Search for a Low Mass Particle Decaying into $\mu^+\mu^-$ in $B^0 \to K^{*0}X$ and $B^0 \to \rho^0 X$ at Belle

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We search for dimuon decays of a low mass particle in the decays $B^0 \to K^{*0}X$ and $B^0 \to \rho^0 X$ using a data sample of $657 \times 10^6 B\bar{B}$ events collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. We find no evidence for such a particle in the mass range from 212 MeV$/c^2$ to 300 MeV$/c^2$ for lifetimes below 10^{-12} s, and set upper limits on its branching fractions. In particular, we search for a particle with a mass of 214.3 MeV$/c^2$ reported by the HyperCP experiment, and obtain upper limits on the products $\mathcal{B}(B^0 \to K^{*0}X) \times \mathcal{B}(X \to \mu^+\mu^-) < 2.26(2.27) \times 10^{-8}$ and $\mathcal{B}(B^0 \to \rho^0 X) \times \mathcal{B}(X \to \mu^+\mu^-) < 1.73(1.73) \times 10^{-8}$ at 90% C.L. for a scalar (vector) X particle.

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The possibility of a weakly interacting light particle with a mass from a few MeV to a few GeV has been extensively discussed [1]. Recent astrophysical observations by PAMELA [2] and ATIC [3] have been interpreted as dark matter annihilation mediated by a light gauge boson, called the U boson [4], which couples to standard model particles. In addition, the HyperCP collaboration [5] has reported three $\Sigma^+ \to p\mu^+\mu^-$ events with dimuon invariant masses clustered around 214.3 MeV$/c^2$ that are consistent with the process $\Sigma^+ \to pX$, $X \to \mu^+\mu^-$. Phenomenologically, X could either be a pseudoscalar or an axial-vector particle [6] with a lifetime for the pseudoscalar case estimated to be about 10^{-14} s [7]. Many plausible explanations for such a particle have been proposed, a pseudoscalar sgoldstino particle [8] in various supersymmetric models [9], a light pseudoscalar Higgs boson [10] in the next-to-minimal-supersymmetric standard model as well as a vector U boson [11] as described above.

Recently there have been searches for a similar light particle at the Tevatron [12], e^+e^- colliders [13] and fixed-target experiments [14,15]. In those searches, the light particle was assumed to be a pseudoscalar and no evidence has been found. The KTeV result in K_L decay disfavors a pseudoscalar explanation of the HyperCP results [15].

The large sample of B^0 decays at Belle provides a good opportunity to search for a light scalar or vector particle. In particular, the estimated branching fractions for $B^0 \to VX$, $X \to \mu^+\mu^-$ where X is a sgoldstino particle with a mass of 214.3 MeV$/c^2$ and V is either a K^{*0} or ρ^0 meson, are in the range 10^{-9} to 10^{-6} [16]. Using the latest experimental data, the branching fraction for the decay $B^0 \to K^{*0}X$ ($B^0 \to \rho^{*0}X$) with a vector X particle is extracted to be less than 2.3×10^{-8} (0.81×10^{-8}) [17].

We report a search for a light particle using the modes, $B^0 \to K^{*0}X$, $K^{*0} \to K^+\pi^-$, $X \to \mu^+\mu^-$ ($B^0_{K^*X}$) and $B^0 \to \rho^0 X$, $\rho^0 \to \pi^+\pi^-$, $X \to \mu^+\mu^-$ ($B^0_{\rho X}$) using a data sample of $657 \times 10^6 B\bar{B}$ pairs collected with the Belle detector [18] at the KEKB asymmetric-energy e^+e^- collider [19]. The analysis for $B^0_{K^*X}$ uses the same data set as Ref. [20]. In this analysis, we assume that the light X particle is either a scalar or vector particle. Unless specified otherwise, charge-conjugate modes are implied. The term scalar (vector) X particle implies either a scalar (vector) or pseudoscalar (axial-vector) particle throughout this Letter.

In the initial event selection, at least two oppositely charged muon tracks with momenta larger than 0.690 GeV$/c$ are required. These muon tracks are selected using a likelihood ratio formed from a combination of the track penetration depth and hit pattern in the muon identification system. We reduce the number of badly reconstructed tracks by requiring that $|dz| < 5.0$ cm and $dr < 1.0$ cm, where $|dz|$ and dr are distances of closest approach of a track to the interaction point in the beam direction (z) and in the transverse plane ($r - \phi$), respectively. Charged kaons and pions are identified using information from the aerogel threshold Cherenkov counters, the time-of-flight scintillation counter system, and the energy loss (dE/dx) measurements in the central drift chamber [21].

The reconstruction of K^{*0} (ρ^0) in the $B^0_{K^*X}$ ($B^0_{\rho X}$) decay uses identified K^+ (π^+) and π^- (π^-) tracks. The reconstructed invariant mass $M_{K^{*0}}$ (M_{ρ^0}) of K^{*0} (ρ^0) candidates for the decay mode $B^0_{K^*X}$ ($B^0_{\rho X}$) is required to be in the ranges 0.815 GeV$/c^2 < M_{K^{*0}} <$ 0.975 GeV$/c^2$ (0.633 GeV$/c^2 < M_{\rho^0} <$ 0.908 GeV$/c^2$), corresponding to $\pm 1.5\sigma$ ($\pm 1\sigma$) in the reconstructed mass distribution. The $\mu^+\mu^-$ dimuon tracks are used to reconstruct low mass X candidates.

$B^0_{K^*X}$ ($B^0_{\rho X}$) candidates are reconstructed from a K^{*0} (ρ^0) candidate and a pair of muons. Reconstructed B^0 candidates are selected using the beam-energy-constrained mass $M_{\rm bc} = \sqrt{E^2_{\rm beam} - p^2_B}$ and energy difference $\Delta E = E_B - E_{\rm beam}$, where $E_{\rm beam}$ is the beam energy and E_B (p_B) are the energy (momentum) of the reconstructed B^0 candidates evaluated in the center-of-mass frame. B^0 candidates are required to lie in the signal regions, $5.27\ \mathrm{GeV}/c^2 < M_{\mathrm{bc}} < 5.29\ \mathrm{GeV}/c^2$ and $-0.03\ \mathrm{GeV} < \Delta E < 0.04\ \mathrm{GeV}$ ($-0.04\ \mathrm{GeV} < \Delta E < 0.04\ \mathrm{GeV}$) for the decay $B^0_{K^*X}$ ($B^0_{\rho X}$). In events containing more than one B^0 candidate, we select the best B^0 candidate with the smallest χ^2 value, where χ^2 is obtained when the four charged tracks are fitted to a common vertex. Using this algorithm, we select the correct $B^0_{K^*X}$ and $B^0_{\rho X}$ combinations in the M_{bc} and ΔE signal region 96.6% (96.7%) and 93.7% (93.5%) of the time for a scalar (vector) X particle, respectively. The signature for $X \to \mu^+\mu^-$ in $B^0_{K^*X}$ and $B^0_{\rho X}$ decays would be a peak in the dimuon mass. The width of the signal region for the light particle search with mass below 300 MeV$/c^2$ is $\pm 3\sigma$ in dimuon mass resolution. The dimuon mass resolutions for $B^0_{K^*X}$ and $B^0_{\rho X}$ vary from 0.5 MeV$/c^2$ to 1.9 MeV$/c^2$ as the mass of X (M_X) increases from 212 MeV$/c^2$ to 300 MeV$/c^2$. The mass resolution is proportional to $\sqrt{\frac{(M_X^2 - 4m_\mu^2)}{M_X^2}}\delta p$, where m_μ is the muon mass and δp is the momentum resolution of a muon track. The signal region for dimuon mass ($M_{\mu\mu}$) of 214.3 MeV$/c^2$ of the HyperCP event search is defined to be $211.6\ \mathrm{MeV}/c^2 < M_{\mu\mu} < 217.2\ \mathrm{MeV}/c^2$ where the width of the search region is $\pm 3\sigma$ in the combined mass resolution, which is obtained by linearly summing the uncertainty in the mass of X and the mass resolution of the Belle detector.

For background studies, we employ two different techniques referred to as the counting ($\mathcal{C}$) and fitting ($\mathcal{F}$) methods. Method $\mathcal{C}$ uses generic $B\bar{B}$ and continuum ($e^+e^- \to q\bar{q}$, $q = u, d, s, c$) Monte Carlo (MC) samples that correspond to an integrated luminosity about 3 times larger than the data sample. In the $\Delta E - M_{\mathrm{bc}}$ signal region, there are no events in the dimuon mass region $M_{\mu\mu} < 225\ \mathrm{MeV}/c^2$ ($M_{\mu\mu} < 239\ \mathrm{MeV}/c^2$) for the decay $B^0_{K^*X}$ ($B^0_{\rho X}$). In method $\mathcal{F}$, we use the MC samples as described above, and select B^0 candidates in the sideband regions defined as $-0.12\ \mathrm{GeV} < \Delta E < -0.06\ \mathrm{GeV}$ and $0.06\ \mathrm{GeV} < \Delta E < 0.12\ \mathrm{GeV}$, and $5.25\ \mathrm{GeV}/c^2 < M_{\mathrm{bc}} < 5.27\ \mathrm{GeV}/c^2$. By fitting the dimuon mass distributions for the B^0 candidates with a probability density function, $(x - 0.21)^n$ for $x > 2m_\mu$, where x is a dimuon mass in GeV$/c^2$ and the parameter n is extracted from the fit, we estimate the number of background events with dimuon mass below 300 MeV$/c^2$. We also compare the shape of the probability density function with the B^0 candidates in data sideband regions. No significant discrepancy is found. The estimated numbers of background events for methods $\mathcal{C}$ and $\mathcal{F}$ for the HyperCP event search are 0 (0) and $0.13^{+0.04}_{-0.03}$ ($0.12^{+0.03}_{-0.02}$) for the decays $B^0_{K^*X}$ ($B^0_{\rho X}$), respectively. The background estimates for both methods give results that are equivalent within statistical errors for masses below 300 MeV$/c^2$. The main background source arises from the continuum.

Before examining the full data sample, various distributions, including M_{bc}, ΔE, dimuon mass and dz in the background MC samples are compared with a small fraction of the data. These are in good agreement. Figure 1 shows the data and MC comparison for the ΔE and M_{bc} distributions after the best B^0 candidates are selected. The peaks in the ΔE and M_{bc} distributions for the $B^0_{K^*X}$ are mainly due to $B^0 \to J/\psi K^{*0}$, $J/\psi \to \mu^+\mu^-$. The dimuon mass distributions including the J/ψ and ψ' mass regions for $B^0_{K^*X}$ and $B^0_{\rho X}$ candidates in the signal regions of M_{bc} and ΔE are shown in Fig. 2. There are no events observed in the HyperCP mass region.

For the full data sample, no significant signal is observed for the decays $B^0_{K^*X}$ and $B^0_{\rho X}$ for M_X below ~ 300 MeV$/c^2$. We derive an upper limit for the signal yield (S_{90}) at a 90% confidence level (C.L.) by using the POLE program [22] with the Feldman-Cousins method [23]. This procedure takes into account Poisson fluctuations in the number of observed signal events and Gaussian fluctuations in the estimated number of background events as well as systematic uncertainties. The S_{90} values for the HyperCP event search are 2.33 (2.33) for $B^0_{K^*X}$ decay with a scalar (vector) X and 2.33 (2.33) for $B^0_{\rho X}$ decay with a scalar (vector) X particle.

Upper limits on the branching fraction for the decays $B^0_{K^*X}$ and $B^0_{\rho X}$ are obtained from

$$\mathcal{B}(B^0 \to VX, X \to \mu^+\mu^-) < \frac{S_{90}}{\epsilon \times N_{B\bar{B}} \times \mathcal{B}_V},$$

where V stands for either K^{*0} or ρ^0, and $\mathcal{B}_V$ [24] are the intermediate vector meson branching fractions, $\mathcal{B}(K^{*0} \to K^+\pi^-)$ or $\mathcal{B}(\rho^0 \to \pi^+\pi^-)$. Here $N_{B\bar{B}}$ and ϵ denote the number of $B\bar{B}$ pairs and the signal efficiency with small

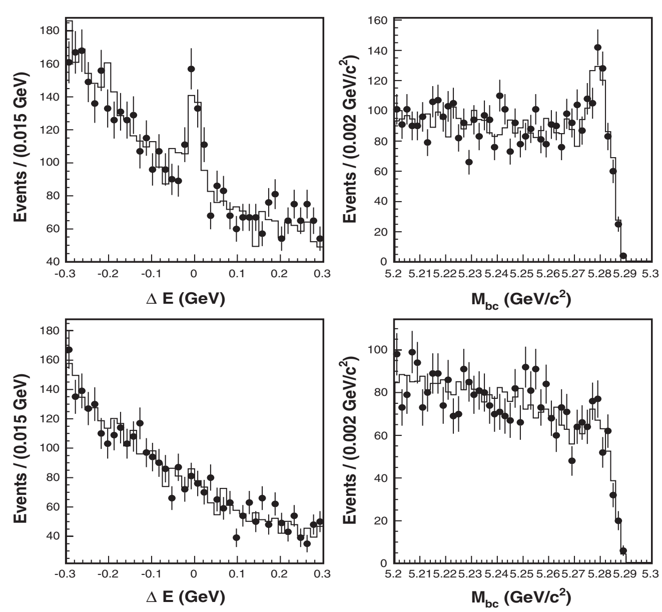

FIG. 1. Data and MC simulation comparison for ΔE and M_{bc} distributions for $B^0_{K^*X}$ (top) and $B^0_{\rho X}$ (bottom) candidates. The points with error bars and histograms represent data and background MC calculations, respectively.

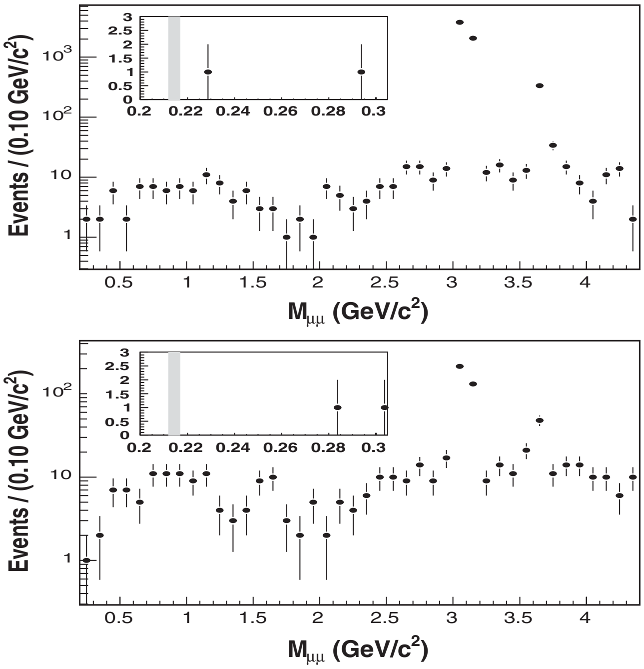

FIG. 2. Dimuon mass distribution for the $B^0_{K^*X}$ (top) and $B^0_{\rho X}$ (bottom) candidates in the signal regions for $M_{\rm bc}$ and ΔE. The shaded region in the inset shows the HyperCP mass region.

data or MC corrections for charged particle identification, respectively.

The signal efficiency is determined by applying the same selection criteria to the signal MC sample as those used for the data. The signal MC samples for a scalar (vector) X particle are generated for X masses in the range $212\ {\rm MeV}/c^2 \le M_X \le 300\ {\rm MeV}/c^2$ using the $P \to VS$ ($P \to VV$) model in the EVTGEN generator [25] for a scalar (vector) X particle. In the MC generation of the vector X particle, we assume that the polarization of X is either fully longitudinal or transverse. The absolute efficiency differences between longitudinal and transverse polarizations of the X for both modes in the search range are less than 7%. Since the efficiencies for a fully longitudinal polarized X are lower than for a fully transversely polarized X, we conservatively use the efficiencies for full longitudinal polarization of the X for upper limit estimations. In the HyperCP event search for a scalar (vector) X particle, the efficiencies for $B^0_{K^*X}$ and $B^0_{\rho X}$ decays are 23.6% (23.5%) and 20.7% (20.7%), respectively. We also check the efficiencies for different X lifetimes. The efficiencies are the same for lifetimes below 10^{-12} s because the primary and secondary vertices are indistinguishable. The efficiencies for two different vertex fitting methods for the HyperCP event search are compared. One method assumes that the dimuon tracks from the X originate from the primary B^0 decay vertex, while the other assumes that the dimuon tracks from the X are from a secondary vertex. The difference in the efficiencies is about 1%.

To obtain the final upper limit, we use the backgrounds determined from the fitting method. Since the efficiencies for a scalar (vector) and a pseudoscalar (axial-vector) are the same, the upper limits for the scalar (vector) and the pseudoscalar (axial-vector) X searches are identical. From the $B^0_{K^*X}$ ($B^0_{\rho X}$) sample, the upper limits for a scalar and vector X particle in the HyperCP mass range are determined to be $2.26(1.73) \times 10^{-8}$ and $2.27(1.73) \times 10^{-8}$, respectively. Table I summarizes the number of observed events, the expected number of background events, the efficiencies, the signal yields, and the upper limits at 90% C.L. in the interval $212\ {\rm MeV}/c^2 \le M_X \le 300\ {\rm MeV}/c^2$.

The systematic uncertainties in the upper limits for the decays $B^0_{K^*X}$ and $B^0_{\rho X}$ in the HyperCP mass range are summarized in Table II. The total systematic uncertainties in the upper limits for both decay modes vary from 6% to 8% as the mass of X increases from $212\ {\rm MeV}/c^2$ to $300\ {\rm MeV}/c^2$. The dominant systematic uncertainties come from tracking efficiency and muon identification.

TABLE I. Summary of the number of observed events ($N_{\rm obs}$), estimated number of background events ($N_{\rm bg}$), efficiencies (ϵ), signal yields (S_{90}) and upper limits (U.L.) at 90% C.L. for the decays $B^0_{K^*X}$ and $B^0_{\rho X}$ with the scalar (vector) X particle. The errors on $N_{\rm bg}$ are statistical only.

$M_{\mu\mu}$ (MeV/c^2)	$B^0 \to K^{*0}X,\ K^{*0} \to K^+\pi^-,\ X \to \mu^+\mu^-$					$B^0 \to \rho^0 X,\ \rho^0 \to \pi^+\pi^-,\ X \to \mu^+\mu^-$				
	$N_{\rm obs}$	$N_{\rm bg}$	ϵ	S_{90}	U.L. (10^{-8})	$N_{\rm obs}$	$N_{\rm bg}$	ϵ	S_{90}	U.L. (10^{-8})
212.0	0	$0.03^{+0.01}_{-0.01}$ ($0.03^{+0.01}_{-0.01}$)	23.8 (23.7)	2.43 (2.43)	2.34 (2.34)	0	$0.02^{+0.01}_{-0.01}$ ($0.02^{+0.01}_{-0.01}$)	21.2 (21.1)	2.44 (2.44)	1.77 (1.78)
214.3	0	$0.13^{+0.04}_{-0.03}$ ($0.13^{+0.04}_{-0.03}$)	23.6 (23.5)	2.33 (2.33)	2.26 (2.27)	0	$0.12^{+0.03}_{-0.02}$ ($0.12^{+0.03}_{-0.02}$)	20.7 (20.7)	2.33 (2.33)	1.73 (1.73)
220.0	0	$0.13^{+0.02}_{-0.02}$ ($0.13^{+0.02}_{-0.02}$)	23.0 (22.9)	2.33 (2.33)	2.31 (2.33)	0	$0.11^{+0.02}_{-0.01}$ ($0.11^{+0.02}_{-0.01}$)	20.2 (20.1)	2.33 (2.33)	1.78 (1.78)
230.0	1	$0.24^{+0.02}_{-0.02}$ ($0.25^{+0.02}_{-0.02}$)	21.4 (21.4)	4.09 (4.12)	4.37 (4.40)	0	$0.21^{+0.01}_{-0.01}$ ($0.21^{+0.01}_{-0.01}$)	18.8 (18.9)	2.27 (2.27)	1.86 (1.85)
240.0	0	$0.38^{+0.02}_{-0.02}$ ($0.39^{+0.02}_{-0.02}$)	20.0 (20.0)	2.09 (2.09)	2.40 (2.39)	0	$0.32^{+0.01}_{-0.01}$ ($0.32^{+0.01}_{-0.01}$)	17.5 (17.5)	2.16 (2.16)	1.90 (1.90)
250.0	0	$0.51^{+0.01}_{-0.01}$ ($0.51^{+0.01}_{-0.01}$)	18.0 (18.4)	1.92 (1.94)	2.43 (2.41)	0	$0.42^{+0.00}_{-0.00}$ ($0.42^{+0.00}_{-0.00}$)	15.9 (16.3)	2.06 (2.06)	1.99 (1.94)
260.0	0	$0.63^{+0.01}_{-0.01}$ ($0.63^{+0.01}_{-0.01}$)	16.5 (17.2)	1.83 (1.83)	2.54 (2.43)	0	$0.60^{+0.01}_{-0.00}$ ($0.70^{+0.01}_{-0.00}$)	14.5 (15.2)	1.84 (1.80)	1.95 (1.82)
270.0	0	$0.75^{+0.02}_{-0.02}$ ($0.75^{+0.02}_{-0.02}$)	15.4 (16.4)	1.76 (1.76)	2.61 (2.45)	0	$0.61^{+0.02}_{-0.01}$ ($0.61^{+0.02}_{-0.01}$)	13.7 (14.4)	1.83 (1.83)	2.06 (1.96)
280.0	0	$0.69^{+0.03}_{-0.03}$ ($0.86^{+0.04}_{-0.04}$)	14.6 (15.8)	1.78 (1.69)	2.78 (2.45)	1	$0.83^{+0.03}_{-0.03}$ ($0.90^{+0.04}_{-0.03}$)	13.0 (13.9)	3.52 (3.45)	4.17 (3.83)
290.0	1	$0.98^{+0.06}_{-0.06}$ ($0.97^{+0.06}_{-0.06}$)	14.0 (15.5)	3.35 (3.37)	5.47 (4.99)	0	$0.80^{+0.04}_{-0.04}$ ($0.78^{+0.04}_{-0.04}$)	12.4 (13.6)	1.74 (1.74)	2.16 (1.97)
300.0	1	$1.08^{+0.08}_{-0.08}$ ($1.08^{+0.08}_{-0.08}$)	13.6 (15.1)	3.28 (3.28)	5.53 (4.97)	1	$0.87^{+0.05}_{-0.05}$ ($0.87^{+0.05}_{-0.05}$)	11.9 (13.3)	3.48 (3.48)	4.51 (4.01)

TABLE II. Summary of fractional systematic uncertainties in the upper limit for a scalar (vector) X particle in the HyperCP mass range for the decays $B^0_{K^*X}$ and $B^0_{\rho X}$, respectively.

	$\sigma_{\mathcal{B}}/\mathcal{B}(\%)$	
Source	$B^0_{K^*X}$	$B^0_{\rho X}$
$N_{B\bar{B}}$	1.4 (1.4)	1.4 (1.4)
$\mu^{\pm}$ identification	4.2 (4.2)	4.1 (4.1)
$K^{\pm}$ identification	0.8 (0.8)	-
$\pi^{\pm}$ identification	0.5 (0.5)	1.0 (1.0)
Tracking efficiency	4.2 (4.2)	4.4 (4.3)
$M_{\rm bc}$	0.5 (0.3)	0.3 (0.6)
ΔE	0.5 (0.3)	0.3 (0.6)
K^{*0} tagging	0.5 (0.3)	-
ρ^0 tagging	-	0.3 (0.6)
MC statistics	0.1 (0.1)	0.1 (0.1)
Total	6.2 (6.2)	6.2 (6.3)

The uncertainty for the tracking efficiency is estimated by linearly summing the single track systematic errors, which are $\sim$1%/track. The uncertainty of muon identification is measured as a function of momentum and direction by using the $\gamma\gamma \to \mu^+\mu^-$ data sample.

In summary, we searched for a scalar and vector particle in the decays $B^0 \to K^{*0}X$, $K^{*0} \to K^+\pi^-$, $X \to \mu^+\mu^-$ and $B^0 \to \rho^0 X$, $\rho^0 \to \pi^+\pi^-$, $X \to \mu^+\mu^-$ in the mass region 212 MeV$/c^2 \leq M_X \leq$ 300 MeV$/c^2$ for lifetimes below 10^{-12} s. No significant signals are observed in a sample of $657 \times 10^6 B\bar{B}$ pairs. We set 90% C.L. upper limits of $\mathcal{B}(B^0 \to K^{*0}X, K^{*0} \to K^+\pi^-, X \to \mu^+\mu^-) < 2.26 \times 10^{-8} (2.27 \times 10^{-8})$ and $\mathcal{B}(B^0 \to \rho^0 X, \rho^0 \to \pi^+\pi^-, X \to \mu^+\mu^-) < 1.73 \times 10^{-8} (1.73 \times 10^{-8})$ for a 214.3 MeV$/c^2$ mass scalar (vector) X particle; our results rule out models II and III for the sgoldstino interpretation of the HyperCP observation [16].

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