Search for the dark photon in $B^0 \rightarrow A'A'$, $A' \rightarrow e^+e^-, \mu^+\mu^-$, and $\pi^+\pi^-$ decays at Belle

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Abstract: We present a search for the dark photon $A'$ in the $B^0 \to A'A'$ decays, where $A'$ subsequently decays to $e^+e^-$, $\mu^+\mu^-$, and $\pi^+\pi^-$. The search is performed by analyzing $772 \times 10^6 B\bar{B}$ events collected by the Belle detector at the KEKB $e^+e^-$ energy-asymmetric collider at the $\Upsilon(4S)$ resonance. No signal is found in the dark photon mass range $0.01 \text{ GeV}/c^2 \leq m_{A'} \leq 2.62 \text{ GeV}/c^2$, and we set upper limits of the branching fraction of $B^0 \to A'A'$ at the 90% confidence level. The products of branching fractions, $\mathcal{B}(B^0 \to A'A') \times \mathcal{B}(A' \to e^+e^-)^2$ and $\mathcal{B}(B^0 \to A'A') \times \mathcal{B}(A' \to \mu^+\mu^-)^2$, have limits of the order of $10^{-8}$ depending on the $A'$ mass. Furthermore, considering $A'$ decay rate to each pair of charged particles, the upper limits of $\mathcal{B}(B^0 \to A'A')$ are of the order of $10^{-8}$–$10^{-5}$. From the upper limits of $\mathcal{B}(B^0 \to A'A')$, we obtain the Higgs portal coupling for each assumed dark photon and dark Higgs mass. The Higgs portal couplings are of the order of $10^{-2}$–$10^{-1}$ at $m_{h'} \simeq m_{B^0} \pm 40 \text{ MeV}/c^2$ and $10^{-1}$–$1$ at $m_{h'} \simeq m_{B^0} \pm 3 \text{ GeV}/c^2$.

Keywords: $e^+e^-$ Experiments, B physics, Beyond Standard Model, Branching fraction
1 Introduction

The validity of the Standard Model (SM) has been confirmed by various experimental measurements [1], but it is also known that the SM is incomplete and cannot explain several phenomena occurring in nature, e.g. neutrino oscillations [2, 3] and the baryon asymmetry [4]. A possible way to explain the above problems while keeping the internal structure of the SM unaffected is to introduce a dark sector [5] that interacts with the SM particles only very weakly. For example, a vector mediator of hypothetical $U'(1)$ gauge interaction in the dark sector, the so-called dark photon, may interact with matter through various portals with a small coupling strength [6–8]. Such a model of the dark sector with portal interaction to the SM could explain the muon $g–2$ anomaly [9–12], baryogenesis [13], and high energy positron fraction anomaly in cosmic rays [14–18].

In this paper, we report a search for the dark photon $A'$, in the decays of $B^0$ mesons by analyzing the $e^+e^-$ collision data from the Belle experiment. In particular, we study $B^0$ decays into a pair of dark photons, $B^0 \rightarrow A'A'$, which are mediated by an off-shell dark Higgs $h'$ [5] (Fig. 1), wherein we scan the $A'$ mass range between 0.01 GeV/$c^2$ and 2.62 GeV/$c^2$ in 10 MeV/$c^2$ ($m_{A'} < 1.1 \text{ GeV}/c^2$) and 20 MeV/$c^2$ ($m_{A'} > 1.1 \text{ GeV}/c^2$) intervals. Throughout the paper, the charge-conjugate modes are always implied. We consider only prompt decays of $A'$ to $e^+e^-$, $\mu^+\mu^-$, or $\pi^+\pi^-$. Lepton-flavor-violating decays [19, 20] $A' \rightarrow e^+\mu^-$ are not considered in this analysis.

1.1 Branching fraction of dark photon decay

In order to obtain $B(B^0 \rightarrow A'A')$ from the analysis of the decays into the final states considered, we need to know the branching fractions of $A'$ to a particular final state. Below
the $\tau^+\tau^-$ threshold, the branching fraction of the dark photon is obtained as

$$\mathcal{B}(A' \to \ell^+\ell^-/\pi^+\pi^-) = \frac{\Gamma_{A'\to\ell^+\ell^-/\pi^+\pi^-}}{\Gamma_{A'\to e^+e^-} + \Gamma_{A'\to \mu^+\mu^-} + \Gamma_{A'\to \text{hadrons}}}, \quad (1.1)$$

where $\ell = e$ or $\mu$. Following Ref. [21], we write down the partial widths to $\ell^+\ell^-$ and hadrons as

$$\Gamma_{A'\to \ell^+\ell^-} = \frac{1}{3} \alpha_{\text{mix}}^2 m_{A'} \sqrt{1 - 4m_\ell^2/m_{A'}^2 (1 + 2m_\ell^2/m_{A'}^2)},$$

$$\Gamma_{A'\to \text{hadrons}} = \Gamma_{A'\to \mu^+\mu^-} \times R(s = m_{A'}^2), \quad (1.2)$$

with the square of the total center-of-mass (CM) frame energy $s$, the kinetic mixing parameter $\varepsilon_{\text{mix}}$, and $R(s) = \sigma(e^+e^-\to \text{hadrons})/\sigma(e^+e^-\to \mu^+\mu^-)$ which is determined by various experiments [1]. The branching fraction of $A' \to \pi^+\pi^-$ is then obtained as [22]:

$$\mathcal{B}(A' \to \pi^+\pi^-) = \mathcal{B}(A' \to \text{hadrons}) \times \sigma(e^+e^-\to \pi^+\pi^-)/\sigma(e^+e^-\to \text{hadrons}). \quad (1.3)$$

### 1.2 The SM expectation of $B^0$ decays to four charged leptons

The $B^0$-decay final states that we analyze are $e^+e^-e^+e^-, e^+e^-\mu^+\mu^-, \mu^+\mu^-\mu^+\mu^-, e^+e^-\pi^+\pi^-$, and $\mu^+\mu^-\pi^+\pi^-$. In the SM, branching fractions of $B^0$-meson decays to four-charged-lepton final states are expected to be $\mathcal{O}(10^{-12})$ [23]. Due to the low SM expectation and background, these multileptonic $B$-meson decay channels can be a sensitive probe for dark sector bosons. The LHCb experiment has set an upper limit $\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.9 \times 10^{-10}$ at 95% confidence level (C.L.) [24] and measured $\mathcal{B}(B^0 \to \mu^+\mu^-\pi^+\pi^-) = (2.1 \pm 0.5) \times 10^{-8}$ [25].

### 2 The Belle detector

Our analysis is based on the full 711 fb$^{-1}$ integrated luminosity of the $Y(4S)$ data set from the Belle detector [26, 27] at KEKB $e^+e^-$ energy-asymmetric collider [28, 29]. The Belle detector consists of seven subdetectors with 1.5 T magnetic field along the beam axis. Inside the coil, there are silicon vertex detector, central drift chamber, aerogel threshold
Cherenkov counters, time-of-flight scintillation counters, and electromagnetic calorimeter (ECL). In the return yoke outside the coil, a \(K_L^0\) meson and muon detector (KLM) is instrumented.

We perform a blind search in this analysis, for which we generate Monte Carlo (MC) simulation samples using EvtGen \[30\] for event generation and GEANT3 \[31\] for detector simulation. Signal efficiencies are determined from the signal MC set, where one million events are generated for each signal mode and dark photon mass. The event shape and amount of the background events are studied by using generic MC samples simulating \(e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}\) and \(e^+e^- \rightarrow q\overline{q} (q = u, d, s, c)\) \('\text{continuum}'\) processes. The size of MC samples for \(\Upsilon(4S)\) and continuum simulation corresponds to 10 and 6 times that of real data, respectively.

3 Signal event selection

To select signal events, we retain tracks satisfying the following track reconstruction quality requirements. Because we assume prompt dark photon decays, all tracks are required to originate from near the interaction point (IP). In particular, each track should satisfy the following conditions on the impact parameters in the transverse and longitudinal directions, \(dr < 0.2\) cm and \(|dz| < 3.0\) cm, respectively. The impact parameters are calculated using the beam IP and track helix, and the z-axis is aligned opposite the direction of positron beam. We also require a good track fit based upon \(\chi^2\) per degree of freedom \((N_{d.o.f.})\) by accepting only the tracks with \(\chi^2/N_{d.o.f.} < 5\).

The species of the charged particles are identified by considering the likelihood ratios. Muons are identified by requiring \(L_\mu/(L_\mu + L_K + L_\pi) > 0.9\), where the likelihood \(L_j (j = \mu, K, \pi)\) \[32\] is constructed by the hit position and penetration in the KLM. Electrons are required to meet \(L_e/(L_e + L_{\text{not-}e}) > 0.9\) where the likelihood \(L_j (j = e, \text{not-}e)\) \[33\] is determined by \(dE/dx\) from the CDC, ratio of the ECL cluster energy to the matched track momentum, shower shape of the ECL cluster, and the ACC photoelectron response. Charged pions and kaons are identified by the likelihood \[34\] using the \(dE/dx\) from the CDC, the ACC photoelectron response, and the time-of-flight information from the TOF. The tracks with \(L_\pi/(L_K + L_\pi) > 0.4\) are identified as pions.

To recover energy losses by \(e^\pm\) candidates due to bremsstrahlung, radiative photons are added to the electron momentum if they fall within a 0.05 radian cone of the \(e^\pm\) direction. We require these photons to exceed an energy threshold that depends on the ECL region: \(E_{\gamma} > 50\) (barrel), 100 (forward endcap), and 150 (backward endcap) MeV.

The dark photon candidate is reconstructed in the following modes: \(A' \rightarrow e^+e^-, \mu^+\mu^-,\) and \(\pi^+\pi^-\). For \(B^0 \rightarrow e^+e^-\mu^+\mu^-\) and \(e^+e^-\mu^+\mu^-\) modes, we have an ambiguity between \((\ell_1^+\ell_1^-)(\ell_2^+\ell_2^-)\) and \((\ell_1^+\ell_1^-)(\ell_2^+\ell_1^-)\), where the lepton pair from a single \(A'\) decay is indicated in parentheses. To find a single dark photon combination per event, we choose that corresponding to the smallest invariant mass difference of dark photon candidates, \(\Delta M_{A'}\).

Finally, \(B^0\) candidates are reconstructed from two dark photon candidates. To extract signal events from data, we use the following five variables, defined in the CM frame: \(M_{bc}\), \(\Delta E\), \(E_{\text{miss}}\), \(\Delta M_{A'}\), and \(\Sigma \delta M_{A'}\). \(M_{bc} \equiv \sqrt{(\sqrt{s}/2)^2 - \vec{p}_T^2}\) is the beam-energy-constrained
mass, where $\vec{p}_B$ is the momentum of the reconstructed $B^0$. $\Delta E \equiv E_{B^0} - (\sqrt{s}/2)$ is the difference between the $B^0$-candidate energy and the beam energy ($= \sqrt{s}/2$), and $E_{\text{miss}}$ is the missing energy. $E_{\text{miss}} \equiv \sqrt{s} - \sum_j E_j$ where the index $j$ is for all charged and neutral particles in the event. The missing energy is useful to reduce combinatorial background due to multiple semileptonic decays from $b \to c\ell^-\nu$ and $c \to (s,d)\ell^+\nu$ for both $B$ and $\bar{B}$. For the two dark photon candidates in an event, we calculate $\Delta M_A' \equiv |M_{A'1} - M_{A'2}|$ and $\sum \delta M_{A'} \equiv |(M_{A'1} - M_{A'\exp}) + (M_{A'2} - M_{A'\exp})|$ where $M_{A'1,2}$ is the reconstructed $A'_{1,2}$ mass and $m_{A'\exp}$ is the expected $A'$ mass.

For the signal event selection, we require $M_{bc} > 5.27$ GeV/c$^2$ and $E_{\text{miss}} < 3.5$ GeV for all modes. Considering the energy loss from $e^\pm$, $\Delta E$ requirements are chosen separately for different modes: 

- $0.2$ GeV $< \Delta E < 0.05$ GeV for $B^0 \to e^+e^-\mu^+\mu^-$, $0.04$ GeV for $B^0 \to e^+e^-\mu^+\mu^-$ and $e^+e^-\pi^+\pi^-$, and $0.03$ GeV $< \Delta E < 0.03$ GeV for $B^0 \to \mu^+\mu^-\mu^+\mu^-$.  
- The requirements on $\Delta M_{A'}$ and $\Sigma\delta M_{A'}$ depend on both $A'$ mass and the number of electrons among the final-state particles. The selections on both variables become more restrictive for higher $A'$ mass and fewer number of electrons. For $m_{A'} > 0.1$ GeV/c$^2$, we require $\Delta M_{A'}(\Sigma\delta M_{A'}) < 0.06 \times m_{A'} + 0.03$ GeV/c$^2$ for $B^0 \to e^+e^-\mu^+\mu^-$, $\Delta M_{A'}(\Sigma\delta M_{A'}) < 0.03 \times m_{A'} + 0.01$ GeV/c$^2$ for $B^0 \to e^+e^-\mu^+\mu^-$ and $e^+e^-\pi^+\pi^-$, and $\Delta M_{A'}(\Sigma\delta M_{A'}) < 0.01 \times m_{A'} + 0.01$ GeV/c$^2$ for $B^0 \to \mu^+\mu^-\mu^+\mu^-$. The above conditions are determined so that if we consider the distribution of $\Delta M_{A'}$ the upper edge of the accepted region has a value of nearly 3–5% of the peak value. In addition, we make use of the approximately linear increase of the $\Delta M_{A'}$ width as a function of $m_{A'}$. We choose the same selection for $\Sigma\delta M_{A'}$ since the distribution is almost the same as $\Delta M_{A'}$. For $m_{A'} \leq 0.1$ GeV/c$^2$, we apply slightly different selection conditions for $\Delta M_{A'}$ and $\Sigma\delta M_{A'}$, while requirements on $M_{bc}$ and $\Delta E$ remain the same as for $m_{A'} > 0.1$ GeV/c$^2$. We do not use $E_{\text{miss}}$ for $m_{A'} \leq 0.1$ GeV/c$^2$, because for such low-mass dark photons, little background is expected from generic $B$ decays. In the low $m_{A'}$ region, both of the resolutions are nearly independent of the expected value of $m_{A'}$. Therefore, we apply $\Delta M_{A'}$ and $\Sigma\delta M_{A'} < 0.02$ GeV/c$^2$ for all $m_{A'} \leq 0.1$ GeV/c$^2$. The union of the signal regions of $\Delta M_{A'}$ and $\Sigma\delta M_{A'}$ for each $m_{A'}$ covers the entire dark photon mass range of our study without any gap.

The dominant SM background sources for $\ell^+\ell^-$ pairs are photon conversion and charmonium meson decays, mostly $J/\psi$ and $\psi(2S)$. To reduce the background events from photon conversion, $e^+e^-$ pairs with $M_{e^+e^-} < 0.1$ GeV/c$^2$ are rejected when we search for $m_{A'} > 0.1$ GeV/c$^2$. On the other hand, this veto is not applied for the searches in the region $m_{A'} \leq 0.1$ GeV/c$^2$. To suppress the lepton pairs from charmonium decays such as $J/\psi$ or $\psi(2S) \to \ell^+\ell^-$, we reject two regions: $3.00(3.05)$ GeV/c$^2 < M_{e^+e^-}(\mu^+\mu^-) < 3.15(3.13)$ GeV/c$^2$ for $J/\psi$ and $3.60(3.65)$ GeV/c$^2 < M_{e^+e^-}(\mu^+\mu^-) < 3.75(3.73)$ GeV/c$^2$ for $\psi(2S)$.

For the charged pion pairs, there is strong background from light mesons, such as $K_S^0$, $\rho^0$, and $f_0(980)$. Because of possible $K^-\pi^+$ misidentification, $K^{*0}$, $\phi$ and so on are also a source of possible background. Since production of such mesons is copious, especially that of $\rho^0$ mesons, we reject the $0.45$ GeV/c$^2 < M_{\pi^+\pi^-} < 1.1$ GeV/c$^2$. Another source of pion pairs is $D^0$ meson. Two decay channels, $D^0 \to \pi^+\pi^-$ and $D^0 \to \pi^+K^-$ are considered.
A direct $D^0$ veto is applied by removing $\pi^+\pi^-$ combinations which satisfy $1.85 \text{ GeV/c}^2 < M_{\pi^+\pi^-} < 1.88 \text{ GeV/c}^2$. The other decay channel, $D^0 \rightarrow \pi^+K^-$, can mimic the signal via $K^-\pi$ misidentification. We reject these events by discarding the $1.85 \text{ GeV/c}^2 < M_{\pi^+K^-} < 1.88 \text{ GeV/c}^2$ mass range.

After signal selection, most of the combinatorial background is in the $B^0 \rightarrow \ell^+\ell^-\pi^+\pi^-$ mode, coming from the continuum processes $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$ or $c$). In the four-lepton mode, on the other hand, there is almost no background left. The continuum background is suppressed via multivariate analysis (MVA) using the Fisher discriminant [35] method in the TMVA [36] package. We make use of 16 event shape variables: the cosine of angle between the beam axis and $B^0$ momentum ($\cos\theta_B$), the cosine of angle between the thrust axis of the $B^0$ daughters and that of the rest of the event ($\cos\theta_T$), and the Fisher discriminant components of modified Fox-Wolfram moments [37]. The MVA training is performed for the $\ell^+\ell^-\pi^+\pi^-$ final state for each assumed value of $m_{A'}$, using the signal and continuum MC. We apply MVA selection criteria to retain from 75% to 90% of signal and from 10% to 30% of continuum background, depending on $m_{A'}$ and final state.

4 Systematic uncertainties

We determine the branching fraction of $B^0 \rightarrow A'A'$ as

$$
B(B^0 \rightarrow A'A') = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\epsilon \times 2 \times N_{BB} \times B_0},
$$

where $B_0$ is the branching fraction of $\Upsilon(4S) \rightarrow B^0\bar{B}^0$, of which the current world-average value is $0.486 \pm 0.006$ [1]. $N_{\text{obs}}$ is the yield, $N_{\text{bkg}}$ is the number of expected background events determined from MC, $\epsilon$ is the signal reconstruction efficiency considering branching fraction of $A'$ subdecays, and $N_{BB} = (772 \pm 11) \times 10^6$ is the number of $B\bar{B}$ pairs which are collected by the Belle detector.

The most important source of systematic uncertainties is the signal reconstruction efficiency, which is obtained by MC. The sources of uncertainty include the statistical error in the signal MC, track reconstruction efficiency, particle identification (PID) efficiency, and uncertainties in the MVA method used to suppress continuum background. The uncertainties due to background estimation are very small compared to other systematic uncertainties. The uncertainties of the total error are approximately 2% (1%) per lepton (pion), with the resulting correction factor being about 90%. The exact correction factor and uncertainty depend on $m_{A'}$ through different kinematics.
The MVA correction factor and uncertainty are studied using the control mode, $B^0 \rightarrow J/\psi K^{*0} \rightarrow e(\mu)^+ e(\mu)^- \pi^- K^+$. We apply MVA training results for the continuum suppression of $\ell^+ \ell^- \pi^+ \pi^-$ modes for each assumed value of $m_{A'}$ to $B^0 \rightarrow J/\psi K^{*0}$ MC and data. We then calculate the double ratio $(N_{\text{data,A}}/N_{\text{data,B}})/(N_{\text{MC,A}}/N_{\text{MC,B}})$, where $N_{\text{data(MC),B}}$ and $N_{\text{data(MC),A}}$ are the number of signal candidates in data(MC) before and after MVA training application, respectively. The systematic uncertainty due to MVA training is taken from the uncertainties in the double ratio, and these uncertainties are approximately 2% at all values of $m_{A'}$.

After multiplying all correction factors, signal efficiencies are approximately 20% in the
low and high dark photon mass region, and 10% in the remainder. This difference is due to energy threshold differences between the ECL and KLM. The summary of signal-efficiency-related systematic uncertainties is shown in Fig. 2, and the total systematic uncertainties are 7.5–10% for $e^+e^-e^+e^-$ and $\mu^+\mu^-\mu^+\mu^-$ final states and 5–7.5% for $e^+e^-\mu^+\mu^-$, $e^+e^-\pi^+\pi^-$, and $\mu^+\mu^-\pi^+\pi^-$ final states.

5 Results

Figure 3 shows the number of $B^0 \to A'A'$ candidate events. There are no events observed in any bin in the $e^+e^-\mu^+\mu^-$ and $\mu^+\mu^-\mu^+\mu^-$ mode, while we find $N_{\text{obs}} \leq 2$ events for $e^+e^-e^+e^-$, $e^+e^-\pi^+\pi^-$, and $\mu^+\mu^-\pi^+\pi^-$ modes. The yields are consistent with the expected number of background events and we set the upper limits at 90% C.L.

For the limits of $B(B^0 \to A'A')$, we combine the number of expected background events, signal candidates in data, and signal reconstruction efficiencies of the five final states. The combined numbers of expected background events and signal candidates in data are calculated by simply adding the results for the individual final states. For the signal efficiencies, we first obtain the ratio $F_f \equiv B(B^0 \to A'A' \to f)/B(B^0 \to A'A')$, where $f$ is each final state, using Eq. (1.1). In case of $e^+e^-\mu^+\mu^-$, for example, $F_f$ is $2 \times B(A' \to e^+e^-) \times B(A' \to \mu^+\mu^-)$. The graph of $F_f$ is presented in Fig. 4. With this ratio $F_f$, the combined efficiency is determined as $\sum_f \epsilon_f F_f$ where $\epsilon_f$ is the signal efficiency of the final state $f$. The upper limits are calculated using the POLE program [38], which is based on the Feldman-Cousins unified approach [39]. We report the limits on the products of branching fractions $B(B^0 \to A'A') \times B(A' \to e^+e^-)^2$ and $B(B^0 \to
Figure 4. $\mathcal{B}(B^0 \to A'A' \to f)/\mathcal{B}(B^0 \to A'A')$ distributions for each final state and dark photon mass. $e^+e^−\pi^+\pi^−$ and $\mu^+\mu^−\pi^+\pi^−$ distributions are almost the same for the whole region. $e^+e^−\mu^+\mu^−$ and $\mu^+\mu^−\mu^+\mu^−$ distributions are the same and $e^+e^−\mu^+\mu^−$ distribution is twice that of four-electron or four-muon final states in the region $m_{A'} > 0.5\text{ GeV}/c^2$.

$A'A') \times \mathcal{B}(A' \to \mu^+\mu^-)^2$, as well as the limits on $\mathcal{B}(B^0 \to A'A')$. For $\mathcal{B}(B^0 \to A'A')$, we use Eq. (1.1) to combine the five final states. The upper limits of $\mathcal{B}(B^0 \to A'A')$ are obtained in the mass range $0.01\text{ GeV}/c^2 \leq m_{A'} \leq 1.10\text{ GeV}/c^2$ with $10\text{ MeV}/c^2$ bin and $1.10\text{ GeV}/c^2 \leq m_{A'} \leq 2.62\text{ GeV}/c^2$ with $20\text{ MeV}/c^2$ bin.

The obtained limits are shown in Fig. 5 as functions of $m_{A'}$. The limits on the products of branching fractions are $\mathcal{O}(10^{-8})$ for both modes and in all $m_{A'}$ bins. For $\mathcal{B}(B^0 \to A'A')$, the upper limits are $\mathcal{O}(10^{-8})-\mathcal{O}(10^{-5})$. Due to the light meson veto in the $\ell^+\ell^-\pi^+\pi^−$ final states and the large fraction of $A' \to \text{hadrons}$ in the veto region from Eq. (1.1), the upper limits near the masses of $\rho^0$ and $\phi$ mesons are less restrictive than others. Table 1 lists the signal efficiency, the expected number of backgrounds and number of observed events ($N_{\text{obs}}$) for some of $m_{A'}$. 

![Diagram of $A'$ mass distribution](image.png)
Figure 5. Upper limits of $B^0 \to A'A'$ branching fraction at 90% C.L.
Table 1. Signal efficiency, expected number of backgrounds, yields for each $B^0$ final state and upper limits of $B^0 \to \phi \phi'$ branching fraction with 90% confidence interval. The table presents a part of the results for dark photons with (i) 20 MeV/c² interval in $m_{\phi'} < 2m_\gamma$ region, (ii) 100 MeV/c² interval on the other region.

| $m_\mu$ (GeV/c²) | Eff. (%) | $e^+e^-e^+e^-$ | $e^+e^-\mu^+\mu^-$ | $\mu^+\mu^-\pi^+\pi^-$ | $\mu^+\mu^-\pi^+\pi^-$ | Yield (10⁻⁸) |
|------------------|----------|-----------------|----------------------|-----------------|-----------------|----------|
| 0.02             | 14.82    | 0.83±0.37       | 2                    | -               | -               | -        |
| 0.04             | 14.62    | 0.00±0.17       | 1                    | -               | -               | -        |
| 0.06             | 14.40    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.08             | 14.07    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.10             | 13.63    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.12             | 13.66    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.14             | 13.85    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.16             | 13.57    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.18             | 13.37    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.20             | 13.25    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.30             | 12.78    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.40             | 12.35    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.50             | 11.67    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.60             | 11.07    | 0.10±0.19       | 0                    | -               | -               | -        |
| 0.70             | 10.96    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.80             | 11.29    | 0.00±0.17       | 0                    | -               | -               | -        |
| 0.90             | 11.47    | 0.00±0.17       | 0                    | -               | -               | -        |
| 1.00             | 11.26    | 0.00±0.17       | 0                    | -               | -               | -        |
| 1.10             | 11.10    | 0.00±0.17       | 0                    | -               | -               | -        |
| 1.20             | 11.07    | 0.00±0.17       | 0                    | -               | -               | -        |
| 1.30             | 11.22    | 0.00±0.17       | 0                    | -               | -               | -        |
| 1.40             | 11.48    | 0.00±0.17       | 0                    | -               | -               | -        |
| 1.50             | 11.75    | 0.00±0.17       | 0                    | -               | -               | -        |
| 1.60             | 12.13    | 0.00±0.17       | 0                    | -               | -               | -        |
| 1.70             | 12.34    | 0.00±0.17       | 0                    | -               | -               | -        |
| 1.80             | 12.69    | 0.00±0.17       | 0                    | -               | -               | -        |
| 1.90             | 13.06    | 0.10±0.19       | 0                    | -               | -               | -        |
| 2.00             | 13.43    | 0.25±0.22       | 0                    | -               | -               | -        |
| 2.10             | 13.90    | 0.15±0.20       | 0                    | -               | -               | -        |
| 2.20             | 14.50    | 0.20±0.22       | 0                    | -               | -               | -        |
| 2.30             | 15.32    | 0.00±0.17       | 0                    | -               | -               | -        |
| 2.40             | 16.47    | 0.20±0.22       | 0                    | -               | -               | -        |
| 2.50             | 18.15    | 0.20±0.22       | 0                    | -               | -               | -        |
| 2.60             | 21.05    | 0.00±0.17       | 0                    | -               | -               | -        |
The $B^0 \to A'A'$ branching fraction with off-shell $H-h'$ mixing, for all but the $m_{h'} \sim m_{B^0}$ region, is calculated as [5, 40],

$$B(B^0 \to A'A') \simeq 6.9 \times 10^{-7} \times \lambda^2 \times V_{A'A'}^{1/2} \times \frac{V_{A'A'} + 12 m_{A'}^2 / m_{B^0}^2}{(1 - m_{h'}^2 / m_{B^0}^2)^2} \quad (5.1)$$

where $\lambda$ is the Higgs portal coupling with a new scalar field $H'$ from $\mathcal{L}_{Higgs} = -\lambda (H^\dagger H)(H'^\dagger H')$ and $V_{A'A'} = 1 - 4 m_{A'}^2 / m_{B^0}^2$. From Eq. (5.1) and the limits on $B(B^0 \to A'A')$, we determine the 90% C.L. upper limits on $\lambda$ versus $m_{A'}$ (Fig. 6) and $m_{h'}$ (Fig. 7). In the region where $m_{h'} \simeq m_{B^0}$, the upper limit on $\lambda$ gets as low as $\mathcal{O}(10^{-2})$. Otherwise, the upper limits are $\mathcal{O}(10^{-1})\sim\mathcal{O}(1)$.

6 Conclusions

In summary, we have searched for $B^0 \to A'A'$ decays for the first time using the full data set of $772 \times 10^6 \ B\bar{B}$ events of Belle. We consider five final states of $B^0$ which are $e^+e^-\mu^+\mu^-$, $\mu^+\mu^-\mu^+\mu^-$, $e^+e^-\pi^+\pi^-$, and $\mu^+\mu^-\pi^+\pi^-$. As one of the plausible scenarios, prompt $A'$ decay through kinetic mixing with the SM photon is assumed. From the branching fraction of $A'$, the five $B^0$ final states are merged into $B^0 \to A'A'$. We find no significant signal in any assumed $A'$ mass and decay mode, so we determine upper limits on $B(B^0 \to A'A') \times B(A' \to e^+e^-)$, $B(B^0 \to A'A') \times B(A' \to \mu^+\mu^-)$ and $B(B^0 \to A'A')$, each at 90% C.L. The limits on the products of branching fractions are of the order of $\mathcal{O}(10^{-8})$, while the limits on $B(B^0 \to A'A')$ are $\mathcal{O}(10^{-8})\sim\mathcal{O}(10^{-5})$. We also set 90% C.L. upper limits on the Higgs portal coupling $\lambda$ for each assumed value of $m_{A'}$ and $m_{h'}$. The
upper limits on $\lambda$ are of the order of $10^{-2}$–$10^{-1}$ at $m_{h'} \simeq m_{B^0} \pm 40$ MeV/$c^2$ and $10^{-1}$–$1$ at $m_{h'} \simeq m_{B^0} \pm 3$ GeV/$c^2$. With minor modifications our analysis can be used to set limits on the other new physics models which include prompt $B^0 \rightarrow XX$ and $X \rightarrow \ell^+\ell^-/\pi^+\pi^-$ decays. We expect to have much more stringent results from the Belle II experiment [41, 42], with nearly two orders of magnitude increase in statistics, in the future.

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References

[1] P. A. Zyla et al. (Particle Data Group), The Review of Particle Physics, PTEP 2020 (2020) 083C01.

[2] Q. R. Ahmad et al. (SNO Collaboration), Measurement of the Rate of $\nu_e + d \rightarrow p + p + e^-$ Interactions Produced by $^8B$ Solar Neutrinos at the Sudbury Neutrino Observatory, Phys. Rev. Lett. 87 (2001) 071301.

[3] Y. Fukuda et al. (Super-Kamiokande Collaboration), Evidence for Oscillation of Atmospheric Neutrinos, Phys. Rev. Lett. 81 (1998) 1562.

[4] A. D. Sakharov, Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe, Sov. Phys. Usp. 34 (1991) 392.

[5] B. Batell, M. Pospelov and A. Ritz, Multi-lepton Signatures of a Hidden Sector in Rare $B$ Decays $B$ Decays, Phys. Rev. D 83 (2011) 054005 [arXiv:0911.4938].

[6] B. Holdom, Two $U(1)'s$ and $e$ Charge Shifts, Phys. Lett. B 166 (1986) 196.

[7] P. Fayet, Effects of the Spin 1 Partner of the Goldstino (Gravitino) on Neutral Current Phenomenology, Phys. Lett. B 95 (1980) 285.

[8] P. Fayet, On the Search for a New Spin 1 Boson, Nucl. Phys. B 187 (1981) 184.

[9] G. W. Bennett et al. (Muon g-2 Collaboration), Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL, Phys. Rev. D 73 (2006) 072003 [arXiv:hep-ex/0602035].

[10] M. Pospelov, Secluded $U(1)$ below the weak scale, Phys. Rev. D 80 (2009) 095002 [arXiv:0811.1030].

[11] D. Tucker-Smith and I. Yavin, Muonic hydrogen and MeV forces, Phys. Rev. D 83 (2011) 101702 [arXiv:1011.4922].
12. B. Batell, D. McKeen and M. Pospelov, *New Parity-Violating Muonic Forces and the Proton Charge Radius*, Phys. Rev. Lett. 107 (2011) 011803 [arXiv:1103.0721].

13. N. Haba and S. Matsumoto, *Baryogenesis from Dark Sector*, Prog. Theor. Phys. 125 (2011) 1311 [arXiv:1008.2487].

14. J. Chang *et al.*, *An excess of cosmic ray electrons at energies of 300-800 GeV*, Nature 456 (2008) 362.

15. O. Adriani *et al.* (PAMELA Collaboration), *Cosmic-Ray Positron Energy Spectrum Measured by PAMELA*, Phys. Rev. Lett. 111 (2013) 081102 [arXiv:1308.0133].

16. M. Ackermann *et al.* (Fermi-LAT Collaboration), *Measurement of separate cosmic-ray electron and positron spectra with the Fermi Large Area Telescope*, Phys. Rev. Lett. 108 (2012) 011103 [arXiv:1109.0521].

17. M. Aguilar *et al.* (AMS Collaboration), *Electron and Positron Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station*, Phys. Rev. Lett. 113 (2014) 021102.

18. C. R. Chen, F. Takahashi and T. T. Yanagida, *High-energy Cosmic-Ray Positrons from Hidden-Gauge-Boson Dark Matter*, Phys. Lett. B 673 (2009) 255 [arXiv:0811.0477].

19. C. Y. Chen, H. Davoudiasl, W. J. Marciano and C. Zhang, *Implications of a light "dark Higgs" solution to the g_μ − 2 discrepancy*, Phys. Rev. D 93 (2016) 035006 [arXiv:1511.04715].

20. G. Arcadi *et al.*, *Lepton Flavor Violation Induced by Dark Matter*, Phys. Rev. D 97 (2018) 075022 [arXiv:1712.02373].

21. B. Batell, M. Pospelov and A. Ritz, *Probing a Secluded U(1) at B-factories*, Phys. Rev. D 79 (2009) 115008 [arXiv:0903.0363].

22. J. P. Lees *et al.* (BaBar Collaboration), *Search for Low-Mass Dark-Sector Higgs Bosons*, Phys. Rev. Lett. 108 (2012) 211801 [arXiv:1202.1313].

23. A. V. Danilina and N. V. Nikitin, *Four-Leptonic Decays of Charged and Neutral B Mesons within the Standard Model*, Phys. Atom. Nucl. 81 (2018) 347.

24. R. Aaij *et al.* (LHCb Collaboration), *Search for decays of neutral beauty mesons into four muons*, JHEP 03 (2017) 001 [arXiv:1611.07704].

25. R. Aaij *et al.* (LHCb Collaboration), *Study of the rare B^0_s and B^0 decays into the π^+π^-μ^+μ^- final state*, Phys. Lett. B 743 (2015) 46 [arXiv:1412.6433].

26. A. Abashian *et al.* (Belle Collaboration), *The Belle Detector*, Nucl. Instrum. Meth. A 479 (2002) 117.

27. J. Brodzicka *et al.* (Belle Collaboration), *Physics Achievements from the Belle Experiment*, PTEP 2012 (2012) 04D001 [arXiv:1212.5342].

28. S. Kurokawa and E. Kikutani, *Overview of the KEKB accelerators*, Nucl. Instrum. Meth. A 499 (2003) 1.

29. T. Abe *et al.*, *Achievements of KEKB*, PTEP 2013 (2013) 03A001.

30. D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Methods Phys. Res., Sect. A 462 (2001) 152.

31. R. Brun, F. Bruyant, M. Maire, A. C. McPherson and P. Zanarini, *Geant3*, CERN-DD-EE-84-1.
[32] A. Abashian, K. Abe, K. Abe, P. K. Behera, F. Handa, T. Iijima, Y. Inoue, H. Miyake, T. Nagamine and E. Nakano, et al. Muon identification in the Belle experiment at KEKB, Nucl. Instrum. Meth. A 491 (2002), 69-82.

[33] K. Hanagaki, H. Kakuno, H. Ikeda, T. Iijima and T. Tsukamoto, Electron identification in Belle, Nucl. Instrum. Meth. A 485 (2002), 490-503 [arXiv:hep-ex/0108044].

[34] E. Nakano, Belle PID, Nucl. Instrum. Meth. A 494 (2002), 402-408.

[35] R. A. Fisher, The use of multiple measurements in taxonomic problems, Annals Eugen. 7 (1936) 179.

[36] H. Voss, A. Hocker, J. Stelzer and F. Tegenfeldt, TMVA - Toolkit for Multivariate Data Analysis, PoS ACAT (2007) 040 [arXiv:physics/0703039].

[37] S. H. Lee et al. (Belle Collaboration), Evidence for $B^0 \rightarrow \pi^0 \pi^0$, Phys. Rev. Lett. 91 (2003) 261801 [arXiv:hep-ex/0308040].

[38] J. Conrad, O. Botner, A. Hallgren and C. Perez de los Heros, Including systematic uncertainties in confidence interval construction for Poisson statistics, Phys. Rev. D 67 (2003) 012002 [arXiv:hep-ex/0202013].

[39] G. J. Feldman and R. D. Cousins, A Unified approach to the classical statistical analysis of small signals, Phys. Rev. D 57 (1998) 3873 [arXiv:physics/9711021].

[40] B. Batell, private communication, 2020.

[41] T. Abe et al. (Belle II Collaboration), Belle II Technical Design Report, [arXiv:1011.0352].

[42] E. Kou et al. (Belle II Collaboration), The Belle II Physics Book, PTEP 2019 (2019) 123C01 [arXiv:1808.10567].
1 Tables of signal efficiency, the number of expected background events, and the number of observed events at Belle

In this section, tables of signal efficiency ($\epsilon$) in signal MC, the number of expected background events ($N_{bkg}$) in Belle background MC, and the number of observed events ($N_{obs}$) in the Belle data are introduced. The dark photon masses are in the range of ($m_{A'}$) in 0.01 – 2.62 GeV/$c^2$ with 10 MeV/$c^2$ (0.01 – 1.10 GeV/$c^2$) and 20 MeV/$c^2$ (1.10 – 2.62 GeV/$c^2$) intervals for $e^+e^-$, $\mu^+\mu^-$, $\mu^+\mu^+\mu^-$, $e^+e^-\pi^+\pi^-$, $\mu^+\mu^-\pi^+\pi^-$ final states and $B^0 \rightarrow A'A'$ combined results.

For the combined signal efficiencies, we first obtain the ratio $F_f \equiv B(B^0 \rightarrow A'A' \rightarrow f)/B(B^0 \rightarrow A'A')$, where $f$ is each final state, using the dark photon branching fraction. The dark photon branching fraction below the $\tau^+\tau^-$ threshold is obtained as

$$B(A' \rightarrow \ell^+\ell^-/\pi^+\pi^-) = \frac{\Gamma_{A' \rightarrow \ell^+\ell^-/\pi^+\pi^-}}{\Gamma_{A' \rightarrow \ell^+\ell^-/\pi^+\pi^-} + \Gamma_{A' \rightarrow \mu^+\mu^-} + \Gamma_{A' \rightarrow \text{hadrons}}}, \quad (1.1)$$

where $\ell = e$ or $\mu$. Following Ref. [2], we write down the partial widths to $\ell^+\ell^-$ and hadrons as

$$\Gamma_{A' \rightarrow \ell^+\ell^-} = \frac{1}{3} \alpha_{\text{mix}}^2 m_{A'} \sqrt{1 - 4m_{\ell}^2/m_{A'}^2(1 + 2m_{\ell}^2/m_{A'}^2)},$$
\n$$\Gamma_{A' \rightarrow \text{hadrons}} = \Gamma_{A' \rightarrow \mu^+\mu^-} \times R(s = m_{A'}^2), \quad (1.2)$$

with the square of the total center-of-mass (CM) frame energy $s$, the kinetic mixing parameter $\alpha_{\text{mix}}$, and $R(s) = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ which is determined by various experiments [1]. The branching fraction of $A' \rightarrow \pi^+\pi^-$ is then obtained as [3]:

$$B(A' \rightarrow \pi^+\pi^-) = B(A' \rightarrow \text{hadrons}) \times (\sigma(e^+e^- \rightarrow \pi^+\pi^-)/\sigma(e^+e^- \rightarrow \text{hadrons})). \quad (1.3)$$

From the $A'$ branching fraction, we calculate $F_f$ for each final state. In case of $e^+e^-\mu^+\mu^-$, for example, $F_{e^+e^-\mu^+\mu^-}$ is $2 \times B(A' \rightarrow e^+e^-) \times B(A' \rightarrow \mu^+\mu^-)$. With this ratio $F_f$, the combined efficiency is determined as $\sum_f \epsilon_f F_f$ where $\epsilon_f$ is the signal efficiency of the final state $f$.

| $m_{A'}$ (GeV/$c^2$) | $\epsilon$ (%) | $N_{bkg}$ | $N_{obs}$ | $m_{A'}$ (GeV/$c^2$) | $\epsilon$ (%) | $N_{bkg}$ | $N_{obs}$ |
|----------------------|---------------|----------|-----------|----------------------|---------------|----------|-----------|
| 0.01                 | 14.56 ± 1.34  | 0.33 ± 0.24 | 1         | 0.94                 | 11.27 ± 1.04  | 0.00 ± 0.17 | 0         |
| 0.02                 | 14.82 ± 1.36  | 0.83 ± 0.37 | 2         | 0.95                 | 11.31 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.03                 | 14.72 ± 1.35  | 0.50 ± 0.29 | 1         | 0.96                 | 11.34 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.04                 | 14.62 ± 1.33  | 0.00 ± 0.17 | 1         | 0.97                 | 11.33 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.05                 | 14.51 ± 1.32  | 0.00 ± 0.17 | 1         | 0.98                 | 11.32 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.06                 | 14.40 ± 1.31  | 0.00 ± 0.17 | 0         | 0.99                 | 11.29 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.07                 | 14.24 ± 1.30  | 0.00 ± 0.17 | 1         | 1.00                 | 11.26 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.08                 | 14.08 ± 1.28  | 0.00 ± 0.17 | 1         | 1.01                 | 11.26 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.09                 | 13.86 ± 1.26  | 0.00 ± 0.17 | 0         | 1.02                 | 11.27 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.10                 | 13.64 ± 1.24  | 0.00 ± 0.17 | 0         | 1.03                 | 11.25 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.11                 | 13.65 ± 1.24  | 0.00 ± 0.17 | 0         | 1.04                 | 11.24 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.12                 | 13.66 ± 1.24  | 0.00 ± 0.17 | 0         | 1.05                 | 11.20 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.13                 | 13.76 ± 1.25  | 0.00 ± 0.17 | 0         | 1.06                 | 11.17 ± 1.05  | 0.00 ± 0.17 | 0         |
| 0.14                 | 13.85 ± 1.26  | 0.00 ± 0.17 | 0         | 1.07                 | 11.18 ± 1.05  | 0.00 ± 0.17 | 0         |
|     |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
Table 2: Signal efficiency ($\epsilon$), the number of expected background events ($N_{\text{bkg}}$), and the number of observed events ($N_{\text{obs}}$) for $B^0 \to A^+A^- \to e^+e^-\mu^+\mu^-$ mode.

| $m_{A'}$ (GeV/$c^2$) | $\epsilon$ (%) | $N_{\text{bkg}}$ | $N_{\text{obs}}$ | $m_{A'}$ (GeV/$c^2$) | $\epsilon$ (%) | $N_{\text{bkg}}$ | $N_{\text{obs}}$ |
|---------------------|----------------|-----------------|-----------------|---------------------|----------------|-----------------|-----------------|
| 0.22                | 23.93 ± 1.68   | 0.00 ± 0.17     | 0               | 1.05                | 9.89 ± 0.68    | 0.00 ± 0.17     | 0               |
| 0.23                | 22.79 ± 1.59   | 0.00 ± 0.17     | 0               | 1.06                | 9.99 ± 0.68    | 0.00 ± 0.17     | 0               |
| 0.24                | 21.65 ± 1.51   | 0.00 ± 0.17     | 0               | 1.07                | 9.99 ± 0.69    | 0.00 ± 0.17     | 0               |
| 0.25                | 20.06 ± 1.39   | 0.00 ± 0.17     | 0               | 1.08                | 9.98 ± 0.69    | 0.00 ± 0.17     | 0               |
| 0.26                | 18.46 ± 1.28   | 0.00 ± 0.17     | 0               | 1.09                | 9.95 ± 0.68    | 0.00 ± 0.17     | 0               |
| 0.27                | 17.35 ± 1.21   | 0.00 ± 0.17     | 0               | 1.10                | 9.91 ± 0.68    | 0.00 ± 0.17     | 0               |
| 0.28                | 16.25 ± 1.13   | 0.00 ± 0.17     | 0               | 1.12                | 9.95 ± 0.69    | 0.00 ± 0.17     | 0               |
| 0.29                | 15.63 ± 1.09   | 0.00 ± 0.17     | 0               | 1.14                | 9.94 ± 0.69    | 0.00 ± 0.17     | 0               |
| 0.30                | 15.01 ± 1.04   | 0.00 ± 0.17     | 0               | 1.16                | 9.92 ± 0.69    | 0.00 ± 0.17     | 0               |
| 0.31                | 14.63 ± 1.02   | 0.00 ± 0.17     | 0               | 1.18                | 9.93 ± 0.69    | 0.00 ± 0.17     | 0               |
| 0.32                | 14.26 ± 0.99   | 0.00 ± 0.17     | 0               | 1.20                | 9.88 ± 0.69    | 0.00 ± 0.17     | 0               |
|    |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |�
| $m_{A'}$ (GeV/c²) | $\epsilon$ (%) | $N_{\text{bkg}}$ | $N_{\text{obs}}$ | $m_{A'}$ (GeV/c²) | $\epsilon$ (%) | $N_{\text{bkg}}$ | $N_{\text{obs}}$ |
|------------------|--------------|----------------|----------------|------------------|--------------|----------------|----------------|
| 0.22             | 34.57 ± 2.86 | 0.00 ± 0.17    | 0              | 1.05             | 6.35 ± 0.52  | 0.00 ± 0.17    | 0              |
| 0.23             | 31.31 ± 2.54 | 0.00 ± 0.17    | 0              | 1.06             | 6.31 ± 0.52  | 0.00 ± 0.17    | 0              |
| 0.24             | 28.05 ± 2.23 | 0.00 ± 0.17    | 0              | 1.07             | 6.28 ± 0.51  | 0.00 ± 0.17    | 0              |
| 0.25             | 24.10 ± 1.91 | 0.00 ± 0.17    | 0              | 1.08             | 6.26 ± 0.51  | 0.00 ± 0.17    | 0              |
| 0.26             | 20.16 ± 1.60 | 0.00 ± 0.17    | 0              | 1.09             | 6.26 ± 0.52  | 0.00 ± 0.17    | 0              |
| 0.27             | 17.91 ± 1.42 | 0.00 ± 0.17    | 0              | 1.10             | 6.27 ± 0.52  | 0.00 ± 0.17    | 0              |
| 0.28             | 15.67 ± 1.25 | 0.00 ± 0.17    | 0              | 1.12             | 6.28 ± 0.52  | 0.00 ± 0.17    | 0              |
| 0.29             | 14.45 ± 1.15 | 0.00 ± 0.17    | 0              | 1.14             | 6.32 ± 0.53  | 0.00 ± 0.17    | 0              |
| 0.30             | 13.22 ± 1.05 | 0.00 ± 0.17    | 0              | 1.16             | 6.32 ± 0.53  | 0.00 ± 0.17    | 0              |
| 0.31             | 12.56 ± 1.00 | 0.00 ± 0.17    | 0              | 1.18             | 6.32 ± 0.53  | 0.00 ± 0.17    | 0              |
| 0.32             | 11.90 ± 0.95 | 0.00 ± 0.17    | 0              | 1.20             | 6.34 ± 0.54  | 0.00 ± 0.17    | 0              |
| 0.33             | 11.41 ± 0.91 | 0.00 ± 0.17    | 0              | 1.22             | 6.39 ± 0.54  | 0.00 ± 0.17    | 0              |
| 0.34             | 10.93 ± 0.87 | 0.00 ± 0.17    | 0              | 1.24             | 6.41 ± 0.55  | 0.00 ± 0.17    | 0              |
| 0.35             | 10.38 ± 0.82 | 0.00 ± 0.17    | 0              | 1.26             | 6.36 ± 0.54  | 0.00 ± 0.17    | 0              |
| 0.36             | 9.83 ± 0.78  | 0.00 ± 0.17    | 0              | 1.28             | 6.41 ± 0.55  | 0.00 ± 0.17    | 0              |
| 0.37             | 9.74 ± 0.77  | 0.00 ± 0.17    | 0              | 1.30             | 6.40 ± 0.55  | 0.00 ± 0.17    | 0              |
| 0.38             | 9.65 ± 0.77  | 0.00 ± 0.17    | 0              | 1.32             | 6.41 ± 0.56  | 0.00 ± 0.17    | 0              |
| 0.39             | 9.41 ± 0.75  | 0.00 ± 0.17    | 0              | 1.34             | 6.43 ± 0.56  | 0.00 ± 0.17    | 0              |

**Table 3:** Signal efficiency ($\epsilon$), the number of expected background events ($N_{\text{bkg}}$), and the number of observed events ($N_{\text{obs}}$) for $B^0 \rightarrow A'A' \rightarrow \mu^+\mu^-\mu^+\mu^-$ mode.
| Value | Mean ± Standard Error | Confidence Interval ± Standard Error |
|-------|----------------------|--------------------------------------|
| 0.40  | 9.18 ± 0.73          | 0.00 ± 0.17                          |
| 0.41  | 9.00 ± 0.71          | 0.00 ± 0.17                          |
| 0.42  | 8.83 ± 0.70          | 0.00 ± 0.17                          |
| 0.43  | 8.67 ± 0.69          | 0.00 ± 0.17                          |
| 0.44  | 8.52 ± 0.68          | 0.00 ± 0.17                          |
| 0.45  | 8.43 ± 0.67          | 0.00 ± 0.17                          |
| 0.46  | 8.34 ± 0.66          | 0.00 ± 0.17                          |
| 0.47  | 8.25 ± 0.65          | 0.00 ± 0.17                          |
| 0.48  | 8.15 ± 0.65          | 0.00 ± 0.17                          |
| 0.49  | 8.06 ± 0.64          | 0.00 ± 0.17                          |
| 0.50  | 7.98 ± 0.63          | 0.00 ± 0.17                          |
| 0.51  | 7.93 ± 0.63          | 0.00 ± 0.17                          |
| 0.52  | 7.88 ± 0.62          | 0.00 ± 0.17                          |
| 0.53  | 7.81 ± 0.62          | 0.00 ± 0.17                          |
| 0.54  | 7.74 ± 0.61          | 0.00 ± 0.17                          |
| 0.55  | 7.70 ± 0.61          | 0.00 ± 0.17                          |
| 0.56  | 7.66 ± 0.60          | 0.00 ± 0.17                          |
| 0.57  | 7.61 ± 0.60          | 0.00 ± 0.17                          |
| 0.58  | 7.57 ± 0.60          | 0.00 ± 0.17                          |
| 0.59  | 7.55 ± 0.60          | 0.00 ± 0.17                          |
| 0.60  | 7.53 ± 0.59          | 0.00 ± 0.17                          |
| 0.61  | 7.49 ± 0.59          | 0.00 ± 0.17                          |
| 0.62  | 7.44 ± 0.59          | 0.00 ± 0.17                          |
| 0.63  | 7.39 ± 0.58          | 0.00 ± 0.17                          |
| 0.64  | 7.34 ± 0.58          | 0.00 ± 0.17                          |
| 0.65  | 7.32 ± 0.58          | 0.00 ± 0.17                          |
| 0.66  | 7.31 ± 0.58          | 0.00 ± 0.17                          |
| 0.67  | 7.28 ± 0.57          | 0.00 ± 0.17                          |
| 0.68  | 7.25 ± 0.57          | 0.00 ± 0.17                          |
| 0.69  | 7.22 ± 0.57          | 0.00 ± 0.17                          |
| 0.70  | 7.18 ± 0.57          | 0.00 ± 0.17                          |
| 0.71  | 7.15 ± 0.56          | 0.00 ± 0.17                          |
| 0.72  | 7.12 ± 0.56          | 0.00 ± 0.17                          |
| 0.73  | 7.08 ± 0.56          | 0.00 ± 0.17                          |
| 0.74  | 7.04 ± 0.55          | 0.00 ± 0.17                          |
| 0.75  | 7.04 ± 0.55          | 0.00 ± 0.17                          |
| 0.76  | 7.04 ± 0.55          | 0.00 ± 0.17                          |
| 0.77  | 7.00 ± 0.55          | 0.00 ± 0.17                          |
| 0.78  | 6.96 ± 0.55          | 0.00 ± 0.17                          |
| 0.79  | 6.96 ± 0.55          | 0.00 ± 0.17                          |
| 0.80  | 6.97 ± 0.55          | 0.00 ± 0.17                          |
| 0.81  | 6.93 ± 0.55          | 0.00 ± 0.17                          |
| 0.82  | 6.89 ± 0.54          | 0.00 ± 0.17                          |
| 0.83  | 6.86 ± 0.54          | 0.00 ± 0.17                          |
| 0.84  | 6.82 ± 0.54          | 0.00 ± 0.17                          |
| 0.85  | 6.83 ± 0.54          | 0.00 ± 0.17                          |
| 0.86  | 6.83 ± 0.54          | 0.00 ± 0.17                          |
| 0.87  | 6.76 ± 0.54          | 0.00 ± 0.17                          |
| 0.88  | 6.69 ± 0.53          | 0.00 ± 0.17                          |
| $m_{A'}$ (GeV/$c^2$) | $\epsilon$ (%) | $N_{bkg}$ | $N_{obs}$ | $m_{A'}$ (GeV/$c^2$) | $\epsilon$ (%) | $N_{bkg}$ | $N_{obs}$ |
|-------------------|----------|--------|--------|-------------------|----------|--------|--------|
| 0.28              | 20.84 ± 0.25 | 0.00 ± 0.49 | 0     | 1.70              | 13.74 ± 0.82 | 0.40 ± 0.53 | 0     |
| 0.29              | 21.00 ± 0.25 | 0.50 ± 0.50 | 0     | 1.72              | 12.70 ± 0.76 | 0.30 ± 0.52 | 0     |
| 0.30              | 21.16 ± 0.26 | 0.00 ± 0.49 | 0     | 1.74              | 13.48 ± 0.81 | 0.20 ± 0.51 | 0     |
| 0.31              | 21.08 ± 0.25 | 0.00 ± 0.49 | 0     | 1.76              | 9.27 ± 0.55  | 0.30 ± 0.52 | 0     |
| 0.32              | 21.00 ± 0.25 | 0.00 ± 0.49 | 0     | 1.78              | 7.13 ± 0.43  | 0.40 ± 0.53 | 0     |
| 0.33              | 20.97 ± 0.24 | 0.00 ± 0.49 | 0     | 1.80              | 13.49 ± 0.82 | 0.40 ± 0.53 | 0     |
| 0.34              | 20.94 ± 0.24 | 0.00 ± 0.49 | 0     | 1.82              | 18.39 ± 1.10 | 0.60 ± 0.55 | 0     |
| 0.35              | 20.82 ± 0.23 | 0.00 ± 0.49 | 0     | 1.84              | 17.80 ± 1.07 | 0.90 ± 0.54 | 0     |
| 0.36              | 20.70 ± 0.23 | 0.00 ± 0.49 | 0     | 1.86              | 1.89 ± 0.11  | 0.80 ± 0.53 | 0     |
| 0.37              | 20.52 ± 0.22 | 0.00 ± 0.49 | 0     | 1.88              | 10.01 ± 0.60 | 1.30 ± 0.73 | 0     |
| 0.38              | 20.33 ± 0.21 | 0.00 ± 0.49 | 0     | 1.90              | 17.73 ± 1.06 | 0.50 ± 0.54 | 0     |
| 0.39              | 19.79 ± 0.18 | 0.50 ± 0.50 | 0     | 1.92              | 18.53 ± 1.11 | 0.85 ± 0.57 | 0     |
| 0.40              | 19.25 ± 0.15 | 0.50 ± 0.50 | 0     | 1.94              | 19.28 ± 1.15 | 1.05 ± 0.58 | 0     |
| 0.41              | 19.10 ± 0.15 | 0.50 ± 0.50 | 0     | 1.96              | 19.23 ± 1.15 | 0.97 ± 0.58 | 0     |
| 0.42              | 18.96 ± 0.14 | 0.00 ± 0.49 | 0     | 1.98              | 19.51 ± 1.16 | 1.52 ± 0.59 | 0     |
| 0.43              | 18.52 ± 0.11 | 0.00 ± 0.49 | 0     | 2.00              | 19.94 ± 1.19 | 1.32 ± 0.57 | 0     |
| 0.44              | 18.08 ± 0.09 | 0.50 ± 0.50 | 0     | 2.02              | 19.80 ± 1.17 | 1.39 ± 0.58 | 0     |
| 1.10              | 14.73 ± 0.87 | 0.30 ± 0.52 | 0     | 2.04              | 20.18 ± 1.20 | 1.57 ± 0.59 | 1     |
| 1.12              | 14.70 ± 0.87 | 0.24 ± 0.51 | 0     | 2.06              | 20.27 ± 1.20 | 1.32 ± 0.60 | 1     |
| 1.14              | 14.77 ± 0.88 | 0.64 ± 0.51 | 0     | 2.08              | 20.39 ± 1.21 | 0.95 ± 0.58 | 1     |
| 1.16              | 14.69 ± 0.87 | 0.62 ± 0.51 | 0     | 2.10              | 20.10 ± 1.19 | 0.75 ± 0.56 | 0     |
| 1.18              | 14.40 ± 0.86 | 0.85 ± 0.53 | 1     | 2.12              | 20.50 ± 1.21 | 1.80 ± 0.62 | 2     |
| 1.20              | 14.72 ± 0.88 | 0.25 ± 0.51 | 1     | 2.14              | 20.58 ± 1.21 | 1.60 ± 0.60 | 2     |
| 1.22              | 14.82 ± 0.88 | 0.20 ± 0.50 | 0     | 2.16              | 20.61 ± 1.21 | 2.00 ± 0.63 | 2     |
| 1.24              | 14.58 ± 0.87 | 0.25 ± 0.51 | 0     | 2.18              | 20.68 ± 1.21 | 1.60 ± 0.63 | 0     |

Table 4: Signal efficiency ($\epsilon$), the number of expected background events ($N_{bkg}$), and the number of observed events ($N_{obs}$) for $B^0 \rightarrow A'A' \rightarrow e^+e^-\pi^+\pi^-$ mode.
| $m_{A'}$ (GeV/$c^2$) | $\epsilon$ (%) | $N_{\text{bkg}}$ | $N_{\text{obs}}$ | $m_{A'}$ (GeV/$c^2$) | $\epsilon$ (%) | $N_{\text{bkg}}$ | $N_{\text{obs}}$ |
|----------------------|-----------------|-----------------|-----------------|----------------------|-----------------|-----------------|-----------------|
| 0.28                 | 20.99 ± 1.25    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.70                 | 8.68 ± 0.52     | 0.00 ± 0.49     | 0.00 ± 0.49     |
| 0.29                 | 20.42 ± 1.22    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.72                 | 8.02 ± 0.48     | 0.00 ± 0.49     | 0.00 ± 0.49     |
| 0.30                 | 19.85 ± 1.18    | 0.50 ± 0.50     | 0.00 ± 0.49     | 1.74                 | 8.67 ± 0.52     | 0.00 ± 0.49     | 0.00 ± 0.49     |
| 0.31                 | 19.41 ± 1.15    | 0.50 ± 0.50     | 0.00 ± 0.49     | 1.76                 | 5.68 ± 0.34     | 0.10 ± 0.50     | 0.00 ± 0.49     |
| 0.32                 | 18.97 ± 1.12    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.78                 | 4.48 ± 0.28     | 0.10 ± 0.50     | 0.00 ± 0.49     |
| 0.33                 | 18.45 ± 1.09    | 0.50 ± 0.50     | 0.00 ± 0.49     | 1.80                 | 8.58 ± 0.54     | 0.00 ± 0.49     | 0.00 ± 0.49     |
| 0.34                 | 17.93 ± 1.06    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.82                 | 11.76 ± 0.72    | 0.20 ± 0.51     | 0.10 ± 0.50     |
| 0.35                 | 17.67 ± 1.04    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.84                 | 11.40 ± 0.71    | 0.10 ± 0.50     | 0.00 ± 0.49     |
| 0.36                 | 17.42 ± 1.02    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.86                 | 0.76 ± 0.05     | 0.00 ± 0.49     | 0.00 ± 0.49     |
| 0.37                 | 16.87 ± 1.00    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.88                 | 6.46 ± 0.40     | 0.10 ± 0.50     | 0.00 ± 0.49     |
| 0.38                 | 16.33 ± 0.97    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.90                 | 12.91 ± 0.80    | 0.00 ± 0.49     | 0.00 ± 0.49     |
| 0.39                 | 15.81 ± 0.94    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.92                 | 13.31 ± 0.82    | 0.00 ± 0.49     | 0.00 ± 0.49     |
| 0.40                 | 15.30 ± 0.91    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.94                 | 13.75 ± 0.85    | 0.10 ± 0.50     | 0.00 ± 0.49     |
| 0.41                 | 14.98 ± 0.90    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.96                 | 14.01 ± 0.86    | 0.00 ± 0.49     | 0.00 ± 0.49     |
| 0.42                 | 14.66 ± 0.88    | 0.00 ± 0.49     | 0.00 ± 0.49     | 1.98                 | 14.22 ± 0.88    | 0.20 ± 0.51     | 0.00 ± 0.49     |
| 0.43                 | 14.31 ± 0.86    | 0.00 ± 0.49     | 0.00 ± 0.49     | 2.00                 | 14.62 ± 0.90    | 0.10 ± 0.50     | 0.00 ± 0.49     |
| 0.44                 | 13.95 ± 0.84    | 0.00 ± 0.49     | 0.00 ± 0.49     | 2.02                 | 14.84 ± 0.91    | 0.20 ± 0.51     | 0.00 ± 0.49     |
| 1.10                 | 9.87 ± 0.56     | 0.50 ± 0.50     | 0.00 ± 0.49     | 2.04                 | 15.19 ± 0.92    | 0.10 ± 0.50     | 0.00 ± 0.49     |
| 1.12                 | 9.88 ± 0.56     | 0.50 ± 0.50     | 0.00 ± 0.49     | 2.06                 | 15.53 ± 0.94    | 0.10 ± 0.50     | 0.00 ± 0.49     |

Table 5: Signal efficiency ($\epsilon$), the number of expected background events ($N_{\text{bkg}}$), and the number of observed events ($N_{\text{obs}}$) for $B^0 \rightarrow A'A' \rightarrow \mu^+ \mu^- \pi^+ \pi^-$ mode.
| $m_{A'}$ (GeV/$c^2$) | $\epsilon$ (%) | $N_{bkg}$ | $N_{obs}$ | $m_{A'}$ (GeV/$c^2$) | $\epsilon$ (%) | $N_{bkg}$ | $N_{obs}$ |
|---------------------|----------------|-----------|----------|---------------------|----------------|-----------|----------|
| 0.01                | 14.56 ± 1.34   | 0.33 ± 0.24 | 1        | 0.01                | 3.63 ± 0.08    | 0.10 ± 0.30 | 0        |
| 0.02                | 14.82 ± 1.36   | 0.83 ± 0.37 | 2        | 0.02                | 3.84 ± 0.09    | 0.10 ± 0.30 | 0        |
| 0.03                | 14.72 ± 1.35   | 0.50 ± 0.29 | 1        | 0.03                | 3.91 ± 0.09    | 0.00 ± 0.29 | 0        |
| 0.04                | 14.62 ± 1.33   | 0.00 ± 0.17 | 1        | 0.04                | 4.19 ± 0.10    | 0.00 ± 0.29 | 0        |
| 0.05                | 14.51 ± 1.32   | 0.00 ± 0.17 | 1        | 0.05                | 4.03 ± 0.10    | 0.00 ± 0.29 | 0        |
| 0.06                | 14.40 ± 1.31   | 0.00 ± 0.17 | 1        | 0.06                | 4.28 ± 0.11    | 0.00 ± 0.29 | 0        |
| 0.07                | 14.24 ± 1.30   | 0.00 ± 0.17 | 1        | 0.07                | 3.53 ± 0.09    | 0.00 ± 0.29 | 0        |
| 0.08                | 14.08 ± 1.28   | 0.00 ± 0.17 | 1        | 0.08                | 1.98 ± 0.05    | 0.00 ± 0.29 | 0        |
| 0.09                | 13.86 ± 1.26   | 0.00 ± 0.17 | 0        | 0.09                | 0.02 ± 0.00    | 0.00 ± 0.29 | 0        |
| 0.10                | 13.64 ± 1.24   | 0.00 ± 0.17 | 0        | 0.10                | 1.24 ± 0.03    | 0.00 ± 0.29 | 0        |
| 0.11                | 13.65 ± 1.24   | 0.00 ± 0.17 | 0        | 0.11                | 2.73 ± 0.07    | 0.00 ± 0.29 | 0        |
| 0.12                | 13.66 ± 1.24   | 0.00 ± 0.17 | 0        | 0.12                | 3.42 ± 0.09    | 0.00 ± 0.29 | 0        |
| 0.13                | 13.76 ± 1.25   | 0.00 ± 0.17 | 0        | 0.13                | 3.84 ± 0.11    | 0.00 ± 0.29 | 0        |

Table 6: Signal efficiency ($\epsilon$), the number of expected background events ($N_{bkg}$), and the number of observed events ($N_{obs}$) for a combined $B^0 \to A'A'$. 


|   | 13.85 ± 1.26 | 0.00 ± 0.17 | 0.14 | 13.71 ± 1.25 | 0.00 ± 0.17 | 0.15 | 13.57 ± 1.24 | 0.00 ± 0.17 | 0.16 | 13.47 ± 1.23 | 0.00 ± 0.17 | 0.17 | 13.37 ± 1.22 | 0.00 ± 0.17 | 0.18 | 13.31 ± 1.21 | 0.00 ± 0.17 | 0.19 | 13.25 ± 1.21 | 0.00 ± 0.17 | 0.20 | 13.22 ± 1.20 | 0.00 ± 0.17 | 0.21 | 19.39 ± 1.06 | 0.00 ± 0.29 | 0.22 | 19.91 ± 1.00 | 0.00 ± 0.29 | 0.23 | 19.50 ± 0.95 | 0.00 ± 0.29 | 0.24 | 18.39 ± 0.88 | 0.00 ± 0.29 | 0.25 | 17.04 ± 0.80 | 0.00 ± 0.29 | 0.26 | 16.12 ± 0.76 | 0.00 ± 0.29 | 0.27 | 15.14 ± 0.71 | 0.00 ± 0.75 | 0.28 | 14.62 ± 0.68 | 0.50 ± 0.76 | 0.29 | 14.10 ± 0.64 | 0.50 ± 0.76 | 0.30 | 13.84 ± 0.62 | 0.50 ± 0.76 | 0.31 | 13.58 ± 0.60 | 0.00 ± 0.75 | 0.32 | 13.37 ± 0.58 | 0.50 ± 0.76 | 0.33 | 13.16 ± 0.57 | 0.00 ± 0.75 | 0.34 | 12.97 ± 0.55 | 0.00 ± 0.75 | 0.35 | 12.80 ± 0.53 | 0.00 ± 0.75 | 0.36 | 12.65 ± 0.52 | 0.00 ± 0.75 | 0.37 | 12.45 ± 0.50 | 0.00 ± 0.75 | 0.38 | 12.69 ± 0.51 | 0.50 ± 0.76 | 0.39 | 12.54 ± 0.49 | 0.50 ± 0.76 | 0.40 | 12.63 ± 0.48 | 0.50 ± 0.76 | 0.41 | 12.89 ± 0.48 | 0.00 ± 0.75 | 0.42 | 12.50 ± 0.46 | 0.00 ± 0.75 | 0.43 | 11.85 ± 0.44 | 0.50 ± 0.76 | 0.44 | 8.27 ± 0.29 | 0.00 ± 0.29 | 0.45 | 8.34 ± 0.29 | 0.00 ± 0.29 | 0.46 | 7.83 ± 0.26 | 0.00 ± 0.29 | 0.47 | 7.42 ± 0.24 | 0.00 ± 0.29 | 0.48 | 7.18 ± 0.23 | 0.00 ± 0.29 | 0.49 | 6.93 ± 0.21 | 0.00 ± 0.29 | 0.50 | 6.54 ± 0.20 | 0.00 ± 0.29 | 0.51 | 6.49 ± 0.19 | 0.00 ± 0.29 | 0.52 | 5.90 ± 0.17 | 0.00 ± 0.29 | 0.53 | 5.58 ± 0.15 | 0.00 ± 0.29 | 0.54 | 5.36 ± 0.14 | 0.00 ± 0.29 | 0.55 | 5.09 ± 0.13 | 0.00 ± 0.29 | 0.56 | 4.79 ± 0.11 | 0.00 ± 0.29 | 0.57 | 4.52 ± 0.10 | 0.00 ± 0.29 | 0.58 | 4.10 ± 0.08 | 0.10 ± 0.30 | 0.59 | 3.74 ± 0.07 | 0.10 ± 0.30 | 0.60 | 3.37 ± 0.06 | 0.10 ± 0.30 | 0.61 | 3.14 ± 0.06 | 0.10 ± 0.30 | 0.62 | 3.83 ± 0.11 | 0.00 ± 0.29 | 0.63 | 3.94 ± 0.12 | 0.00 ± 0.29 | 0.64 | 4.19 ± 0.13 | 0.00 ± 0.29 | 0.65 | 7.64 ± 0.25 | 0.80 ± 0.78 | 0.66 | 7.30 ± 0.25 | 0.74 ± 0.77 | 0.67 | 6.85 ± 0.24 | 0.74 ± 0.77 | 0.68 | 6.49 ± 0.23 | 0.62 ± 0.76 | 0.69 | 6.38 ± 0.23 | 0.85 ± 0.78 | 0.70 | 6.08 ± 0.23 | 0.25 ± 0.76 | 0.71 | 5.53 ± 0.22 | 0.70 ± 0.77 | 0.72 | 5.75 ± 0.21 | 0.25 ± 0.76 | 0.73 | 5.27 ± 0.21 | 0.85 ± 0.78 | 0.74 | 4.54 ± 0.19 | 1.10 ± 0.77 | 0.75 | 4.68 ± 0.19 | 0.30 ± 0.77 | 0.76 | 4.53 ± 0.19 | 0.40 ± 0.77 | 0.77 | 4.18 ± 0.17 | 0.40 ± 0.77 | 0.78 | 3.68 ± 0.16 | 0.60 ± 0.76 | 0.79 | 3.48 ± 0.15 | 0.80 ± 0.77 | 0.80 | 3.03 ± 0.14 | 1.10 ± 0.79 | 0.81 | 3.32 ± 0.15 | 0.60 ± 0.79 | 0.82 | 3.51 ± 0.16 | 0.70 ± 0.77 | 0.83 | 3.00 ± 0.14 | 0.80 ± 0.77 | 0.84 | 2.48 ± 0.12 | 1.50 ± 0.93 | 0.85 | 2.27 ± 0.11 | 1.10 ± 0.79 | 0.86 | 2.31 ± 0.11 | 1.15 ± 0.80 | 0.87 | 2.27 ± 0.11 | 0.60 ± 0.78 | 0.88 | 2.18 ± 0.11 | 1.15 ± 0.79 | 0.89 | 2.20 ± 0.11 | 0.90 ± 0.78 | 0.90 | 2.12 ± 0.10 | 0.85 ± 0.78 | 0.91 | 2.14 ± 0.10 | 0.45 ± 0.78 | 0.92 | 1.84 ± 0.09 | 0.55 ± 0.78 | 0.93 | 1.85 ± 0.09 | 0.55 ± 0.78 | 0.94 | 1.95 ± 0.10 | 0.50 ± 0.78 | 0.95 | 1.98 ± 0.10 | 0.40 ± 0.77 | 0.96 | 2.06 ± 0.10 | 0.30 ± 0.77 | 0.97 | 2.11 ± 0.10 | 0.20 ± 0.76 | 0.98 | 1.90 ± 0.09 | 0.40 ± 0.77 | 0.99 | 2.00 ± 0.10 | 0.50 ± 0.78 | 1.00 | 2.30 ± 0.11 | 0.40 ± 0.77 | 1.01 | 2.52 ± 0.12 | 0.80 ± 0.80 | 1.02 | 2.41 ± 0.11 | 1.00 ± 0.79 | 1.03 | 2.87 ± 0.14 | 0.80 ± 0.78 | 1.04 | 2.98 ± 0.14 | 1.40 ± 0.93 | 1.05 | 2.96 ± 0.15 | 0.60 ± 0.79 | 1.06 | 2.95 ± 0.15 | 0.95 ± 0.81 | 1.07 | 2.91 ± 0.15 | 1.25 ± 0.82 | 1.08 | 2.54 ± 0.13 | 1.07 ± 0.81 | 1.09 | 2.53 ± 0.13 | 1.97 ± 0.84 | 1.10 | 2.88 ± 0.14 | 1.67 ± 0.83 |
The following table presents upper limits at 90% confidence level for three kinds of branching fraction: (a) $\text{B.F.}(B^0 \rightarrow A'A') \equiv B$, (b) $\text{B.F.}(B^0 \rightarrow A'A') \times \text{B.F.}(A' \rightarrow e^+e^-)^2 \equiv B_{ee}$, (c) $\text{B.F.}(B^0 \rightarrow A'A') \times \text{B.F.}(A' \rightarrow \mu^+\mu^-)^2 \equiv B_{\mu\mu}$. The dark photon is scanned in $0.01 - 2.62 \text{ GeV}/c^2$ mass range with $10 \text{ MeV}/c^2$ ($0.01 - 1.10 \text{ GeV}/c^2$) and $20 \text{ MeV}/c^2$ ($1.10 - 2.62 \text{ GeV}/c^2$) intervals. The upper limits are calculated using the POLE program [4] which is based on the Feldman-Cousins unified approach [5].

### Table 7: Upper limits of branching fractions at 90% confidence level.

| $m_{A'}$ (GeV/c^2) | $B$ ($10^{-8}$) | $B_{ee}$ ($10^{-8}$) | $B_{\mu\mu}$ ($10^{-8}$) | $m_{A'}$ (GeV/c^2) | $B$ ($10^{-8}$) | $B_{ee}$ ($10^{-8}$) | $B_{\mu\mu}$ ($10^{-8}$) |
|--------------------|-----------------|---------------------|--------------------------|--------------------|-----------------|---------------------|--------------------------|
| 0.01               | 3.64            | 3.64                | -                        | 0.94               | 8.22            | 2.83                | 4.80                     |
| 0.02               | 4.55            | 4.55                | -                        | 0.95               | 7.78            | 2.82                | 4.81                     |
| 0.03               | 3.47            | 3.47                | -                        | 0.96               | 7.79            | 2.81                | 4.81                     |
| 0.04 | 3.85 | 3.85 | - | 0.97 | 7.25 | 2.81 | 4.83 |
| 0.05 | 3.88 | 3.88 | - | 0.98 | 7.54 | 2.82 | 4.84 |
| 0.06 | 2.21 | 2.21 | - | 0.99 | 7.10 | 2.82 | 4.88 |
| 0.07 | 3.95 | 3.95 | - | 1.00 | 8.63 | 2.83 | 4.92 |
| 0.08 | 4.00 | 4.00 | - | 1.01 | 15.4 | 2.83 | 4.94 |
| 0.09 | 2.30 | 2.30 | - | 1.02 | 1763 | 2.83 | 4.94 |
| 0.10 | 2.34 | 2.34 | - | 1.03 | 24.5 | 2.83 | 4.95 |
| 0.11 | 2.33 | 2.33 | - | 1.04 | 11.1 | 2.84 | 4.96 |
| 0.12 | 2.33 | 2.33 | - | 1.05 | 8.89 | 2.84 | 4.99 |
| 0.13 | 2.32 | 2.32 | - | 1.06 | 7.91 | 2.85 | 5.03 |
| 0.14 | 2.30 | 2.30 | - | 1.07 | 7.95 | 2.85 | 5.05 |
| 0.15 | 2.32 | 2.32 | - | 1.08 | 7.72 | 2.85 | 5.07 |
| 0.16 | 2.35 | 2.35 | - | 1.09 | 7.26 | 2.86 | 5.07 |
| 0.17 | 2.37 | 2.37 | - | 1.10 | 3.30 | 2.87 | 5.06 |
| 0.18 | 2.38 | 2.38 | - | 1.12 | 3.51 | 2.87 | 5.06 |
| 0.19 | 2.39 | 2.39 | - | 1.14 | 3.74 | 2.88 | 5.02 |
| 0.20 | 2.41 | 2.41 | - | 1.16 | 4.05 | 2.88 | 5.02 |
| 0.21 | 2.41 | 2.41 | - | 1.18 | 7.21 | 2.88 | 5.02 |
| 0.22 | 1.58 | 2.42 | 0.92 | 1.20 | 8.29 | 2.88 | 5.00 |
| 0.23 | 1.53 | 2.44 | 1.01 | 1.22 | 4.68 | 2.87 | 4.97 |
| 0.24 | 1.57 | 2.46 | 1.13 | 1.24 | 4.89 | 2.88 | 4.95 |
| 0.25 | 1.66 | 2.46 | 1.31 | 1.26 | 8.74 | 2.86 | 4.99 |
| 0.26 | 1.79 | 2.46 | 1.57 | 1.28 | 14.0 | 2.86 | 4.95 |
| 0.27 | 1.89 | 2.46 | 1.76 | 1.30 | 5.95 | 2.84 | 4.96 |
| 0.28 | 1.94 | 2.47 | 2.02 | 1.32 | 6.03 | 2.83 | 4.95 |
| 0.29 | 1.84 | 2.48 | 2.19 | 1.34 | 6.54 | 2.83 | 4.93 |
| 0.30 | 1.91 | 2.49 | 2.39 | 1.36 | 18.6 | 2.81 | 4.95 |
| 0.31 | 1.95 | 2.50 | 2.52 | 1.38 | 13.3 | 2.79 | 4.90 |
| 0.32 | 2.16 | 2.51 | 2.66 | 1.40 | 14.5 | 2.78 | 4.93 |
| 0.33 | 2.01 | 2.52 | 2.77 | 1.42 | 7.92 | 2.75 | 4.91 |
| 0.34 | 2.23 | 2.53 | 2.89 | 1.44 | 7.38 | 2.76 | 4.91 |
| 0.35 | 2.26 | 2.54 | 3.04 | 1.46 | 8.41 | 2.73 | 4.92 |
| 0.36 | 2.29 | 2.55 | 3.21 | 1.48 | 8.19 | 2.72 | 4.90 |
| 0.37 | 2.32 | 2.56 | 3.24 | 1.50 | 19.3 | 2.71 | 4.94 |
| 0.38 | 2.36 | 2.56 | 3.27 | 1.52 | 18.7 | 2.69 | 4.90 |
| 0.39 | 2.12 | 2.57 | 3.36 | 1.54 | 21.1 | 2.67 | 4.90 |
| 0.40 | 2.15 | 2.58 | 3.44 | 1.56 | 10.6 | 2.64 | 4.89 |
| 0.41 | 2.13 | 2.59 | 3.51 | 1.58 | 11.2 | 2.64 | 4.84 |
| 0.42 | 2.28 | 2.60 | 3.58 | 1.60 | 11.8 | 2.63 | 4.81 |
| 0.43 | 2.35 | 2.61 | 3.64 | 1.62 | 12.7 | 2.63 | 4.83 |
| 0.44 | 2.27 | 2.61 | 3.71 | 1.64 | 14.4 | 2.62 | 4.79 |
| 0.45 | 3.69 | 2.63 | 3.75 | 1.66 | 14.3 | 2.61 | 4.73 |
| 0.46 | 3.66 | 2.65 | 3.79 | 1.68 | 13.7 | 2.59 | 4.70 |
| 0.47 | 3.90 | 2.67 | 3.83 | 1.70 | 13.8 | 2.58 | 4.70 |
| 0.48 | 4.11 | 2.69 | 3.88 | 1.72 | 13.6 | 2.56 | 4.62 |
| 0.49 | 4.25 | 2.71 | 3.92 | 1.74 | 13.5 | 2.56 | 4.56 |
| 0.50 | 4.39 | 2.73 | 3.96 | 1.76 | 14.4 | 2.55 | 4.53 |
| 0.51 | 4.65 | 2.76 | 3.99 | 1.78 | 13.4 | 2.53 | 4.48 |
| 0.52 | 4.69 | 2.79 | 4.01 | 1.80 | 11.9 | 2.51 | 4.42 |
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2.62 2.88 1.47 1.15

References

[1] P. A. Zyla et al. (Particle Data Group), The Review of Particle Physics, to be published in PTEP 2020 (2020) 083C01.

[2] B. Batell, M. Pospelov and A. Ritz, Probing a Secluded U(1) at B-factories, Phys. Rev. D 79 (2009) 115008 [arXiv:0903.0363].
[3] J. P. Lees et al. (BaBar Collaboration), *Search for Low-Mass Dark-Sector Higgs Bosons*, Phys. Rev. Lett. **108** (2012) 211801 [arXiv:1202.1313].

[4] J. Conrad, O. Botner, A. Hallgren and C. Perez de los Heros, *Including systematic uncertainties in confidence interval construction for Poisson statistics*, Phys. Rev. D **67** (2003) 012002 [arXiv:hep-ex/0202013].

[5] G. J. Feldman and R. D. Cousins, *A Unified approach to the classical statistical analysis of small signals*, Phys. Rev. D **57** (1998) 3873 [arXiv:physics/9711021].