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Dark photon search with neutral meson decays at the PHENIX experiment

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Several theoretical models have introduced an additional U(1) gauge field for dark matter to explain several experimental results showing a deviation from the standard model (SM) calculations, such as the measured value of the muon anomalous magnetic moment $(g-2)_\mu$. The additional U(1) field couples very weakly with the SM, and its gauge boson, U, called as a "dark photon" mixes in ordinary photons with a very small mixing strength as a result. The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) has performed a search for electron pairs from a dark photon showing up within π^0, η Dalitz decays. Upper limits on the dark photon mixing strength has been obtained for $30 < m_U < 90$ MeV/c^2. Combining with the other recent experimental results, the dark photon is ruled out as the explanation of the desrepancy on $(g-2)_\mu$ between the measured result and SM calculations.

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1. Introduction

The standard model (SM) of particle physics has succeeded in describing a huge number of experimental results. The measured muon anomalous magnetic moment $(g-2)_\mu$, which deviates from SM calculations by 3.6σ [1] is one of exceptions known as beyond-the-SM phenomena as well as the positron excess in cosmic rays observed by several satellite experiments [2, 3, 4] and so on. An additional U(1) gauge field has been introduced in several theoretical models to give an explanation for described beyond-the-SM phenomena at the same time. According to one of the simplest scenarios, a "dark photon" as a gauge boson of the additional U(1) gauge field mixes with ordinary photons via a "kinetic coupling" term in the Lagrangian [5, 6, 7, 8],

$$\mathscr{L}_{mix} = -\frac{\varepsilon}{2} F^{\mathrm{QED}}_{\mu\nu} F^{\mu\nu}_{\mathrm{dark}}, \tag{1.1}$$

where ε is the mixing strength. If the dark photon mass, m_U is twice higher than the electron mass, it can decay into an electron pair and this decay mode is dominant until $m_U < 2m_\mu$.

2. Search for dark photon in Dalitz decays of π^0, η

We have conducted a search for possible decays of $\pi^0, \eta \to \gamma U, U \to e^+e^-$ in a huge sample of π^0, η Dalitz decays with the PHENIX detector at Relativistic Heavy Ion Collider (RHIC). The Kroll-Wada equation [9] gives the invariant yield of electron pairs from the π^0, η Dalitz decays as

$$\left(\frac{dN_{ee}}{dm_{ee}}\right)_{\pi^0,\eta\to\gamma e^+e^-} = N_{2\gamma}\frac{4\alpha_{EM}}{3\pi}\frac{1}{m_{ee}} KW_{\pi^0,\eta}(m_{ee})|F_{\pi^0,\eta}(m_{ee}^2)|^2, \tag{2.1}$$

where

$$KW_{\pi^0,\eta}(m_{ee}) = \sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)\left(1-\frac{m_{ee}^2}{m_{\pi^0,\eta}^2}\right)^3, \tag{2.2}$$

and $N_{2\gamma}, \alpha_{EM}$ are the invariant yield of $\pi^0, \eta \to 2\gamma$ and the fine structure constant, respectively. The transition form factor $F(q^2)$ can be regarded as unity in our calculation, since the variation of $F(q^2)$ is small enough [10] for our interest mass range of $30 < m_{ee} < 90$ MeV/c^2. The dark photon natural width is very narrow due to the weak coupling to ordinary photons, and the expected dark photon peak width is dominated by the detector mass resolution, σ. Therefore, the dark photon invariant yield can be expressed by

$$\left(\frac{dN_{ee}}{dm_{ee}}\right)_{\pi^0,\eta\to\gamma U} = N_{2\gamma}\frac{2\varepsilon^2}{\sqrt{2\pi}\sigma} e^{\frac{-(m_{ee}-m_U)^2}{2\sigma^2}} KW_{\pi^0,\eta}(m_{ee}). \tag{2.3}$$

Finally the dark photon mixing parameter can be determined as

$$\varepsilon^2 = \frac{2\alpha_{EM}}{3\pi}\frac{\sigma}{m_U}\sqrt{2\pi}R(m_U), \tag{2.4}$$

with the peak height ratio of $R(m_U) = (dN_{ee}/dm_{ee})_{\pi^0,\eta\to\gamma U}/(dN_{ee}/dm_{ee})_{\pi^0,\eta\to\gamma e^+e^-}$.

PoS(DIS2015)129

3. e^+e^- measurement with the PHENIX detector

The 2006 and 2009 $p+p$, 2008 d+Au data sets with a collision energy of $\sqrt{s_{NN}} = 200$ GeV were analyzed. A Hadron Blind Detector (HBD) was installed around the beam pipe prior to the 2009 $p+p$ run, and it brought a material budget of $2.4\% \times X_0$ in addition to $0.39\% \times X_0$ for runs before 2009. Momentum measurement for charged tracks is made by the drift and pad chambers in the PHENIX central arms covering $|\eta| < 0.35$ in pseudorapidity and $\pi/2$ in azimuthal angle. Electron tracks are identified by the RICH and energy-momentum matching at the EMCal. Then, electron pairs are formed from all combinations of electrons and positrons in an event. The measured e^+e^- mass distribution includes background pairs from random combinations, jet-induced correlations and fake correlations in double Dalitz decays ($\pi^0, \eta \to 2e^+e^-$) as well as physical pairs from hadron decays. The background pair contributions are evaluated using like-sign pair mass distribution. The correlated background contributions are consistent in $p+p$ and d+Au with scaling by the number of nucleon-nucleon collisions, indicating that these backgrounds are well understood. After subtraction of the background pairs from the measured e^+e^- mass spectrum, 1.7M pairs in total were obtained in $m_{ee} < 90$ MeV/c^2 where a dominant source of pairs is π^0, η Dalitz decays. Figure 1 shows the measured e^+e^- spectra for the 2006 $p+p$, 2008 d+Au and 2009 $p+p$ data sets from left to right. Circle symbols show the data and contributions from known hadron decays are also shown together as dotted lines as well as the background pairs by the shaded part.

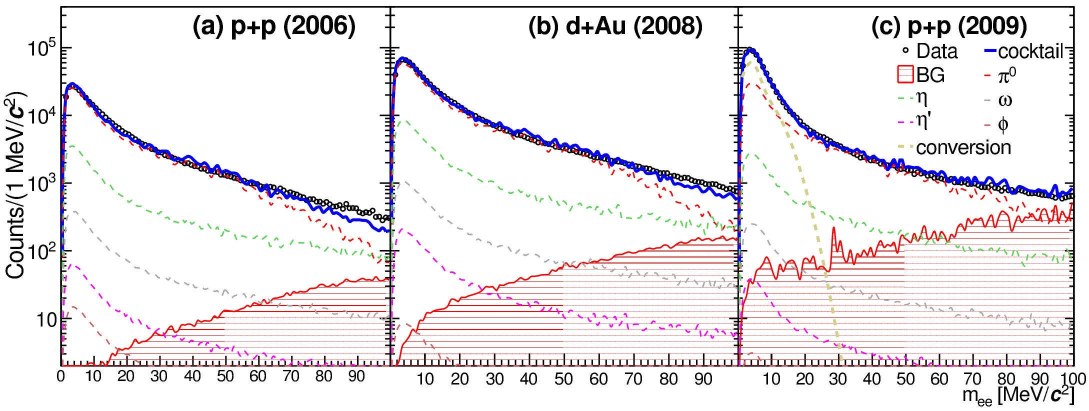

Figure 1: The measured e^+e^- spectra for the 2006 $p+p$, 2008 d+Au and 2009 $p+p$ data sets.

A statistical test is needed to extract a possible dark photon signal behind a huge amount of e^+e^- pairs from Dalitz decays. First, the shape of the distribution of pairs from Dalitz decays is parameterized by fitting with a physics-motivated function. The fit function, Eq. 3.1 consists of the Kroll-Wada formula for the e^+e^- pair yield from Dalitz decays and a fourth-order Chebychev polynomial, $T_4(m_{ee})$ to allow for shape distortions due to detector effects.

$$f(m_{ee}) = \frac{1}{m_{ee}} \times \left[\left(1 - \frac{m_{ee}^2}{m_{\pi^0}^2}\right)^3 + r_{\eta/\pi^0} \times \left(1 - \frac{m_{ee}^2}{m_\eta^2}\right)^3 \right] \times T_4(m_{ee}), \tag{3.1}$$

A simultaneous fit to the three data sets with different scale factors is made for two separate fit ranges to avoid having a local bad χ^2. These two fit functions are connected smoothly at the break point, and the best-fit result for the Dalitz decay contribution is shown in Fig. 2.

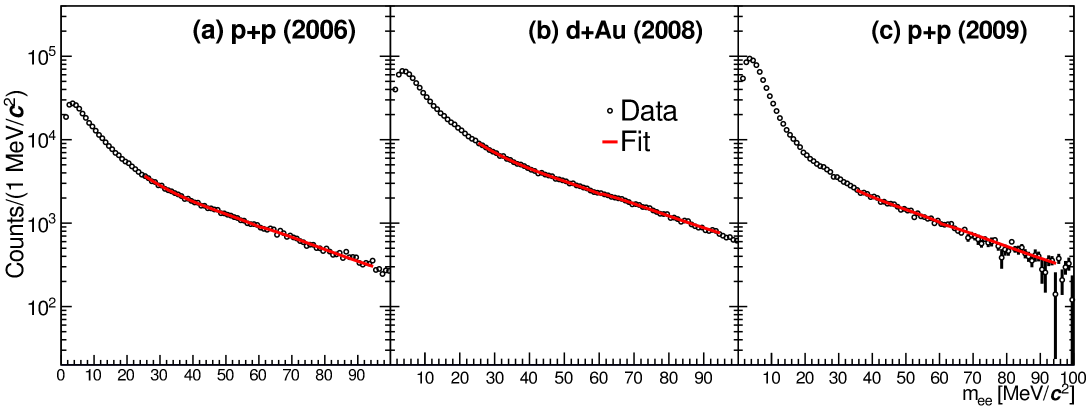

Figure 2: The best-fit result for the Dalitz decay contribution with the Kroll-Wada formula+4-th Chebychev polynomial.

4. Results

The CL$_s$ statistical approach [11] is employed to determine a limit on the number of dark photon candidates in each data set. The relative likelihood between the Dalitz parameterization with and without the dark photon signal is calculated with a 1 MeV/c^2 step for $30 < m_{ee} < 90$ MeV/c^2. Here, the expected dark photon signal shape is a Gaussian with 3.1 MeV/c^2 of its width equal to the PHENIX detector mass resolution. Figure 3 shows the upper limits at 90% CL on the number

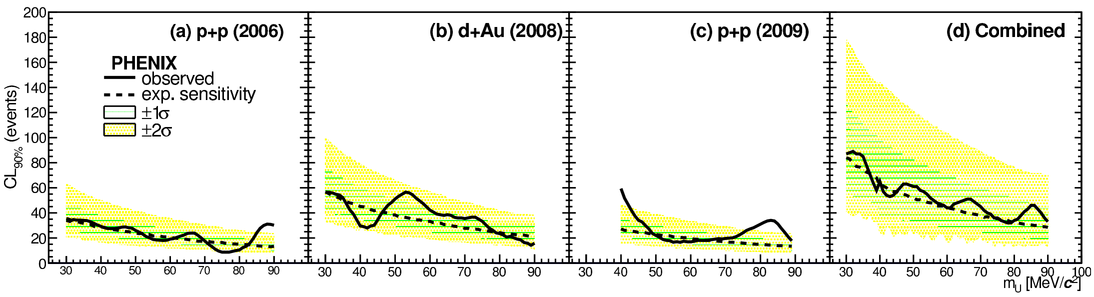

Figure 3: Upper limits at 90% CL on the number of dark photon candidates as a function of mass together with the experimental sensitivity.

of dark photon candidates as a function of mass together with the experimental sensitivity. The observed limits and experimental sensitivity are shown as solid and dotted lines, and the green and yellow bands also indicate $\pm 1,2\sigma$ fluctuations of the experimental sensitivity. The combined result of the upper limits is consistent with the experimental sensitivity within 1σ fluctuation. Then, the combined limit on the number of dark photon candidates is translated into a limit on the dark photon mixing parameter using Eq. 2.4. Figure 4 shows the upper limit at 90% CL determined by PHENIX

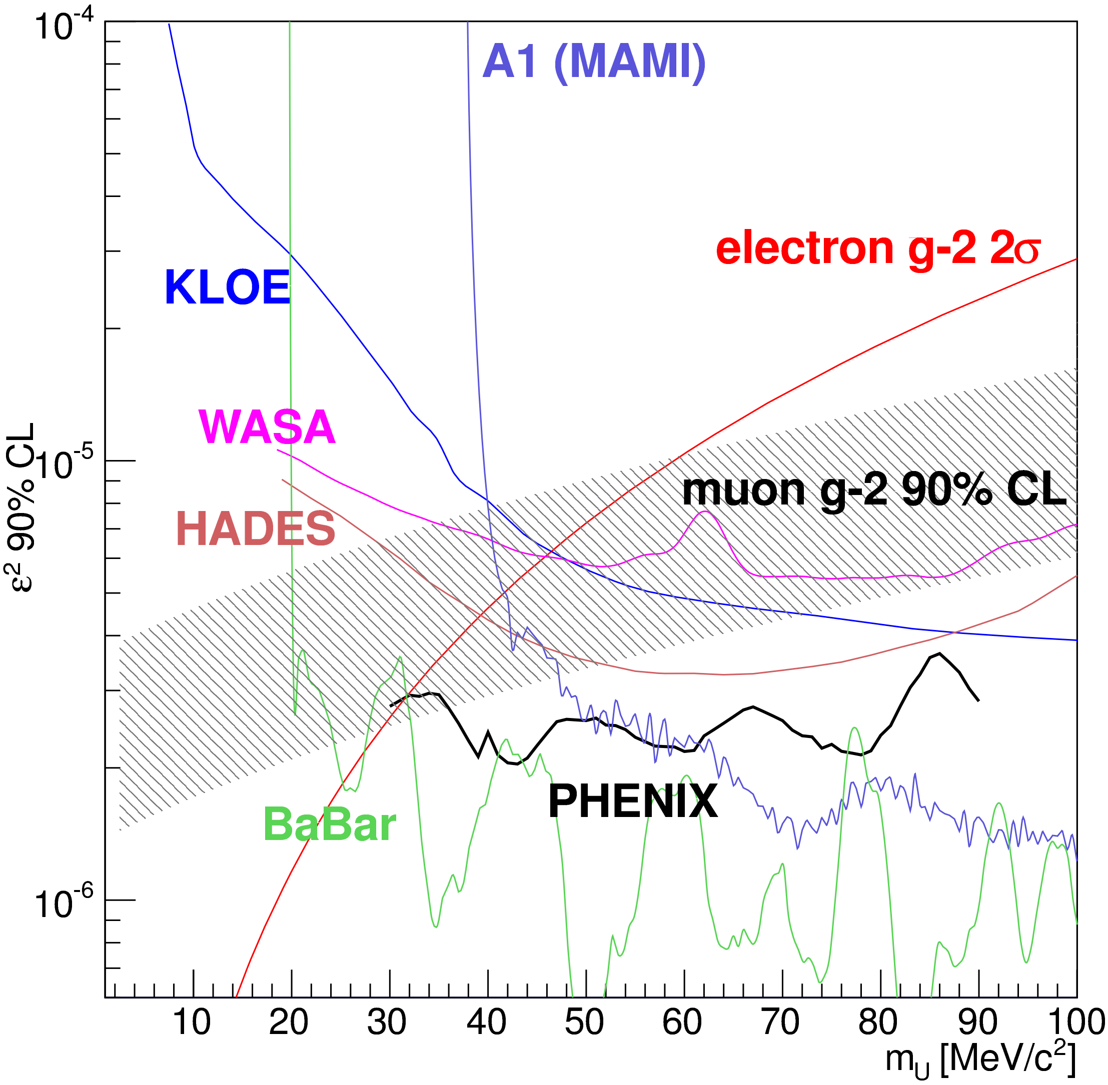

Figure 4: Upper limits at 90% CL in the dark photon mixing parameter space.

in the dark photon mixing parameter space [12]. Relevant results from other experiments [13, 14, 15, 16, 17] and the 2σ limitation from $(g-2)_e$ are shown together with our result. The band indicates the range of parameters if the $(g-2)_\mu$ anomaly can be explained by the dark photon at 90% CL. Combining with other experimental results, the possibility of the explanation of the $(g-2)_\mu$ anomaly by the dark photon is almost ruled out at 90% CL, and furthermore the recent published result from NA48/2 excludes the entire band favored for the $(g-2)_\mu$ [18].

5. Summary

A search for the dark photon has been performed using π^0, η Dalitz decays at the PHENIX experiment. We successfully determined upper limits at 90% CL in the dark photon mixing parameter space for $30 < m_U < 90$ MeV/c^2. Combining with the recent results from BABAR and NA48/2 experiments, the entire region of mixing parameters favored for the $(g-2)_\mu$ anomaly is completely ruled out.

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PoS(DIS2015)129