First years of running for the LHCb calorimeter system

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On behalf of the LHCb collaboration
The LHCb detector

- Precision measurements in the beauty and charm quark sectors
  - Study of CP violation, rare decays
  - discovery of new states, indirect search for new physics beyond the standard model
- LHCb is a single-arm spectrometer
  - 4% of the solid angle
  - 30% of the heavy quarks cross-section production at LHC
The LHCb detector
The LHCb detector

[The LHCb Detector at the LHC, JINST 3 (2008) S08005]
The calorimeter system

The calorimeter system: SPD, PS
The calorimeter system: ECAL, HCAL

ECAL
HCAL

Inner region
Outer region
Middle region
LHCb trigger

- **L0 trigger**
  - first level trigger of LHCb
  - 4μs latency at 40MHz
  - Apply selection cuts
    - $E_T(\gamma/e) > 2.7$ GeV
    - $E_T(h) > 3.6$ GeV
    - $P_T(\mu) > 1.4$ GeV

- **HLT : software trigger**
  - 300k tasks in parallel
  - More than 1500 nodes

- **Storage : 5kHz**

- **Combined efficiency**
  - 90% for muon channels
  - 30% for multi-hadronic final states
LHCb Integrated Luminosity

<table>
<thead>
<tr>
<th>Year</th>
<th>Energy (TeV)</th>
<th>Luminosity (fb⁻¹)</th>
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</thead>
<tbody>
<tr>
<td>2012</td>
<td>8</td>
<td>2.1</td>
</tr>
<tr>
<td>2011</td>
<td>7</td>
<td>1.1</td>
</tr>
<tr>
<td>2010</td>
<td>7</td>
<td>0.038</td>
</tr>
</tbody>
</table>

Semi-continuous (automatic) adjustment of offset of colliding beams allows luminosity to be *levelled*

Detectors all with >99% active channels

ε(operation)>94%

~98% are good data!

LHCb operation

4 times more collisions per crossing than in the design
Calorimeter system geometry

- 40MHz trigger on energetic $e, \pi^0, \gamma, h$
- Distance to IP $\sim 13m$
- Solid angle coverage $300 \times 250 \text{mrad}$
- Four sub-detectors:
  - SPD, PS, ECAL, HCAL
- Independently retractable halves
- Granularity:
  - SPD, PS, ECAL: 6016 cells with 3 sizes
    - 4x4, 6x6, 12x12 cm$^2$ (2 zones for HCAL)
Calorimeter system

- 40MHz trigger on energetic $e$, $\pi^0$, $\gamma$, $h$
- Distance to IP ~13m
- Solid angle coverage 300x250mrad
- Four sub-detectors: SPD, PRS, ECAL, HCAL
- Independently retractable halfes
- Granularity :
  - PRS, ECAL, HCAL : 6016 cells with 3 sizes
    - 4x4, 6x6, 12x12 cm$^2$
- Detection
  - Sandwich of scintillator/lead (iron for HCAL)
  - WLS are used to collect the light and to propagate it to photomultipliers
    - MAPMT for the SPD/PS
Scintillating Pad Detector - Preshower

- Scintillator pads
  - 2.5 $X^0$ lead
  - 15mm thick
  - Light collected by WLS
- Signal read by 64 channel MAPMT
- Average light yield
  - 20 pe/mip
- SPD
  - 1 bit
- PS
  - 10 bits
  - Dynamic range 0 - 100mip
**ECAL**

- Electromagnetic calorimeter
  - 66 layers
    - 2mm Pb, 4mm scintillator
    - Light collected by WLS
    - Moliere radius ~ 3.5cm
    - Longitudinal size
      - 25 $X_0$
      - 1.1 $\lambda_l$

- Average light yield:
  - 3000 pe/GeV

- Dynamic range ~12 GeV (Et)

- Energy resolution (test beam)
  \[
  \frac{\sigma(E)}{E} = 10\% \oplus 0.9\%
  \]
HCAL

- Hadronic calorimeter
  - 26x2 modules
  - Interleaved scintillator and iron plates
  - Parallel to the beam axis
  - Volume ratio
    - Fe:Sc = 5.58:1
  - Longitudinal size
    - 5.6 $\lambda_I$
  - Average light yield $\sim$ 105pe/GeV
  - Dynamic range $\sim$15 / 30 GeV
  - Energy resolution (test beam)
    \[
    \frac{\sigma(E)}{E} = \frac{(69 \pm 5)\%}{\sqrt{E}} \oplus (0 \pm 2)\%
    \]
Calorimeter particle identification

- PS / SPD for L0 electron/photon trigger
  - Electron/photon separation from SPD
  - Photon/mip separation PS
  - Charge multiplicity given by the SPD

<table>
<thead>
<tr>
<th>SPD</th>
<th>PS</th>
<th>ECAL</th>
<th>HCAL</th>
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<td>1</td>
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- ECAL
  - Et of electrons, photons, $\pi^0$ for L0 trigger
  - Offline reconstruction of $\pi^0$ and photons
  - Particle identification

- HCAL
  - Et of hadrons for L0, $\Sigma$Et for L0 trigger
    (~ 500 MHz out of the 1MHz bandwidth of the L0)
Calibration : SPD

- SPD (LHCb-PUB-2011-24)
  - Threshold set at 0.5 mip
  - Binary detector
    - No straight mip calibration
    - Tracks are extrapolated to the SPD
    - Collect data at different thresholds
      - Get mip efficiency by comparing with theoretical value

\[ \epsilon = \text{Landau} \times \text{Poisson} \]

Energy loss  Fluctuations of the npe at the photocathode

Precision on the mip position better than 5%

~95% efficient for MIPs

SPD efficiency as a function of threshold

\[ \epsilon = \frac{\# \text{of SPD hits}}{\# \text{tracks} \rightarrow \text{SPD}} \]
Preshower

- Mip signal set at ~10 ADC counts (~1mip)
  - Use extrapolation of the tracks to the PS
  - Mip signal is fitted (Landau ⊗ Gauss for statistical resolution) and fixed to a given number of photoelectrons
    - 5% precision level

\[
\begin{align*}
\mu &: 10.87 \pm 0.03 \\
\sigma &: 0.83 \pm 0.02 \\
\mu &: 10.41 \pm 0.03 \\
\sigma &: 0.90 \pm 0.02 \\
\mu &: 10.87 \pm 0.03 \\
\sigma &: 0.83 \pm 0.02 
\end{align*}
\]
Calibration : ECAL

- Fine calibration using reconstructed $\pi^0$
  - Iterative procedure based on the $\pi^0$ mass fit
  - Find the calibration coeff that moves the $\pi^0$ mass close to the theoretical value
    - $\lambda = m_{th}/m_{rec}$ → one coefficient per cell (more than 6000 cells)
- $\sim$1% precision reached
  - 100 million events needed (200pb$^{-1}$, 1 month)

![Graph showing $\pi^0$ mass vs. $N_{iter}$](image1)

![Graph showing $\pi^0$ mass distribution](image2)

- $\pi^0$ selection cuts:
  - No SPD hit
  - Pt($\gamma$)>300 MeV
  - E(PS)<10 MeV
  - pT ($\pi^0$)>800 MeV

Initial calibration value
Final calibration value
Calibration : ECAL

- ECAL calibration with electrons
  - Comparison of the electron momentum from the tracking with its energy measured in the ECAL and PS (electrons from conversions selected with RICH PID)
  - Also used to monitor the ageing and applying trend corrections every 40pb⁻¹
Calibration: HCAL

- **Cs$^{137}$ source**
  - 1 source per half (10mCi)
  - Driven by an hydraulic system
  - Each source travels at 20-40cm/s through 26 modules
  - Dedicated integrators measure the anode current every 5ms
    - Absolute normalisation ~10%
    - Cell to cell calibration ~4%
    - Done during technical stops

- **LED system**
  - Control HCAL response
  - During data taking
Detector ageing

- Combination of several effects
  - Scintillator ageing due to radiations (~0.25Mrad/y)
    - Plastic tiles are less transparents
    - Proportional to the particle flux
  - PMT ageing as a function of the integrated current
    - Depends on cell size and position

\[
\pi^0 \text{ mass as a function of time (luminosity)}
\]
Towards an automatic calibration

- Plan is to have a fully automatic calibration for run 2
  - Based on LED and RAW occupancy

  - Promising method: reach 1% precision
    - Test on 2012 data sample for PS, ECAL and HCAL
    - Adjust PMT gain for each fill
    - Stable trigger

\[
\text{OCC} = \frac{\text{Nentries}(\text{adc}_\text{reading} > \text{threshold})}{\text{Nentries}}
\]
Electron identification

- Likelihood difference for the signal (electron) and background hypothesis
  - Based on data distributions
    - Signal: electrons from conversions
    - Backgrounds: hadrons from $D^0 \rightarrow K\pi$

- Mis-ID rate ~5% for electron eff 90%

- Combined Calo Delta Log – Likelihood
  - + RICH information:
    - Mis_ID rate <2%
    - for electron eff >97%

From $B^+ \rightarrow J/\psi K$
**π⁰ reconstruction**

- Low energy pions: resolved as a photon pair – $σ \sim 8$ MeV
- Above 2.5 GeV (Pt), reconstructed as merged photons

\[ D^0 \rightarrow K^+ \pi^+ \pi^- (\text{resolved } \pi^0) \]
\[ D^0 \rightarrow K^- \pi^- \pi^0 \text{ with resolved } \pi^0 \quad (\int L \, dt = 610 \, \text{pb}^{-1}) \]

\[ \sigma = 17.4 \text{ MeV/c}^2 \]

\[ D^0 \rightarrow K^+ \pi^- \pi^0 = 32.2 \text{ MeV/c}^2 \]

Resolved pair of well separated photons

Photons that cannot be resolved as a pair of clusters within ECAL granularity
Radiative b → s γ FCNC decay, penguin diagram:
- Important candidate to identify new physics at LHC (BR measurement)
- Asymmetry give a direct constraint on the CP violation
  - BR predictions suffer from high uncertainties (hadronic form factor)
    \[ B^0 \rightarrow K^* \gamma = (4.3 \pm 1.4) \times 10^{-5} \]; \[ B_s \rightarrow \phi \gamma = (4.3 \pm 1.4) \times 10^{-5} \]
    \[ \rightarrow R(BR) = 1.23 \pm 0.06 \pm 0.04 \pm 0.10(fs/fd) \] [Th: 1.0±0.2]
- LHCb measures precisely ratio of BR and asymmetries
  - 1fb⁻¹ [NP B 867(2012)1]
    • \[ N(B^0 \rightarrow K^*\gamma) = 5279 \pm 93 \]; \[ N(B_s \rightarrow \phi\gamma) = 691 \pm 36 \] → \[ BR(B_s \rightarrow \phi\gamma) = (3.5 \pm 0.4) \times 10^{-5} \]
    • \[ A_{CP}(B^0 \rightarrow K^*\gamma) = (0.8 \pm 1.7 \pm 0.9)\% \] [Th: (-0.61±0.43)\%]
- World best measurement

**Invariant mass resolution: ~92 MeV/c²**
LHCb Upgrade

- The sub-detectors should be able to sustain $2 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$ at 14 TeV
- Full software trigger
  - The calorimeter electronics will send data to a large PC farm @ 40MHz
  - Reduction of the gain of the PMT to keep them alive (compensated in the FEB)
- LHCb upgrade PID TDR: CERN/LHCC 2013-022
Conclusion

- The LHCb calorimeters are running smoothly
  - \( O(10^{-3}) \) dead channels
- Good performances
  - Key role on the trigger:
    - Hadrons, electrons, photons channels
  - Important measurements
    - \( b \to s\gamma \) decay type, \( \gamma \) polarisation
    - \( B^0 \to K^*\gamma, B_s \to \phi\gamma \)
    - \( \chi_c \) states production at LHC (\( \chi_c \to J/\psi\gamma \))
- Significant ageing effects (PMT, scintillator) → expected
  - Automation of PMT HV adjustment procedure
- Calorimeter part of the LHCb upgrade program (2019)
Thank You!
**HCAL ageing effect**

- Degradation of a significant number of HCAL PMT
  - ~ 15% (only affect the HCAL)

- Three types of problems:
  - Significant rate effect
    - up to +5 … +30 %
  - Dark current appears
  - Degradation of the gain

- The effects are correlated

- No correlation with the occupancy
Readout of the (MA)PMT

- 192 ECAL FEB
- 54 HCAL FEB
- 12-bit ADC
- 32 channels
- 100 PS/SPD FEB
- 10-bit ADC
- 64 channels

Detector

VFE-boxes

FE-crates

ECAL

HCAL

PM

PM

clip

clip

Analog 10 m

same electronics

40 MHz

Trigger: Validation Card (TVB)

Readout: CROC

1 MHz

1 MHz

32 channels

40 MHz

Optical link Selection Crate (L0 decision)

40 MHz

Optical link

Control Board (CB)

Control and TFC distribution

SPD Multiplicity

FE card (LPC-CfD)

Pipeline

Marathon PS

SPD

VFE

PreShower

Optical fibres

MAPMT

Optical fibres

MAPMT

Analogue

LVDS- 2.5 Gb/s

Digital

02/06/2014

Tuesday July 1st, 2014

Frédéric Machefert - NDIP 2014 - Tours
ECAL ageing

- After calibration (preliminary, 2011 data):

- April, May, June, July, August
HCAL ageing

- 137Cs source
  - Allow to separate the light yield degradation from the PMT gain loss
  - Radiation damage of tiles and fibers

The hadronic shower maximum lays ~ within the tile row 0; the dose in the row 5 is much less. Radiation damage of scintillator tiles and fibers can therefore manifest itself as a decrease of relative response of upstream rows (0, 1) with respect to row 5.