PROCEEDINGS OF SCIENCE

Searches for light dark sectors at Belle II, Belle, and BaBar

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Amongst the various beyond-Standard-Model topics, dark matter plays a pivotal role in today's particle physics. Searches for Dark Matter involve many fields and span a wide array of theoretical models, one of them being the dark sector. This review presents results of recent dark-sector searches performed by the e^+e^- B factories: BaBar, Belle, and Belle II.

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1. Dark Sector at B Factories

Dark matter (DM) searches are a central part of today's particle physics given the abundant astrophysical evidences for its existence (e.g., [1]). Amongst the various DM models, the one of interest for this talk is the Dark Sector (DS): according to this model, Standard Model (SM) matter and DM were in thermal equilibrium in the early universe; with the passing time, the universe expanded and cooled down to the point when the DM interaction with SM matter (annihilation and production) stopped, i.e., a *freeze-out* happened, which left a *relic density* of DM. This DM would satisfy current astrophysical and cosmological constraints by being low-mass and interacting with the SM matter via a new feeble interaction. The hypothetical particle connecting the SM with the DS matter is called *dark mediator*.

The DS typical mass range is from order keV to GeV, perfectly fitting with the approximately 10 GeV center-of-mass energy of B factories. B factories (namely the BaBar, Belle, and Belle II experiments [2, 3]) are good candidates to explore the DS for other reasons too: they offer hermetic detectors (they cover almost the entirety of the solid angle); they benefit from a clean environment (the initial state is extremely well-known, and events are much lower multiplicity than ones of hadronic colliders) because they are placed on electron-positron colliders; and they have dedicated triggers for low-multiplicity events, down to single-photon triggers.

In the following, recent DS searches performed at each B factories are summarized.

2. BaBar

BaBar operated at the SLAC laboratory, USA, from 1999 to 2008. It was located on the PEP-II collider, which provided it e^+e^- beams.

2.1 Axion-Like Particles in B decays: $B \to Ka, a \to \gamma\gamma$

Axion-Like Particles (ALPs) arise from a theroetical framework similar to that of Peccei-Quinn QCD axions. They are massive, neutral, pseudoscalar particles, and possibly constitute dark mediators. Most often what is investigated is their coupling to gluon and photons; for the analysis reported in this Section, instead, it is investigated their coupling to $W^\pm$ via the B-into-K process. More specifically, the production-and-decay channel is $B^\pm \to K^\pm a, a \to \gamma\gamma$. The analysis studies both prompt and non-prompt (i.e. displaced) decay. It is the first search for visibly decaying ALPs coming from B mesons.

The dataset used for this analysis is the full BaBar one collected on the $\Upsilon(4S)$ resonance, and corresponds to and integrated luminosity of 424 fb^{-1}. A random 8% of the dataset has been used to optimize the search strategy, and henceforth not used for the actual search and upper-limit setting. The signal signature is one track and two photons, with the three particles together summing up to the mass of the B meson. The main backgrounds are: $e^+e^- \to q\bar{q}$ ($q = u, d, c, s$), also called *continuum*, which is the dominant but non-peaking one; $B^\pm \to K^\pm h^0$, $h^0 \to \gamma\gamma$ ($h^0 = \pi^0, \eta, \eta'$), which is peaking, but can be vetoed using the diphoton invariant mass; and $B^\pm \to K^\pm \eta_c$, $\eta_c \to \gamma\gamma$, which is a small, peaking, and non-vetoed background. The background rejection has been performed with two BDTs, one optimized to reject the continuum background, the other against the $B\bar{B}$ one.

The search strategy is a 1D fit on the $m(\gamma\gamma$ variable, searching for a peaking signal over a smooth background.

In Fig. 1 the 90%-confidence level (CL) upper limit (UL) on the coupling constant g_{aW} is shown. The UL extraction has been re-performed for non-zero lifetimes too, namely 1, 10, and 100 mm. These limits improve on previous constraints by two orders of magnitude.

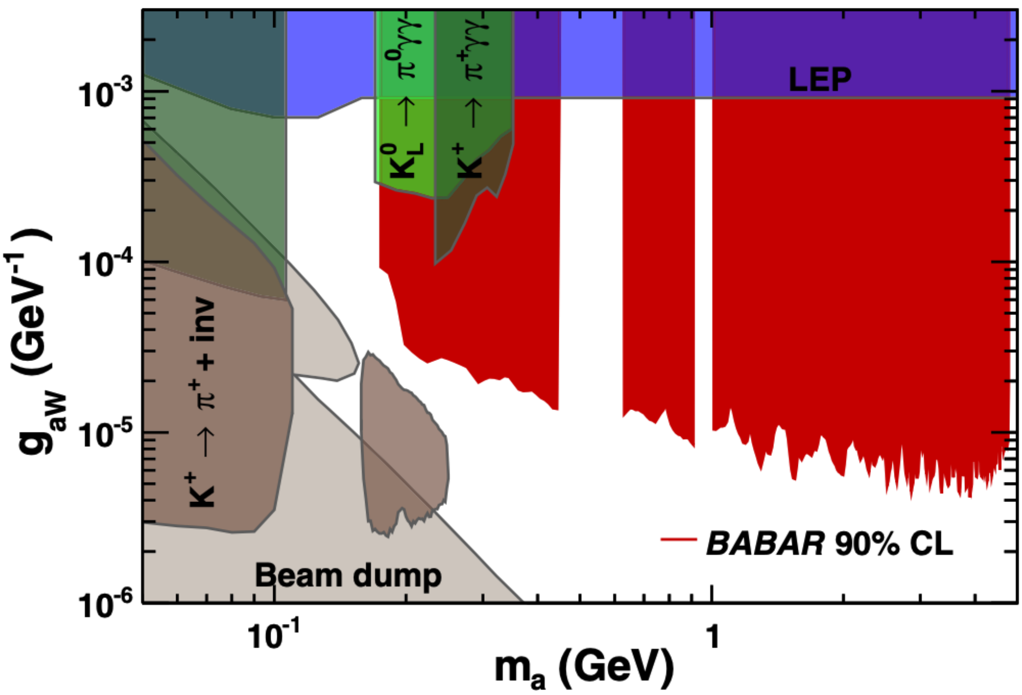

Figure 1: 90%-confidence-level upper limit on the ALP-W coupling g_{aW} from BaBar and previous constraints from other experiments. Plot from [4].

2.2 Darkonium: dark bound state

The model considered for this search is that of a so-called *darkonium* Υ_D, a case of bound DM, i.e., self-interacting DM. An initial-state radiation (ISR) photon emitted with the right energy would make the mass of the virtual photon deriving from the e^+e^- annihiliation equal to the that of the Υ_D, hence allowing kinetic mixing between the two. Then the darkonium would decay into three dark photons A', each of them decaying into a pair of charged tracks. The production-and-decay channel under analysis is thus $e^+e^- \to \gamma_{ISR}\Upsilon_D, \Upsilon_D \to A'A'A', A' \to x\bar{x}$ $(x = \mu, e, \pi)$. The bounds are set on the kinetic mixing ϵ and the coupling constant $g_D \propto \sqrt{\alpha_D}$. This is the first search for a bound dark state decaying into three dark photons. The dataset used for this analysis is the full BaBar one collected on and in the proximity of the $\Upsilon(4S)$, $\Upsilon(3S)$, and $\Upsilon(2S)$ resonances, and corresponds to and integrated luminosity of 514 fb^{-1}.

The signal signature consists of three pairs of oppositely charged tracks (μ, e, π) with similar masses; if the recoil momentum is within the calorimenter, then it is required to be compatible with the detected ISR photon. Backgrounds are deemed to be too complex to be properly simulated, henceforth 5% of data was used to optimize selection, and discarded from the UL-extraction dataset. The signal search is carried out in the $m(A') - m(\Upsilon_D)$ plane, where the signal is a point.

In Fig. 2 the 90%-CL UL on ϵ is shown, as function of $m(A')$, for different values of $\alpha_D \propto g_D^2$ and $m(\Upsilon_D)$. These limits improve on previous constraints for large dark coupling and darkonium masses.

3. Belle

Belle operated at the KEK laboratory, Japan, from 1999 to 2010. It was located on the KEKB collider, which provided it e^+e^- beams.

3.1 $B^0 \to \Lambda$ + dark baryon

The B-mesogenesis mechanism is a model that aims to address both DM and the baryon asymmetry via CP-violating oscillations. It predicts the branching fraction of $B^0 \to \Lambda$ + missing energy + any light mesons to be of the order of 10^{-4}. This happens via a dark mediator Y which decays into SM matter and a dark baryon Ψ_D, the latter decaying into DM, and thus invisibly. The process searched in this analysis is $B^0 \to \Lambda$ + missing energy, $\Lambda \to p^+\pi^-$. The non-signal B meson (the *tag side*) is fully reconstructed with hadronic channels, using the Full-Event Interpretation (FEI) [5] from the Belle II software. The dataset used for this analysis is the full Belle one, corresponding to 711 fb^{-1} at the $\Upsilon(4S)$ resonance, and 89 fb^{-1} off-resonance.

The signal signature is a B meson, fully reconstruct hadronically with the FEI, for the *tag side*, while for the signal side it is a proton, a π^-, and missing energy. The backgrounds are mainly $e^+e^- \to B\bar{B}$ and continuum $e^+e^- \to q\bar{q}$ ($q = u, d, c, s$). The discriminating variable is the residual energy in calorimeter E_{ECL}. The search strategy is an event count in the signal region defined by said variable.

In Fig. 3 the 90%-CL UL on branchig ratio is shown, as function of $m(\Psi_D)$. This result partially excludes the B-mesogenesis mechanism as a valid model and it improves on previous results.

4. Belle II

Belle II operates at the KEK laboratory Japan. It started its data taking in 2018, and it is planned to continue operation until reaching a world-record total integrated luminosity of 50 ab^{-1}. It is located on the SuperKEKB collider, which provides it e^+e^- beams.

4.1 $L_\mu - L_\tau$ extension: Z' to invisible

The so-called $L_\mu - L_\tau$ extension proposes a new Z' particle that would couple only to 2nd- and 3rd-generation leptons. It could simultaneously be a dark mediator, solve the $(g-2)_\mu$ anomaly, and explain anomalies observed in B decays. The search channel is $e^+e^- \to \mu\mu Z'$, $Z' \to$ invisible, as the Z' is assumed to decay either into neutrinos or DM. The obtained limits change in case Z' coupled exclusively to DM.

The dataset used for this analysis is an early on from Belle II, and corresponds to an integrated luminosity of only 80 fb^{-1}. The signal signature consists of two muons and missing energy. The

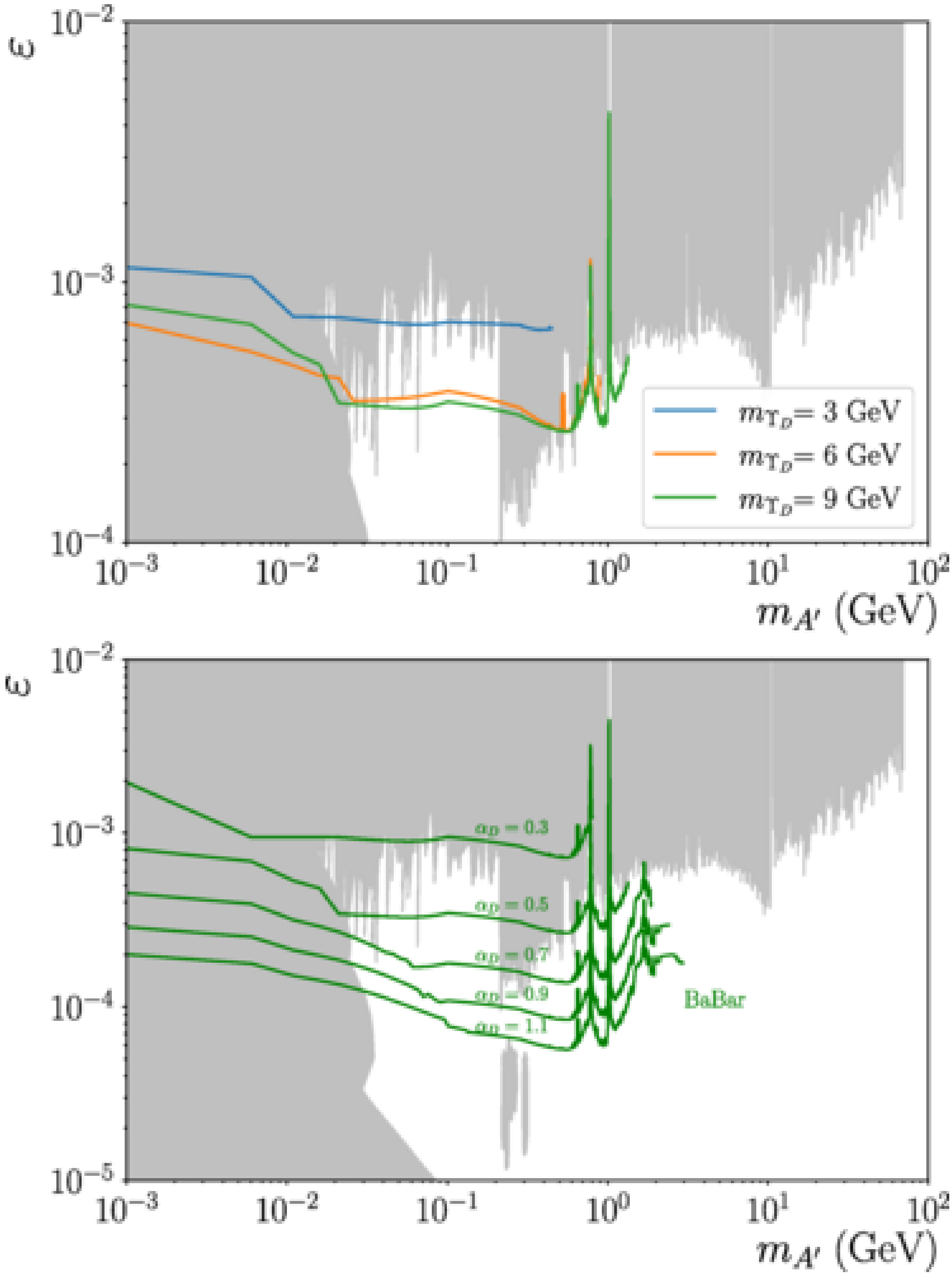

Figure 2: 90%-confidence-level upper limit on the kinetic mixing of darkonium to SM photon, for different values of $\alpha_D \propto g_D^2$ and $m(\Upsilon_D)$. Plot from [6].

main backgrounds are $e^+e^- \to \mu\mu(\gamma)$, $e^+e^- \to \tau\tau(\gamma)$, and $e^+e^- \to ee\mu\mu$. The search strategy is a 2D fit to the recoil mass, which would correspond to $m(Z')$, vs. the polar angle of the recoil momentum with respect to the detector's axis of symmetry in the center-of-mass reference frame.

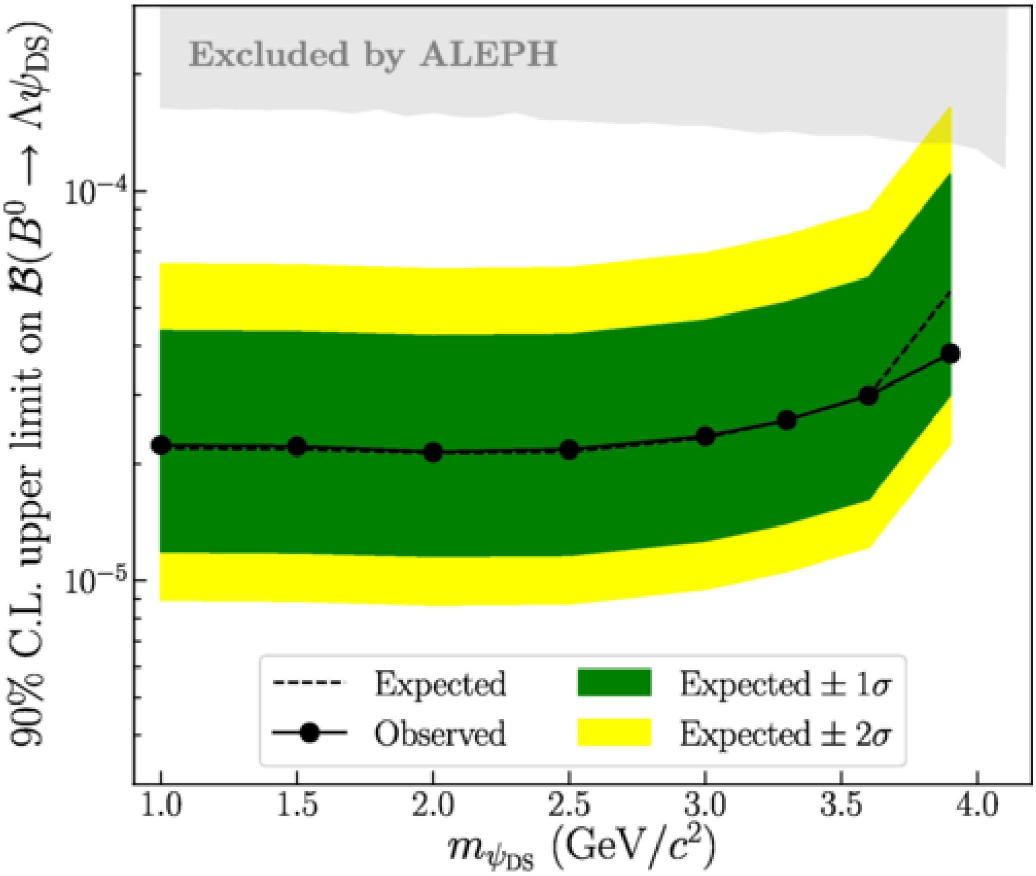

Figure 3: 90%-confidence-level upper limit on the branching ratio of $B^0 \to \Lambda\Psi_D$. Plot from [7].

In Fig. 4 the 90%-CL UL on g' (the coupling of Z' to muons) is shown, as function of $m(Z')$. This result excludes the parameter space that would solve the $(g-2)_\mu$ anomaly in the range $0.8 < m(Z') < 5.0$ GeV. It is a world-leader result for mass values above 11 MeV.

4.2 Dark photon + dark Higgs

This analysis investigates a model including a dark photon A' and a dark Higgs h'. The two hypothetical particles would be produced together from the e^+e^- collision; the A' would decay into a muon pair, while the h' is assumed to be lighter than A' and so would be long-lived and thus invisible. The process is henceforth the following: $e^+e^- \to A'h'$, $A' \to \mu\mu$, $h' \to$ invisible. The final state is the same as the analysis presented in Sec. 4.1, hence the signal signature and the backgrounds are the same.

The dataset used for this analysis is an early on from Belle II, and corresponds to an integrated luminosity of only 8 fb^{-1}. The search strategy is a 2D fit to the recoil mass, which would correspond to $m(h')$, vs. the dimuon invariant mass $m(\mu\mu)$, which would correspond to $m(A')$.

In Fig. 5 90% CL UL on $\epsilon^2\alpha_D$ (where ϵ is the kinetic mixing parameter between SM photons and A', and α_D is the coupling of A' to h') as function of $m(A')$ and $m(h')$. Next iterations of this

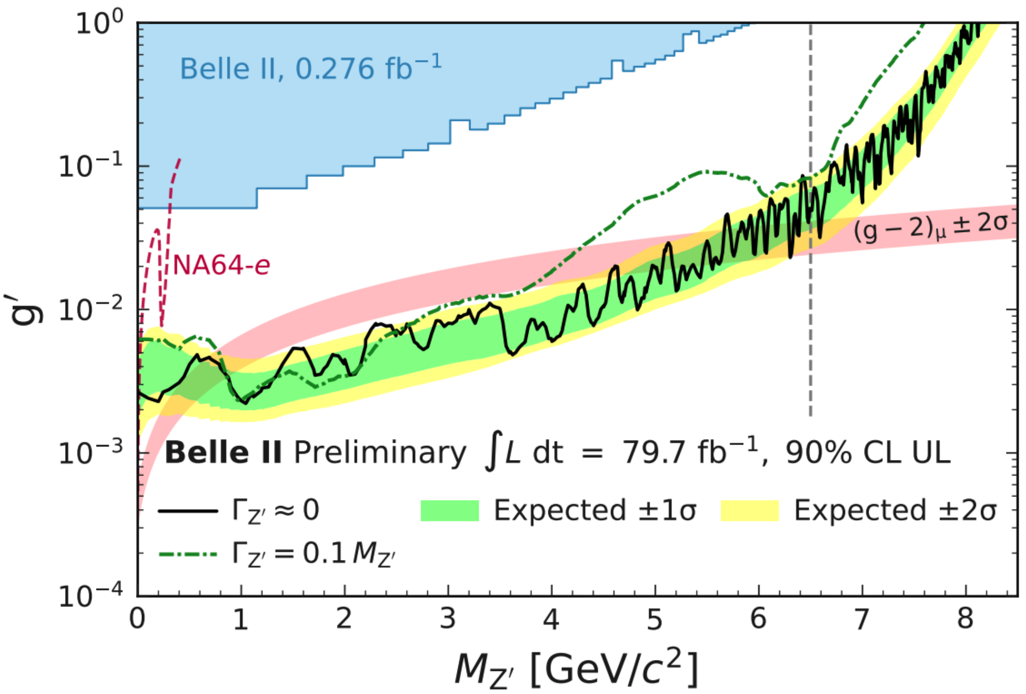

Figure 4: 90%-confidence-level upper limit on the the coupling of Z' to muons. Plot from [8].

analysis will benefit from much data and improved triggers. These are the first limits for these mass ranges.

4.3 ALPs in ee collisions: $ee \to \gamma a, a \to \gamma\gamma$

The particle searched for on this analysis is an ALP (see Sec. 2.1). In this case, the ALP is photophilic, i.e., couples predominantly with photons: it is produced from e^+e^- collisions in association with a recoil photon, and decays promptly into a photon pair. The production-and-decay channel under study is thus the following: $e^+e^- \to \gamma a,\ a \to \gamma\gamma$. This model has two free parameters: m_a and coupling $g_{a\gamma\gamma}$.

A challenge for this analysis is to push to the lowest masses. This is difficult because when the ALP is light it is highly boosted, so the two photons coming from its decay are close to each other and tend to be detected as one single particle by the electromagnetic calorimeter. Additionally, the peak corresponding to the π^0 irreducible background makes searching for ALPs in its proximity less effective; these issues will be addressed in a second iteration of the analysis.

The dataset used for this analysis is the early Belle II one, primarily meant to be used for calibration and tuning purposes, and corresponds to an integrated luminosity of only 0.445 fb^{-1}. The signal signature is three photons and nothing else in the event. The main backgrounds are: $e^+e^- \to \gamma\gamma(\gamma)$, $e^+e^- \to ee(\gamma)$, and $e^+e^- \to h^0\gamma,\ h^0 \to \gamma\gamma$ ($h^0 = \pi^0, \eta, \eta'$). The selection is performed using multi-dimensional rectangular cuts. For a second iteration, a neutral network could be used, possibly proving itself useful for the challenging low-mass region. The search strategy is a peak hunt in the squared diphoton or recoil mass variable.

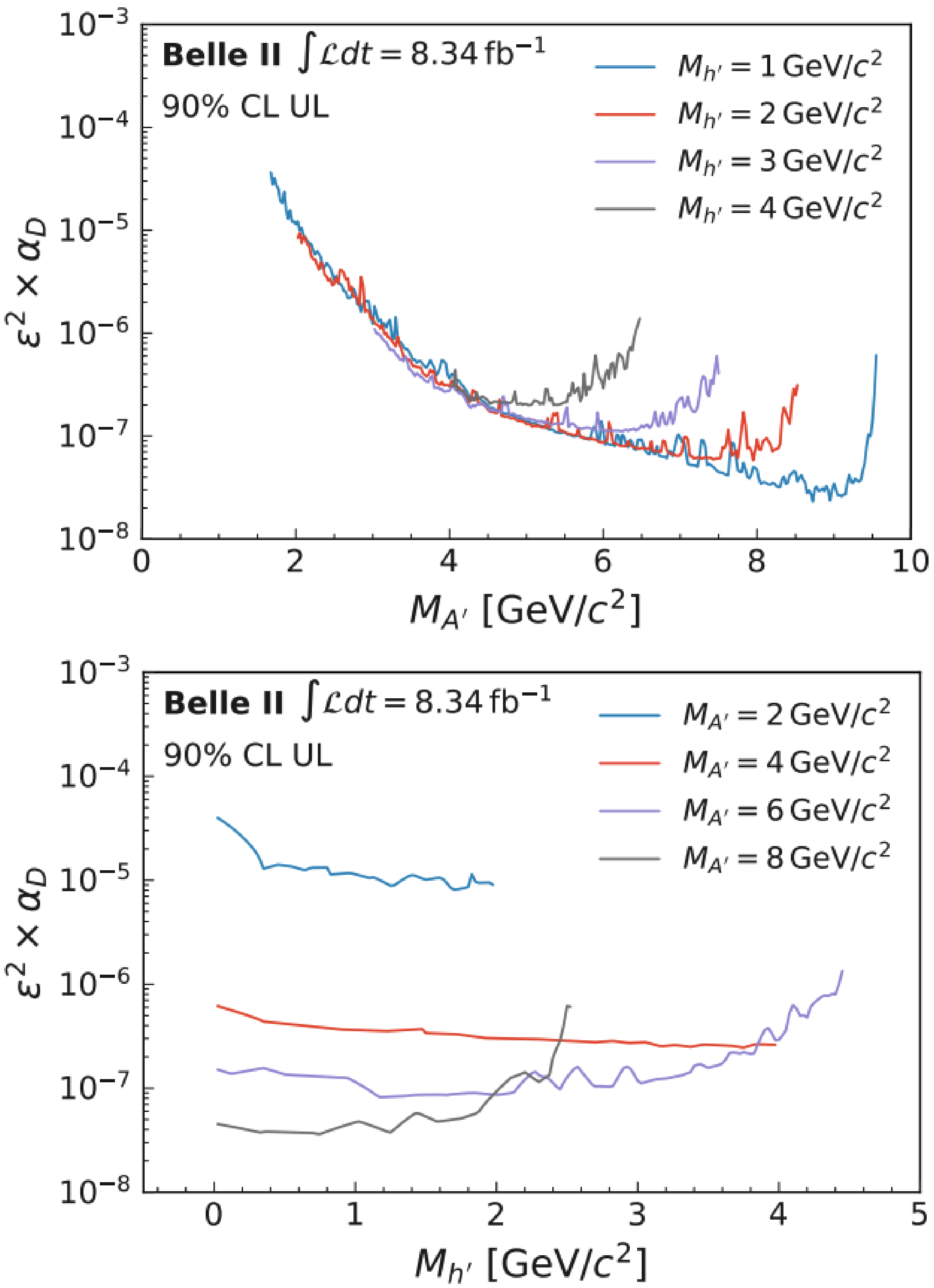

Figure 5: 90%-confidence-level upper limit on $\epsilon^2\alpha_D$; ϵ is the kinetic mix between SM photons and A', and α_D is the coupling of A' to h'. Plot from [9].

In Fig. 6 the 95%-CL UL on the coupling constant $g_{a\gamma\gamma}$ is shown. This limit is already competitive despite the usage of a low-luminosity preliminary data. Belle II has unique areas of sensitivity which will be further explored in the future with a much larger dataset.

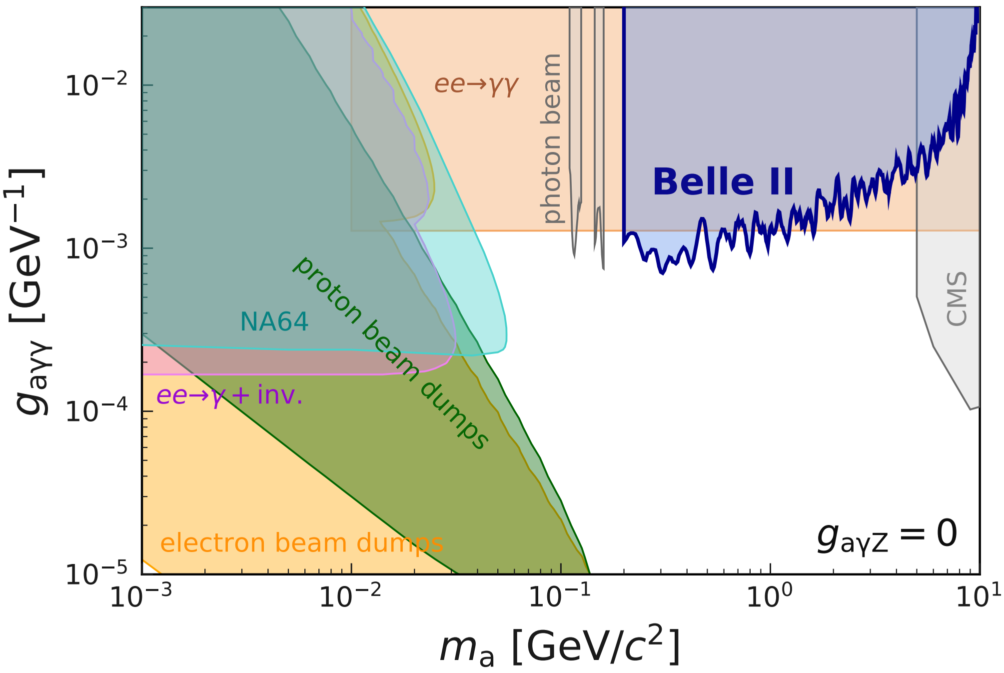

Figure 6: 95%-confidence-level upper limit on the ALP-photon coupling $g_{a\gamma\gamma}$ from Belle II and previous constraints from other experiments. Plot from [10].

5. Summary

Searches for Dark Matter are central in today's particle physics, and the Dark Sector is a promising Dark Matter model, which can be efficiently explored by *B* factories experiments. A number of world-leading results have already been achieved, and this document summarizes some of the most recent ones.

Over the next decade, Belle II, the currently operating *B* factory, will increase its already world-record instantaneous luminosity and will collect two orders of magnitude more data than it already had. With this vast data set obtained on a clean e^+e^- environment with low-multiplicity triggers, Belle II has a unique sensitivity to Dark Matter searches, complementary to that of higher-energy experiments.

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PoS(DISCRETE2022)008