SUMMARY

Have a look at the following pictures: The picture on the left [132] has been taken

![Microscope image of cartilage cells](image1)

![Electron microscope image of DNA double helix](image2)

with a microscope\(^3\) and shows cartilage cells from a human sample. The scale of
the cell is of the order of a micrometre (\(\mu m\)), that is \(10^{-6}\) m, a millionth of metre.
The picture on the right [133] instead has been taken with an electron microscope
and shows the first direct image of the DNA double helix. We are now at the
nanometre scale (nm), that is \(10^{-9}\) m, a billionth of metre.

Cells and DNA are not only part of our body, but also part of our common
thinking. Even if at first glance our skin appears smooth and seamless, we know
today that skin, as well as plants, animals and the matter around us, is the result of
aggregations of tinier components. Most of these are far too small to be seen with
naked eye, and can be pictured or probed only by means of specific instruments.

We can place such components on a scale of relative size, that I will hereby call
“the relative scale of matter”:

![The relative scale of matter](image3)

\(^3\) It has been taken precisely with a confocal microscope. The confocal microscopy is an imaging technique
that allows to increase resolution and contrast of an optical image.
The research presented in this dissertation deals with objects that are even smaller than cells and DNA and are placed at the very end of the relative scale. Atoms are not the most elementary component of matter, but they are made of subatomic (smaller than an atom) particles called protons, neutrons and electrons. These are the base of all matter surrounding us. As a simple example, more than 60% of our body is water: a molecule of water (H$\textsubscript{2}$O) counts two atoms of hydrogen and one atom of oxygen. The hydrogen atom is the simplest in nature and made of one proton and one electron. It is slightly tricky to talk about size of subatomic particles, but we can place them at the scale of a femtometre (fm), that is $10^{-15}$ m, or below. Protons and neutrons are themselves an “aggregation” (bound state) of elementary particles that we call quarks.

We can now extend the relative scale of matter to the domain of particle physics:

At the present time, the framework that best describes particles and forces binding particles together is known as the Standard Model. It includes the 6 kinds (“flavours”) of quarks observed so far: the two lightest (“up” and “down”) compose protons and neutrons, while the remaining four (“charm”, “strange”, “beauty” and “top”) existed only briefly at the beginning of the universe evolution and today can only be recreated in the lab. Moreover, the Standard Model places the electron ($e$) in a family of elementary particles called leptons, together with muons ($\mu$), taus ($\tau$) and neutrinos ($\nu$).

The following sketch illustrates the Standard Model particles “zoo”:
For every matter particle there is a corresponding antimatter particle, that is completely identical but having opposite charge (quantum characteristics). Some antimatter particles, like the positron (antielectron) and the antineutrino, are generated by natural processes such as radioactive decays, but we can also generate antiparticles in the laboratory. Let’s see how.

(Anti)Particles in the Lab: a Particle Experiment

For decades the nature of matter has been probed with particle physics experiments. The Standard Model seems to be extremely successful in accommodating most of the phenomena observed in those experiments, but at the same it still leaves open questions. Some of the questions relate to the origin and evolution of the universe and their answers might lie beyond the Standard Model, in other models that we call “New Physics”.

The main goal of particle physics today is to find evidence to support potential New Physics models. A way to proceed requires creating higher energy environments to experiment on. This will generate standard particles not present in the ordinary matter (as heavier quarks and leptons), and might lead to the creation of totally new particles, belonging to even earlier stages in the history of the universe.

To work at such high energy environments, we build particle accelerators, machines that are able to accelerate “ordinary matter particles” at extremely high velocities and to “smash” them in very high energy collisions. The more energetic we can make the particles, the better we can see the underlying structure of matter. The Large Hadron Collider (LHC) is a circular particle accelerator, the largest and most energetic in the world. In 2012 it accelerated protons at about the speed of light, with a collision energy up to 8 teraelectronvolts (10^{12} \text{ eV})

\[ \text{A particle collider} \]

What happens at the collision point? The protons break into their constituent quarks, in what we call “proton-proton interaction”, and other particles are generated from the energy transfer. For instance, a quark of type “strange” (s) and and anti-quark of type “beauty” (\bar{b}) might be created and then form a bound state, another particle, named “B^0_s meson”. The B^0_s can live for about one millionth of a second, travelling in space thanks to the energy boost received at the collision point. At the end of its life, it will simply disintegrate to form lighter and eventually more stable states, in a process called decay.
The interaction process and the particle event that follows are characterised by *tracks* (particle trajectories) and *vertices*, obtained from the intersection of multiple tracks. The primary vertex identifies the collision point in space, while the decay (or secondary) vertex corresponds to the point where the created particle disintegrates.

To capture a “snapshot” of the collision and observe particle decays we use a *particle detector*, which is the equivalent of a powerful microscope, able to deal with the scales typical of particle physics processes. Detectors are built around the collision point and gather information on measurable variables – including velocity, mass, charge – from which we can assign the particle’s identity. Modern particle detectors consist of layers of subdetectors, each designed to look for a particular property or a specific type of particle.

An example of a particle accelerator and a particle detector from our everyday life is the cathode ray tube of old TV’s. It accelerates electrons and then smashes them into phosphor molecules on the screen; the collision results in a lighted spot, or pixel, on your TV monitor.

For the research presented in this dissertation, I used the LHCb detector, one of the particle detectors installed along the circumference of the LHC. Its main purpose is to study events involving the “beauty”-quark, since many of them still require more understanding and might be good probes of New Physics models. Since $b$-quarks are predominantly produced in a cone following a “forward” direction from the collision point, the LHCb detector has been designed as a single-arm forward detector.
Commissioning of the Pile-Up detector

The protons circulating in the LHC machine are not guided to the collision point one by one, but they travel in bunches of billions of protons each. Therefore it is very likely that multiple proton-proton interactions are observed simultaneously when two bunches are “smashed” against each other (so-called bunch crossing). Events with more than one proton-proton interaction are called pile-up events. Such events can be a challenge for data analysis of $b$-physics at LHCb. The Pile-Up sub-detector has been designed to count the number of vertices per event and eventually discard events that are too crowded.

The Pile-Up is positioned opposite of all the other subdetectors with respect to the collision point, as visible in the previous sketch. It has two parallel measuring planes; each plane consists of two circular sensors carrying microstrips of silicon. When a charged particle crosses a Pile-Up sensor, it intersects one of its strips (in red in the following sketch). A current is correspondently generated, allowing to determine the position of a point on the particle trajectory (here identified by a blue cross). Such a position is measured in the radial ($r$) and longitudinal ($z$) coordinates.

By combining the information in ($r, z$) gathered by all four sensors, we can determine the position of collision vertices along the beam line and hence count them.

For my PhD research I tested the Pile-Up and tuned the parameters needed to operate the system. This is called commissioning the detector.

One of my projects, for instance, focused on the spatial alignment of the Pile-Up sensors with respect to the VELO detector. Without knowing precisely where the subdetectors are located with respect to each other, it’s impossible to optimally reconstruct particle events.

The position of the Pile-Up sensors was initially measured “by hand”, during the installation of the subdetector in the LHCb cavern. To test that measurement, we used a set of tracks reconstructed by the VELO detector and intersecting the Pile-Up sensors. Each track crosses one of the sensors in a point, whose position can be compared to that of the closest strip registering a signal. We expect the distance between the point and the strip to be zero, if averaged over all sampled tracks. But the comparison revealed that the sensor positions were in need of alignment.
corrections. To determine the required corrections, we first studied the dependence of such distance with the spatial coordinates of the hit position; afterwards, we estimated the optimal set of corrections able to minimise the distance.

Once the alignment corrections were applied, we could verify that the position of the vertices reconstructed by the Pile-Up was on average closer than before to the position of the vertices reconstructed by the VELO. This proved the effectiveness of the alignment procedure and lead to an overall better Pile-Up vertex reconstruction.

The commissioning of the Pile-Up was successful and allowed to operate the detector within the LHCb experiment.

A “rare beauty” in the crowd: First evidence of the $B_s^0 \rightarrow \mu^+ \mu^-$ decay

Particle physicists consider the disintegration of a $B_s^0$ meson into two muons (written as $B_s^0 \rightarrow \mu^+ \mu^-$) as especially convenient to probe models beyond the Standard Model. According to the Standard Model, in fact, only about three $B_s^0$ mesons out of a billion are expected to decay in this way. Being so rare, the $B_s^0 \rightarrow \mu^+ \mu^-$ decay is a powerful probe of New Physics: measuring more than the expected amount of events would mean that we are “hitting” New Physics. In some New Physics models, for instance, the decay rate is expected to be much higher than in the Standard Model. Observing the decay and accurately measuring its rate (or branching fraction, labeled as $B$) is then extremely important.

For decades, various experiments have looked for $B_s^0 \rightarrow \mu^+ \mu^-$ decays, but no evidence was found so far. LHCb is particularly suitable to this search, thanks to its excellent performance in reconstructing $b$-physics events. To be able to measure a $B_s^0 \rightarrow \mu^+ \mu^-$ signal, we firstly select so-called “candidate” events containing pairs of muons of opposite charge (a muon $\mu^-$ and an antimuon $\mu^+$). For each one we reconstruct the energy and momentum of the muons and combine these quantities in the invariant mass of the event. All candidate events can then be placed on a distribution of invariant mass. A signal is observed when the distribution reveals a (statistically significant enough) “peak” over the background, around the $B_s^0$ mass. The height of the peak will also give us information on the rate of the $B_s^0 \rightarrow \mu^+ \mu^-$ signal under study.

The $B_s^0 \rightarrow \mu^+ \mu^-$ analysis is very challenging because the expected rate of the process is very low: this translates in a high background contamination of the
selected data sample and explains why it is extremely important to separate signal from background.

My research aimed at improving such statistical separation. In particular, I focused on the study of background events called “peaking components” because they can fake our signal and create a peak in the invariant mass distribution. They could then populate the signal peak-region or contaminate the surrounding regions, modifying the rate estimate. For example, when a $B^0_s$ decays into a muon and a different particle, the latter can be wrongly identified as a muon during the reconstruction procedure.

Using simulated peaking events and information extracted from data concerning the probability of a wrong particle identification, we estimated the number of fake $B^0_s \rightarrow \mu^+\mu^-$ candidates due to peaking events expected in our sample. The distribution of candidates obtained with LHCb data collected in 2012 is shown in the following figure.

![Distribution of candidates](image)

We observed an excess of $B^0_s \rightarrow \mu^+\mu^-$ signal candidates (a “peak”, in red) with respect to the background expectations (in dashed blue). By evaluating the statistical significance of this excess, the first world evidence of $B^0_s \rightarrow \mu^+\mu^-$ decays was obtained. We measured a corresponding decay branching fraction of $\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.17^{+1.45}_{-1.18}(\text{likelihood}) \pm 0.23(\text{systematics})) \times 10^{-9}$, which is compatible with the Standard Model expectations. The measurement sets more stringent constraint on some New Physics models and apparently leads to another successful test of the Standard Model, but the possible contribution of New Physics to the decay cannot be excluded yet. Higher statistics will allow to improve the experimental precision of the result and to explore new observables describing the decay.