CHEF2013
Calorimetry for High Energy Frontier

22 – 25 April 2013, Paris

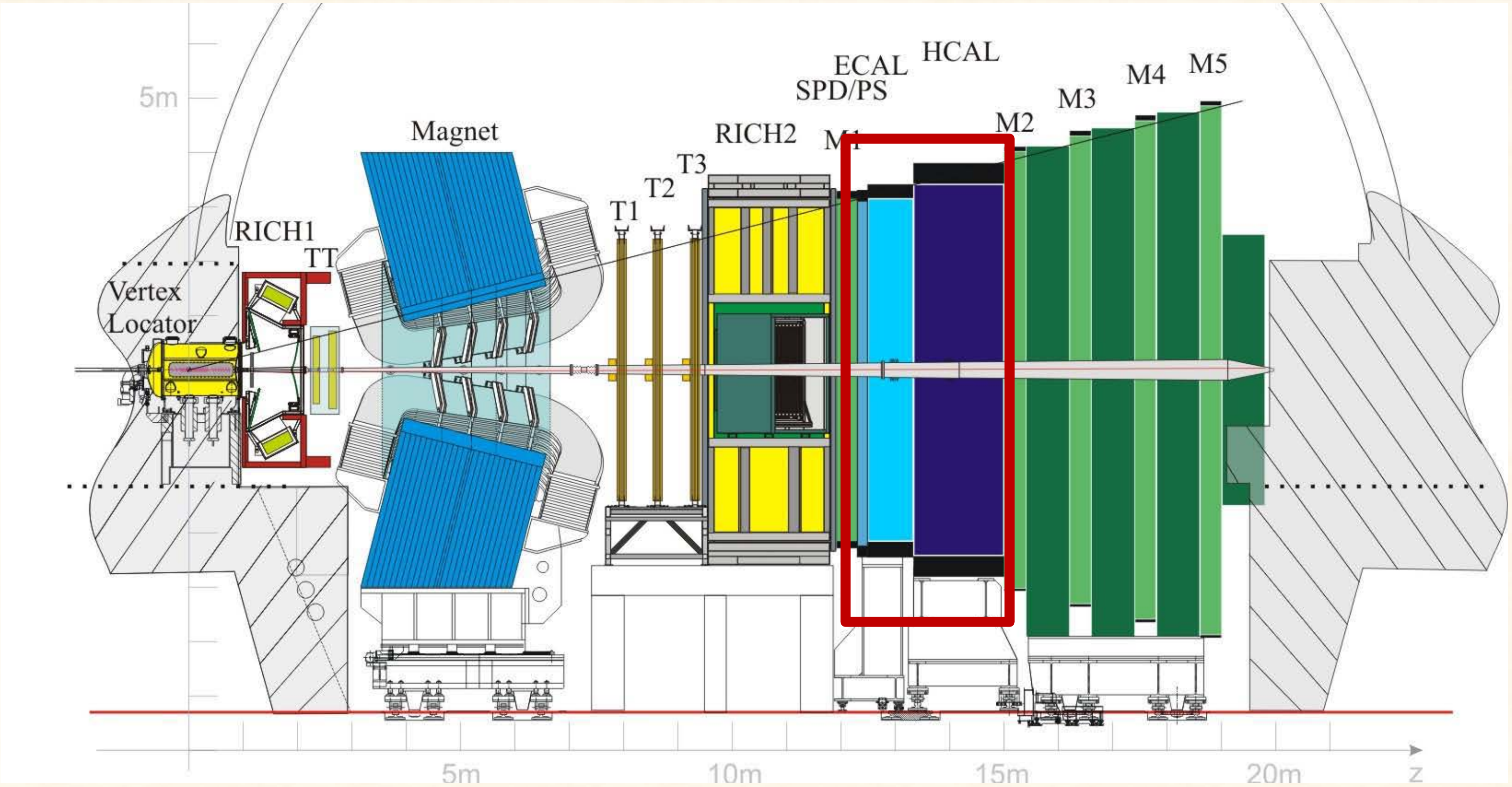
LHCb Calorimeter Upgrade

Yu. Guz (IHEP Protvino / CERN),
on behalf of the LHCb collaboration

Other LHCb talks at CHEF 2013:

- First years of running for the LHCb calorimeter system – Irina Machikhiliyan 22/04
- Calibration of the electromagnetic calorimeter of the LHCb experiment – Daria Savrina 22/04
- LHCb calorimeter upgrade electronics – Eduardo Picatoste Olloqui 24/04

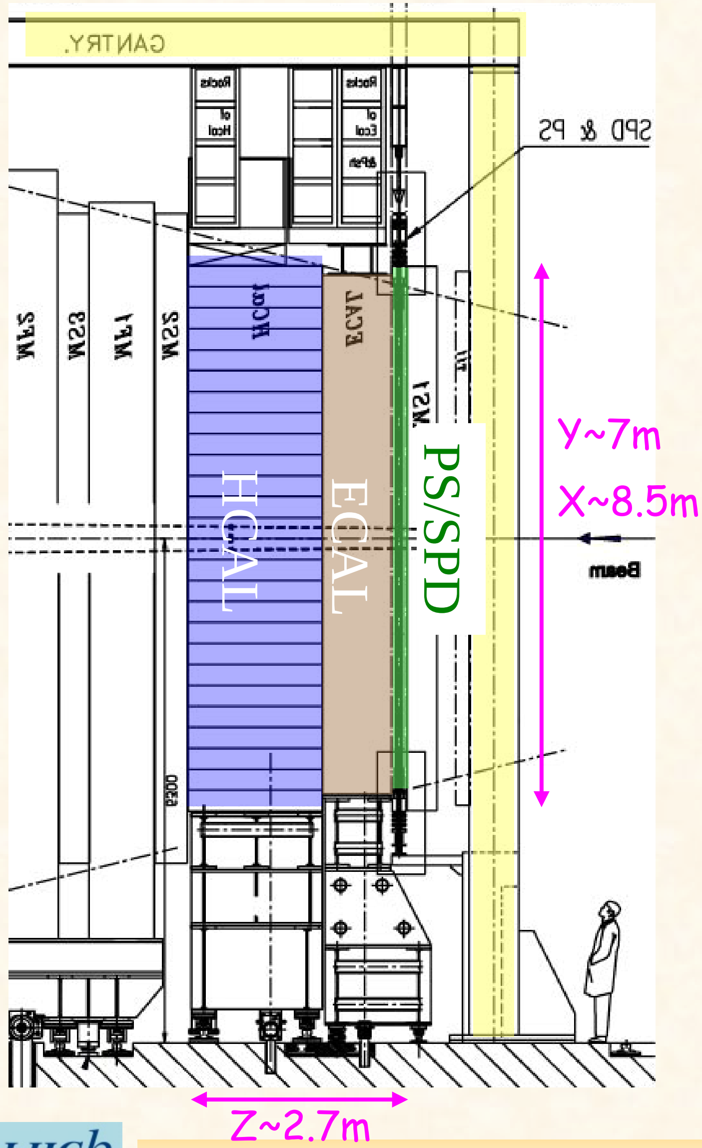
The LHCb detector



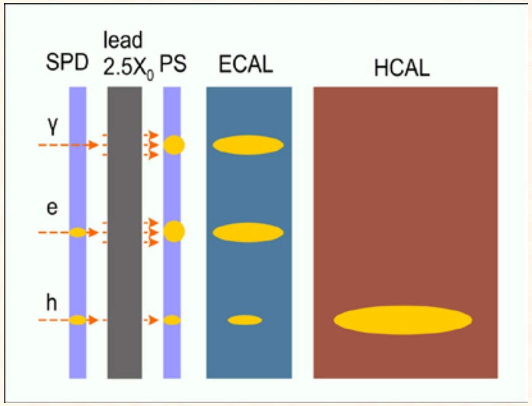
Main subdetectors:

- Vertex Locator (VeLo): a silicon strip detector surrounding the IP
- warm magnet, ~4 Tm;
- tracker stations (inner: silicon; outer: straw)
- two RICH detectors
- ***electromagnetic calorimeter with preshower***
- ***hadron calorimeter***
- muon identification system

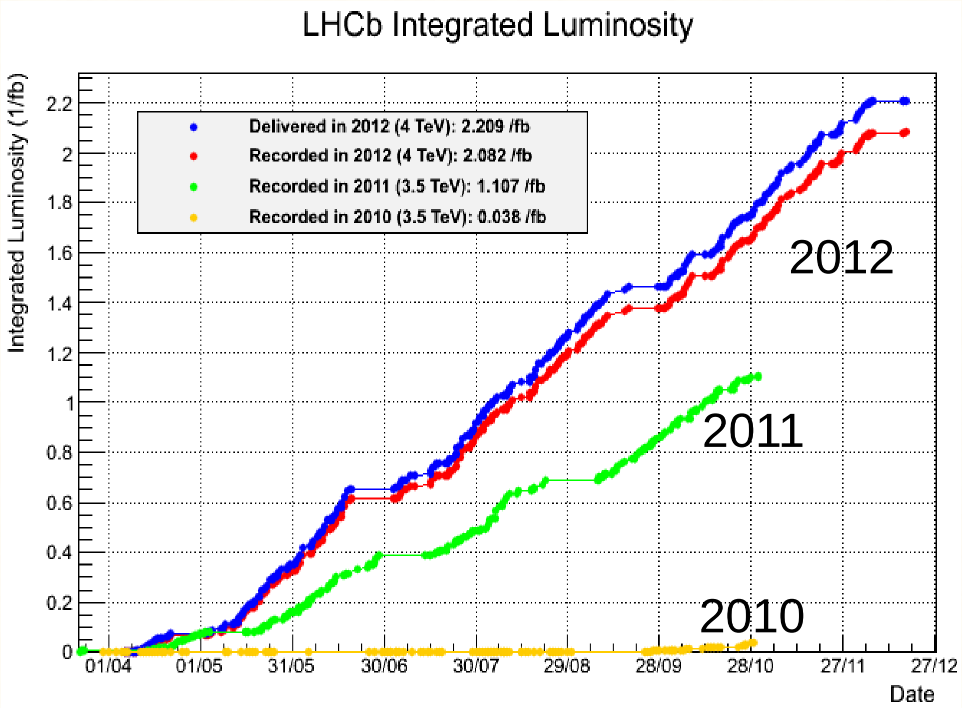
The LHCb Calorimetry System

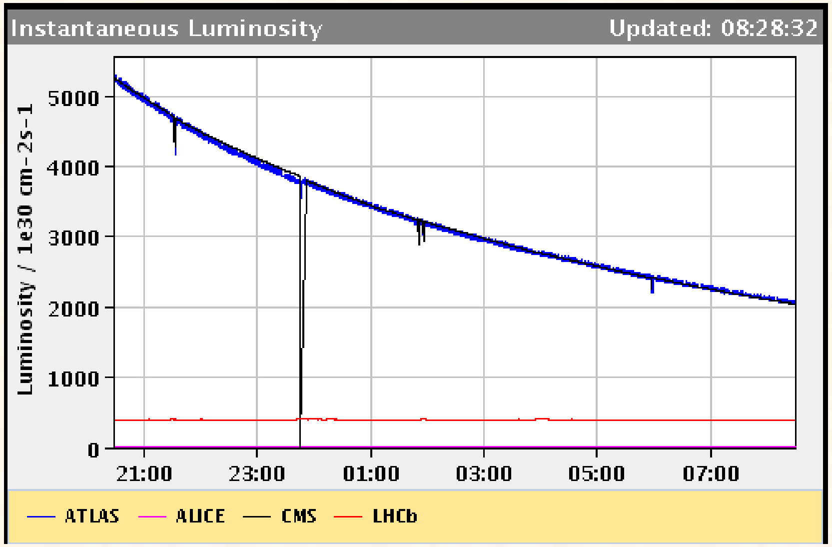


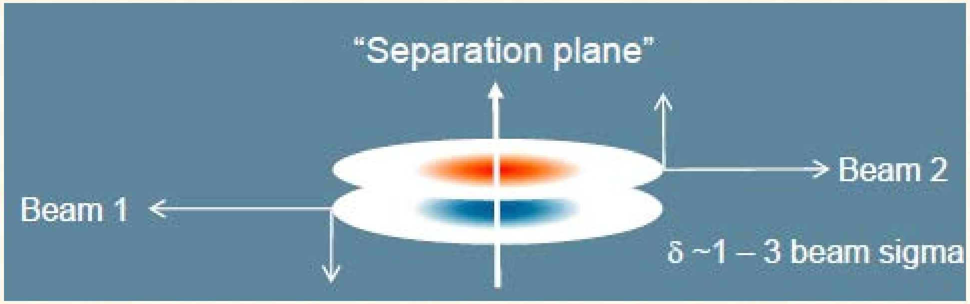
- solid angle coverage 300x250 mrad
- distance from IP: ~13 m
- four subdetectors: SPD,PS,ECAL,HCAL
- based on scint./WLS technique, light readout with PMT
  - ECAL: 25 X_0 Pb/scint. shashlik, 6016 cells, 3 types (4x4, 6x6, 12x12 cm^2)
  - SPD, PS, ECAL: 6016 cells each, match ECAL
  - HCAL: TileCal Fe/scint. technique, 1488 cells
- provides:
  - L0 trigger on high p_T $e^{\pm}$, π^0, γ, hadron
  - precise energy measurement of $e^{\pm}$ and γ
  - particle identification: $e^{\pm}$/γ/hadron; contributes to Muon ID (HCAL).
- *more details on present LHCb CALO system: talk of Irina Machikhiliyan, this conference*



The LHCb detector operation

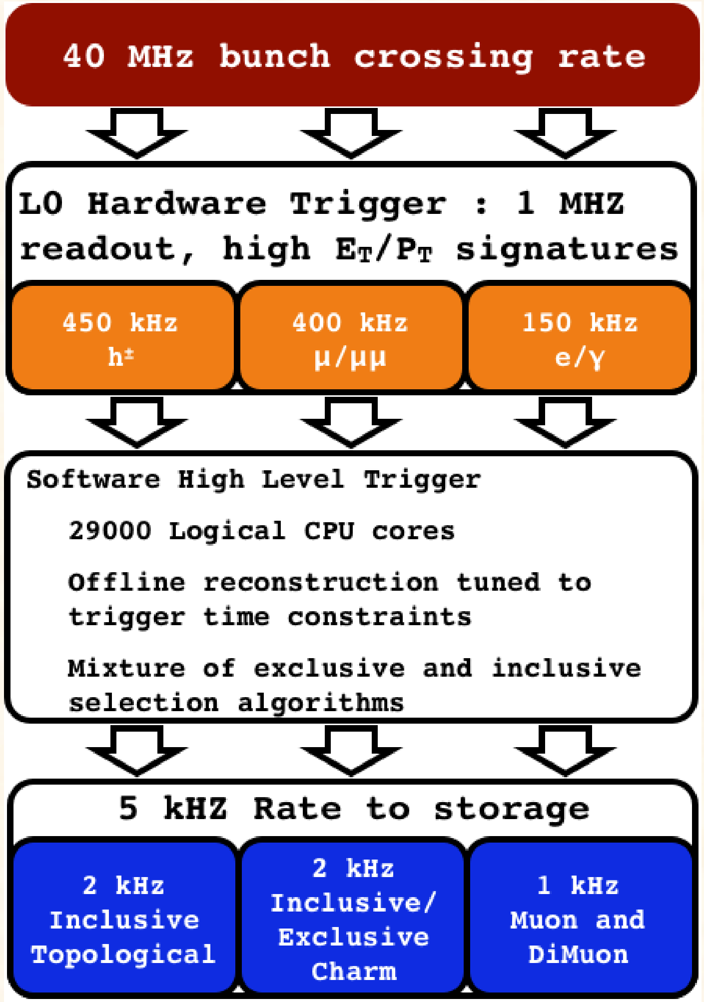






LHCb is running at a lower luminosity than ATLAS and CMS ($4 \cdot 10^{32}$ cm^{-2}s^{-1} in 2012) using luminosity leveling technique.

The LHCb trigger organization



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHZ readout, high E_T/P_T signatures

450 kHz $h^{\pm}$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHZ Rate to storage

2 kHz Inclusive Topological

2 kHz Inclusive/ Exclusive Charm

1 kHz Muon and DiMuon

➢Hardware Level-0 trigger

- SPD multiplicity ← CALORIMETRY
- search for a highest ET object:
  - E_T ($e^{\pm}/\gamma$) > 2.7 GeV ← CALORIMETRY
  - E_T (hadron) > 3.6 GeV ← CALORIMETRY
  - p_T (μ) > 1.4 GeV/c ← MUON ID system
- up to 1 MHz output

➢Software High Level Trigger (HLT)

- ~30000 processes in parallel on ~1500 farm nodes

➢Storage rate: 5 kHz

➢Efficiency (L0+HLT):

- ~90 % for di-muon channels
- ~30 % for multi-body hadronic final states – limitation from hadron trigger

LHCb Upgrade

LHCb upgrade

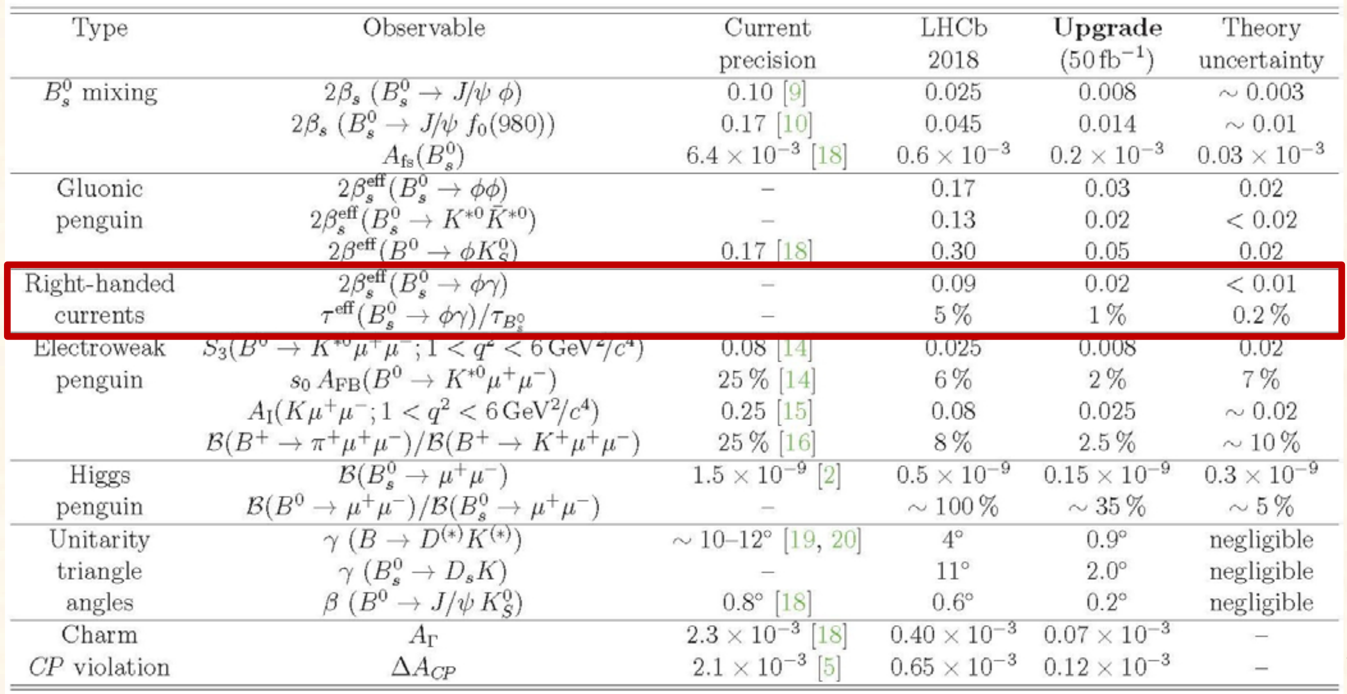
In 2015-2017, LHCb is expected to take 5-7 fb^{-1} of data @13 TeV.

There is strong physics case to continue the flavor physics programme.
Next step is to collect other >50 fb^{-1} → probe NP effects at % level.

This requires running at higher luminosities: $(1\text{-}2)\cdot 10^{33}$ @$\sqrt{s}$ = 14 TeV.

→ ***UPGRADE***

LHCb Upgrade LoI: CERN-LHCC-2011-001
LHCb Upgrade Framework TDR: CERN-LHCC-2012-007

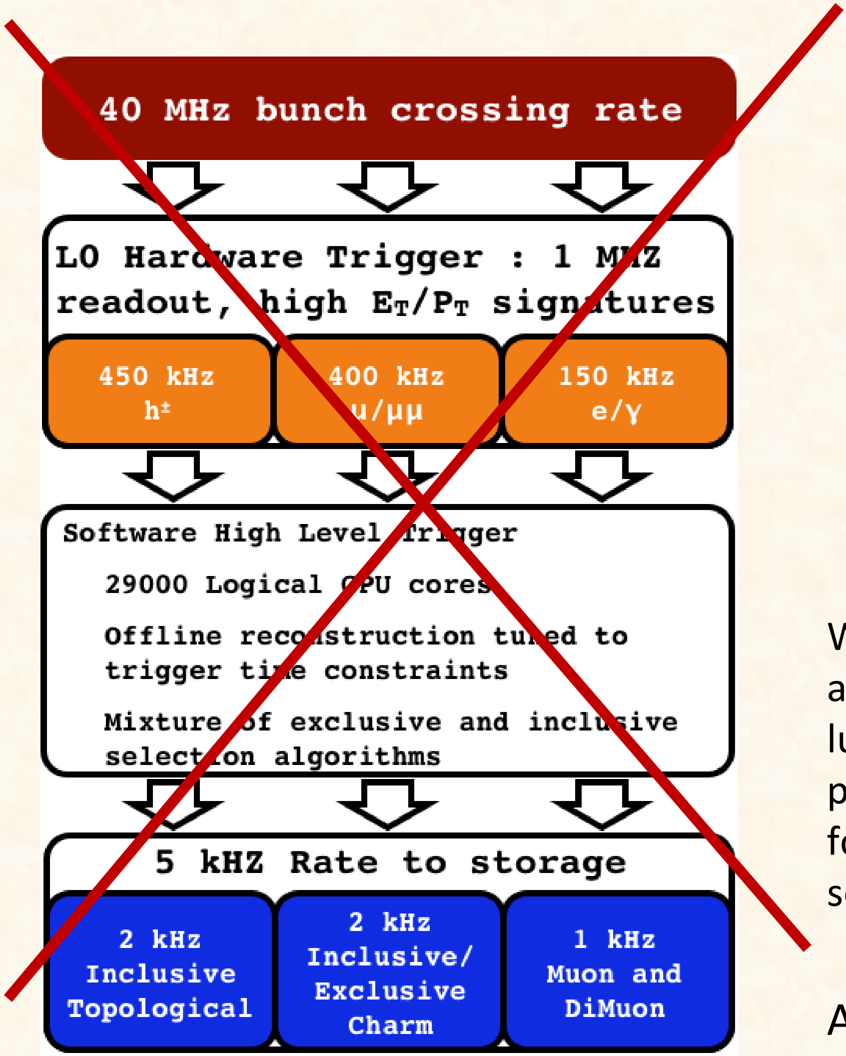


Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\,A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Year	Energy	Int. Lumi.
2010	7 TeV	37 pb^{-1}
2011	2.76TeV	71 pb^{-1}
2011	7 TeV	1.0 fb^{-1}
2012	8 TeV	2.2 fb^{-1}
2013	LHC splice repair	
2014		
2015	13 TeV 25 ns bunch crossing	>5 fb^{-1}
2016		
2017		
2018	LHCb upgrade	
2019	5-10 fb^{-1}/year	
2020		
2021		
2022	LHC lumi upgrade	
2023		
2024		

Continue the extensive programme of studies of *B* decays with photons in final state (*e.g.* $B_s \to \varphi\gamma$ is one of the key measurements).

LHCb upgrade



40 MHz bunch crossing rate

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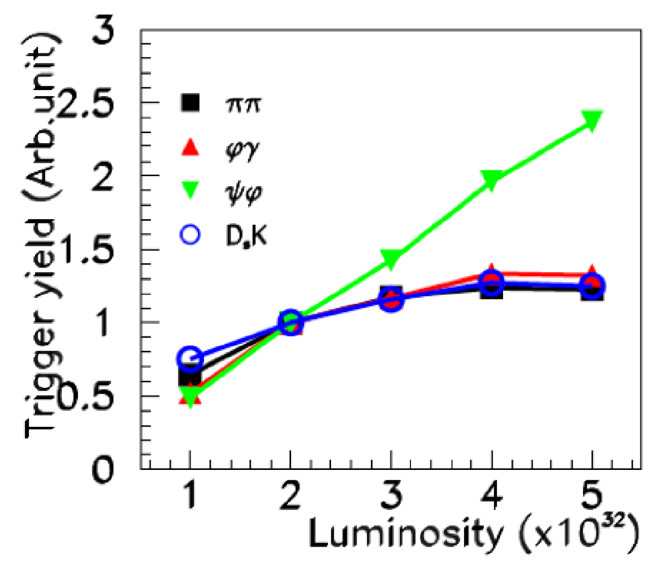
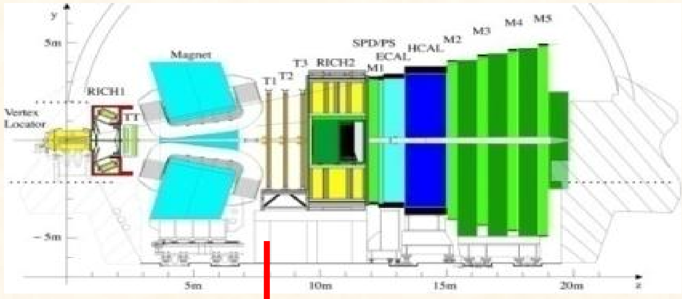
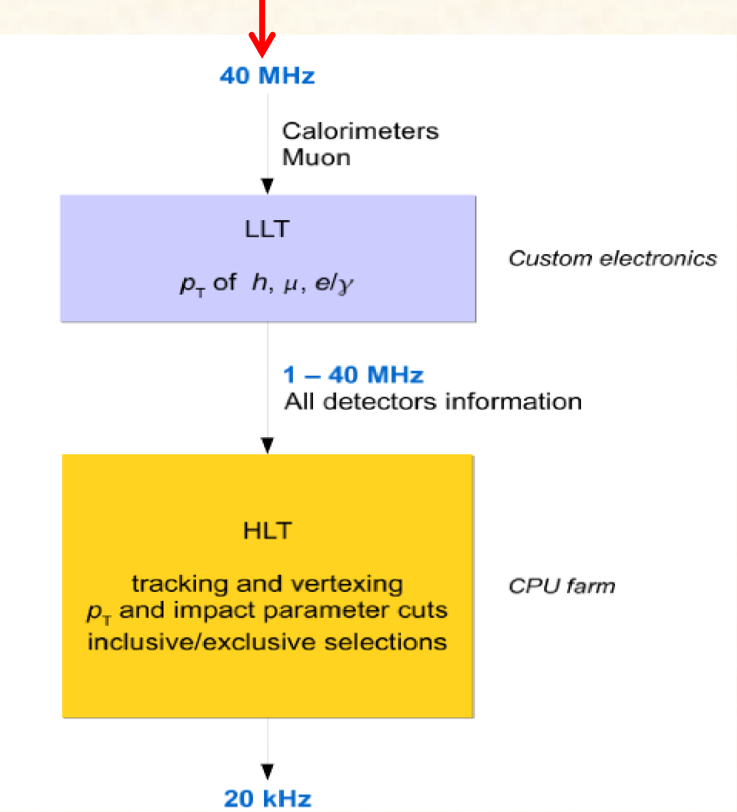


With the present trigger organization, 1 MHz L0 limit: for all the hadronic final states, no gain from increasing the luminosity! The hadron trigger selects ***b***-events, but not particular final state. The increasing of the p_T threshold for hadrons, after certain limit, does not improve the selection purity.

A fully software trigger is necessary to select desired final states.

LHCb upgrade





40 MHz

Calorimeters
Muon

LLT

p_T of h, μ, e/γ

Custom electronics

1 – 40 MHz
All detectors information

HLT

tracking and vertexing
p_T and impact parameter cuts
inclusive/exclusive selections

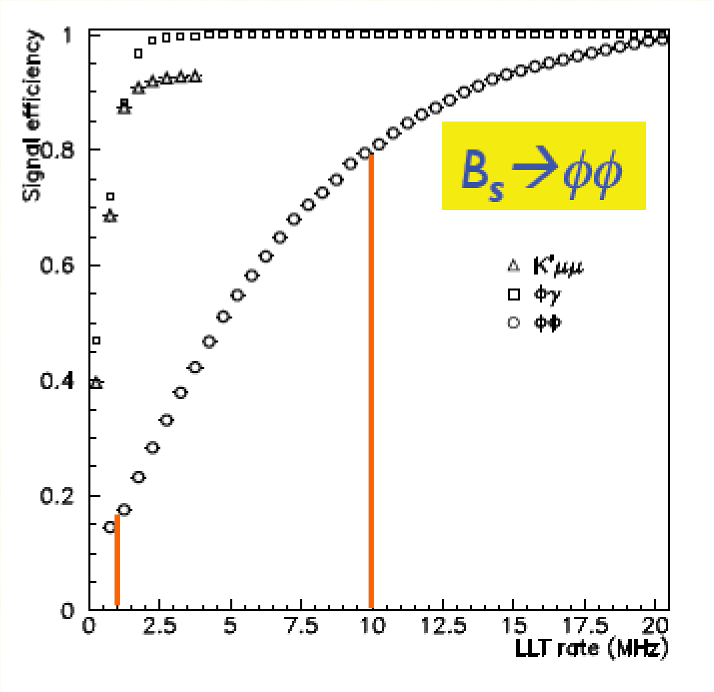
CPU farm

20 kHz

Solution: get rid of the 1 MHz limit. Enlarge the CPU farm such that it could process the whole 40 MHz input.

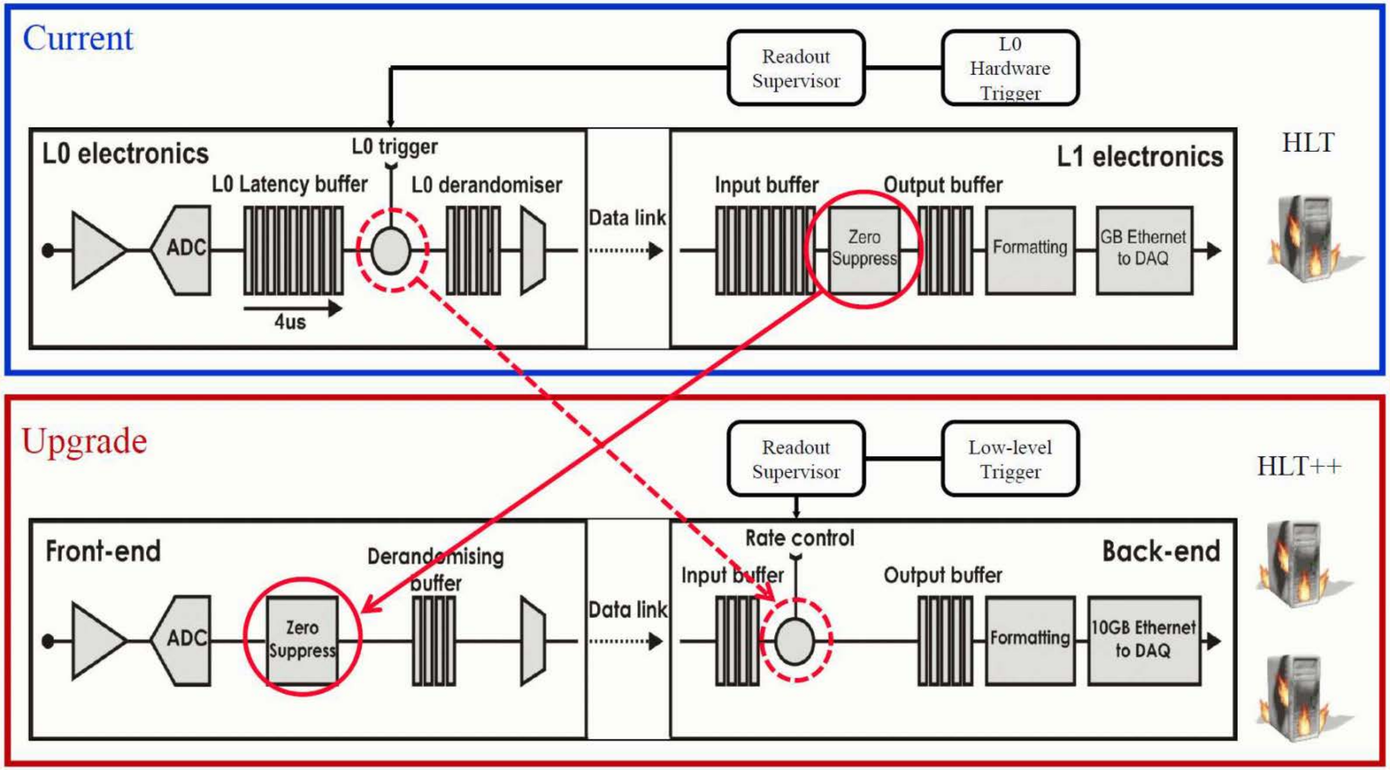
Use a L0-like LLT (with 1-40 MHz output) as a throttle for HLT, to follow gradual growth of the HLT farm.

All the Front End electronics should work at 40 MHz. Has to be rebuilt for most subdetectors.



LHCb upgrade: electronics architecture

Current: latency-buffer in FE, and zero-suppress after L0 trigger

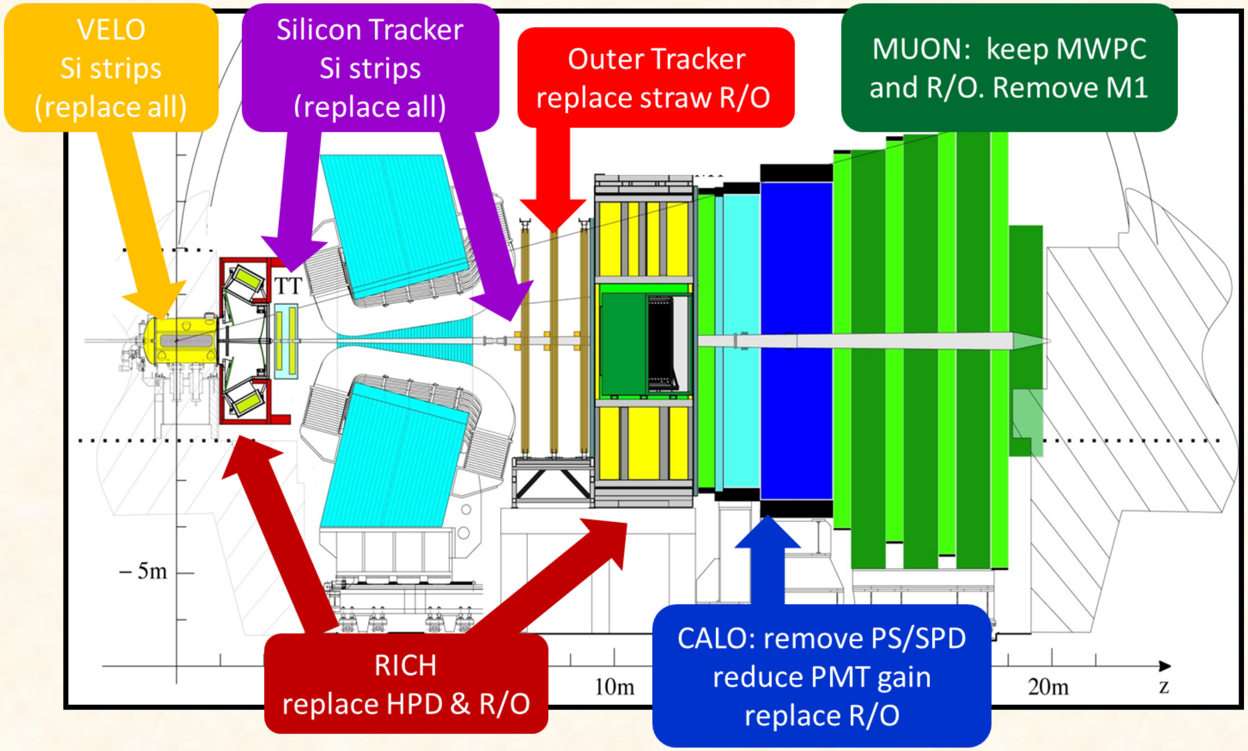


Upgrade: zero-suppress in FE, no trigger decision to FE, LLT in back-end.

More details on LHCb CALO electronics upgrade: talk of Eduardo Picatoste, this conference

LHCb upgrade detector

- VELO: replace the whole detector (rad damage). New readout chips. Choice between strip and pixel options.
- other tracking detectors: leave present OT straw tubes at the periphery. Central part: the options are silicon strips or scintillating fibers.
- RICHes: replace all the photodetectors, as present HPDs include readout electronics. MAPMTs is baseline. Remove aerogel in RICH1 (material budget).
- additional PID detector: Time of Internally Reflected Cherenkov Light (TORCH). Quartz plate radiator, 10-15 ps resolution. Installed between RICH2 and calorimeters.



VELO
Si strips
(replace all)

Silicon Tracker
Si strips
(replace all)

Outer Tracker
replace straw R/O

MUON: keep MWPC
and R/O. Remove M1

RICH
replace HPD & R/O

CALO: remove PS/SPD
reduce PMT gain
replace R/O

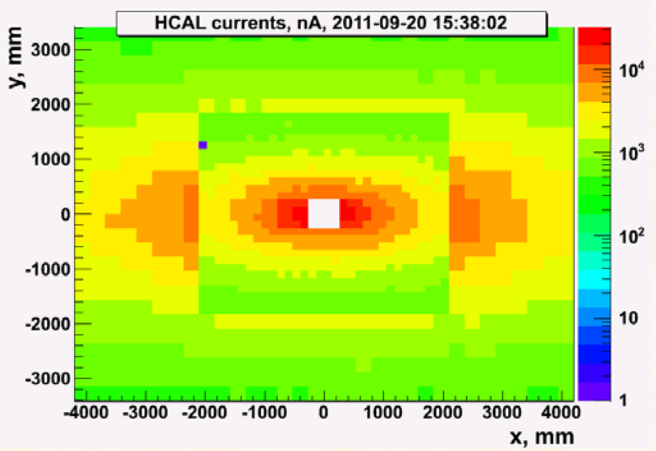
- CALO: reduce PMT gain. Remove PS/SPD. Rebuild Front End electronics. Possibly replace few modules in hottest areas.

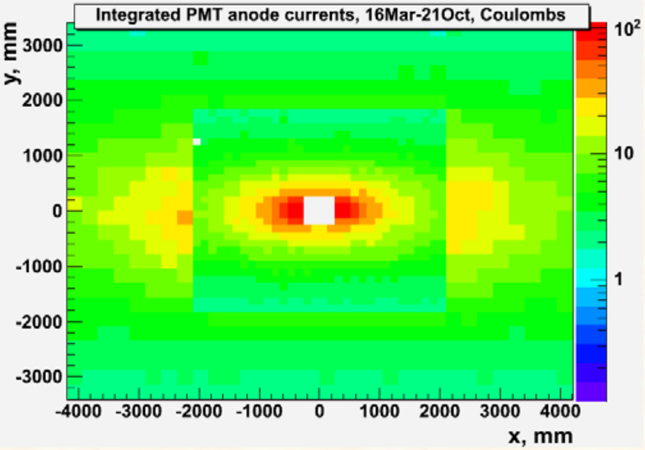
- MUON: present frontend electronics can work at 40 MHz. Remove the M1 station before calorimeters.

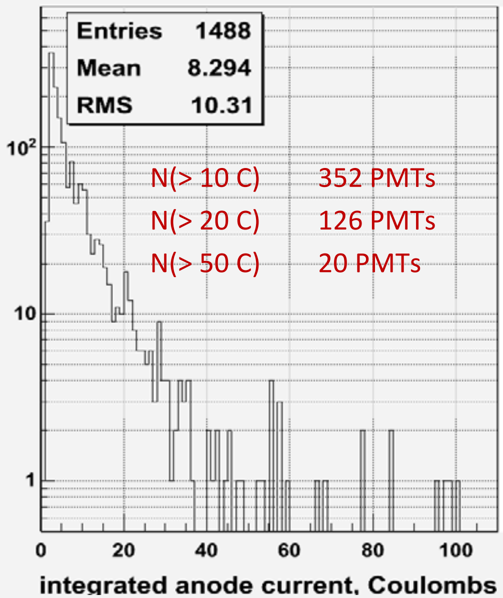
LHCb Calorimetry system upgrade

- present ECAL and HCAL will be kept
- PS and SPD can be removed: for particle ID in HLT the tracker information will be used
- The ECAL and HCAL PMT gain will be reduced by factor of 5
- The ECAL and HCAL Frontend electronics will be rebuilt, with increased x5 preamplifier gain
- detector maintenance should follow radiation degradation of detector components:
  - regular replacement of PMTs / CW bases
  - possible replacement of ECAL Inner modules

PMT operation conditions







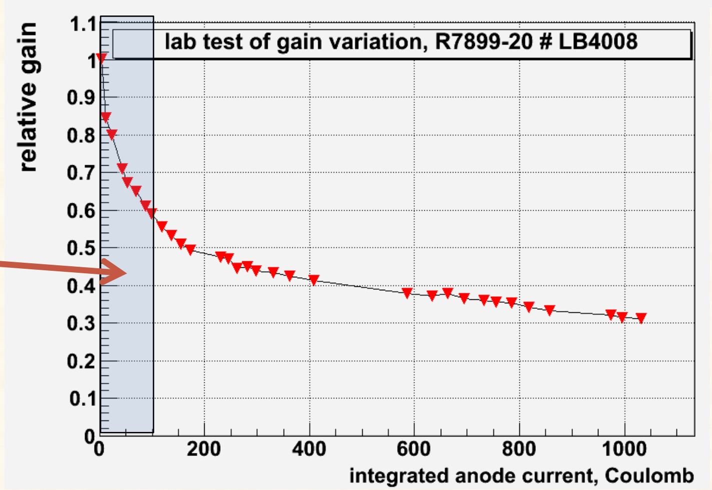
Consider anode currents of the HCAL PMTs (they are continuously monitored with integrators of the source calibration system).

Even in 2011-2012, PMT anode current was significant, up to 20-30 μA in the HCAL centre (it is not recommended to exceed 10 μA).

The PMT gain was reduced by factor of 2 in 2012.

The integrated anode currents are up to 100 C each year

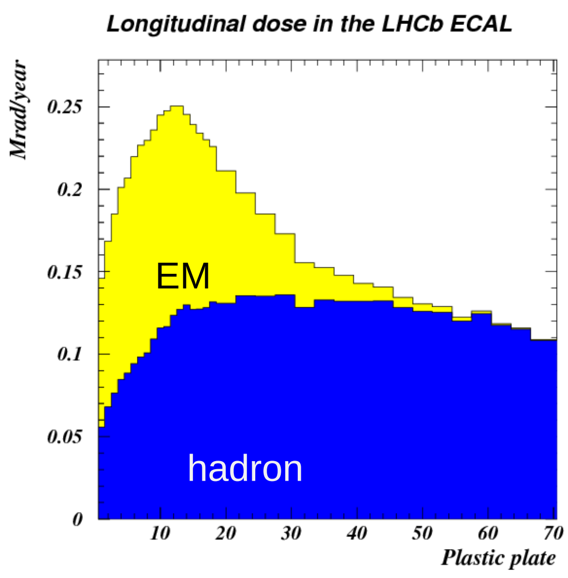
The dynode system ageing was tested in the lab:

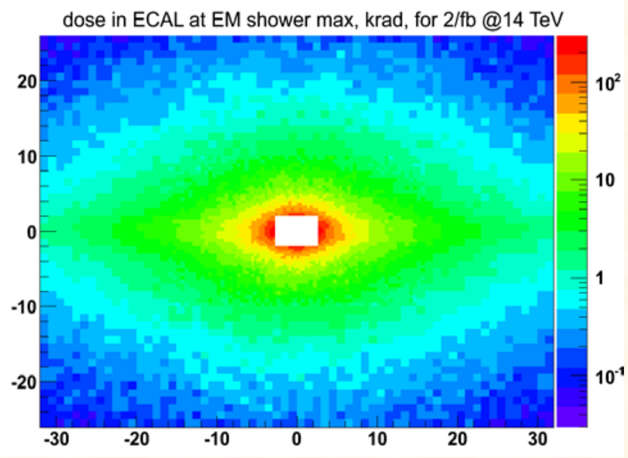


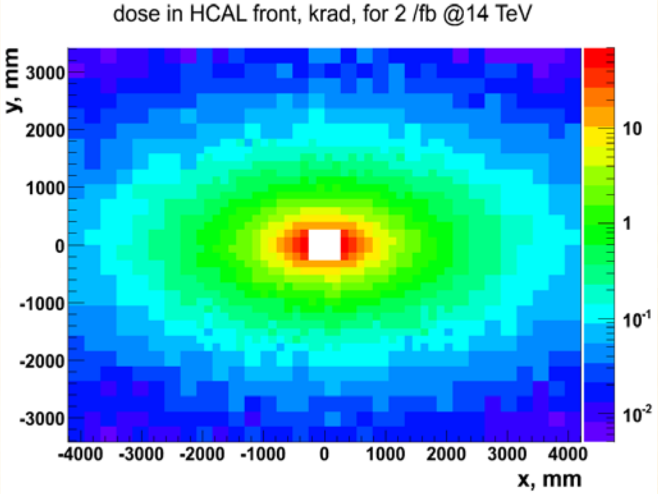
After upgrade, with x5 higher luminosity, to avoid damaging PMTs, we will have to reduce the gain by factor of 5, compensating in by higher gain of the input amplifier of new Front End electronics

ECAL and HCAL radiation doses

doses per 2 fb^{-1} at $\sqrt{s}$=14 TeV (x25 for 50 fb^{-1})







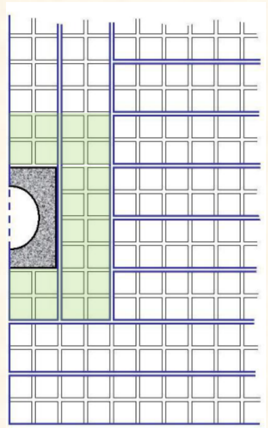
The radiation tolerance is an issue for :

- ECAL modules: scintillator and fibers
- ECAL light readout elements
  - light guides
  - PMTs (entrance window)
  - CW boards
- HCAL modules: scintillator and fibers

Not an issue for the HCAL light readout elements (lesser dose behind HCAL)

Replaceable are:

- ECAL (and HCAL) PMTs, CW bases and light guides (the CW bases remain operational till 1.5-2 Mrad; ~500 CW bases to be replaced while taking 50 fb^{-1})
- 48 central ECAL modules (although not an easy task)
- WLS fibers of ECAL modules (check)

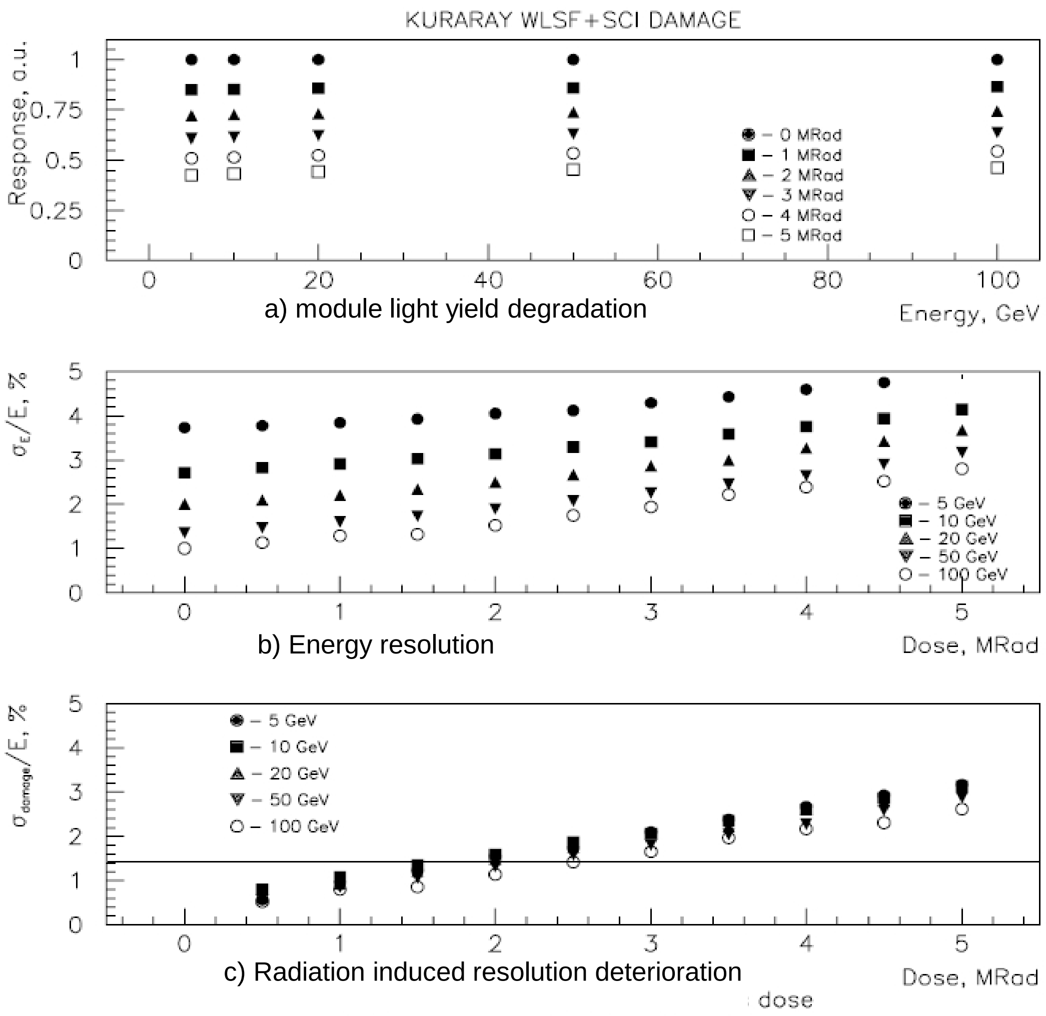


Not replaceable:

- other ECAL modules
- HCAL modules, plastic and fibers

ECAL ageing studies: e^- beam

e^- irradiation (LIL, 1999) (from LHCb CALO TDR)



a) module light yield degradation

b) Energy resolution

c) Radiation induced resolution deterioration

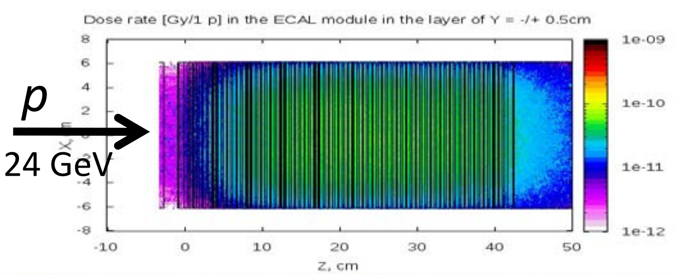
These studies were performed with electron beam irradiation of a ECAL module prototype (not final design).

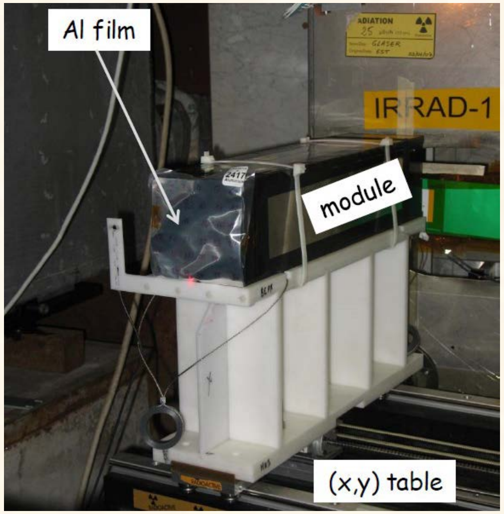
The performance is expected to remain satisfactory till ~2.5 Mrad at maximum (20 fb^{-1} for the ECAL centre).

Tests with mass production modules are ongoing now; preliminarily, agrees with the above limit.

ECAL ageing studies: proton beam

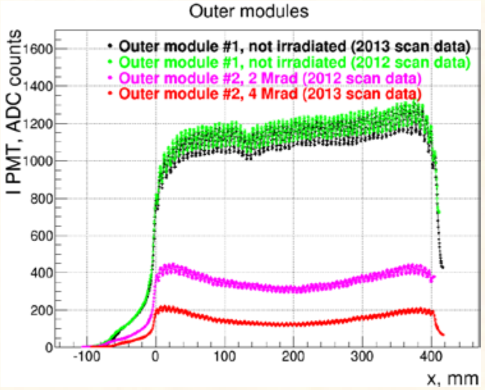
Irradiation of an Outer ECAL module at CERN PS with 24 GeV protons: 2 runs (2010 and 2012) to ~10^{13} p/cm^2 (~2 Mrad @ shower max) each time, total of 4 Mrad.





Irradiation runs:
Nov 2010 and Jun 2012
Beam tests with e- at SPS:
Jul 2011, Aug 2012
Longitudinal scan with ^{137}Cs source: Feb 2012, Apr 2013

The module performance is satisfactory with 2 Mrad; not any more with 4 Mrad. Expected to be better for Inner modules: higher fiber density. We believe therefore that the ECAL modules will remain operational till ~20 fb^{-1} at least.



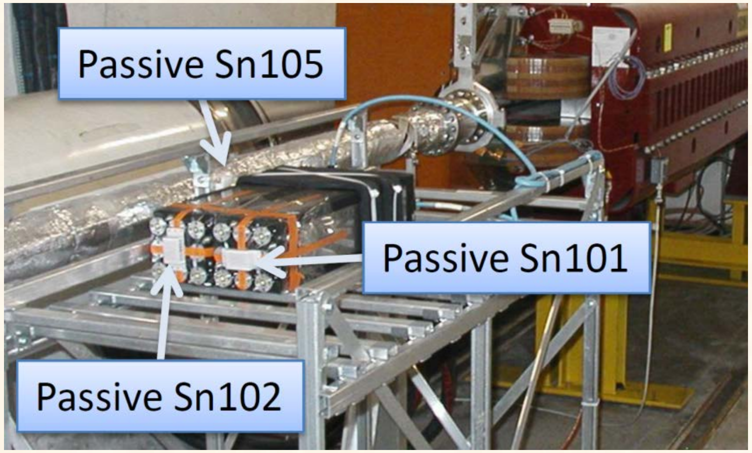
Cs scan results

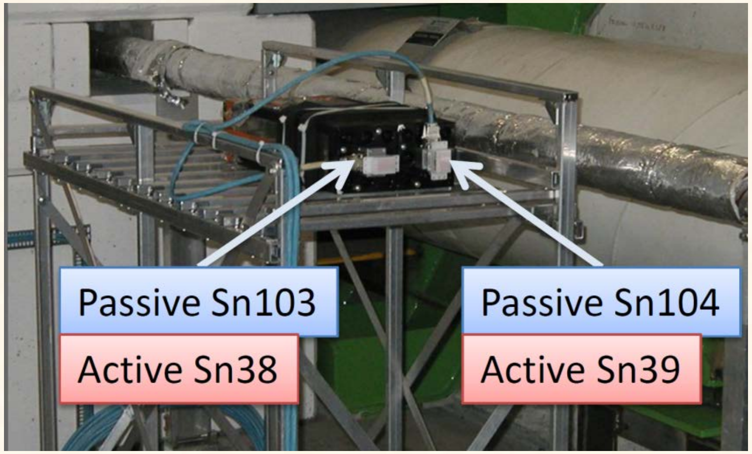
E beam, GeV	module #2, not irradiated		module #1, 2 Mrad		module #1, 4 Mrad	
	light yield, ph.el./GeV	resolution, %	light yield ph.el./GeV	resolution, %	light yield ph.el./GeV	resolution, %
50	2598±52	1.37±0.04	583±12	2.16±0.04	223±10	2.74±0.04
100	2611±52	1.01±0.03	576±12	1.57±0.03	221±10	2.26±0.05
120	2604±52	0.98±0.03	571±12	1.36±0.03		
125					220±10	2.06±0.05
150					219±10	1.77±0.05

Beam test results: CERN SPS e$^-$ beam

ECAL ageing studies: LHC radiation field

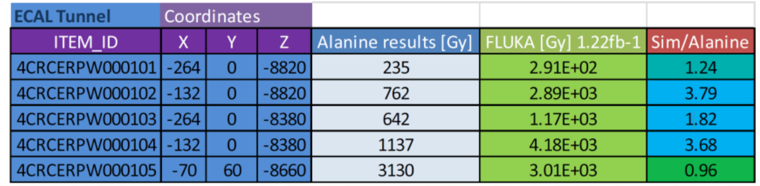
Before the LHC startup, in 2009, two Inner type modules were placed in the LHC tunnel at the opposite side from the LHCb interaction point. Several dosimeters installed.





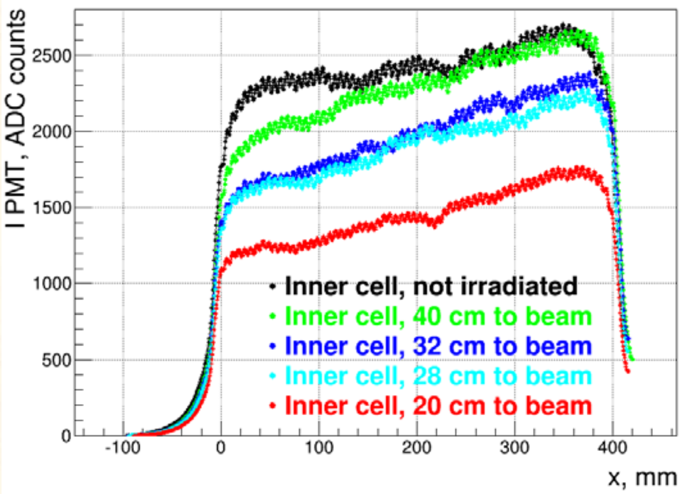
Readout of dosimeters was performed at the 2011/2012 shutdown (1.2 fb-1) and after the 2012 run (3.4 fb-1)

1.2 fb^{-1}: ~300 krad at the cell near the beam pipe



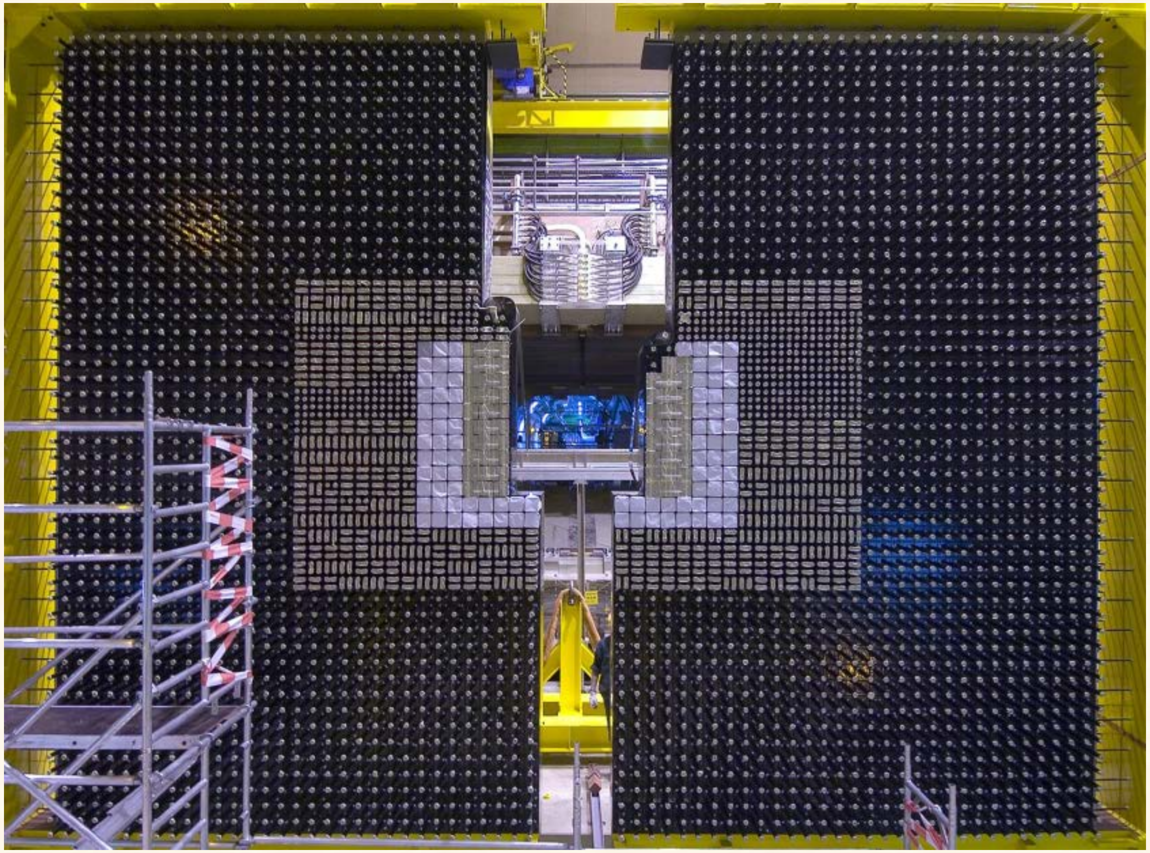
ECAL Tunnel	Coordinates					
ITEM_ID	X	Y	Z	Alanine results [Gy]	FLUKA [Gy] 1.22fb-1	Sim/Alanine
4CRCERPW000101	-264	0	-8820	235	2.91E+02	1.24
4CRCERPW000102	-132	0	-8820	762	2.89E+03	3.79
4CRCERPW000103	-264	0	-8380	642	1.17E+03	1.82
4CRCERPW000104	-132	0	-8380	1137	4.18E+03	3.68
4CRCERPW000105	-70	60	-8660	3130	3.01E+03	0.96

For 3.4 fb-1: no dose map yet (~1 Mrad expected).



A (moderate) degradation in the light yield is seen after ~1 Mrad at the ^{137}Cs source scan.

ECAL



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2017		
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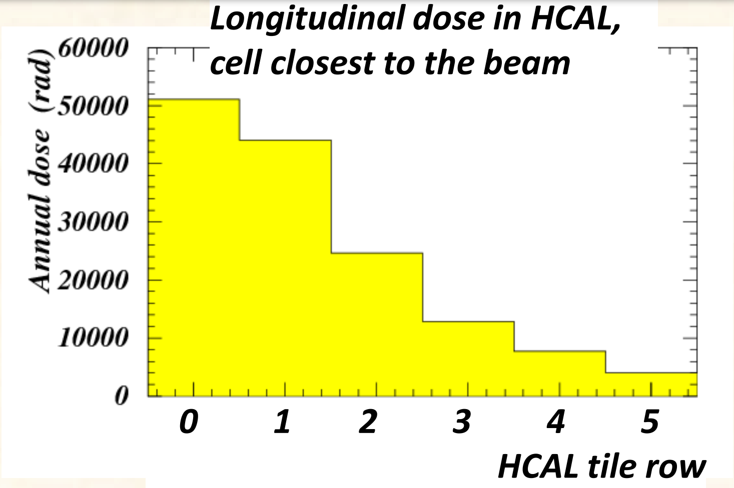
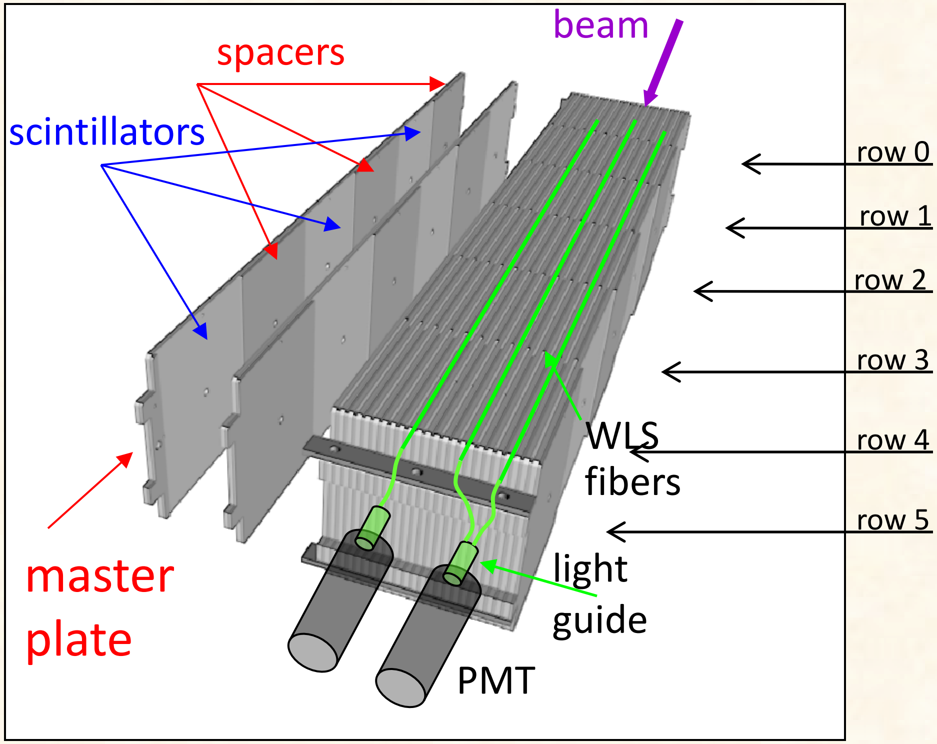
2019	5-10 fb^{-1}/year	
2020		
2021		
2022	LHC lumi upgrade	
2023		
2024		

The performance of ECAL central modules is expected to remain satisfactory till 20-30 fb^{-1}.
We are considering replacement of central modules during LS3 (2022).
This is not a simple task, and even can be found impossible.
The effect of degradation of the ECAL centre to physics performance is under study.

HCAL ageing

The HCAL radiation tolerance can be evaluated *in situ*. using the ^{137}Cs calibration system.
HCAL cells are longer in Z than ECAL → longer WLS fibers → faster degradation expected.
However, its performance in the inner area after upgrade is much less crucial.
Anyway, the HCAL modules are not replaceable.

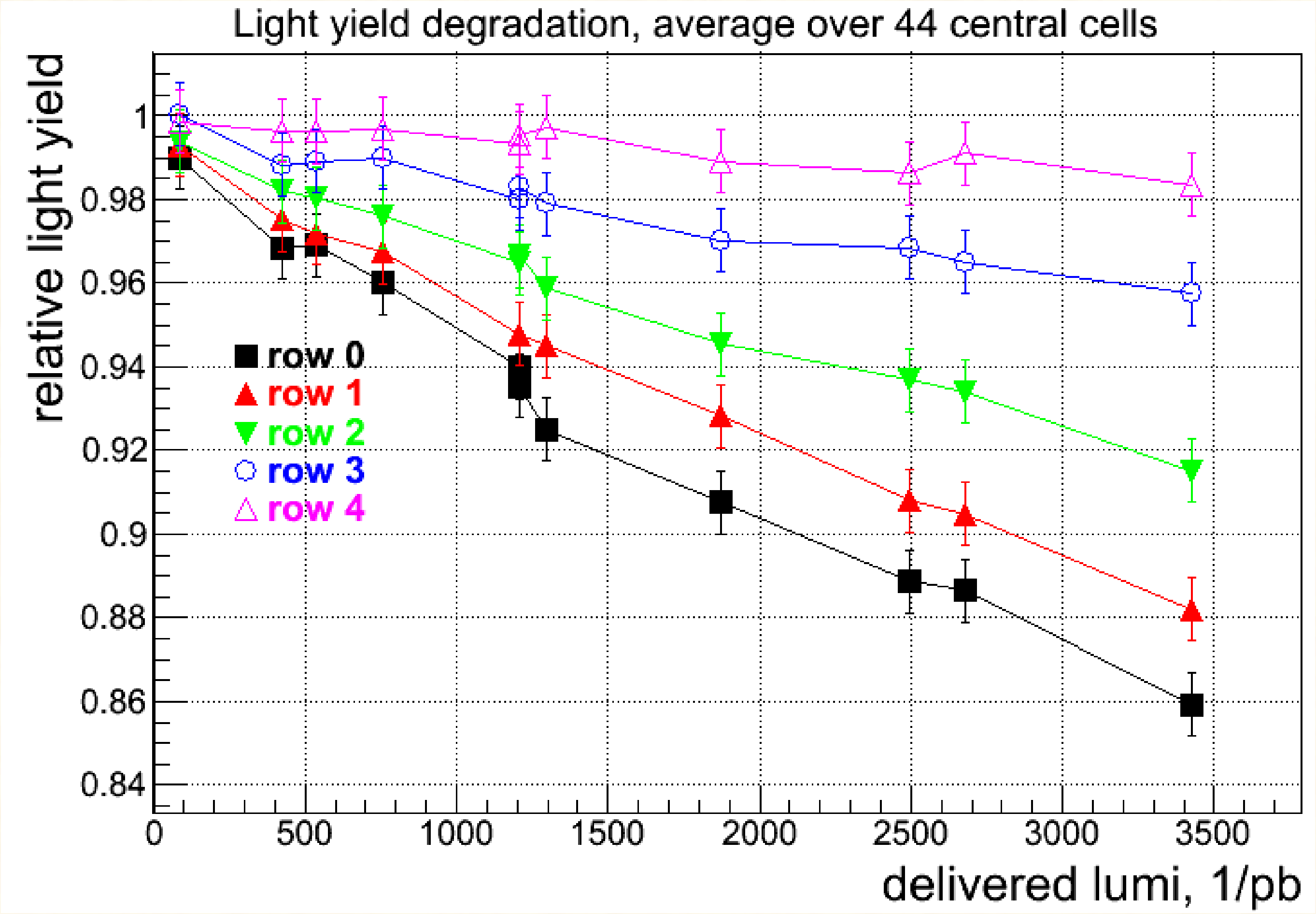

Longitudinal dose in HCAL, cell closest to the beam



The hadronic shower maximum lays within the tile row 0 (ECAL is ~1.2 λ_I); the dose in the row 5 is much less.
No significant radiation damage to the LED system, PMTs, their Cockcroft-Walton boards, and integrators of the source calibration system, as all that is placed behind row #5.

The light yield degradation in a tile row #*i* can be determined as a decrease of relative response of this row, (A_i/A_5), with respect to a reference at lumi=0: $R_i = \left(A_i / A_5\right) / \left(A_i / A_5\right)\big|_{L=0}$

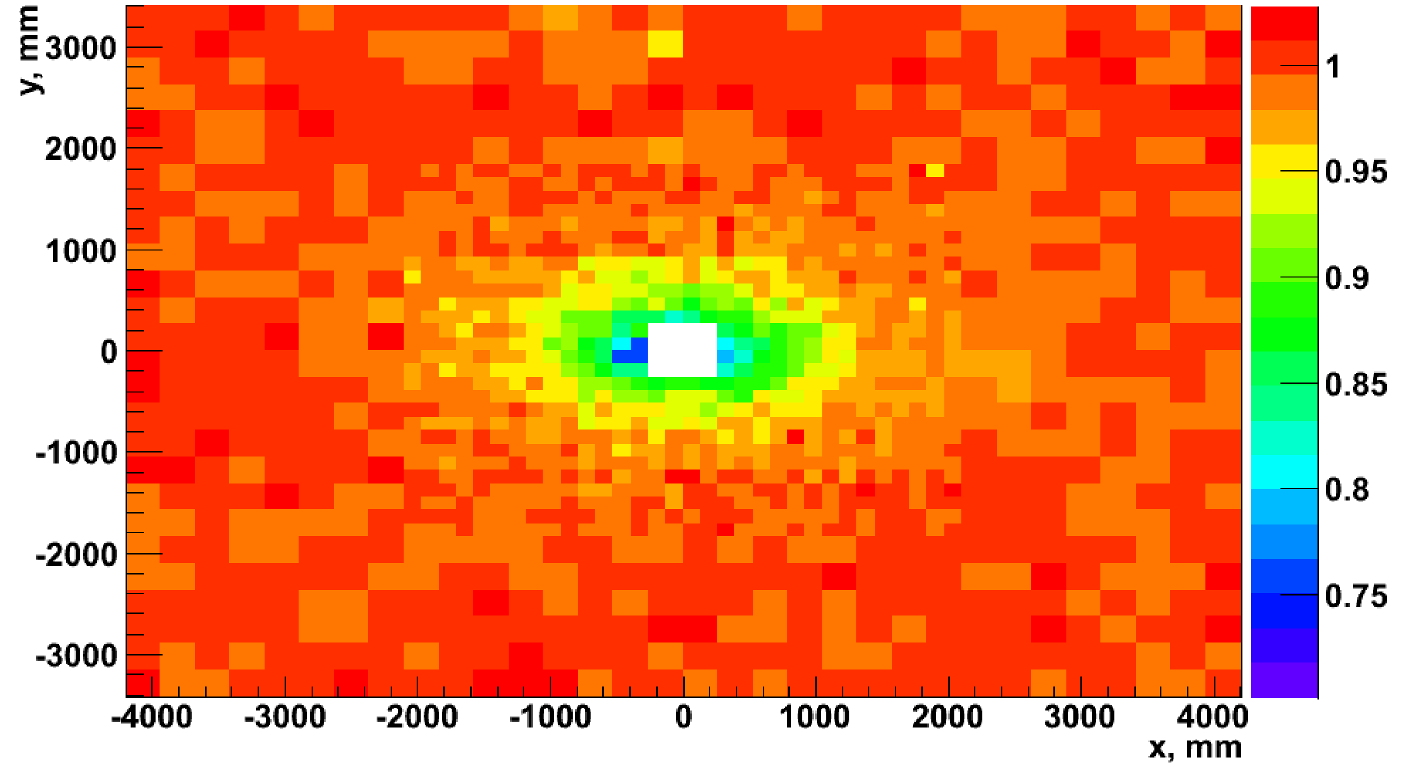
HCAL ageing



Light yield degradation in the HCAL centre, 2011+2012 (3.4 fb^{-1}).

HCAL ageing

Light yield degradation of front row in each HCAL cell, 2011+2012 (3.4 fb^{-1}).



Can be compensated by calibration (PMT gain).

The HCAL will (finally) not be used to provide the trigger on high-pT hadron.

It will be still usable for Muon ID in the Outer region (does not suffer much from radiation).

Conclusions

- LHCb is running successfully if 2010-2012, demonstrating very good detector performance, and collected by now ~3.2 fb^{-1} of physics data. The Calorimetry system is an important part of LHCb, providing photon and electron reconstruction, as well as input information for L0 trigger decision.

- LHCb will continue present mode of operation till 2018, then upgrade for higher luminosity is foreseen.

- The Calorimetry system will play an important role in the upgraded detector

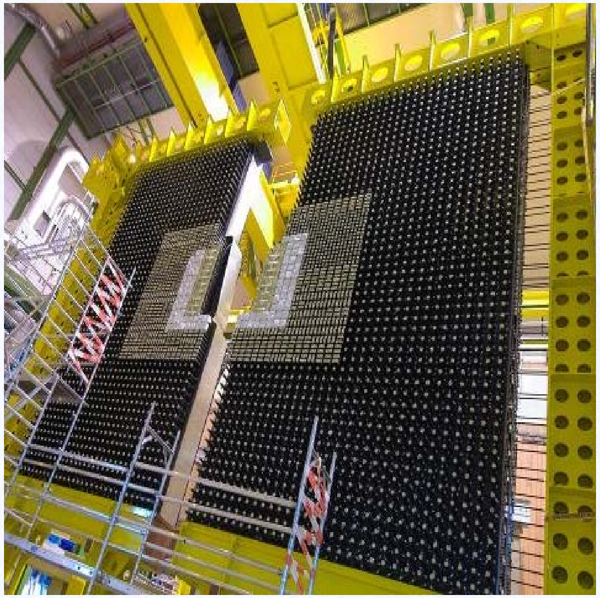
- The system will be subject to the following modifications:
  - The Preshower, SPD and lead converter will be removed
  - All the Front End electronics of HCAL and ECAL will be rebuilt.
  - The gain of all the PMTs will be reduced by factor of 5, with corresponding increase of sensitivity of input amplifiers of Front End Boards

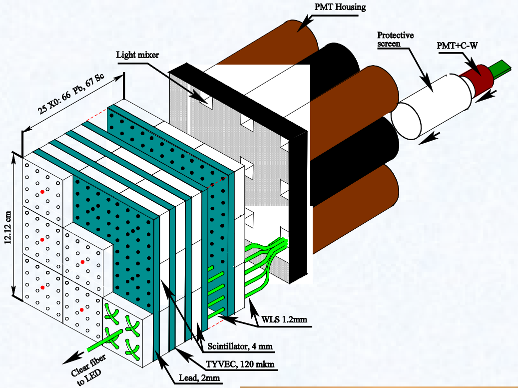
- The main components of the system are expected to remain operational under increased radiation. Some components of the central part, namely PMTs and Cockcroft-Walton HV sources, and possibly ECAL modules, will be regularly replaced

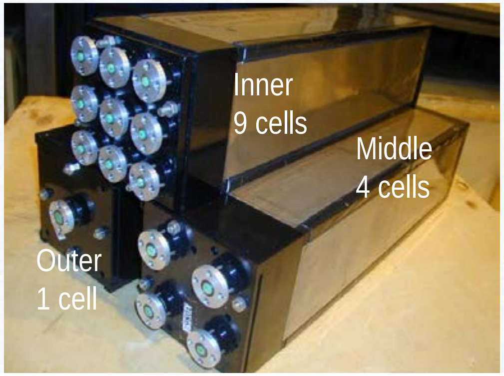
Thank you!

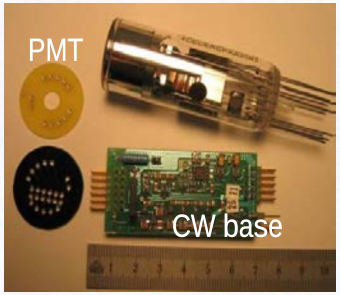
Backup

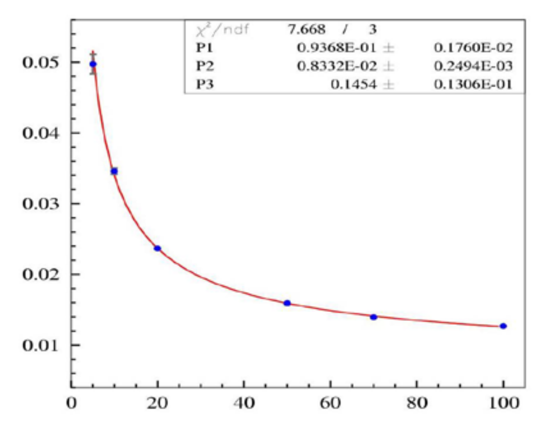
ECAL











Shashlik technology

- scintillator: PSM-115 polystyrene +1.5% PTP +0.03% POPOP; WLS fibers: : KURARAY Y11(250)MS Ø1.2 mm
- 4 mm thick scintillator tiles and 2 mm thick lead plates, ~25 X_0 (1.1 λ_I); Moliere radius ~ 35 mm;
- modules 121.2 x 121.2 mm^2, 66 Pb +67 scintillator tiles;
- Segmentation: 3 zones → 3 module types, Inner (9 cells per module), Middle (4), Outer (1). Total of 3312 modules, 6016 cells, (7.7 x 6.3) m^2, ~100 tons.
- Light readout: PMT R-7899-20, HAMAMATSU. HV supply: individual Cockcroft-Walton circuit at each PMT.
- LED monitoring system. The LED light is distributed by clear fibers running at the ECAL front face

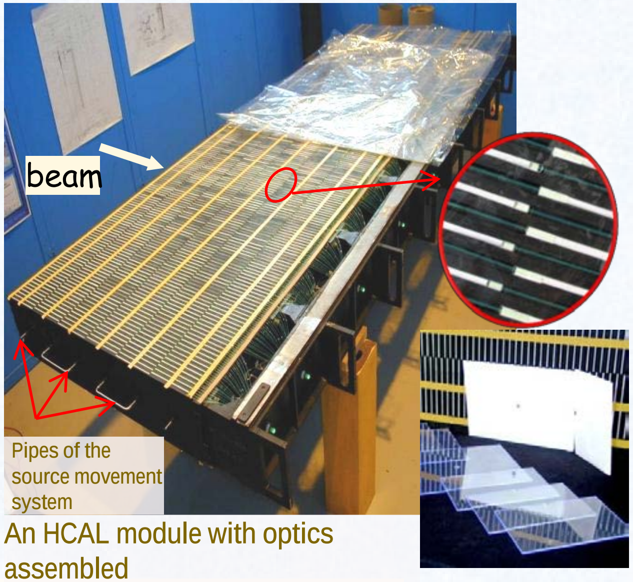
Average performance figures from beam test (there is slight difference between zones):

Light yield: ~ 3000 ph.el. / GeV

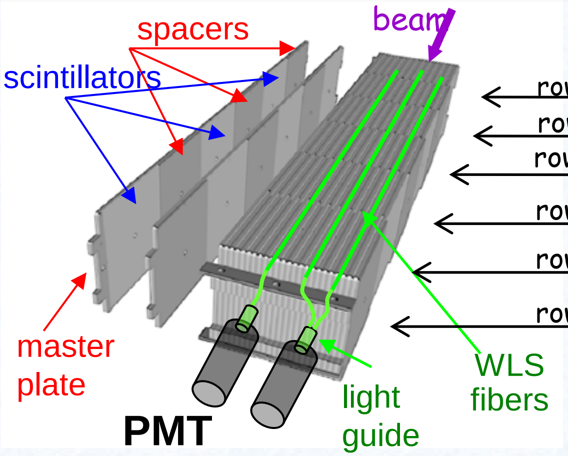
Energy resolution: $$\frac{\sigma_E}{E} = \frac{(8 \div 10)\%}{\sqrt{E(\mathrm{GeV})}} \oplus 0.9\%$$

HV setting rule: gain ~ proportional to distance to the beam (to measure E_T): $E_t$max = (10 + 7*sinϑ) GeV
HV range: ~ 500 – 1000 V

HCAL



An HCAL module with optics assembled



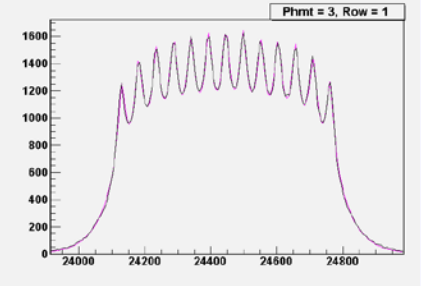
HCAL module: self-supporting structure containing either 16 outer or 8 outer + 32 inner cells. HCAL consists of 52 modules, 9.5 tons each.

- Tilecal technology (originally developed for ATLAS): iron/scintillator structure arranged parallel to the beam direction. The volume ratio Sc:Fe ~ 3:16.
- Instrumented depth: 1.2 m, 6 tile rows, ~5.6λ_I
- Outer cells: 26x26 cm^2, Inner : 13x13 cm^2 (half tiles)
- HCAL stack: 26 modules each of A and C side.
- Total of 1488 cells, 47424 full and 34320 half tiles
- ~(8.3 x 6.7) m^2, 500 tons.
- Scintillator, fibers, PMTs, LED system: similar to ECAL
- unlike ECAL, equipped with ^{137}Cs calibration system

Performance from the beam test:

- energy resolution $$\frac{\sigma}{E} = \frac{(69\pm5)\%}{\sqrt{E}} \oplus (9\pm2)\%$$
- light yield 105±10 ph.el. / GeV

Source calibration. Hydraulic motion system. The pipes passing through the centres of each of the 6 tile rows are connected sequentially. The PMT anode DC current is measured as a function of time by a dedicated system (integrators). The response of each tile is being dete



- One ~10 mCi sources per side
- Pipe length: ~700 m per side
- Source speed: 30 cm/sec

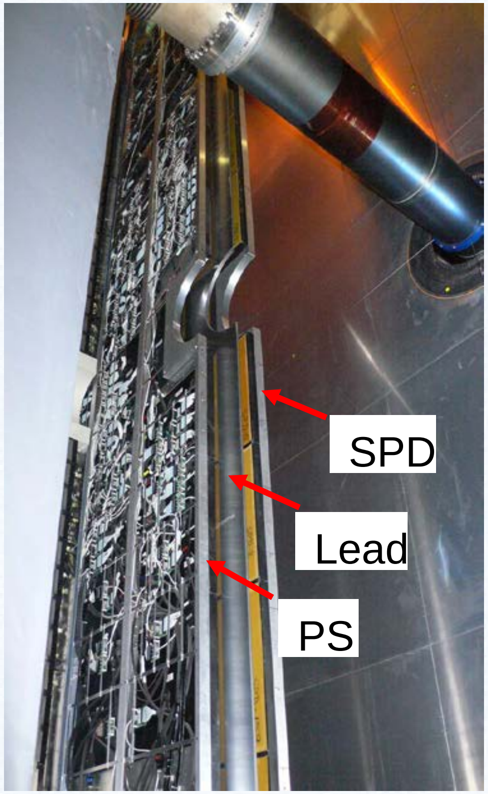
One source passage (from top to bottom and back): ~90 min

The integrators are also used at data taking to permanently monitor the PMT anode current

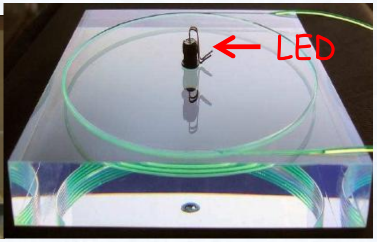
HV setting rule: E$_t$max = 15 GeV; HV range: ~ 700 – 1300 V

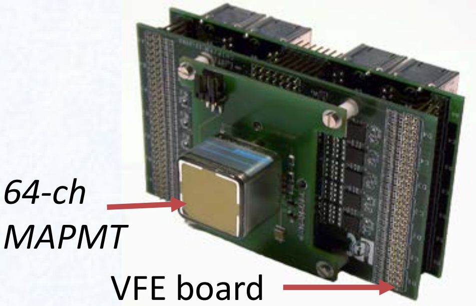
PS / SPD

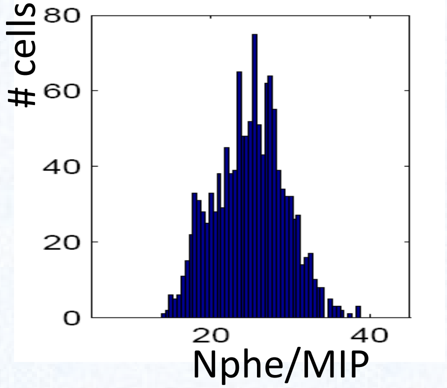
Preshower detector: two planes of scintillator tiles, with 1.5 cm thick lead plane between them. Size and segmentation: matches ECAL.



The scintillator tiles are 15 mm thick. The light is captured and re-emitted by WLS fiber (3.5 loops) glued in a deep groove machined at the surface of the tile. Light readout: multi-anode PMT.







The scintillation light is captured by WLS fibers glued into the tiles, and transported via clear fibers to 64-channel HAMAMATSU multi-anode PMT R7600-00-M64MOD.

Both PS and SPD are equipped with LED monitoring system

The light yield of all 12032 cells measured on cosmics at production: ~ 25+-12 ph.el. / MIP

HV setting: uniform, ~700-800 V

LHCb upgrade

In 2015-2017, LHCb is expected to take 5-7 fb^{-1} of data @13 TeV.

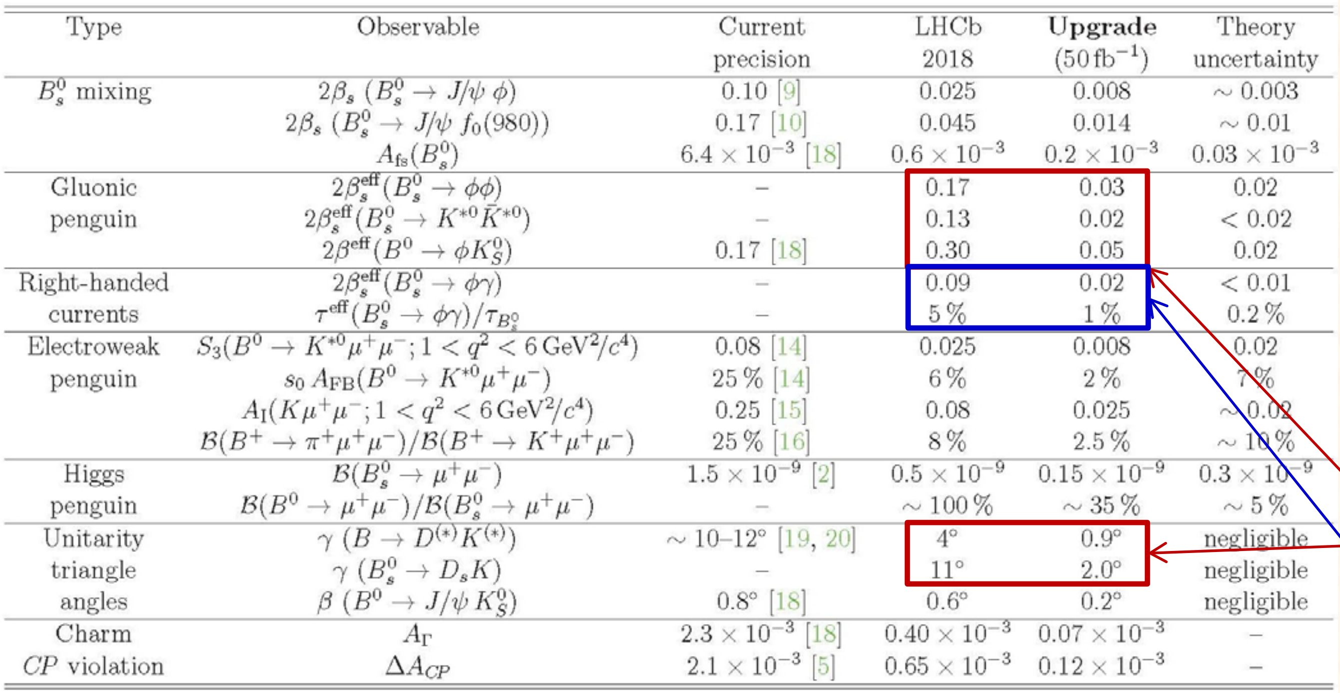
There is strong physics case to continue the flavor physics programme.
Next step is to collect other >50 fb^{-1} → probe NP effects at % level.

This requires running at higher luminosities: (1-2)·10^{33} @$\sqrt{s}$ = 14 TeV.

➔ ***UPGRADE***

LHCb Upgrade LoI: CERN-LHCC-2011-001
LHCb Upgrade Framework TDR: CERN-LHCC-2012-007

Year	Energy	Int. Lumi.
2010	7 TeV	37 pb^{-1}
2011	2.76TeV	71 pb^{-1}
2011	7 TeV	1.0 fb^{-1}
2012	8 TeV	2.2 fb^{-1}
2013	LHC splice repair	
2014		
2015	13 TeV 25 ns bunch crossing	>5 fb^{-1}
2016		
2017		
2018	LHCb upgrade	
2019	5-10 fb^{-1}/year	
2020		
2021		
2022	LHC lumi upgrade	
2023		
2024		



Type	Observable	Current precision	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B^0_s mixing	$2\beta_s\ (B^0_s \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B^0_s \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\rm fs}(B^0_s)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta^{\rm eff}_s(B^0_s \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta^{\rm eff}_s(B^0_s \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K^0_S)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta^{\rm eff}_s(B^0_s \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B^0_s \to \phi\gamma)/\tau_{B^0_s}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\,A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B^0_s \to D_sK)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K^0_S)$	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

max gain for hadronic final states; also $B_s \to \varphi\gamma$