Physics benchmarks of the VELO upgrade

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Abstract: The LHCb Experiment at the LHC is successfully performing precision measurements primarily in the area of flavour physics. The collaboration is preparing an upgrade that will start taking data in 2021 with a trigger-less readout at five times the current luminosity. The vertex locator has been crucial in the success of the experiment and will continue to be so for the upgrade. It will be replaced by a hybrid pixel detector and this paper discusses the performance benchmarks of the upgraded detector. Despite the challenging experimental environment, the vertex locator will maintain or improve upon its benchmark figures compared to the current detector. Finally the long term plans for LHCb, beyond those of the upgrade currently in preparation, are discussed.

Contents

1 The LHCb experiment and its upgrade

The LHCb experiment [1] has been taking data at the LHC since 2010 and has to date collected $5\,\mathrm{fb}^{-1}$ of integrated luminosity and published over 300 papers. It was designed to make precision measurements of CP-violation and rare decays of beauty and charm hadrons. The physics programme has been substantially expanded to include for instance hadron spectroscopy, semi-leptonic decays, electroweak measurements, top quark decays and heavy ion physics.

This broad physics programme is enabled by the full spectrum of hadrons produced in the LHC collisions, where beauty and charm flavoured hadrons are produced in vast quantities. For instance, the $b\bar{b}$ production cross section is $165 \pm 15\,\mu b$ [2] within the acceptance of LHCb at 13 TeV. This is approximately 1.5×10^5 times larger than the $b\bar{b}$ production cross section at the B-factories.

Developments towards a detector upgrade [3] are ongoing and it will be installed during the second long shutdown of the LHC operation in 2019-2020. The principal change in the upgrade is the removal of the hardware trigger to enable readout the whole detector at the full bunch-crossing frequency. The online event selection will be done by a software trigger which will significantly improve the selection efficiency, in particular for purely hadronic final states. In addition, the instantaneous luminosity will increase from the current $4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with the aim of collecting an integrated luminosity of $50\,\mathrm{fb}^{-1}$. This will permit LHCb to achieve even greater precision in its core areas and to further broaden the physics programme, becoming a general purpose detector in the forward region.

The majority of the on- and off-detector electronics will be replaced to enable the trigger-less readout and significant upgrades are made to the detector to accommodate the higher luminosity. The vertex locator (VELO) [4], will be replaced by a hybrid pixel detector with square tracking planes covering a distance from 5.1 to 33 mm from the beam. The pixel size is $55 \times 55\,\mu m^2$ and there are 26 tracking planes spaced 25 mm apart around the interaction region spreading out further away to cover the pseudo-rapidity range of $\eta = 2 - 5$. For more details see ref. [5].

The large production cross sections at the LHC will give unprecedented statistics for many important measurements, but it comes at the price of a challenging experimental environment. The total inelastic cross section is roughly three orders of magnitude larger than the $b\bar{b}$ cross section. This means that there will be on average five visible interactions per bunch crossing whereas only one out of every 60 bunch crossings will contain a $b\bar{b}$-pair. In addition, the track multiplicity is high; a minimum bias primary vertex (PV) has on average 55 tracks.

Both the current and upgraded detectors are designed to reconstruct, trigger on and select signal candidates with high purity and good efficiency in this challenging environment. The VELO is crucial in all these steps and essential in the precision measurements performed on the selected candidates.
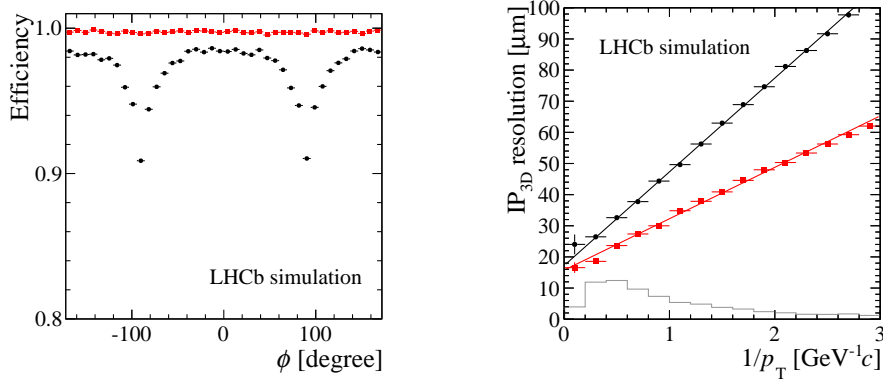
2 Performance benchmarks

The performance plots in this sections are, unless stated otherwise, taken from the VELO Technical Design Report (TDR) [6]. The design of the VELO has evolved since the TDR and the details of the detector simulation have been refined but the results from the TDR still give a reliable picture of the expected performance. The discussion here is centred around heavy flavour physics, where the signal candidates travel a measurable distance before decaying, but most of the conclusions carry over to the broader physics programme. The performance numbers are given for the nominal upgrade luminosity of 2×10^{33} cm^{-2}s^{-1} and an average number of visible interactions per bunch crossing of $\langle \mu \rangle = 5.2$.

Tracking efficiency. The first step in the process of identifying signal candidates is to reconstruct the tracks from the measured space points. This has to be done with high efficiency and within the timing constraints given by the software trigger. The track reconstruction efficiency of the current silicon micro-strip based VELO is measured to be greater than 98% in the 2011 running conditions [4] and can be performed within the required time budget. However, since the luminosity will be increased by a factor five and the input rate for the software trigger will be increased from 1 to approximately 30 MHz, the current VELO layout would not perform satisfactorily. Studies showed that a finer pitch micro-strip detector could give 95% track reconstruction efficiency within an acceptable timing budget [7], whereas the chosen pixel detector layout will have better than 99% tracking efficiency.
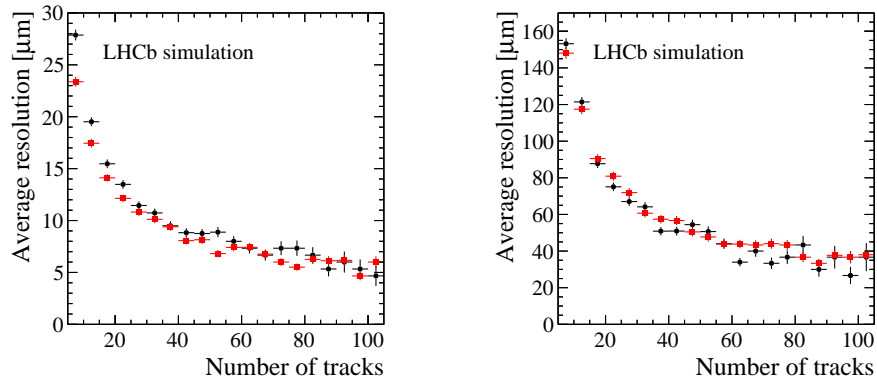
In addition to the improved average tracking efficiency provided by the pixel geometry, the efficiency is more uniform across variables such as azimuthal angle, pseudo-rapidity, radial flight distance and z-origin of the tracks. As an example the tracking efficiency as a function of azimuthal angle is shown in figure 1 (left) for the current and upgraded VELO detector. Non-uniform efficiencies are a potential source of systematic uncertainties, and reducing these are crucial for the high precision measurements to be made by the upgraded detector. For a detailed study of the effects of the non-uniform reconstruction efficiency in the current detector, see ref. [8].

Primary vertex resolution. The identified tracks are used to reconstruct the primary vertices of the proton-proton collisions. The resolution depends on the number of tracks that emerge from the PV, as shown in figure 2. The performance of the current VELO is maintained for the upgraded detector. The average number of tracks from a PV that has produced a b$\bar{\text{b}}$-pair is 120 [4] and the resolutions are approximately 5 μm and 40 μm transverse to and along the beam axis respectively.

Due to the large number of tracks, the uncertainty of the PV position only contributes marginally to the uncertainty of derived quantities such as track impact parameters or b-hadron flight distances. However, a decay vertex could be associated with the wrong PV if there several of them in one bunch crossing. The probability of this depends on the number of interactions per bunch crossing and it happens for approximately 1% of the signal candidates at the upgrade luminosity, which is

Figure 1. (left) The track reconstruction efficiency as a function of the azimuthal angle ϕ. (right) Impact parameter resolution as a function of the inverse of the transverse momentum ($1/p_T$). The light grey histogram shows the relative population of b-hadron tracks in each bin. Black dots are for the current VELO and red dots for the upgraded detector, both simulated in upgrade conditions where the average number of visible interactions per bunch crossing is $\langle \mu \rangle = 5.2$.

Figure 2. Primary vertex resolution as a function of the number of track per primary vertex, transverse to (left) and along (right) the beam axis. Black dots are for the current VELO and red dots for the upgraded detector, both simulated in upgrade conditions where the average number of visible interactions per bunch crossing is $\langle \mu \rangle = 5.2$.

an acceptable level. If the luminosity would be increased significantly beyond that planned for the upgrade, e.g. in the the scenario discussed in section 3, it may become an issue.

Impact parameter resolution. The impact parameter (IP) is the distance of closest approach between a track and its associated primary vertex. The IP resolution can be modelled as a linear function of the inverse of the transverse momentum ($1/p_T$) [9]. The simulated IP resolution and the fitted model for the current and upgraded VELO are shown in figure 1. The resolution model has two terms: the first (multiple scattering) term gives the slope and it depends on the radius of the first measured point and the amount of material encountered before the second measured point; the second (resolution) term gives the offset of the curve and depends on the hit resolution and the distance between the measured points.

The multiple scattering term dominates for low momentum tracks and the upgrade gives a significant improvement in resolutions for these as can be seen in figure 1. This comes from two changes going from the current to the upgraded detector. The sensors are closer to the beam with the radius of the first sensitive element reduced from 8.2 mm to 5.1 mm. And there is a reduction in the material encountered before the second measure point, mainly from the foil separating the VELO from the beam vacuum. This is enabled by the L-shaped detector geometry and the use of micro-channel cooling. Since signal tracks typically have a momentum larger than 1 GeV/c, this term is mainly of importance for background rejection. The resolution term dominates for high momentum tracks and here the performance is similar for the current and upgraded VELO. Here two changes compensate each other: the detector is moved closer and the inter-module pitch is reduced, but the minimum strip or pixel pitch is increased from 40 μm to 55 μm. Hence the upgraded VELO detector maintains its IP resolution for signal tracks, which translates into a maintained performance for the secondary vertex resolution.

Secondary vertex resolution. The secondary vertex (SV) resolution is important for identifying long-lived signal candidates, an improved resolution means that it is possible to put tighter requirements on the distance of closest approach (DOCA) of two tracks when combining them into a signal candidate. For most decays that only have charged particles in the final state, the SV resolution is sufficiently good for LHCb to select very pure samples of signal decays and this will remain to be the case for the upgrade. Final states with neutral particles are more challenging for LHCb, for instance semi-leptonic decays. Here kinematic and geometrical constraints are used to reconstruct the signal decay since the neutrino escapes undetected. Quantities such as the corrected mass [10] are used to discriminate between signal and background and any increase in resolution would result in an increase in signal yield.

Decay time resolution. The decay time is determined from the flight distance measured by the VELO and the momentum and invariant mass measured by the tracking system. The decay time resolution of the upgraded LHCb detector will improve slightly to approximately $\sigma_t = 43$ fs. It has a negligible effect on the measurement uncertainty of particle lifetimes as long as the lifetime of the particle is significantly longer than the decay time resolution. This is the case for b-hadrons and charm mesons, where the the lifetimes are $0.4 - 1.5$ ps, but for charmed baryons it does play a role since many of them have lifetimes in the order of 100 fs or less.

The decay time resolution is of particular importance for oscillation measurements of neutral mesons. The resolution enters as a statistical dilution factor $D = \exp\left(-\frac{\Delta m^2 \sigma_t^2}{2}\right)$, where Δm is the mass difference between the mass eigenstates. This is of particular importance for B_s^0 mesons since the oscillations are rapid with an angular frequency (Δm_s) of 17.8 ps^{-1}. The improvement in decay time resolution for the upgrade correspond to an increase in an effective signal yield of 15%.

3 Outlook and long-term plans

LHCb has shown that it is possible to perform high precision flavour physics measurements at the LHC and the excellent performance of the VELO has been crucial in this success. The upgraded VELO detector will be read out at the full bunch-crossing frequency in an even higher multiplicity environment, with maintained or improved performance.

The LHCb upgrade will start taking data in 2021 and will collect an integrated luminosity of $50\,\text{fb}^{-1}$ through LHC Runs 3 and 4 until approximately 2030. There will be a long shutdown from 2024–2026 when the general purpose detectors (GPD) will install their high-luminosity upgrade. This shutdown will be used by LHCb for detector consolidation and further upgrades to some systems, to cope with the increased luminosity and radiation damage, and to enhance the detector performance. There are currently no plans for upgrades of the VELO in this period.

The LHC will continue to operate beyond 2030, to permit the GPDs to collect their target integrated luminosity. LHCb have started to form plans for a possible phase 2 upgrade for this era, aiming to take data at an luminosity of up to $2 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ collecting an integrated luminosity of $300\,\text{fb}^{-1}$. The physics case for this upgrade is currently under study and the detector requirements are being worked out. These running conditions will imply an increase expected radiation damage of up to $5 \times 10^{16}\,1\,\text{MeV}\,\text{n}_{\text{eq}}$ fluency for the VELO if the detector geometry remains the same. Moreover, it means an increase by a factor 10 in data rates if the same trigger-less readout is kept, a challenging requirement since the expected data rates for the VELO upgrade are in the excess of $15\,\text{Gbit/s}$ per detector module. The increased luminosity will further increase the number of visible interactions per bunch crossing and track multiplicity, putting even more stringent requirements on the VELO performance. Clearly these are very challenging prospects which also present some exciting detector R&D opportunities to realise this future upgrade.

Acknowledgments

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