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The standard model (SM) of particle physics is spectacularly successful, yet the measured value of the muon anomalous magnetic moment $(g-2)_\mu$ deviates from SM calculations by 3.6σ. Several theoretical models attribute this to the existence of a "dark photon," an additional U(1) gauge boson, which is weakly coupled to ordinary photons. The PHENIX experiment at the Relativistic Heavy Ion Collider has searched for a dark photon, U, in $\pi^0, \eta \rightarrow \gamma e^+e^-$ decays and obtained upper limits of $\mathcal{O}(2\times10^{-6})$ on U-γ mixing at 90% CL for the mass range $30 < m_U < 90$ MeV/c^2. Combined with other experimental limits, the remaining region in the U-γ mixing parameter space that can explain the $(g-2)_\mu$ deviation from its SM value is nearly completely excluded at the 90% confidence level, with only a small region of $29 < m_U < 32$ MeV/c^2 remaining.

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Introduction. The standard model (SM) of particle physics provides unprecedented numerical accuracy for quantities such as the anomalous magnetic moment of the electron $(g-2)_e$, as well as predicting the existence of the vector bosons $W^{\pm}$ and Z^0 and the recently discovered Higgs boson. Hence, measurements which lie outside SM predictions warrant special scrutiny. One such result is the measured value of $(g-2)_\mu$ for the muon [1], which deviates from SM calculations by 3.6σ [2]. An intriguing explanation for this discrepancy has been proposed by adding a "dark" gauge boson [3–6]. While the possibility of a hidden U(1) gauge sector had been considered shortly after the advent of the Standard Model [7, 8], it has recently gained more relevance, because it provides a simultaneous explanation of various beyond-the-standard-model phenomena in addition to $(g-2)_\mu$. These include, for example, the discrepancy between the world's data on proton charge radius [9] and that obtained by the Lamb shift in muonic hydrogen [10, 11], and the positron excess in cosmic rays observed by ATIC [12], PAMELA [13] and AMS-II [14] by providing a new mechanism for the decay of dark matter [15, 16].

While a variety of mechanisms can be introduced to parameterize dark sector physics, a simple formulation postulates a "dark photon" of mass m_U which mixes with QED photons via a "kinetic coupling" term in the Lagrangian [7, 8, 17, 18]

$$\mathcal{L}_{\rm mix} = -\frac{\varepsilon}{2} F^{\rm QED}_{\mu\nu} F^{\mu\nu}_{\rm dark}, \tag{1}$$

where ε parametrizes the mixing strength. Dark photons can then mix with QED photons through all processes that involve QED photons, with an effective strength $\alpha_U = \varepsilon^2 \alpha_{EM}$. If the dark photon mass exceeds twice the electron mass, it can decay into an e^+e^- pair, and in the minimal version of the model, this is its dominant decay mode in the interval $2m_e < m_U < 2m_\mu$. To date, a wide range of searches [18] have excluded most of the $[m_U, \varepsilon]$ parameter space that could explain the deviation of $(g-2)_\mu$ from its SM value. In this work, we report on new limits that exclude at the 90% confidence level essentially all of the remaining allowed parameter space, thereby rendering the dark photon an unlikely candidate to resolve the discrepancy of $(g-2)_\mu$ with the Standard Model.

Searching for $\pi^0, \eta \to \gamma U, U \to e^+e^-$. We search for possible decays of $\pi^0, \eta \to \gamma U, U \to e^+e^-$ by examining the invariant mass m_{ee} of e^+e^- pairs in a large sample of Dalitz decays, $\pi^0, \eta \to \gamma e^+e^-$ for $30 < m_U < 90$ MeV/c^2 in the dark photon parameter space, where the possibility of disentangling the $(g-2)_\mu$ anomaly by the dark photon survives at the 90% confidence level. The invariant yield of virtual photons from the Dalitz decays of π^0, η is given by the Kroll-Wada equation [19]:

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

where

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

$N_{2\gamma}$ is the invariant yield of 2γ decays of π^0, η, α_{EM} is the fine structure constant, and $m_e, m_{\pi^0,\eta}$ are masses for the electron, π^0 and η, respectively. The deviation of the transition form factor $F(q^2)$ from unity is 0.0157 even at $m_{ee} = 90$ MeV/c^2 from the parameterization of $F(q^2) = (1 - q^2/\Lambda^2)^{-1}$ with $\Lambda = 0.72$ GeV [20]. Therefore, the variation of $F(q^2)$ is small enough in the mass range of interest to set $F(q^2) = 1$ in the calculation. The weak coupling of the dark photon to the QED photon implies that the natural width of the dark photon is very narrow, and as a result the expected line shape of the dark photon is set by the mass resolution, σ, of the detector

$$\left(\frac{dN_{ee}}{dm_{ee}}\right)_{\gamma U} = N_{2\gamma} \frac{2\varepsilon^2}{\sqrt{2\pi}\sigma} e^{\frac{-(m_{ee}-m_U)^2}{2\sigma^2}} KW_{\pi^0,\eta}(m_{ee}). \tag{4}$$

From the peak height ratio,

$$R(m_U) = (dN_{ee}/dm_{ee})_{\pi^0,\eta\to\gamma U} / (dN_{ee}/dm_{ee})_{\pi^0,\eta\to\gamma e^+e^-}, \tag{5}$$

the dark photon mixing parameter can then be determined as:

$$\varepsilon^2 = \frac{2\alpha_{EM}}{3\pi} \frac{\sigma}{m_U} \sqrt{2\pi} R(m_U). \tag{6}$$

Note that in this approach the efficiencies for detection of e^+e^- pairs from Dalitz decays and from dark photons cancel in the ratio $R(m_U)$.

The analysis presented here is based on a precise measurement of virtual photons from π^0 and η Dalitz decays [21] across three PHENIX data sets at a collision energy of $\sqrt{s_{_{NN}}} = 200$ GeV with an integrated luminosity of 4.8 pb^{-1} of p+p collected in 2006, 82.3 nb^{-1} of d+Au collected in 2008, and 6.0 pb^{-1} of p+p collected in 2009. Here, the d+Au statistics corresponds to $2 \times 197 \times 82.3$ nb^{-1} = 32.4 pb^{-1} of nucleon-nucleon collisions. All three data sets include an electron triggered sample, and the single electron trigger threshold for the d+Au run was higher than that for the p+p runs. A hadron blind detector (HBD) [22], was installed in the experiment around the primary collision point prior to the 2009 data taking period. The additional material of the HBD resulted in a corresponding increase in the external photon conversion rate. The experiment was also operated with a reduced magnetic field integral during the period of HBD data taking. These effects substantially alter the shape of the 2009 e^+e^- mass spectrum below 35 MeV/c^2 relative to the spectra from 2006 and 2008. Therefore, we restrict the 2009 analysis to the mass region above 40 MeV/c^2 to avoid the edge effect at parameterization of the Dalitz contribution.

The PHENIX apparatus [23] was designed with only 0.39% of a radiation length (X_0) in front of the tracking detectors. It generates a small rate of conversions in the experimental aperture and provides excellent momentum resolution and electron identification. The HBD brought an additional material budget of 2.4% $\times X_0$ for the 2009 run. The tracking system comprises drift wire and pad chambers with a momentum resolution of $\delta p/p = 1\% \oplus 1.1\% \times p$ [GeV/c]. Charged tracks with momenta above 0.2 GeV/c and pseudorapidity $|\eta| < 0.35$ fall within the PHENIX acceptance. Electron identification requires hits in a Ring Imaging Čerenkov detector and energy-momentum matching in an electromagnetic calorimeter with an energy resolution of $\delta E/E < 10\%/\sqrt{E\ [\mathrm{GeV}]}$.

All combinations of electrons and positrons in an event are taken as pairs for the analysis. The contributions due to random combinations, correlated fake pairs from double Dalitz decays ($\pi^0, \eta \rightarrow e^+e^-e^+e^-$) and jet-induced correlations are evaluated using like-sign pairs. After scaling by the number of nucleon-nucleon collisions, the correlated backgrounds in p+p and d+Au are very similar, indicating these background contributions are well understood. Pairs stemming from photon conversions in the material of the detector are removed by a cut on their characteristic angular orientation with respect to the magnetic field [24]. For the 2009 p+p data, conversion pairs are rejected by a cut on the cluster size in the HBD, which depends on the pair opening angle [25], because the lower magnetic field of the 2009 run reduces the rejection power of the angular orientation cut. Conversions in the HBD readout plane were removed by an analysis technique of mass reconstruction assuming electrons come from the HBD readout plane [26]. In the 2009 dataset we consider pairs with an invariant mass above 40 MeV/c^2, where the contribution of conversion pairs becomes negligible. Excluding these nonhadronic background pairs, we obtained 67k, 167k and 75k e^+e^- pairs for 2006 p+p, 2008 d+Au, and 2009 p+p, respectively in the mass range $30 < m_{ee} < 90$ MeV/c^2, where most pairs originate from π^0, η Dalitz decays. Contributions to the electron pair spectrum are estimated by a GEANT3 based detector simulation using the measured invariant yields for hadrons as input. Effects such as the single electron trigger efficiency and inactive areas in the detector are taken into account. Figure 1 shows the raw spectra of e^+e^- pairs with the hadronic decay and background contributions for the 2006 p+p, 2008 d+Au and 2009 p+p data sets.

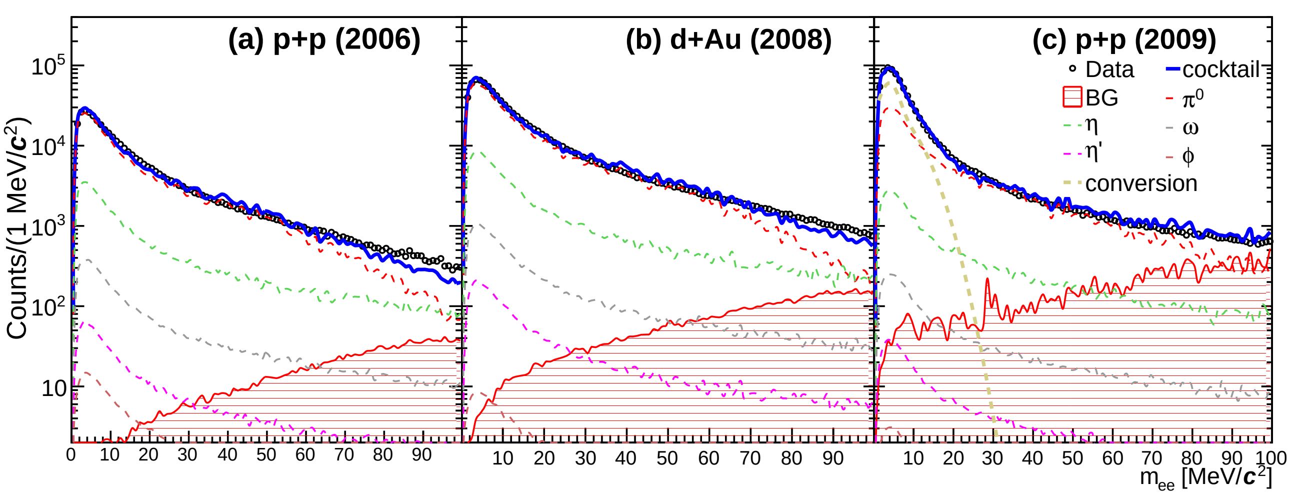

FIG. 1. (Color online) The raw spectra of e^+e^- pairs for the 2006 p+p, 2008 d+Au and 2009 p+p data sets. The contributions of various background components to the measured invariant mass spectra are shown. The 2009 p+p data has a significant contribution to the conversion background coming from the material of the HBD which is not present in the 2006 and 2008 data sets.

If the expected dark photon invariant mass distribution follows a normal distribution, then the standard deviation is equal to the detector mass resolution, as already described. This resolution is determined using a Monte Carlo procedure based on a GEANT3 description of the experimental apparatus. Spectra of dark photons with a flat distribution in transverse momentum for $p_T < 5$ GeV/c, covering the full azimuth, with rapidity $|y| < 0.5$, and with an initial vertex within 35 cm of the nominal vertex position are generated and forced to decay as $U \rightarrow e^+e^-$. Dark photon masses from 20–90 MeV/c^2 were investigated, with 20 million decays generated at each mass hypothesis. The reconstructed e^+e^- pairs were then weighted according to their pair p_T to follow the experimental e^+e^- pair spectrum after background subtraction. The e^+e^- invariant mass resolution for the PHENIX detector in $30 < m_{ee} < 90$ MeV/c^2 is $\sigma = 3.1$ MeV/c^2 with a 3% uncertainty. The calculated mass resolution is also confirmed with the data via a shape matching of the π^0 Dalitz peak around 5 MeV/c^2.

To establish a limit on the dark photon yield, we first describe the shape of the background-subtracted e^+e^- spectrum with a physics motivated curve composed of the Kroll-Wada formula for virtual photon yield from both the π^0 and the η multiplied by a 4$^{\text{th}}$-order Chebychev polynomial $T_4(x)$ to allow for slight deviations due to various detector effects:

$$f(m_{ee}) = \frac{1}{m_{ee}} \times \left[\left(1 - \frac{m_{ee}^2}{m_{\pi^0}^2}\right)^3 + r_{\eta/\pi^0} \times \left(1 - \frac{m_{ee}^2}{m_{\eta}^2}\right)^3 \right] \times T_4(m_{ee}). \tag{7}$$

The η/π^0 ratio, r_{η/π^0}, is fixed at 0.17, a value determined using a realistic "cocktail" of hadronic decays filtered through a model of the detector acceptance. The ω/π^0 ratio is fixed at 0.03. The shapes of the e^+e^- mass spectra from η and ω decays are indistinguishable for $m_{ee} < 100$ MeV/c^2, and their combined yield relative to the π^0, $0.17 + 0.03 = 0.20$, is taken as the effective η/π^0 ratio for the analysis.

We divide the full mass ranges of $25 < m_{ee} < 95$ MeV/c^2 and $35 < m_{ee} < 95$ MeV/c^2 into lower and higher mass ranges after nonhadronic background subtraction, use Eq. 7 to describe each portion, and demand continuity of the model at the mass where the two ranges abut. A simultaneous fit to the three mass spectra, allowing each an independent normalization, results in a combined description of the Dalitz continuum. This procedure produces a lower reduced χ^2 for the overall fit than using a single mass range for each dataset. The break point dividing the lower and upper mass ranges was allowed to vary, with 61 MeV/c^2 giving the best reduced χ^2. Figure 2 shows the

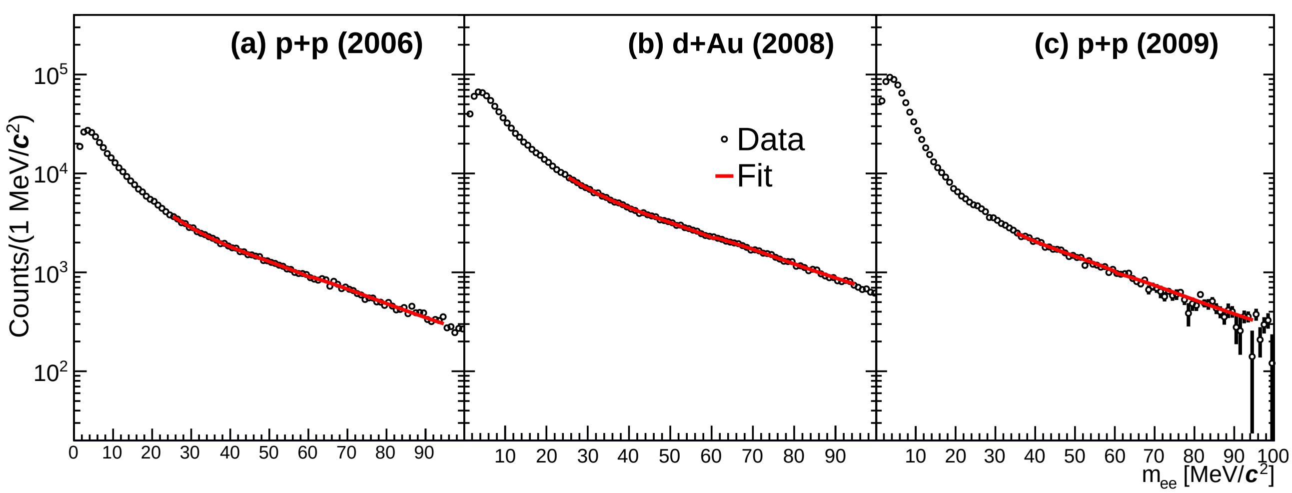

FIG. 2. (Color online) The best fit to the three mass spectra with the physics motivated function describing the e^+e^- distributions from hadron decays.

best fit result to the Dalitz decay contribution in each dataset after subtraction of unphysical background pairs. The contribution of the fit procedure to the total uncertainty is explored by varying the break point above and below this preferred value until the reduced χ^2 statistic rises by one and then taking the resulting 16% effect on the experimental sensitivity as the systematic uncertainty due to the procedure.

Results. The fitted background describes the yield of e^+e^- counts absent a dark photon signal. We employ the CL$_s$ statistical approach [27] to determine a limit on the number of dark photon candidates, which is in line with the current practice of setting limits for a hypothetical particle. This method has the effect of reducing the strength of

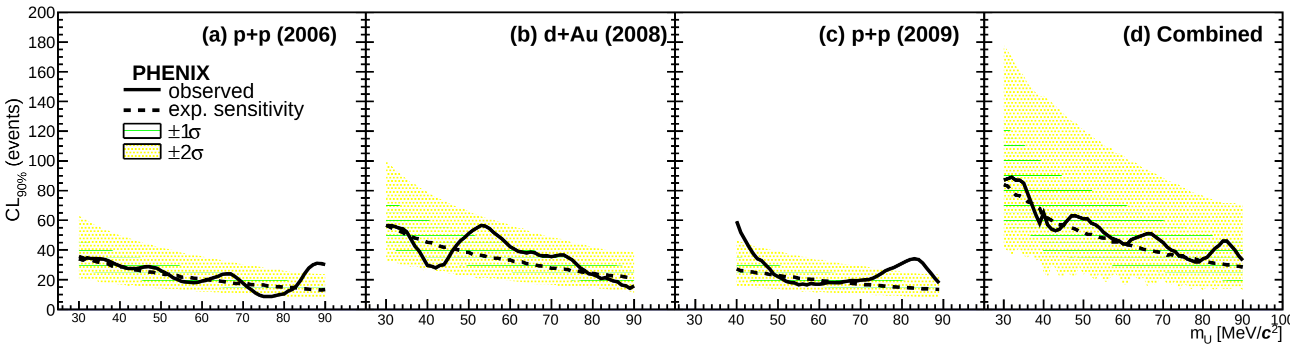

FIG. 3. (Color online) The experimental sensitivity and observed limit on the number of dark photon candidates as a function of the assumed dark photon mass. The $\pm1\sigma$ and $\pm2\sigma$ bands of the combined statistical and systematic uncertainties around the experimental sensitivity are shown in green and yellow, respectively.

the limit determination in the case of low (or no) signal strength, generally resulting in a conservative estimate of the CL. We step through the full mass range with a 1 MeV/c^2 step repeatedly refitting the spectrum with the addition of a Gaussian of width equal to the mass resolution and centered at each mass hypothesis. This determines the observed yield as a function of m_U, which may be greater or less than the experimental sensitivity at each mass, with a significance that is determined by the underlying probability distribution of the background, which is calculated by a likelihood ratio between the signal + background and background only hypotheses. The assumed background yield in any mass window will have uncertainties due to statistical fluctuations in the data used to determine the parameters describing the background by Eq. 7 and from systematic uncertainties in alternative background shapes. We evaluated the variation in the experimental sensitivity due to fluctuations in these uncertainties in addition to the uncertainty in the e^+e^- mass resolution. The observed value, the experimental sensitivity, and one- and two-standard deviation bands around the experimental sensitivity (shown as green and yellow bands) are all indicated on the plots for the different data sets as well as the combined result in Fig. 3.

The p-value under the null hypothesis from the combined result is calculated considering only the statistical uncertainty and is always greater than 0.27 in the entire range $30 < m_U < 90$ MeV/c^2. The minimum p-value is consistent with the background only hypothesis if the *look-elsewhere effect* [28] is taken into account. Therefore the limit on the number of dark photon candidate events can be translated directly into a limit on the dark photon coupling parameter using the peak-height ratio, Eq. 5. Figure 4 shows the limit determined by PHENIX along with the 90% confidence level (CL) limits from the WASA [29], HADES [30], KLOE [31], A1(MAMI) [32] and BaBar [33] experiments and the 2σ upper limit theoretically calculated from $(g-2)_e$ [34]. The bands indicate the range of parameters which would allow the dark photon to explain the $(g-2)_\mu$ anomalies with the 90% CL. The upward fluctuation apparent in the 2008 d+Au data compensates for a downward fluctuation of similar scale in the 2009 p+p data, leading to the slightly modulated limit of the combined result. The PHENIX results cover the mass range $30 < m_U < 90$ MeV/c^2, and over that range set a stricter limit than those of WASA, HADES or KLOE, and complement the A1(MAMI) results for their less sensitive region below 50 MeV/c^2. The PHENIX limits exclude the values of the coupling favored by the $(g-2)_\mu$ anomaly above $m_U > 36$ MeV/c^2. Recently, BaBar reported stricter limits from a search of the reaction $e^+e^- \to \gamma U, U \to l^+l^-$, excluding values of the preferred $(g-2)_\mu$ region for $m_U > 32$ MeV/c^2, and covering a mass range up to 10.2 GeV/c^2. As a result, nearly all the available parameter space which would allow the dark photon to explain the $(g-2)_\mu$ results are ruled out at the 90% CL by independent experiments. Figure 5 shows the PHENIX limits in the dark photon parameter space with different confidence levels, focusing on the small remaining parameter space for $30 < m_U < 32$ MeV/c^2. The entire parameter space to explain the $(g-2)_\mu$ anomaly by the dark photon can be excluded at the 85% CL by the PHENIX data alone. The level of the compatibility between our data and the coupling strength favored for the $(g-2)_\mu$ anomaly is 10% with a statistical test [35].

Conclusions. In summary, the PHENIX results set limits for the coupling of a dark photon to the QED photon over the mass range $30 < m_U < 90$ MeV/c^2, improving upon the recent results of the KLOE, WASA, HADES, and A1 experiments. Combining with the BaBar results, the dark photon is ruled out at the 90% CL as an explanation for the $(g-2)_\mu$ anomaly for $m_U > 32$ MeV/c^2, leaving only a small remaining part of parameter space in the region $29 < m_U < 32$ MeV/c^2. The probability that the theoretically predicted coupling strength required to explain the $(g-2)_\mu$ anomaly is compatible with the PHENIX results is only 10%. Future analyses by PHENIX would be able to provide even more stringent limits due to both increased data sets and improved detector technology that allow measurement of displaced vertices. As the coupling to the dark photon gets weaker, the distance traveled by the dark

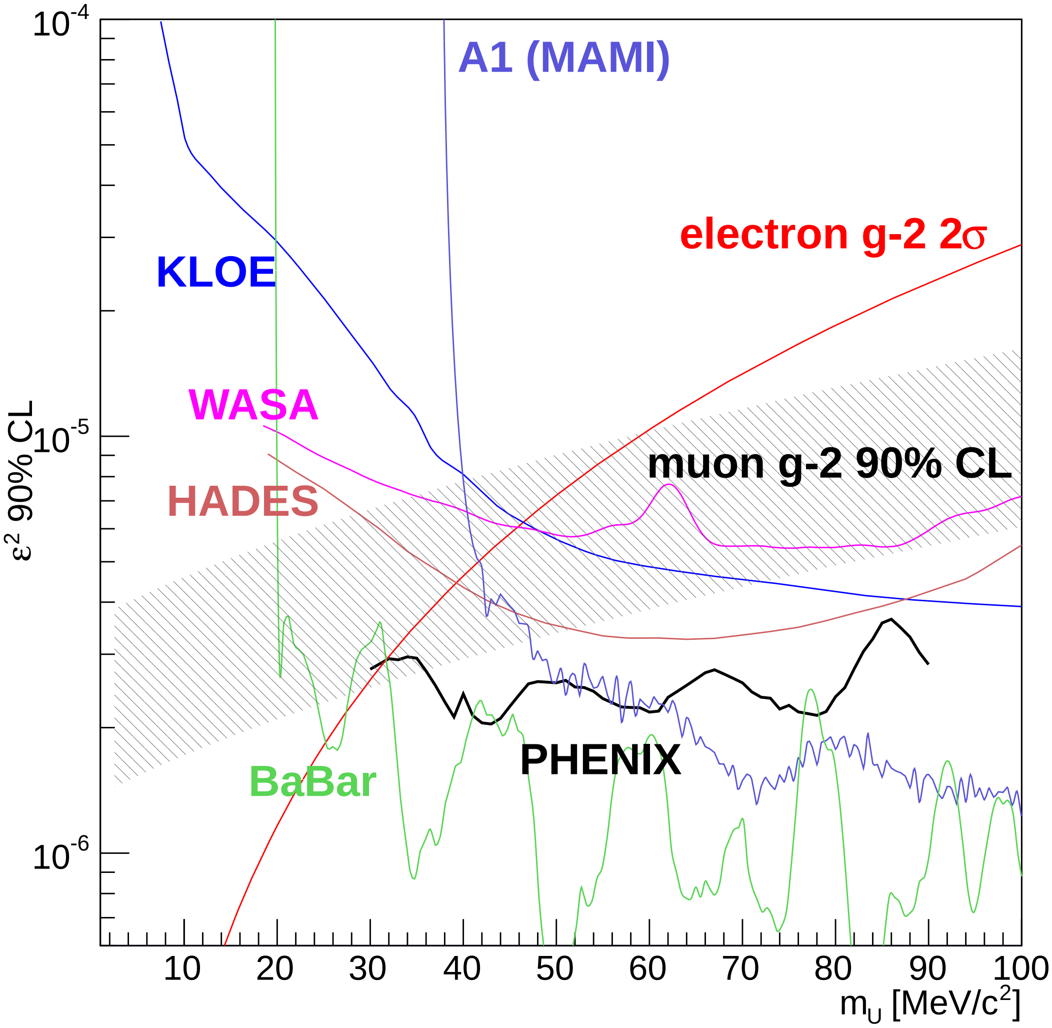

FIG. 4. (Color online) A compilation of the limits on the U-γ mixing parameter, showing the PHENIX results. Also shown are the limits at 90% CL from WASA [29], HADES [30], KLOE [31], A1(MAMI) [32], and BaBar [33] experiments and the band indicating the range of mass and coupling parameters favored by the $(g-2)_\mu$ anomaly at 90% CL. Also shown is the 2σ upper limit obtained from $(g-2)_e$ [34].

photon before decaying into e^+e^- grows longer [36]. The high statistics dataset taken after the recently commissioned PHENIX silicon vertex detector was installed in 2011 is being analyzed to look for such weakly coupled dark photons to provide limits even more restrictive than those reported here.

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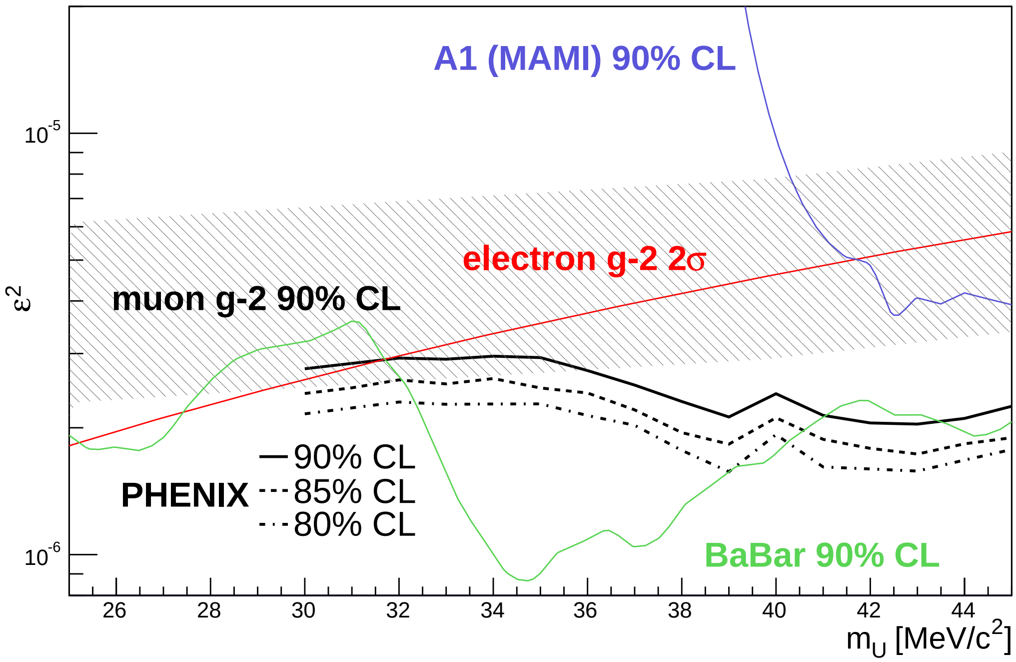

FIG. 5. (Color online) Limits on the U-γ mixing parameters from PHENIX at different confidence levels, together with the 90% CL limits from BaBar [33], and A1(MAMI) [32], the 2σ upper limit derived from $(g-2)_e$ [34] and the region favored by $(g-2)_\mu$.

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