# Search for exotic long-lived particles with the LHCb detector

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# Summary

Are the currently known elementary particles and their interactions the most fundamental picture of nature? If yes, how did the universe as we observe it come about?

The standard model of particle physics describes the electromagnetic interaction and the strong and weak nuclear force as relativistic quantum field theories with interactions derived from gauge symmetries between twelve elementary fermions. It extends quantum electrodynamics, which very successfully describes the interactions between electrons, nuclei and light or other types of electromagnetic radiation that are relevant for processes at atomic and molecular scales. The strong nuclear force, which holds nuclei together, is described by a theory that confines the colored quarks in color-neutral bound states, *e.g.* the proton and the neutron. The weak interaction that is responsible for nuclear decays, is modelled by the exchange of charged and neutral vector bosons. The large mass of the messenger particles causes this interaction to be weak compared to the strong and electromagnetic interaction, and nuclear decays to proceed slowly.

In general the theory is in excellent agreement with experimental tests. It does, however, not explain the structure observed in the mass spectrum of the fermions and in their properties, and why the scale of electroweak symmetry breaking, which determines the the masses of the gauge bosons associated with the weak interaction, is so small: the natural scale of a more fundamental theory would be the Planck scale, where gravity needs a quantum description. Therefore, the standard model is considered incomplete, and a natural solution of the aforementioned problems prefers new effects to become visible at energy scales in the TeV range.

Another argument why the standard model is incomplete comes from cosmology. Current models can describe the large-scale evolution of the universe as well as the structure observed at small scales under the assumption that the universe contains a non-baryonic gravitationally interacting matter-like component, dark matter, and a cosmological constant or dark energy component, besides the matter that we observe. Both are well-motivated — dark matter is also needed to describe the observed dynamics of galaxies; the accelerated expansion of the universe is an experimental fact — but their precise nature and origin are not known. New interactions are also required to arrive at a correct prediction of the amount of matter produced in the early universe.

These questions motivate the search for a more complete description of nature, and for experimental evidence to guide its development. Over the last decades, many models for physics beyond the standard model have been proposed, but so far experimental results have not given conclusive evidence for any of those. On the contrary, the possible visible effects of new particles and interactions have been severely constrained.

The large collision data samples collected by the LHC experiments since 2009 have allowed to perform experimental tests of the standard model and searches for new particles at unprecedented energies and precision. Since most inelastic proton-proton collisions at TeV-scale energies are due to the strong interaction and most of the rare processes are accurately described by the standard model, collisions that include new states or other deviations are obscured by large backgrounds. To separate the processes of interest from background, a variety of experimental signatures is used. These include collisions with a large amount of undetected outgoing momentum in the transverse plane, inferred from the recoiling visible particles, fully reconstructible decays of resonances to known particles *etc.*

The focus of this work is the detection of new particles through their decay at a position displaced from the primary proton-proton collision point. Decays as nearby as a few mm to the collision point can be reconstructed by using the precise particle tracking capabilities close to the interaction region provided by silicon vertex detectors. These are nowadays commonly used by collider experiments to identify and study beauty and charm hadron decays, with lifetimes of the order of 1 ps, which translates to typical displacements of the order of 1 cm at the LHC.

The LHCb detector, which was specifically designed for studying heavy flavour decays, can naturally also be used to search for exotic long-lived particle decays, because its vertex detector can reconstruct tracks from decays displaced up to 20 cm along the beam line, and up to about 4 cm in the transverse direction, with high precision and efficiency. Furthermore, it is fully instrumented in the forward region, for angles with the beam line up to 250–300 mrad, with charged particle tracking and identification detectors and calorimeter detectors sensitive to all electromagnetically and strongly interacting particles.

The experimental challenge of discovering new phenomena in LHC detector datasets consists of removing $\mathcal{O}(10^{14})$ background collisions while retaining the capability to identify the searched-for signal process based on as few occurences as possible. This is done in several stages, most with tight constraints on the computing resources used. The first and least flexible step is a hardware trigger system that steers the readout of the detector: only for $1 \times 10^6$ out of the about $12 \times 10^6$ collisions produced during one second of LHC operation can the LHCb detector fully be read out. This decision is based on a rough estimate of the particles with the highest transverse momenta detected by the calorimeter and muon systems.

The fully read out events are then sent to a trigger software application that runs in about $30 \times 10^3$ processes on a computing cluster, where the next two stages of triggering are performed. The first is based on full track reconstruction using the vertex detector information. Interesting tracks, with a displacement typical for heavy flavour decay products, or compatible with a muon detector segment, are further reconstructed beyond the magnetic field, such that their transverse momentum, typically larger for processes of interest than for background, can be used for further discrimination. For the signal studied in this work, a displaced multi-track vertex, an additional selection was added that keeps pairs of tracks, such that the track quality criteria that penalise tracks from decays at more than about 5 mm from the interaction region could be relaxed with respect to the nominal selection requirement. The second software trigger stage consists of a large number of different selections, all reconstructing candidates that are similar to those used for the final measurements. Exotic long-lived particle decays are reconstructed here by an algorithm that considers all tracks in the vertex detector to find their production vertices. High-multiplicity vertices outside the interaction region are candidate decays. The reconstructed invariant mass and the track momenta are used to limit the accept rate. All events that contain at least one candidate passing these selections are stored.

The first analysis step performed on the stored datasets usually consists of the complete re-reconstruction of the candidates, from the level of the read out detector signals up, using the full-precision version of the reconstruction that is executed on the worldwide LHC computing grid, without the tight trigger computing time constraints. For this search, the complete re-reconstruction of the vertex is supplemented by a parallel approach based on the trigger candidates, in order to maximise the efficiency and overlap with the triggered sample. The vertices are used as reference points to attempt the full reconstruction of the two quarks in the final state: a pair of jets of hadrons. This is done with a clustering algorithm that combines reconstructed particles with similar momentum directions, charged as well as neutral. For the charged particles, the information of the vertex detector and the tracking system is maximally used: tracks incompatible with the reconstructed decay position, the vertex, are not considered, and the momentum estimate helps to improve the precision on the jet momentum. The requirement of two jets compatible with a trigger candidate provides sufficient reduction at this stage. The resulting sample is augmented with a set of candidates built from vertices found in the larger track collection that is reconstructed offline.

The data sample is then split into categories based on the transverse displacement from the interaction region. The background yield decreases much faster as a function of this variable than typical signals, because of their different lifetime. Additional vertex, jet quality, and jet-vertex matching requirements are applied in order to further reduce the background. Two classes of instrumental backgrounds can completely be removed: when a particle from a proton-protoncollision interacts with detector material, more particles may be produced,whose tracks give rise to a pattern similar to a signal vertex. Such vertices are removed by vetoing candidates in a region around the detector parts. A second class of background was found to be related to near-parallel tracks, possibly from interactions of the beam with collimators, and collision tracks. If many silicon strips are hit in the same detector region, the reconstruction algorithm can find a large number of tracks that are very close together, such that high-multiplicity vertices can be made. This background is vetoed by exploiting some distinctive properties of the track and hit distributions observed in such events.

The remaining background vertices are due to random combinations of tracks from heavy flavour decays, from material interactions and poorly reconstructed low-momentum particles from the same or different primary collisions. Two categories can be distinguished: candidates dominated by a single heavy flavour jet or material interaction, where the particles are clustered in two nearby jets, and candidates where final-state particles from either side of a collision that produces a heavy quark pair contribute, which gives two jets that are nearly back-to-back in the transverse plane. The invariant mass distribution of the former category, with small opening angle, peaks at low mass and falls rapidly, while the second category leads to a less steeply falling spectrum. The high-mass part of the latter contribution is strongly reduced by two selection requirements applied on the candidates: the candidate should point back to a primary proton-proton collision point and the opening angle should not be too large.

The dijet invariant mass spectrum is then fitted, separately in each of the transverse displacement categories, using an empirical model that contains a contribution for the searched-for signal and for each of these background types: the dominating small-angle background contribution is described by an analytical model that tends to an exponential at high values, and is fully determined from data, in every category separately. For the second contribution, a fixed shape is added, also with an exponential high-mass tail, with the slope fixed from the high-mass distribution of the whole sample before the final selections. Statistical hypothesis tests are performed, and upper limits on the production of long-lived particles with the assumed decay properties are obtained.

A sensitivity down to the level of a few pb, or a branching fraction of 20 % of the standard model Brout-Englert-Higgs boson is obtained, for long-lived particle lifetimes in the range 2–500 ps and masses in the range 25–50 GeV/$c^2$. This covers the low-mass low-lifetime region that is difficult to probe by the other LHC experiments, and that has previously been studied at the Tevatron collider with a lower centre-of-mass energy and smaller datasets. For the studied part of parameter space, the LHCb results are the most stringent to date.

Due to the minimal assumptions made to perform this search — only a single long-lived particle decay is assumed, and the selection only exploits the decay of such a particle to quarks, and no other features of the same collision — the obtained results apply to any other model that predicts the production of long-lived particles that decay to quarks, if corrected for the possibly different fraction of decays contained in the forward region visible to the detector. The developed methods can be applied to the large data sets that will be collected at a higher collision energy in the coming years, and to other final states, in order to discover or further constrain the production of exotic long-lived particles.