

## Search for Darkonium in $e^+e^-$ Collisions

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Collider searches for dark sectors, new particles interacting only feebly with ordinary matter, have largely focused on identifying signatures of new mediators, leaving much of dark sector structures unexplored. In particular, the existence of dark matter bound states (darkonia) remains to be

investigated. This possibility could arise in a simple model in which a dark photon ( $A'$ ) is light enough to generate an attractive force between dark fermions. We report herein a search for a  $J^{PC} = 1^{--}$  darkonium state, the  $\Upsilon_D$ , produced in the reaction  $e^+e^- \rightarrow \gamma\Upsilon_D, \Upsilon_D \rightarrow A'A'A'$ , where the dark photons subsequently decay into pairs of leptons or pions, using  $514 \text{ fb}^{-1}$  of data collected with the *BABAR* detector. No significant signal is observed, and we set bounds on the  $\gamma - A'$  kinetic mixing as a function of the dark sector coupling constant for  $0.001 < m_{A'} < 3.16 \text{ GeV}$  and  $0.05 < m_{\Upsilon_D} < 9.5 \text{ GeV}$ .

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The possibility of dark sectors, new quantum fields neutral under all standard model (SM) forces, has emerged as an intriguing framework to explain the presence of dark matter in the universe [1, 2]. While these particles don't couple directly to ordinary matter, indirect interactions through low-dimensional operators called "portals" are possible [3]. The physics of these dark sectors could involve an arbitrary number of fields and interactions, including the possibility of self-interacting dark matter. This scenario can be realized in a minimal dark sector model containing a single Dirac fermion ( $\chi$ ) charged under a new U(1) gauge group with a coupling constant  $g_D$  [4]. The corresponding force carrier is conventionally referred to as a dark photon ( $A'$ ), and couples to the SM photon via kinetic mixing with strength  $\varepsilon$  [5, 6]. A light dark photon would give rise to an attractive force between the  $\chi$  and  $\bar{\chi}$  particles, resulting in the formation of bound states (darkonia) when  $1.68m_{A'} < \alpha_D m_\chi$  for  $\alpha_D = g_D^2/4\pi$  [4, 7].

The two lowest energy bound states in this model are denoted  $\eta_D$  ( $J^{PC} = 0^{-+}$ ) and  $\Upsilon_D$  ( $J^{PC} = 1^{--}$ ), in analogy with similar SM states. The quantum numbers predict the following production and decay mechanisms at  $e^+e^-$  colliders:  $e^+e^- \rightarrow \eta_D + A', \eta_D \rightarrow A'A'$  and initial-state radiation (ISR) process  $e^+e^- \rightarrow \Upsilon_D + \gamma_{\text{ISR}}, \Upsilon_D \rightarrow A'A'A'$ . In the regime  $m_{A'} < 2m_\chi$ , the dark photon decays visibly into a pair of SM fermions with a decay width proportional to the product  $m_{A'}\varepsilon^2$ . Depending on the value of these parameters, the decays can be prompt or significantly displaced from the  $e^+e^-$  interaction point. Current constraints on visible  $A'$  decays [8–18] exclude values of  $\varepsilon \gtrsim 10^{-3}$  over a wide range of masses from the dielectron threshold up to tens of GeV [19].

We report herein a search for darkonium in the ISR process  $e^+e^- \rightarrow \gamma_{\text{ISR}}\Upsilon_D, \Upsilon_D \rightarrow A'A'A'$ , where the dark photons subsequently decay into pairs of electrons, muons, or pions. The cross section is determined for prompt  $A'$  decays in the region  $0.001 \text{ GeV} < m_{A'} < 3.16 \text{ GeV}$  and  $0.05 \text{ GeV} < m_{\Upsilon_D} < 9.5 \text{ GeV}$ . For  $m_{A'} < 0.2 \text{ GeV}$ , the dark photon decay length becomes significant for values of  $\varepsilon$  we expect to probe, and we additionally report cross sections for lifetimes  $\tau_{A'}$  corresponding to  $c\tau_{A'}$  values of 0.1, 1, and 10 mm. This search is based on  $514 \text{ fb}^{-1}$  of data collected with the *BABAR* detector at the SLAC PEP-II  $e^+e^-$  collider at the  $\Upsilon(4S)$ ,  $\Upsilon(3S)$ , and  $\Upsilon(2S)$  resonances and their vicinities [20]. The *BABAR* de-

tor is described in detail elsewhere [21, 22]. To avoid experimental bias, the data are not examined until the selection procedure is finalized. The analysis is developed using simulated signal events and a small fraction of real data for background studies.

Signal events are generated using MadGraph5 [23] with prompt dark photon decays for 119 different  $A'$  and  $\Upsilon_D$  mass hypotheses. For  $m_{A'} < 0.2 \text{ GeV}$ , we also simulate samples with non-zero dark photon lifetimes corresponding to proper decay lengths 0.1 mm, 1 mm, and 10 mm. The detector acceptance and reconstruction efficiencies are estimated with a simulation based on GEANT4 [24]. Since the background is too complex to be accurately simulated, we use 5% of the data to optimize the selection criteria, assuming that any signal component has a negligible impact on this procedure. This data set, referred to as the optimization sample, is discarded from the final results.

The event selection for prompt  $A'$  decays proceeds by selecting events containing exactly six charged tracks, and reconstructing dark photon candidates as pairs of oppositely charged tracks identified as electrons, muons, or pions by particle identification algorithms. We require the presence of at least one lepton pair of opposite charge with the same flavor to limit the large accidental background. We form  $\Upsilon_D$  candidates by combining three dark photon candidates, and fit them, constraining all tracks to originate from a common point compatible with the beam interaction region. For each  $\Upsilon_D$  candidate, we additionally form same-sign track combinations by swapping particles with identical flavor between reconstructed  $A'$  pairs, such as  $(e^+e^+)(e^-e^-)(\mu^+\mu^-)$  or  $(\pi^+\pi^+)(\pi^-\pi^-)(e^+e^-)$ . For the fully mixed final state  $(\mu^+\mu^-)(\pi^+\pi^-)(e^+e^-)$ , we use the same-sign combination  $(\mu^+\pi^+)(\mu^-\pi^-)(e^+e^-)$ , since pions are more easily misidentified as muons than electrons. The mass difference between same-sign pairs, distributed more broadly for signal events than for combinatorial background, is used to further improve the signal selection as discussed below.

The detection of the ISR photon accompanying  $\Upsilon_D$  production is not explicitly required. Instead, we infer the kinematics of the particle recoiling against the  $\Upsilon_D$  candidates, and we select the ISR photon candidate that is most compatible with the photon hypothesis as follows. If the recoil particle is determined to have been emit-

ted inside the electromagnetic calorimeter acceptance, we search for the presence of a corresponding ISR photon candidate, which is defined as a neutral cluster having an energy within 10% of that of the recoiling particle, and an angle compatible with the direction of the recoiling particle to better than 0.1 rad.

To improve the signal purity, we train three multivariate classifiers consisting of logistic regressions stacked on top of Random Forest (RF) classifiers [25]. The following 13 variables are used as inputs to the RF: the  $\chi^2$  of the constrained fit to the  $\mathcal{Y}_D$  candidate; combined particle identification information of the six tracks; the maximum mass difference between any pair of  $A'$  candidates; the polar angle and the invariant mass of the particle recoiling against the reconstructed  $\mathcal{Y}_D$  candidate; a categorical feature indicating whether the recoiling particle is emitted inside the calorimeter acceptance and if a corresponding ISR photon candidate is found; the sum of neutral energy deposited in the electromagnetic calorimeter, excluding the ISR photon candidate; the average of the three dark photon helicity angles [26]; the average of the angles between pairs of dark photons in the  $\mathcal{Y}_D$  rest frame; the average of the dihedral angles between pairs of dark photons; the average of the three helicity angles of the tracks produced in the  $A'$  decays; the average of the dark photon decay lengths, defined as the distances between the primary interaction point and the  $A'$  decay vertices; and the maximum mass difference between same-sign pairs.

To improve the robustness of the predictions of the classifiers, we group the final states into three categories based on the number of pion pairs: zero ( $C_0$ ), one ( $C_1$ ), or two ( $C_2$ ) pion pairs. A classifier is trained for each category with a sample of simulated events for different  $\mathcal{Y}_D$  and  $A'$  masses and a fraction of the optimization sample to describe the background. The classifier outputs are then transformed into classifier scores using a logit function [27], with higher scores indicating greater probabilities of being signal events. The distribution of the classifier scores for each category are shown in Fig. 1. The optimal selection criteria are determined by maximizing a figure of merit averaged over a wide range of  $\mathcal{Y}_D$  and  $A'$  masses. We adopt a conservative approach and treat observed events as signal candidates for the purposes of calculating the figure of merit. If multiple  $\mathcal{Y}_D$  candidates are selected in an event, a single one is chosen based on its final state according to the following sequence of hypotheses:  $6e$ ,  $4e2\mu$ ,  $2e4\mu$ ,  $6\mu$ ,  $4e2\pi$ ,  $2e2\mu2\pi$ ,  $4\mu2\pi$ ,  $2e4\pi$ ,  $2\mu4\pi$ .

A total of 69 events pass all the selection criteria. The corresponding  $(m_{\mathcal{Y}_D}, m_{A'})$  distribution is shown in Fig. 2. The events near  $m_{\mathcal{Y}_D} \sim 0.1$  GeV and  $m_{A'} \sim 0.05$  GeV arise from  $e^+e^- \rightarrow \gamma\gamma\gamma$  events in which all three photons convert to  $e^+e^-$  pairs.

The signal is extracted by combining all event categories into a single sample, and scanning the  $(m_{\mathcal{Y}_D}, m_{A'})$

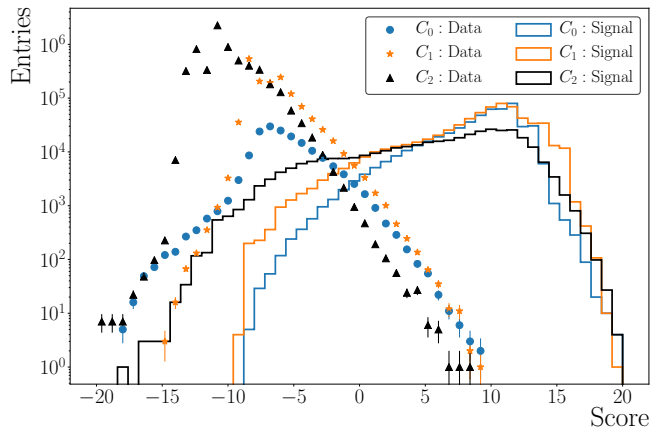


FIG. 1: The distribution of the classifier scores for each event category for the data (markers) and signal Monte Carlo (solid lines) samples. The MC simulations are arbitrarily normalized.

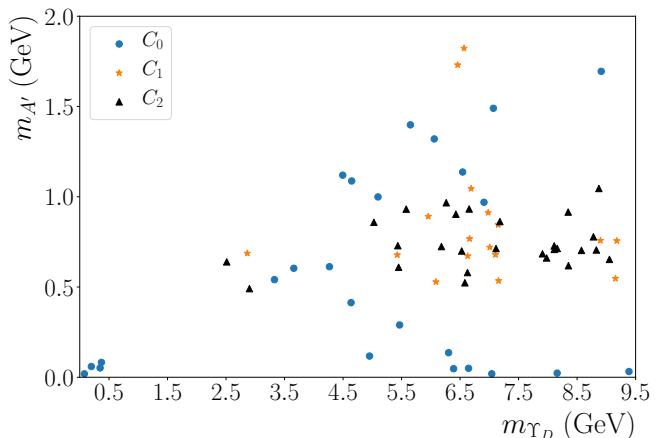


FIG. 2: The  $(m_{\mathcal{Y}_D}, m_{A'})$  distribution for events passing all selection criteria for prompt dark photon decays.

plane in steps of the signal resolution. The signal region for a given mass hypothesis is defined as the interval  $[m_{\mathcal{Y}_D} - 4\sigma_{m_{\mathcal{Y}_D}}; m_{\mathcal{Y}_D} + 4\sigma_{m_{\mathcal{Y}_D}}]$  and  $[m_{A'} - 4\sigma_{m_{A'}}; m_{A'} + 4\sigma_{m_{A'}}]$ , where  $\sigma_{m_{\mathcal{Y}_D}}$  ( $\sigma_{m_{A'}}$ ) denotes the corresponding  $\mathcal{Y}_D$  ( $A'$ ) mass resolution. The resolutions are determined by fitting the different signal Monte Carlo (MC) samples with a Crystal Ball function [28] and interpolating the results throughout the full mass range. The  $\mathcal{Y}_D$  ( $A'$ ) mass resolution varies between 5 – 40 MeV (1 – 8 MeV); the detailed results are available in the Supplemental Material [29]. The number of observed background events is estimated by averaging two neighboring regions along the  $m_{\mathcal{Y}_D}$  axis:  $[m_{\mathcal{Y}_D} - 8\sigma_{m_{\mathcal{Y}_D}}; m_{\mathcal{Y}_D} - 4\sigma_{m_{\mathcal{Y}_D}}]$  and  $[m_{\mathcal{Y}_D} + 4\sigma_{m_{\mathcal{Y}_D}}; m_{\mathcal{Y}_D} + 8\sigma_{m_{\mathcal{Y}_D}}]$ . This choice is motivated by the potential background contribution due to hadronic resonances or photon conversions, which would be concentrated at similar values of dark photon masses. The signal significance is assessed from MC samples, using

sideband data from the classifier score distribution to model the  $(m_{\Upsilon_D}, m_{A'})$  distribution of the background. The most significant measurement contains two events in the signal window, corresponding to a p-value of 30%, which is compatible with the null hypothesis.

In the absence of signal, we derive 90% confidence level (CL) upper limits on the  $e^+e^- \rightarrow \gamma\Upsilon_D$  cross section using a profile likelihood method [30]. The probability of observing  $N$  events in a given signal region is described by the following model:

$$P(N|n+b) = \frac{e^{-n}n^N}{N!} \frac{e^{-b}b^B}{B!} \frac{1}{2\pi\sigma_Z\sigma_L} e^{-\frac{(z-Z)^2}{2\sigma_Z^2}} e^{-\frac{(l-L)^2}{2\sigma_L^2}}$$

where  $b$  ( $B$ ) is the expected (estimated) number of background events, and  $n = lz\sigma(e^+e^- \rightarrow \gamma\Upsilon_D)$  is the expected number of signal events given by the product of the integrated luminosity  $l$ , the  $e^+e^- \rightarrow \gamma\Upsilon_D$  cross section, and the signal efficiency  $z$ . The measured luminosity, signal efficiency, and their uncertainties are denoted by  $L$ ,  $Z$ ,  $\sigma_L$ , and  $\sigma_Z$ , respectively. The signal efficiency includes the dark photon branching fractions, taken from Ref. [31]. The efficiency is determined for each simulated sample and interpolated to the full parameter space, ranging from 0.1% for  $m_{\Upsilon_D} \sim 0.15$  GeV,  $m_{A'} \sim 0.05$  GeV to 34% for  $m_{\Upsilon_D} \sim 8.0$  GeV,  $m_{A'} \sim 1.0$  GeV. The uncertainty in the signal efficiency arises mainly from particle identification algorithms, assessed with high-purity samples of leptons and pions. This source of uncertainty varies between 9% and 11%. The uncertainty associated with the efficiency extrapolation procedure ranges from 4% to 7%, depending on the  $m_{\Upsilon_D}$  and  $m_{A'}$ . Other uncertainties include the tracking efficiency (1.2%) and the limited statistical precision of the simulated sample (1%-5%). The uncertainty in the dark photon branching fraction [31] ranges from parts per mille to 1%. The uncertainty in the luminosity is determined to be 0.6% [20]. The cross section at 90% CL upper limits are displayed in Fig. 3. The dark photon decays predominantly into  $\pi^+\pi^-\pi^0$  ( $K^+K^-$ ) near the  $\omega$  ( $\phi$ ) resonance which are not considered in this analysis, resulting in much looser bounds around  $m_{A'} \sim 0.8$  GeV ( $m_{A'} \sim 1$  GeV).

We follow a similar procedure to determine the  $e^+e^- \rightarrow \gamma\Upsilon_D$  cross section for each dark photon lifetime hypothesis. The measurement is performed for  $m_{A'} < 0.2$  GeV. In this mass range, the  $A'$  decays almost exclusively to an  $e^+e^-$  pair. The event selection is analogous to that previously described, except that we constrain the momentum vector of the  $A'$  candidates to point back to the beam interaction region instead of requiring the tracks to originate from this location when performing the  $\Upsilon_D$  kinematic fit. To further suppress photon conversions in the detector material, we add the following variables to the RF classifier, averaged over the three dark photon candidates: the  $\chi^2$  of a fit of the  $A'$  candidate; the angle between the secondary vertex flight direction and the  $A'$  momentum; and the ratio between

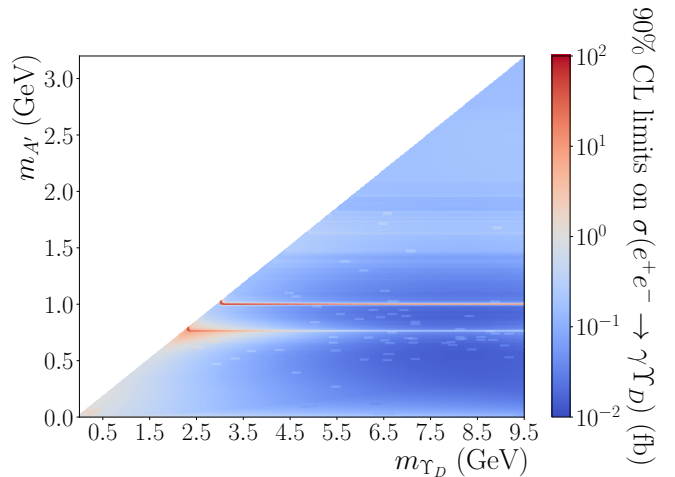


FIG. 3: The 90% CL upper limits on the  $e^+e^- \rightarrow \gamma\Upsilon_D$  cross section for prompt dark photon decays.

the flight length and its uncertainty. We train a classifier for each  $c\tau_{A'}$  value to improve the search sensitivity. A total of 56, 33, and 31 events are selected for the  $c\tau_{A'} = 0.1, 1, \text{ and } 10$  mm data sample, respectively. The resulting mass distributions are shown in Fig. 4. The signal extraction procedure described above is applied to each selected sample separately. No significant signal is observed for any  $A'$  lifetime hypothesis, and limits on the cross section for each value of  $c\tau_{A'}$  are extracted. The classifier score distributions and the cross section at 90% CL upper limits are shown in the Supplemental Material [29].

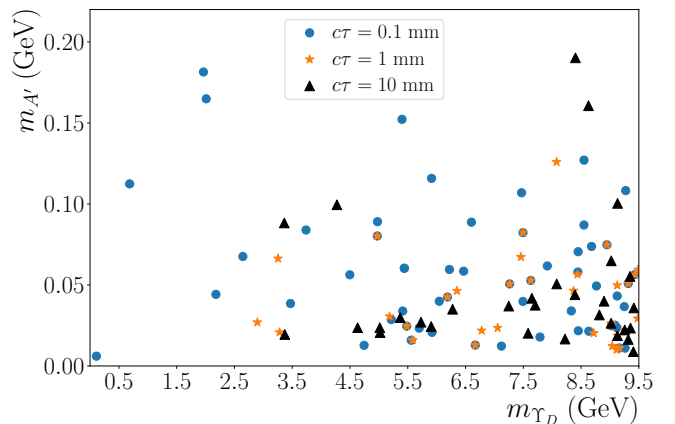


FIG. 4: The  $(m_{\Upsilon_D}, m_{A'})$  mass distribution of event candidates passing all selection criteria for the datasets optimized for each dark photon lifetime.

The 90% CL upper limits on the kinetic mixing parameter are extracted by an iterative procedure taking into account the effect of the potentially long dark photon lifetime. At each step, we estimate the dark photon lifetime given the current value of the kinetic mixing, compare

the limit on the production cross section interpolated at that lifetime, update the kinetic mixing, and repeat the procedure until convergence is obtained. Since the dark photon lifetime is independent of the dark sector coupling constant, we derive separate limits for  $\alpha_D$  values set to 0.1, 0.3, 0.5, 0.7, 0.9, and 1.1. The results are shown in Fig. 5 for  $\alpha_D = 0.5$ , and in the Supplemental Material [29] for the remaining values. Bounds on the mixing strength  $\varepsilon$  down to  $5 \times 10^{-5} - 10^{-3}$  are set for a large fraction of the parameter space. Constraints for different values of  $\alpha_D$ ,  $m_{A'}$  and  $m_{\Upsilon_D}$  are also shown in Fig. 6.

In summary, we report the first search for a dark sector bound state decaying into three dark photons in the range  $0.001 \text{ GeV} < m_{A'} < 3.16 \text{ GeV}$  and  $0.05 \text{ GeV} < m_{\Upsilon_D} < 9.5 \text{ GeV}$ . No significant signal is seen, and we derive limits on the  $\gamma - A'$  kinetic mixing  $\varepsilon$  at the level of  $5 \times 10^{-5} - 10^{-3}$ , depending on the values of the model parameters. These measurements improve upon existing constraints over a significant fraction of dark photon masses below 1 GeV for large values of the dark sector coupling constant.

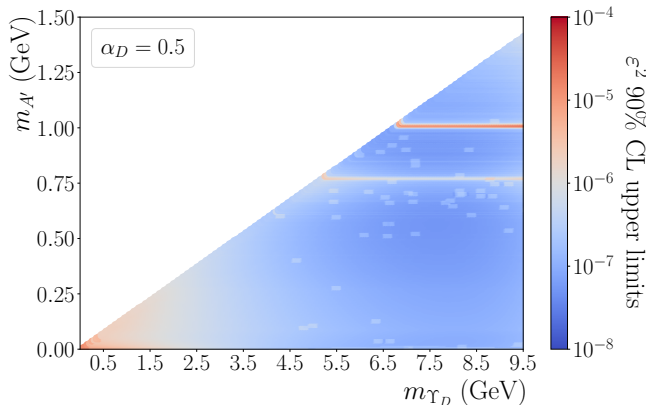


FIG. 5: The 90% CL upper limits on the kinetic mixing  $\varepsilon^2$  as a function of the  $\Upsilon_D$  mass,  $m_{\Upsilon_D}$ , and dark photon mass,  $m_{A'}$ , assuming  $\alpha_D = 0.5$ .

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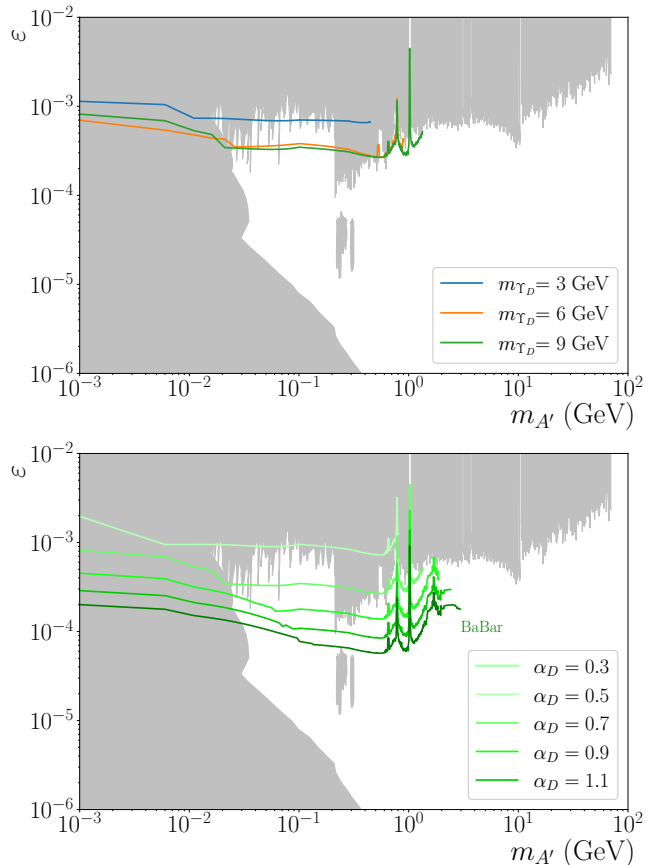


FIG. 6: The 90% CL upper limits on the kinetic mixing  $\varepsilon$  for (top) various  $\Upsilon_D$  masses assuming  $\alpha_D = 0.5$  and (bottom) various  $\alpha_D$  values assuming  $m_{\Upsilon_D} = 9 \text{ GeV}$  together with current constraints (gray area) [8–18].

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# Supplemental Material for *BABAR-PUB-21/002*

## *Search for Darkonium in $e^+e^-$ Collisions*

Additional figures for the dark sector bound state search are presented in this Supplemental Material.

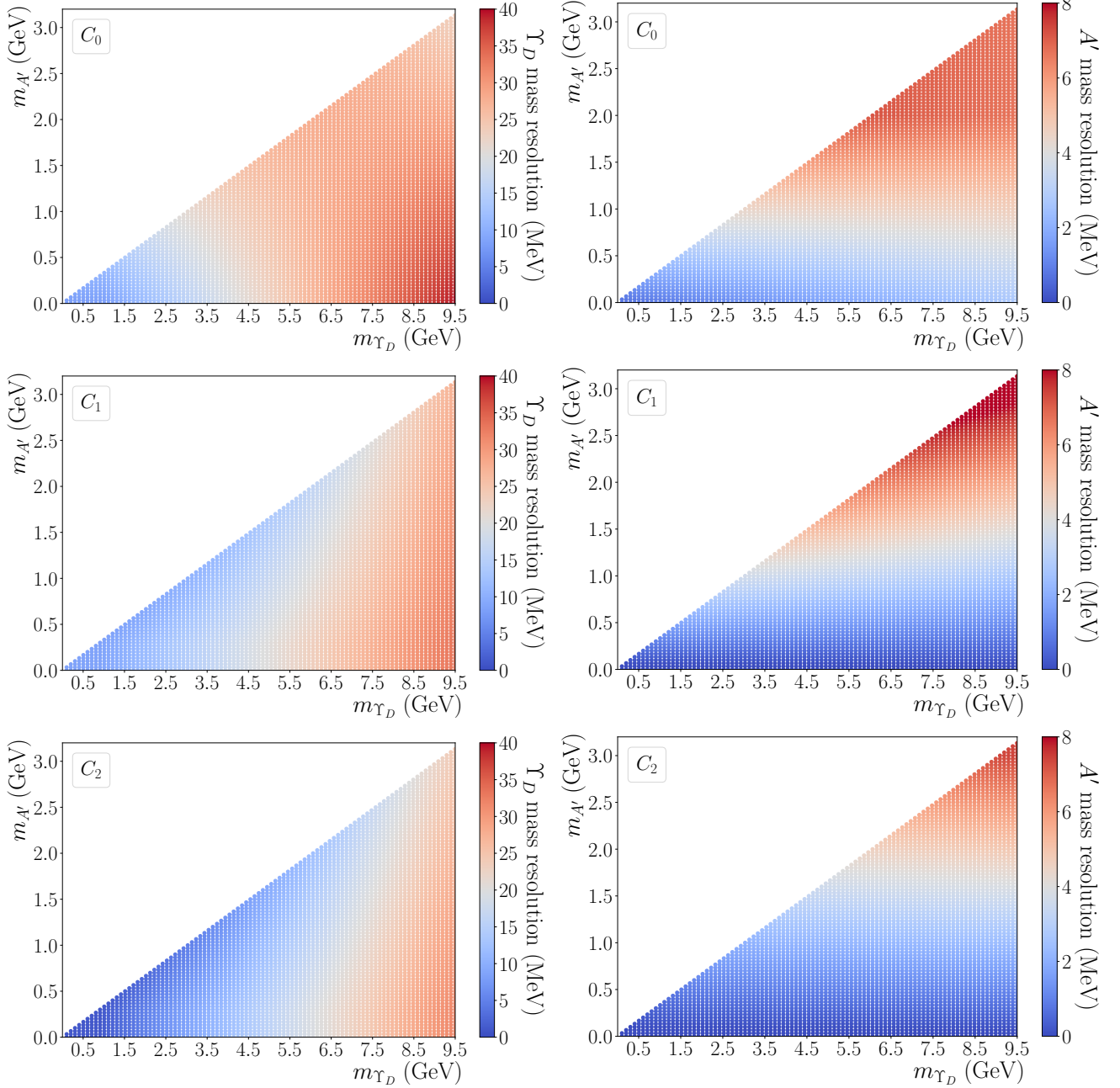


FIG. 7: The  $\Upsilon_D$  and  $A'$  mass resolution for each category of events (see text) for prompt  $A'$  decays.



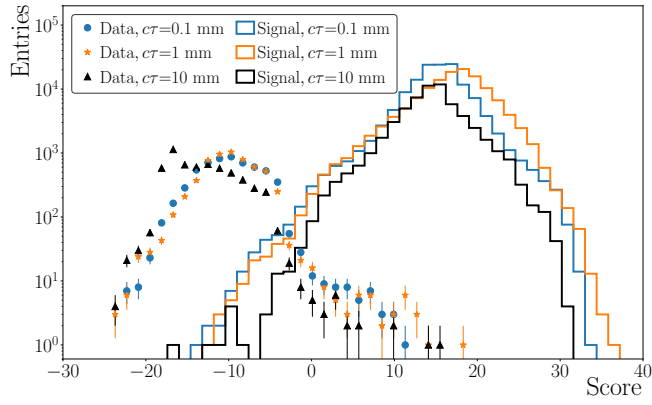


FIG. 8: The distribution of the classifier scores for data (markers) and signal MC simulations (solid lines) for dark photon lifetimes corresponding to (top)  $c\tau_{A'} = 0.1$  mm, (middle)  $c\tau_{A'} = 1$  mm, and (bottom)  $c\tau_{A'} = 10$  mm. The MC simulations are arbitrarily normalized.

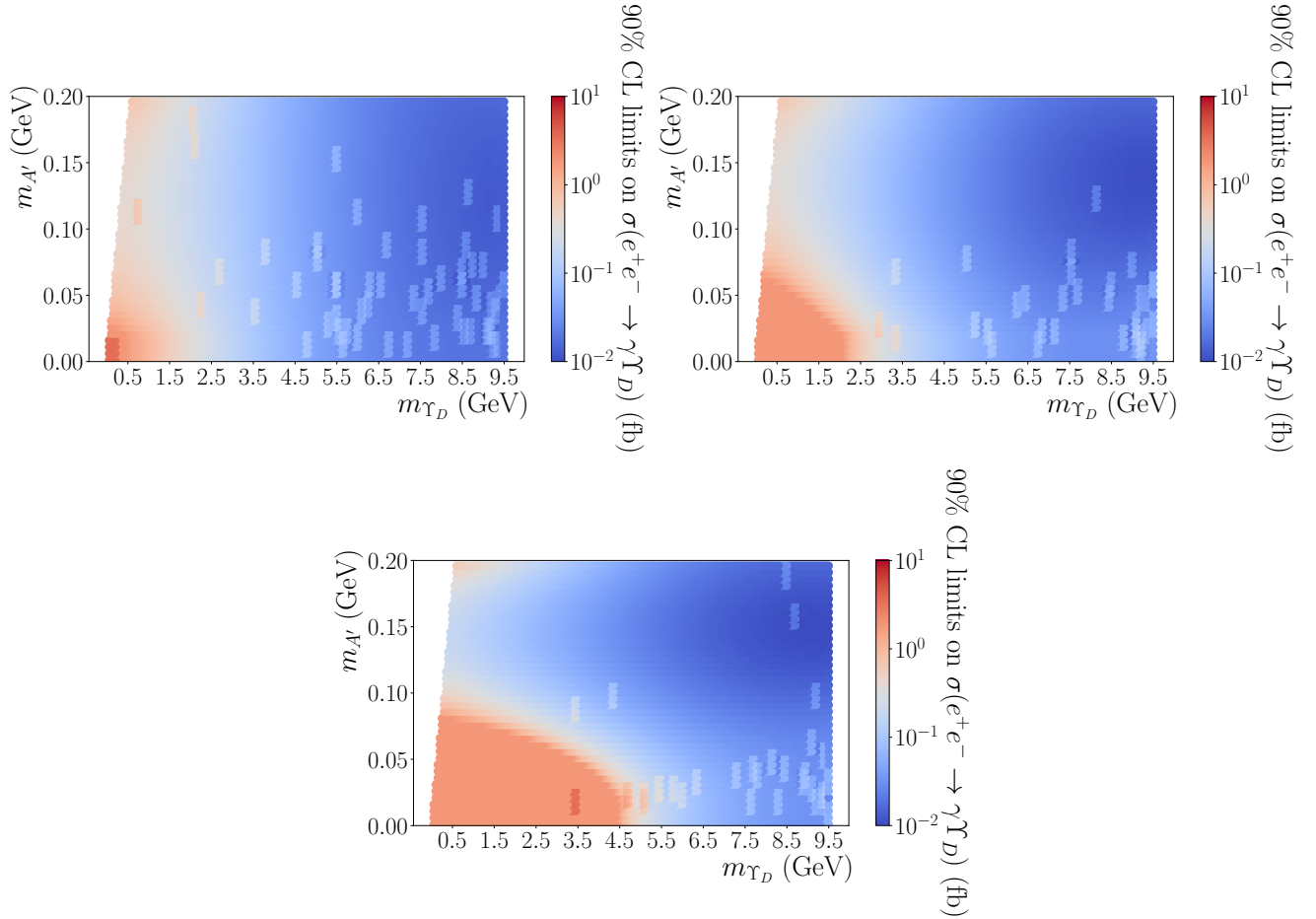


FIG. 9: The 90% CL upper limits on the  $e^+e^- \rightarrow \gamma\Upsilon_D$  cross section for dark photon lifetimes corresponding to (top left)  $c\tau_{A'} = 0.1$  mm, (top right)  $c\tau_{A'} = 1$  mm, and (bottom)  $c\tau_{A'} = 10$  mm.

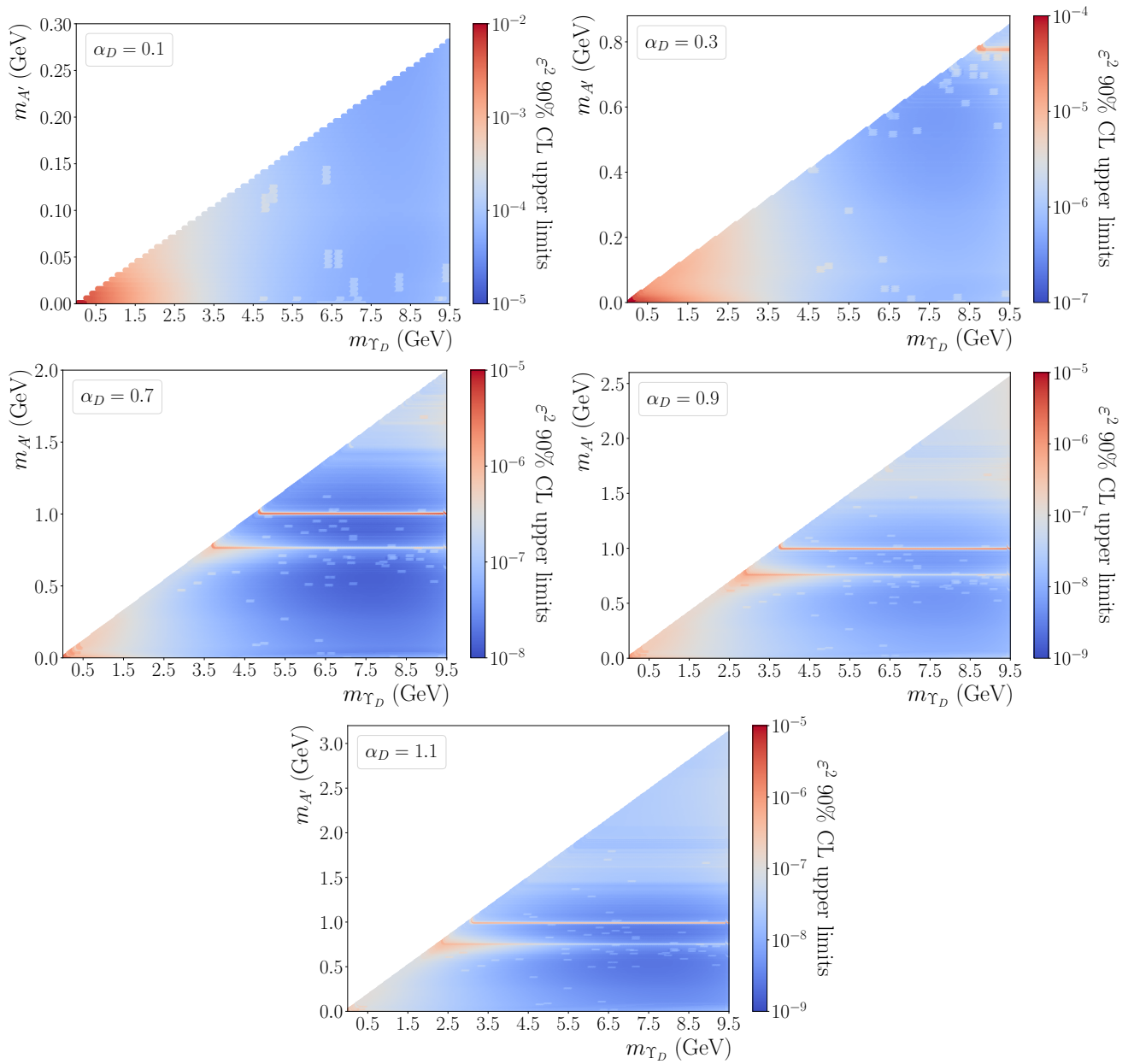


FIG. 10: The 90% CL upper limits on the kinetic mixing  $\varepsilon^2$  as a function of the  $\Upsilon_D$  mass,  $m_{\Upsilon_D}$ , and dark photon mass,  $m_{A'}$ , assuming (top left)  $\alpha_D = 0.1$ , (top right)  $\alpha_D = 0.3$ , (middle left)  $\alpha_D = 0.7$ , (middle right)  $\alpha_D = 0.9$ , and (bottom)  $\alpha_D = 1.1$ .