Summary

As we study matter in detail, we can zoom in from molecules to atoms down to the smallest blocks that make up matter, the subatomic particles. The first challenge in the subatomic realm is to understand how these particles interact with each other. Physicists have been developing theories to explain these interactions and have been performing experiments in order to examine them. The most successful theory so far that describes interactions between the subatomic particles is the Standard Model. Although this theory has been vigorously tested, a number of questions remain unanswered, e.g. why is there no antimatter in the universe and what is the nature of dark matter? A search for physics beyond the Standard Model can be carried out through precision measurements of decays of $B$-mesons.

$B$-mesons are produced by colliding bunches of high energy protons. This is achieved at the Large Hadron Collider at CERN where the colliding protons have a center of mass energy of 13 TeV. Among the particles produced by the colliding protons, large amounts of $B$-mesons are produced at small angles with respect to the interacting beams. These particles travel on average about 1 cm from the point they are produced until the point they decay. These two points are called primary and secondary vertex, respectively. To identify a $B$-meson, the lifetime of the particle can be used. The lifetime is reconstructed from the distance between the primary and the secondary vertex. In addition, a characteristic aspect of neutral $B$-mesons is that particle-antiparticle transitions, called oscillations, occur on average nine times during the lifetime of the particle. To study these fast oscillations, that occur between the primary and secondary vertex, a good decay time resolution of the detector is required.

The LHCb experiment at CERN is optimised to study $B$-mesons. The LHCb detector setup consists of a tracking system and a particle identification system. One of the detectors of the tracking system is the Vertex Locator (VELO), which is a silicon strip detector. The VELO plays a central role in studying $B$-meson properties like their primary and secondary vertices.

In the coming years LHCb will operate its detectors at a higher luminosity in order to collect more data. To increase the data rate a new trigger scheme will be adopted that requires the upgrade of all tracking detectors. This upgrade brings a number of challenges. The VELO upgrade is required to read out all data from each bunch crossing, have a good decay time resolution and operate...
smoothly after accumulating fluences up to $8 \times 10^{15}$ 1 MeV \(n_{eq}/cm^2\). To meet these challenges the VELO upgrade will feature a new silicon pixel detector.

The new silicon detector is based on a new pixel front-end chip, the VeloPix ASIC. The ASIC is built in a 130 nm CMOS technology and consists of a pixel matrix of $256 \times 256$ square pixels with a $55 \mu m$ pitch. To reduce the amount of material, the chip will be thinned down to 200 $\mu m$. If the charge liberated by a traversing particle is above a certain threshold, the Time of Arrival (ToA) is measured with a timing resolution of 25 ns and stored with the pixel location.

The signature of a single particle track originating from the decay of a $B$-meson is a large impact parameter with respect to the primary vertex. Measuring the impact parameter (IP) with a small error is one of the key ingredients leading to a good decay time resolution.

The IP resolution worsens with the amount of material traversed by the particle and depends on the detector resolution, the particle momentum and the extrapolation length from the position of the first measurement plane to the particle vertex. The VELO upgrade will feature channels with coarser pitch and a radiation thickness larger by a factor of 1.3 resulting in a worse detector resolution and larger extrapolation error, respectively. However, the edge of the sensors in the VELO upgrade will be 3 mm closer to the beam thereby reducing the extrapolation error.

The performance of the VELO upgrade has been simulated in order to predict how these factors contribute to the IP resolution. Although the worse detector resolution and the larger radiation length in the VELO upgrade have a small negative effect on the IP, the reduced extrapolation error results in a better IP resolution. The VELO upgrade is expected to perform better than the current VELO in terms of IP resolution.

An important element of the VELO upgrade is the silicon sensor. The baseline option for the VELO upgrade sensors are 200 $\mu m$ thick, $n$-on-$p$ type diodes. In addition to the baseline option, other design variants in terms of thickness and sensor type were also considered.

A number of prototype silicon sensors with the above sensor characteristics were produced by the companies VTT, Hamamatsu and Micron. A subset of these sensors were irradiated with neutrons at the JSI institute in Ljubljana up to the highest fluence the VELO upgrade will be exposed to. Ideally, all sensors would have been tested with the VeloPix readout. However, VeloPix was not available at the time the prototype sensors were tested.

Most of the prototype sensors were instead bump-bonded to Timepix3 ASICs and were placed in a beam of 180 GeV protons and pions at the SPS at CERN. To perform dedicated studies on these sensors, a telescope of 8 Timepix3 detectors was assembled. The Timepix3 telescope planes were equally divided
in two arms. Each prototype sensor was placed as Device-under-Test (DuT) between the two telescope arms where the track-pointing resolution is better than 2 µm. This resolution allowed the study of pixel sensors with sub-pixel precision.

By placing the sensors perpendicular with respect to the beam, tracking efficiency and charge collection efficiency measurements were performed. Using the sub-pixel point resolution of the telescope, the tracking efficiency at the edge of active-edge sensors from VTT was measured. These sensors are about 100% efficient through all the pixel matrix and >99% efficient up to 10 µm from the physical edge.

During operation, the VELO upgrade sensors will be irradiated. The charge collection yield in an irradiated sensor decreases due to various radiation induced defects as for example charge trapping. For the VELO upgrade at the benchmark voltage of 1000 V, a minimum signal yield of 6000 e⁻ is required when the sensors are irradiated at the maximum fluence of $8 \times 10^{15}$ 1 MeV n$_{eq}$/cm$^2$. The charge collection efficiency of the irradiated sensors was measured in order to investigate whether enough charge is collected. The irradiated sensors can deliver 7000 e⁻ when operated at 1000 V satisfying the VELO upgrade requirements.

A set of precision measurements was performed with the sensors at large (grazing) angles with respect to the beam such that the incoming particle traverses multiple adjacent pixels. Knowing the angle of incidence, the path length from the entry point of a track to a pixel is assigned to a certain depth in the sensor. Using this technique the collected charge and time to threshold versus the depth of charge deposition were measured.

According to the charge collection profile of the sensors irradiated to the highest fluence, most of the charge is collected from depths close to the pixel electrode. The depleted region does not reach the backplane even when the sensor is operated at 1000 V. To understand the charge collection profile data, the charge trapping from both electrons and holes needs to be taken into account.

Besides the charge collection profile, the time to threshold profile has also been investigated. The time it takes for the charge to drift and cross the threshold can be calculated by subtracting the time the track intercepted the telescope ($t_{\text{track}}$) by the time a pixel hit is recorded on the DuT ($t_{\text{hit}}$). A simulation of the time to threshold based on Ramo’s theorem, which describes well the charge collection time in a non-irradiated sensor, fails to describe the data. Including the average timewalk in the simulation describes well the time to threshold profile of an irradiated sensor because the time is dominated by timewalk.

Both prototype silicon sensors from Hamamatsu and Micron qualify for the VELO upgrade in terms of charge collection and time of arrival. Additional
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future measurements will reveal more information on how radiation induced effects influence charge collection.

The road is open for new exciting results with VeloPix prototype sensor assemblies and finally the installation and commissioning of the VELO upgrade.