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Search for Low-mass Dark-Sector Gauge Boson with the BABAR Detector

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We report searches for a new muonic dark force mediated by a gauge boson (Z') coupling only to the second and third lepton families. The existence of the Z' boson is probed in $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$ events based on the full data sample collected with the BABAR detector at the PEP-II e^+e^- collider. No significant signal is observed. Limits on dark-sector coupling constants are derived; these improve upon current bounds, and further constrain the allowed parameter space.

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1. Introduction

Some models of physics beyond Standard Model (SM) predict the existence of a new non-Abelian gauge group Higgs with gauge boson masses below 10 GeV [1]. The WIMP hypothesis suggested that dark matter is assumed to consist of stable particle with low masses. Such new gauge bosons can typically interact with other Standard Model elementary particles. Based on the $L_\mu - L_\tau$ model [2] the most promising candidate is the gauge group associated with the difference between muon and tau-lepton number. The gauge $L_\mu - L_\tau$ predicts that the Z' is being coupled only to the second and third generation of leptons.

2. The BABAR Detector and Data Set

We used the data collected by the BABAR detector with the total luminosity of 514 fb^{-1}. A detail description of the BABAR detector is presented elsewhere [3]. The data were taken at the $\Upsilon(4S)$ resonance plus 28 fb^{-1} taken at $\Upsilon(3S)$, 14 fb^{-1} taken at $\Upsilon(2S)$, and 48 fb^{-1} taken at 40 MeV below the $\Upsilon(4S)$ (off-resonance). The $\Upsilon(4S)$ resonance decays to a pair of $\bar{B}B$ [4]. The data was only examined after finish finalizing the analysis method. For the background study we generated signal Monte Carlo (MC) samples. Signal MC events are generated using MadGraph 5 [5], which calculates matrix elements for the sample. The MC then were showered using Pythia 6 [6] for about 30 different Z' mass hypotheses. The most dominant background comes from the QED processes. We generate the direct processes of $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ using Diag36 [7], which includes the full set of the lowest order diagrams. The events of the process of $e^+e^- \to e^+e^-(\gamma)$ is generated using BHWIDE [8] and the MC events of $e^+e^- \to \mu^+\mu^-(\gamma)$ and $e^+e^- \to \tau^+\tau^-(\gamma)$ are generated using KK [9]. The off-resonance data samples, $e^+e^- \to \bar{q}q$ (q = u, d, s, c), are simulated using EvtGen [10]. The detector acceptance and reconstruction efficiency are determined using MC simulation based on GEANT4 [11].

3. Measurement of $Z' \to \mu^+\mu^-$

Events with the process of $e^+e^- \to \mu^+\mu^- Z'$ and $Z' \to \mu^+\mu^-$ final state that exactly contain two pairs of oppositely charged tracks are selected. The muons are identified by particle identification algorithms for each track. We require the sum of energies of the electromagnetic clusters that are not associated to any track must be less than 200 MeV. We finally reject events that come from the $\Upsilon(3S)$ and $\Upsilon(2S)$, where $\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$ decays if the dimuon combination is within 100 MeV of the $\Upsilon(1S)$.

Figure 1 (left) shows the reduced dimuon mass which is calculated by $m_R = \sqrt{m^2_{\mu^+\mu^-} - 4m^2_\mu}$ in a log scale. The most dominant samples is coming from the direct decay of $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ process. The contribution from the decay of $\Upsilon(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \mu^+\mu^-$ is shown around 3 GeV. The signal yield is extracted from the unbinned likelihood fits to the reduced dimuon mass spectrum within the range of $0.212 < m_R < 10$ GeV for the $\Upsilon(4S)$ resonance data and $0.212 < m_R <$ 9 GeV for $\Upsilon(2S)$ and $\Upsilon(3S)$ data. A region of ± 30 MeV around the nominal known J/ψ mass is excluded. The total of 2219 mass hypotheses are found. The cross section of $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$ is extracted as a function of Z' mass as shown in Fig. 1 (right).

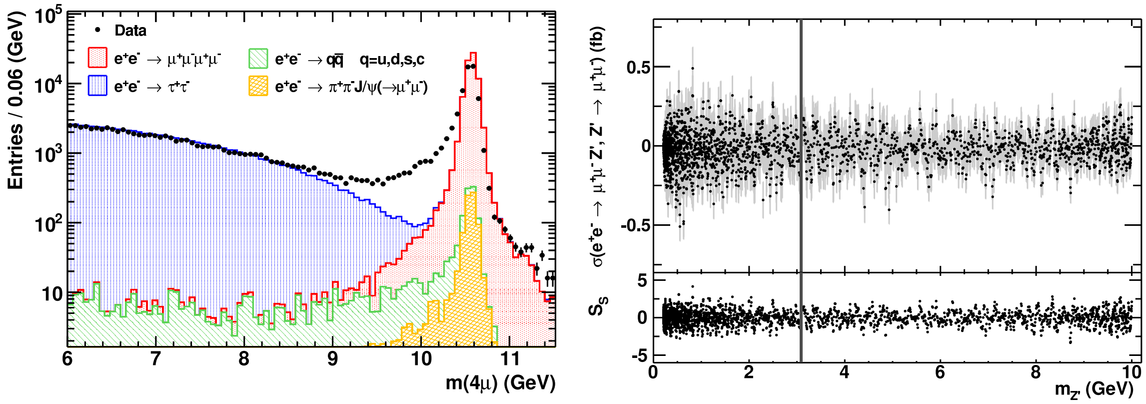

Figure 1: Left: The distribution of the reduced dimuon mass, $m_R = \sqrt{m^2_{\mu^+\mu^-} - 4m^2_\mu}$ in a log scale with the various processes of the Monte Carlo events. It is normalized to the data luminosity. Right: The measurement of $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$ cross section as a function of the Z' mass. The excluded region is indicated by the gray band.

We exclude the J/ψ region when calculating the correction factors by fitting the simulated and reconstructed reduced dimuon masses in the range of $1 < m_R < 9$ GeV. The cross section of $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$ is extracted as a function of Z' mass as shown in Fig. 2 (left). The gray band indicates the excluded region. We find the largest local significance is 4.3σ around Z' mass of 0.82 GeV that is corresponding to the global significance of 1.6σ. It is consistent with the zero-hypothesis. We derive 90% confidence level (CL) Bayesian upper limit on the cross section of $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$. We finally extract the corresponding 90% CL on the coupling parameter g' by assuming the equal magnitude vector couplings muons, taus, and the corresponding neutrinos together with the existing limits from Borexino and neutrino experiments as shown in Fig. 2 (right).

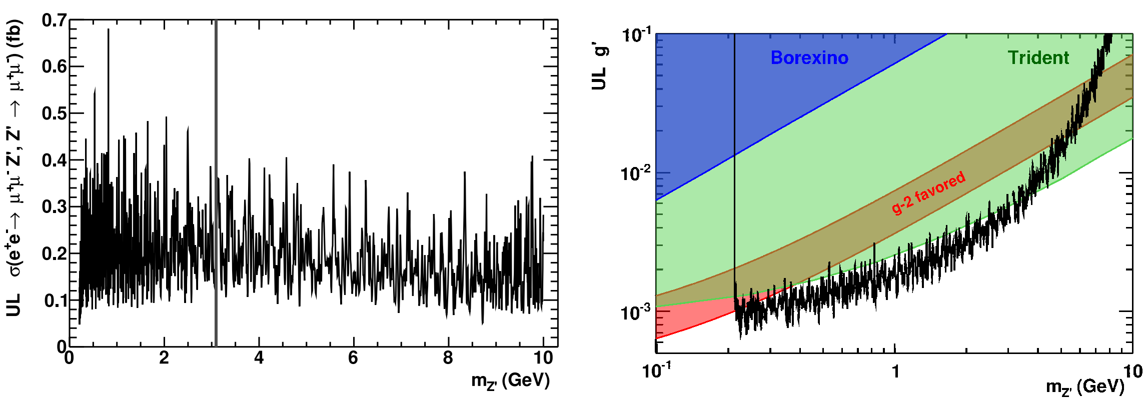

Figure 2: Left: The limit on the cross section $\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to \mu^+\mu^-)$ as a function of the Z' mass. The excluded region is indicated by the gray band. Right: Upper limit on the new gauge coupling g' as a function of the mass of Z' together with the existing limits from Borexino and neutrino experiments.

4. Summary

In summary, we have performed the first direct measurement of Z' production from the decay of $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$ at BABAR. No significant signal is observed for Z' masses in the range of 0.212 - 10 GeV. We set limits on the coupling parameters g' down to 7×10^{-4} near the dimuon threshold. We set a strongest bounds for much of the parameter space below 3 GeV. We exclude most of the remaining parameter space preferred by the discrepancy between the calculated and measured anomalous magnetic moment of the muon above the dimuon threshold [12].

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