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 $\mathcal{B}(B^0 \rightarrow K^*(892)^0 \chi) \times \mathcal{B}(\chi \rightarrow \mu^+ \mu^-)$ 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.
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 $1 \ll f(\chi) \ll 3$ 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 $J/\psi$ 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 $\chi \to \mu^+\mu^-$.](image-url)
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 $B^0 \rightarrow K^{*0}\chi$ 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.

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 $\mathcal{B}(B^0 \rightarrow K^{*0}\chi(\rightarrow \mu^+\mu^-))$ is set. Figure 3 shows the upper limits both on the absolute branching fraction $\mathcal{B}(B^0 \rightarrow K^{*0}\chi(\mu^+\mu^-))$ and on the relative ratio to the normalization channel $\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$ 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
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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 $\mathcal{B}(B^0 \rightarrow K^{*0}\chi(\mu^+\mu^-))/\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$, where the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay has $1.1 < m^2(\mu^+\mu^-) < 6.0$ GeV$^2$ and (right-axis) on $\mathcal{B}(B^0 \rightarrow K^{*0}\chi(\mu^+\mu^-))$ 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: $\mathcal{B}(\chi \rightarrow hadrons) = 0$ 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 $\mathcal{B}(B^0 \rightarrow K^{*0}\chi) \times \mathcal{B}(\chi \rightarrow \mu^+\mu^-)$. 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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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.

References