Dark Photon Search at PHENIX

Deepali Sharma

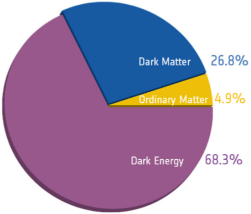
PHENIX Collaboration

Stony Brook University

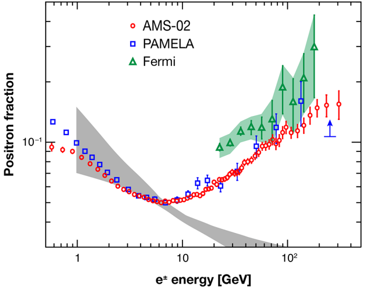
26th January, 2015

Our universe is composed of 27% dark matter and 68% dark energy.

- Considerable interest in exploring the nature of dark matter
  - Long list of candidates; e.g. WIMPS, Axions, extra dimensions and many more.
- A new possibility - dark sector.
  1. Extension of the Standard model.
  2. Additional new gauge field –**Dark photon**

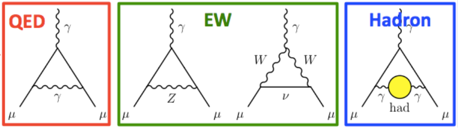


Positron excess in cosmic rays

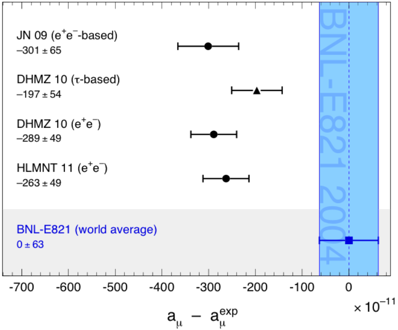


Experimental results suggesting possible BSM phenomenon

- Excess in positron fraction compared to SM prediction; seen by PAMELA and AMS-02.
- μ anamolous magnetic moment
  - Very precise measurement as well as theoretical clculations
  - **Strong motivation for our measurement.**



(M.Davier et al. 2011)



Standard Model predicts very precisely the value of "a” defined as:

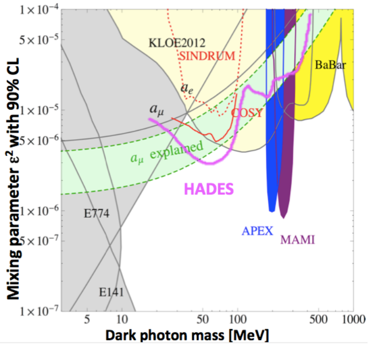
- $a_i = \dfrac{(g-2)_i}{2}$, $i = e, \mu$.
- $a^{SM} = a^{QED} + a^{EW} + a^{Had}$.
- For the electron: $a_e^{SM} \approx a^{QED}$
  $\rightarrow$ serves as a QED test
  $a_e^{EXP} - a^{SM_e} = -(1.06 \pm 0.82) \times 10^{-12}$
- Muon: a_μ^{EW}, a_μ^{Had} are not negligible
  $\rightarrow$ a SM test
- $a_\mu^{SM} = (116591802 \pm 49) \times 10^{-11}$
- Precise measurement by BNL-E821 experiment
  $a_\mu^{EXP} - a^{SM_\mu} = (287 \pm 80) \times 10^{-}11$
- About $2.4\sigma - 3.6\sigma$ discrepancy.

Possibility to expalin a_μ^{EXP} by dark photon

- Simplest hidden sector model introduces one extra $U(1)$ gauge symmetry and a corresponding gauge boson: the dark photon.
  - leaves the SM particles unchanged.
  - Associated gauge boson can communicate with the SM through a small mixing on the kinetic term of the QED Lagrangian.

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

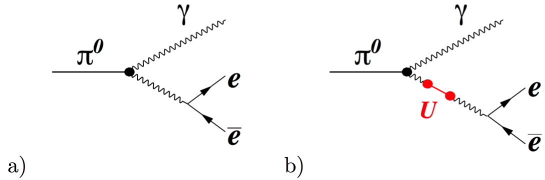
  - The gauge boson U (also A$'$ or Z'_d) is referred to as a dark photon since it can mix with the real photon in all processes.
  - Strength of the mixing parameter ε as suggested by phenemenological arguments must be of the order of $10^{-4} - 10^{-2}$ and the boson mass M_U below 2 GeV.



Mapping in the parameter space shown as a function of the dark photon mass (about 1 year ago). Theory curves from Hye-Sung Lee & Bill Marciano.

Batell, Pospelov and Ritz, PRD80 (2009) 095024

Ref: PLB 726, 187 (2013)

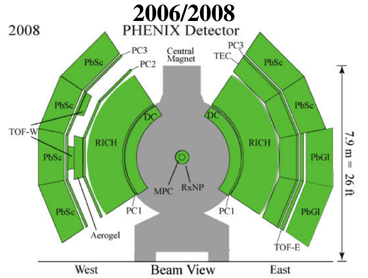


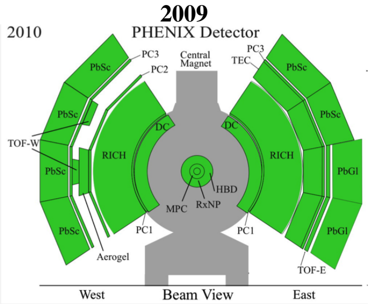
Measurement of $\pi^0/\eta \to \gamma U \to \gamma e^+e^-$ in π^0/η Dalitz decays

- **Assumption:** Dark photon exclusively decays into an e^+e^- pair.
  - its natural width is very narrow !
    - Expected peak width = detector mass resolution.
  - Same approach was used in COSY-WASA & HADES

Important requirements for this measurement

1. Large statistics of e^+e^- from π^0/η Dalitz decays.
2. Good mass resolution of e^+e^- spectrum.





PHENIX Central arms Acceptance:
$-0.35 < \eta < 0.35$, $2\times90^\circ$ in φ

- Data sets used in the analysis are from the years 2006, 2008 and 2009.
  - Hadron Blind Detector installed in 2009 (radiation length increase by 2.4%).
- Vertex determination: **BBC**
- Tracking: **DC/PC1**
  - $\delta p/p = 1\% \oplus 1.1\% \times$ p [GeV/c].

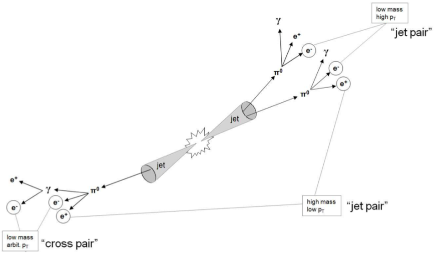
Electron identification based on:

- **RICH** (Ring Imaging Čerenkov detector) (e/π rejection >1000)
- **EMCal** (Electromagnetic Calorimeter) (E-p matching, e/π rejection $\sim$ 10)

Understanding the background

The unlike sign mass spectrum consists of two types of backgrounds:

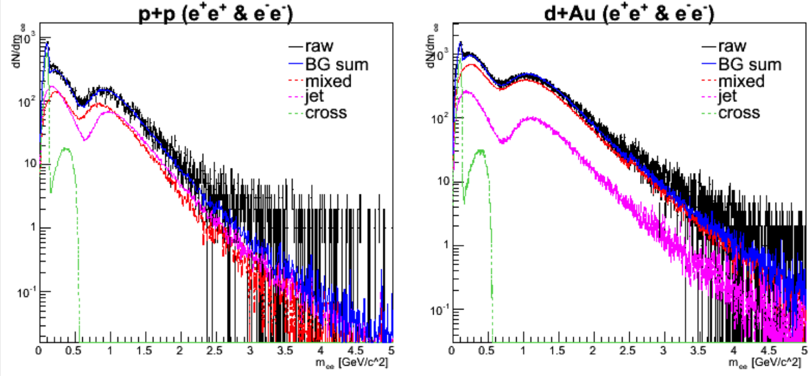
- **Uncorrelated Combinatorial Background:** arises from all the combinations where the origin of two electrons is totally uncorrelated.
- **Correlated Background:**
  - Cross Pairs: If there are two e^+e^- pairs in the final state of a meson, e.g. π^0 double Dalitz decay ($\pi^0 \rightarrow e_1^+ e_1^- e_2^+ e_2^-$), or a Dalitz decay ($\pi^0 \rightarrow \gamma e_1^+ e_1^-$) where γ converts to $e_2^+ e_2^-$.
  - Jet Pairs: Hadrons either from the same jet or in back-to-back jets, that decay into electron pairs.



Two methods are used to estimate the background:

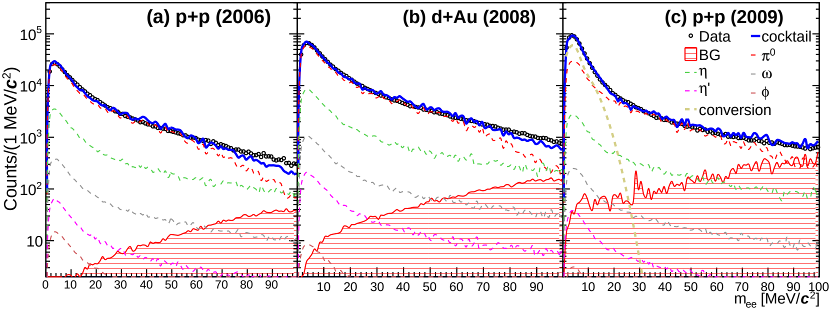
- Like sign event technique that takes into account both combinatorial and correlated background (2009 analysis).
- Subtract the combinatorial using Mixed Event Technique and then subtract the correlated background estimated from simulations (2006 and 2008 analysis).

Like-sign pairs



- Like-sign pairs are used to evaluate the contributions from different components.
- Sum of all the components describe the distribution well.

e^+e^- mass spectra for the different analyzed data sets

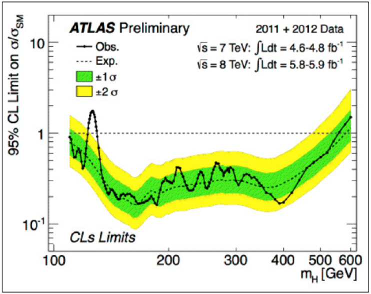


- Measured e^+e^- spectra is well described by an expected "cocktail" of hadronic decays + the background.
- No significant dark photon peak visible.
- Use a statistical analysis based approach to extrack the dark photon signal, *if any*.

CLs approach

- Widely accepted method to set confidence levels for hypothetical particles.
  - Famous “Brazil band plot “ for Higgs search at LHC.
- Relative likelihoods of how well the data is described by
  - Only background (Dalitz continuum).
  - Signal (Dark photon) + Background.
- Requires an **expected shape** of the dark photon peak and background.

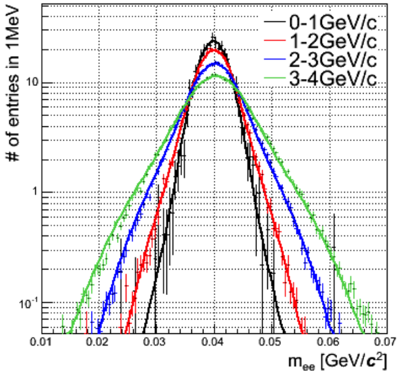
ATLAS Brazil band plot



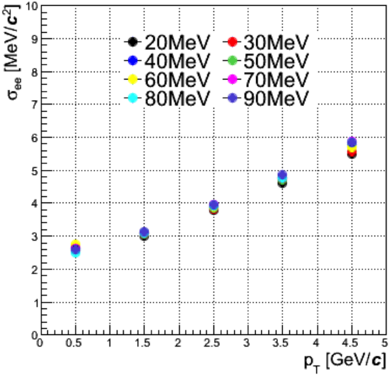
Extracting dark photon mass resolution in PHENIX

- The dark photon couples weakly to QED photon ⇒ narrow natural width.
  - ⇒ expected line shape of the dark photon is set by the mass resolution σ of the detector.
- Mass resolution of the PHENIX was calculated by the GEANT based simulation tuned to match the real data.
  - The expected dark photon peak width is $\sim$ 3 MeV (for inclusive p_T).

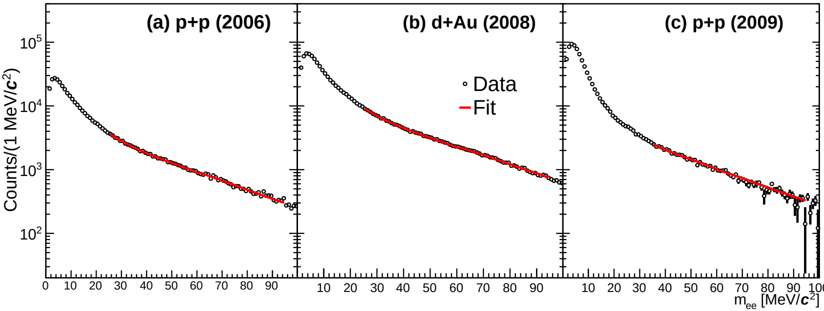
Dark photon mass = 40MeV



Mass resolution as a function of p_T



Background shape for the peak search

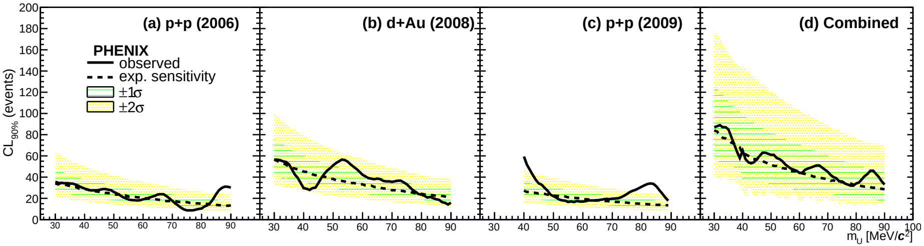


- Common fit function for the three data sets with different scale factors.

$$f_{fit}(m_{ee}) = \frac{1}{m_{ee}} \times \left[\left(1 - \frac{m_{ee}^2}{m_{\pi^0}^2}\right)^3 + r_{\eta/\pi^0} \cdot \left(1 - \frac{m_{ee}^2}{m_\eta^2}\right)^3 \right] \times f^i_{chebychev}(m_{ee})$$

- Chebychev polynomial allows for any slight deviations from Kroll-Wada shape due to detector effects.
- Two separate fit ranges to avoid having a local bad χ^2.
  - Smoothly connects at the break-point.

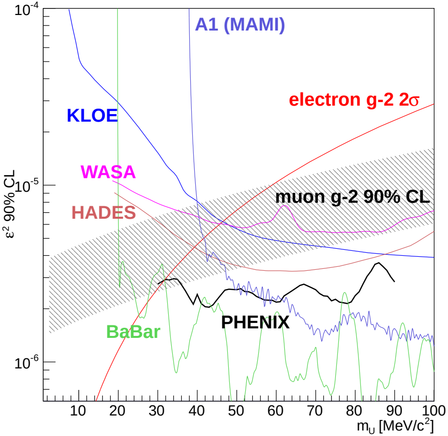
Possible dark photon events



- Possible events with dark photon candidates with 90% CL using CLs approach.
- Shown are experimental sensitivity, and its $\pm$ 1,2 σ uncertanities.
- Observed limits within the 2σ fluctuation of our sensitivity.
- $\Rightarrow$ No dark photon signal is observed.

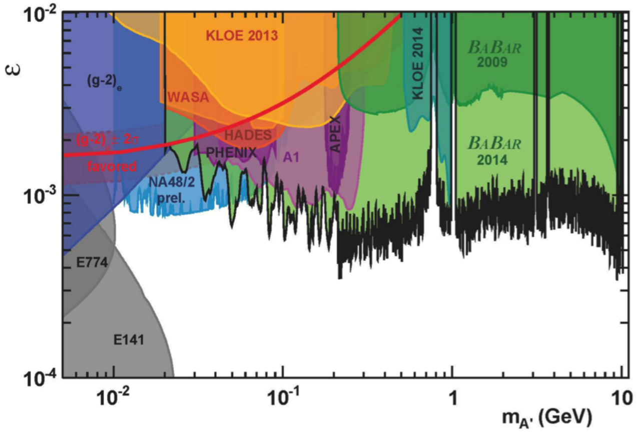
Results- dark photon mixing

$$\varepsilon^2 = \frac{2\alpha_{EM}}{3\pi}\frac{\sigma}{m_U}\sqrt{2\pi}R(m_U);\ R(m_U) = \frac{N_U(m_U)}{N_{Dalitz}(m_U)}$$



- PHENIX results cover the mass range $30 < m_U < 90$ MeV/c^2
  - Set a stricter limit than those of WASA, HADES or KLOE in the mass region between $30 < m_U < 50$ MeV/c^2.
  - Complement the A1(MAMI) results by covering their less sensitive area.
  - Excludes the values of the coupling favored by the $(g-2)_\mu$ region for $m_U > 32$ MeV/c^2.

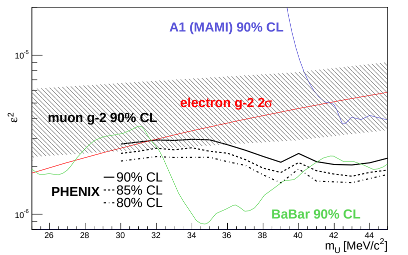
NA48 Results(arXiv:1412.8053); BABAR(PRL 113 (2014) 201801)



- Together with the BABAR and NA48/2 results, full "g-2 band" is excluded at the 90% CL.

Summary

- PHENIX carried out a search for the dark photon in π^0/η Dalitz decays.
- 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.
- Combining with the other world data, dark photon is ruled out with 90% CL as the explanation for observed $(g-2)_\mu$ anamoly.
- Accepted to be published as Phys.Rev.C. Rapid (arXiv:1409.08501).



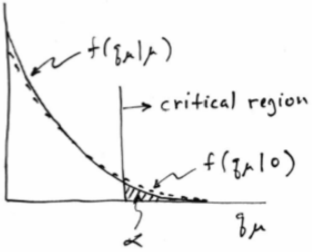
Outlook

- Analysis of the high statistics dataset taken in 2014 using Vertex detector will provide more stringent limits.

Back-ups

Why CLs method is better?

- Test of the hypothesis:
  - q_μ: likelihood ratio with a signal level, μ
  - $f(q_\mu|\mu)$: likelihood distribution for μ
    - ✓ $f(q_\mu|0)$ means the distribution for only background.
  - P-value for observed q_μ : $p_\mu = \int_{q_{\mu,\mathrm{obs}}}^{\infty} f(q_\mu|\mu)\, dq_\mu$
  - Normally 90%CL limit for μ is the highest value for p_μ>0.10.
- If a given μ is very small:
  - $f(q_\mu|\mu, 0)$ are almost consistent.
  - Probability to reject μ for $f(q_\mu|0)$ is slightly larger than that for $f(q_\mu|\mu)$ = 90%CL limit for normal case.
  - → This leads to exclude hypotheses to which one has no sensitivity.



"Spurious exclusion"

CLs method

- The CLs method is very popular in HEP to calculate a upper limit with avoiding the spurious exclusion.

1. Calculate the likelihood ratio of Poisson probabilities with two different hypotheses, Q:
   a. signal+background
   b. only background

$$Q = \frac{P_{\text{poiss}}(data|signal + background)}{P_{\text{poiss}}(data|background)},$$

2. Log-likelihood ratio, lnQ:

$$\ln Q = \sum_{i=1}^{n_{bins}} \{s_i - n_i \ln(1 + s_i/b_i)\},$$

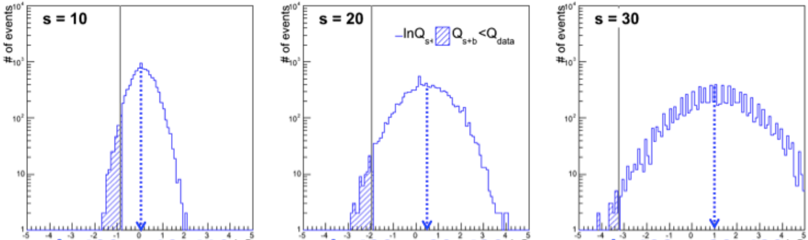
   - s_i = estimated dark photon signal in bin i
     - ✓ Scan a signal amplitude of expected dark photon peak
   - b_i = Dalitz continuum background in bin i
     - ✓ From the fit function of Dalitz continuum distribution
   - n_i = the number of entries in bin I
     - ✓ $\ln Q_{data}$: $n_i = n_{data}$
     - ✓ $\ln Q_{s+b}$: n_i=Poisson(s_i+b_i)
     - ✓ $\ln Q_b$: n_i=Poisson(b_i)

CLs method (cont.)

3. $\ln Q_{s+b}$ & $\ln Q_b$ are calculated with 10000 sample, then calculate:
   a. $CL_{s+b} = P(Q_{data} > Q_{s+b})$
   b. $CL_b \;= 1 - P(Q_b > Q_{data})$ (= $P(Q_{data} > Q_b)$)
   – Example: $n_{data}=370$, $b_i=400$

$\ln Q_{s+b}$ distributions with different signal amplitudes

$\ln Q_{data}$ ($n_{dara}=370$) **$\ln Q_{data}$** **$\ln Q_{data}$**



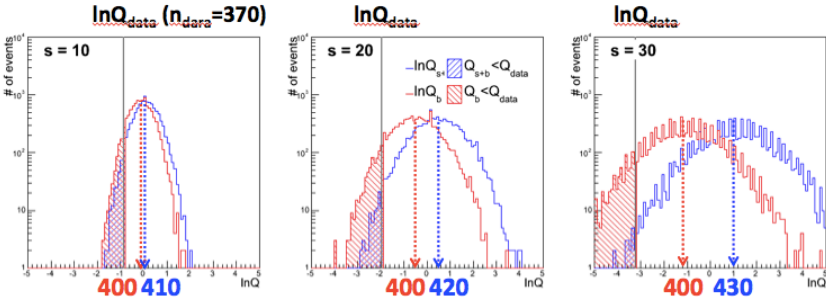
b_i:400+s_i:10=410 b_i:400+s_i:20=420 b_i:400+s_i:30=430

→ $P(Q_{data} > Q_{s+b})$ is interpreted as the probability that n_{data} can be explained by a statistical fluctuation with a mean value of $s_i + b_i$.

CLs method (cont.)

3. $\ln Q_{s+b}$ & $\ln Q_b$ are calculated with 10000 sample, then calculate:
   a. $CL_{s+b} = P(Q_{data} > Q_{s+b})$
   b. $CL_b = 1 - P(Q_b > Q_{data})$ (= $P(Q_{data} > Q_b)$)
   – Example: $n_{data}=370$, $b_i=400$

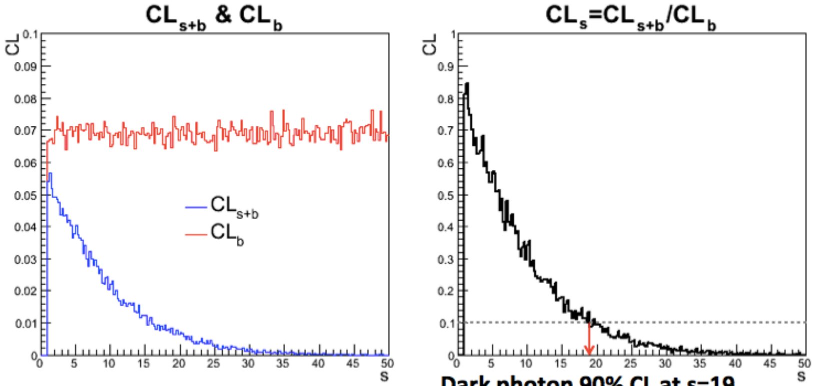
$\ln Q_{s+b}$ & $\ln Q_b$ distributions with different signal amplitudes



→ The hatched areas indicate the fractions that the data can be explained by the s+b and b hypotheses out of 10^4 samples.

CLs method (cont.)

4. CL_s is calculated as:
   - $CL_s = CL_{s+b}/CL_b$
     - ✓ CL_s is explained as CL_{s+b} re-normalized by CL_b.



Dark photon 90% CL at s=19

References of CLs method

- More detailed descriptions for the CLs method are:
  1. A.L. Read, J. Phys. G 28, 2693, 2002
  2. V. Buescher, et al., D0 Note 4629, 2004
  3. G. Cowan, Lecture note for Day 3 of Statistical Data Analysis for High Energy Physics 2011
     http://www.pp.rhul.ac.uk/~cowan/stat_freiburg.html