Dark sector searches with BABAR

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Abstract

The BABAR Collaboration has obtained limits on several dark sector models. Primarily designed for the study of CP violation in B meson decays, the BABAR experiment is also, thanks to its huge data sample and its powerful particle identification, sensitive to many other interesting physics processes. These include topics linked to the dark sector, such as searches for dark photons with either visible or invisible decays, a new Z' boson coupling preferentially to muons, and a stable six-quark state as a dark matter candidate.

1 Introduction

The BABAR experiment was installed at the SLAC PEP-2 high intensity e^+e^- collider. It took a huge quantity of data, more than half an attobarn inverse, over 10 years from 1999 to 2008, running 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 heavy flavour physics and CP violation in the quark sector, which were the main physics goals of the experiment. However, at the end of the data taking, substantial data samples were taken on the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances.

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 electromagnetic calorimeter with precise photon detection, all inside a 1.5 T solenoid, and finally muon chambers.

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 some dedicated triggers and its huge data sample, BABAR was able to search for manifestations of the dark sector in low energy e^+e^- collisions. Even if it was not its original goal.

2 Dark Photon

A simple dark sector scenario is to add a new U(1) gauge symmetry. The associated gauge boson A', the so-called dark photon, provides a portal to the dark sector, mixing to the standard model photon with kinetic mixing strength ϵ. If its mass is in the GeV range, it can be produced at BABAR in e^+e^- collisions with initial state radiation (ISR). It then decays to either dark matter or standard model particles depending on their kinematic accessibility. The BABAR Collaboration performed a search for such a process $e^+e^- \to \gamma A'$ in both cases.

The full BABAR data sample of 516 fb^{-1} was used for the search performed in case of visible decays of the dark photon into two leptons, either two electrons or two muons, $A' \to \ell^+\ell^-$ [2]. We require one ISR photon, with energy greater than 200 MeV, and two leptons with opposite sign in the event. Except in the low di-electron mass region, where the Monte Carlo is known to fail to reproduce the data, the di-lepton mass distribution in the data in the electron and muon cases is well reproduced by all known processes included in the simulation. Apart for a resonant part around 3 GeV corresponding to the J/ψ and $\psi(2S)$ resonances, the background, dominated by radiative Bhabha and radiative dimuon production, is varying smoothly, and there is no sign of a new peak due to a dark photon.

By scanning the dark photon mass, considering more then five thousand mass hypotheses from threshold up to 10.2 GeV, we measure as a function of the dark photon mass the cross section of dark photon production, which fluctuates around 0, and the associated signal significance. No signal evidence is seen. By combining the two di-lepton channels, we put 90% confidence level (C.L.) upper limit on the mixing strength ϵ at the level of 10^{-3} for dark photon mass up to 10.2 GeV, as illustrated in figure 1.

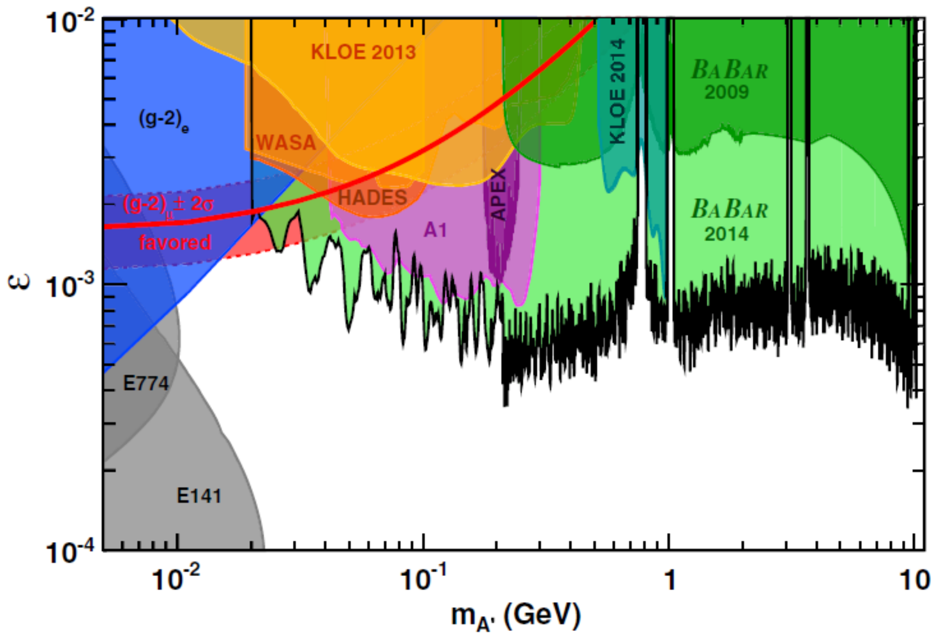

Figure 1: Upper limits (90% C.L.) on the mixing strength ϵ as a function of the dark photon mass (for visible decays). The region excluded by BABAR is shown in green and is compared to previous constraints.

In the case the dark photon may kinematically decay into dark matter particles $A' \to \chi\bar{\chi}$, it would escape detection. This process was also searched for by the BABAR experiment [3]. Here we detect only the photon from initial state radiation and missing energy due to the dark photon. The dark photon mass can be determined from the known beam energy and the measured photon energy.

The analysis was made possible by the introduction of a special trigger during the last months of data taking with the BABAR detector. On the level 1 hardware trigger, a new line was added requiring a calorimeter cluster with energy greater than 0.8 GeV. On the level 3 software trigger, two triggers were introduced requiring no tracks and a photon candidate with a threshold on the centre-of-mass photon energy at 2 GeV and then at 1 GeV, corresponding respectively to the last 53 fb^{-1} and 38 fb^{-1} of the data taking.

The main backgrounds are QED processes with two photons or radiative Bhabha with undetected particles. Thus, in the analysis, we check for additional detector activity and combine several variables providing such information in a boosted decision tree to separate the expected signal from the background.

For each dark photon mass hypothesis from 0 to 8 GeV in 166 steps, the signal yield is extracted from a fit to the photon recoil mass. The signal significance as a function of dark photon mass has a maximum around 6 GeV, corresponding to 3.1 σ local significance, but only 2.6 σ global significance, so not enough to claim any signal evidence. Consequently, we sets 90% C.L. upper limits on the mixing strength ϵ at the level of 10^{-3}, as illustrated in figure 2.

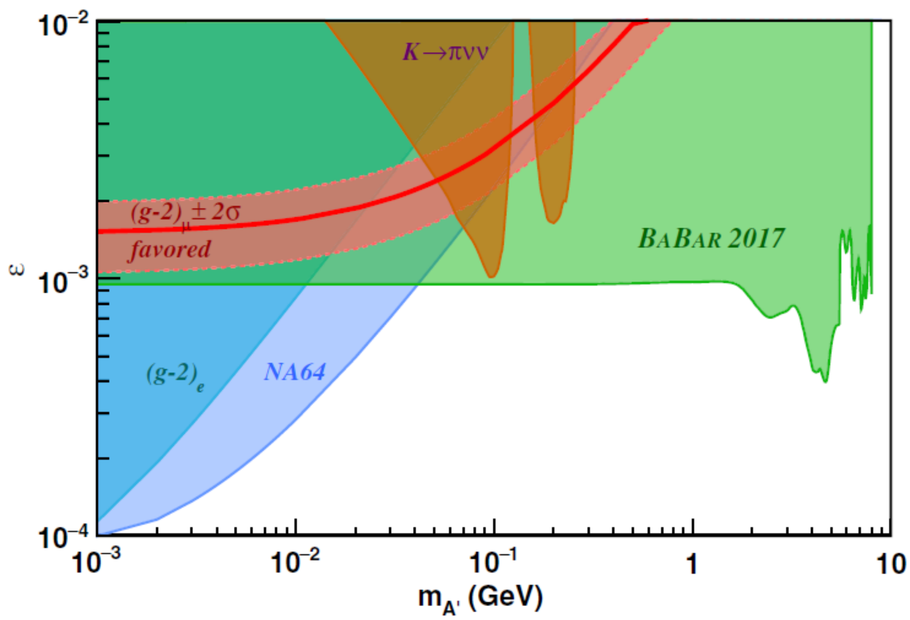

Figure 2: Upper limits (90% C.L.) on the mixing strength ϵ as a function of the dark photon mass (for invisible decays). The region excluded by BABAR is shown in green and is compared to previous constraints.

3 Muonic dark force

A search was also performed for muonic dark force, more precisely a dark boson Z' coupling to the second and third generation of leptons [4]. This can be motivated by various anomalies in the muon sector, such as the discrepancy between the calculated and mesured values for $g-2$. The Z' dark boson could be produced in $e^+e^- \to \mu^+\mu^-$ events and decay to two muons, giving a final state of four muons.

The principle of the analysis, performed on the whole dataset of BABAR (514 fb^{-1}), is to search for a di-muon mass peak in four muon final state events. The main background comes from combinatorial QED process. The dark boson production cross-section and the corresponding signal significance is measured as a function of the Z' mass, probing 2219 mass hypotheses up to 10 GeV. No signal is seen. Consequently we can set 90% C.L. upper limits on the g' coupling parameter down to 10^{-3}, as illustrated in figure 3. Most of the region that would explain the $g-2$ anomaly is excluded.

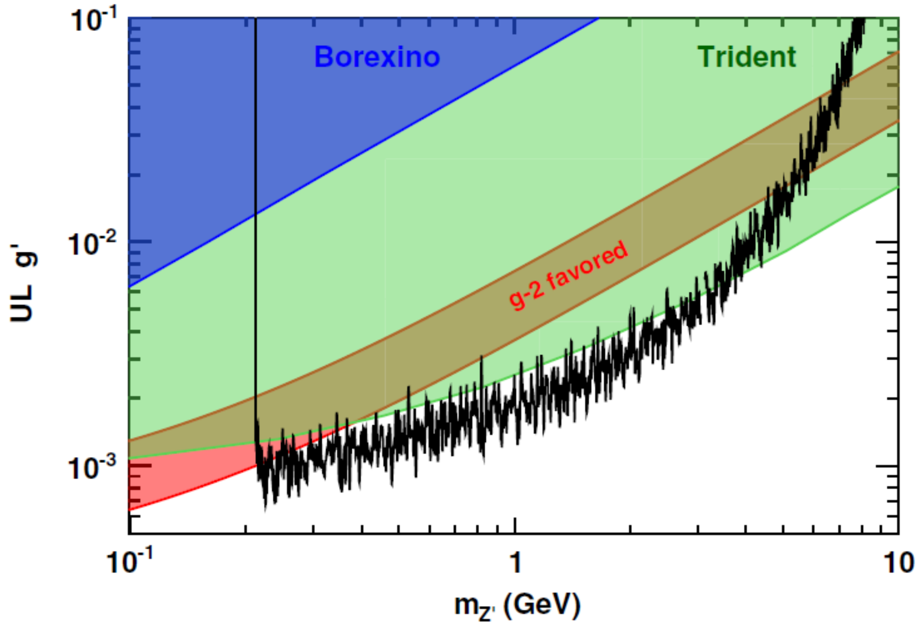

Figure 3: Upper limits (90% C.L.) on the coupling parameter g' as a function of the Z' mass, shown in black and compared to previous experiments. The region to explain the $g-2$ discrepancy is shaded in red.

4 Six-quark state

A six-quark state was proposed by Farrar [5] as a possible dark matter candidate. This state S is a $uuddss$ combination, with charge 0 and baryon number 2. If its mass is smaller than 2.055 GeV, the usual weak decay is forbidden so that it will have a very long lifetime. If it is smaller than 1.878 GeV, the state would be absolutely stable. A six-quark state has never been observed, but is allowed in QCD and not excluded by present experiments.

So BABAR recently performed a first search for such a state [6] which could be produced in the hadronic decays of the $\Upsilon(2S)$ and $\Upsilon(3S)$ in association with two Λ particles. We use the whole data sample taken on these two resonances, corresponding to 90 million $\Upsilon(2S)$ decays and 110 million $\Upsilon(3S)$ decays. We fully reconstruct two Λ candidates in their decay in a proton and a charged pion with a displaced vertex and pointing to the interaction point. The observable is the recoil mass square against the two Λ candidates, which for the signal should be the hexa-quark mass square.

The other main variable used in the analysis is $E_{\rm extra}$ which measures the additional activity in the electromagnetic calorimeter. Figure 4 shows the distribution of the squared recoil mass for the signal region with $E_{\rm extra} < 0.5$ GeV and for the sideband with $E_{\rm extra} > 0.5$ GeV. The signal is expected at low values of the recoil mass squared. The $E_{\rm extra}$ sideband shows that the background is well reproduced in the simulation and that no background event is expected in the signal region. In the $E_{\rm extra}$ signal region, four candidates are kept in the final selection with recoil mass compatible with the background and away from the signal region.

So we have no evidence for a signal and we set a 90% C.L. on the branching fraction of $\Upsilon \to \bar{S}\Lambda\Lambda$, for the $\Upsilon(2S)$ sample, the $\Upsilon(3S)$ sample, and the combined sample assuming the same partial width. The combined limit on the branching fraction varies with the hexaquark mass in the range from 0 to 2.05 GeV between $1.2\,10^{-7}$ and $1.4\,10^{-7}$.

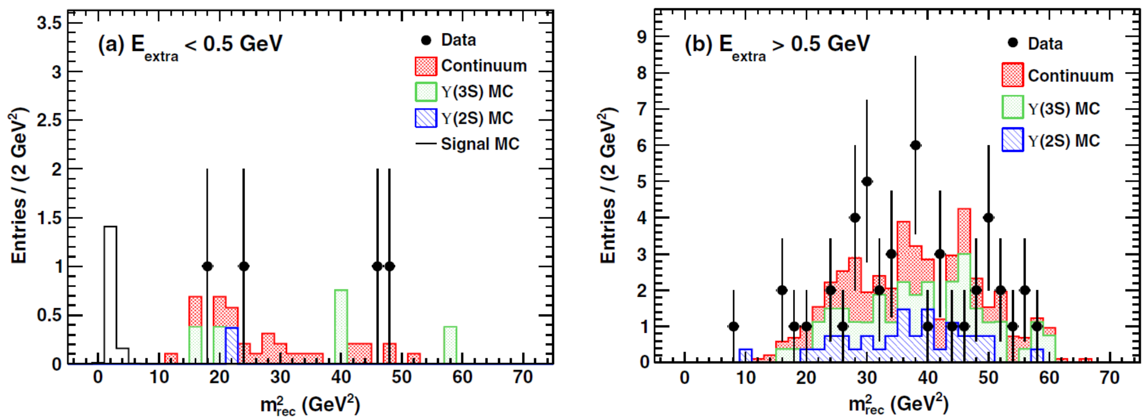

Figure 4: Distribution of the recoil mass squared for (a) the $E_{\rm extra} < 0.5$ GeV signal region and (b) the $E_{\rm extra} > 0.5$ GeV sideband. The data are the black points with error bars. The white histogram shows where the signal is expected. The stacked histograms show background estimates.

5 Conclusions

In summary, the BABAR experiment has performed a number of dark sector searches in low energy e^+e^- annihilations. No signal have been seen and constraints have been set for dark photon with visible or invisible decays, muonic dark force, and recently on a six-quark state as possible dark matter candidate.

References

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