Today we have strong evidence that in addition to normal matter, the Universe contains an about five times larger amount of so-called Dark Matter, the nature of which is currently not known. If Dark Matter is composed of as yet undiscovered elementary particles, then those could affect the decay characteristics of B-mesons and precision measurements would provide information about their properties. This illustrates the general strategy of using precision measurements to look for deviations from the Standard Model predictions, which in turn lead to answers to the currently open questions in particle physics. Other measurements motivated by this strategy are tests of the CPT symmetry, e. g. by studying particle-antiparticle mass differences, or tests of Lorentz invariance in high-energy interactions. Both subjects are pursued at MPIK.

Quark-Gluon Plasma and Extensive Air Showers

Another open question concerns the properties of the matter in the Universe immediately after the Big Bang and still before the formation of the nuclear building blocks (protons and neutrons). This state can be studied at the LHC in high-energy collisions of lead nuclei. A problem in the characterisation of this so-called quark-gluon plasma is that the properties of normal nuclear matter are presently still not sufficiently well known to really pinpoint the properties of the plasma. Here measurements of proton-lead collisions provide important insights, since in such interactions only the effects of normal nuclear matter are present. A quark-gluon plasma is not formed.

Measurements of proton-ion and ion-ion collisions are also required to understand better what happens when high-energy cosmic rays hit the Earth's atmosphere, where they produce secondary particles in collisions with nitrogen or oxygen nuclei, which in turn hit air molecules and produce further secondaries. In such extensive air showers, reactions at very different energy scales contribute. At the LHC, the high-energy processes can be studied in collisions between the counter-rotating beam particles, measurements in fixed-target mode provide access to the lower-energy regime. High-energy processes determine the start of the shower development, lower-energy reactions occur in the later stages. LHCb thus is in the unique position that it can study the physics of the entire shower within a single experiment. Also here MPIK is involved.

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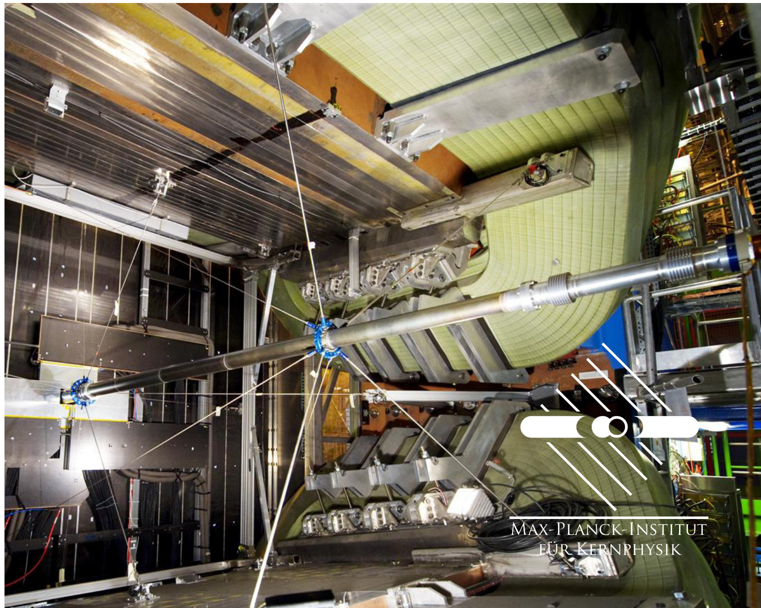
The LHCb Experiment

Precision Physics at the Highest Energies



The LHCb Experiment

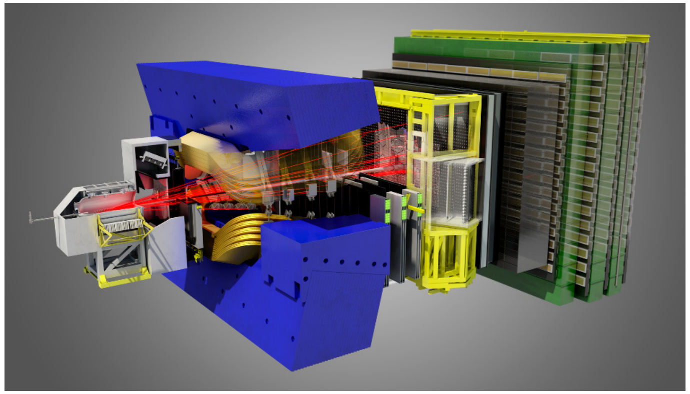
Precision Physics at the Highest Energies

The large Hadron Collider (LHC) at CERN in Geneva is presently the most powerful accelerator world-wide. The LHCb experiment exploits this machine for a broad spectrum of precision measurements and tests of fundamental symmetries in order to explore the limitations of the Standard Model of particle physics. The aim is to find answers to the questions of how the Universe looked before the formation of the nuclear building blocks, why none of the antimatter created in the Big Bang is left in the Universe and what constitutes Dark Matter, but also what happens in interactions of cosmic-ray particles with the Earth's atmosphere.

The LHC and the LHCb Experiment

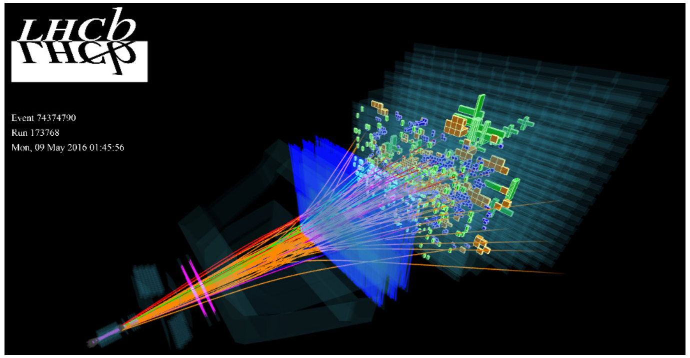
The LHC storage ring has a circumference of 27 km, is located at a depth of about 100 m under ground and has four interaction regions where protons (hydrogen nuclei) or heavy ions, such as lead or xenon nuclei, can be collided at so far unrivalled energies. The kinetic energy of the particles in the two counter-rotating beams is up to 7000 times larger than their rest energy. The particles travel at velocities larger than 99.99999% of the speed of light. Up to 40 million collisions per second occur in the interaction regions, in which part of the kinetic energy of the projectiles is converted into new, also as yet unknown, particles. In collisions of lead nuclei, for example, more than 10 000 particles can be created in a single interaction.

LHCb is one of the four large experiments at the LHC and is operated by an international collaboration of more than 1400 scientists from 88 institutes in 18 countries. The LHCb detector consists of a magnetic spectrometer to record charged particles, calorimeters for neutrals and Cherenkov detectors plus a muon system for particle identification. Between 2010 and 2018, LHCb registered more than 5000 billion collisions, a fraction of which was recorded for further analysis. The analysis is done on the world-wide computing grid with thousands of crosslinked CPUs and attached storage systems. In spring 2022, an upgraded LHCb detector with a significantly improved filter system to select and store interesting events will go into operation at up to five times higher beam intensities.



Schematic view of the about 20 m long and 10 m high LHCb detector. Collisions occur to the left of the spectrometer magnet (blue). Parts of the tracking system and the Cherenkov detectors are visible on both sides. To the right follow calorimeters and muon system. (The title page shows a photo of the region inside the magnet.)

LHCb is currently the leading experiment in the field of heavy-quark physics. Beyond that, and aside from spectacular discoveries of previously unknown particles, the experiment also contributes to electro-weak and strong interaction physics and studies collisions with heavy ions. LHCb is the only experiment at the LHC that in addition can study fixed-target interactions by injecting small amounts of noble gases into the interaction region. MPIK played a leading role in establishing this extension of the LHCb physics portfolio, which in the meantime has become a very visible part of the physics program of the experiment. Here LHCb does address topics that are of interest not only for the particle physics community, but also for astrophysics and cosmic-ray physics.



Visualisation of particle tracks from a collision inside the LHCb detector.

Matter, Antimatter, and Dark Matter

For every elementary particle, there is an antiparticle with the same mass and the same spin but with opposite charge. In a particle-antiparticle collision the two can annihilate, for example into two gamma rays. Conversely, particle-antiparticle pairs can be created from pure energy.

In the Big Bang, initially equal amounts of matter and antimatter were produced from the available energy, and one of the big puzzles in particle physics today is the absence of any evidence for antimatter in the Universe, such as e. g. annihilation radiation from a collision between a normal galaxy and an antimatter galaxy. The Standard Model cannot explain the matter dominance of the Universe. From Standard Model physics alone, one would expect the Universe to contain only matter for about 100 galaxies instead of the 100 billion we see.

Collision of the spiral galaxies NGC 2207 and IC 2163, about 114 million light year away. (Photo: Hubble Space Telescope)

Certain elementary particles, so-called B-mesons, are about five times heavier but a hundred thousand times smaller than a hydrogen atom. They consist to almost 100% of antimatter while the mass of their antiparticles is practically all matter. Both decay to final states consisting of equal amounts of matter and antimatter, where, however, some decay processes exhibit differences when comparing B-mesons and their antiparticles. The LHCb detector is optimised for the study of such processes, with the aim to provide measurements that lead to an understanding of the matter-antimatter asymmetry of the Universe.