First years of running for the LHCb Calorimeter System

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on behalf of the LHCb collaboration

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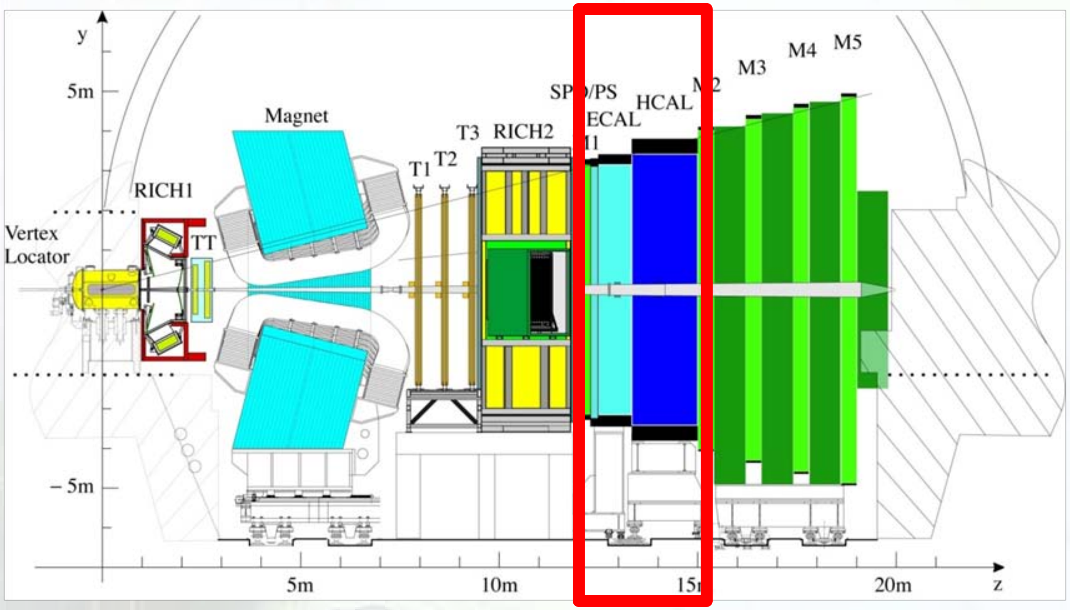
LHCb detector

- LHCb experiment is dedicated for the heavy-flavour sector studies with main focus on the searches of the physics beyond Standard Model in beauty sector
- forward single arm spectrometer with solid angle coverage $1.9 < \eta < 4.9$



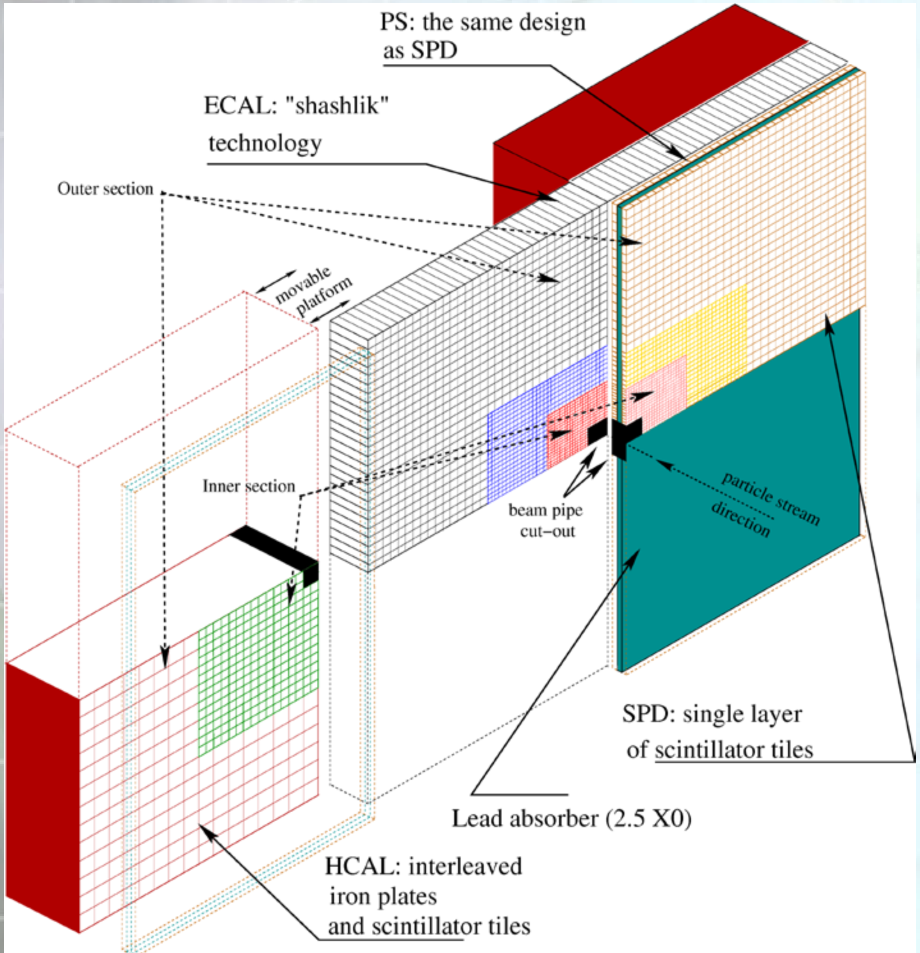
LHCb Calorimeters

LHCb Calorimeter System:

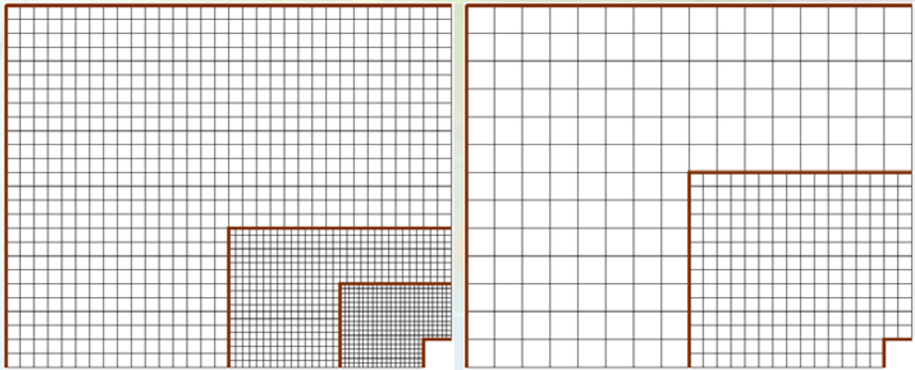
- distance to i.p. ~13 m
- solid angle coverage 300x250 mrad
- events rate 40 MHz (25 ns bunch spacing)
- radiation dose: up to 0.25 Mrad / year (TDR value)

LHCb Calorimeter System

The LHCb Calorimeter system:
- fast trigger (L0) on high-E_T $e/\gamma/\pi^0/h$
- reconstruction of photons and Particle Id



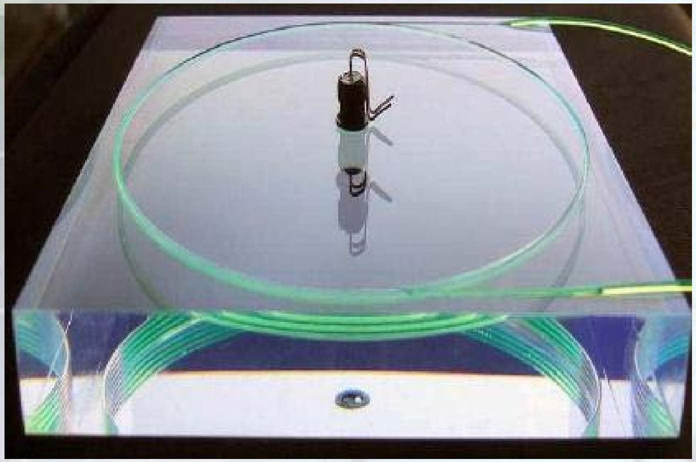
Four sub-detectors:
- Scintillator Pad Detector (SPD)
  - e/γ separation (L0)
- Preshower (PS)
  - rejection of charged π (L0)
- Electromagnetic calorimeter (ECAL)
  - providing L0 $e/\gamma/\pi^0$ candidates
  - precise reconstruction of photons
- Hadron calorimeter(HCAL)
  - selection of hadron candidates for L0



SPD/PS/ECAL:
- 6016 cells
- three sections of different granularity
- cell sizes ~4x4, 6x6 and 12x12 cm²

HCAL:
- 1488 cells
- two sections of different granularity
- cell sizes 13.1x13.1 and 26.2x26.2 cm²

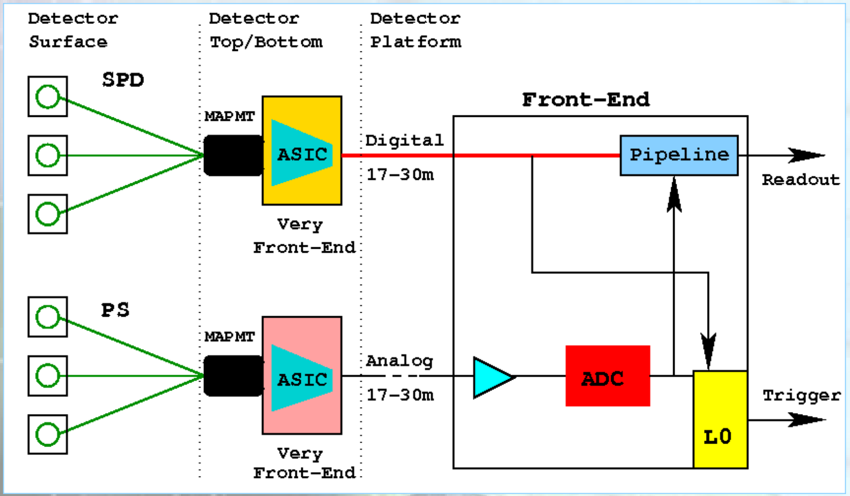
SPD and PS



Scintillator pad with WLS fiber

DETECTORS:

- two mono-layers of scintillator pads separated by lead absorber ($2.5X_0$)
- light collection: coiled WLS fibers
- light readout: 64-channel MAPMT
- dynamic range: 0.1÷100 MIPs
- typical light yield: ~25 p.e. per MIP

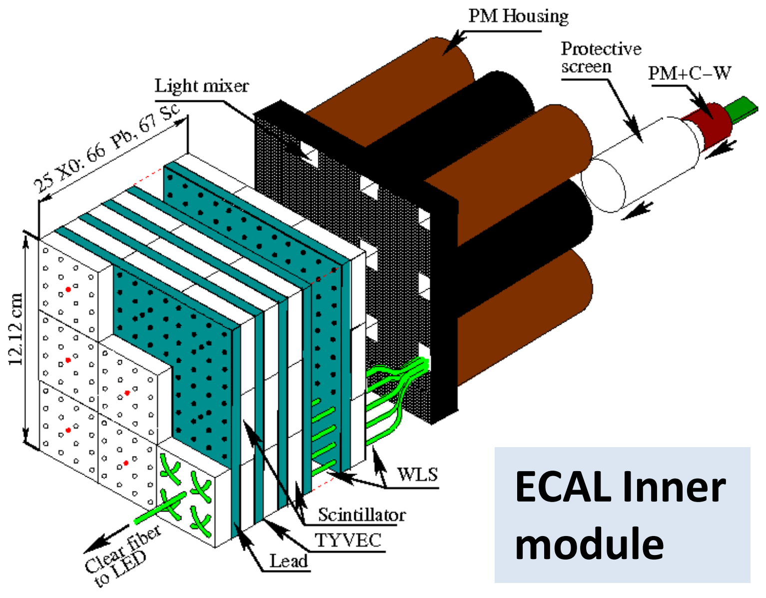


Readout of SPD/PS

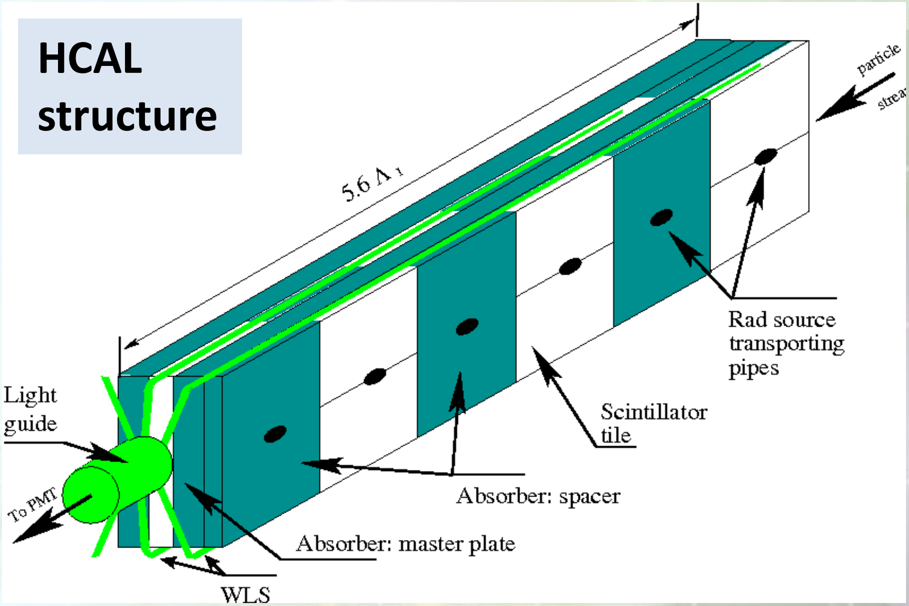
READOUT:

- Large fluctuation of signals → maximal integration time within 25 ns slot
- VFE board: two integrators per r/o channel alternating each 25 ns
- 100 Front-End Boards (FEBs):
  - SPD: 1 bit signal (yes/no, 0.5 MIP thr)
  - PS: 10-bit ADC 40 MHz
  - parameters for pedestal subtraction, corrections for pile-up and gains to uniformise response
  - digital pipe-line to store data until L0 decision
  - trigger block: production of data for L0 trigger

ECAL and HCAL



ECAL Inner module



HCAL structure

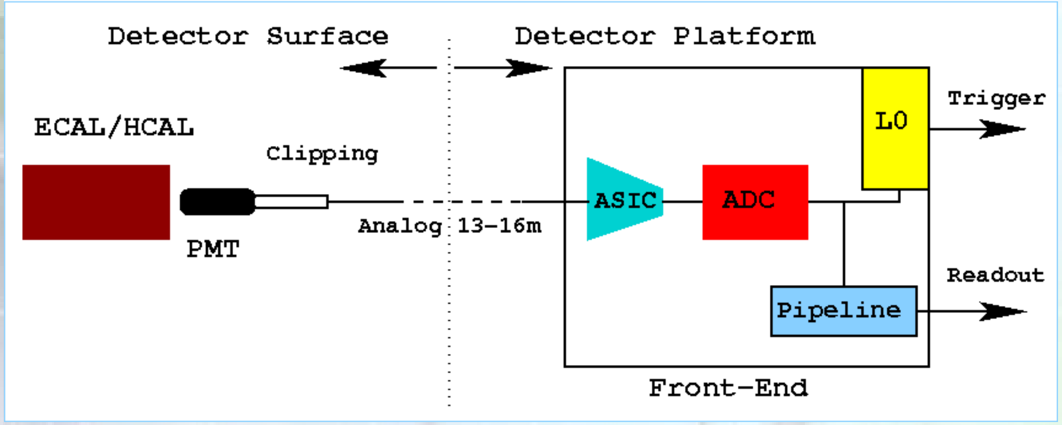
ECAL: modular, “shashlik” technology

- interleaving scintillator and lead absorber, volume ratio Pb:Sc 2:4
- light collection: WLS fibers
- Moliere radius: 3.5 cm
- longitudinal size: 25 X_0 / 1.1 λ_I
- light readout: photomultipliers
- average light yield:~3000 p.e./GeV
- energy resolution (beam tests):
  $\sigma E/E = (8. \div 10.)\%/\sqrt{E} \oplus 0.9\%$
- dynamic range: E(max, GeV)=7 + 10 /sin(θ)

HCAL: ATLAS TileCal design

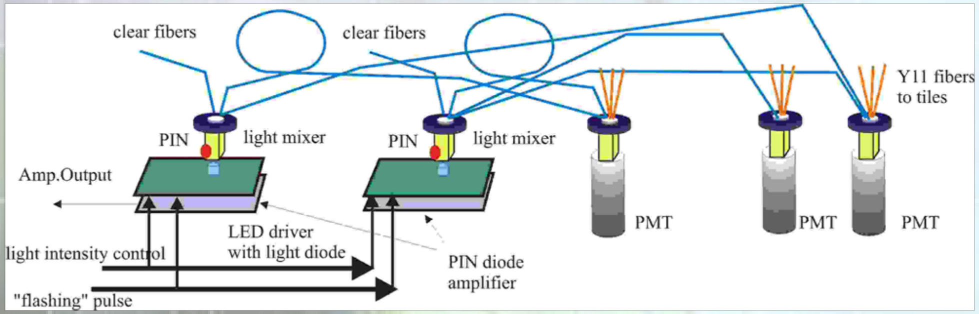
- interleaving Sc tiles and iron plates running parallel to the beam axis, volume ratio Fe:Sc = 5.58:1
- light collection: WLS fibers
- longitudinal size: 5.6 λ_I → mostly used as triggering device (~70% of L0 decisions)
- light readout: photomultipliers
- average light yield: 105 p.e./GeV
- energy resolution (beam tests):
  $\sigma E/E = (69\pm5)\%/\sqrt{E} \oplus (9\pm2)\%$
- dynamic range (Et): 15 GeV

ECAL/HCAL readout



- PMT signal shaping to eliminate small tail beyond 25 ns
- 192 Ecal + 54 Hcal FEBs
  - 12-bit ADC 40 MHz (80 pC)
  - pedestal subtraction
  - digital pipe-line to store data until L0 decision
  - trigger block: production of data for L0 trigger

ECAL/HCAL LED monitoring system

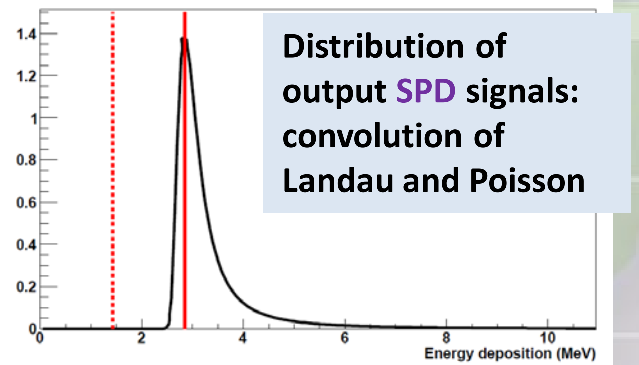


- Major goals:
  - fast monitoring of readout channels serviceability
  - control the stability of r/o chains
- ECAL: one LED illuminates a group of channels (9 in the Inner, 16 in the Middle/Outer sections)
- HCAL: 2 LEDs per each PMT
- Stability of LEDs themselves is traced by PIN photodiodes

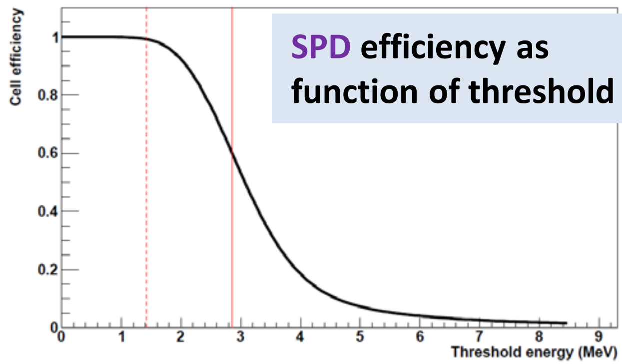
Calibration of SPD and PS

SPD (note LHCb-PUB-2011-024):

- SPD efficiency to detect charged particles:
  ε = # tracks with hit in SPD / # of tracks
- dependence of the efficiency ε on threshold value is fitted by known theoretical function allowing to extract gain correction factor for an individual cell
- achieved precision of correction factors: better than the resolution of DAC-chip used for threshold setting (3% for MIP)
- efficiency for calibrated cells: 95% in average, 3% r.m.s.



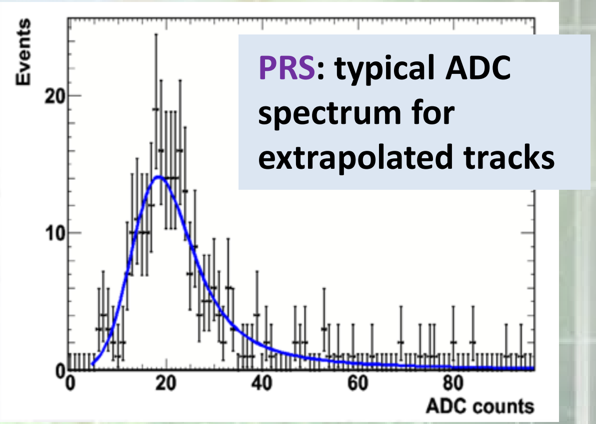
Distribution of output SPD signals: convolution of Landau and Poisson



SPD efficiency as function of threshold

PS:

- all reconstructed tracks are extrapolated to preshower
- calibration factor is extracted from the position of MIP peak
- 5% precision achieved

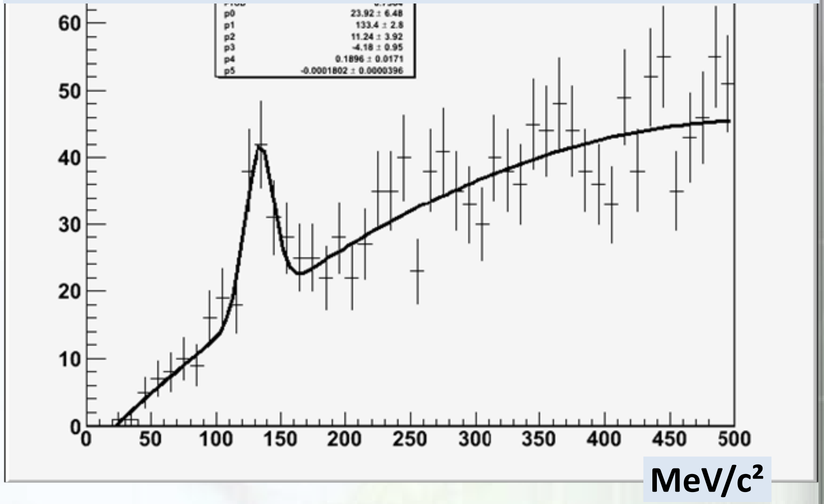


PRS: typical ADC spectrum for extrapolated tracks

Calibration of ECAL

- **Initial scale adjustment**:
  1. pre-calibration of PMT gains by photostatistics method (accuracy 8%)
  2. overall cell-to-cell intercalibration precision: 13% (I. + dispersion in modules’ light yield)

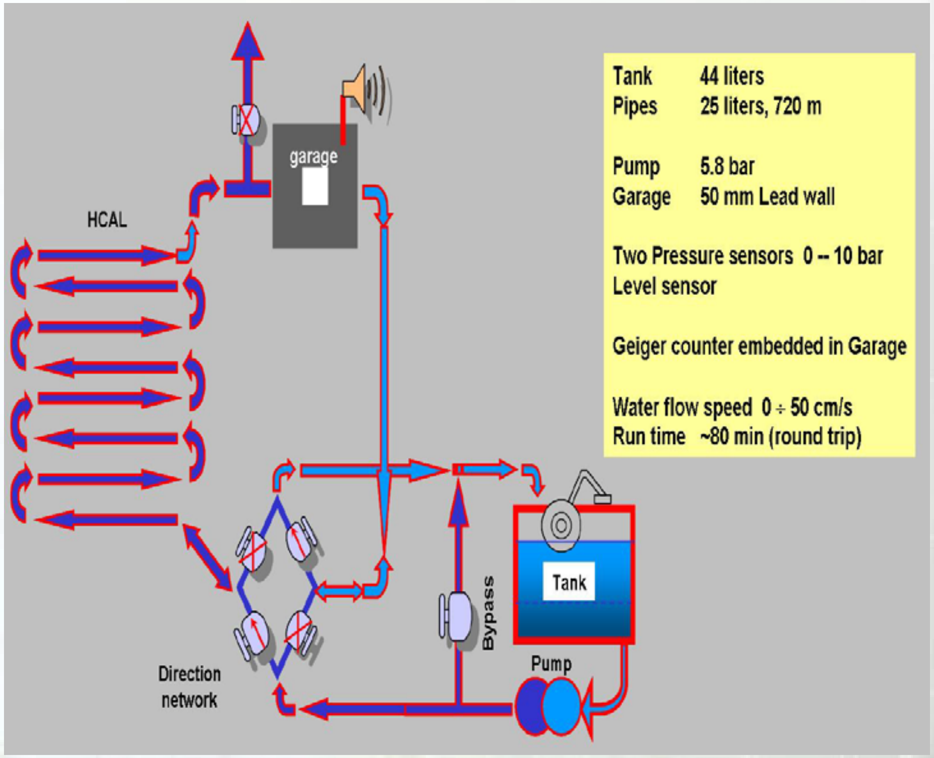
- Fast relative cell-to-cell intercalibration with **energy flow method** (4% level)
- **Fine calibration** is done with π^0’s


Invariant mass distribution for di-photon candidates, 2009

Dedicated talk follows (Dasha)

Calibration of HCAL

- two 10 mCi ^{137}Cs sources (one per each detector half) driven by hydraulic system (the same as in ATLAS TileCal)
- a source propagates consecutively through 26 modules passing each scintillator tile. PMT anode currents are measured every 5 ms with dedicated integrators installed at the back of each phototube
- relation factor between anode current and deposited energy is known from test beam:
  - Inner: C=41.07 (nA/mCi)/(pCl/GeV)
  - Outer: C=20.88 (nA/mCi)/(pCl/GeV)
- calibration is performed on the regular basis (every 1÷3 months).
- achieved accuracy is better than 5% - enough to fulfill design requirements



Tank 44 liters
Pipes 25 liters, 720 m

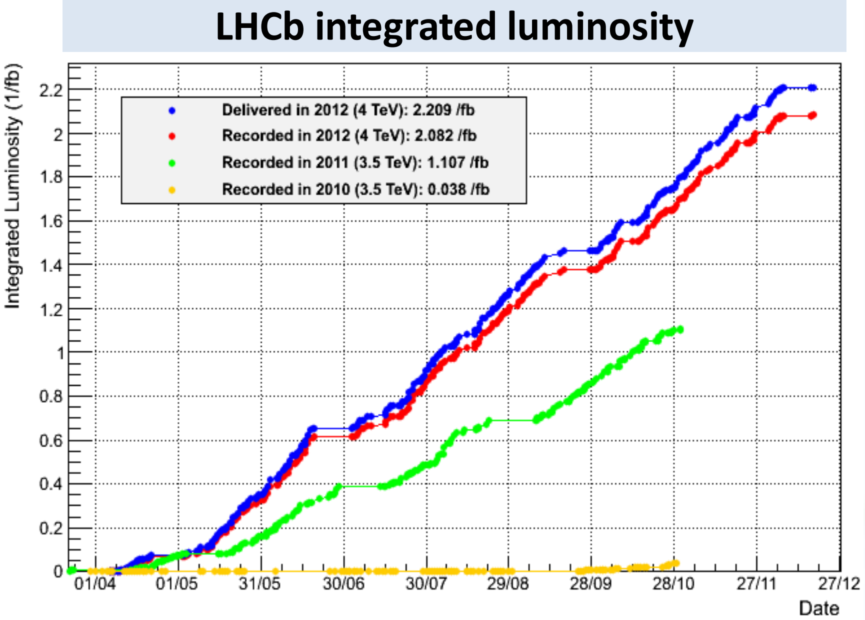
Pump 5.8 bar
Garage 50 mm Lead wall

Two Pressure sensors 0 -- 10 bar
Level sensor

Geiger counter embedded in Garage

Water flow speed 0 ÷ 50 cm/s
Run time ~80 min (round trip)

Operational conditions


LHCb integrated luminosity

LHCb should operate at lower luminosity L than LHC is capable to provide for keeping occupancies at reasonably low level (reconstruction, rad. damage, etc) → lumi leveling by controlling the bunch overlap.

- **TDR settings (@7TeV): L=2.x10^{32} cm $^{-2}$ s^{-1} with average number of interactions per event μ = 0.4**
- **2011 settings (@3.5 TeV, ~half of nominal bunches):**
  L=3.5x10^{32} cm^{-2} s^{-1} with μ<=1.5
- **2012 settings (@4 TeV, ~half of nominal bunches):**
  L=4.x10^{32} cm^{-2} s^{-1} with μ<=1.8

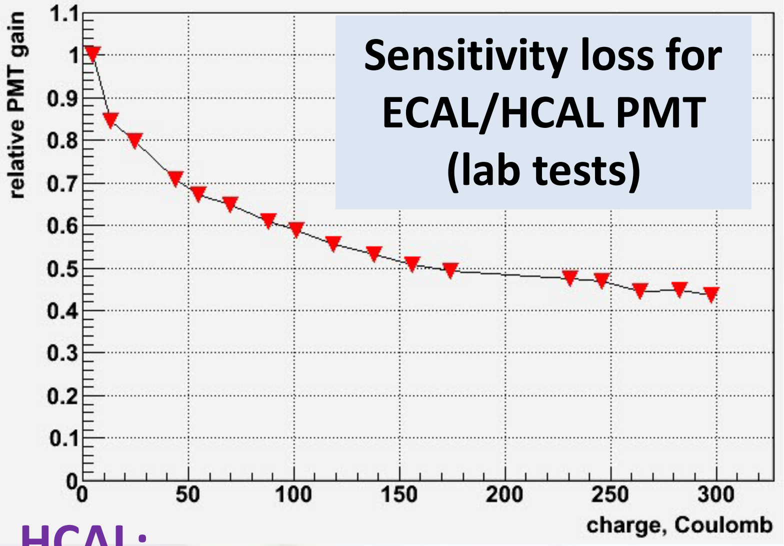
Lumi operational settings are well above design values

Degradation of calorimeters' response

Two major sources:

I. radiation damage of scintillator tiles and WLS fibers

II. PMT sensitivity loss



Sensitivity loss for ECAL/HCAL PMT (lab tests)

HCAL:

All cells are equipped with integrators

Net charge in 2011: up to 100 C

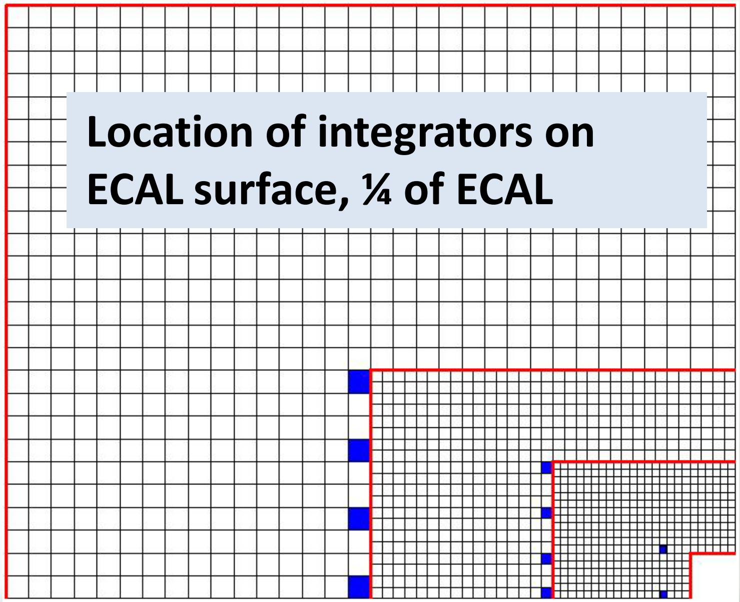
2012: PMT gains were reduced by a factor of two to decrease sensitivity losses and to keep PMT anode currents within recommended limits

ECAL:

40 detector cells are equipped with integrators

Maximal net charge:

20 C (2011) + 37 C (2012)

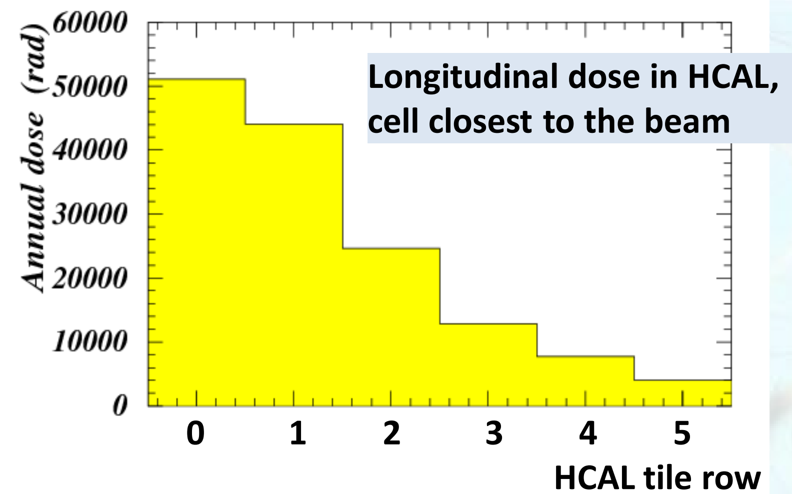


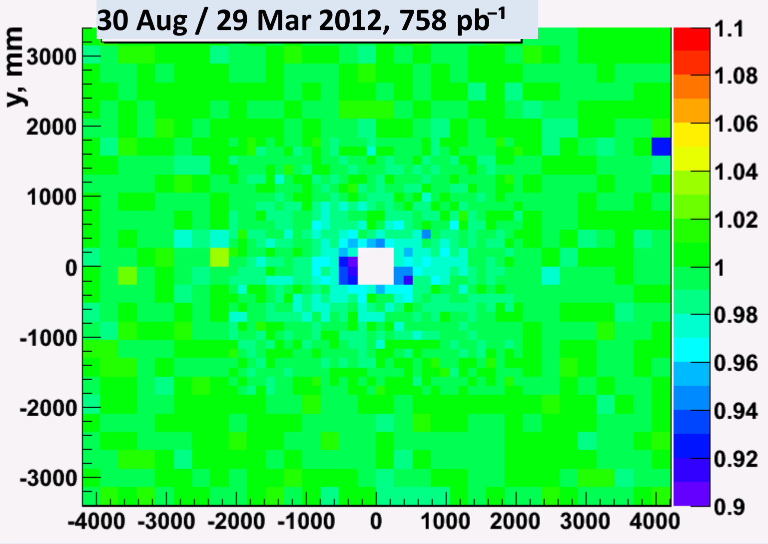
Location of integrators on ECAL surface, ¼ of ECAL

Light yield decrease in HCAL

Radiation damage of tiles and WLS fibers could be checked directly with radioactive source

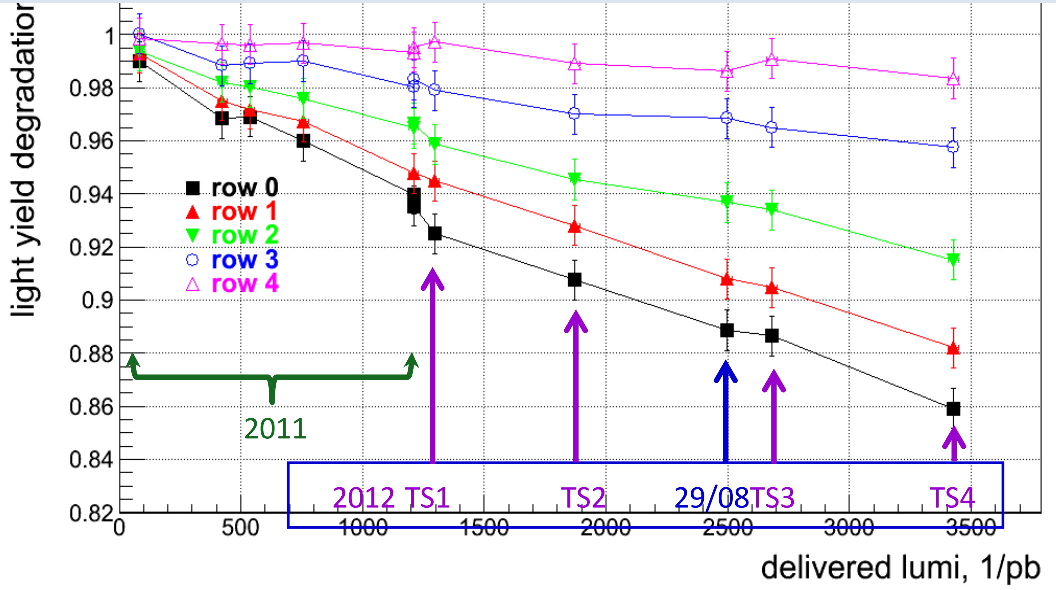
The most affected tiles are in the plane closest to the i.p. (row 0)



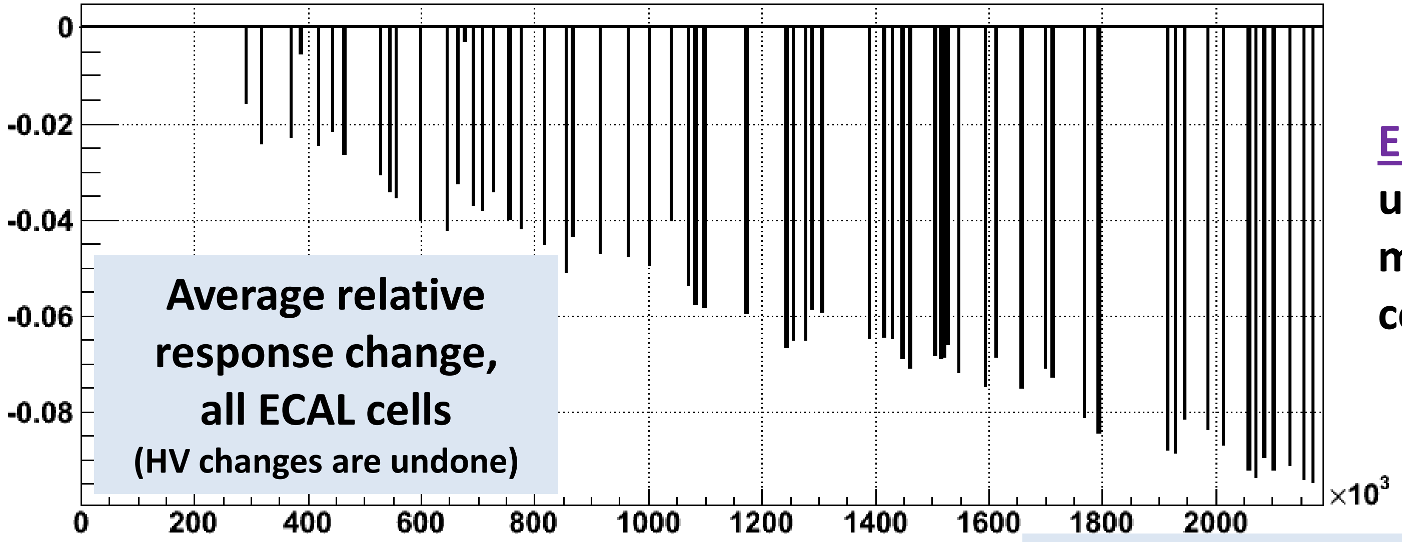


Row 0 / row 5 response change

Light yield degradation, average over 44 central cells



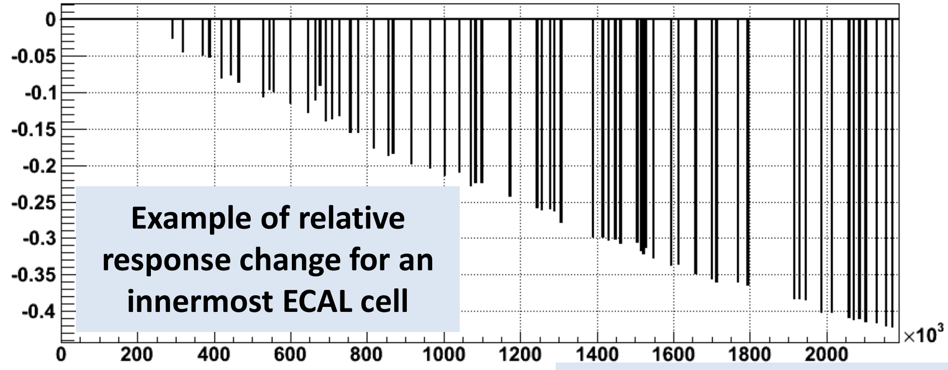
ECAL response change over 2012



Average relative response change, all ECAL cells
(HV changes are undone)

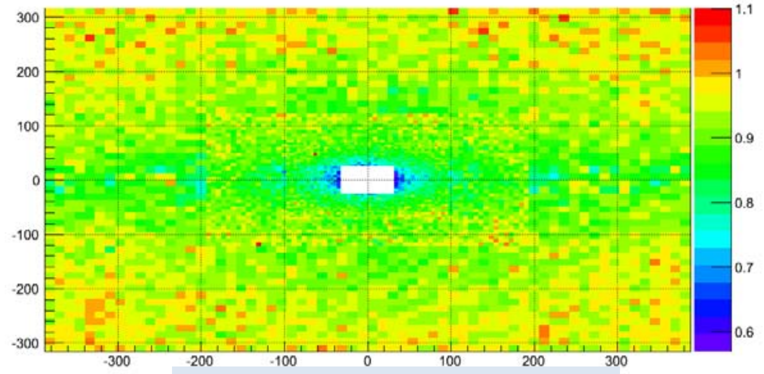
Delivered Lumi, nb⁻¹

ECAL:
up to 40% for the most irradiated cells



Example of relative response change for an innermost ECAL cell

Delivered Lumi, nb⁻¹



Dec / May ratio

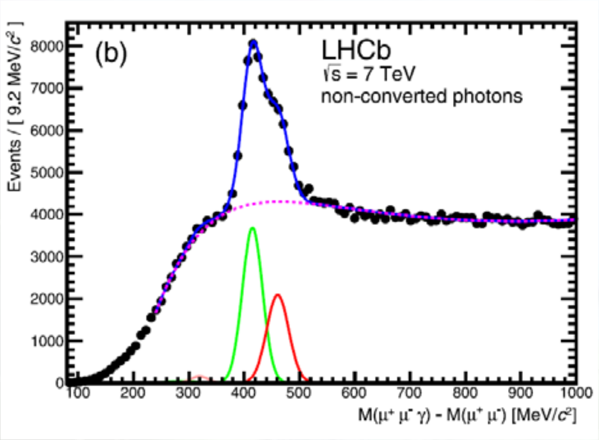
Compensation of aging effects

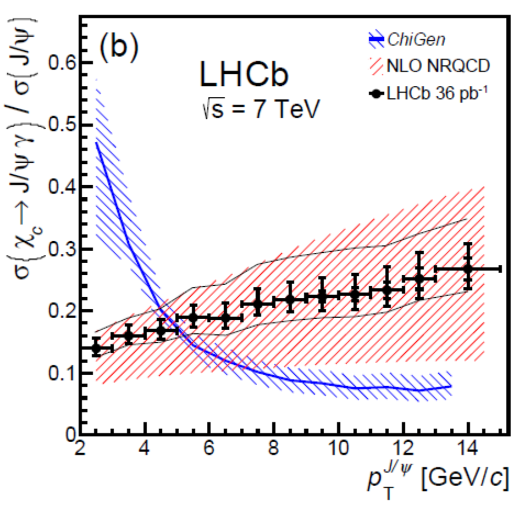
- **ECAL:**
  - regular π^0 calibration on monthly basis
  - in-between: starting from 2011, new set of calibration coefficients was produced each several days to compensate aging effects. Corrections were calculated using electron peak position on e/P distributions for the groups of cells (not enough statistics for individual calibration)
  - once per several months: adjustment of PMT high voltage settings
- **HCAL:**
  - starting from 2012: PMT operational high voltages were tuned on weekly basis using LED monitoring system
  - rad. source calibration each 1÷3 months to account for radiation damage of scintillator tiles and WLS fibers, which cannot be seen by LED system
- **In plans:**
  - fast online procedure producing set of relative correction factors for each long fill (the development is ongoing)

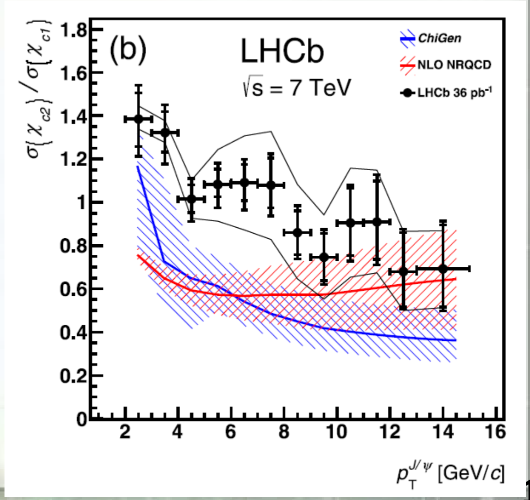
CALO in physics analysis: χ_c in 2010

Two complementary measurements, both in form of dependence on $p_T(J/\Psi)$ in full y-range $2 < y < 4.5$ and in $p_T(J/\Psi)$ range $2 < p_T(J/\Psi) < 15$ GeV/c, using 37 pb^{-1} (2010)

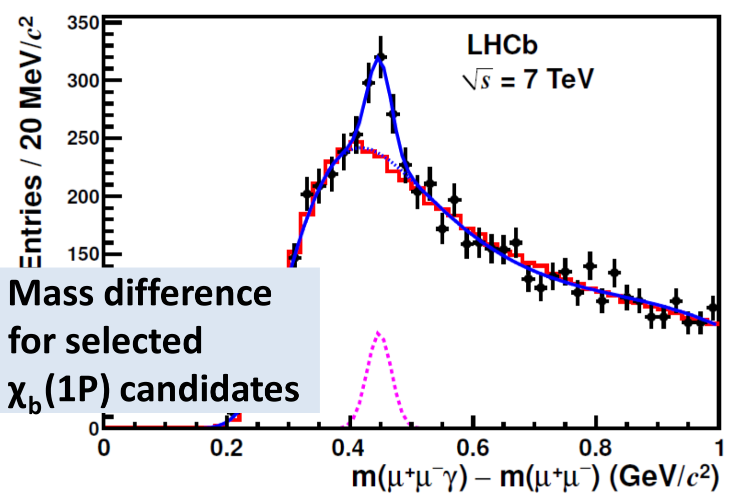
- Ratio of prompt production cross-sections $\sigma(\chi_c \rightarrow J/\Psi\gamma) / \sigma(J/\Psi)$, $\chi_c = \chi_{cJ}(1P)$, $J = 0,1,2$ [*Phys. Lett. B* 718 (2012) 431-440]
- Ratio of prompt production cross-sections $\sigma(\chi_{c2}) / \sigma(\chi_{c1})$ [*Phys. Lett. B* 714 (2012) 215-223]



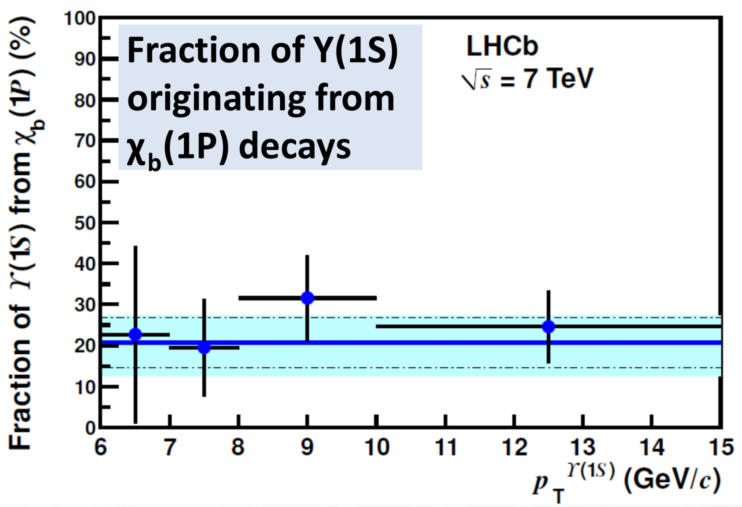




CALO in physics analysis: χ_b states



Mass difference for selected χ_b(1P) candidates



Fraction of Υ(1S) originating from χ_b(1P) decays

[JHEP 1211 (2012) 031]:

Fraction of Υ(1S) originating from χ_b(1P) decays:

$$(20.7 \pm 5.7^{stat} \pm 2.1^{+2.7}_{-5.4})\%$$

$6. < p_T^{\Upsilon(1S)} < 15.$ GeV/c, $2. < y^{\Upsilon(1S)} < 4.5$

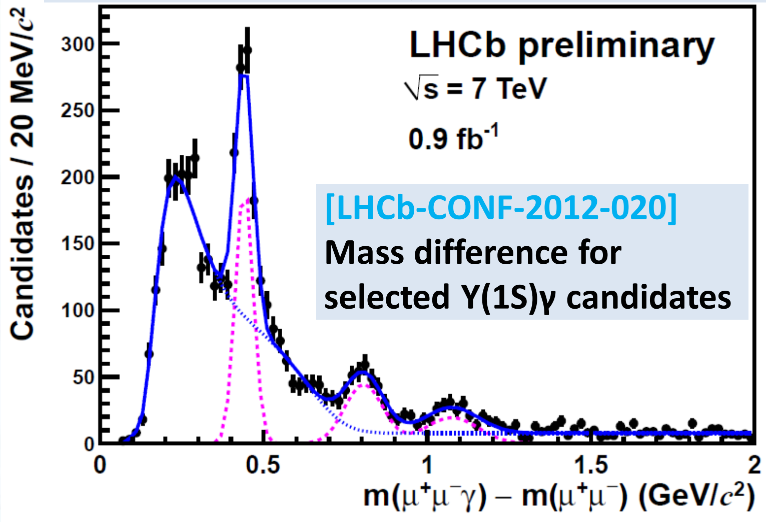
CDF measurement (√s = 1.8 TeV, $p\bar{p}$):

$$(27.1 \pm 6.9^{stat} \pm 4.4^{sys})\%$$

$p^{\Upsilon(1S)} > 8.$ GeV/c, $|\eta^{\Upsilon(1S)}| < 0.7$

[CDF: Phys. Rev. Lett. 84 (2000) 2094]

Evidence of the χ_b(3P) state at LHCb



[LHCb-CONF-2012-020]
Mass difference for selected Υ(1S)γ candidates

Summary

- a lot of experience during long period of data taking, which started at the end of 2009 and continued up to the spring of 2013
- calorimeters were operating smoothly over entire period of data taking
- the deterioration of response was compensated by PMT HV adjustment (ECAL/HCAL) and by calibration coefficients used in the reconstruction software
- neutral particles, reconstructed by CALO, are vital for such topics as radiative penguin decays, heavy quarkonium studies, exclusive B decay modes with photons in final state and many more
- other LHCb CALO presentations:
  - Calibration of ECAL (Dasha, today)
  - CALO Upgrade (Yuri, Wed)
  - CALO electronics upgrade (Eduardo, Wed)