Hybrid Monte Carlo framework, single-module optimisation and DD4hep integration

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On behalf of the LHCb ECAL Upgrade II R&D group

LHCb ECAL Upgrade II Workshop, IJCLab Orsay - 12/12/2022

Outline

- Description of **HybridMC**: framework developed to perform detailed simulations of the modules proposed for ECAL upgrade 1b & II

- **Single module** optimization and studies performed with HybridMC

- Integration of the MC framework into the **LHCb simulation framework**

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HybridMC framework description

Why propagating optical photons?

In principle, ray-tracing of optical photons is useful to **study in detail** the performance of prototypes

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- Impact of scintillating material characteristics
- Impact of light transport, attenuation length
- Impact of surface state of scintillators and absorbers
- Evaluation of performance degradation by radiation damage
- Possibility to develop and test strategies to extract information from detector pulses
- Study of impact of spill over on resolutions
- Possibility to emulate electronics, study signal sampling etc.

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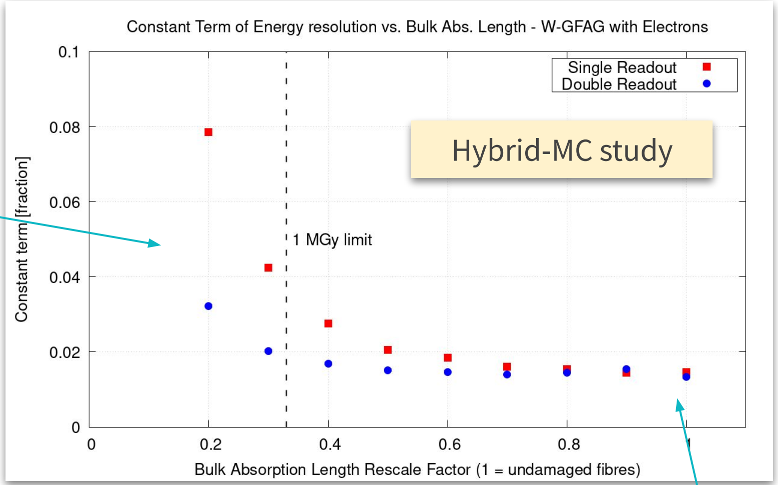

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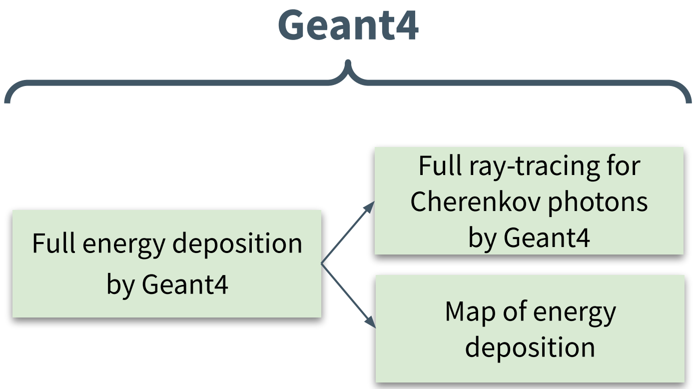
Framework structure



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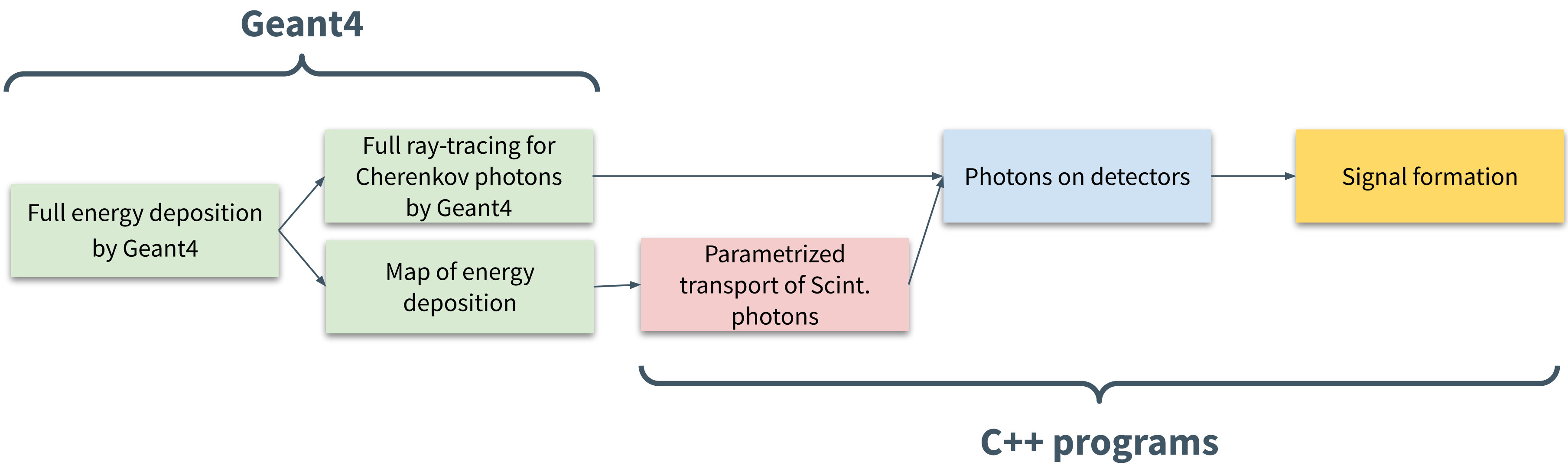

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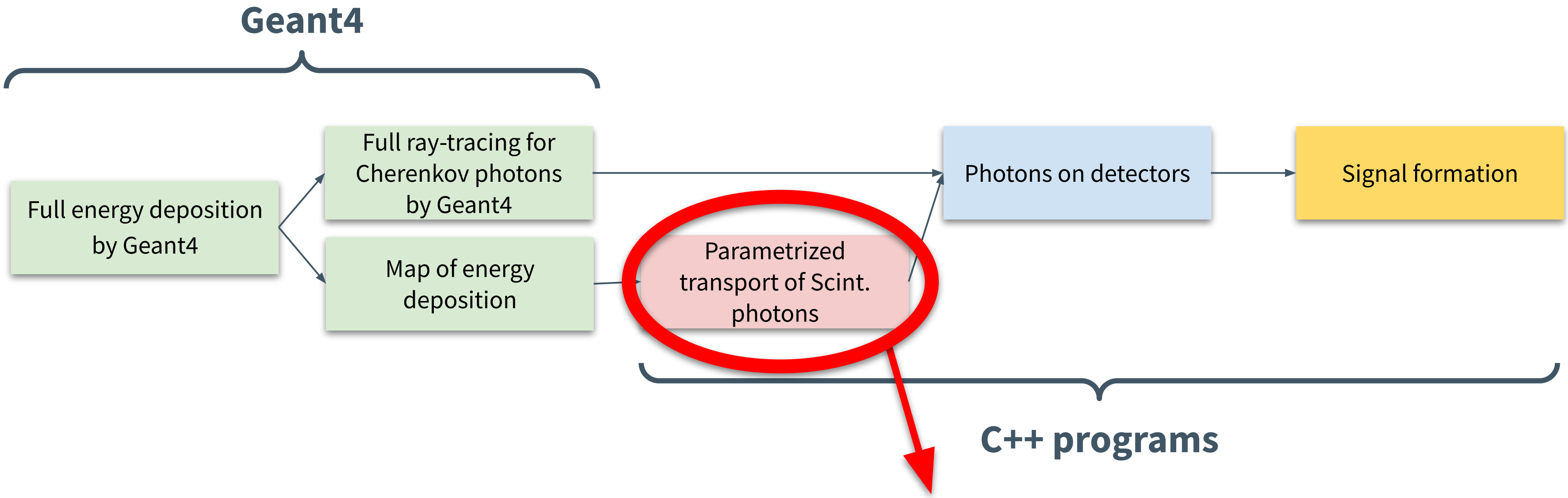

*Obtained via **optical calibration** on the basis of energy deposition map.*
No real ray tracing in G4. More details in next slides, check also:
https://indico.cern.ch/event/892608/contributions/3774763/attachments/2000721/3538041/Hybrid_MonteCarlo_SPACAL-RD.pdf
https://indico.cern.ch/event/914972/contributions/3860898/attachments/2038257/3413428/Update_Hybrid_MC_-_14_May_2020.pdf

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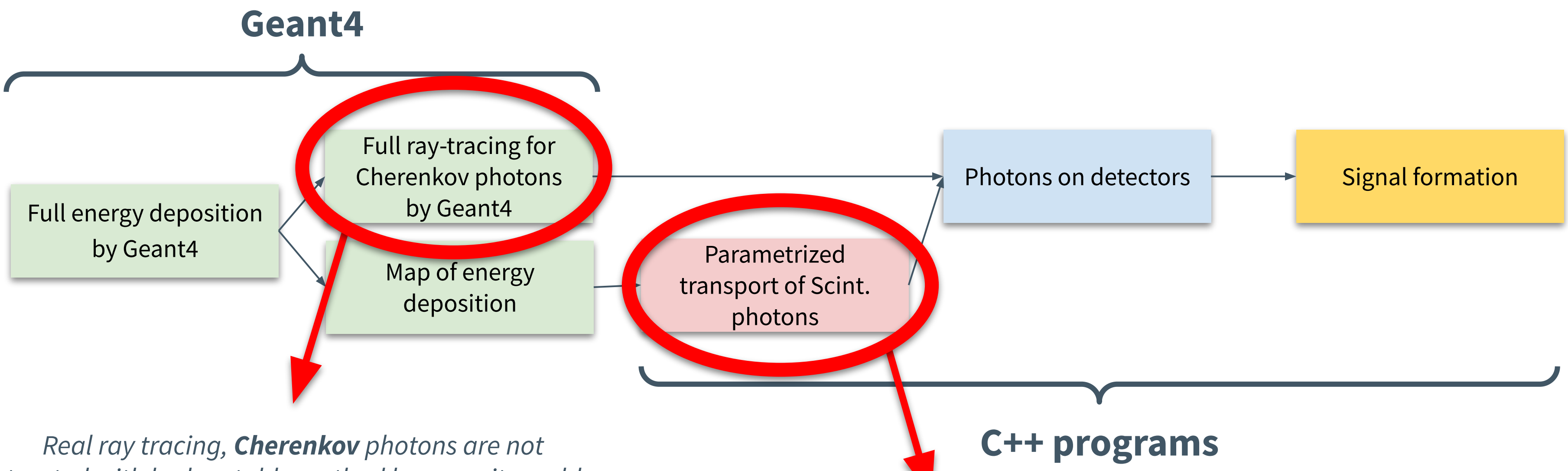

Real ray tracing, ***Cherenkov*** *photons are not treated with lookup table method because it would be more complicated (directionality involved)*

Other optimizations developed to reduce the CPU time due to Cherenkov propagation

Obtained via ***optical calibration*** *on the basis of energy deposition map. No real ray tracing in G4. More details in next slides, check also:*

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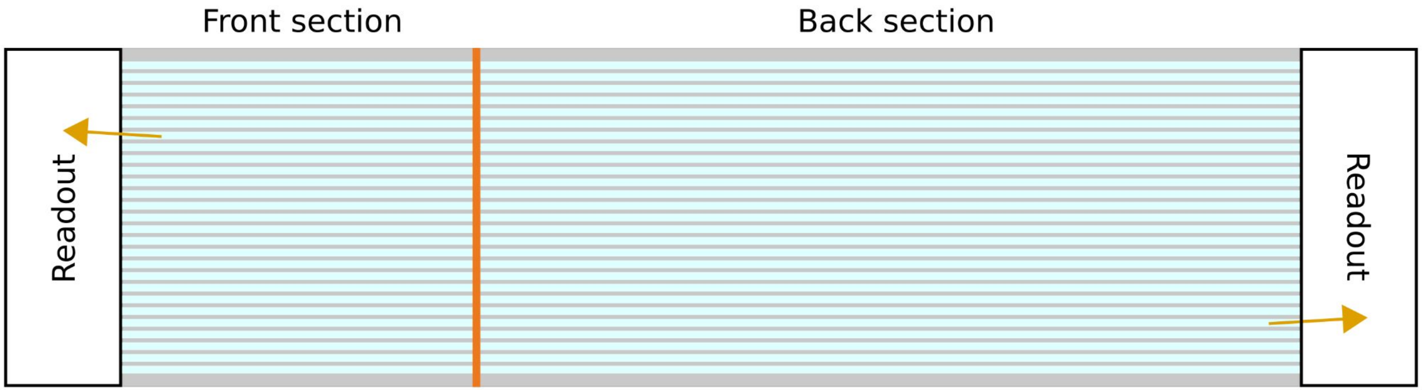
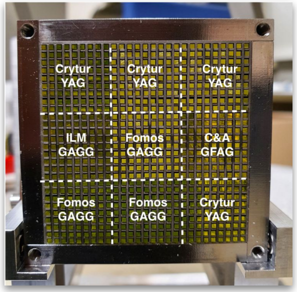
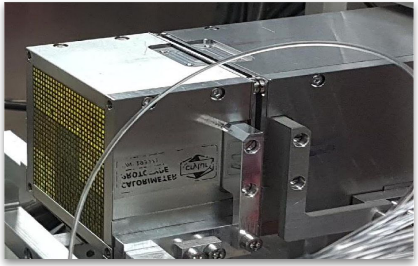
Optical calibration

Transport of optical photons is parametrized with a **lookup table approach**



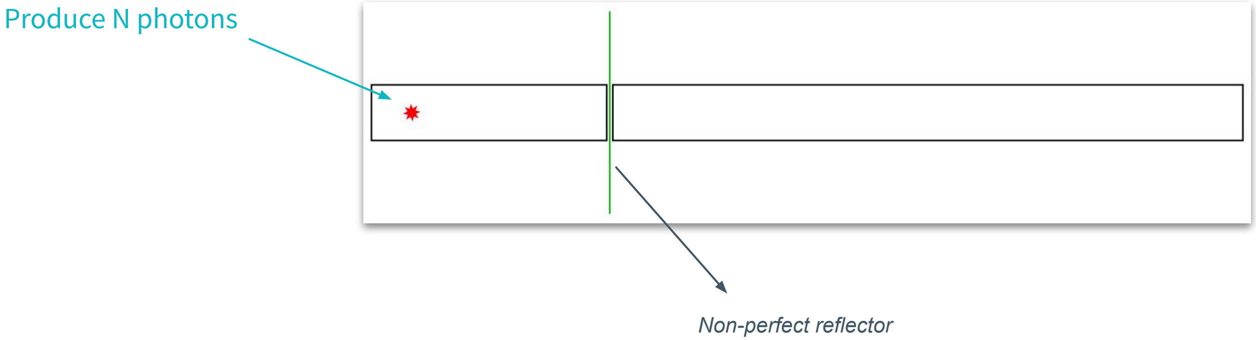




- Assign a **photon extraction and a propagation time distribution** to each point (x,y,z,energy) of the module
- Use these distribution to **decide the fate** of each photon generated by energy deposition
- Exploit SPACAL modules symmetry: transport photons **up to fiber exit** -> one crystal per section is enough
- The procedure (we call it optical calibration) needs to be done **only once for each module** configuration

Optical calibration

Scan the crystal(s) on a space/energy grid, produce distributions of output photons



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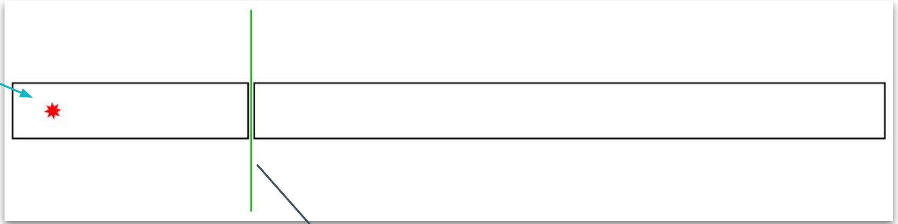
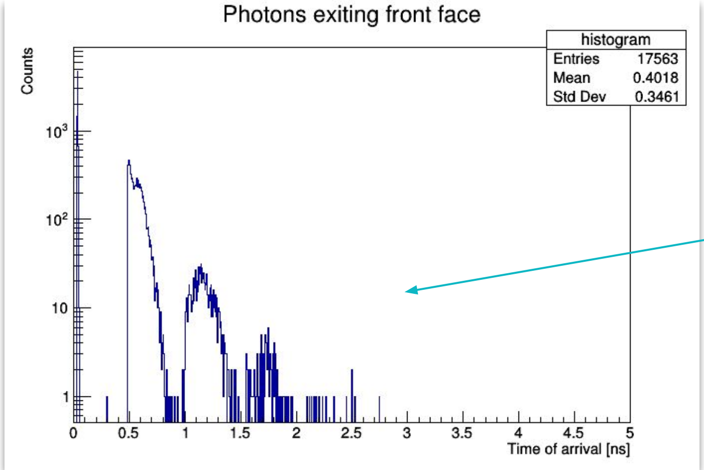
Optical calibration

Scan the crystal(s) on a space/energy grid, produce distributions of output photons

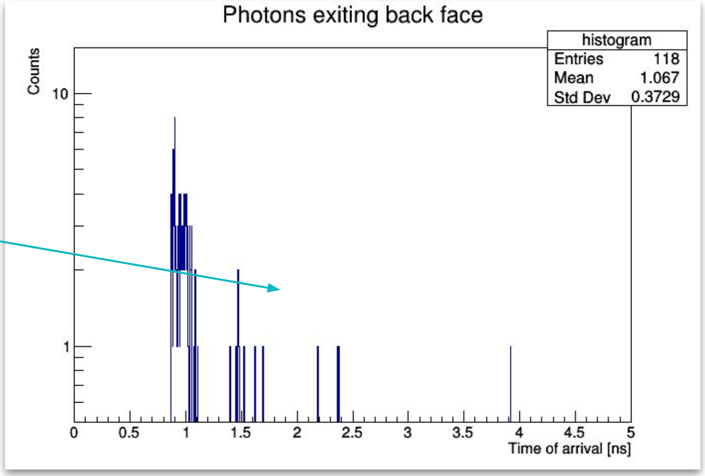
Produce N photons



Non-perfect reflector



Record time of arrival of photons that exit the crystals



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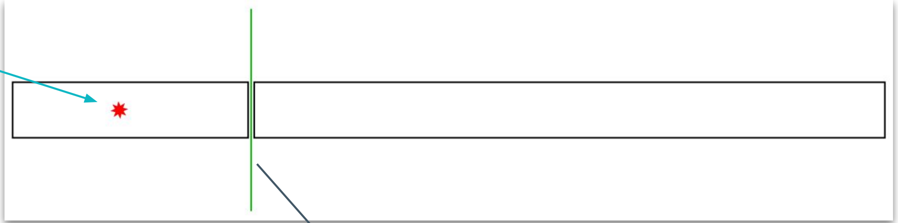

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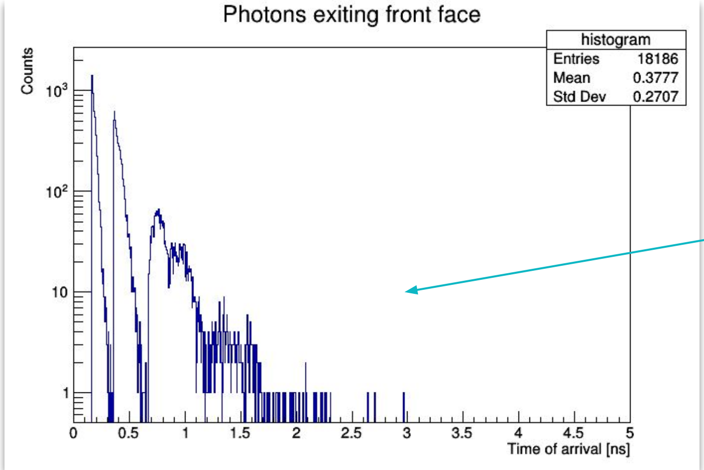

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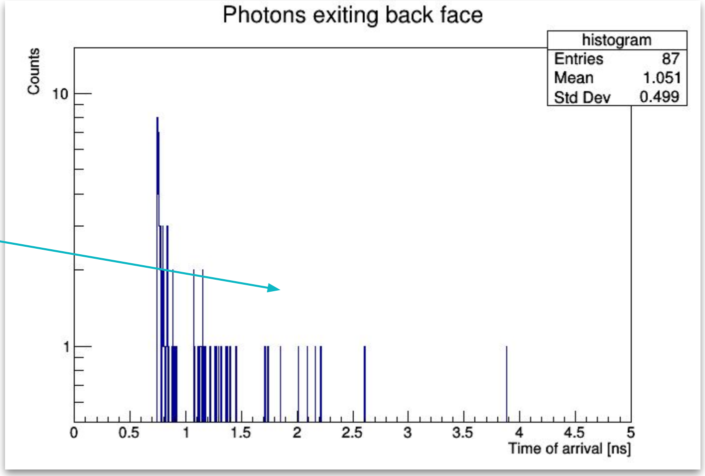

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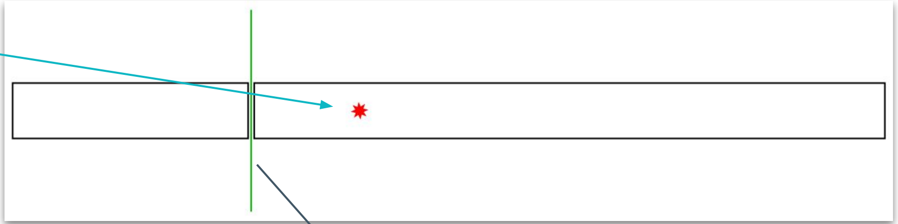

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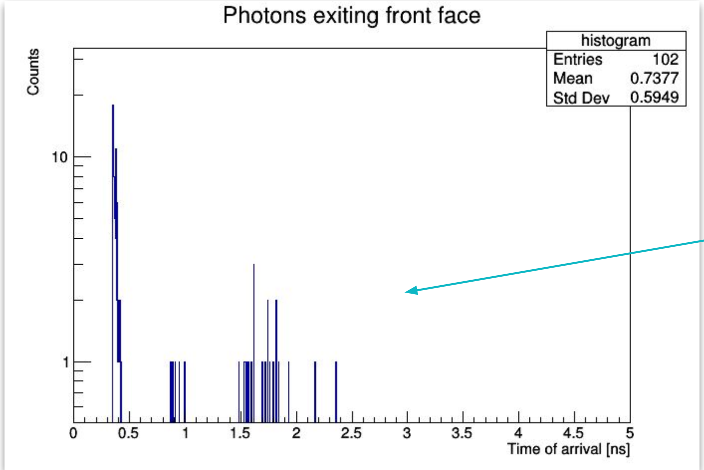

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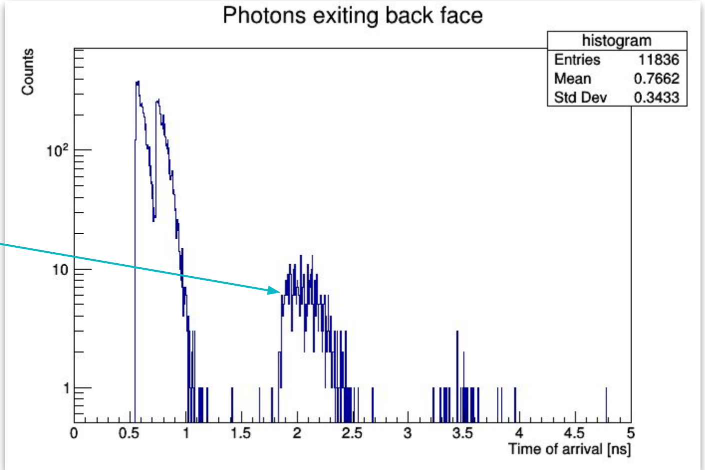

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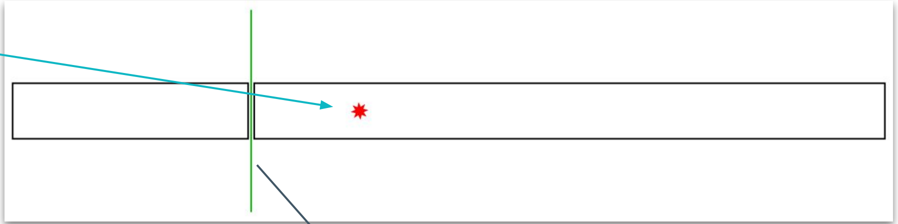

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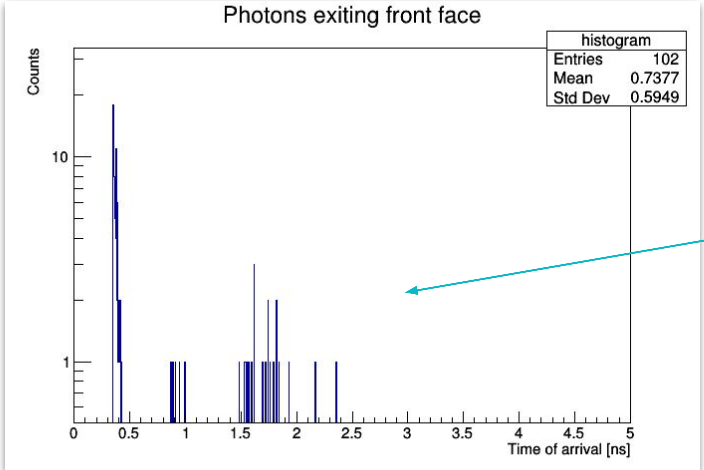
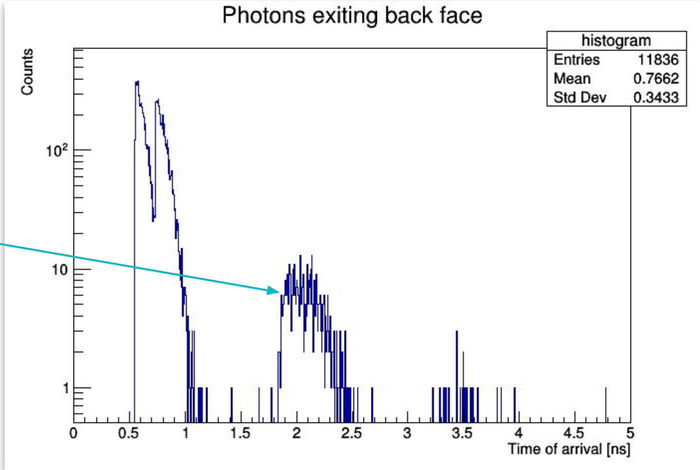


Record time of arrival of photons that exit the crystals



Use these histograms as **PDFs** to generate **photon extraction probability** and **time of transport**

Validation of optical calibration

Check if the optical calibration approach (Hybrid MC) provides same result as letting Geant4 perform full ray-tracing

Simplified configuration, shoot 1 GeV electrons into a single fiber, record photons extracted (e.g. from the right side)

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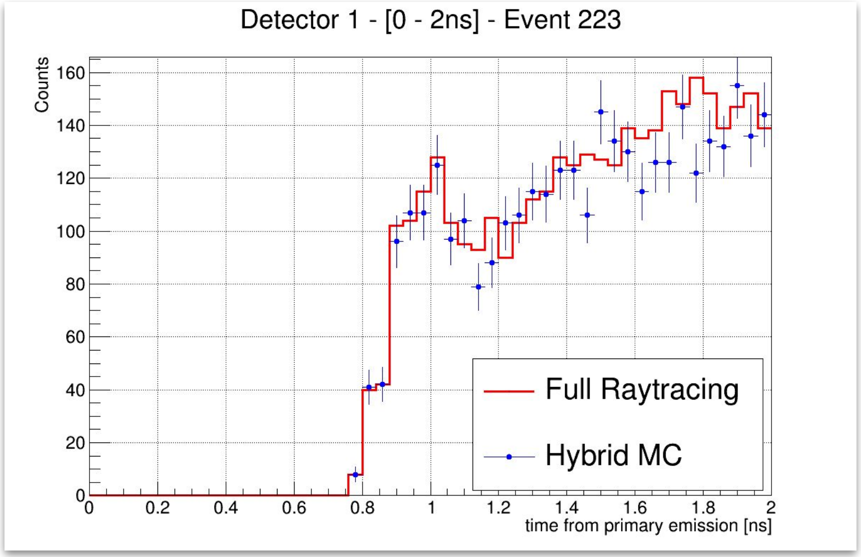
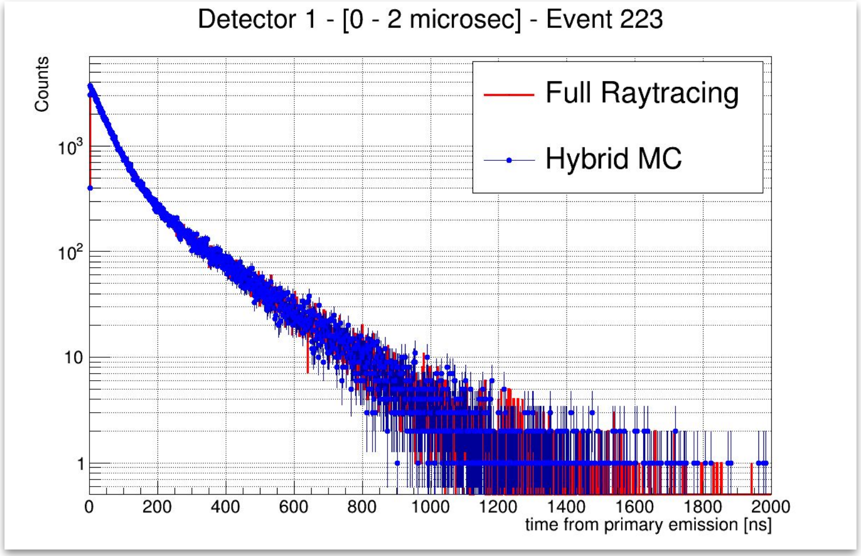
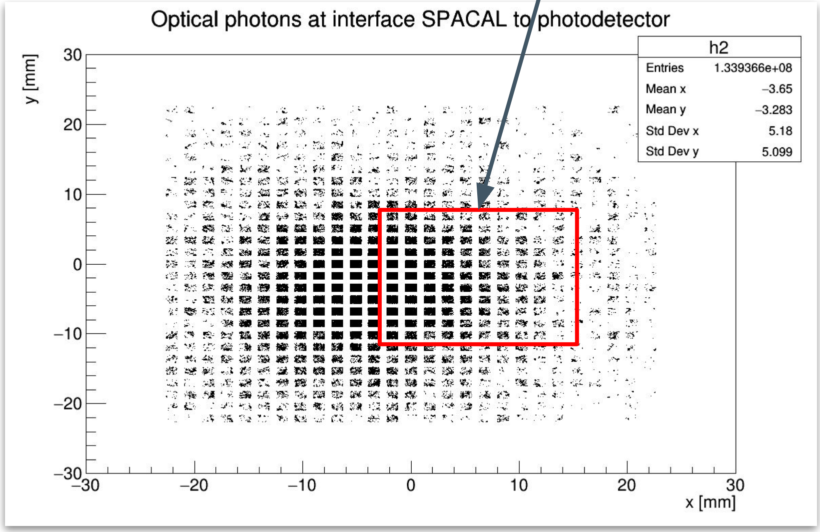


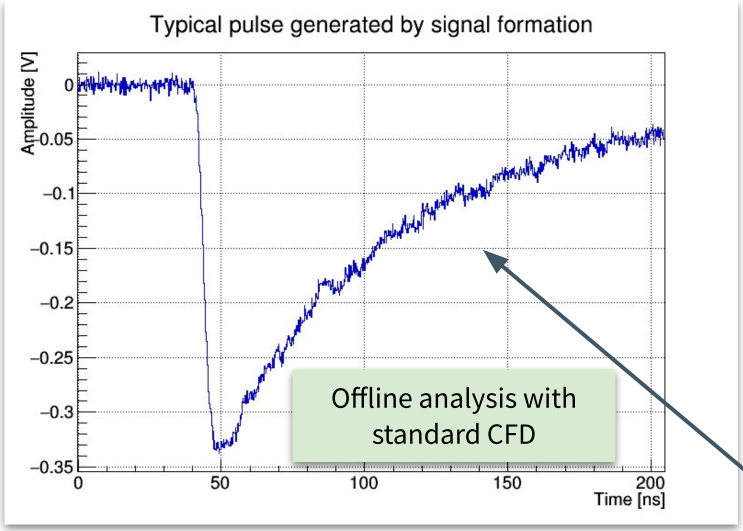


Very good agreement both in number of photons extracted and in time profile

Signal formation and analysis

Output of Hybrid simulation (optical photons) → Group photons per photo-detector → Apply spatial efficiency map → Apply Quantum Efficiency → List of photoelectrons per detector → Digitization based on DRS4 → Single electron response → Sum of all single electron pulses



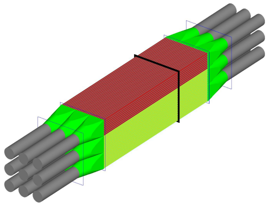


Offline analysis with standard CFD

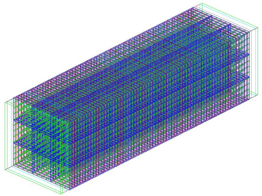
Full ECAL simulations

- Full ECAL configurations **combining single module descriptions**
- 3312 modules, no impact on intrinsic simulation time
- Very useful for **reconstruction** and **physics potential studies** which need a full ECAL
  - Need particle flux at entry of ECAL as input
  - Tilting of modules in central region implemented
  - All needed configuration and calibration files included
  - See ***Physics benchmarking of the baseline*** session tomorrow at 9am
- **Pre-packaged configurations** available:
  - Run3: Shashlik only, current config
  - Run4: 2x2 cm^2 and 3x3 cm^2 SPACAL with poly + W&Pb abs., single side readout
  - Run4_rotated: same as Run4 but with titled SPACAL modules
  - Run5: 1.5x1.5 cm^2 W+GAGG and 3x3 cm^2 Pb+Poly SPACAL, double side readout
  - Run5_rotated: same as Run5 but with titled SPACAL modules
  - Run5_downscoped: same as Run5 but all modules single side readout
  - Run5_option2: same as Run5 but with different module distribution
  - Run5_tungsten: same as Run5 but with W+Poly instead of Pb+Poly
- Example of **ongoing investigation**:
  - Comparison of performance for a physics study of **current ECAL at the end of Run3** with respect to the **Run4 proposed upgraded** configuration
  - Radiation damage of Run3 Shashlik implemented based on irradiation tests

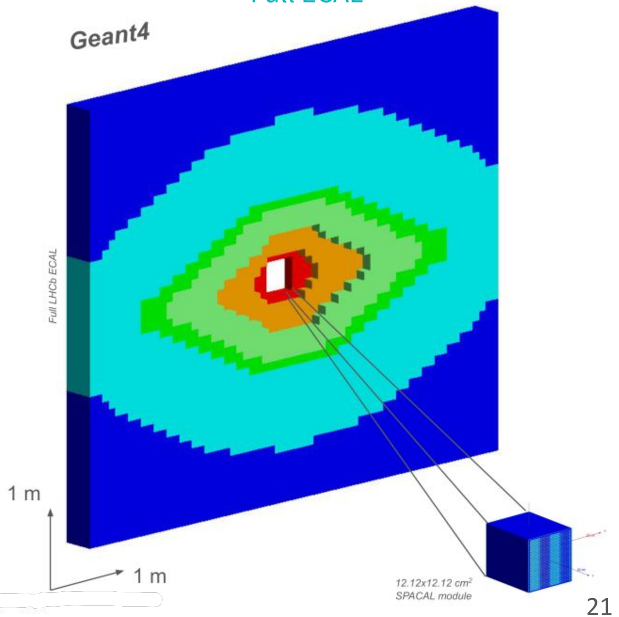
SPACAL



Shashlik

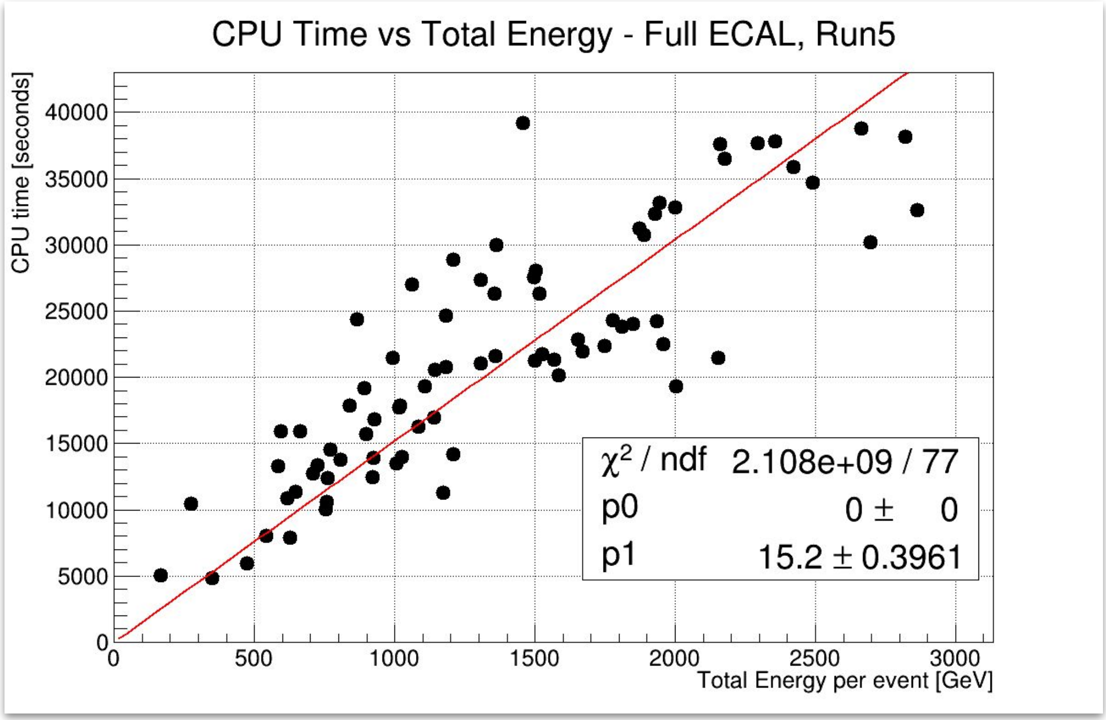


Full ECAL



CPU-time, running on lxplus

Full ECAL simulations (here for Run5 configuration) with LHCb flux: about **15s/GeV** of CPU time -> gain factor 200-500



N.B. a set of scripts is included in the framework to easily **run the HybridMC on the grid**

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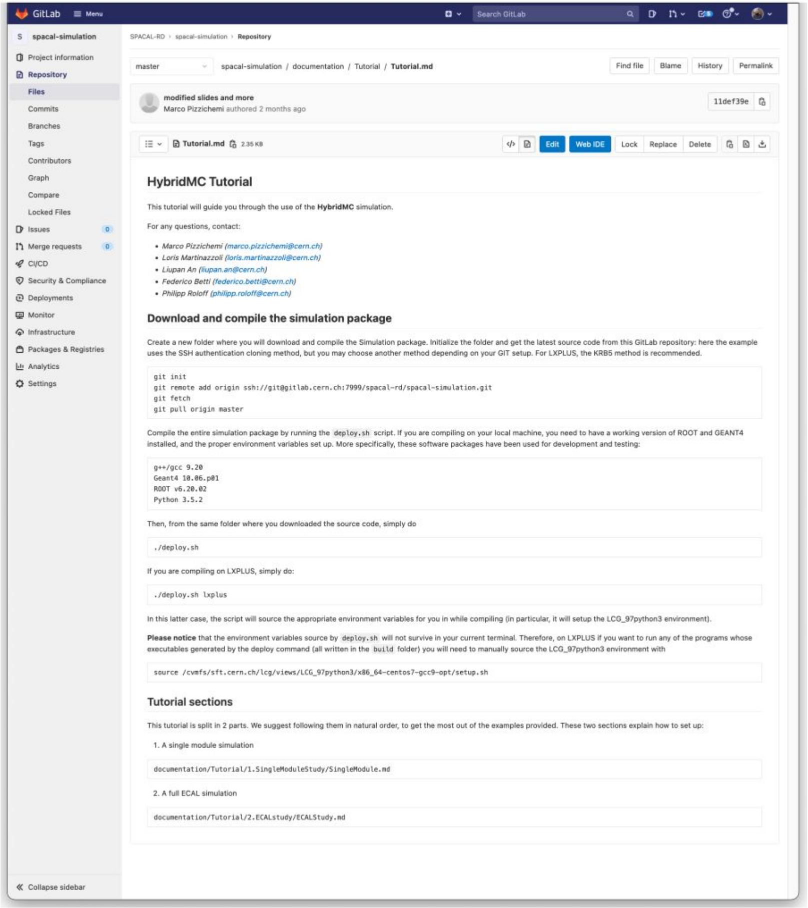
Code and support material

Framework code available to the collaboration on CERN GitLab:

- https://gitlab.cern.ch/spacal-rd/spacal-simulation
- Extensive documentation available in the repository
- Pre-packaged configurations and scripts available in repo

Full tutorial available:

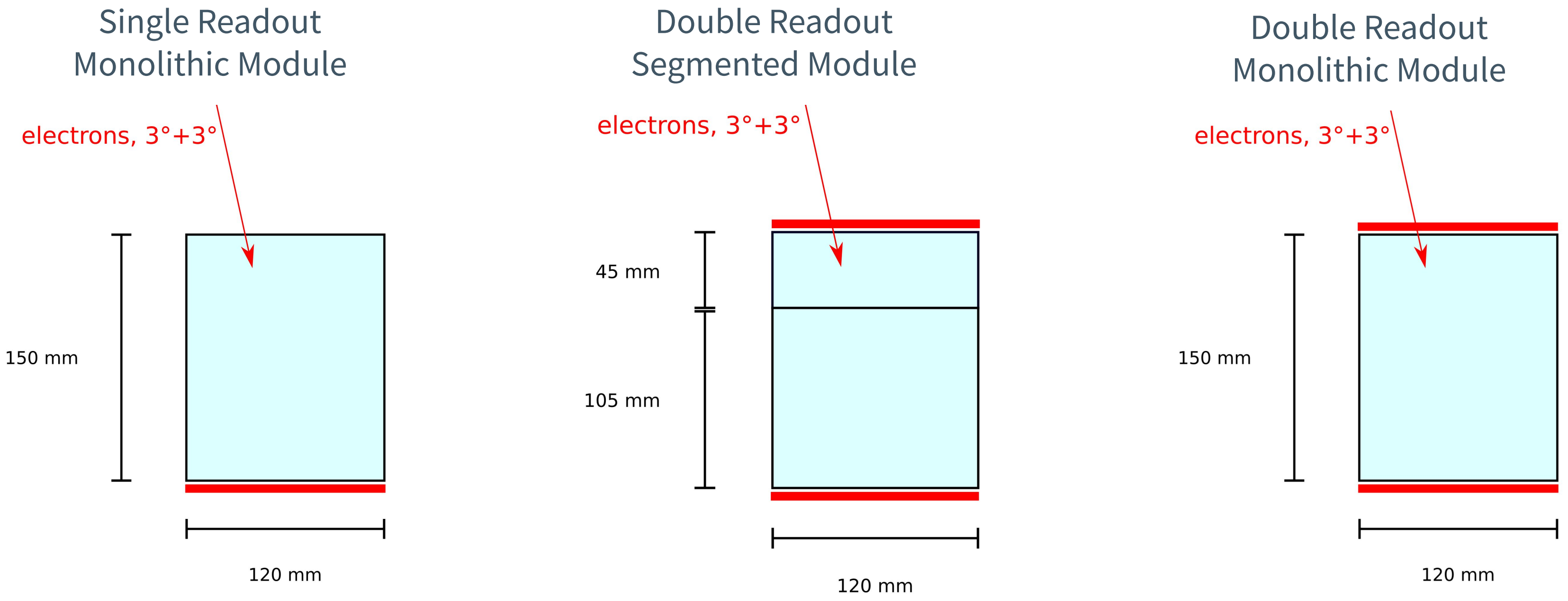
- Introduction (link)
- Part 1 (link): Single module simulation
- Part 2 (link): ECAL physics studies with Hybrid MC
- Extra information (link): creating flux files
- Video recording (link)



Single module studies with HybridMC

Single module performance simulation

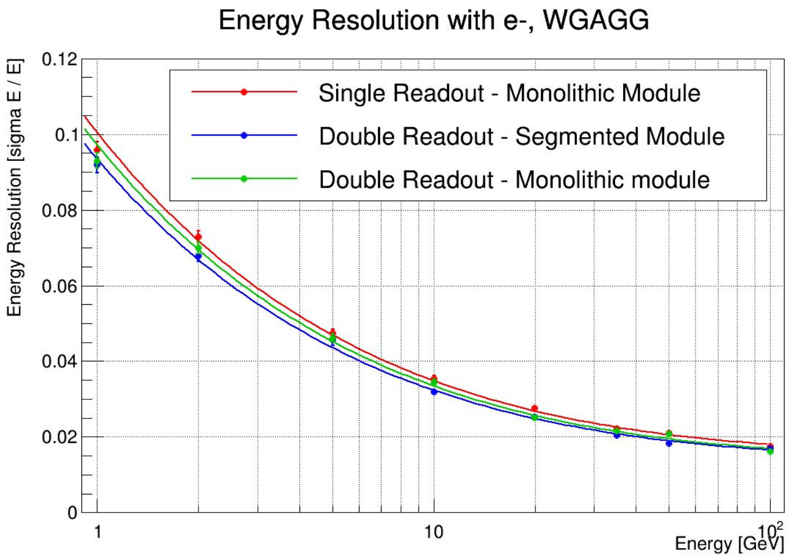
Performance of full scale **SPACAL modules proposed for Run4-5**, varying materials, segmentation and readout strategy

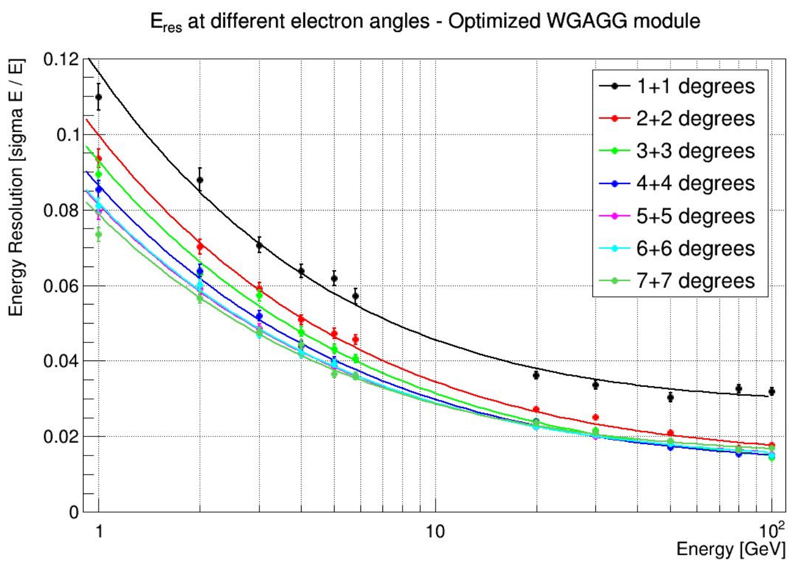


- Readout from face drawn in red
- Always a mirror on section ends, if not coupled to the readout
- In this drawing, dimensions reported for WGAGG modules (but of course different for PbPoly and WPoly)

Energy resolution and angular dependence

Example plots shown for **WGAGG** modules





- Energy resolution mostly not affected by module segmentation and readout scheme
- With longitudinally segmented module, scan of resolution variation with particle incidence angle:
  - Performance degradation at low angles
  - Optimal performance starting from 3°+3°

Front/back timestamps combination

- Time resolution is the performance of **target cell** (seed cell), so either 1 or 2 timestamps are available to use
- **Single Readout, Monolithic Module:** nothing to combine
- **Double Readout,** both **Segmented** and **Monolithic** modules:
  - Simple average:

$$t_{best} = \frac{t_{front} + t_{back}}{2}$$

  - Weighted average:

$$t_{best} = \frac{\sum_{i=1}^{2} w_i \cdot t_i}{\sum_{i=1}^{2} w_i} \qquad w_i = \frac{1}{\sigma_i^2}$$

Time resolution of front or back section

  - Covariance combination:

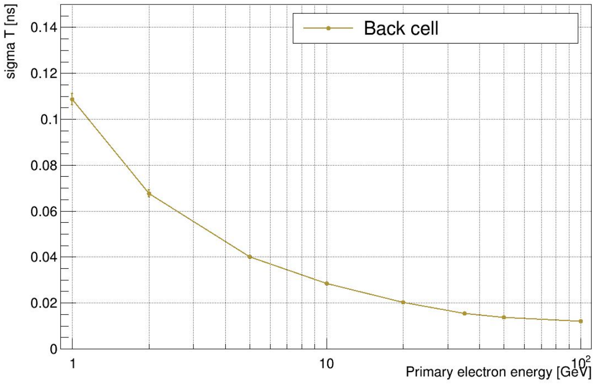
$$t_{best} = \sum_{i=1}^{2} w_i \cdot t_i \qquad w_1 = \frac{\sigma_2^2 - \sigma_{1,2}}{\sigma_1^2 + \sigma_2^2 - 2 \cdot \sigma_{1,2}} \qquad w_2 = \frac{\sigma_1^2 - \sigma_{1,2}}{\sigma_1^2 + \sigma_2^2 - 2 \cdot \sigma_{1,2}}$$

where $\sigma_{1,2}$ is the covariance element, calculated on N events for a given energy as:

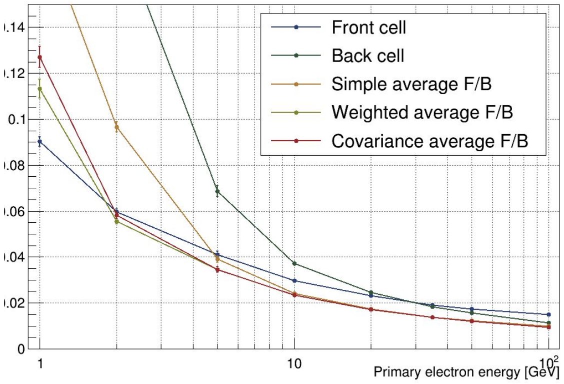
$$\sigma_{1,2} = \frac{1}{N} \sum_{i}^{N} (t_{1,i} - \hat{t_1}) \cdot (t_{2,i} - \hat{t_2})$$

WGAGG time resolution

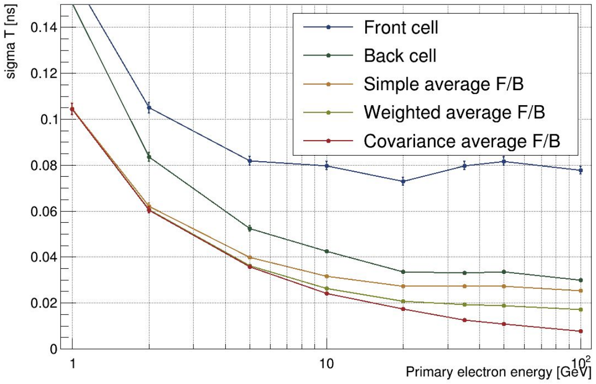
Single Readout
Single module



Double Readout
Segmented module

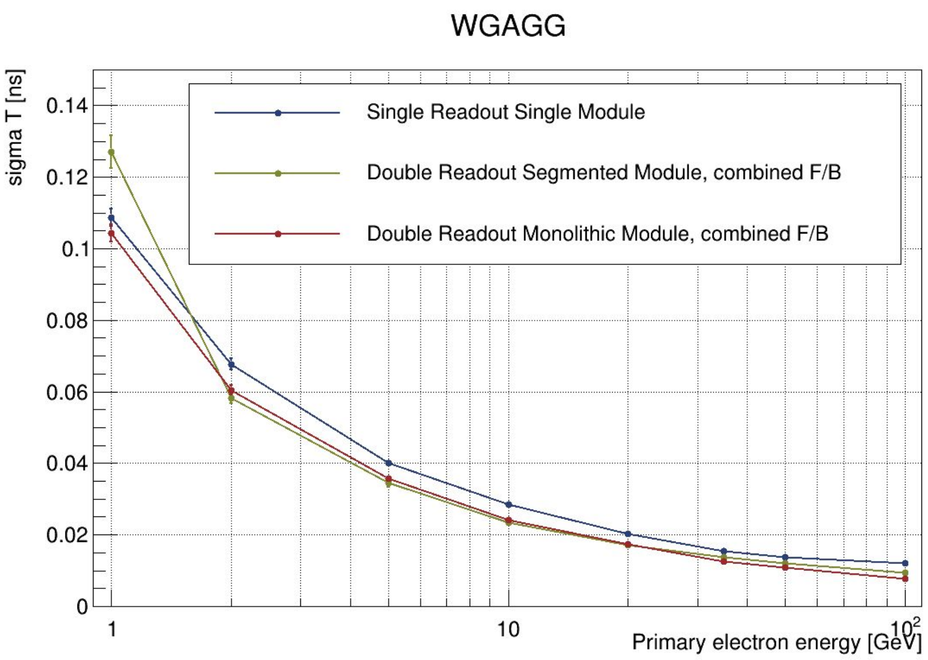


Double Readout
Monolithic module



- Segmented module:
  - Front and back intersect around 30 GeV
  - Simple average performs poorly at low energy
  - Weighted and covariance average performing equal
- Monolithic module with double readout:
  - Back always better than front
  - Covariance average performs better (front/back timestamps correlated)

WGAGG best results for the 3 configurations



- Time resolutions expected to be better than 20 ps above 20 GeV for all configurations
- Single side readout on monolithic modules provides worst timing performance
- Very similar performance from segmented and monolithic modules when using double readout

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Radiation damage study

Radiation damage simulated as a **loss of transparency** in scintillators -> **rescaling** bulk material absorption length

TABLE I

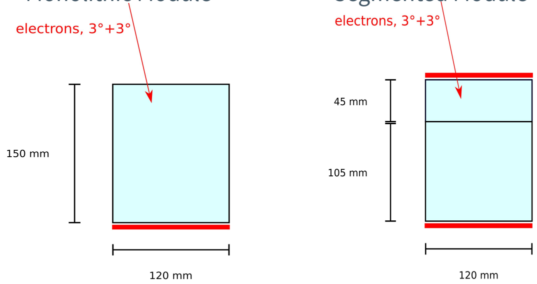
MEASURED ATTENUATION LENGTH OF THE GAGG FIBER BEFORE AND AFTER IRRADIATION

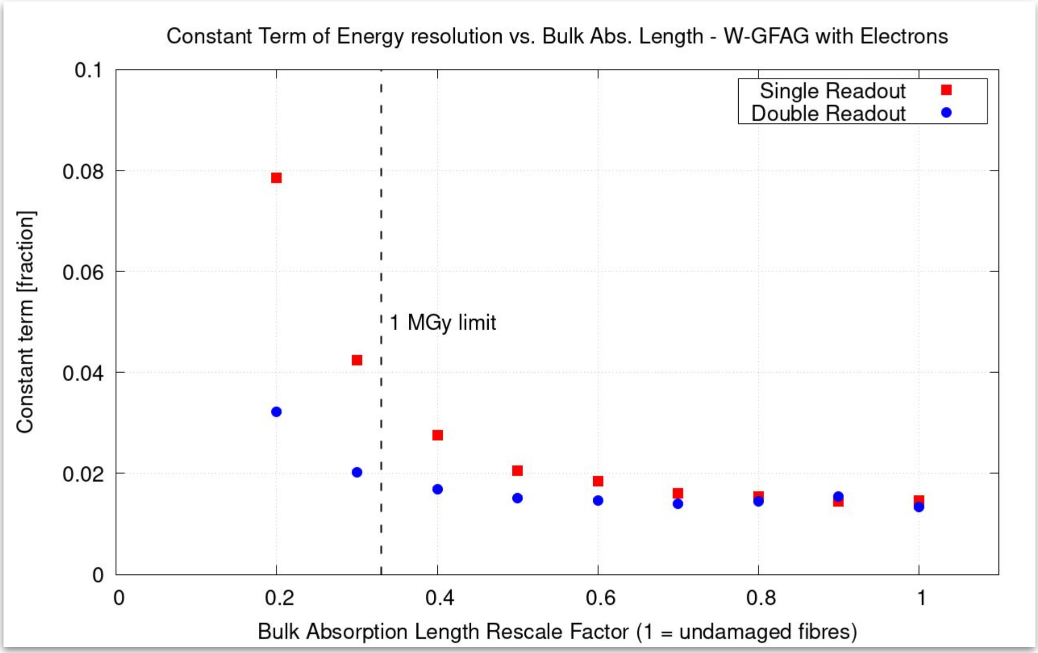
GAGG fibre	λ_{att} [cm]
Before irradiation	101.5
After irradiation	33.6

L. Martinazzoli, doi: 10.1109/TNS.2020.2975570

Single Readout Monolithic Module

Double Readout Segmented Module

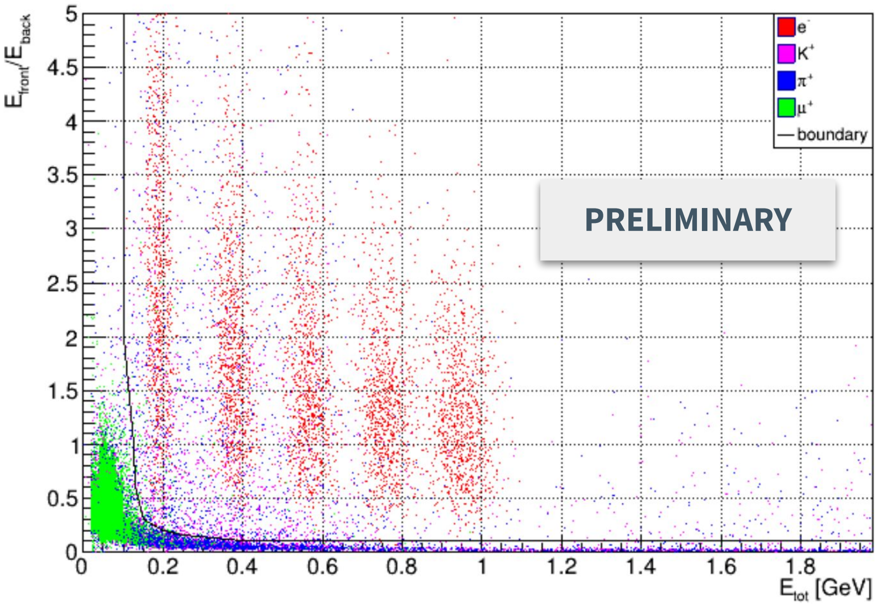


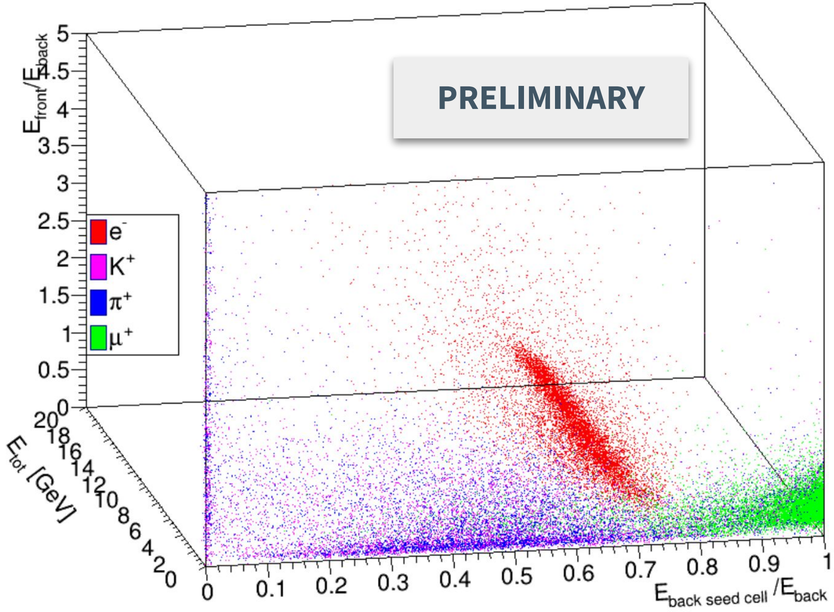


- Double readout segmented more robust to radiation damage, mostly because scintillators are shorter
- Expected performance remains acceptable up to 1 MGy, constant term < 2%

Electrons-hadrons discrimination

Ongoing studies to explore the possibility to **discriminate e$^-$ from hadrons** with SPACAL modules, based on energy distribution





- Several combinations of energy deposited in cells and sections can be used
- Much better e$^-$/$\pi^\pm$ separation efficiency found when the module is segmented longitudinally

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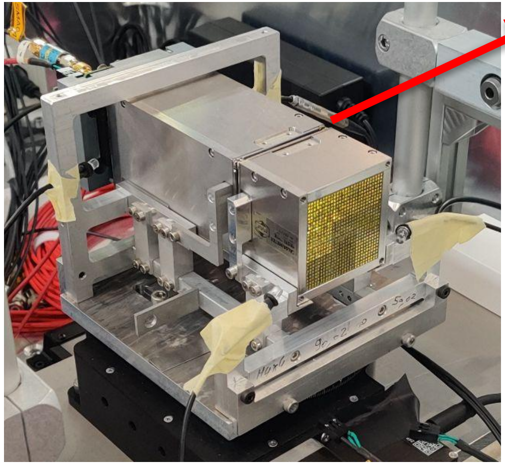
Comparison to test beam results

Simulation of test beam modules

Test beam modules: 3x3 cells with some non-negligible **material budget** between front and back section (easy detachment)

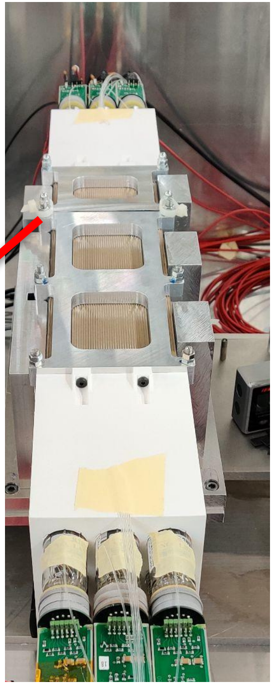


WGAGG

0.065 mm	ESR
0.3 mm	Alu
1.5 mm	**Stainless**
2.37 mm	Air
1.05 mm	**Stainless**
0.3 mm	Alu
0.065 mm	ESR

PbPoly

0.065 mm	ESR
2.0 mm	**Stainless**
1.0 mm	Air
2.0 mm	**Stainless**
0.065 mm	ESR



- Performance degradation expected with respect to optimized modules (12x12 cm^2 section, with negligible separation)

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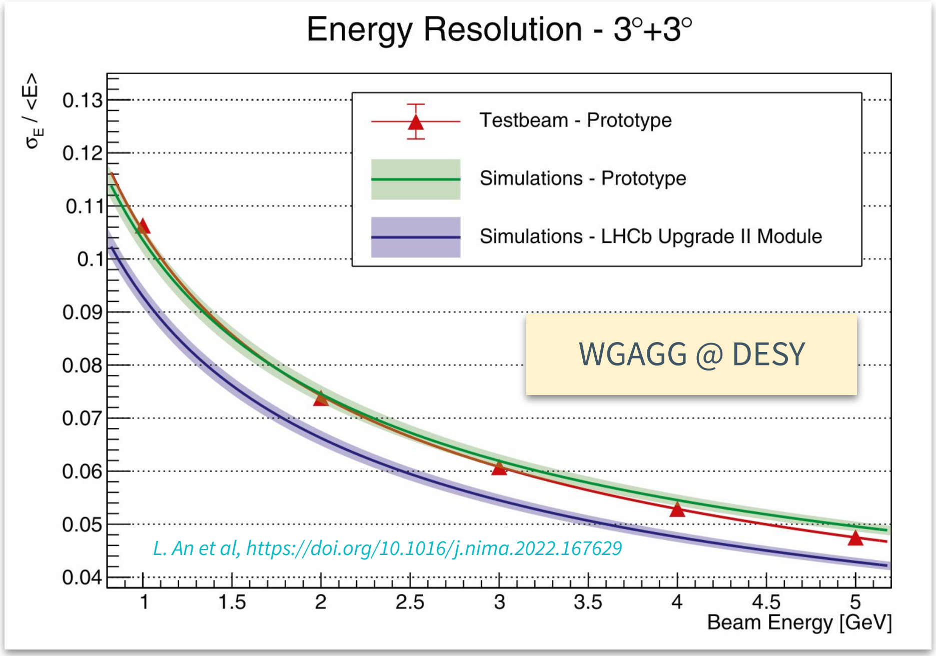
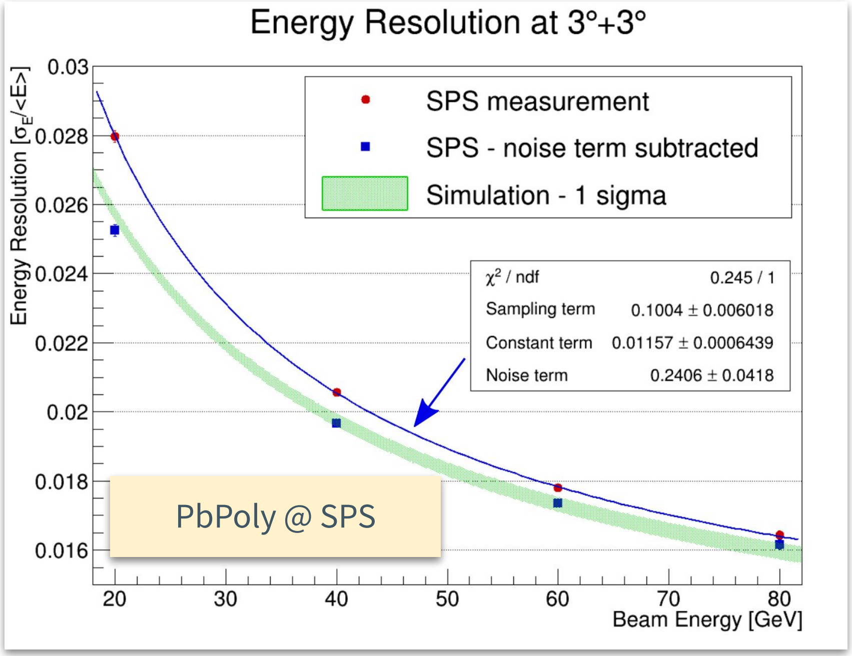
Comparison with test beam data





- The MC framework reproduces well the **test beam measurement**, once the separation material is included
- Modules for usage in **LHCb ECAL** will be designed with optimized separation (e.g. thin reflector foil)
- The framework allows to **predict** the energy resolution expected with **optimized modules**

Comparison with test beam data

		Measurements on TB modules [%]	MC simulations on TB modules [%]	MC simulations on optimized modules [%]
WGAGG	*Sampling term*	10.6 ± 0.1	10.2 ± 0.1	9.2 ± 0.1
	Constant term	1.9 ± 0.5	1.98 ± 0.04	1.18 ± 0.03
PbPoly	*Sampling term*	10.0 ± 0.6	10.3 ± 0.1	9.7 ± 0.1
	Constant term	1.16 ± 0.06	0.94 ± 0.04	0.56 ± 0.05

Expected energy resolution in **optimized modules** in line with requirements

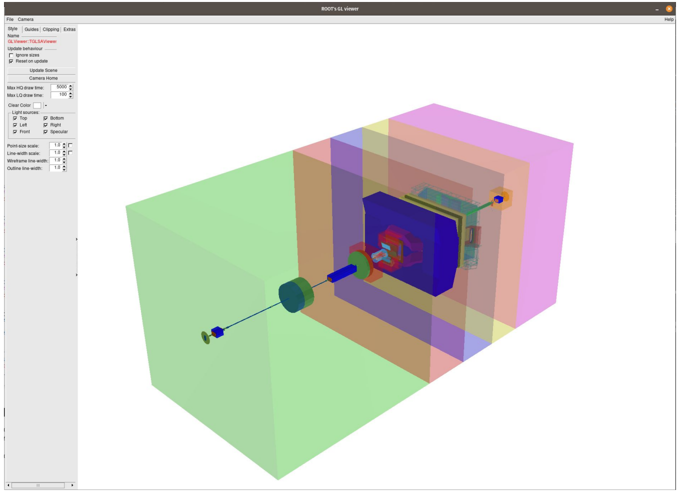
Integration with LHCb framework

Integration into LHCb simulation framework

- Integration of the ECAL upgrade configurations into Gauss is desirable
  - Will allow simulate ECAL with a flux of particles that passed through the other upgraded sub-detectors
  - Needed in any case in time for Run4 & Run5

- Several steps required
  - Port geometry to DD4Hep
  - Implement scoring (hits)
  - Port current parametrization strategy into the LHCb framework, verify functionality against current HybridMC
  - Develop further parametrizations (CPU time currently not compatible with LHCb requirements)

- Current situation
  - Geometry of baseline Run5 ECAL ported to DD4Hep
  - Run4 geometry description in DD4Hep almost completed
  - Checks of geometry ongoing
  - Starting implementation of scoring



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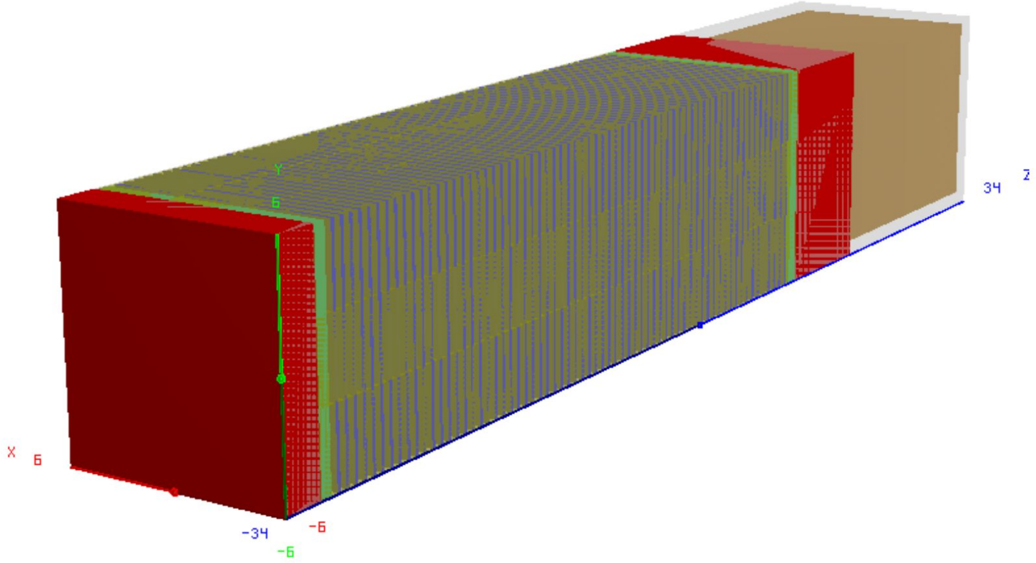
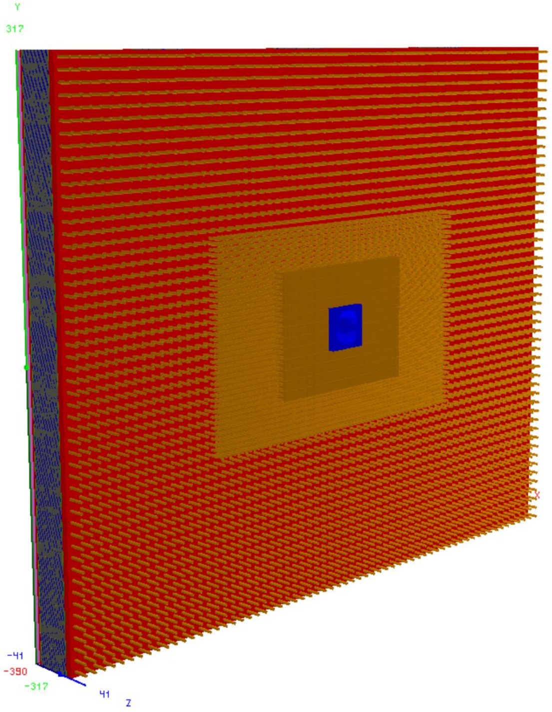
DD4Hep - Run3 ECAL

The Bologna group already implemented the description of Run3 LHCb ECAL (and HCAL) in DD4hep (i.e. SHASHLIK modules)

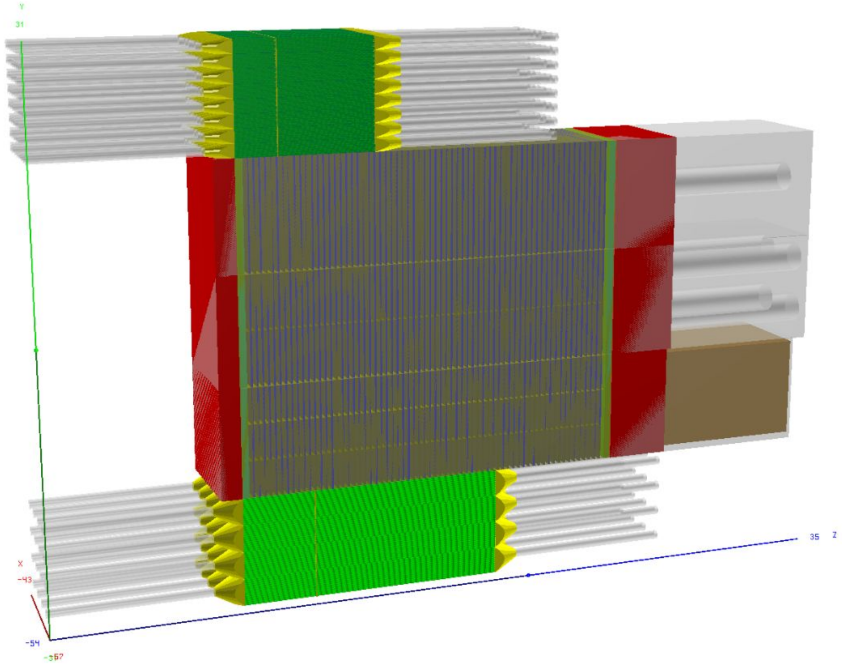


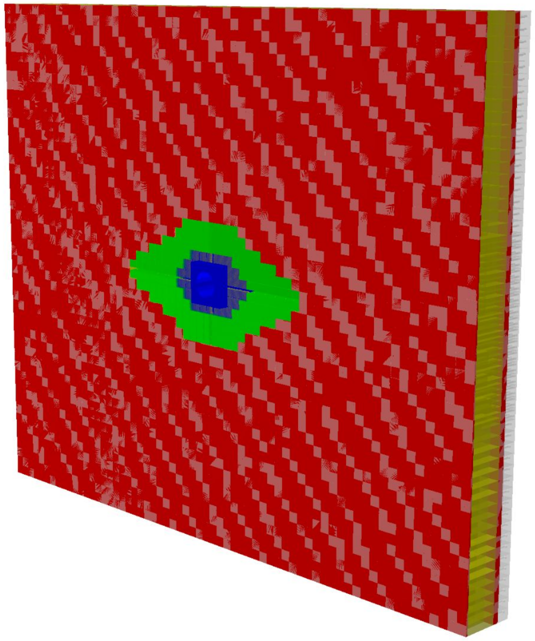


We started the ECAL Run4 and Run 5 implementations based on their code (many thanks to Lorenzo and Stefano!)

Module and ECAL implementations in DD4Hep

Some examples of SPACAL and Shashlik modules geometries, and the full Run5 ECAL, implemented in DD4Hep





Implementation of signal formation ongoing!

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Conclusions

- Full MC simulation framework developed, HybridMC
  - Allows to perform detailed simulations in reasonable time
  - Useful for both prototype developments and physics benchmark studies
  - Well documented, available to the collaboration

- Several single module studies performed
  - Complete characterization and optimization of the various SPACAL flavours
  - Good agreement with test beam data
  - Prediction of optimized module performance in line with requirements

- Integration into the LHCb simulation framework ongoing
  - Geometrical description in DD4Hep of the Run4-5 configuration prepared
  - Ongoing work on signal formation
  - Long term goal: port the HybridMC approach into the LHCb simulation framework and develop further parametrizations to allow speed-up when simulating the entire LHCb experiment

Thank you for your attention!