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SEARCH FOR LONG-LIVED EXOTIC PARTICLES AT LHCb

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Abstract

Many beyond the Standard Model theories propose the existence of a long-lived heavy particle decaying into Standard Model particles. The decay of those neutral long-lived particles provides a displaced vertex; a signature which can be detected with the LHCb detector at the Large Hadron Collider. A search has been performed for a Higgs-like boson decaying into two neutralinos, using the dataset collected at the LHCb detector in 2010 corresponding to an integrated luminosity of approximately 35.8 pb^{-1}. The analysis is sensitive to long-lived particle lifetimes from 3 to 25 ps and masses between 30 and 55 GeV. No evidence for the production of these long-lived states is observed, and limits are set on their production rates.

1 Introduction

Although the Standard Model has proven to be a successful description of particle physics, it leaves several fundamental questions unanswered, such as the hierarchy of mass scales, neutrino oscillations, matter-antimatter asymmetry, and the nature of dark matter and dark energy. There exists a wide variety of theoretical models that can solve some of these problems. Several of those models predict the existence of new massive long-lived particles with a measurable flight distance. Those particles would produce vertices displaced from the interaction region, which the LHCb detector can reconstruct efficiently [1].

A first class of models featuring long-lived particles originates in weak scale supersymmetry (SUSY). If R-parity violation in SUSY is allowed, the lightest superpartner decays into Standard Model particles, which leave a displaced vertex signature. A particular model in the framework of minimal supergravity (mSUGRA) R-parity violation models is proposed by Carpenter, Kaplan and Rhee [2]. In this model the lightest neutralino $\tilde{\chi}_1^0$ has a mass in the range 20-60 GeV/c^2 and it decays into three quarks through baryon number violation (BV). Such decays give rise to three soft jets with a total invariant mass related to that of the original sparticle [3]. This study considers neutralino lifetimes in the range from 3 to 25 ps, compatible with the limits on the baryon number violating couplings λ'' [4] [5]. The production of $\tilde{\chi}_1^0$ mainly happens in pairs through the decay of the light Higgs boson h^0 with a mass 110-120 GeV/c^2. At a small value of $\tan\beta$, the SUSY h^0 is essentially equivalent to the Standard Model Higgs, with an expected production cross-section of about 20 pb at 7 TeV pp collisions [6].

A second example is the Hidden Valley (HV) model, in which a new non-abelian gauge group exists, hidden by a large energy scale [7] [8]. The Hidden Valley region may be accessible at the LHC, resulting in the decay of hidden particles into Standard Model particles. A Higgs boson may exist which decays with a significant branching fraction as $h^0 \to \pi_\nu \pi_\nu \to b\bar{b}b\bar{b}$, where the π_ν is a new scalar long-lived particle.

2 LHCb Detector

The analysis is performed using data collected by LHCb during 2010, corresponding to an integrated luminosity of 35.8 pb^{-1}.

The LHCb detector [1] is a single-arm forward spectrometer covering the approximate pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high precision tracking system with a silicon-strip vertex detector (the VErtex LOcator or VELO) surrounding the pp interaction region, enclosed by an RF-foil shielding the sensors from the radio frequency perturbation produced by the beams. In addition, the tracking system consists of a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift-tubes placed downstream. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photon, electron and hadron candidates are measured by a calorimeter system. Muons are identified by a muon system composed of alternating layers of iron and multiwire proportional chambers.

3 Simulated Samples

Monte Carlo events are used to investigate the sensitivity of LHCb to the long-lived particle production and decay processes and to provide an estimate of the overall Higgs detection efficiency. This analysis considers the BV48 and HV10 models, assuming a branching fraction of unity for the Higgs decaying into two long-lived particles. The signal events are generated using Pythia 6.423 [9]. The baryon number violation model BV48 has the following parameters: the lifetime of the long-lived particle (τ_{LLP} = 10 ps), the mass of the long-lived particle (m_{LLP} = 48 GeV/c^2), the Higgs mass (m_{h^0} = 114 GeV), and the standard MSSM parameters (M1 = 62 GeV, M2 = 250 GeV, $\tan\beta = 5$ and μ = 140 GeV). The Hidden Valley model HV10 has the parameters (τ_{LLP} = 10 ps), (m_{LLP} = 35 GeV) and (m_{h^0} = 130 GeV).

For an integrated luminosity of 35.8 pb^{-1}, both models predict about 160 events with at least one reconstructible displaced vertex in the acceptance, and 80 events with at least two vertices. In addition to the signal samples, simulated Standard Model events are used, namely 8.5 M inclusive $b\bar{b}$ events (i.e. events with b-hadrons) with an enhanced contribution of displaced b-hadron decays. The $t\bar{t}$ and $c\bar{c}$ backgrounds are found to be negligible. For the simulation, pp collisions are generated using PYTHIA with a specific LHCb configuration [10]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [11] [12] as described in [13].

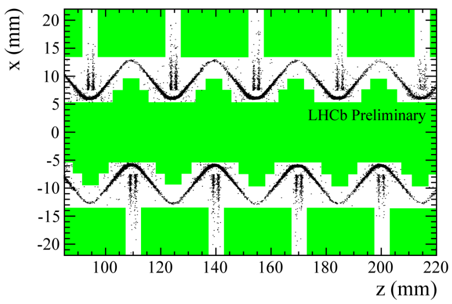

Figure 1: *Distribution in x and z, for $|y| < 1$ mm, of the reconstructed candidate vertices. The visible structures reflect the geometry of the VELO detector, with the doublets of silicon sensors appearing as pairs of vertical bands and the RF foil as the two wave shapes. The green-shaded region represents the fiducial vacuum volume in which displaced vertex candidates are accepted.*

4 Event Selection

4.1 Online Selection

The trigger consists of a hardware stage, based on information from the calorimeter and muon systems, followed by two software stages. The software levels include lines specially defined to select displaced vertices which are reconstructed by a vertexing algorithm in the trigger. The trigger accepts events with two or more displaced vertices, each having no backward going tracks (pseudorapidity in the range $-3.5 < \eta < -1.5$), at least four forward tracks ($2 < \eta < 5$) which form an invariant mass larger than 3 GeV and a distance to the beam-line larger than 0.4 mm. Furthermore there should be at least one primary vertex in the event and at least two candidate vertices downstream of the most upstream primary vertex.

The main source of background arises from particles that have interacted with the detector material. Candidate vertices are required to be in a fiducial volume (of which a slice is shown in fig. 1) defined to exclude the VELO sensors and the RF foil.

A total number of 58,552 events pass the above selection criteria. An identical selection is applied to the signal and background MC samples. Using the measured cross-section $\sigma_{b\bar{b}} = 287 \pm 40\,\mu$b [14) 15)], the analysis of the

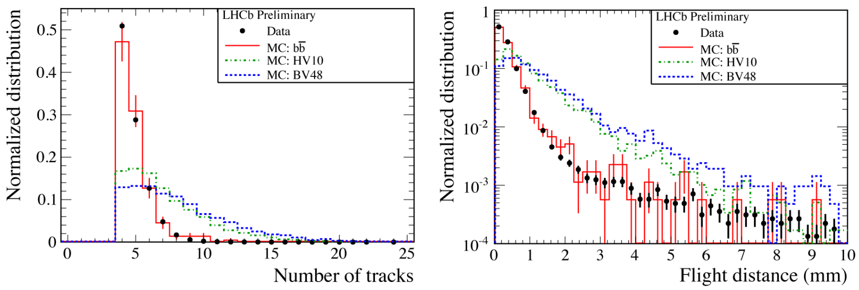

Figure 2: *Number of tracks and flight distance of the long-lived candidates selected at the trigger level.*

inclusive $b\bar{b}$ MC sample predicts $(75 \pm 13) \times 10^3$ events at this stage. Fig. 2 indicates that not only the number of events, but also the distributions in data are compatible with $b\bar{b}$ as the dominant background.

4.2 Offline Selection

The two long-lived particles are expected to travel almost back-to-back in the transverse (x,y) plane, in the absence of radiative effects. Fig. 3 shows the azimuthal angle $\Delta\phi$ between the position vectors drawn from the primary vertex to the displaced vertices. Pairs of candidates with $\Delta\phi > 2.8$ rad are combined to form a parent (Higgs) candidate.

The total number of Higgs-like candidates after the above selection is 13,893 and the resulting invariant mass distribution of candidates is shown in fig. 3. A likelihood fit is performed to the data using the expected shapes of the BV48 signal and of the simulated $b\bar{b}$ events. The fit yields a number of signal events compatible with zero (43 ± 198 signal events with $14,316 \pm 713$ $b\bar{b}$ and a fit χ^2 of 1.4 per degree of freedom). The data are therefore consistent with $b\bar{b}$ background.

The final selection requires at least six tracks and an invariant mass larger than 6 GeV for each candidate. Additionally the displaced vertex position error is required to be $\sigma_r < 0.05$ mm and $\sigma_z < 0.24$ mm. The cuts have been chosen to remove all the Standard Model background, while optimizing the Higgs signal detection efficiency, ϵ. This efficiency can be found in tab. 1 for different stages of the event selection. For the BV48 model $\epsilon = (0.384 \pm 0.017)$ % is

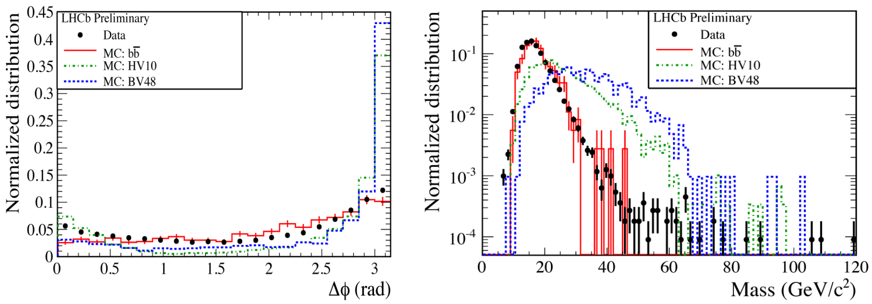

Figure 3: *The azimuthal angle difference and the invariant mass, both normalized to one, of the pairs of long-lived particle candidates selected by the azimuthal angle cut $\Delta\phi > 2.8$.*

predicted, resulting in two expected events in an integrated luminosity of 35.8 pb^{-1}. No data events survive the final selection.

5 Systematic uncertainties

The contributions to the systematic uncertainty are summarized in tab. 2. The uncertainty on the trigger efficiency has been estimated by comparing the number of $b\bar{b}$ events with large time of flight in data and simulation, and agrees within a statistical uncertainty of 15 %. Conservatively this value is adopted as the systematic uncertainty on the trigger efficiency. In addition the results have been cross-checked by using candidates generated in the detector material, and by sampling with independent triggers.

The uncertainty on the total track reconstruction efficiency has been estimated from a comparison of the number of tracks observed in the candidates in data and $b\bar{b}$ MC events. The quoted contribution of 7 % is inferred by artificially varying the track efficiency in simulated events.

The comparison of data and MC distributions gives a calibration uncertainty of 10 % on the measurement of the p_T and the mass of the long-lived particle, and of ± 0.01 mm on the vertex position errors σ_r and σ_z. By shifting the cuts by these amounts the quoted contributions of 6 % and 12 % are obtained.

The effect of the fiducial volume requirement has been estimated by taking

Requirement	ϵ (%)
One LLP in acceptance (generator cut)	29.4
LLP preselection	44.1
Trigger	35.5
Fiducial volume	95.8
LLP selection	66.4
Two LLP found	19.1
$\Delta\phi$ cut	68.4
Total	0.384
Total without trigger	0.589

Table 1: *Fraction of the BV48 signal events surviving at different stages of the analysis.*

Source	%
Integrated luminosity	4
Trigger	15
Track reconstruction	7
p_T and mass calibration	6
Vertex reconstruction	12
Fiducial volume	4
Beam-line position	1
Total	22

Table 2: *Systematic uncertainties on the Higgs detection efficiency.*

into account only displaced vertices restricted to a radial distance < 4.5 mm from the beam-line, far from the RF foil.

A possible bias coming from the cut on the radial distance with respect to the beam-line position uncertainty has been estimated to contribute with less than 1 %.

6 Results and Conclusion

Since no events pass the final selection criteria, the analysis for a particular point of the BV model (m_{LLP}=48 GeV, a lifetime of 10 ps, and m_{h^0}=114 GeV) results in a cross-section upper limit of 32 pb at 95 % CL.

A full MC simulation is made for several other points in the BV model parameter space (varying τ_{LLP}, m_{LLP} and m_{h^0}). In order to cover a larger region of the parameter phase space of the theoretical model, a fast simulation program has been developed, which runs over $h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ events generated by PYTHIA [9]. The charged particles selected within the LHCb acceptance are fed to a vertex reconstruction algorithm similar to the one for real data. Inefficiencies are parameterized as a function of the vertex position to simulate the fiducial volume requirement.

The procedure is compared with the full simulation and tuned to obtain the correct shape for the most relevant distributions. The systematic uncertainties are assumed to be the same as for the full simulation. The results of the fast simulation, which can be found in [16], correspond well with the sample points of the full simulation.

References

1. LHCb collaboration, A.A. Alves Jr. *et al*, The LHCb detector at the LHC, JINST **3** (2008) S08005.

2. L.M. Carpenter, D.E. Kaplan, and E.-J. Rhee, Six-quark decays of the Higgs boson in supersymmetry with R-parity violation, Phys. Rev. Lett. **99** (2007) 211801, arXiv:hep-ph/0607204.

3. J.M. Butterworth, J.R. Ellis, A.R. Raklev, and G.P. Salam, Discovering baryonnumber violating neutralino decays at the LHC, Phys. Rev. Lett. **103** (2009) 241803, arXiv:0906.072.

4. R. Barbier *et al*, R-parity-violating supersymmetry, Physics Reports **420** (2005) 1, arXiv:hep-ph/0406039

5. H.K. Dreiner, M. Kramer, and B. O'Leary, Bounds on R-parity violation from leptonic and semi- leptonic meson decays, Phys. Rev. **D75** (2007) 114016, arXiv:hep-ph/0612278.

6. LHC Higgs Cross Section Working Group, Higgs cross sections at 7, 8 and 14 TeV, (April 2012), https://twiki.cern.ch/twiki/bin/view/LHCPhysics/.

7. M.J. Strassler and K.M. Zurek, Echoes of a hidden valley at hadron colliders, Phys. Lett. **B651** (2007) 374, arXiv:hep-ph/0604261

8. M.J. Strassler and K.M. Zurek, Discovering the Higgs through highly-displaced vertices, Phys. Lett. **B661** (2008) 263, arXiv:hep-ph/0605193.

9. T. Sjöstrand, S. Mrenna, and P. Skands, PYTHIA 6.4 Physics and manual, JHEP **05** (2006) 026, arXiv:hep-ph/0603175.

10. I. Belyaev *et al*, Handling of the generation of primary events in Gauss, the LHCb simulation framework, Nuclear Science Symposium Conference Record (NSS/MIC) IEEE (2010) 1155.

11. GEANT4 collaboration, J. Allison *et al*, Geant4 developments and applications, IEEE Trans. Nucl. Sci. **53** (2006) 270

12. GEANT4 collaboration, S. Agostinelli *et al*, GEANT4: A simulation toolkit, Nucl. Instrum. Meth. **A506** (2003) 250.

13. M. Clemencic *et al*, The LHCb simulation application, Gauss: design, evolution and experience, Journal of Physics: Conference Series **331** (2011), no. 3 032023.

14. LHCb collaboration, R. Aaij *et al*, Measurement of J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. **C71** (2011) 1645, arXiv:1103.0423

15. LHCb collaboration, R. Aaij *et al*, Measurement of $\sigma(pp \to b\bar{b}X)$ at $\sqrt{s} = 7$ TeV in the forward region, Phys. Lett. **B694** (2010) 209, arXiv:1009.2731.

16. LHCb collaboration, R. Aaij *et al*, Search for Higgs-like bosons decaying into long-lived exotic particles (2012), LHCb-CONF-2012-014.