The LHCb Upgrade

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Abstract.   The LHCb experiment is designed to perform high-precision measurements of CP violation and search for New Physics using the enormous flux of beauty and charmed hadrons produced at the Large Hadron Collider (LHC). The operation and the results obtained from the data collected 2011 and 2012 demonstrate that the detector is robust and functioning very well. However, the limit of $\mathcal{O}(1)\mathrm{fb}^{-1}$ of data per year cannot be overcome without improving the detector. We therefore plan for an upgraded spectrometer by 2018 with a 40 MHz readout and a much more flexible software-based triggering system that will increase the data rate as well as the efficiency specially in the hadronic channels. Here we present the LHCb detector upgrade plans.

1. Introduction

The LHCb experiment [1, 2] has demonstrated an excellent running performance in 2011 and 2012. Table 1 summarises the most important parameters. LHCb started in 2011 with the design values for both the luminosity and the number of visible interactions per bunch crossing. The experiment makes the most out of the provided luminosity by constantly adjusting the beam overlap to maintain a constant instantaneous luminosity during a run, as shown in figure 1. An extended tuning campaign to optimise every aspect of the data acquisition enabled LHCb to increase these parameters steadily over the running period. Over the 2012 running period finally four times the design value could be maintained for the number of interactions per bunch crossing as well as two times the design value for the luminosity. At the end of 2012 a successful test was performed with a luminosity of even $6 * 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. An upgrade to the PC farm of

Table 1. LHCb running parameters in 2011 and 2012.

Year	2011	2012
Beam energy	3.5 TeV	4.0 TeV
Luminosity	$2 - 4 * 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$4 * 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Visible interactions/beam crossing	$\mu = 0.4 - 1.4$	$\mu = 1.6$
Data taking efficiency	$> 91\,\%$	$> 95\,\%$
High Level Trigger output rate	3 kHz	4.5 kHz
Integrated luminosity recorded	$1.107\,\mathrm{fb}^{-1}$	$2.082\,\mathrm{fb}^{-1}$
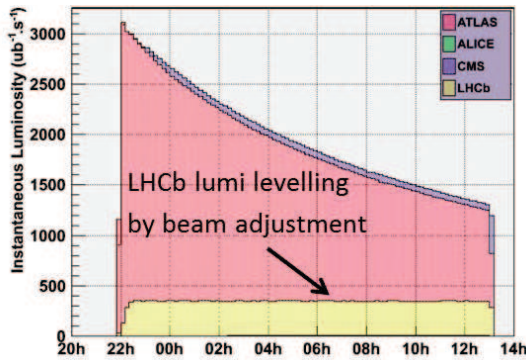
Figure 1. LHCb luminosity leveling during a run; makes optimal use of luminosity provided by the LHC.
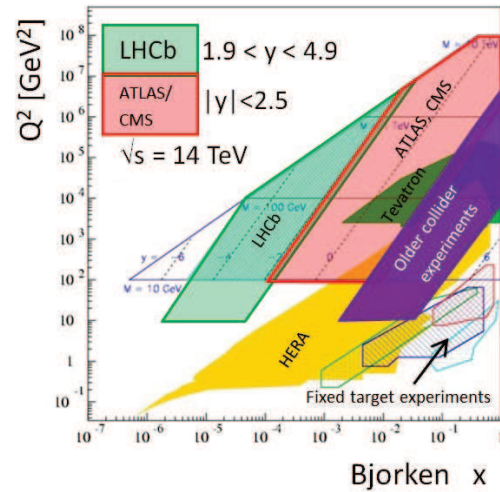
Figure 2. Phase space in (Q^2, x) with coverage for severals generations of experiments [17].

the High Level Trigger increased the output to tape in 2012 by 50%. It is also worth noting that the increase of the LHC beam energy led to an increase of 15% in the $b\bar{b}$ production cross section in 2012 compared to 2011. With that LHCb achieved to record more that $1.0\,\mathrm{fb}^{-1}$ of data in 2011 and in excess of $2.0\,\mathrm{fb}^{-1}$ in 2012. Therefore in 2012 LHCb just surpassed the design luminosity per year, despite the fact that the LHC was only filled with half the number of proton bunches, interacting at a rate of only $20\,\mathrm{MHz}$, i.e. half the design rate.

Using this data LHCb has started to publish new results at high rate, many of which yielding first and best measurements. A personally biased and incomplete selection comprises:

- the first measurement of mixing in the D meson system [3]
- the measurement of direct CP violation in the charmless two-body decay of B mesons [4], where first evidence is presented for $B_s \to K\pi$ and the most precise measurement on $B \to K\pi$ is reported
- the measurement of the phase difference between B_s-mixing and $b \to c\bar{c}s$ amplitudes [5], which dominates the world average
- the first measurement of the zero-crossing point of the forward-backward asymmetry A_{FB} of the decay $B \to K^*\mu\mu$ [6], being consistent with the Standard Model
- the improvement of the world best measurements of the oscillation frequency Δm_d in the B_d-system [7]
- the discovery of new states like $D_{s1}(2536)$ in the decay $B_s \to D_{s1}\pi$ [8] and
- first evidence for the measurement of the $B_s \to \mu\mu$ decay matching the Standard Model prediction [9], and by that ruling out Supersymmetry with large $\tan\beta$.

During the Long Shutdown 1 (LS1) LHCb will harvest more results from the recorded data, will consolidate the detector, study systematic effects and improve the trigger strategies, to prepare for the running periods 2015-17. There we expect to take in excess of $5.0\,\mathrm{fb}^{-1}$ of data. At the increased centre of mass energy of $13 - 14\,\mathrm{TeV}$ we expect about twice the beauty and charm production, and the LHC will introduce the design bunch crossing rate at $40\,\mathrm{MHz}$, i.e. at $25\,\mathrm{ns}$ spacing. With that, while watching out for the unexpected, we expect to perform precision measurements of the unitarity triangles, measure rare hadronic decays and probe for New Physics at the 10% level for key measurements.

2. Physics Motivation for LHCb Upgrade

The plans for the LHCb upgrade are documented in the Letter of Intend [10] and in the Framework Technical Design Report of the LHCb Upgrade [11].

From the restart after LS1 LHCb will meet increasingly challenging conditions. The LHC will increase its beam energy and beam current to the design values, the radiation levels and the occupancies will rise. But the LHCb experiment will not be able to significantly further increase the recorded luminosities before the experiment is upgraded. This upgrade shall take place during the Long Shutdown 2 (LS2) in 2018. After the upgrade the experiment will be designed to operate at luminosities of $2 * 10^{33} \, \mathrm{cm}^{-2}\mathrm{s}^{-1}$, i.e. ten times the current design luminosity and we will collect at least $50 \, \mathrm{fb}^{-1}$ of data over ten years. We expect to increase the yield in the decays with muons by a factor of five, and the yield for hadronic channels by a factor of ten. The running experience from the years 2011 and 2012 will enable us to provide better projections and possibly improve on these design values.

The driving motivation for the LHCb upgrade is to further significantly increase the physics reach, especially for very rare decays. A prime example of this increased reach of LHCb upgrade are the rare decays $\mathrm{B_s} \to \mu\mu$ and $\mathrm{B_d} \to \mu\mu$. LHCb just has reported first evidence for the measurement of the $\mathrm{B_s} \to \mu\mu$ decay, matching the Standard Model prediction [9]. If further established this measurement rules out Supersymmetry with large $\tan\beta$. With the upgrade we expect to yield 50 $\mathrm{B_s} \to \mu\mu$ events per year. This will allow us to perform precision measurements, for example for the ratio of the branching ratios of $\mathrm{BR(B_s} \to \mu\mu)/\mathrm{BR(B_d} \to \mu\mu)$, and become sensitive to distinguish a variety of New Physics models.

With its capabilities LHCb Upgrade also will be unique for New Physics searches in $\mathrm{B_s}$ decays and very competitive in $\mathrm{B_d}$ decays. It will deliver unprecedented charm yields. LHCb provides a general purpose experiment with forward geometry, which also has good potential for non-flavour physics. The upgrade will fully explore the LHC physics in the forward region. It is compatible with the high luminosity upgrade of the LHC, but doesn't require it. It provides direct searches complementary to those of ATLAS and CMS. If new particles are discovered LHCb upgrade will measure their flavour couplings through loop diagrams. If not, LHCb upgrade will probe New Physics at the multi-TeV scale.

Also the rare hadronic penguin transitions b $\to$ q$\bar{\mathrm{q}}$s have been shown to be sensitive to New Physics in their decay amplitude [12, 13]. LHCb will use $\mathrm{B_s} \to \phi\phi$ [14] and $\mathrm{B_s} \to \mathrm{K}^{*0}\overline{\mathrm{K}^{*0}}$ to probe the CP violation weak phase ϕ_s. In the Standard Model the decay and mixing phases cancel, i.e. the predictions of ϕ_s are very close to zero. With the LHCb upgrade the sensitivity will be pushed to about S = 0.03, compared to a Standard Model prediction of S < 0.02. Therefore, any non-zero result will signify New Physics.

The CP Violation in charm was expected to be < 0.1 %. With the recent evidence for direct CP violation in hadronic D-decays, where LHCb measured $\Delta \mathrm{A_{CP}} = (-0.82 \pm 0.21 \pm 0.11 \, \%)$ [15], a new field opens up. This now also has been confirmed by CDF and BELLE, and new LHCb studies are underway. With the upgrade LHCb will collect an unprecedented large charm sample, and we expect to reach a sensitivity on $\Delta \mathrm{A_{CP}}$ of 0.12 ‰.

Beyond these specific examples LHCb upgrade has a rich spectrum of flavour and non-flavour physics in its reach. In the $\mathrm{B_s}$-mixing LHCb upgrade will measure:

- precisely the weak phase ϕ_s from the decay $\mathrm{B_s} \to \mathrm{J}/\Psi\phi$ to $\sigma(\phi_\mathrm{s}) \sim 8 \, ‰$ and
- $\mathrm{A_{SL}}$ to a sensitivity of 2 ‰.

Further LHCb upgrade will reduce the measurement error of the Unitarity Triangle angle γ to $\sigma(\gamma) \sim 0.9\,°$.

In the electroweak sector LHCb can:

- study how the boson follows the quark direction in the forward region
- by measuring $\sin^2\Theta_\mathrm{eff}^\mathrm{lepton}$, determine $\mathrm{A_{FB}}$ of leptons in Z-decays

Table 2. LHCb upgrade performance benchmarks [11].

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s-mixing	$2\beta_s(B_s^0 \to J/\Psi\phi)$	0.10	0.025	0.008	$\sim$0.003
	$2\beta_s(B_s^0 \to J/\Psi f_0(980))$	0.17	0.045	0.014	$\sim$0.01
	$A_{fs}(B_s^0)$	$6.4 * 10^{-3}$	$0.6 * 10^{-3}$	$0.2 * 10^{-3}$	$0.03 * 10^{-3}$
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	-	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\overline{K^{*0}})$	-	0.13	0.02	<0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi K_s^0)$	0.17	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
	$\gamma^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B^0{}_S}$	-	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08	0.025	0.008	0.02
	$S_0 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 %	6 %	2 %	7 %
	$A_I(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25	0.08	0.025	$\sim$0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 %	8 %	2.5 %	$\sim$10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$1.5 * 10^{-9}$	$0.5 * 10^{-9}$	$0.15 * 10^{-9}$	$0.3 * 10^{-9}$
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	-	$\sim$100 %	$\sim$35 %	$\sim$5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	$\sim$10-12°	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_sK)$	-	11°	2.0°	negligible
	$\beta(B^0 \to J/\Psi K_s^0)$	0.8°	0.6°	0.2°	negligible
Charm CP violation	A_Γ	$2.3 * 10^{-3}$	$0.40 * 10^{-3}$	$0.07 * 10^{-3}$	-
	ΔA_{CP}	$2.1 * 10^{-3}$	$0.65 * 10^{-3}$	$0.12 * 10^{-3}$	-

- measure the forward-backward asymmetry of the top quark
- study electroweak penguins, like $B \to K^{*0}\mu\mu$ and
- measure precisely several other electroweak asymmetries: A_I, S_3,... [16].

LHCb upgrade also can contribute to QCD studies by:

- providing further constraints on the Parton Density Functions
- covering unexplored phase space at low x [17], as depicted in figure 2, and
- by studying jets with flavour tagging.

LHCb upgrade also can study Central Exclusive Production:

- in the reaction $pp \to p + X + p$ with rapidity gap
- in the x_b production and
- for the Pomeron/photon exchange.

And finally LHCb can can reach Hidden Valley particles, if they are long-lived and decay in the LHCb vertex detector.

Table 2 presents a compilation of the LHCb and LHCb upgrade performance benchmarks. Listed are the currently achieved precision, the projections for the precision achievable before and after the LHCb upgrade as well as the theoretical uncertainties.

3. The LHCb Upgrade

Figure 3 shows a schematic of the LHCb detector and summarises the upgrades necessary to the sub-systems. These will be detailed in the following.

The bottle neck for harvesting data with the LHCb experiment from increasing luminosity is the current readout architecture, shown in figure 4. This architecture is limited to a maximum rate of $1\,\mathrm{MHz}$, at the output of the on-detector electronics (Level-0) as well as at the input to the Higher Level Triggers (HLT). The Level-0 trigger is implemented in the hardware of the individual sub-detectors, without information cross-feeding between the sub-detectors. The alleys of the HLT are implemented off-detector as software triggers on a CPU farm.
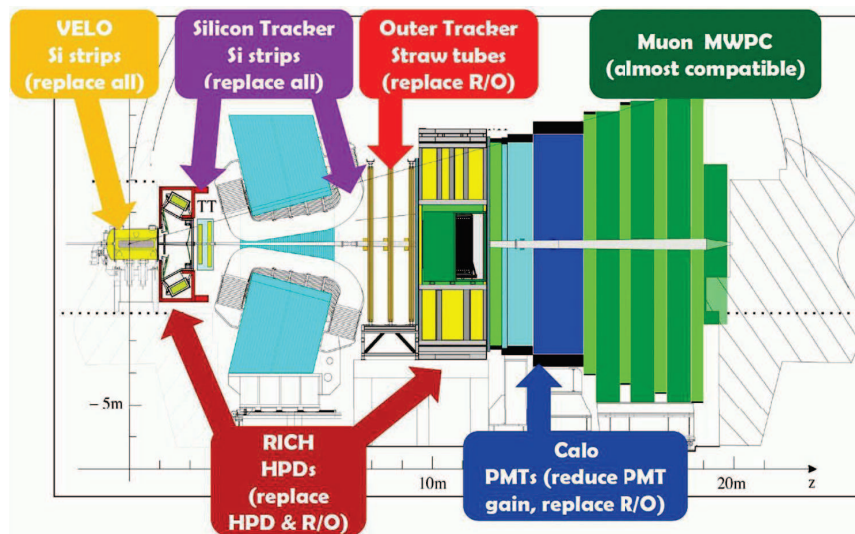
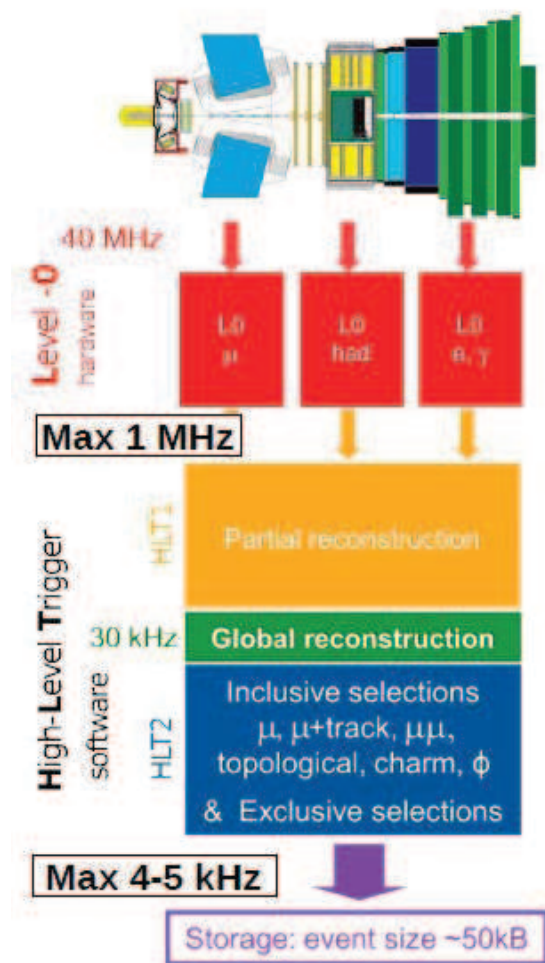**Figure 3.** Summary of the upgrades necessary to the LHCb sub-detector systems.
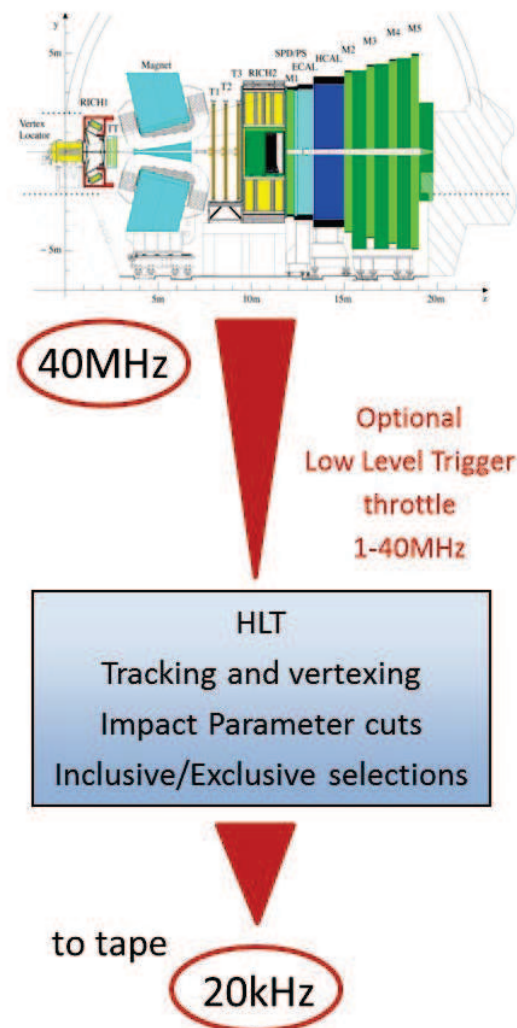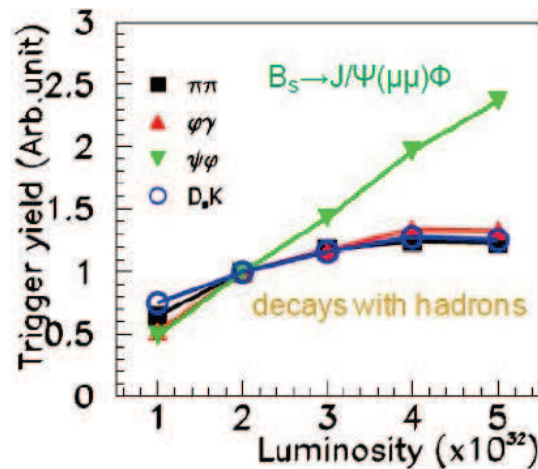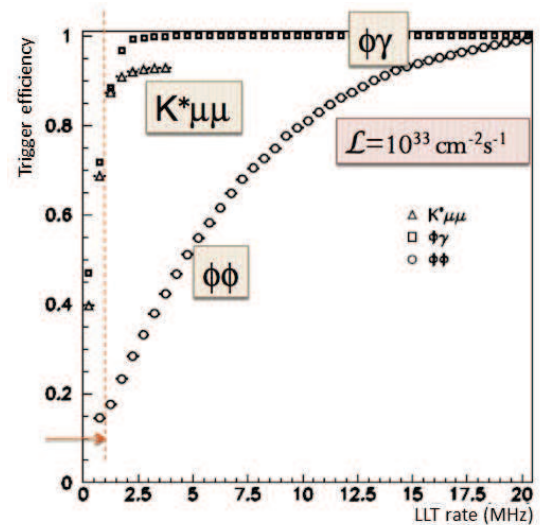

Figure 4. Current LHCb trigger layout.

Figure 5. LHCb upgrade trigger layout.

Figure 6. Simulation of current LHCb trigger yields, depending on luminosity. The efficiency of hadronic channels saturates in the current readout architecture [11].

Figure 7. LHCb upgrade: simulation of trigger efficiency depending on the throughput rate of the Low Level Trigger, at the luminosity of $10^{33} \text{cm}^{-2}\text{s}^{-1}$. The arrow marks the throughput equivalent to the current limit of LHCb [11].

The fixed layout of the Level-0 trigger does not allow for efficient triggering on decays which only have hadronic content. It turns out that as the luminosity increases so does the inefficiency in the hadronic triggers and the net yield of hadronic events levels off, while the yield of events with leptonic content scales with the luminosity increase. Figure 6 demonstrates this from simulations using the current readout for a range of luminosities.

As a first step to improve the current boundaries we recently introduced the deferred HLT, where we use storage capacity and the time between the LHC fills to process those events which otherwise would be discarded by the 20 ms cut-off which is imposed during data taking. This improves the efficiencies of all used trigger alleys, but does not change the scaling problem of the hadronic triggers with luminosity.

With the upgrade LHCb will finally overcome the limitations of the Level-0 trigger by omitting this hardware trigger decision and reading out the full detector information at 40 MHz into the fully flexible software based HLT. This is shown in figure 5. In this scheme the HLT will use all sub-detector information to form the trigger decision and the trigger algorithms will be improved to fully exploit the information becoming available at the HLT level. This e.g. will include an online reconstruction for the Vertex Locator. The HLT eventually will write to tape with a rate of 20 kHz.

The new readout architecture also foresees a Low Level Trigger (LLT) which provides an optional and tunable throttle, to accommodate the detector output to the HLT intake capabilities. These intake capabilities will grow over time as the HLT CPU farm gets enlarged. As the output rate of the Low Level Trigger increases above the current design limit of 1 MHz the trigger efficiencies improve. This is shown in figure 7 for three selected benchmark channels. The efficiencies improve for all channels, but the gains are most significant for the fully hadronic channel $B_s \to \phi\phi$, which becomes fully efficient at an LLT output rate of 20 MHz.

Table 3 finally demonstrates how the HLT efficiencies for the three benchmark channels increases significantly as the size of the CPU farm is scaled up by factors of five and ten with respect to the size in 2011.

Table 3. HLT efficiencies of benchmark channels, depending on number of CPUs in the HLT.

Channel	HLT efficiency	2011 size *5	2011 size *10
$B_s \to \phi\phi$		29 %	50 %
$B_s \to K^*\mu\mu$		75 %	85 %
$B_s \to \phi\gamma$		43 %	53 %

The repeating challenges for the design of the sub-detector upgrades are the increased levels of radiation and the increases in the detector occupancies.

The VELO upgrade is a prime example for this. Its electronics will have to withstand radiation of up to $0.3 * 10^{16} n^{eq} cm^{-2}$ (neutron equivalents/cm^2). Its material budget has to be reduced, by thinning down the sensors to a thickness of $200 \, \mu m$, to limit the number or produced secondary particles. In addition thermal run-away has to be prevented by CO_2) cooling. In effect the VELO upgrade has to maintain, if not improve the current excellent performance.

At present two technologies are still considered. The first is a more conventional strip detector layout, with R- and ϕ-geometry. The layout itself will be improved to better balance the occupancies, featuring a reduced pitch of $30 \, \mu m$ and shorter strip lengths. This option would employ a new readout chip which should be shared with the Inner Tracker. The second technology employs a novel pixel detector solution based on the VELOPIX readout chip[18]. The VELOPIX chip features a matrix of $256 * 256$ pixels at a size of $55\mu m * 55\mu m$, leading to a low occupancy. This readout chip is implemented in the $130 \, nm$ technology, is radiation hard to $> 500 \, MRad$ and tolerant to single-event-upsets (SEU). The VELOPIX will read out an edge-less pixel sensor. Further R&D will be performed on both option before a decision is taken for the VELO upgrade.

The current tracker consists of silicon strip detectors at the location of the TT tracking station as well as in the inner-most part of the tracking stations, where the so-called Inner Tracker (IT) covers the area with the highest occupancy. The Outer Tracker (OT), surrounding the Inner Tracker, is made up from straw tubes. In the baseline option for the upgrade the same technologies are used again. The dominant challenge for the Outer Tracker will be the occupancy which increases strongly towards the centre area around the beam pipe. To limit the occupancy in the Outer Tracker to $< 20 \%$ the size of the Inner Tracker will be scaled up, increasing its current area by a factor of four. The silicon-strip detectors face the same challenges as the VELO, with radiation levels up to $2 * 10^{14} n^{eq} cm^{-2}$. Like for the VELO the sensors will be redesigned and optimised to balance the occupancy and to reduce the material. And both systems will share the readout chip design, if the VELO uses for the silicon strip option.

The current RICH system is made up of two detectors, RICH 1 featuring two radiators, Aerogel and C_4F_{10}, and RICH 2 featuring CF_4 as single radiator. The peculiarity is that the front-end electronics is embedded into the vacuum of the Hybrid Photon Detectors, which therefore need to be replaced as well. The challenge in the upgrade for the RICH is to limit the occupancy. For that the Aerogel radiator will be removed and the RICH 1 optics may be changed to minimise the pixelisation error. Baseline for the new photon detectors now are the 64-channel Multianode Photomultiplier tubes of the new generation, R11265[19], which feature an active area of 80% and can be used without projecting lenses. R&D on the design of the readout electronics is underway. Performance studies demonstrate that the occupancy can be kept below 10% and that the particle identification will work well to beyond luminosities of $2 * 10^{33} \, cm^{-2} s^{-1}$.

The electromagnetic and the hadronic calorimeters can keep the detector modules and the

photo-multipliers, as they reasonably can withstand the radiation. But the photo-multipliers need to be run at lower gain to keep the anode currents constant despite the higher occupancies. The new 40 MHz electronics will compensate the reduced gain with a higher amplification. It has been demonstrated that the signal-to-noise ratio and the energy resolution can be maintained, despite the reduced gain of the photo-multipliers.

It is baseline to remove the Scintillating Pad & Parton Shower Detectors (SPD&PS). They are currently used to form the Level-0 trigger decision and have no use in the Low Level Trigger which only provides a throttle. However, studies are performed to see how well the still needed e/γ identification still can be achieved.

The Multi-Wire Proportional Chambers and the front-end electronics of the muon chambers are almost compatible with the LHCb upgrade. While the chambers can be kept as they are, the electronics needs minor modifications but can be reused. Only the first Muon chamber (M1), in front of the calorimeters, will be removed as its tasks will be taken over by the tracking stations. Further studies are performed to safe-guard the performance under high occupancy and against the aging of the chambers.

4. Conclusions

LHCb and LHC are a great success. By now large New Physics is ruled out in many flavour physics observables. Therefore a large increase in statistics is required to investigate small New Physics deviations from the Standard Model.

The LHCb Upgrade plan is mature. The installation of the LHCb upgrade will take place in the long shutdown 2018. The key element is the readout of all sub-detectors at the full rate of bunch crossings at 40 MHz. A fully flexible software trigger increases the trigger efficiency for hadronic channels by a factor of two at least. And the key performance parameters of LHCb will be retained at the high luminosity running.

The LHCb upgrade will be a general purpose experiment in the forward region, covering beauty, charm, lepton-flavour-violation, QCD and exotica. It will probe or measure New Physics at the percentage level.

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