Search for a light dark sector particle at LHCb

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A search is presented for a hidden-sector boson, $\chi$, produced in the decay $B^0 \rightarrow K^*(892)^0 \chi$, with $K^*(892)^0 \rightarrow K^+\pi^-$ and $\chi \rightarrow \mu^+\mu^-$. 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 $B(B^0 \rightarrow K^*(892)^0 \chi) \times B(\chi \rightarrow \mu^+\mu^-)$ as a function of the mass and lifetime of the $\chi$ 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, \( \chi \)) belonging to the secluded sector and mixing with Higgs boson is performed. Concrete examples of such models are theories where such a \( \chi \) 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].

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 \( \chi \) 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 \( 7 \times 10^{-4} \) and \( 5 \times 10^{-3} \), with the most sensitive region just below the \( J/\psi \)

![Feynman diagram](image.png)

Figure 1: Feynman diagram for the decay \( B^0 \to K^{*0}\chi \), with \( \chi \to \mu^+\mu^- \).
This search is performed with the full Run I dataset collected with the LHCb detector corresponding to an integrated luminosity of 3.0 fb$^{-1}$.

### 3 Selection and strategy

Depending on the strength of the mixing with the Higgs boson and its mass, the particle $\chi$ can decay in a secondary vertex, displaced from the $B^0 \rightarrow K^{*0} \chi$ 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, $\mathcal{L} = \mathcal{L}^{\text{prompt}} \cdot \mathcal{L}^{\text{displaced}}$.

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 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$; the latter suffers of lower reconstruction efficiency 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 $\chi$ signal candidates over the expected background. Since all the theoretical models predict the dark boson $\chi$ to have negligible width compared to the detector resolution, the signal window is entirely determined 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 selected $B^0 \rightarrow K^{*0} \chi$ candidates.

Narrow resonances are vetoed by excluding the regions near the $\omega$, $\phi$, $J/\psi$, $\psi(2S)$ and $\psi(3770)$ resonances. These regions are removed in both the prompt and displaced samples.
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 $J/\psi$, $\psi(2S)$ and $\psi(3770)$ peaks are suppressed to better display the search region.

Figure 3: Upper limit on the (left-axis) ratio of branching fractions $\mathcal{B}(B^0 \to K^{*0}\chi(\mu^+\mu^-))/\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$, where the $B^0 \to K^{*0}\mu^+\mu^-$ decay has $1.1 < m^2(\mu^+\mu^-) < 6.0$ GeV$^2$ and (right-axis) on $\mathcal{B}(B^0 \to K^{*0}\chi(\mu^+\mu^-))$ 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 $2m(\mu)$.

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 $\mathcal{B}(B^0 \to K^{*0}\chi(\rightarrow \mu^+\mu^-))$ is set. Figure 3 shows the upper limits both on the absolute branching fraction $\mathcal{B}(B^0 \to K^{*0}\chi(\mu^+\mu^-))$ and on the relative ratio to the normalization channel $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ 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 $\chi$ 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, $\theta$, 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 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: $B(\chi \rightarrow \text{hadrons}) = 0$ and 0.99.

5 Conclusion

In summary, a search is performed for light scalar dark boson in the decay $B^0 \rightarrow K^{*0} \chi (\rightarrow \mu^+ \mu^-)$ using $pp$-collision data collected at 7 and 8 TeV. No evidence of signal is observed, and upper limits are placed on $B(B^0 \rightarrow K^{*0} \chi) \times B(\chi \rightarrow \mu^+ \mu^-)$. 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.
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