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

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Current LHCb ECAL configuration

- Large **SHASLIK** 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 \(\pi^0\), e\(^-\) and γ identification in the few GeV to 100 GeV region at \(2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}\)

- Radiation hard up to **40 kGy**

- Energy resolution: \(\sigma(E)/E \approx 10%/\sqrt{E} \pm 1\%\)
Requirements for ECAL Upgrade II → PicoCal

Keep current performance while coping with harsher operating conditions

Sustain higher radiation dose (up to 1 MGy and $\leq 6 \times 10^{15}$ 1 MeV neq/cm$^2$ in the center)

New technologies required

Mitigate higher pile-up

Timing $O(10\text{ps})$, preferably directly in the modules

Increased granularity

Longitudinal segmentation
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

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New SpaCal modules with timing and finer granularity

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Radiation tolerance limit of the current Shashlik technology

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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 $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

- **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.
Optical calibration
Optical calibration concept

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

- 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
Optical calibration procedure

[Diagram showing SpaCal components: scintillator, mirror, absorber, light guide]

[Beam direction indicated]
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
Optical calibration procedure

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

Produce N photons

Non-perfect reflector

Example: two scintillators in a longitudinally split SpaCal module
Optical calibration procedure

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

- Produce N photons
- Record time of arrival of photons that exit the crystals
- Non-perfect reflector

Example: two scintillators in a longitudinally split SpaCal module

![Histograms showing photon distributions](image-url)
Optical calibration procedure

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

Example: two scintillators in a longitudinally split SpaCal module

**Photons exiting front face**

**Photons exiting back face**
Optical calibration procedure

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

- Produce N photons
- Record time of arrival of photons that exit the crystals
- Example: two scintillators in a longitudinally split SpaCal module

Histograms showing photons exiting front and back faces with mean and standard deviation values.
Optical calibration procedure

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

- Produce N photons
- Record time of arrival of photons that exit the crystals
- Use these histograms as PDFs to generate photon extraction probability and time of transport

Example: two scintillators in a longitudinally split SpaCal module

Photos exiting front face

Photos exiting back face

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MC production
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)
Hybrid propagation of optical photons

Reproduce the transport of optical photons in a faster way

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

The key features of optical transport are summarized into the PDFs, hence preserved in the final output
Pulse formation and analysis

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

**Map of energy deposition**

- List of photons on detectors

**List of Cherenkov photons produced**

- Geant4
- HybridMC code

**List of photons on detectors**

- List of photons on detectors
- Apply efficiencies (spatial, QE...)
- Build pulses from single photo-electron signals
- Digitization (e.g. DRS4)
- Analysis (e.g. CFD)

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

Typical pulse generated by signal formation
Gain in computation time
### Evaluation of CPU speedup

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

<table>
<thead>
<tr>
<th>Technology</th>
<th>Type</th>
<th>Full ray-tracing $[s/GeV]$ of $e^\pm/\gamma$</th>
<th>HybridMC $[s/GeV]$ of $e^\pm/\gamma$</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SpaCal</strong></td>
<td>W-GAGG</td>
<td>990 ± 20</td>
<td>9.4 ± 0.1</td>
<td>~100</td>
</tr>
<tr>
<td></td>
<td>Pb-Polystyrene</td>
<td>3600 ± 100</td>
<td>2.28 ± 0.04</td>
<td>~1500</td>
</tr>
<tr>
<td></td>
<td>W-Polystyrene</td>
<td>1070 ± 20</td>
<td>2.88 ± 0.04</td>
<td>~400</td>
</tr>
<tr>
<td><strong>Shashlik</strong></td>
<td>–</td>
<td>1800 ± 30</td>
<td>3.83 ± 0.09</td>
<td>~500</td>
</tr>
</tbody>
</table>

When performing full ECAL simulations, this translates to **~1.8 s/GeV** of incoming particles (about $\frac{1}{3}$ kinetic energy is in $e^\pm/\gamma$)

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

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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

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

Very good agreement both in number of photons extracted and in time profile.
Comparison to experimental data
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

The HybridMC framework reproduces well the test beam measurements

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Full ECAL simulations
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
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

- **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

From LHCb TDR 24
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!