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Searches for low mass dark bosons

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A search is presented for a hidden-sector boson, χ, produced in the decay $B^0 \to K^*(892)^0\chi$, with $K^*(892)^0 \to K^+\pi^-$ and $\chi \to \mu^+\mu^-$. The search is performed using a pp-collision data sample collected at $\sqrt{s} = 7$ and 8 TeV with the LHCb detector, corresponding to integrated luminosities of 1 and 2 fb^{-1} respectively. No significant signal is observed in the mass range $214 \leq m_\chi \leq 4350$ MeV, and upper limits are placed on the branching fraction product $\mathcal{B}(B^0 \to K^*(892)^0\chi) \times \mathcal{B}(\chi \to \mu^+\mu^-)$ as a function of the mass and lifetime of the χ boson. These limits place the most stringent constraints to date on many theories that predict the existence of additional low-mass dark bosons.

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1. Introduction

Most extensions of the Standard Model (SM) that address the problem of the existence of Dark Matter, postulate the existence of a hidden sector, see for example the review in Ref. [1]. Particles of the hidden sector are singlets with respect to the SM gauge number, however they can interact with SM particles via kinetic mixing. In this analysis a search for a light scalar particle (dark scalar boson, χ) belonging to the secluded sector and mixing with Higgs boson is performed. Concrete examples of such models are theories where such a χ field was responsible for an inflationary period in the early universe [2], and the associated inflaton particle is expected to have a mass in the range $270 < m(\chi) < 1800$ MeV. Another class of models invokes the axial-vector portal [3] in theories of dark matter that seek to address the cosmic-ray anomalies, and to explain the suppression of charge-parity (CP) violation in strong interactions [4]. These theories postulate an additional fundamental symmetry, the spontaneous breaking of which results in a particle called the axion [5]. The energy scale, $f(\chi)$, at which the symmetry is broken lies in the range $1 \lesssim f(\chi) \lesssim 3$ TeV [6].

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2. Search for $B^0 \to K^*(892)^0\chi(\to \mu^+\mu^-)$

The decay $B^0 \to K^{*0}\chi$, with $K^{*0} \to K^+\pi^-$ and $\chi \to \mu^+\mu^-$ is studied to search for such a hidden-sector particle. An enhanced sensitivity to hidden-sector bosons arises because the $b \to s$ transition is mediated by a top quark loop at leading order (Fig.1). Therefore, a χ boson with $2m(\mu) < m(\chi) < m(B^0) - m(K^{*0})$ and a sizable top quark coupling (obtained via mixing with the Higgs sector), could be produced at a substantial rate in such decays.

Similar searches have been performed in the past by B-factories [7, 8], they were the most stringent direct constraints on a light scalar dark boson. Their exclusion limits on the coupling (i.e. mixing angle) between the Higgs and the dark boson field lie between 7×10^{-4} and 5×10^{-3}, whith the most sensitive region just below the J/ψ threshold [9].

This search is performed with the full Run I dataset collected with the LHCb detector corresponding to an integrated luminosity of 3.0 fb^{-1}.

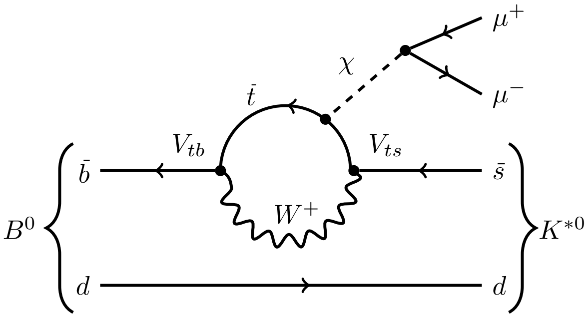

Figure 1: Feynman diagram for the decay $B^0 \to K^{*0}\chi$, with $\chi \to \mu^+\mu^-$.

3. Selection and strategy

Depending on the strength of the mixing with the Higgs boson and its mass, the particle χ can decay in a secondary vertex, displaced from the $B^0 \to K^{*0}\chi$ decay vertex. In order to increase the sensitivity, two regions of reconstructed di-muon lifetime, $\tau(\mu^+\mu^-)$, are defined for each $m(\chi)$ considered in the search: a prompt region, $|\tau(\mu^+\mu^-)| < 3\sigma[\tau(\mu^+\mu^-)]$, and a displaced region, $\tau(\mu^+\mu^-) > 3\sigma[\tau(\mu^+\mu^-)]$, where $\sigma[\tau(\mu^+\mu^-)]$ is the lifetime resolution. When setting a limit on the branching fraction the two regions are combined as a joint likelihood, $\mathscr{L} = \mathscr{L}^{prompt} \cdot \mathscr{L}^{displaced}$. These two regions correspond to the two possible scenarios: the former is sensitive to short lifetime dark boson, it is characterized by high reconstruction efficiency but it is highly contaminated by the irreducible SM background $B^0 \to K^{*0}\mu^+\mu^-$; the latter suffers of lower reconstruction efficieny but offers a very clear signature thanks to lower background yields.

A multivariate selection is applied to reduce the background, the uBoost algorithm [10] is employed to ensure that the performance is nearly independent of $m(\chi)$ and $\tau(\chi)$. The inputs to the algorithm include B^0 transverse momentum, various topological features of the decay, the muon identification quality, and isolation criteria. Only candidates with invariant mass m_{B^0} within 50 MeV of the known B^0 mass are selected. Then, the reconstructed m_{B^0} is constrained to its known value to improve the resolution of the dimuon mass, that results to be less than 8 MeV over the entire $m(\mu^+\mu^-)$ range, and as small as 2 MeV below 220 MeV.

The strategy described in Ref. [11] is adopted: the $m(\mu^+\mu^-)$ distribution is scanned for an excess of χ signal candidates over the expected background. Since all the theoretical models predict the dark boson χ to have negligible width compared to the detector resolution, the signal window is entirely determinated by the di-muon mass resolution and is defined to be $\pm 2\sigma[m(\mu^+\mu^-)]$ around the tested mass. The step sizes in $m(\chi)$ are $\sigma[m(\mu^+\mu^-)]/2$. In order to avoid experimenter bias, all aspects of the search are fixed without examining the $B^0 \to K^{*0}\chi$ candidates.

Narrow resonances are vetoed by excluding the regions near the ω, ϕ, J/ψ, $\psi(2S)$ and $\psi(3770)$ resonances. These regions are removed in both the prompt and displaced samples.

4. Results and exclusion limits

Figure 2 shows the $m(\mu^+\mu^-)$ distributions for the number of observed candidates in both the prompt and displaced regions. The observation is consistent with the background only hypothesis with a p-value of about 80%, therefore an upper limit on $\mathscr{B}(B^0 \to K^{*0}\chi(\to \mu^+\mu^-))$ is set. Figure 3 shows the upper limits both on the absolute branching fraction $\mathscr{B}(B^0 \to K^{*0}\chi(\mu^+\mu^-))$ and on the relative ratio to the normalization channel $\mathscr{B}(B^0 \to K^{*0}\mu^+\mu^-)$ in the $1.1 < m^2(\mu^+\mu^-) < 6.0$ GeV^2 region. Limits are set at the 95% confidence level (CL) for several values of $\tau(\chi)$. The limits become less stringent for higher values of $\tau(\chi)$, as the probability of the χ boson decaying within the LHCb's silicon vertex detector decreases.

Figure 4 shows the interpretation of the exclusion limit in term of two benchmark models: the inflaton model of Ref. [12], which only considers $m(\chi) < 1$ GeV, and the axion model of Ref. [3]. In the first case, constraints are placed on the mixing angle between the Higgs and inflaton fields, θ, which exclude most of the previously allowed region. For the latter, exclusion regions are set in the limit of large ratio of Higgs-doublet vacuum expectation values, $\tan\beta \gtrsim 3$, for charged-Higgs

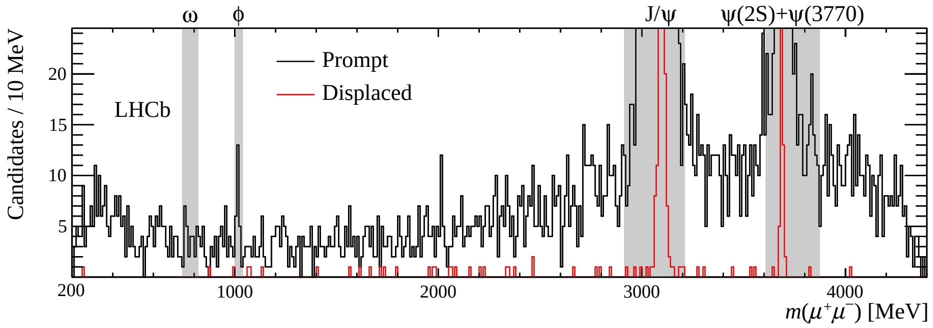

Figure 2: Distribution of $m(\mu^+\mu^-)$ in the (black) prompt and (red) displaced regions. The shaded bands denote regions where no search is performed due to (possible) resonance contributions. The J/ψ, $\psi(2S)$ and $\psi(3770)$ peaks are suppressed to better display the search region.

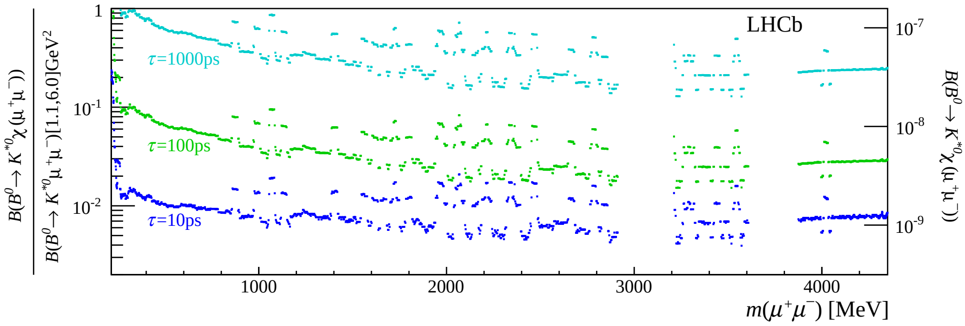

Figure 3: Upper limit on the (left-axis) ratio of branching fractions $\mathscr{B}(B^0 \to K^{*0}\chi(\mu^+\mu^-))/\mathscr{B}(B^0 \to K^{*0}\mu^+\mu^-)$, where the $B^0 \to K^{*0}\mu^+\mu^-$ decay has $1.1 < m^2(\mu^+\mu^-) < 6.0\,\text{GeV}^2$ and (right-axis) on $\mathscr{B}(B^0 \to K^{*0}\chi(\mu^+\mu^-))$ as a function of the dimuon mass. The limits are given at 95% confidence level. Limits are presented for three different lifetimes of the dark boson. The sparseness of the data leads to rapid fluctuations in the limits. The relative limits for $\tau < 10$ ps are between $0.005 - 0.05$ except near $2m(\mu)$.

masses m$(h) = 1$ and 10 TeV. The branching fraction of the axion into hadrons varies greatly in different models, the results for two extreme cases are shown: $\mathscr{B}(\chi \to hadrons) = 0$ and 0.99.

5. Conclusion

In summary, a search is performed for light scalar dark boson in the decay $B^0 \to K^{*0}\chi(\to \mu^+\mu^-)$ using pp-collision data collected at 7 and 8 TeV. No evidence of signal is observed, and upper limits are placed on $\mathscr{B}(B^0 \to K^{*0}\chi) \times \mathscr{B}(\chi \to \mu^+\mu^-)$. This is the most sensitive search to date over the entire accessible mass range and stringent constraints are placed on theories that predict the existence of additional scalar or axial-vector fields.

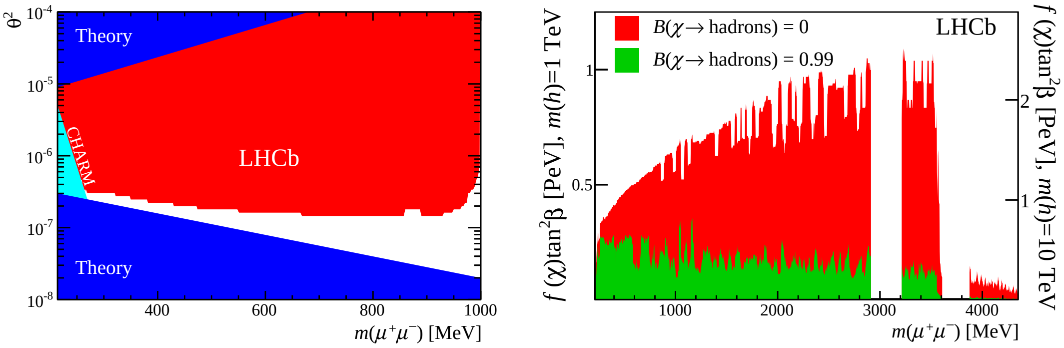

Figure 4: Exclusion regions at 95% CL: (left) constraints on the inflaton model of Ref. [12]; (right) constraints on the axion model of Ref. [3]. The regions excluded by the theory [12] and by the CHARM experiment [13] are also shown.

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