Dark photon search with neutral meson decays at the PHENIX experiment

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Introduction

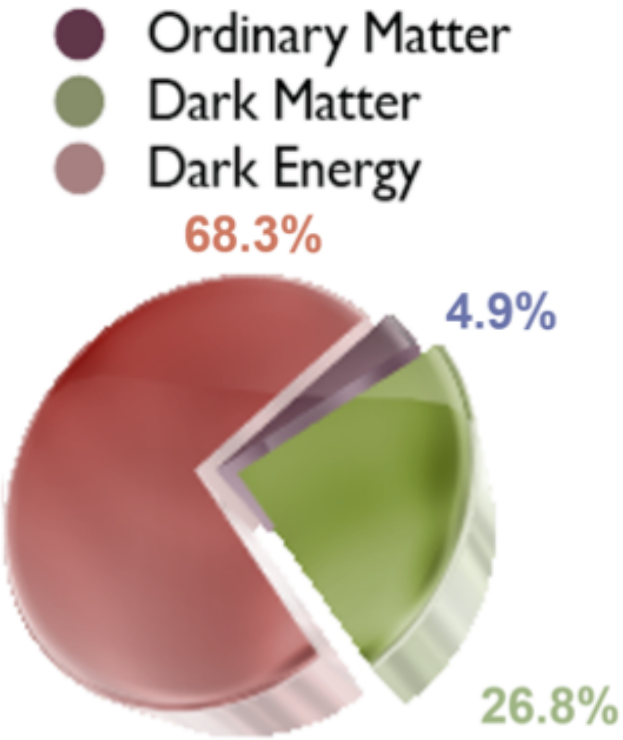
Composition of our universe

✧ Only 5% from ordinary matter, 27% dark matter & 68% dark energy

- ✓ Supported by:
  1. Gravitational lensing
  2. CMB fluctuations

→ Fundamental question: What is dark matter?

- ✓ Long list of candidates (WIMP, Axion, SUSY, …)



New possibility – dark sector

a. Extension of the Standard Model (SM)

b. Additional new gauge field - **Dark photon**

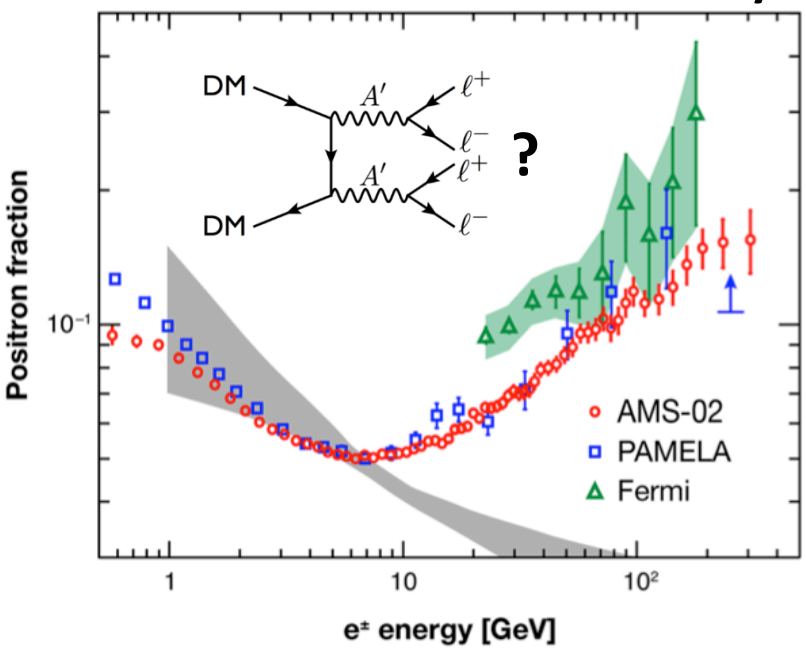
- ✓ Motivated by experimental results can not be described by SM

Possible BSM phenomena

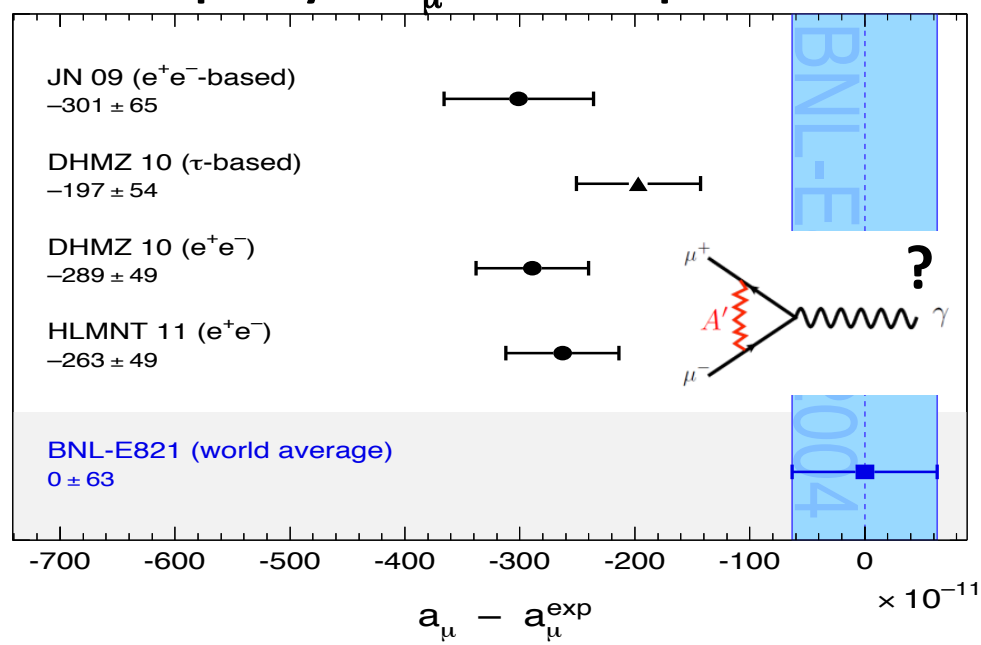
Beyond Standard Model (BSM) phenomena

- ✧ Dark photon models are strongly motivated by:
  1. Positron fraction in cosmic rays
     - ✓ Excess over the SM prediction (PAMELA, AMS-02)
  2. Muon anomalous magnetic moment, $a_\mu \equiv (g_\mu-2)/2$
     - ✓ Very precise measurement as well as theory calculations
     - ✓ About 3σ deviation from the SM predictions (BNL-E821)

Positron excess in cosmic rays



Discrepancy of a_μ from SM predictions



Dark photon

Simplest dark photon scenario

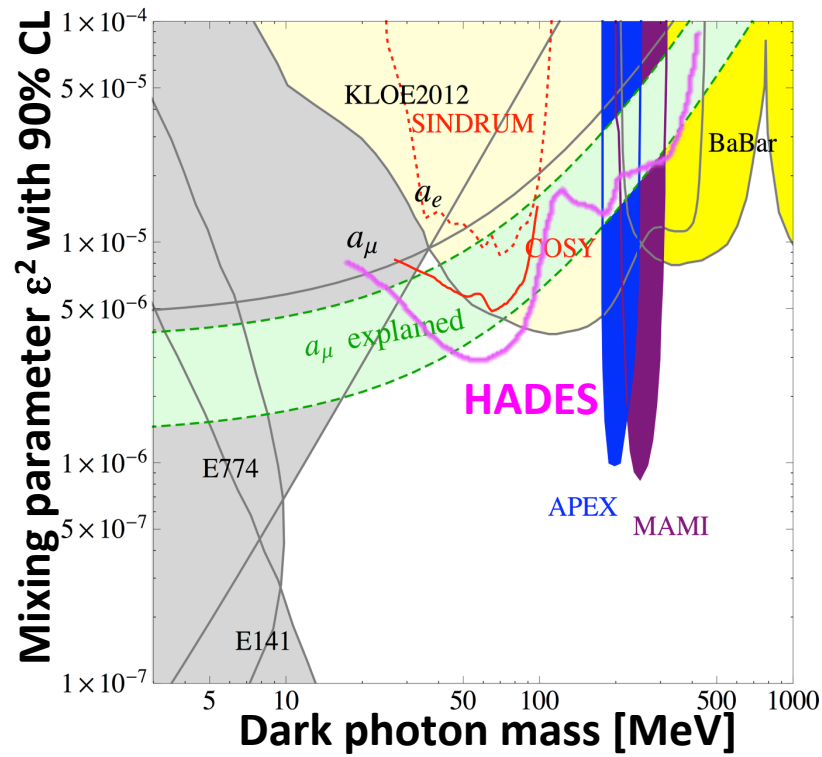
✧ Introduction of an additional *U*(1) gauge symmetry

- ✓ Gauge boson = dark photon referred to as *U* (also A' or Z_d')
- ✓ Communication with SM through a small mixing on the kinetic term of the QED Lagrangian $\mathcal{L}_{\rm mix} = -\frac{\epsilon}{2} F^{\rm QED}_{\mu\nu} F^{\mu\nu}_{\rm dark}$
- ✓ Mixing with ordinary photons in all processes

Mapping in parameter space

✧ Situation about 1 year ago

- ✓ Theory curves from Hye-Sung Lee & Bill Marciano



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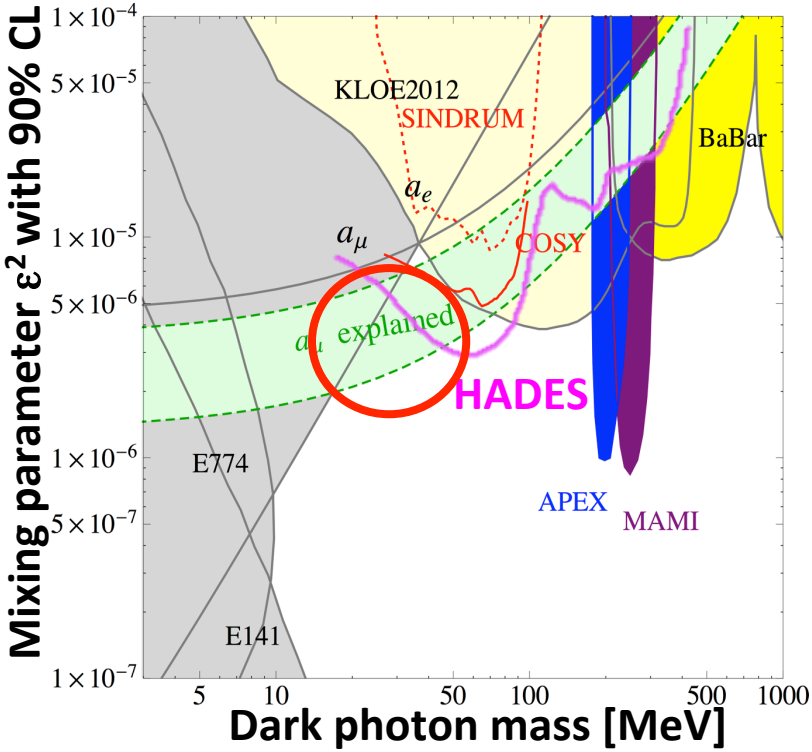
Mapping in parameter space

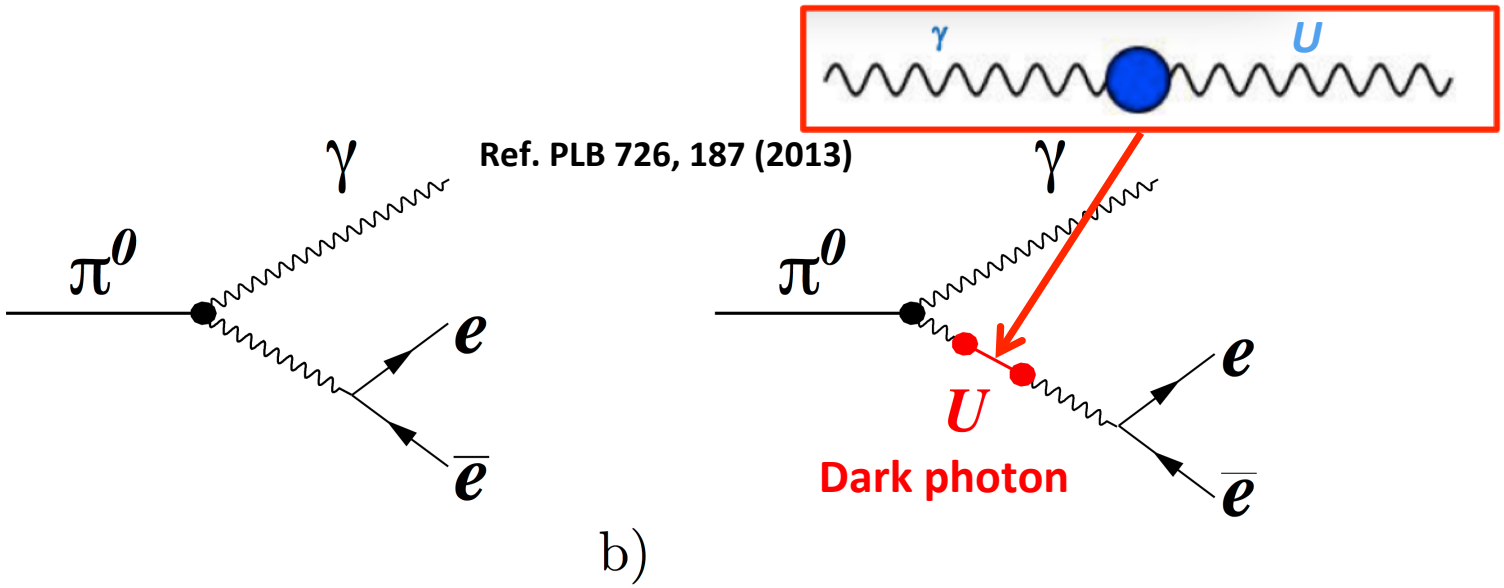
✧ Situation about 1 year ago

- ✓ Theory curves from Hye-Sung Lee & Bill Marciano
- ✓ Uncovered region in 30-50MeV for the muon g-2 explainable band with 90% CL

→ **Strong motivation for our measurement**



Search in π^0/η Dalitz decays



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

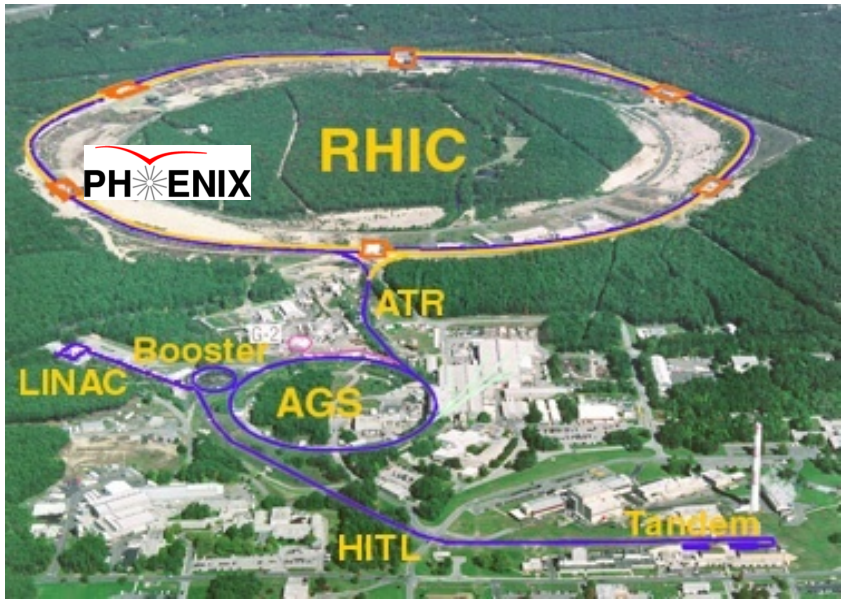
✧ Assumption: Dark photon exclusively decays into e^+e^- pair.

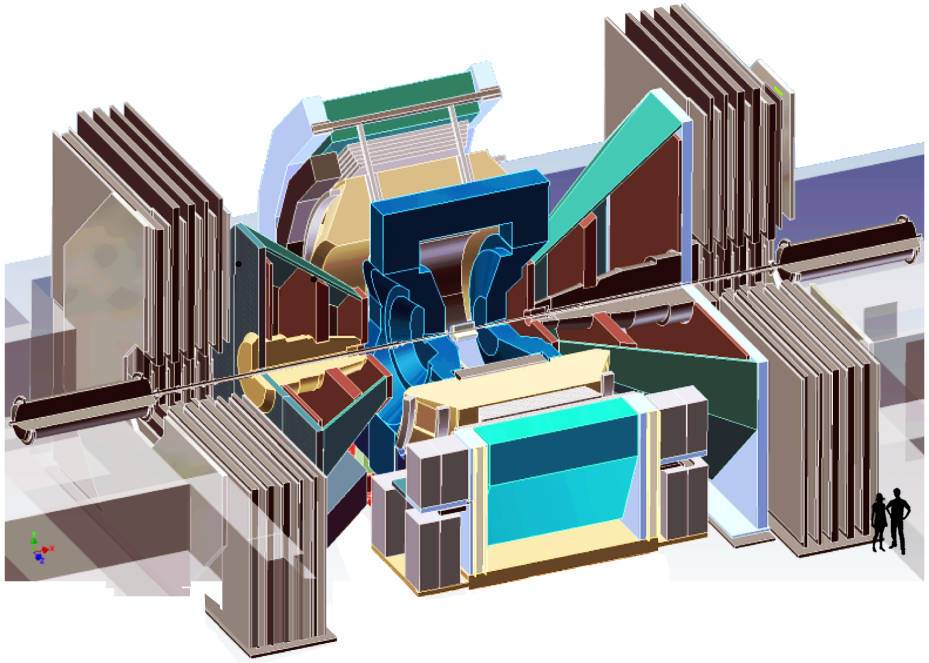
- ✓ Its natural width is very narrow.
  - Expected peak width = detector mass resolution
- ✓ Similar approach with COSY-WASA, HADES, NA48/2

Important requirements for this measurement

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

PHENIX experiment at RHIC

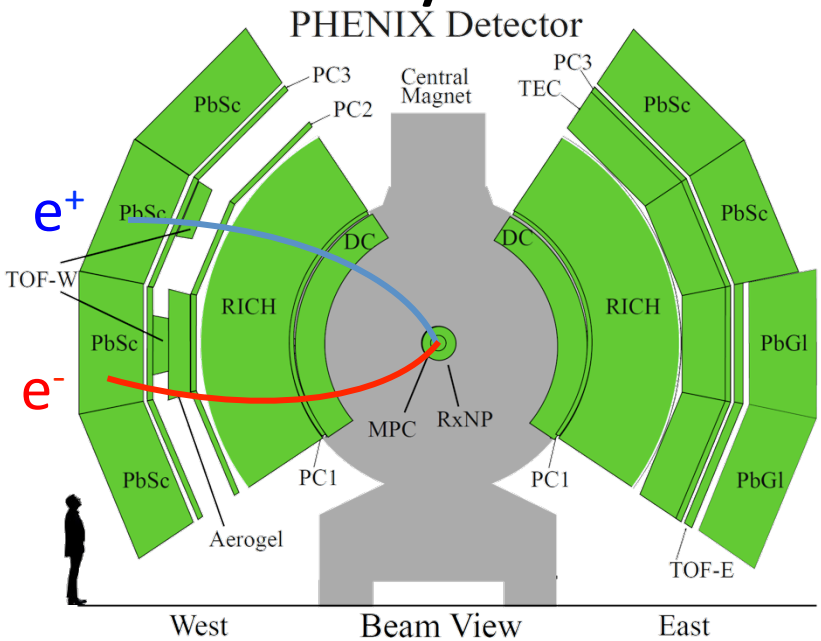




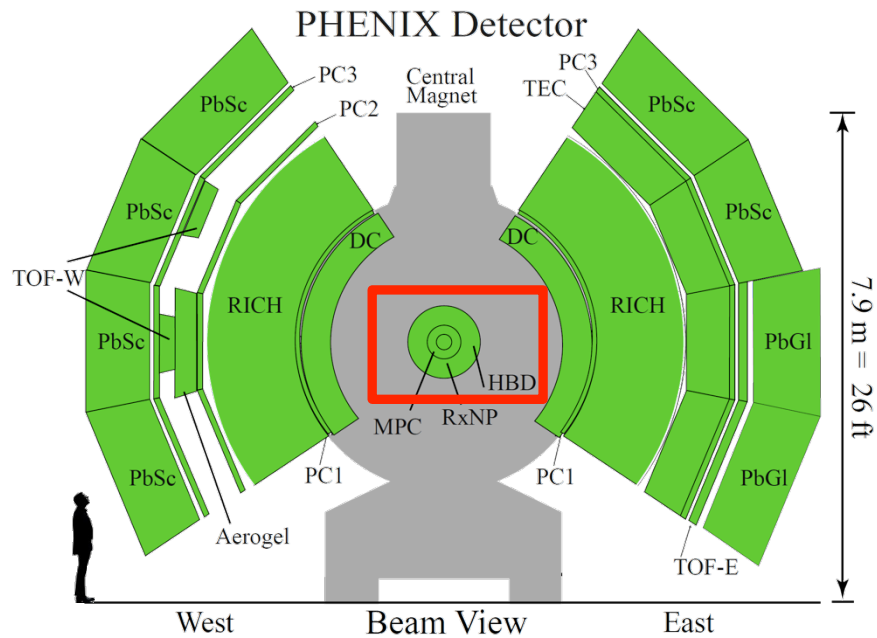
- ✧ Relativistic Heavy Ion Collider at BNL
  - ✓ Collision species: p+p, d+Au, Au+Au, Cu+Cu, U+U, …
  - ✓ Maximum collision energy: 200 (for HI),500 (for p+p) GeV
  - ✓ Running since 2001
- ✧ PHENIX experiment
  - ✓ Originally designed for the study of Quark Gluon Plasma
  - ✓ One of two major experiments at RHIC

e^+e^- measurement at PHENIX

2006/2008



2009



- ✧ Datasets: 200GeV p+p (2006/2009) & d+Au (2008)
  - ✓ Material budget before DC: 0.39% X_0 for 2006 & 2008 runs
  - ✓ 2009 run w/ Hadron Blind Detector (additional 2.4% X_0)
- ✧ e^+e^- measurement in $|\eta|<0.35$, 2×90° in ϕ
  - ✓ Tracking: Drift Chamber & Pad Chamber
    - $\delta p/p = 1\% \oplus 1.1\% \times p$ [GeV/c]
  - ✓ Electron trigger & ID: RICH & EMCal (E-p matching)
    - Hadron rejection > 10^3

Background subtraction

Unphysical background pairs

✧ Evaluation of the following BG contributions using e^+e^+ & e^-e^- pairs

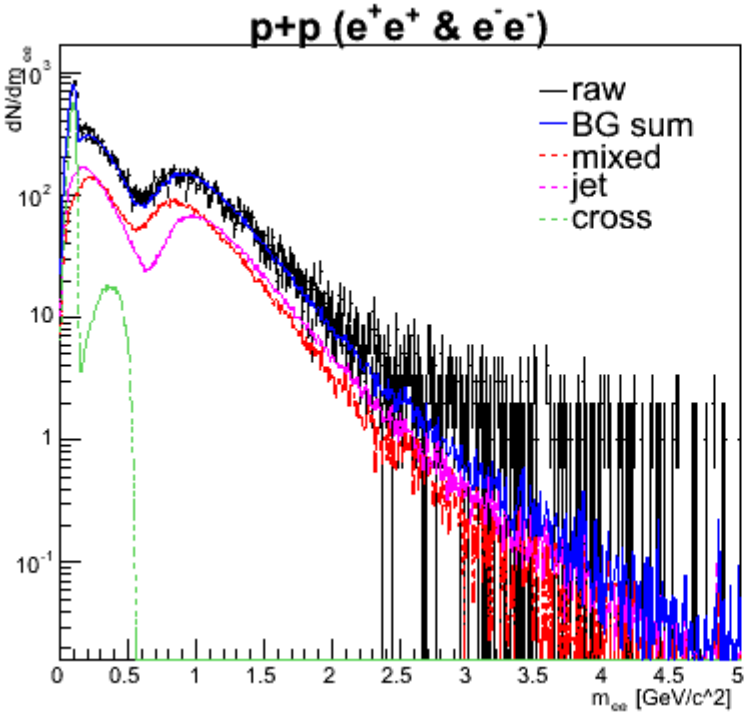
a. Combinatorial pairs between totally uncorrelated electrons

b. Jet pairs: electrons from hadrons in the same or back-to-back jets

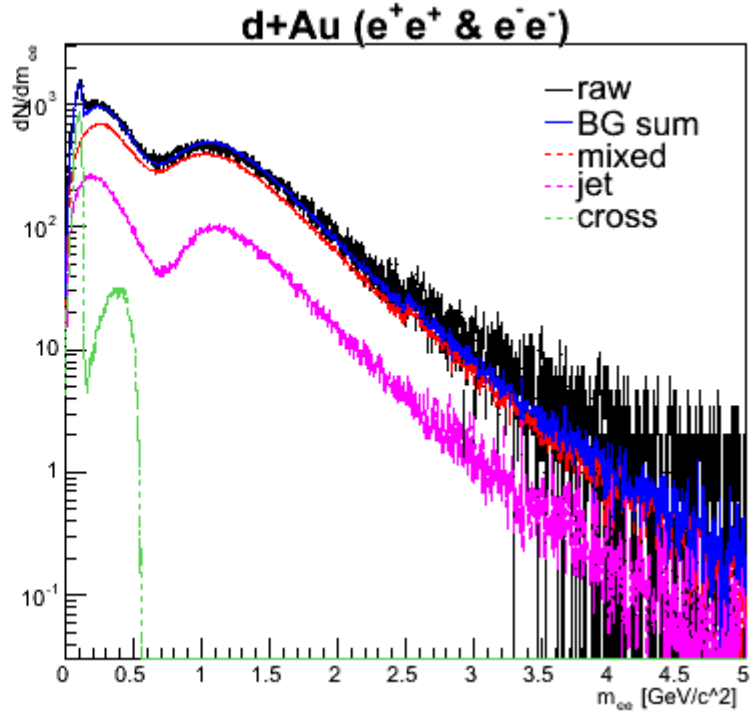
c. Cross pairs: fake pairs from decays with $2e^+e^-$ in a final state

✧ Sum of Background contributions < 10% in m_{ee}<100MeV for e^+e^-

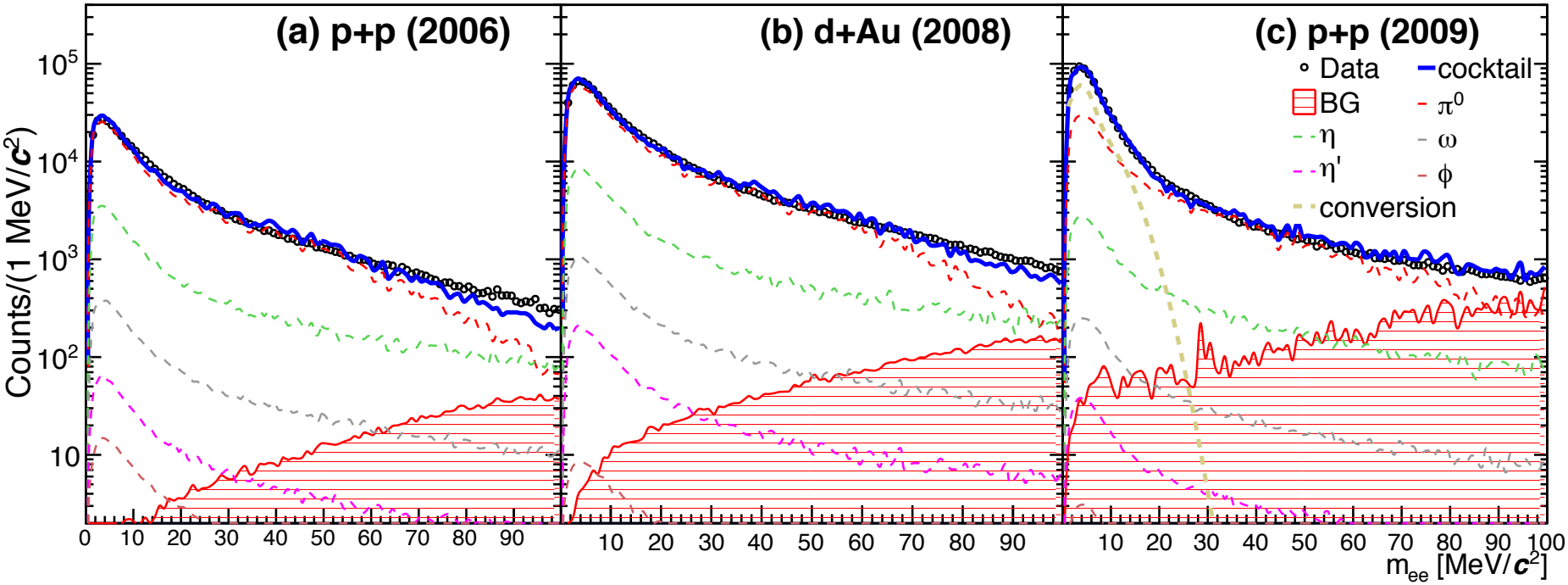
2006Run



2008Run



e^+e^- mass spectra

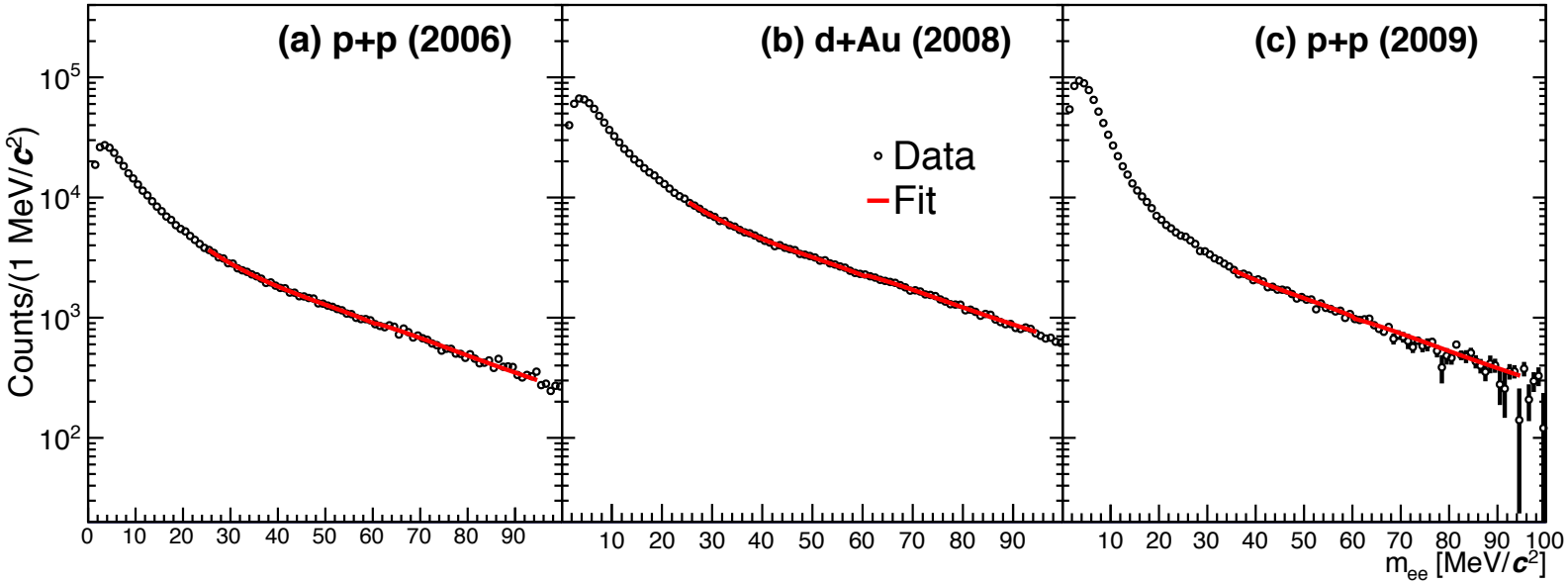


Correlated e^+e^- mass spectra after BG subtraction

- ✧ 700k (p+p) + 1.0M (d+Au) = total 1.7M e^+e^- from π^0/η Dalitz decays
- ✧ Described well by a "cocktail" of known hadron decays + BG
- ✧ No significant dark photon peak visible

→ A statistical test to extract a possible dark photon signal behind a huge amount of e^+e^- from Dalitz decays

BG description for peak search



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

Kroll-Wada **Chebychev polynomial**

✧ Common fit function for the data sets with different scale factors

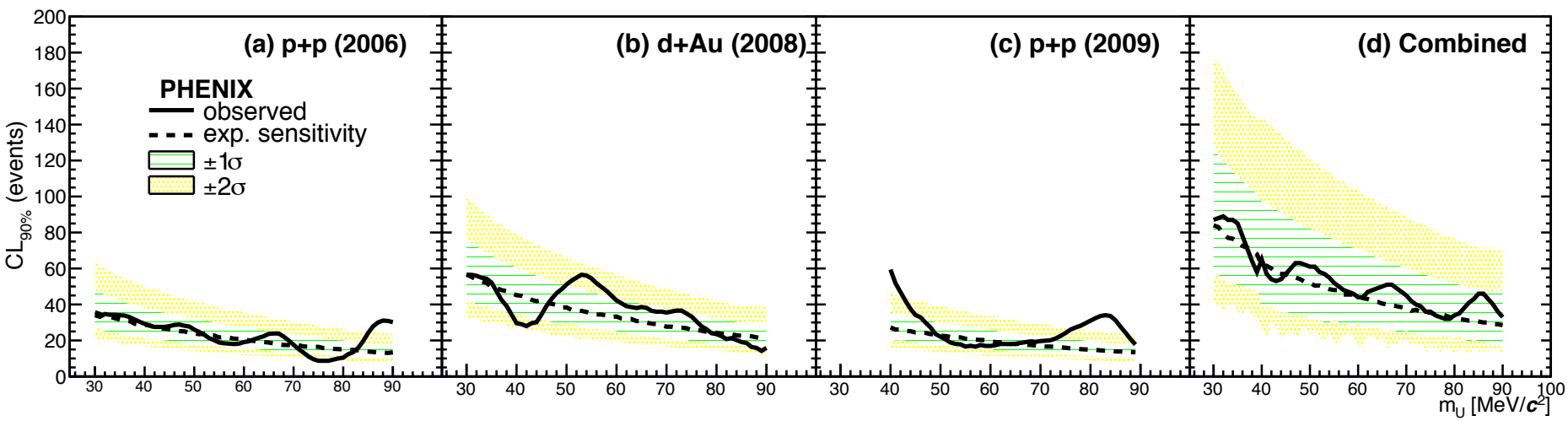
- ✓ **Chebychev polynomial** allows for a slight deviation from **Kroll-Wada** shape due to detector effects.
- ✓ Two separate fit ranges to avoid having a local bad χ^2
  - Smoothly connecting at the break-point

Dark photon event limits

CLs approach

✧ Calculate relative likelihoods of how well the data is described by:

1. Only Dalitz background
2. Dark photon signal + Dalitz background
   - ✓ Peak width = 3.1MeV dominated by detector resolution



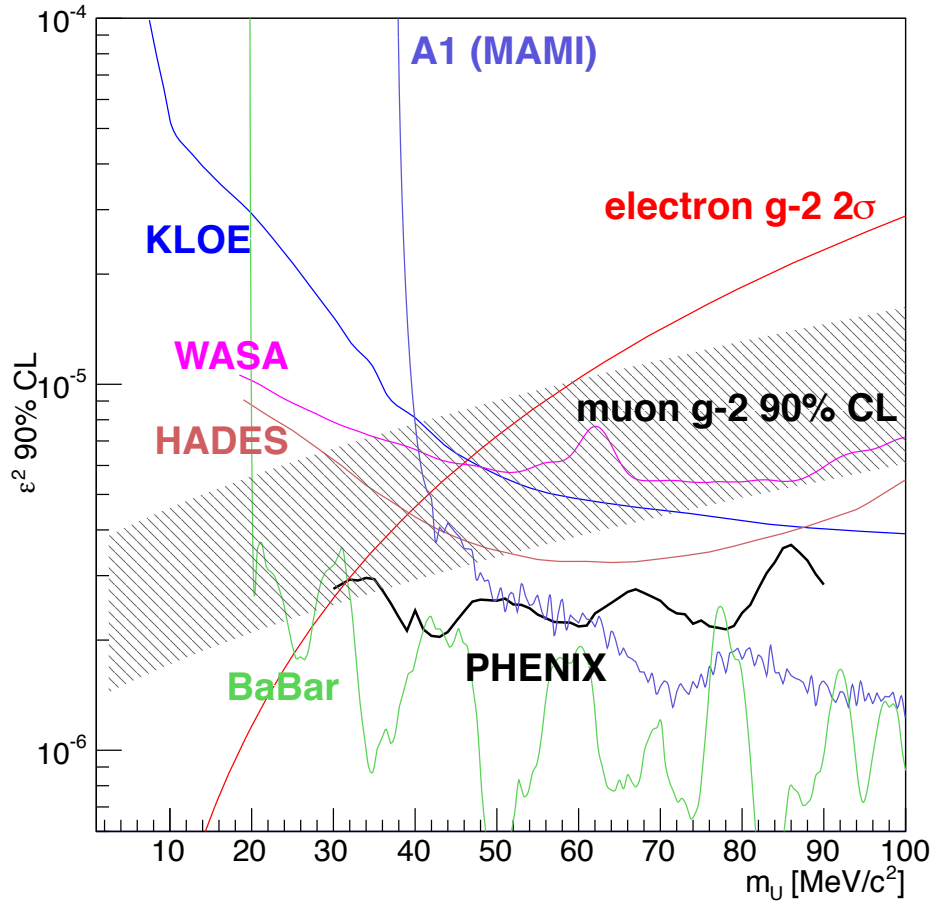
✧ Upper limits of dark photon candidates with 90% CL

- ✓ Experimental sensitivity with ±1,2σ uncertainties are shown.
- ✓ Observed limits within the 2σ fluctuation of our sensitivity
- → No dark photon signal was observed.

Upper limits in parameter space

- ✧ Translation into limits in m_U-ε^2 space
  - ✓ $\epsilon^2 = \frac{2\alpha_{EM}}{3\pi}\frac{\sigma}{m_U}\sqrt{2\pi}R(m_U)$
  - ✓ $R(m_U)=N_U(m_U)/N_{Dalitz}(m_U)$
- ✧ Upper limits in 30-90MeV
  - ✓ Stricter than KLOE, WASA, HADES, A1
  - ✓ Combining with BaBar, the muon g-2 explainable band is almost ruled out.

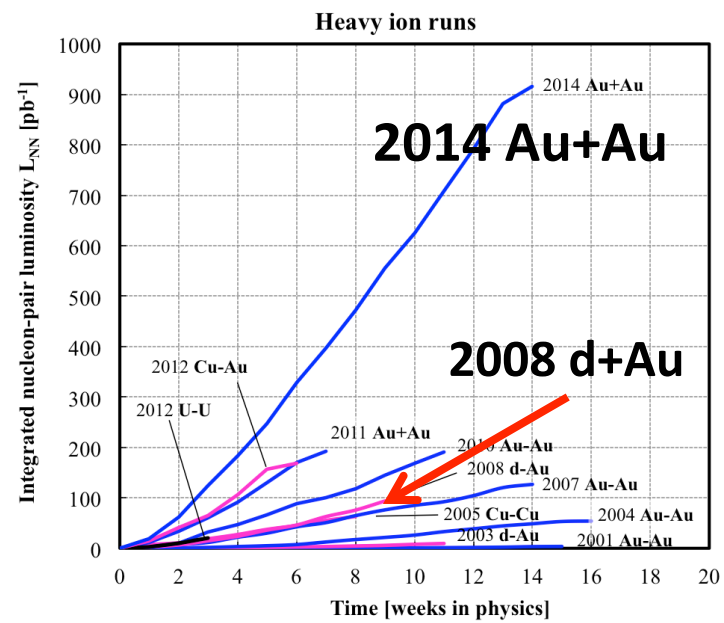
→ Completely excluded by NA48/2 recently (arXiv: 1504.0607)



Summary and outlook

Summary

- ✧ Dark photon search was performed through π^0/η Dalitz decays at PHENIX
  - ✓ Analyzed 1.7M pairs in 2006-2009 data
  - ✓ No dark photon signal was observed.
  - ✓ Combining with the other experimental results, dark photon is ruled out as the explanation for measured a_μ anomaly.
  - ✓ Published paper: Phys. Rev. C 91, 031901 (2015)

Outlook

- ✧ Further analysis with the recent high luminosity data and a silicon vertex detector