Operation and performance of the LHCb calorimeter system

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CHEF conference, Oct. 2\textsuperscript{nd} 2017, Lyon
Overview

- The LHCb experiment
- Calorimeter design
- Aging effects & monitoring
- Calibration
- Reconstruction & performance
- Conclusion
The LHCb experiment

- Single-arm forward spectrometer at point 8, unique pseudo-rapidity coverage ($2 < \eta < 5$)
  - Precise study of beauty and charm sectors
  - Large bbar cross section in the forward region (catch 25% of bbar pairs)
- Important physics analyses in the LHCb core program are calorimeter-related: radiative decays ($K^*\gamma$), decays with neutral mesons ($B_d \rightarrow \pi\pi\pi^0$, $B_s \rightarrow J/\psi\eta(')$), electrons ($K^*\text{ee}$)
The LHCb detectors

- Tracking system
  vertex locator (Si strips), tracker (Si strips + straws) + warm dipole magnet (4 T.m)

- Particle Identification
  RICH1 & RICH2 with different PT coverage, muon stations (MWPC, GEMs)

- Calorimeters: scintillating plane (SPD), preshower (PS), ECAL, HCAL

Calorimeters & trigger

Purpose of the calorimeter system:

- Provide $E_T$ measurement to level-0 trigger → readout every 25 ns
- Provide EM nature of trigger candidates ($h, e, \gamma$) → SPD, PS, ECAL & HCAL

Choice of technology

- ECAL: good EM resolution ($10\%/\sqrt{E} + 1\%$), fast response (25 ns), rad. hardness of 250 krad/year in inner, small segmentation (energetic $\pi^0$ & minimal pile-up), cost effective.
- HCAL: moderate resolution ($80\%/\sqrt{E} + 10\%$), fast, 50 krad/year in inner, cost effective.
- Sampling technology using scintillators and fibres with readout by common PMT & FE electronics.
The LHCb calorimeters

- At 12 m from IP, active area of $3.5 \times 4 \text{ m}^2$
  - Retractable halves around beam pipe
- SPD-PS-ECAL, 6016 cells each
  - 3 zones: 4x4, 6x6 and 12x12 cm$^2$
- HCAL, 1488 cells
  - 2 zones: 13x13 & 26x26 cm$^2$
- LED-based monitoring system
  - Equip ECAL & HCAL
  - Active during data taking
SPD & PS

- 2 scintillating pad planes with 14 mm Pb absorber in between
  - 15 mm / 14 mm (2.5 $X_0$) / 15 mm
  - WLS fibres guide the light to 64-ch. MAPMT placed at the bottom of the module
- Light yield of 25 p.e. / MIP
- Dynamic range: 0.1-100 MIPs
- Readout: 1 & 10 bits for SPD & PS respectively

SPD/PS performance - LHCb-PUB-2000-031
ECAL

- Shashlik calorimeter of $25 \times X_0$ (1.2 $\lambda_{int}$) & 6016 channels, 100 tons
  - 66 layers with 2/4 mm of Pb/Sc, $R_M = 3.5$ cm
- Modules of 12x12 cm$^2$ with 3 different segmentation
- WLS fibres + PMT, fast shaping, 12-bit precision
  Front-end hosted on top of detector
- Uniform $E_T$ dynamics up to 11 GeV
  ($E < 250$-$150$-$60$ GeV in I/M/O respectively)

![Image](https://example.com/image.png)

\[ \sigma_E / E = (9.4 \pm 0.2) \% \sqrt{E} \]

LHCb-PUB-2007-149
HCAL

- ATLAS-like TileCal design
  - Sc/Fe with 6 rows, 52 modules, 500 tons
  - Longitudinal size of 1.2 m ($5.6 \lambda_{int}$)
- Used for trigger: ($\sigma_E/E = 70\% \sqrt{E} + 10\%$, standalone)
- Uniform $E_T$ dynamic up to 30 GeV
- Similar readout as ECAL + built-in $^{137}$Cs calibration system

*Combined ECAL+HCAL performance - LHCb-PUB-2000-036*

$\sigma_E/E$ VS $1/\sqrt{E}$ for $\pi^+$

$E_{HCAL}$ VS $E_{ECAL}$ for 50 GeV $\pi^+$
Online monitoring

Inner
4x4 cm²
Middle
6x6 cm²
Outer
12x12 cm²

Inner
13x13 cm²
Outer
26x26 cm²
Two main sources of aging
- Radiation damage of Sc tiles & WLS fibers (left plot for HCAL)
- PMT photo-cathode degradation from integrated DC current (right plot)

Effects monitored by LED flashes & compensated fill-by-fill with HV

Full recovery by periodic absolute calibrations of ECAL & HCAL
Aging effects & monitoring

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\[ \pi^0 \text{ calibration} \]

\[ \text{DAQ failure} \]

\[ \text{Annealing @ TS} \]

\[ \text{sum of LED/PIN, ECAL centre, } \sum_{\text{ref}} \text{ Stable Beams} \]

LHCb preliminary
Energy calibration of SPD & PRS

- SPD is a binary detector and is calibrated by threshold scans:
  - Track efficiency @ different thresholds for all cells;
  - HV set for 95% efficiency (performed 3 times: in 2010, 2015 & 2017).

- PS is calibrated in 2 steps:
  - Muon MIP for all cells, HV adjusted to align them;
  - One coefficient per calo section (I/M/O) to minimize the $\pi^0$ peak width (assumes calibrated ECAL).

\[ E_\gamma = \alpha E_{\text{ECAL}} + \beta E_{\text{PRS}} \]

![Energy calibration graph](chart.png)

LAL-11-38
2010 data

LHCb preliminary
So-called $\pi^0$-calibration uses photon candidates with small PS energy:

- combine $\gamma_1$ with all other photons $\gamma_i$ and build invariant mass;
- calculate coefficient to put $m(\gamma_1 \gamma_i)$ at the nominal $\pi^0$ mass (hypo: only the seed cell of $\gamma_1$ cluster is mis-calibrated);
- Iterate seven times until factors are stable;
- (Re-)reconstruct data with new coefficients;
- Iterate seven times again.

LHCb Internal

![Graphs](image.png)

- Energy calibration of ECAL

**LHCb Internal**

![Graphs](image.png)
Energy calibration of ECAL

- The $\pi^0$-calibration requires roughly 200 millions of minimum bias events
  - With current LHCb/LHC performance, this is achieved in 14 fills of 10 h
  - The iterative procedure takes less than 1h30
- In 2017, the goal is to run the $\pi^0$ calibration roughly every month
Two 10 mCi $^{137}$Cs sources:
- One for each detector half
- Propagate through all tile rows
- Current as a function of time
- Performance from current VS time
- 10% absolute (source activity)
- 4% cell-to-cell
- Calibrations performed at each TS
ECAL clusterisation around local maxima, then 3x3 areas around the seed are used. E of overlapping clusters shared according to expected shower profile.

Measured $p$ depends on cluster origin: $\gamma$, $e^-$, brem $\gamma$, high-energy $\pi^0$, converted $\gamma$. 

Calorimeter reconstruction
Calorimeter reconstruction

- Hypo-dependent energy reco. : \( E = \alpha E_{ECAL} + \beta E_{PRS} \)
  - \( \alpha \) factorizes into correction terms for leakage & dead zones

- Direction based on MC-based parametrization of shower profiles :
  - \([X,Y]\), E-weighted barycenter after S-shape corrections,
  - \([Z]\), log(E)-dependent longitudinal barycenter

- Resolution on MC : 1.5 mm, 3 mm & 7 mm in Inner, Middle & Outer section respectively.

Barycentre VS impact position in cell size units

LHCB-PUB-2003-091

\[
E_{\text{pr}} = 0 \quad \Rightarrow \quad \Delta = 16 \ln(E) + 144
\]

No Preshower hit

\[
E_{\text{pr}} > 0 \quad \Rightarrow \quad \Delta = 12 \ln(E) + 102
\]

Preshower hit
\( B^0 \rightarrow K^{*0} \gamma \)

\( \sigma = 88 \text{ MeV}/c^2 \)

\( D^* \rightarrow D[K\pi\pi^0]\pi \)

\( \sigma_{\text{core}} = 30 \text{ MeV}/c^2 \)

\( \sigma_{\text{core}} = 45 \text{ MeV}/c^2 \)

With resolved photons

With merged photons
Run1: resolution on $B_d[K^*\gamma]$ mass consistent with a 2% mis-calibration of the ECAL

No Run2 analysis with Calo-Objects published yet

Mass peaks from control modes are at the right place.
The calorimeters are running smoothly and performing well
  - Proven & robust technologies, $O(10^{-3})$ dead channels
  - Fulfill key role in the trigger
  - Important physics measurements in Run1

Significant aging, as expected, but under control thanks to frequent calibrations
  - Most of the calibrations have been automatized in Run2

Performance in Run2 look good

Important modifications of the calorimeter system (and whole LHCb) after LS2
  - More information in the talk from Iouri Guz on Tuesday: “Upgrade of the LHCb calorimeter system”