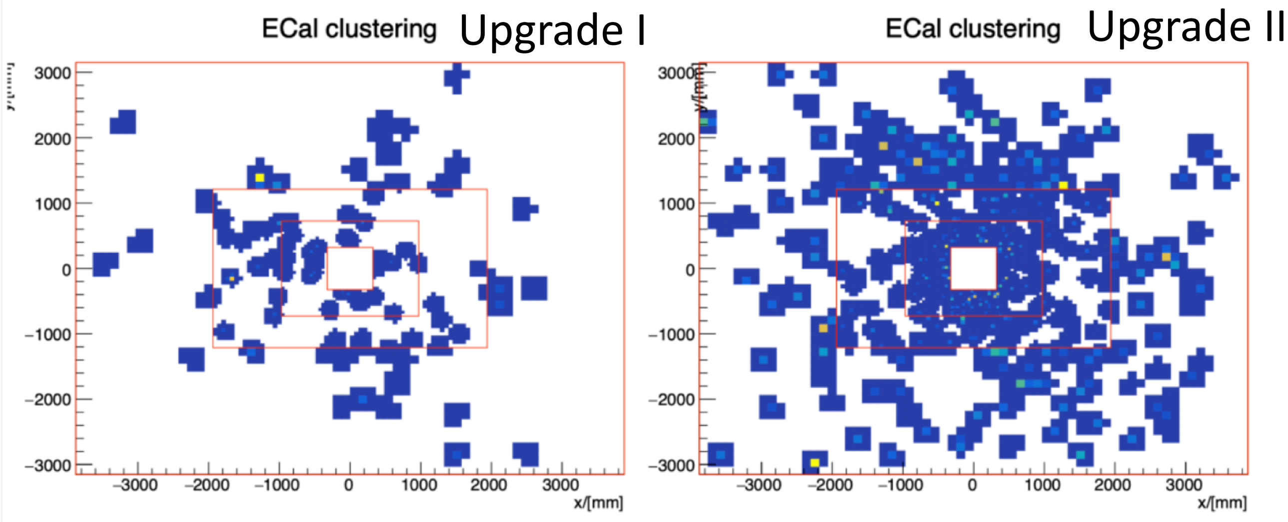
Total $B_d \to K^*\gamma$ reconstruction & MCMatch efficiency in ECAL regions



- All regions contribute equally to signal, inner part most affected by efficiency loss (for *B* decays)

Upgrade II

- Fighting against pile-up effects:
  - Increase granularity
  - Add timing measurement
- One event display



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Upgrade II – Signal fast simulation

- Signal $B^0 \rightarrow \pi^+\pi^-\pi^0$ events (generated with Pythia)
- Only interaction of photons (signal and pile-up) considered in ECAL, using true π^+ and π^-.

Inner Region Side (R Moliere) [cm]	Middle Region Side (R Moliere) [cm]	Outer Region Side (R Moliere) [cm]	
4 (3.5)	**6** (3.5)	**12** (3.5)	← Current ECAL
2 (1.5)	4 (3.5)	8 (3.5)	
1 (1.5)	4 (3.5)	8 (3.5)	
1 (1.5)	2 (1.5)	4 (3.5)	

- Energy deposited according to Moliere radius considering various cell sizes and energy resolution of

$$\frac{\delta E}{E} = \frac{10\,\%}{\sqrt{E}} + 1\,\% \quad (E \text{ in GeV})$$

- Assume *single time measurement (see next slide)* per cell with resolutions of 0, 10 or 50 ps. Estimated as

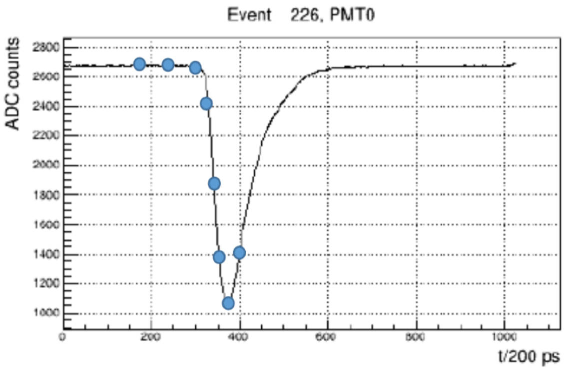
$$t = \sum_i t_i E_i / E$$

- Photon reconstruct as 3x3 clusters, including recovery of merged π^0

David Gascon,
Dominique Breton

Timing measurement

- Impossible to send offline full time waveform: 1 GHz sampling would require, for 15000 channels
  - 15000 x 40 MHz x 25 x 12 bits (energy) = **180000 Gb/s**
- Dedicated (very) Front-End ASIC to sample waveform with required resolution: precise time and energy measurements possible with 8 sampled points. But still too high rate.
- Only send values for hit cells: requiring occupancy less than ~10% will give more manageable rate (in that case, it is necessary to send also the BCId and address to recognize the hit cells):
  - 15000 x 4 MHz x [8 x 12 bits (energy) + 16 bits (BCId) + 4 bits (address)] = **6960 Gb/s**
- Process information (in a FPGA, in the Front-End board or at the latest in the back-end) can reduce further to 1 energy value (12 bits) and 1 time value (11 bits for 12.5 ps precision)
  - 15000 x 4 MHz x [12 bits (energy) + 16 bits (BCId) + 4 bits (address) + 11 bits (time)] = **2580 Gb/s**



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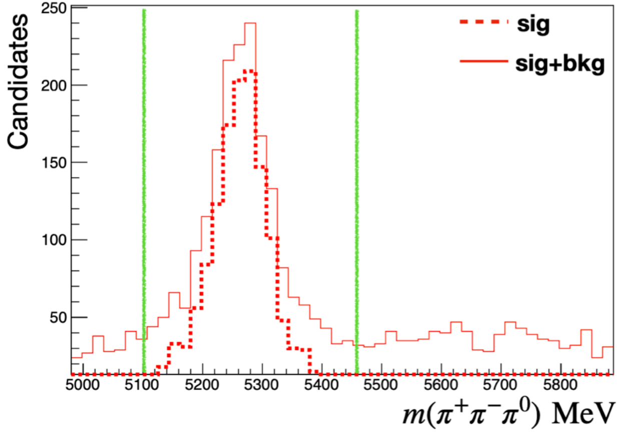
Upgrade II – Signal fast simulation

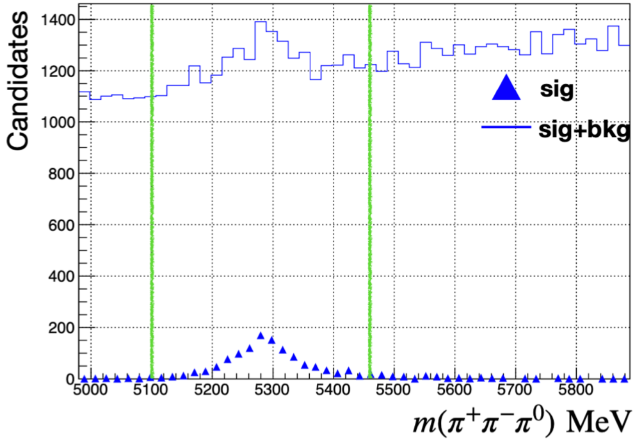
Luminosity : Run1
Cell Size : (4, 6, 12) cm

Increase of granularity →

Luminosity : Upgrade 2
Cell Size : (2, 4, 8) cm

(*same cuts as Run1*)





- Clear indication that increase of granularity is not enough to fight against large increase of pile-up background.
- Use time information
- And cut on R_t (timing of the two photons from the π^0 decay)
  NB: this can only decrease signal efficiency

$t_i \equiv$ **time of the seed cell**

$$t_i^{expected} \equiv \frac{\sqrt{(x_i^{CALO} - x_B^{END})^2 + (y_i^{CALO} - y_B^{END})^2 + (z_i^{CALO} - z_B^{END})^2}}{c} + t_B^{END}$$

$$R_t = \sqrt{(t_1 - t_1^{expected})^2 + (t_2 - t_2^{expected})^2}$$

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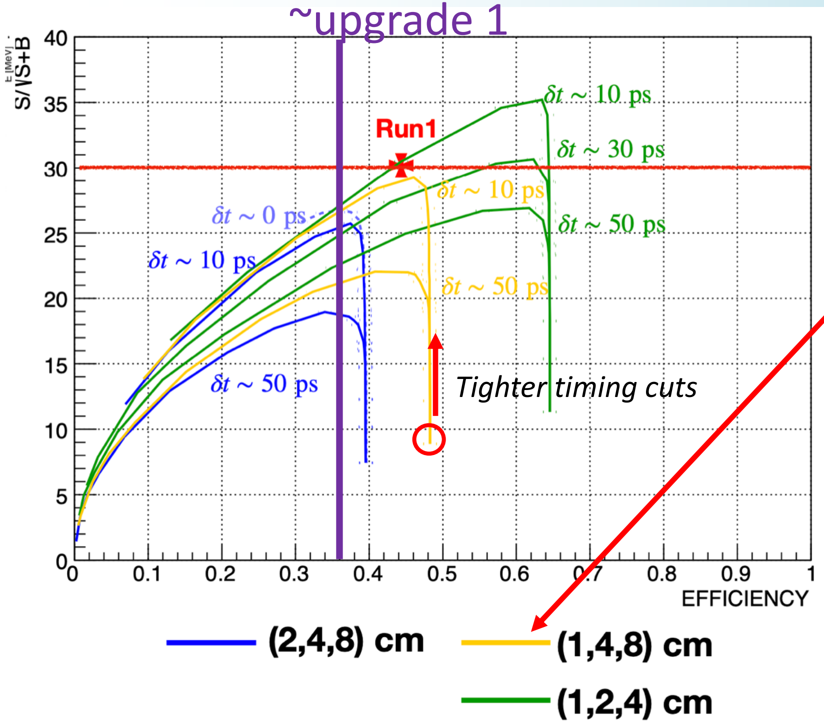
Upgrade II – Signal fast simulation



- Increase of granularity in inner section to 1 cm cells and timing resolution of 10 ps to recover Run1 performances.
- All regions are contributing with the decrease of cell size, not only inner section

Upgrade II – Use of timing

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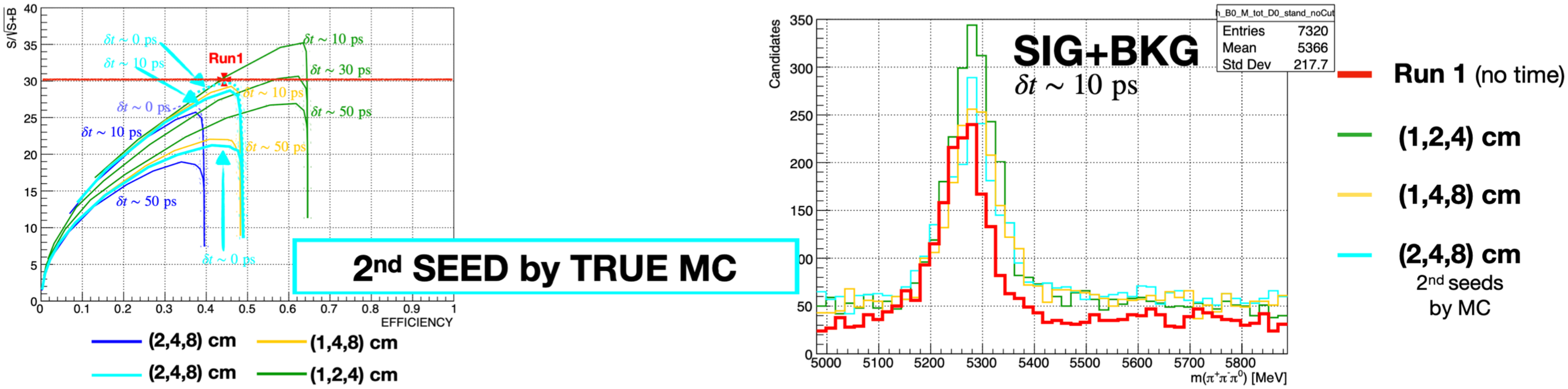
- Timing information could be used in a better way than just to remove clusters with large pile-up contamination.
- For example to disentangle energies of two overlapping cluster. Test this idea using true information to find a seed with the second largest energy deposit in a cluster (to give an estimate of the maximum gain of a better use of timing): large extra gain to be expected.

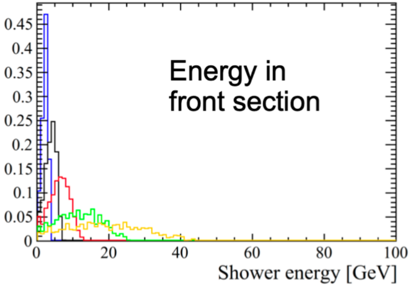


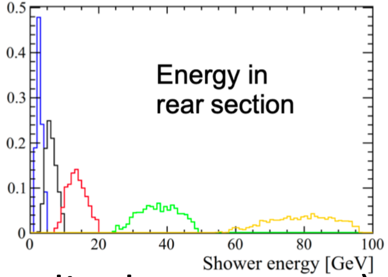
- <u>Segmentation in *z*</u> is also not exploited yet and can help the clustering algorithm.

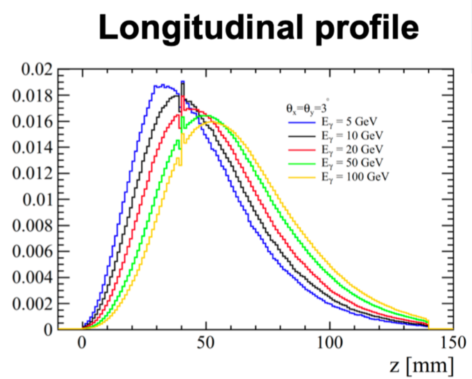
z segmentation

Philipp Roloff, Yanxi Zhang

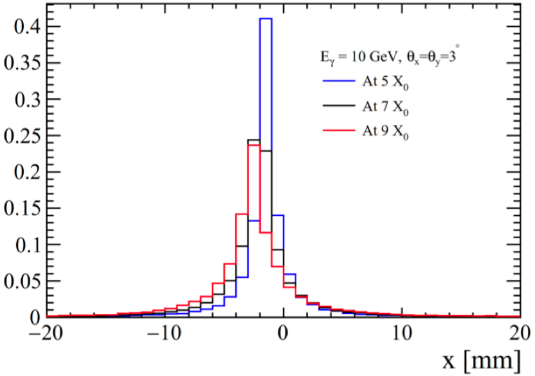
- Full simulation of SPACAL modules in Geant4 exist, with *z* segmentation, that can be used in the future as input to the full simulation to use it in the reconstruction

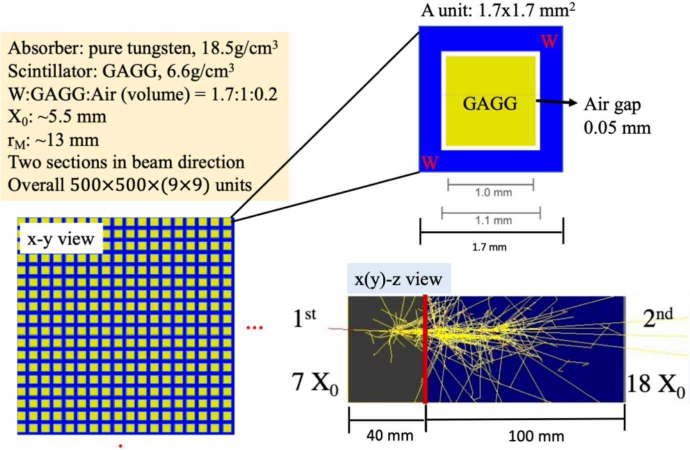






Energy profiles (longitudinal, transverse)



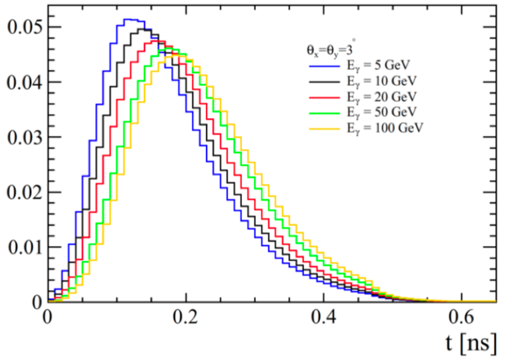


Time properties

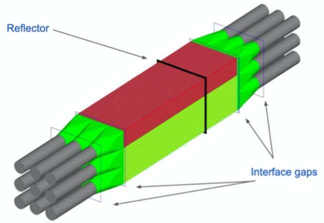
Philipp Roloff, Yanxi Zhang, Yuri Guz, Loris Martinazzoli, Marco Pizzichemi

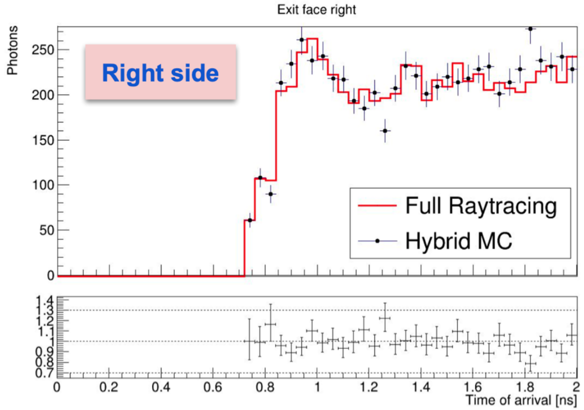
Time (only transport for the moment)

- Timing also simulated, in particular dependence with energy which is not considered in the fast simulation



- Hybrid Monte Carlo ray tracing to simulate precisely timing properties of modules to be added to full simulation in the future





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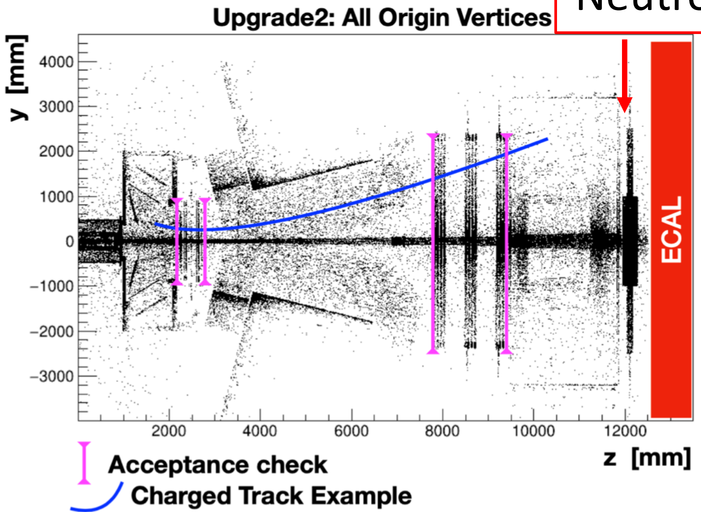
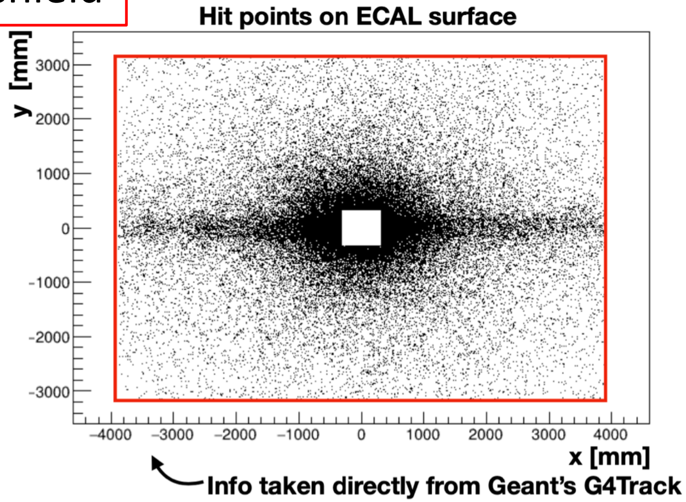
Backgrounds

- For more realism, it is necessary to add the contributions from primary π, e, K, p, μ, … and from secondaries from material interactions
- This is taken from full Gauss/Geant4 simulation with Upgrade 1 detector geometry

For *e* and π charged tracks





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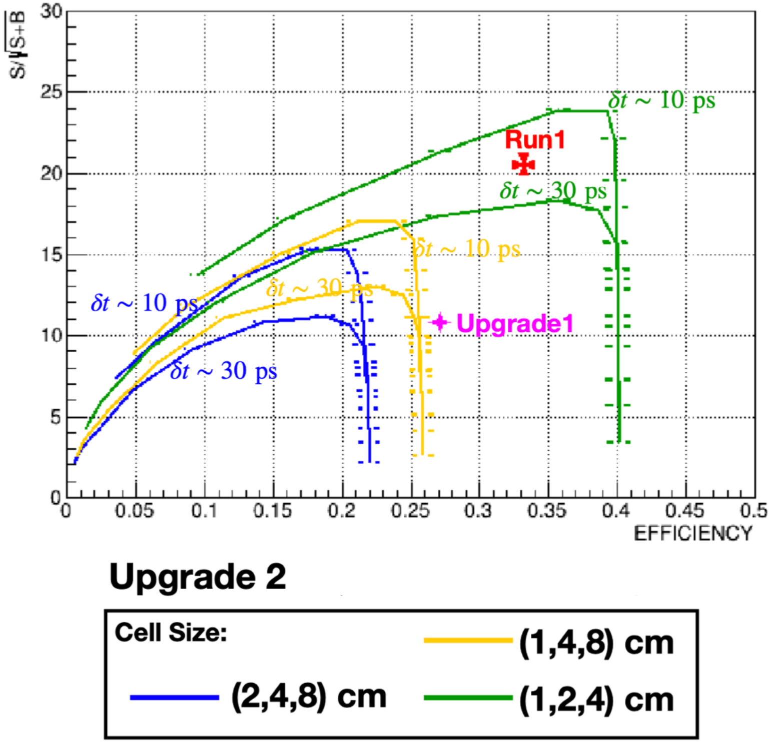
Contributions from $e^{\pm}$

- Add to fast simulation the ECAL response to electrons (on top of photons).
  - Adds a new source of background
  - Allows to simulate the effect of the neutral cluster selection (reject clusters where a charged track points to)
- Large degradation of performances when adding 1 source of background: crucial in the future to consider all others (π, ...)
- In the future:
  - add time information also in the neutral cluster selection
  - Maybe *z* segmentation for further background rejection



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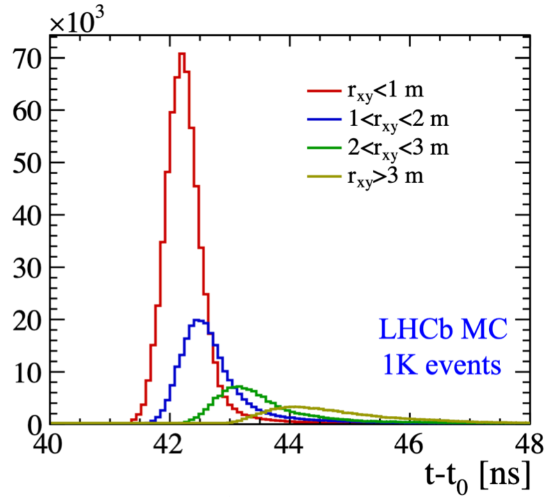
Other effects

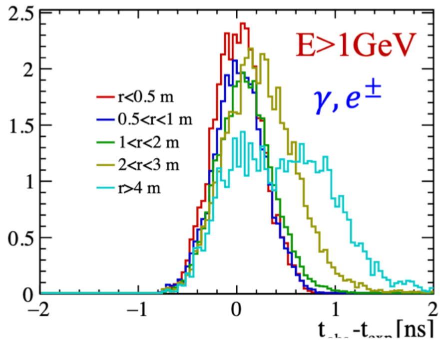
- Other effects from the background must be considered in future studies for more realism, which have been simulated with full simulation
- Timing spread of secondary particles

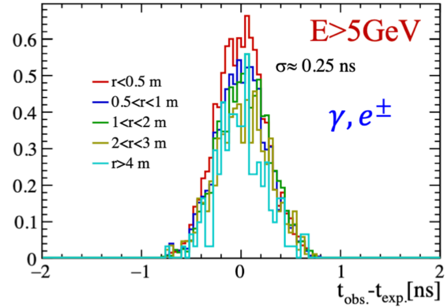


$t_0 \equiv t_0(z=0) \equiv t_{PV}$

r_{xy}: distance to beam line

Evolution as a function of energy (all categories normalized)



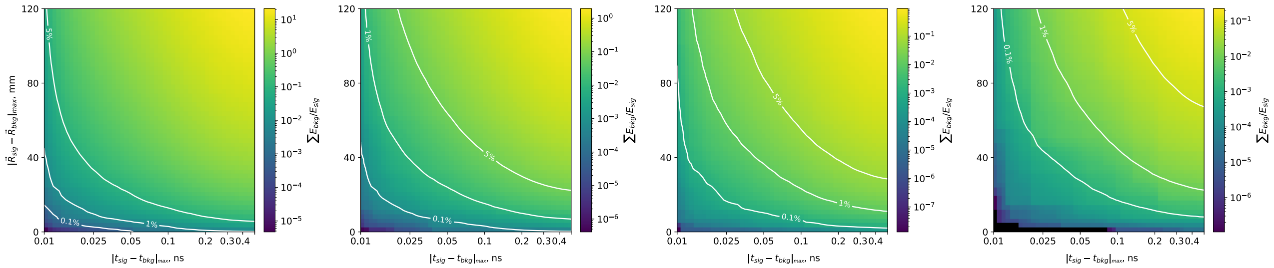


Parametrisation of background

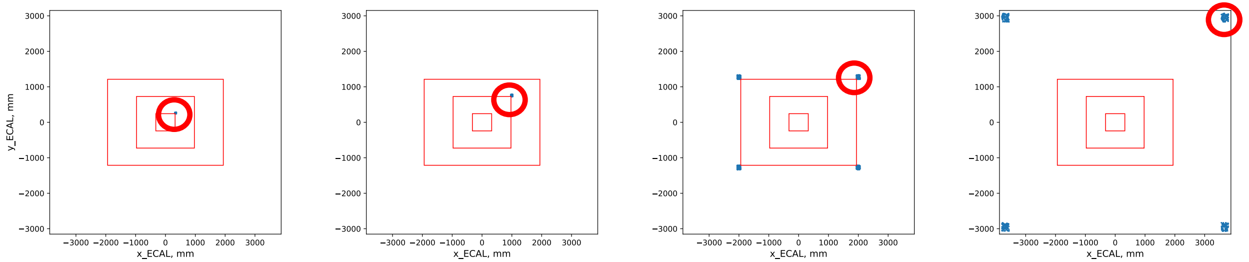
Alexey Boldyrev, Denis Derkach, Pavel Fakanov, Leonid Matyushin, Fedor Ratnikov, Andrey Shevelev

- Novel technique using pipelines based on Machine Learning.
- Sum of all background energy contributions (primary and secondaries of all types) close to the signal ($B \rightarrow J/\psi\ \pi^0$) in time and space.

Sum of background energy compared to signal



ECAL region



Occupancies – Upgrade I

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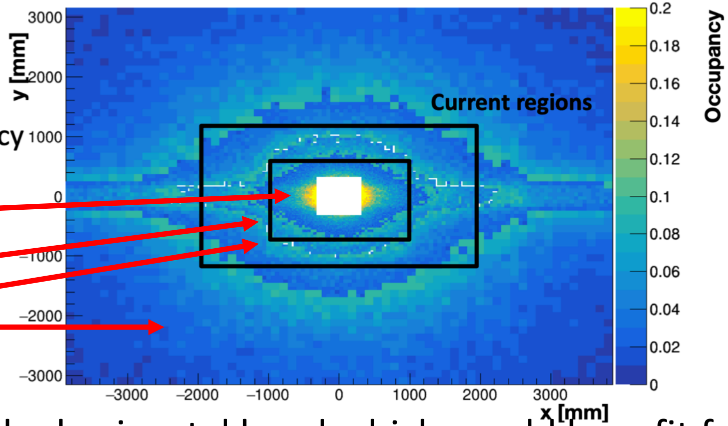
- One of the requirement from the electronics read-out to be able to process realistically timing information is to limit the occupancy per cell to ~10%.
- Optimize ECAL geometry (shapes of different regions) with this requirement

Inner, middle-1, middle-2, outer

  - Cell sizes: {20.2, 40.4, 60.6, 121.2} mm
  - Very rough estimation of channels (requiring occupancy < 0.15):
    - Inner: ~2800
    - Middle-1: ~1000
    - Middle-2: ~1800
    - Outer: ~2600
    - Total: ~ 8200
  - Requiring occupancy < 0.1
    - Inner: ~4300
    - Middle-1: ~1400
    - Middle-2: ~2300
    - Outer: ~2400
    - Total: ~10400

Upgrade I (e and γ from full simulation)

With E > 100 MeV

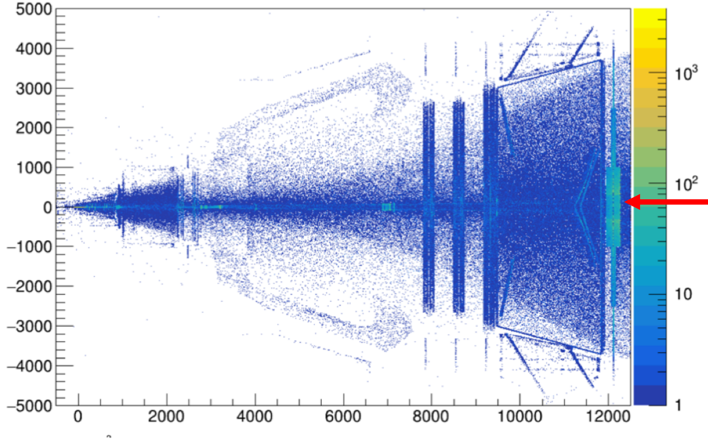


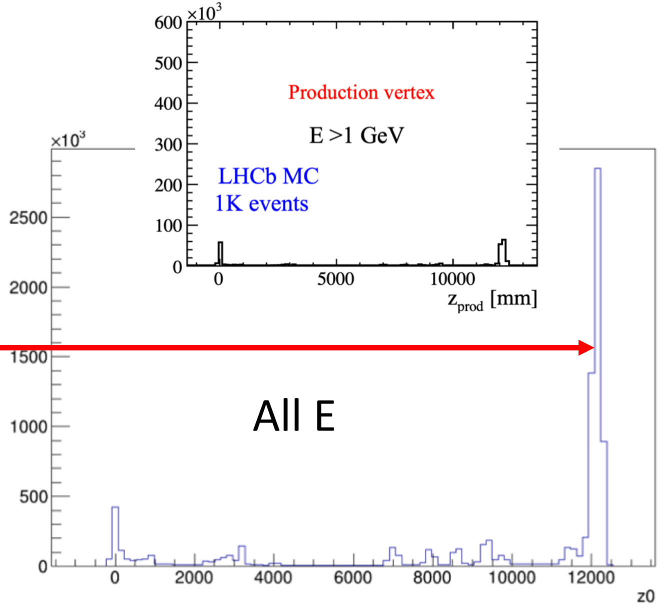
Current geometry is more or less OK apart in the horizontal band which would benefit from being equipped with smaller size cells.

Occupancies

- It is also seen that a large fraction of particles hitting the ECAL are (mostly low energy) secondaries produced in the neutron shield in front of ECAL

Origin of γ and e± hitting the calorimeter





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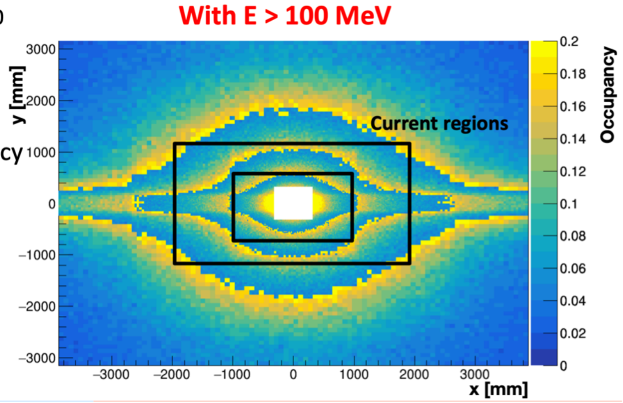
Occupancies – Upgrade II

Upgrade II, number of e or γ per event (full simulation with upgrade I detector geometry)

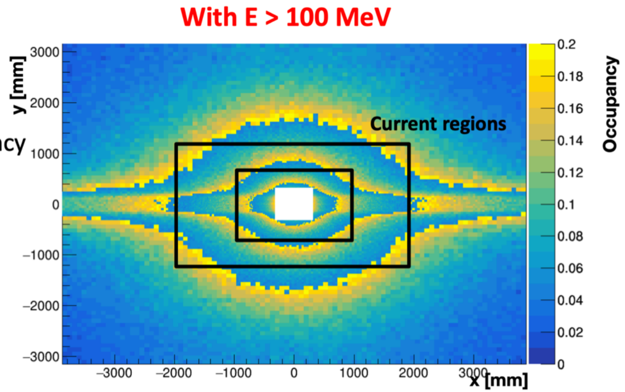
With neutron shield

- Cell sizes: {10.1, 20.2, 40.4, 80.8} mm
- Very rough estimation of channels (occupancy < 0.15):
  - Inner: ~ 16000
  - Middle-1: ~11000
  - Middle-2: ~7300
  - Outer: ~4600
  - Total: ~ 39000
- Requiring occupancy < 0.2
  - Inner: ~11000
  - Middle-1: ~9200
  - Middle-2: ~6000
  - Outer: ~5200
  - Total: ~31400



Without neutron shield

- Cell sizes: {10.1, 20.2, 40.4, 80.8} mm
- Very rough estimation of channels (occupancy < 0.15):
  - Inner: ~ 7000
  - Middle-1: ~9200
  - Middle-2: ~7000
  - Outer: ~5000
  - Total: ~ 28200
- Requiring occupancy < 0.2
  - Inner: ~4200
  - Middle-1: ~6700
  - Middle-2: ~5800
  - Outer: ~5500
  - Total: ~22200

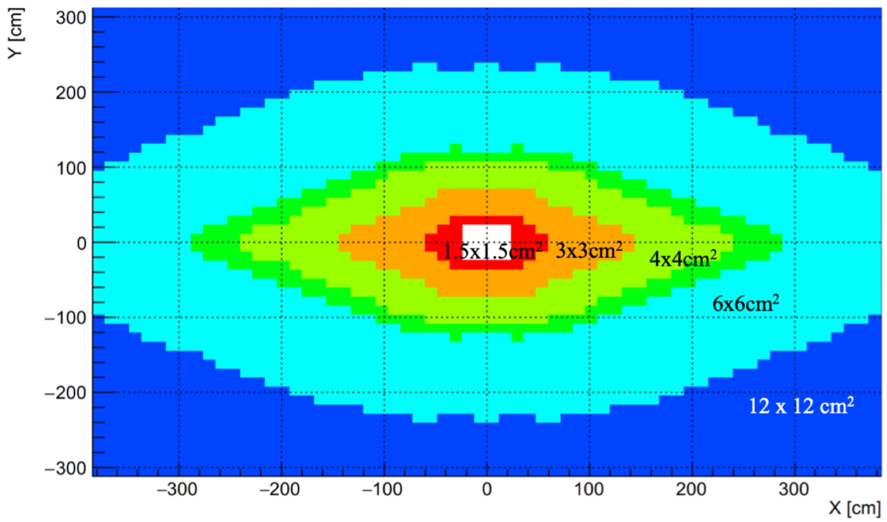


- Preliminary studies but indication that a new geometry, not rectangular anymore, would be better suited.
- Neutron shield has a non negligible impact on occupancy in ECAL which is a crucial parameter for its performance.

Philipp Roloff

New ECAL layout – Upgrade II

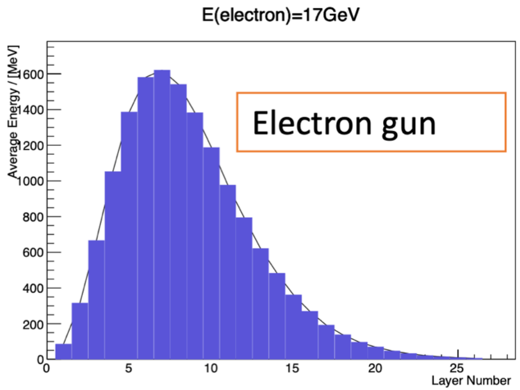
- Definition of a new layout taking occupancy into account, and also reusing a maximum of already existing (current ECAL, 4x4, 6x6 and 12x12 cm^2) modules.
- Used now in the simulation and optimization of the characteristics of the electronics readout chain.



Zehua Xu, Zhihong Shen

Other technologies

- Study performances of Si-W ECAL
- Hypothetical detector with 1 cm cell sizes, with 26 layers of (3.5 mm W, 200 µm Si and 2 mm vacuum gap)
- Simulated with particle guns and full simulation in Gauss/Geant4 (with Upgrade I detector geometry)
- Goal is to parametrize it for a fast simulation and check performances for physics channels
- Work in progress



Conclusions

- Fast simulation framework put in place progressively to optimize ECAL parameters for Upgrade II:
  - With optimistic considerations, confirms that timing with 10ps resolution and smaller cell sizes are mandatory in all ECAL regions to reproduce Run 1/2 performances in Upgrade II conditions
- Several features to add for more realistic estimates and to study new reconstruction techniques:
  - Background from primary and material interactions: first indications that it affects the performances
  - Realistic timing and *z* segmentation: study new reconstruction techniques to mitigate these difficulties
  - Input from full simulation exist, to be included in the fast simulation studies
- Constraints from occupancy for readout lead to a new arrangement of ECAL modules
- Only B decays studies so far: requirements from other channels should also be taken into account.
  - Bremsstrahlung recovery is an important item not yet covered
  - Work is starting with $Z \rightarrow e^+e^-$ (Alessio Gianelle, Donatella Lucchesi, Lorenzo Sestini, Davide Zuliani), which is sensitive to the range of the ECAL energy measurement and to the fact that HCAL will be absent in Upgrade II.