Dark Matter Search in BABAR

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Abstract

We present the most recent BABAR results on searches for new particles, with masses below the electroweak scale, predicted by many extensions of the Standard Model. The results are based on the full data set of about 500 fb^{-1} collected around the $\Upsilon(4S)$ resonance by the BABAR detector at the PEP-II collider. We present, in particular, a search for a light dark-matter bound state, the darkonium Υ_D, produced in $e^+e^- \to \gamma\Upsilon_D$, with $\Upsilon_D \to A'A'A'$ and the dark photon A' decaying to a pair of leptons or pions. We show also searches for leptonically decaying hidden scalars produced in association with τ leptons. This search is sensitive to models that could account for the muon $g-2$ excess. Then we present a model independent search for an additional heavy, mostly sterile, neutral lepton produced in the decay of the τ lepton using a kinematic approach. We finally show a search for an axion-like particle a, produced in the flavour-changing neutral-current decay $B \to Ka$, with $a \to \gamma\gamma$, which is expected to be competitive with the corresponding electroweak processes.

1 The BABAR experiment

The BABAR detector was installed at the SLAC PEP-II high intensity e^+e^- collider. It took a huge quantity of data, more than $500\,\mathrm{fb}^{-1}$, over 10 years from 1999 to 2008. The centre-of-mass energy of the collider was set to run on various Υ resonances and on the nearby quark-antiquark continuum. In fact the bulk of data was taken on the $\Upsilon(4S)$, above the threshold for the production of pairs of B mesons, in order to study CP violation in the quark sector and heavy flavour physics, which were the main physics topics of the experiment.

The BABAR detector [1] was made of a silicon vertex detector providing a good reconstruction of displaced vertices, a drift chamber for momentum measurement, a DIRC Cherenkov detector for particle identification with a very good pion-kaon separation, a CsI crystal electromagnetic calorimeter with precise photon detection, all inside a solenoid producing a 1.5 T magnetic field, and finally muon chambers instrumented in the flux return of the solenoid.

Thanks to its good particle detection and identification, the clean environment in e^+e^- collisions, and the hermetic detector coverage, which together provide a precise reconstruction of the missing energy, thanks to its inclusive triggers and its huge data sample, the BABAR experiment was used to search for many possible manifestations of the dark sector in low energy e^+e^- collisions.

2 Search for darkonium

In a minimal dark sector model with a dark photon A' coupling to a dark fermion and a dark antifermion, a bound state between the dark fermion and dark antifermion is possible [2] for large enough values of the dark sector coupling constant α_D. In analogy with the Standard Model (SM), we call Υ_D the lightest vector darkonium with quantum numbers $J^{PC} = 1^{--}$. If its mass is in the few GeV range, it can be produced at BABAR in e^+e^- collisions with initial state radiation (ISR). It can then decay to three dark photons. In the regime where the dark photon mass is less than twice the dark fermion mass, the dark photon decays visibly in a pair of SM particles, such as electrons, muons or pions.

The BABAR Collaboration used its full data set of $514\,\mathrm{fb}^{-1}$ to perform the first search for darkonium [3] in the channel $e^+e^- \to \gamma\Upsilon_D$, with $\Upsilon_D \to A'A'A'$ and $A' \to X^+X^-$ where $X = e, \mu, \pi$. We select events with exactly six tracks, corresponding to three pairs of identified electrons or muons or pions. At least one of the three pairs has to be a lepton pair, as the background is too high in the pion-only channel. The Υ_D candidate is reconstructed as the combination of the three pairs. We require the three lepton or pion pairs to have similar masses and the recoil mass against the Υ_D candidate to be compatible with 0, the mass of the ISR photon, which may be inside or outside the calorimeter acceptance.

As the dark photon lifetime may be large at small mass, we perform both prompt and displaced vertices analyses. We scan the plane $m(\Upsilon_D) - m_{A'}$ to quantify a possible signal over the expected background, except in the regions of $m_{A'}$ around the mass of the SM mesons ω and ϕ. We do not observe a significant signal anywhere.

We extract 90% confidence level (C.L.) upper limits on the kinetic mixing strength ϵ between the photon and the dark photon in the range from 10^{-3} down to 5×10^{-5} as a function of the dark photon mass (up to $m(\Upsilon_D)/3$), the Υ_D mass (up to 9.5 GeV) and α_D, as illustrated in figure 1.

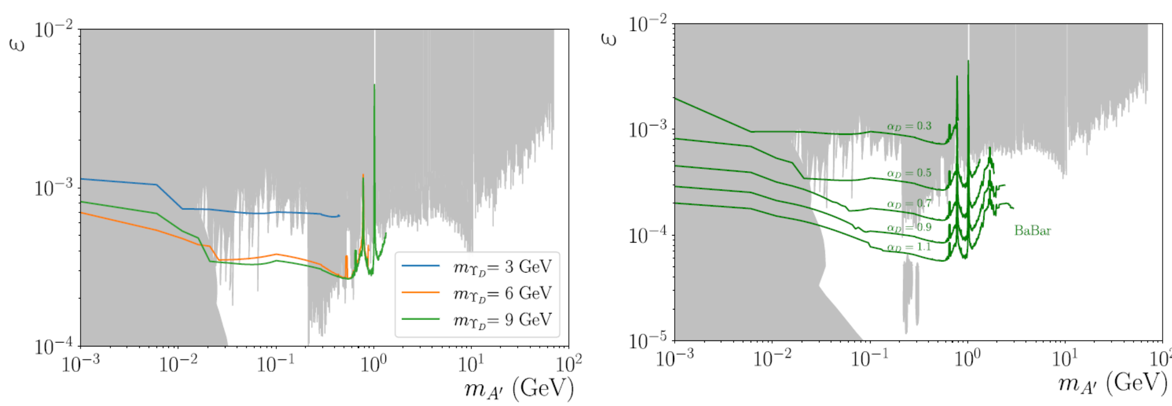

Figure 1: The 90% C.L. upper limits on the kinectic mixing ϵ as a function of the dark photon mass for (left) various $m(\Upsilon_D)$ values assuming $\alpha_D = 0.5$ and (right) various α_D values assuming $m(\Upsilon_D) =$ 9 GeV. The gray area shows the current constraints.

3 Search for a dark leptophilic scalar

A dark leptophilic scalar ϕ_L, interacting mainly with leptons rather than with quarks, would escape the current constraints on dark scalars. Furthermore, it could explain the muon $g-2$ anomaly. Higgs-like mass-proportional coupling implies that ϕ_L is produced preferentially with the most massive τ leptons, and that it decays mostly to the most massive kinematically accessible lepton pair.

Therefore, the BABAR Collaboration performed the first search for the production in e^+e^- collisions of a τ pair with a dark leptophilic scalar decaying either in an electron pair, the dominant process up to the muon pair threshold, or in a muon pair, the dominant process between the muon pair threshold and the τ pair threshold. Unfortunately, the decay to a τ pair leads to a final state with too many neutrinos to be experimentally exploitable.

This analysis [4] is also performed on the full dataset of $514\,\mathrm{fb}^{-1}$ from BABAR. We search for $e^+e^- \rightarrow \tau^+\tau^-\phi_L$, with $\phi_L \rightarrow \ell^+\ell^-$ where $\ell = e\,\mathrm{or}\,\mu$. We select events with exactly four tracks, corresponding to two 1-prong τ decay candidates and an identified electron or muon pair. In the electron case corresponding to small masses of ϕ_L, the analysis is performed assuming various values of the ϕ_L lifetime, which may be large. We fit for peaks in the dilepton mass over sliding intervals, excluding the regions around the J/ψ mass and $\psi(2S)$ mass, and observed no signal. So we set 90% C.L. upper limits on the production cross section of the order of $1\,\mathrm{fb}^{-1}$ up to the τ pair threshold.

This leads to 90% C.L. upper limits on the coupling strength ξ of the dark scalar with leptons as a function of the dark scalar mass, as illustrated in figure 2. The new result from BABAR improves significantly the current constraints. It also excludes most of the parameter space where a dark leptophilic scalar could explain the muon $g-2$ anomaly up to a dark scalar mass of about 4 GeV.

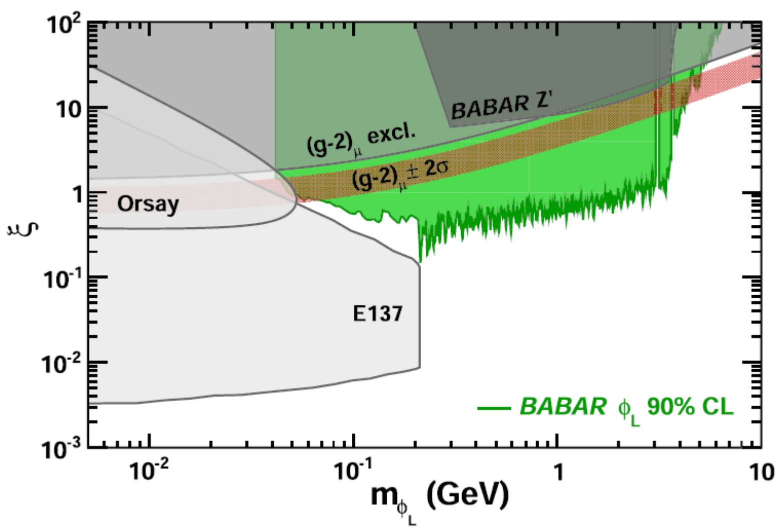

Figure 2: The 90% C.L. upper limits on the coupling ξ as a function of the scalar mass. The region excluded by the present analysis, shown in green, is compared to existing constraints and to the parameter region that could explain the muon $(g-2)$ anomaly.

4 Search for a heavy neutral lepton

A heavy neutral lepton, so called sterile neutrino, would mix with the known active neutrinos with a mixing strength given by the relevant element of the extended PMNS matrix. Robusts bounds have already been set on the mixing of heavy neutrinos with both ν_e and ν_μ, but the constraints are weaker for the mixing with ν_τ.

The BABAR Collaboration has performed a first model independent search, based only on kinematics, for such a heavy neutral lepton mixing with ν_τ. We tag e^+e^- annihilations to τ pairs by a clean leptonic decay of the τ on one side. On the other side, the signal side, we reconstruct a three-prong τ decay into pions and look for the production of a sterile neutrino by oscillation from ν_τ.

The analysis [5] is performed on 424 fb^{-1} of data. It uses both electron and muon tags. The two main variables are the energy and invariant mass fraction of the hadronic system recoiling against the neutrino in the three-prong τ decay. According to the mass of the sterile neutrino, the expected signal is found in different regions of the 2D plot energy fraction versus mass fraction.

A likelihood fit is performed to extract an hypothetical sterile neutrino signal from the contribution of ν_τ and the contribution of additional backgrounds. We see no significant signal and set 95% C.L. upper limits on the mixing strength from 2×10^{-2} to 5×10^{-5} as a function of the sterile neutrino mass between 0.1 and 1.3 GeV, shown in figure 3. The best limits are obtained at high mass, where the constraints from previous experiments are weaker.

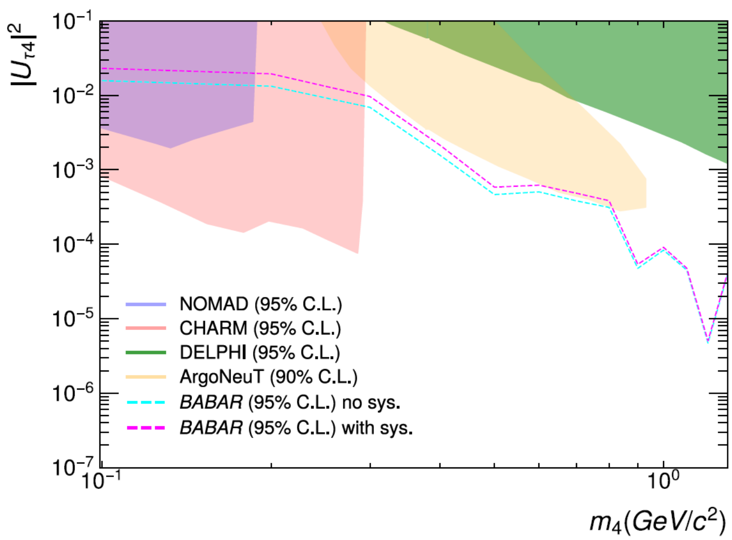

Figure 3: The 95% C.L. upper limits on the coupling $|U_{\tau 4}|^2$ as a function of the sterile neutrino mass. The region excluded by the present analysis, shown by the blue (systematics not included) and magenta (systematics included) lines, is compared to existing constraints.

5 Search for an axion-like particle

An axion-like particle a is a pseudo-Goldstone boson coupling predominantly to pairs of bosons. It could be both a dark matter candidate and a dark sector mediator. A good place to search for axion-like particles is in modes that are extremely suppressed in the SM, such as flavour-changing neutral-current decays, which allow to test the coupling with the W boson of an hypothetical axion-like particle [6].

In B-meson decays, we can use the $b \to s$ transition and search for the decay $B^+ \to K^+ a$ with $a \to \gamma\gamma$. This analysis [7] has been done for the first time by the BABAR Collaboration. We use the $424\,\mathrm{fb}^{-1}$ of data taken on the $\Upsilon(4S)$ resonance above the B-meson pair threshold. B candidates are formed by combining a well identified charged kaon with two photons.

Depending on their mass, axion-like particles can be long-lived. So the analysis is done for prompt decays and for several decay length hypotheses. We fit for peaks in the $\gamma\gamma$ mass distribution over a smooth background. No significant signal is found. We set 90% C.L. upper limits on the branching fraction product $\mathcal{B}(B^+ \to K^+ a) \times \mathcal{B}(a \to \gamma\gamma)$ in the range from 10^{-6} down to 10^{-7} as a function of m_a, except in the regions around the mass of light mesons: π^0, η, and η'.

This translates to 90% C.L. upper limits on the coupling g_{aW} of the axion-like particle with the W boson as a function of its mass, as illustrated in figure 4. The new result from BABAR improves the current constraints by up to two orders of magnitude over a large mass range in the GeV region, reaching limits down to better than 10^{-5}.

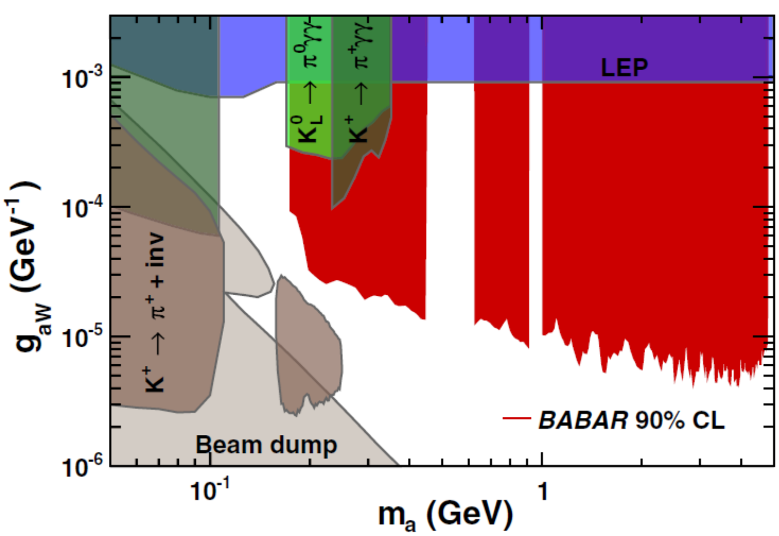

Figure 4: The 90% C.L. upper limits on the coupling g_{aW} as a function of the axion-like particle mass. The region excluded by the present analysis, shown in red, is compared with existing constraints.

6 Summary

B-factories are able to perform competitive searches for dark sector particles in low energy e^+e^- annihilations. The BABAR Collaboration has performed a number of such analyses in the last decade. The effort is still on going, more than 14 years after the end of data taking. New constraints have been set recently for darkonia, dark leptophilic scalars, heavy neutral leptons, and axion-like particles.

References

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