The HybridMC: a fast detailed Monte-Carlo framework for the LHCb electromagnetic calorimeter upgrade

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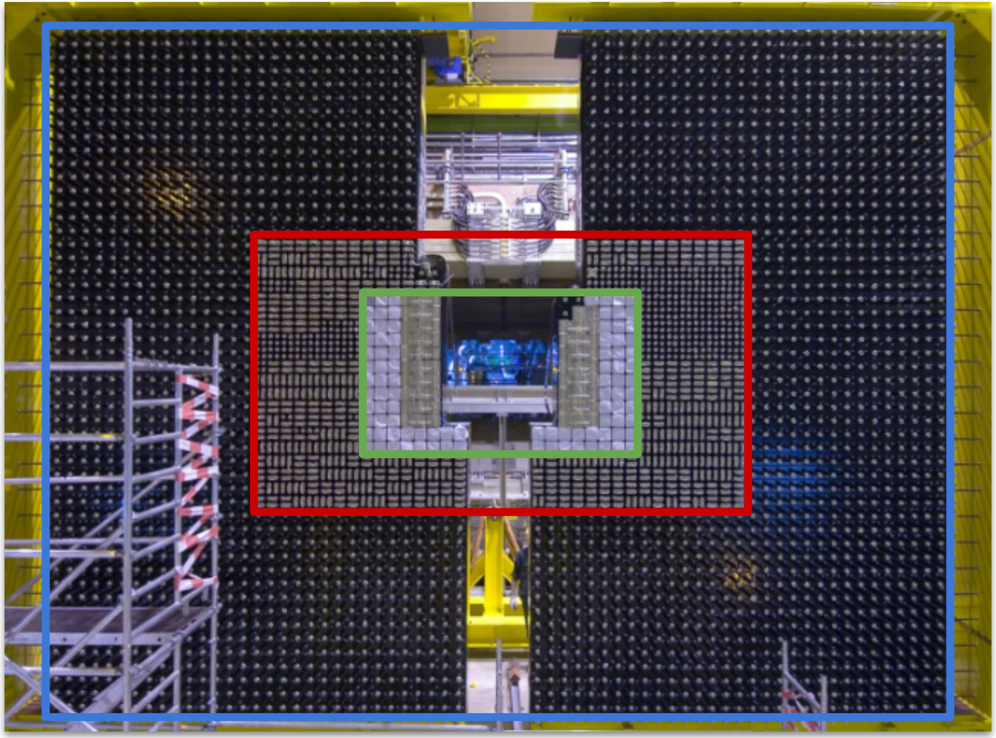
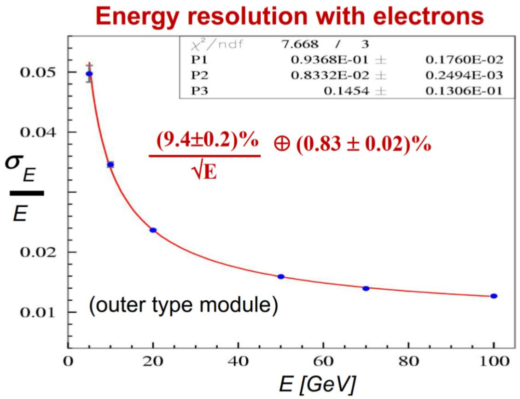
On behalf of the LHCb ECAL Upgrade II R&D group

16th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD23), 25-29 September 2023, Siena, Italy

Current LHCb ECAL configuration



- Large **SHASHLIK** array (about 50 m^2) with 3312 modules and 6016 channels:
  - 176 modules 4x4 cm^2 cell size
  - 448 modules 6x6 cm^2 cell size
  - 2688 modules 12x12 cm^2 cell size
- Optimized for π^0 , e^- and γ identification in the few GeV to 100 GeV region at **2×10^{32} cm^{-2} s^{-1}**
- Radiation hard up to **40 kGy**
- Energy resolution: **$\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$**



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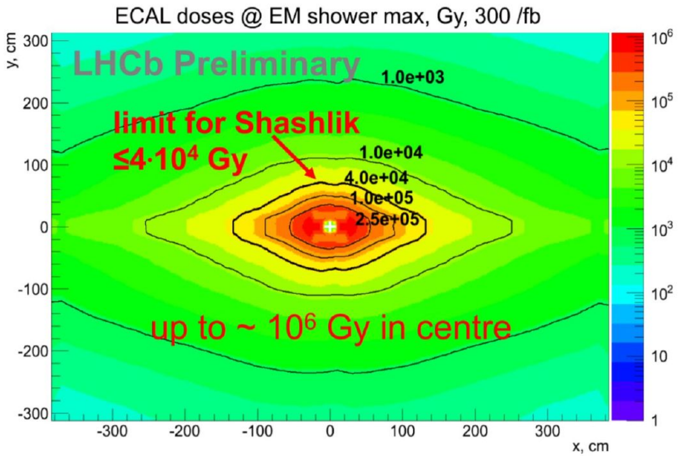
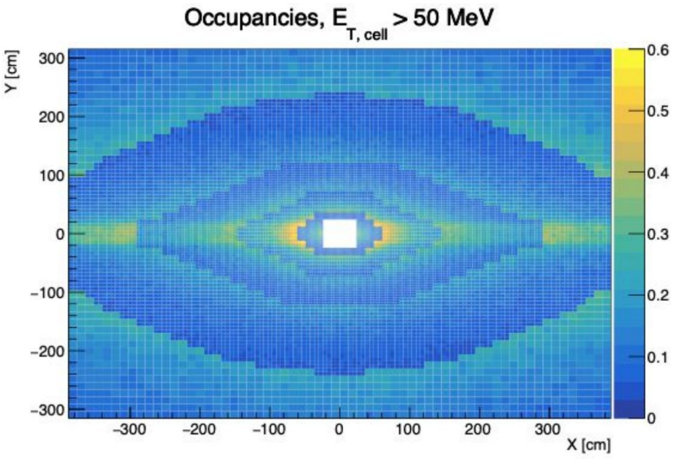
Requirements for ECAL Upgrade II → PicoCal

Keep current performance while coping with **harsher operating conditions**





Sustain higher **radiation dose**

(up to 1 MGy and ≤ 6 x 10^{15} 1 MeV neq/cm^2 in the center)

New technologies required

Mitigate higher **pile-up**

Timing O(10ps), preferably directly in the modules

Increased **granularity**

Longitudinal **segmentation**

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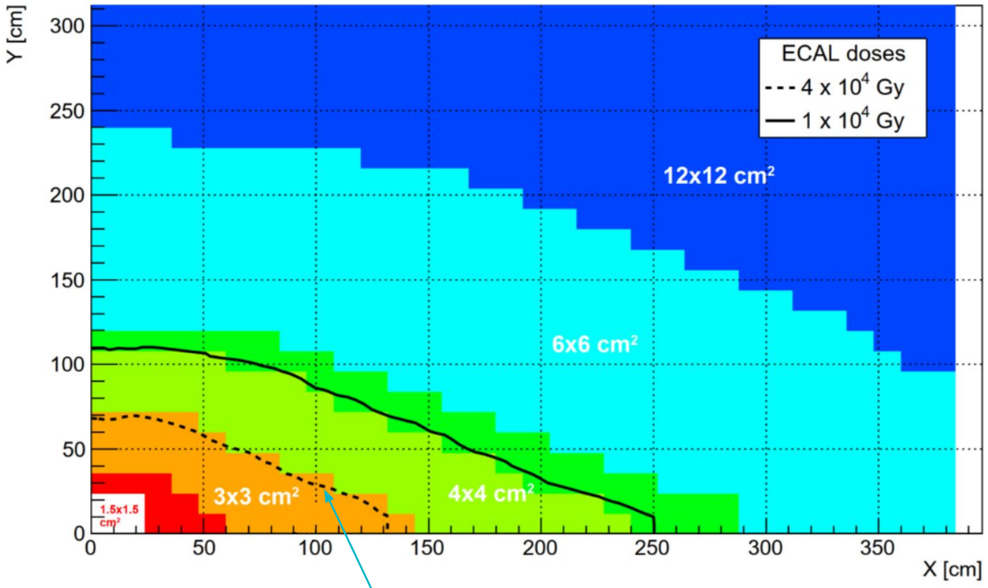
Technologies for the LHCb PicoCal

New technologies, and new module configuration **optimized for radiation** dose level

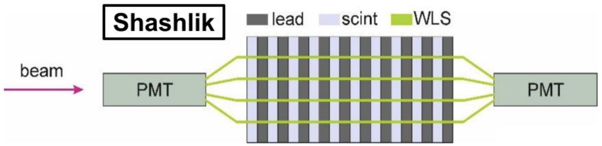
One ECAL quadrant



Radiation tolerance limit of the current Shashlik technology

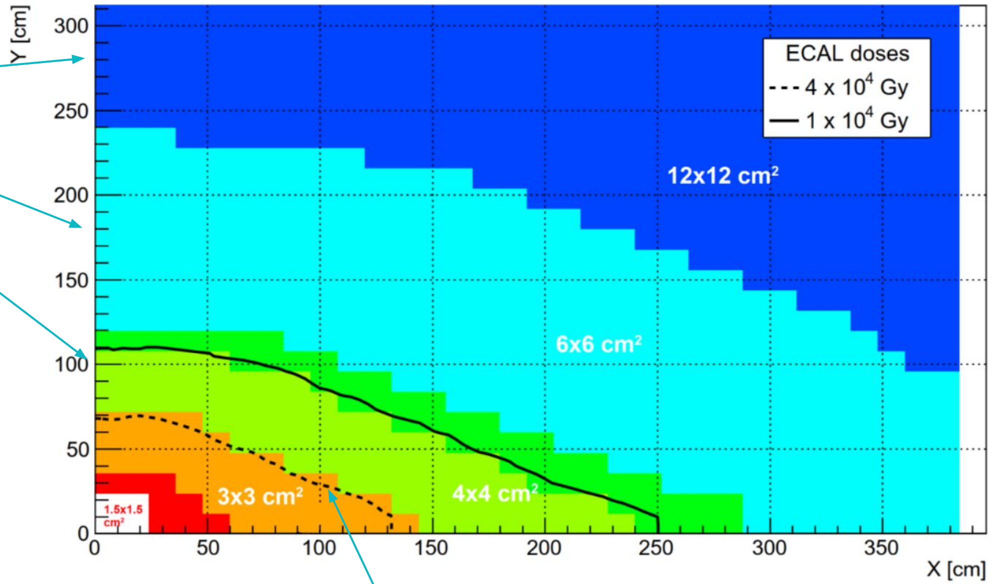
Technologies for the LHCb PicoCal

New technologies, and new module configuration **optimized for radiation** dose level



Reshuffle Shashlik modules, introduce timing and longitudinal segmentation

One ECAL quadrant



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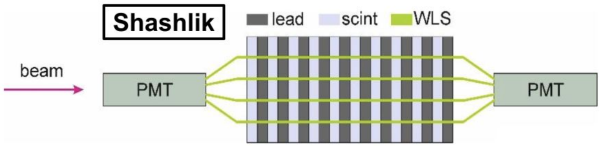

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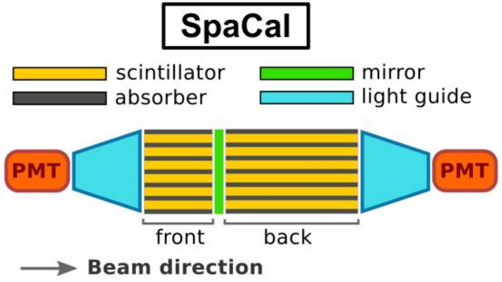
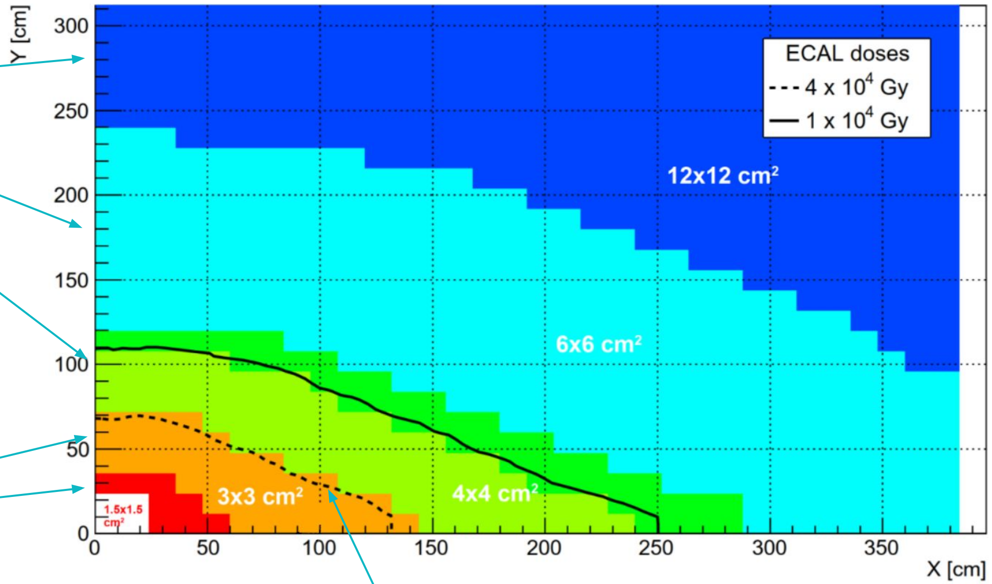


New SpaCal modules with timing and finer granularity

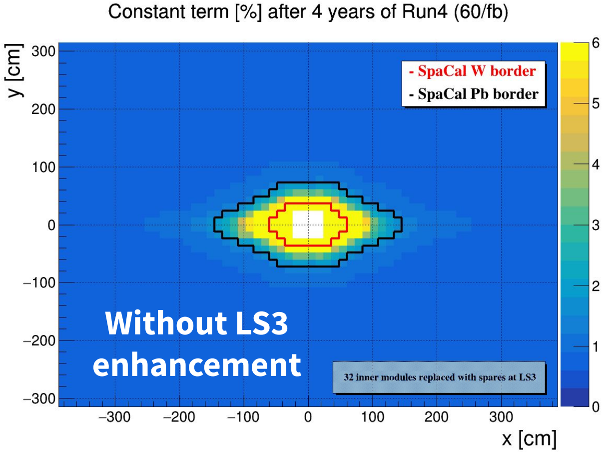
One ECAL quadrant



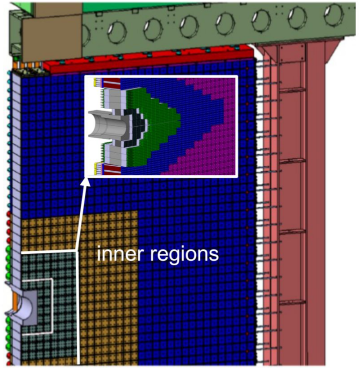
Radiation tolerance limit of the current Shashlik technology

For more info see presentations by:
E. Picatoste "Scintillating sampling ECAL technology for the LHCb PicoCal"
L. Martinazzoli "R&D of GAGG single crystals for fast timing detectors in high rate and radiation environments"
F. Ferrari "Latest feasibility studies of LAPPD as a timing layer for the LHCb Upgrade-2 ECAL"

LHCb ECAL upgrade strategy



- **Run 3** in 2022-2025:
  - Run with unmodified ECAL Shashlik modules at 2 x 10^{33} $cm^{-2}s^{-1}$
- **LS3 enhancement** in 2026-2028:
  - Introduce single-section rad. tolerant SpaCal (2 x 2 and 3 x 3 cm^2 cells)
    - 32 SpaCal-W and 144 Spacal-Pb modules with plastic fibres
  - Rebuild ECAL in rhombic shape to improve performance
  - Option to include timing information with single-sided readout
- **LS4 Upgrade II** in 2033/2034:
  - Introduce double-section rad. hard SpaCal (1.5 x 1.5 and 3 x 3 cm^2 cells)
    - Innermost SpaCal-W modules equipped with crystal fibres
  - Improve timing of Shashlik modules
  - Include timing information and double-sided readout to full ECAL for pile-up mitigation



Motivation for HybridMC

- Detailed simulations are crucial both during the **R&D phase** and the **operation** of the upgraded ECAL
  - Optimizing the geometry of modules
  - Optimizing the geometry of the entire calorimeter
  - Understand performance evolution with time (radiation damage)
  - Assess impact of design choices on physics analysis

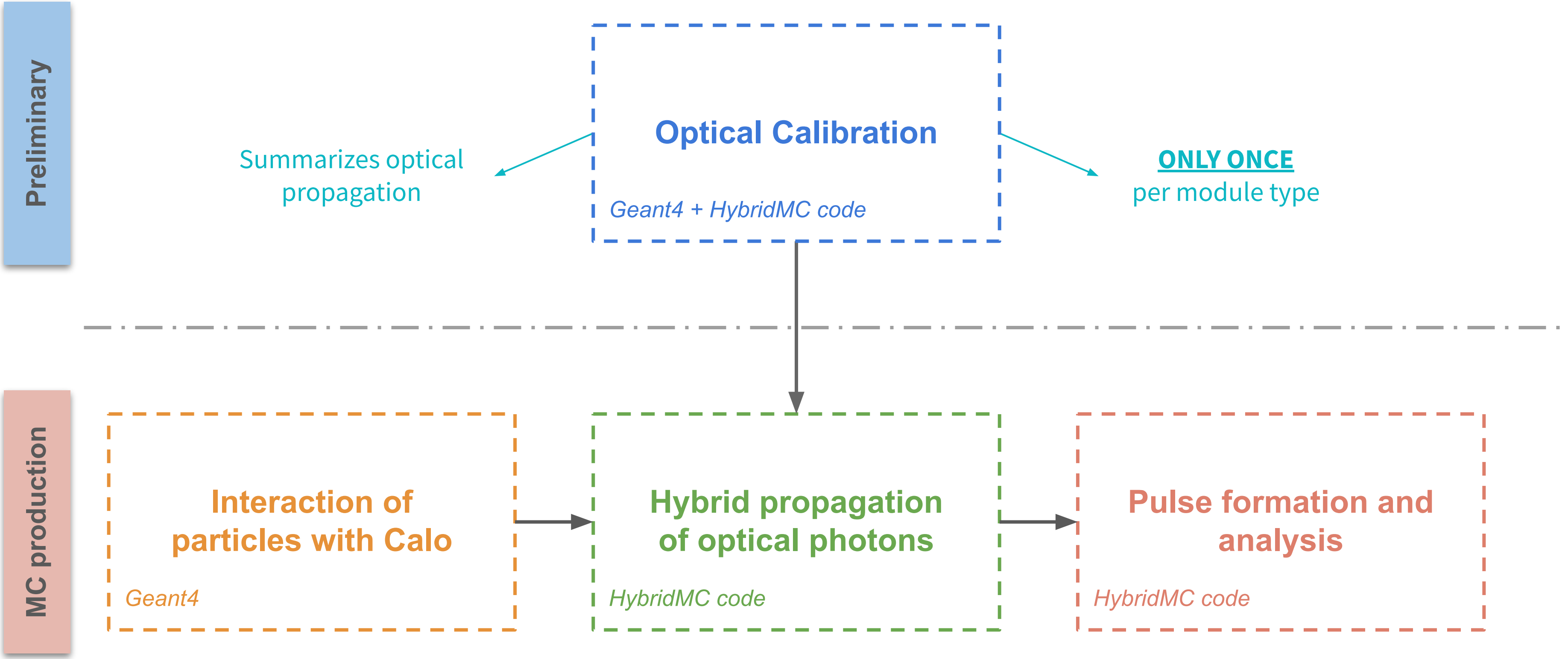
- Bright scintillators are needed to fulfill the ECAL upgrade requirements, especially for timing
  - Great quantity of optical photons produced
  - **Full ray-tracing** of optical photons becomes quickly **unfeasible**: CPU time around 1 h/GeV of $e^{\pm}/\gamma$

- Nevertheless , **optical photons cannot be neglected** in our application
  - Crucial to predict timing performance
  - Allow to evaluate impact of complex effects (scintillator surface state, attenuation length, radiation damage…)

A speedup strategy is needed!

The HybridMC concept

Move the transport of optical photons **outside of Geant4**, reproduce it faster while keeping the necessary level of details



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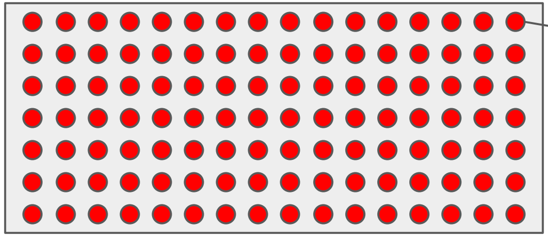
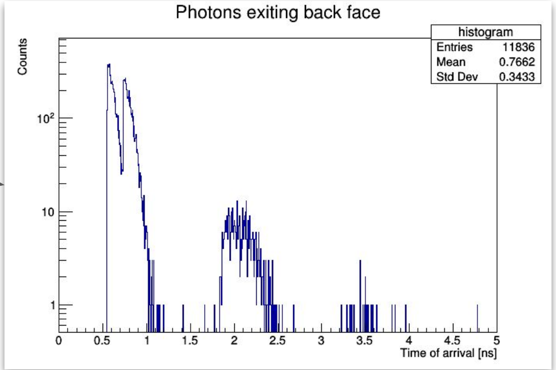
Optical calibration

Optical calibration concept

Procedure to **parametrize** the optical photon output of Shashlik and SpaCal modules



Calo module
Grid of calibration points
(x,y,z,direction,wavelength)



- Special **full ray-tracing** runs
  - Optical photons are produced scanning a grid of points, propagated and collected at the exit of the modules
  - Histograms of the extracted photons are recorded

- Fundamental features of optical transport are **encoded in the histograms** (extraction efficiency, time distribution)
- Need to be performed **only once per module type** (so CPU time doesn't matter)
- Symmetries of the modules can be exploited to reduce number of points necessary on the grid

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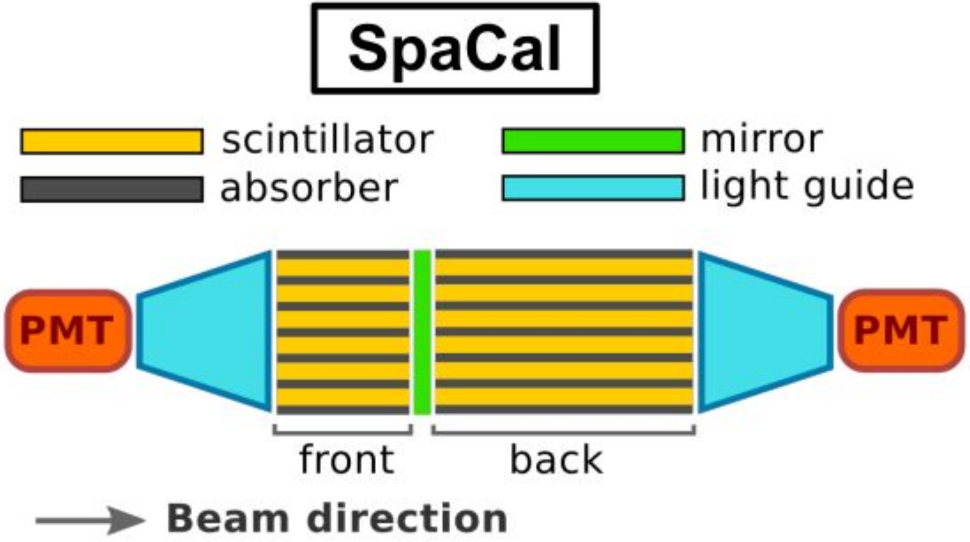
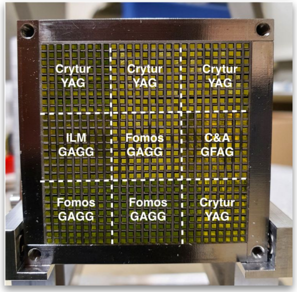
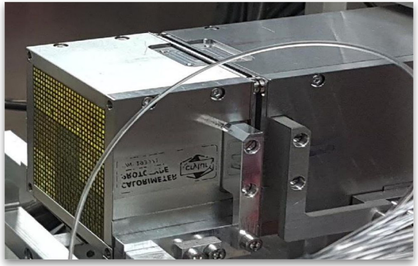
Optical calibration procedure







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Optical calibration procedure

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

Example: two scintillators in a longitudinally split SpaCal module

Non-perfect reflector

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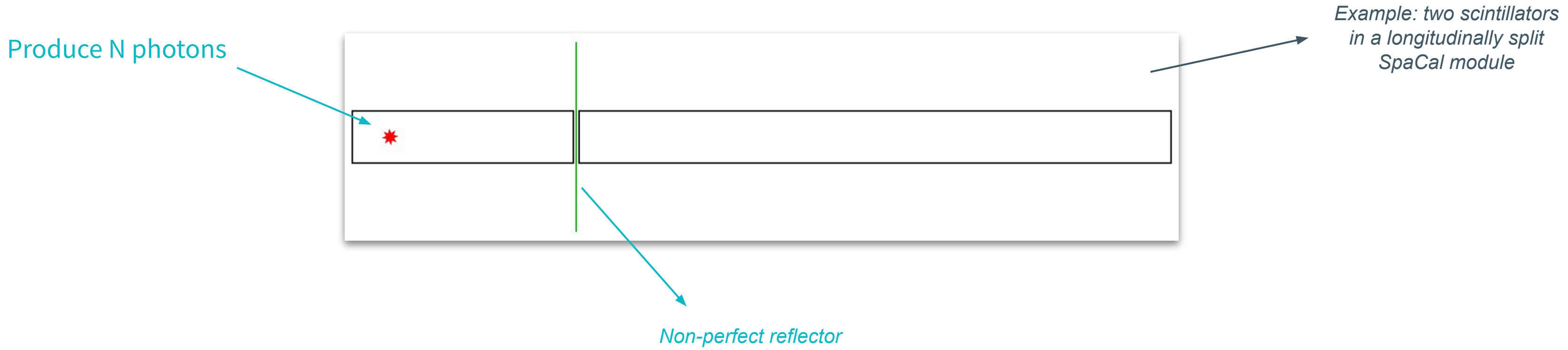

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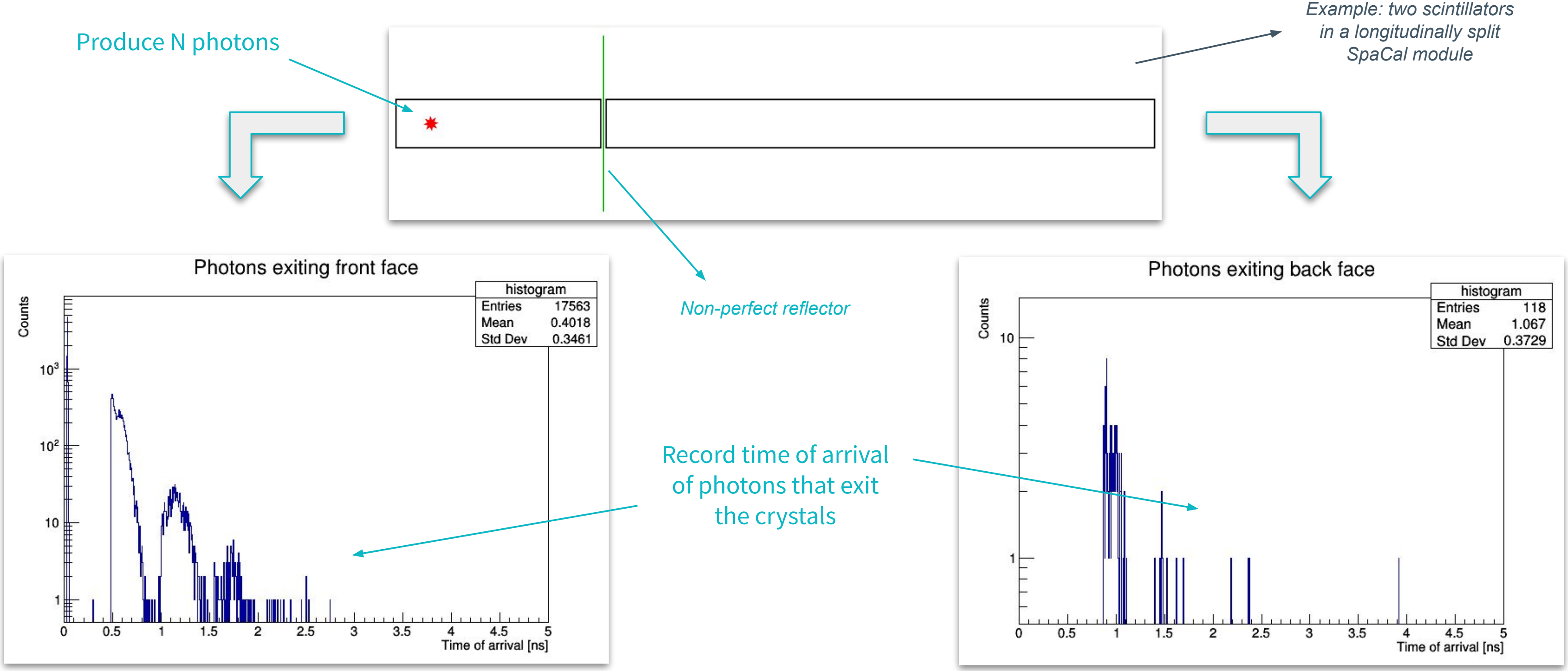

Optical calibration procedure

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

Produce N photons

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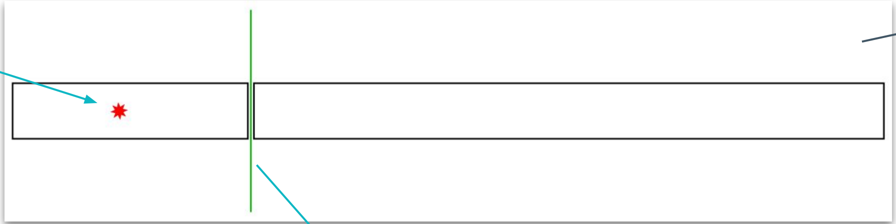
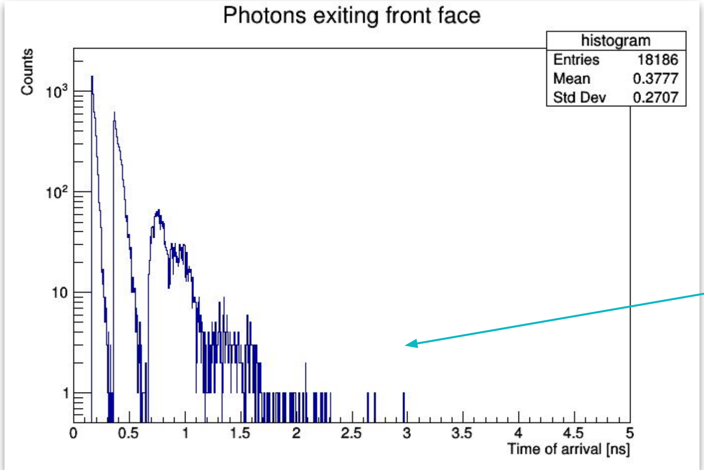
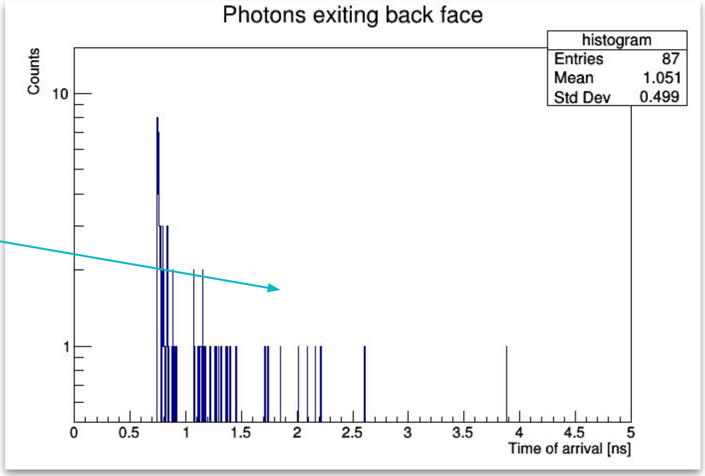


Non-perfect reflector



Record time of arrival of photons that exit the crystals



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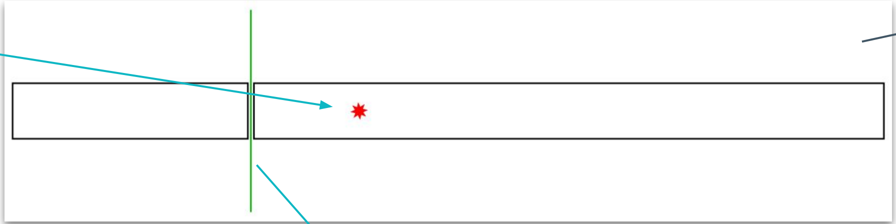

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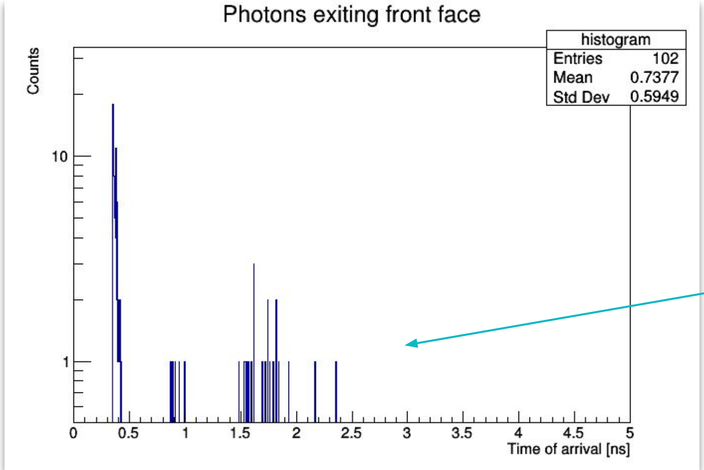

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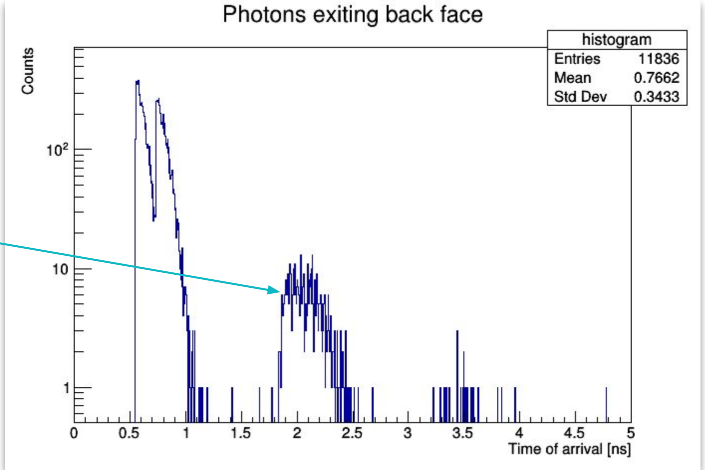

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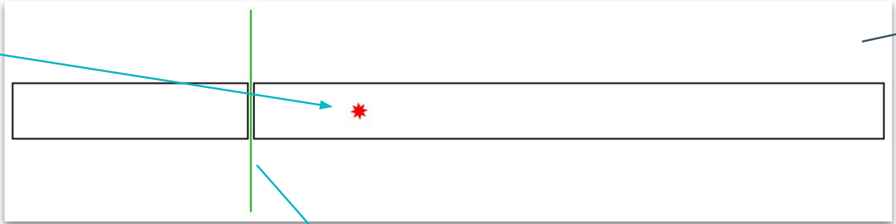

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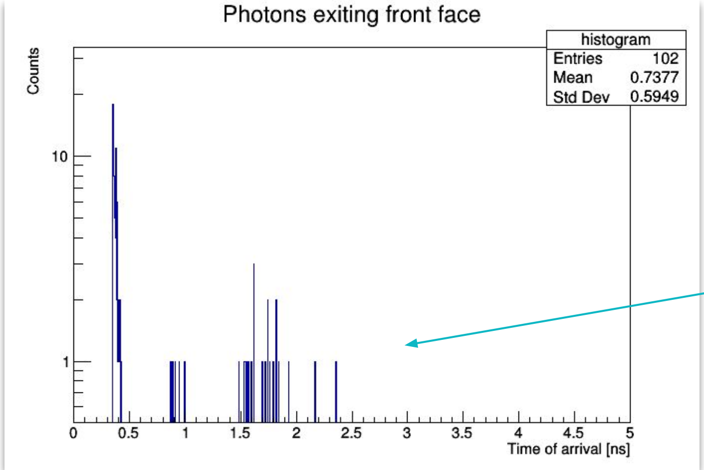

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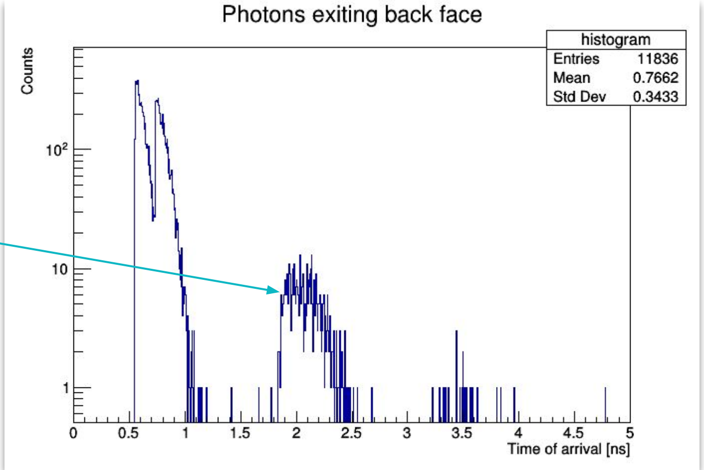
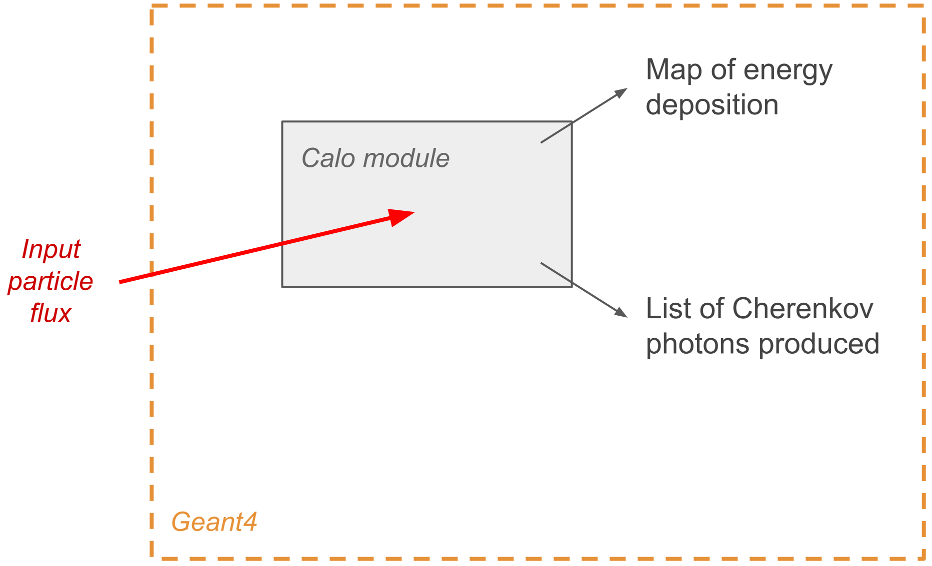


Use these histograms as **PDFs** to generate **photon extraction probability** and **time of transport**

MC production

Interaction of particles with Calo

The Geant4 simulation is performed **deactivating** the propagation of optical photons and the production of scintillation photons



- The information necessary to reproduce the optical propagation is saved:
  - The **map of energy deposition** (position, energy)
  - The **list of Cherenkov photons** produced by Geant4 (position, wavelength, emission direction)

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Hybrid propagation of optical photons

Reproduce the transport of optical photons in a faster way

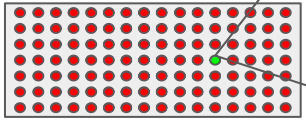
Map of **energy deposition**

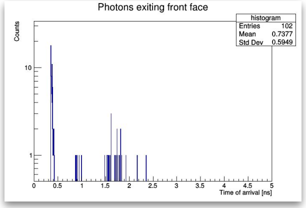
List of **Cherenkov** photons produced

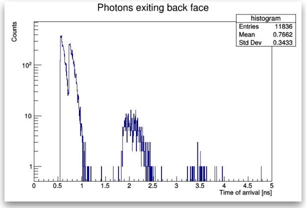
Geant4

Scintillation photons produced

For each photon, find **closest calibration point**







Run simple Monte-Carlo, producing just 2 random numbers:

- **Assign** photon to a detector or **absorb** it, using the histogram **n° of entries**
- Assign **timestamp** using the histogram cumulative

HybridMC code

The key features of optical transport are **summarized into the PDFs**, hence **preserved** in the final output

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Pulse formation and analysis

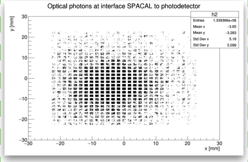
Produce a **realistic pulse** on each detector in the simulated module/calorimeter

Map of **energy deposition**

List of **Cherenkov** photons produced

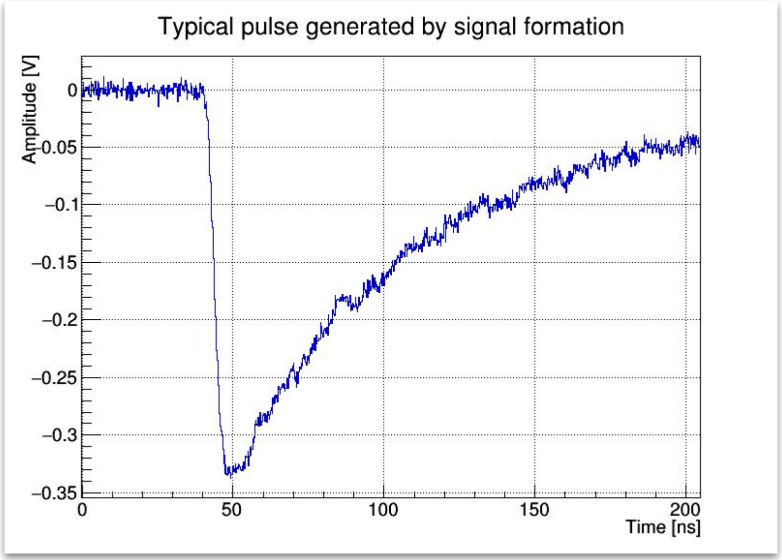
Geant4

List of **photons** on detectors



HybridMC code

- Group photons per detector
- Apply efficiencies (spatial, QE…)
- Build pulses from single photo-electron signals
- Digitization (e.g. DRS4)
- Analysis (e.g. CFD)



HybridMC code

Energy and **time** information extracted for each readout channel

Gain in computation time

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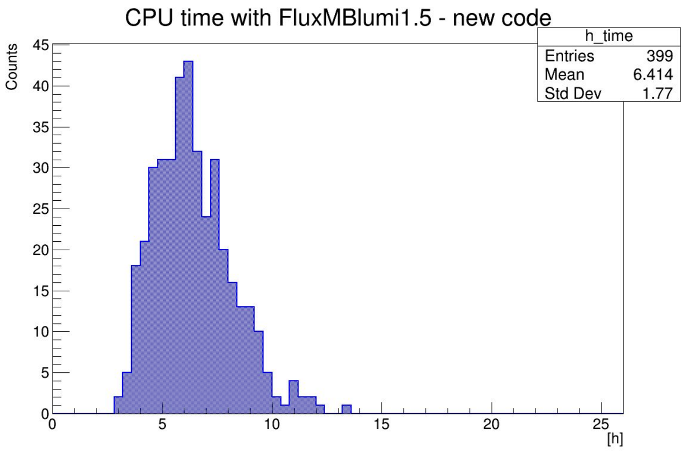
Evaluation of CPU speedup

Comparison of total **CPU time** between HybridMC and full ray-tracing, for the same e.m. particle source on **lxplus**

Technology	Type	Full ray-tracing *[s/GeV] of e±/γ*	HybridMC *[s/GeV] of e±/γ*	Gain
SpaCal	*W-GAGG*	990 ± 20	9.4 ± 0.1	~100
	Pb-Polystyrene	3600 ± 100	2.28 ± 0.04	~1500
	W-Polystyrene	1070 ± 20	2.88 ± 0.04	~400
Shashlik	–	1800 ± 30	3.83 ± 0.09	~500

Full ray-tracing → Scintillator surface state and geometry

HybridMC → Light yield, Sampling fraction



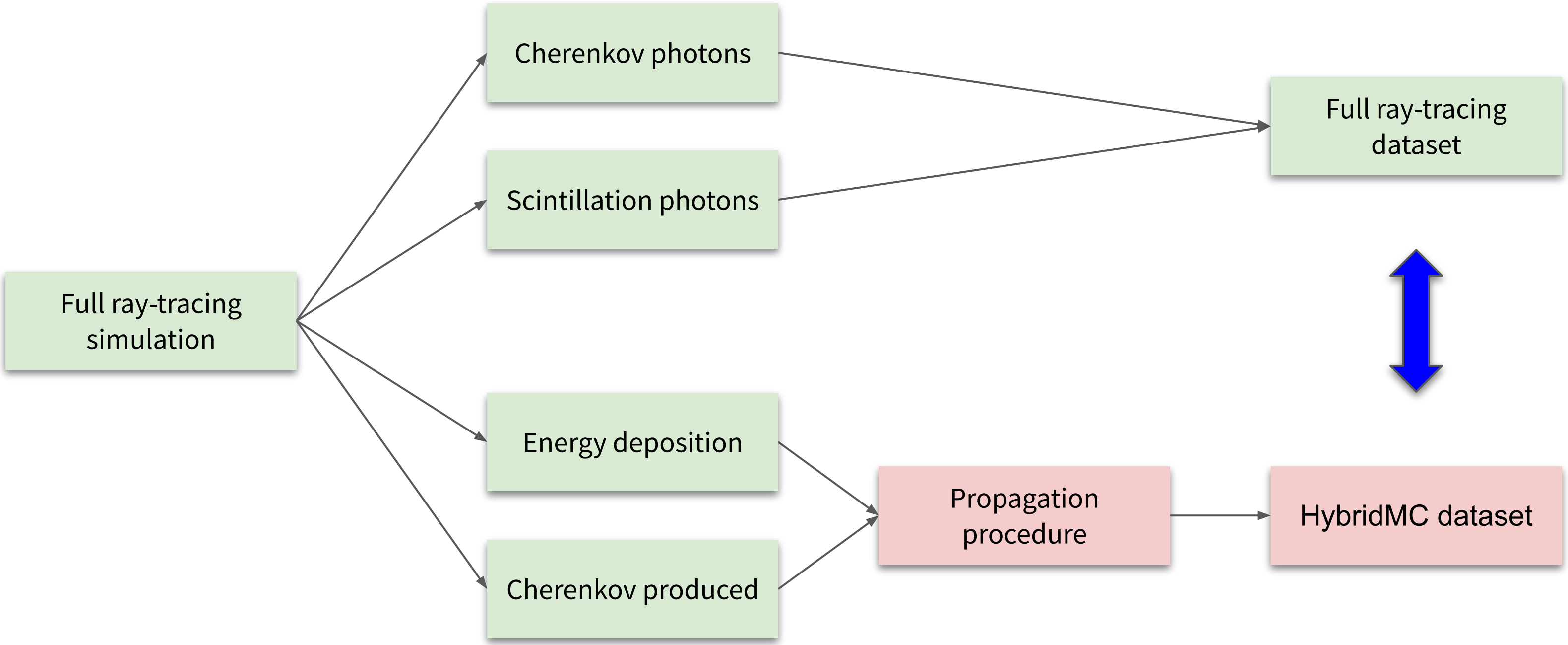
When performing full ECAL simulations, this translates to **~1.8 s/GeV** of incoming particles (about ⅓ kinetic energy is in *e±/γ)*

In **Run5** conditions (~10 TeV total kinetic energy to Calo) the computation time is on average **6h/event**

Validation of HybridMC propagation

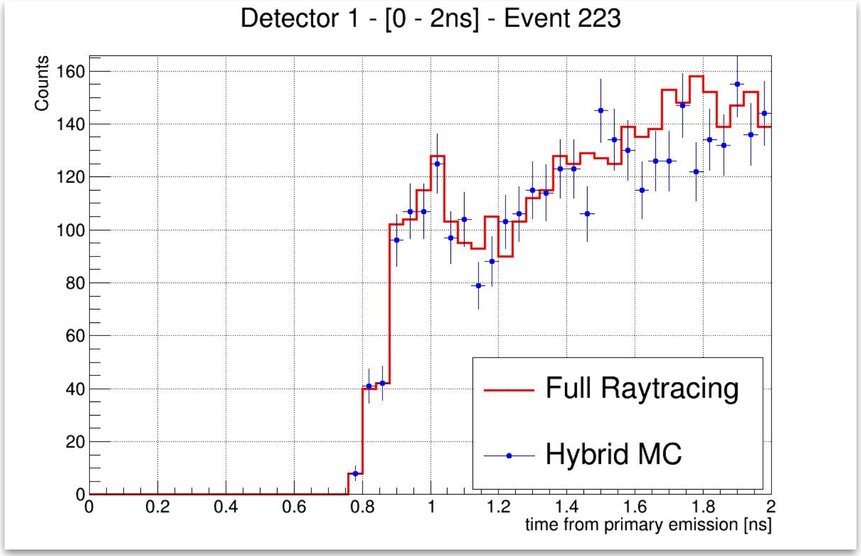
Validation of HybridMC approach

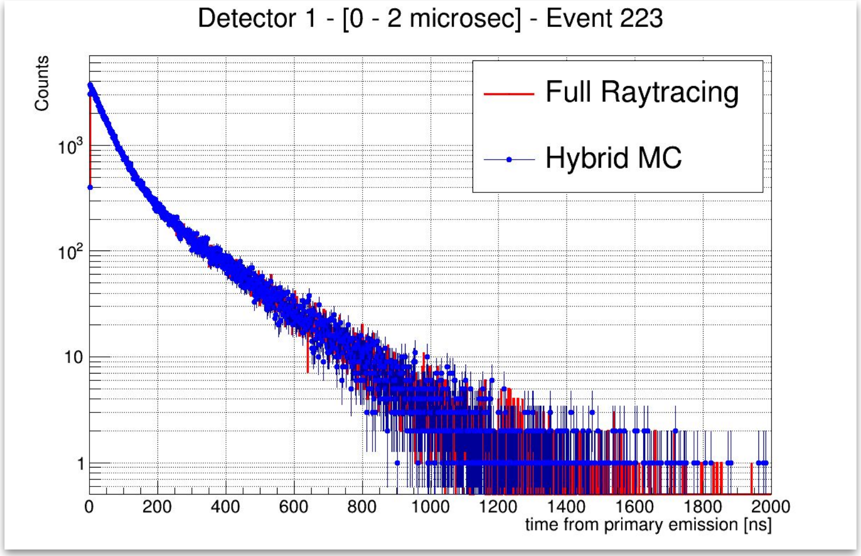
Check if the optical calibration approach provides results **compatible with Geant4 full ray-tracing**



Produce a full ray-tracing dataset while **saving also the information to perform the hybrid procedure**, then compare

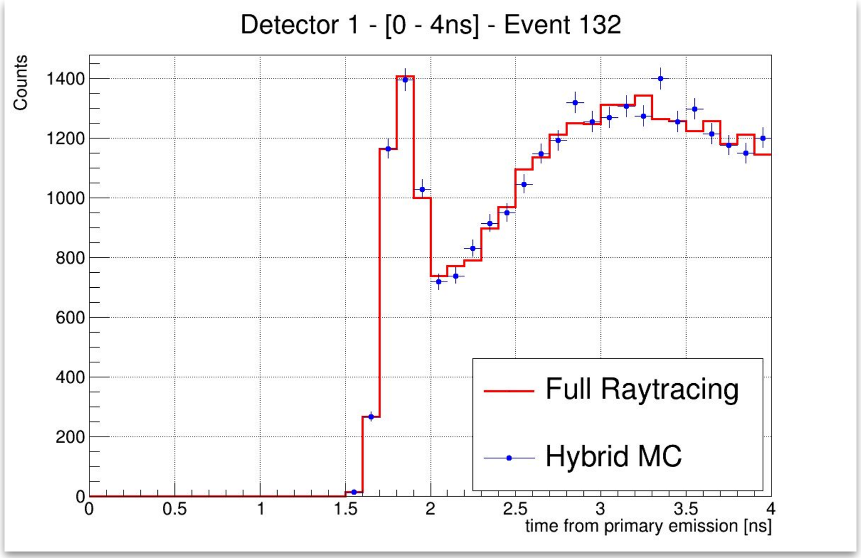
Validation: SpaCal W-GAGG

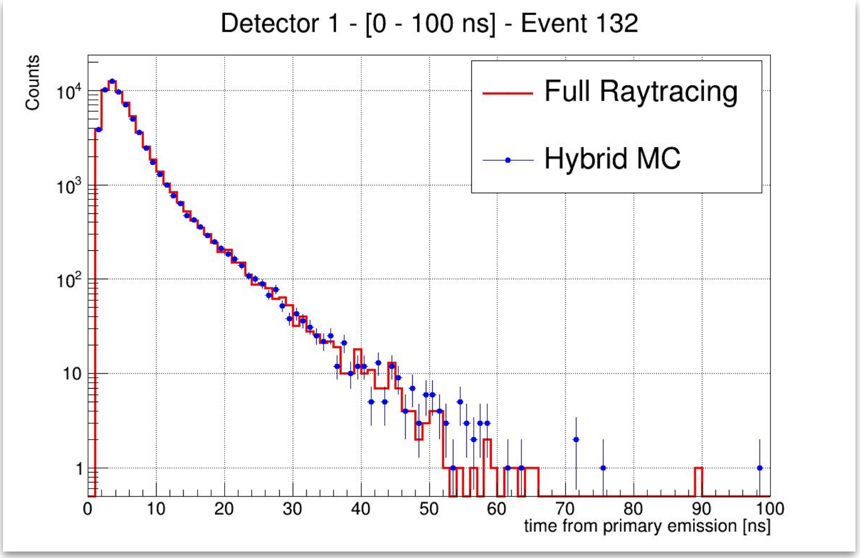




Very good agreement both in number of photons extracted and in time profile

Validation: SpaCal Pb-Polystyrene





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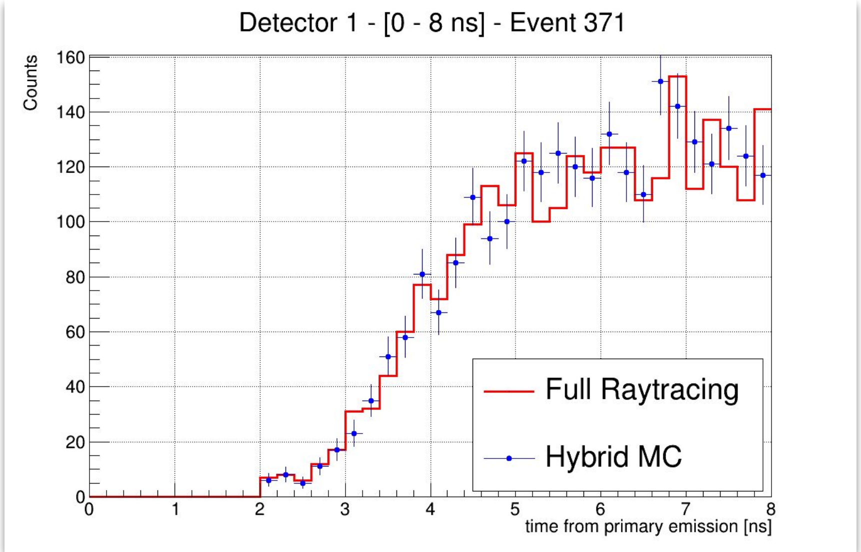

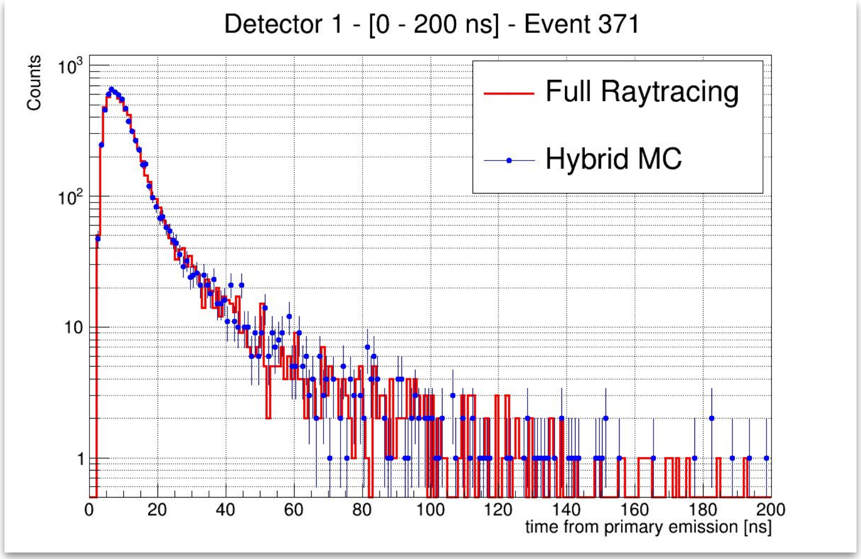

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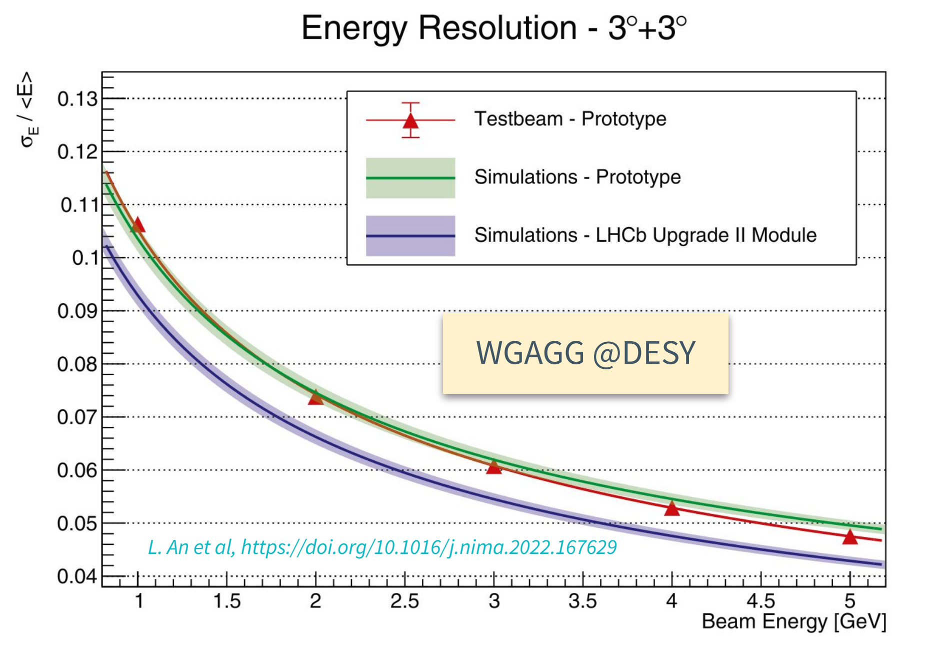
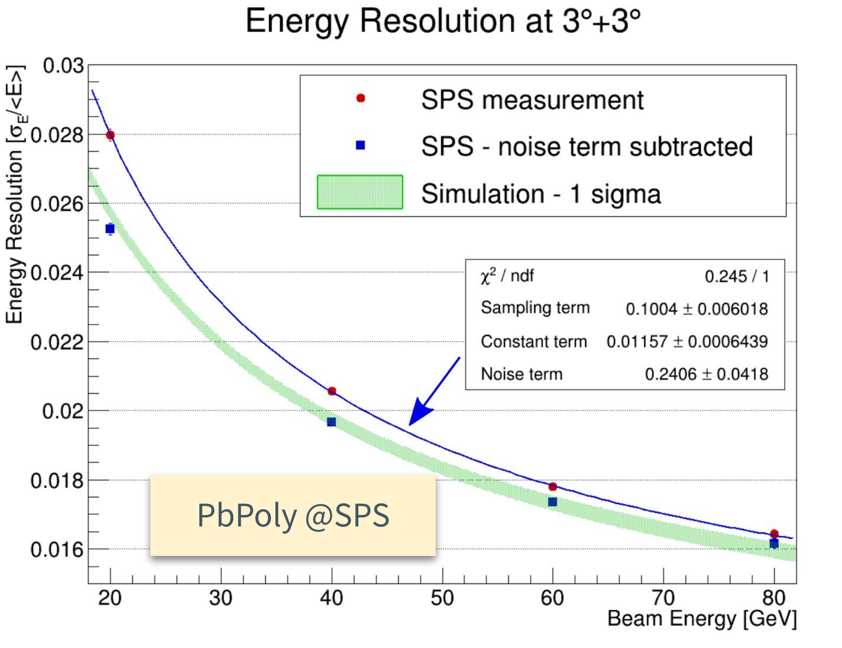
Comparison to experimental data

Comparison with test beam data: SpaCal

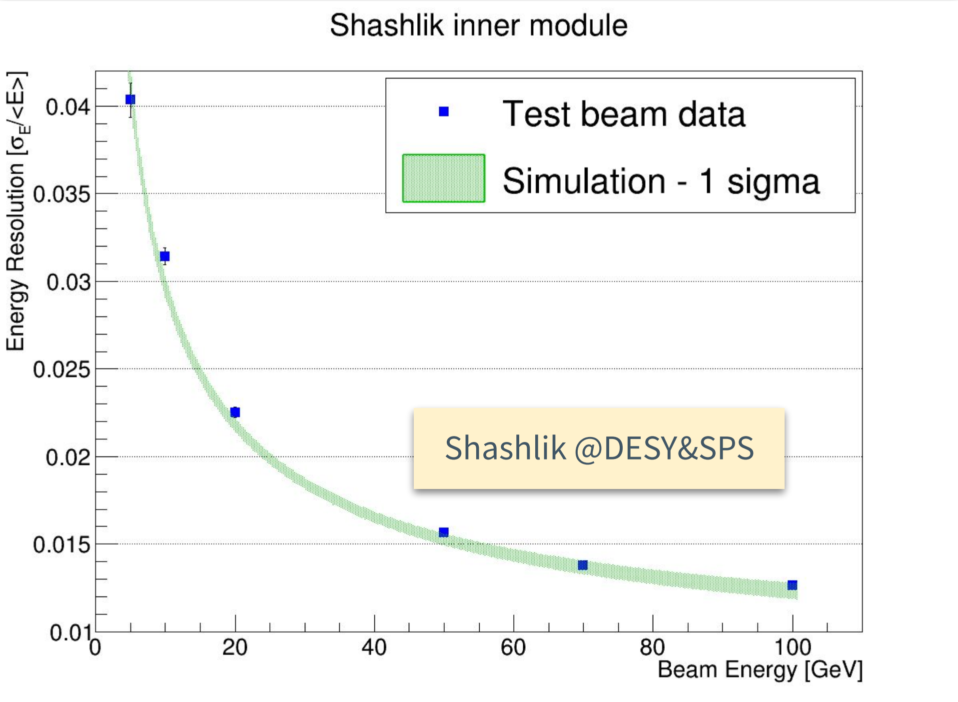




The HybridMC framework **reproduces well** the test beam measurements

For more info on test beam setups and module configurations see presentations by
E. Picatoste "Scintillating sampling ECAL technology for the LHCb PicoCal"

Comparison with test beam data: SHASHLIK



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Full ECAL simulations

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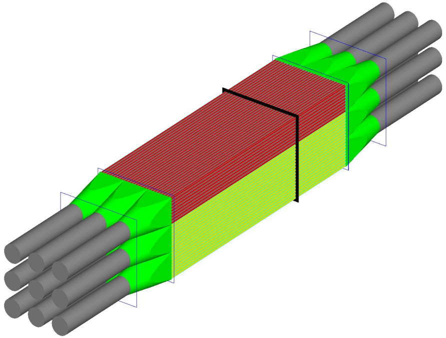
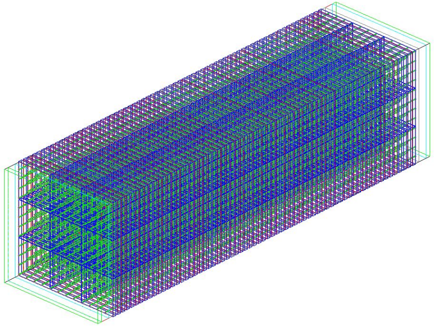
Full PicoCal simulations

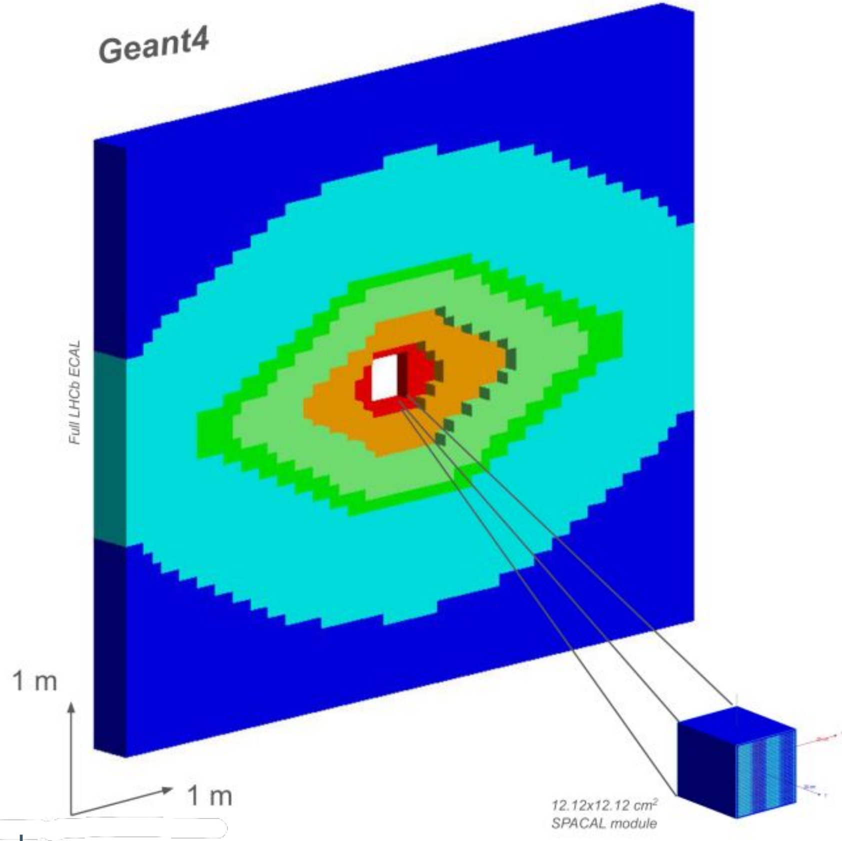
SpaCal



Shashlik



Full ECAL



- Full PicoCal configurations **combining single module** descriptions
  - **3312** modules
  - **Tilting** of modules in central region included
  - **Input particle flux** from LHCb simulation upstream of PicoCal

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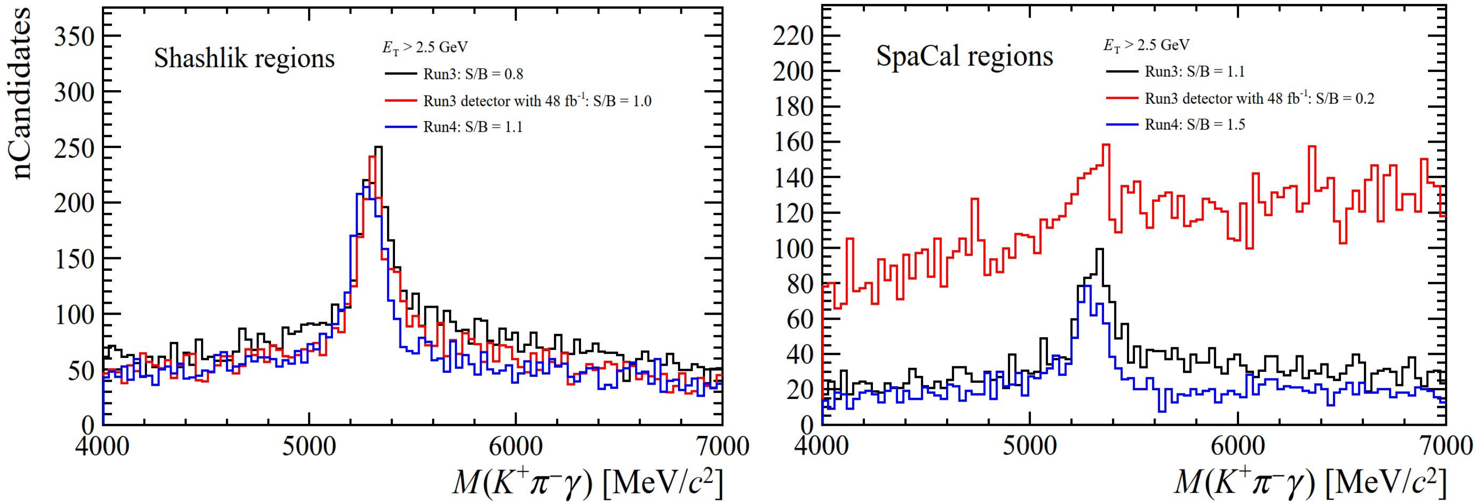
Sample study of physics performance: $B^0 \rightarrow K^{*0}\gamma$

The HybridMC framework actively used by the collaboration to study the impact of upgrade choices on physics performance



From LHCb TDR 24
https://cds.cern.ch/record/2866493/files/LHCB-TDR-024.pdf

- **Shashlik** region: Run3 and Run4 performance compatible
- **SpaCal** region (35% of the photons from $B^0 \rightarrow K^{*0}\gamma$)
  - Improvements due to smaller cell size in Run4 (LS3 enhancement)
  - Without LS3 enhancement, combinatorial background expected to strongly increase in Run4 because of radiation damage

Conclusions

- Fast detailed MC simulation framework developed for PicoCal Run 4-5: HybridMC
  - Speedup **between 2 and 3 orders of magnitude**: allows to perform detailed simulations in reasonable time
  - Useful for both prototype developments and full PicoCal physics benchmark studies
- Output of HybridMC in **agreement with full ray-tracing** simulations
  - Detailed simulations of full PicoCal configuration computationally affordable
- Excellent **agreement with experimental data** obtained in test beam campaigns
  - Useful to predict performance of proposed solutions of future PicoCal configuration with good level of confidence
- Integration into the **LHCb simulation framework** ongoing

Thank you for your attention!

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