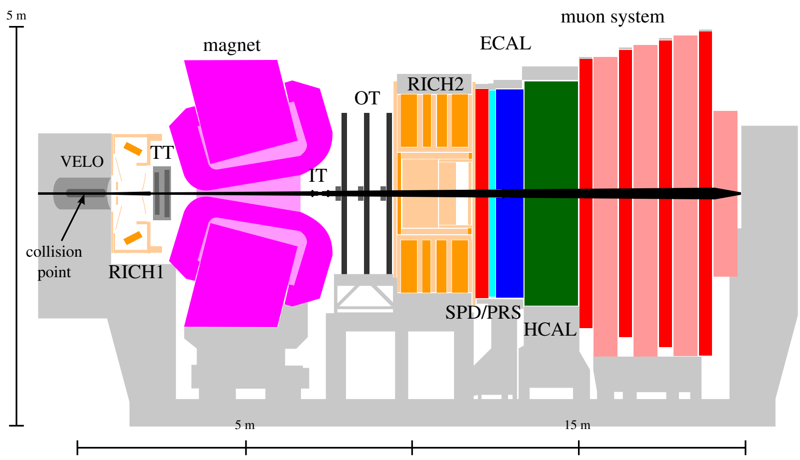
Year 3 Particle Physics Computing
LHCb Vertex Locator Project Description

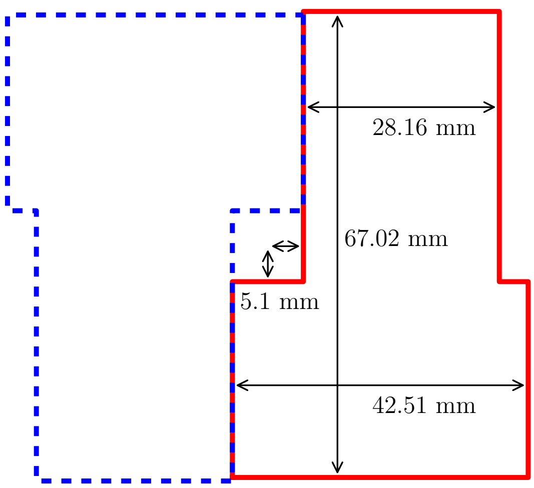
Resource 1 *LHCb VELO Upgrade Technical Design Report* by the LHCb collaboration

In particle detectors, the passage of charged particles is measured using tracking sub-detectors. These trackers are oftentimes made out silicon sensors. Each time a charged particle passes through one of the sensors of the detector, an electronic signal is produced and recorded. These signals are called hits, corresponding to an (x, y, z)-position through which the particle passed. By combining hits together from all the sensors through which the particle passed, it is possible to determine the path, or track, the particle took through the tracker. If a magnetic field is present in the tracker, then the charged particles will bend as they pass through the detector due to the Lorentz force. The curvature of the track left by the particle can then be used to determine the momentum of the particle. This is the primary method by which modern particle detectors are able to measure the momentum of charged particles.

The LHCb detector on the Large Hadron Collider (LHC), pictured on the right, was designed specifically to measure the decays of B-mesons. Because B-mesons can fly some small but measurable distance in the detector before decaying, LHCb has a tracking sub-detector with a particularly high resolution very near the collision point. This detector is called the vertex locator (VELO) and is split in half. After the LHC beams become stable for a data taking run, the two sides of the VELO close down around the beam. Each side of the detector has silicon sensors. In the original VELO, which was used during LHC runs 1 and 2, these sensors were strip-sensor pairs, with one set of semi-circular strips and another set of straight strips radiating outward. The semi-circular strips would provide a radial measurement r of the hit and the straight strips would provide an angular measurement ϕ. A hit from both of these strip-sensors together provided a radial and angular coordinate, r and ϕ, which then allowed for a full (x, y, z)-point to be determined, given the position of the sensor pair.



The LHCb detector is now being upgraded for run 3 of the LHC, which will last from 2022 until 2024. The old VELO has been removed and a new VELO is being installed in its place. In this design of the VELO, the sensors are pixel detectors rather than strip detectors, so each hit corresponds to a pixel or cluster of pixels, rather than two strip-sensor readouts. The full details of the upgrade VELO can be found in *LHCb VELO Upgrade Technical Design Report* by the LHCb collaboration. This is a rather hefty tome, so feel free to ask where certain information might be (*you actually don't need much from here to complete the project*). The goal of this project is to model the performance of the upgrade VELO detector. We will use the passage of electrons through the detector to characterise its performance.



Both the left and right side of the VELO have 26 silicon sensors for a total of 52 sensors. The geometry of these sensors in the (x, y)-plane is given in the schematic on the left. Each sensor has a thickness of roughly 0.2 mm, *e.g.* the dimension of the sensor along the z-axis. The VELO is roughly 1 m in length, with the sensors centred at the following z-positions for the left and right sides.

	left side	right side
z [mm]	-277, -252, -227, -202, -132, -62, -37, -12, 13, 38, 63, 88, 113, 138, 163, 188, 213, 238, 263, 325, 402, 497, 616, 661, 706, 751	-289, -264, -239, -214, -144, -74, -49, -24, 1, 26, 51, 76, 101, 126, 151, 176, 201, 226, 251, 313, 390, 485, 604, 649, 694, 739

The VELO is outside any magnetic field, so the tracks produced in the VELO are just straight lines. If a particle track has three or more hits, the particle is then considered to be reconstructed, *i.e.* it has enough hits to be used.

There are three detector effects which complicate this. The first is a per hit efficiency. When a charged particle passes through the detector, it does not always produce a signal that is recorded. The VELO has a hit efficiency of $\approx 98\%$. The second issue is hit resolution. Each sensor has a hit resolution of ≈ 0.012 mm in both x and y, with a z resolution dependent upon the alignment of the detector, but assumed for practical purposes to be zero. The third is multiple scattering, as charged particles pass through material, they will scatter through small angles. Combining all of these effects results in tracks that are no longer straight lines and might have some points missing. In the end, there are even more detector effects which need to be considered, but other than bremsstrahlung which is rather complicated and only significant for light charged particles (i.e. electrons), these are the main ones. Within this project, we will only consider the first two effects ().

Goal 1 Define a particle class given by a momentum vector and an initial starting point, *e.g.* (x, y, z).

Goal 2 Create a class that represents a right-side VELO sensor, with a method that checks if an (x, y) point is within the sensor.

Goal 3 Repeat Goal 2, but for a left-side VELO sensor.

Goal 4 Make a class which represents the VELO, including all the VELO sensors.

Goal 5 Implement a hits method in the VELO class which returns all the expected sensor hits, given an input particle.

Goal 6 Calculate the track reconstruction efficiency as a function of pseudo-rapidity (η), for charged particles produced at the origin. A particle is considered to be reconstructed if it has three or more hits.

Goal 7 Add an additional argument to the hits method of Goal 5 which specifies the per hit efficiency. Determine whether a hit is generated using this efficiency.

Goal 8 Repeat Goal 6, but take into account the hit efficiency.

Goal 9 Include an argument to Goal 5 which specifies the per hit resolution. Assume the resolution follows a Gaussian distribution and randomly smear each hit by this resolution.

Goal 10 Perform a straight line fit of the hits for particles produced at the origin with uniformly sampled η and ϕ and a momentum magnitude of 10 GeV. From this fit, determine the resolution on the p_{T} of the electrons, assuming the magnitude of their momentum is known.