Searching for Dark Photons at PHENIX

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What is a dark photon?

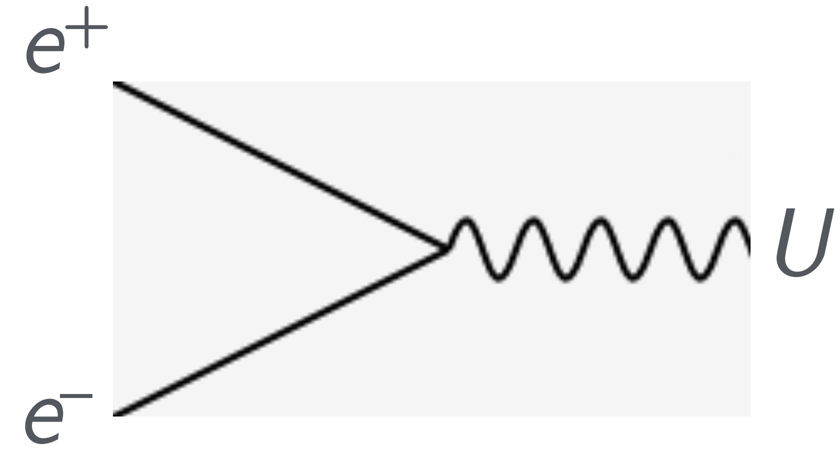
Dark sector doesn't interact (much) with SM particles

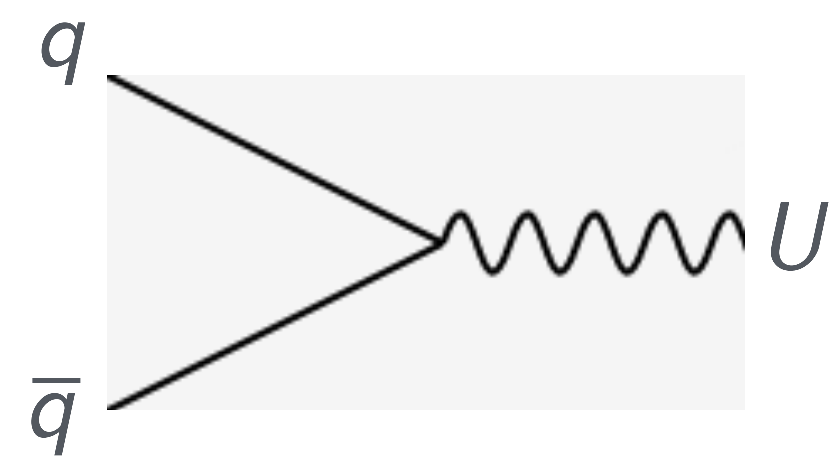
Dark photon U (or A') analogous to SM photon γ

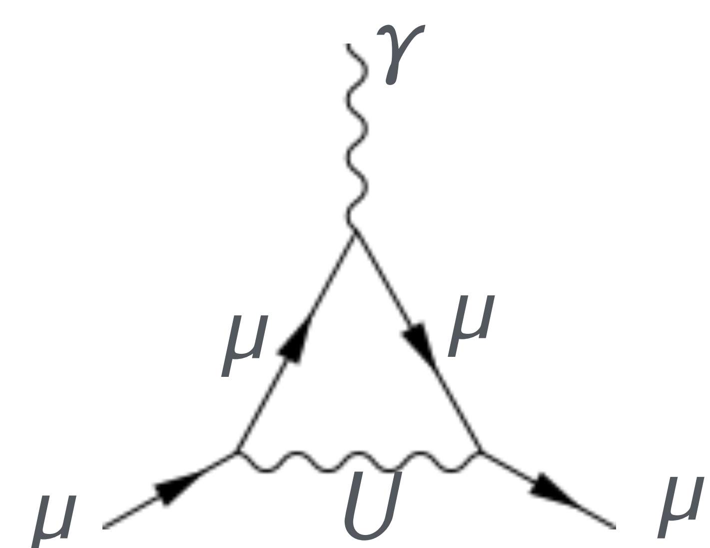
Hypothesized mixing with γ in Lagrangian

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

Source: [1]







Source: Wikipedia

Muon anomalous magnetic moment

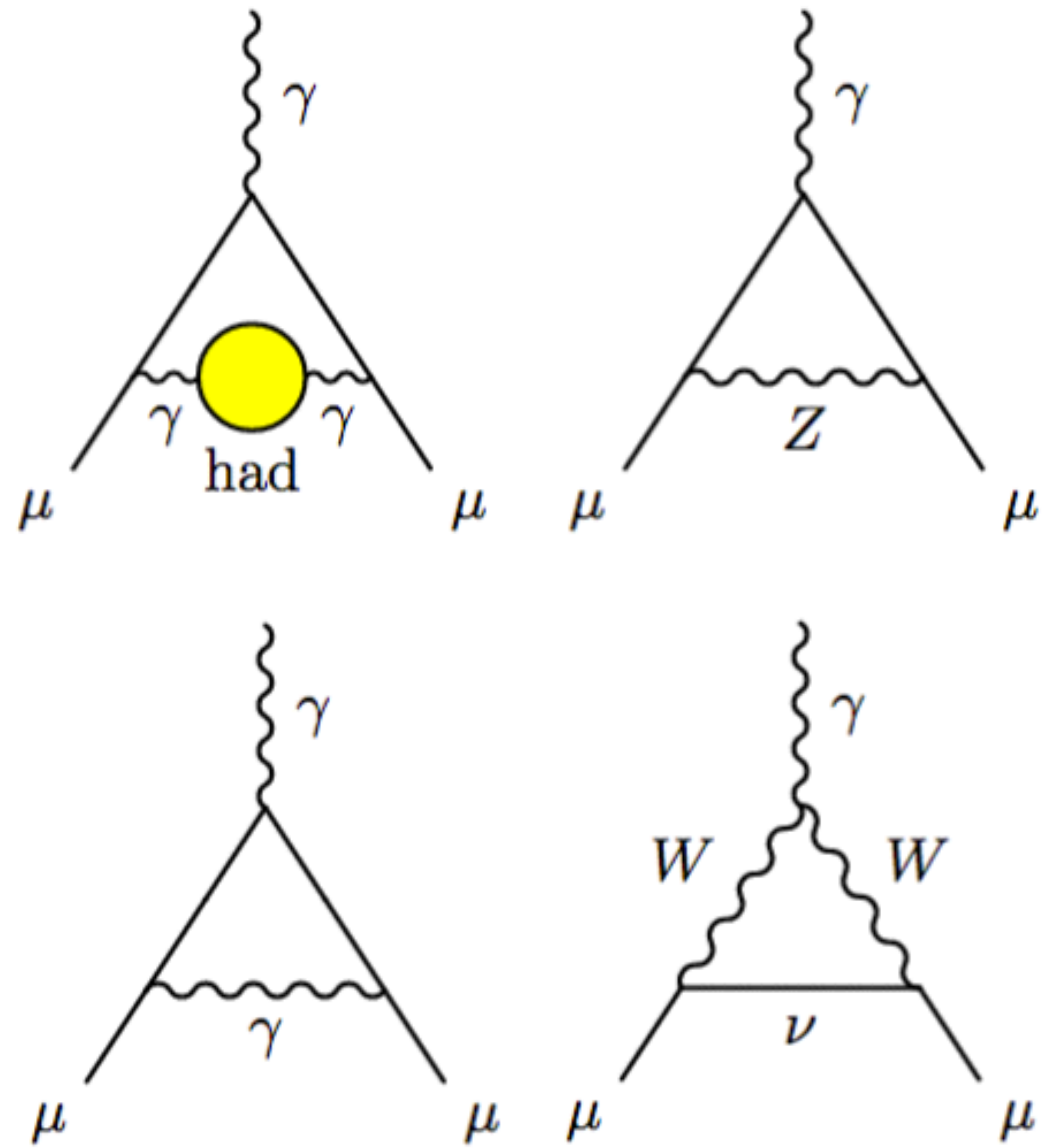
A.k.a. $g - 2$

At tree level $g = 2$

$$\boldsymbol{\mu} = g \frac{e}{2m} \boldsymbol{S}$$

$g - 2$ provided by loops $\Longrightarrow$ gives insight into virtual particles

E821 at Brookhaven found a 3.6σ discrepancy from SM



Source: [2]

Muon $g - 2$ experiment

E821 magnet moved to Fermilab to use more intense beam

Measure spin precession of muons in $\mathbf{B}$ field

Translate into magnetic moment using the Larmor precession formula

Source: Fermilab

Possible causes for discrepancy

Popular today

Statistical fluctuation

SUSY

Dark photon (sort of)

Popular at some point (including possibly today?)

Radiative mass generation

New gauge bosons

Anomalous W boson properties

Source: [3]

Dark photon properties

To resolve the $g-2$ anomaly, the dark photon should

mix with regular photons via something like $\mathcal{L}_{\text{mix}} = -\frac{\varepsilon}{2} F^{\text{QED}}_{\mu\nu} F^{\mu\nu}_{\text{dark}}$

have a mass $\gtrsim$ 25 MeV to avoid ruining electron $g-2$

have a coupling $\varepsilon^2 \sim 10^{-6}$-$10^{-5}$ for masses 25-100 MeV

How to search for dark photons

Note: much lighter and much heavier dark photon models exist. Search methods are different. Your mileage may vary.

If you have a dark photon, it could decay into particle-antiparticle pairs (via mixing with the photon)

Find a situation where you know the decay energy spectrum well—and look for a bump (surprise surprise...)

At PHENIX, that's $\pi^0 \rightarrow \gamma U \rightarrow \gamma e^+ e^-$ (or the same with η)

PHENIX detector

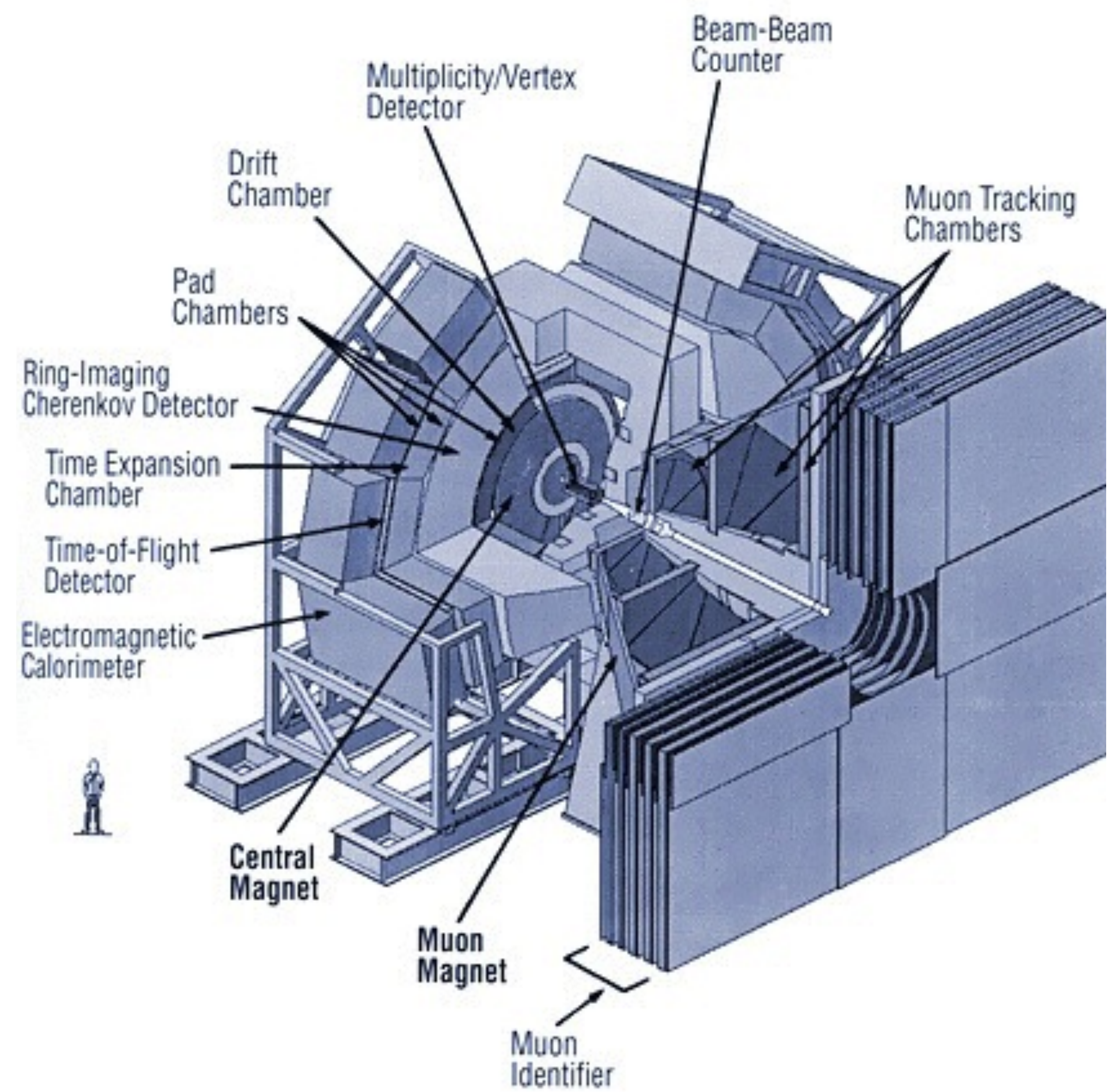
At RHIC (Brookhaven)

$\sqrt{s_{NN}} = 200$ GeV, *p*-*p* and *d*-Au collisions (3 data sets)

Inner tracker to identify $e^{\pm}$ candidates

Cherenkov detector + EM-cal gives an energy-momentum criterion to accept $e^{\pm}$ tracks

γ just show up in EM-cal



Source: https://www.flickr.com/photos/brookhavenlab/3707885404

Predicted mass spectra

Spectrum of invariant e^+e^- mass m_{ee} for Dalitz decay (π, η to γe^+e^-) calculable using Kroll-Wada formula

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

where

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

Spectrum from Dark photon decay given by finite detector resolution (narrow width spectrum)

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

Detector effects

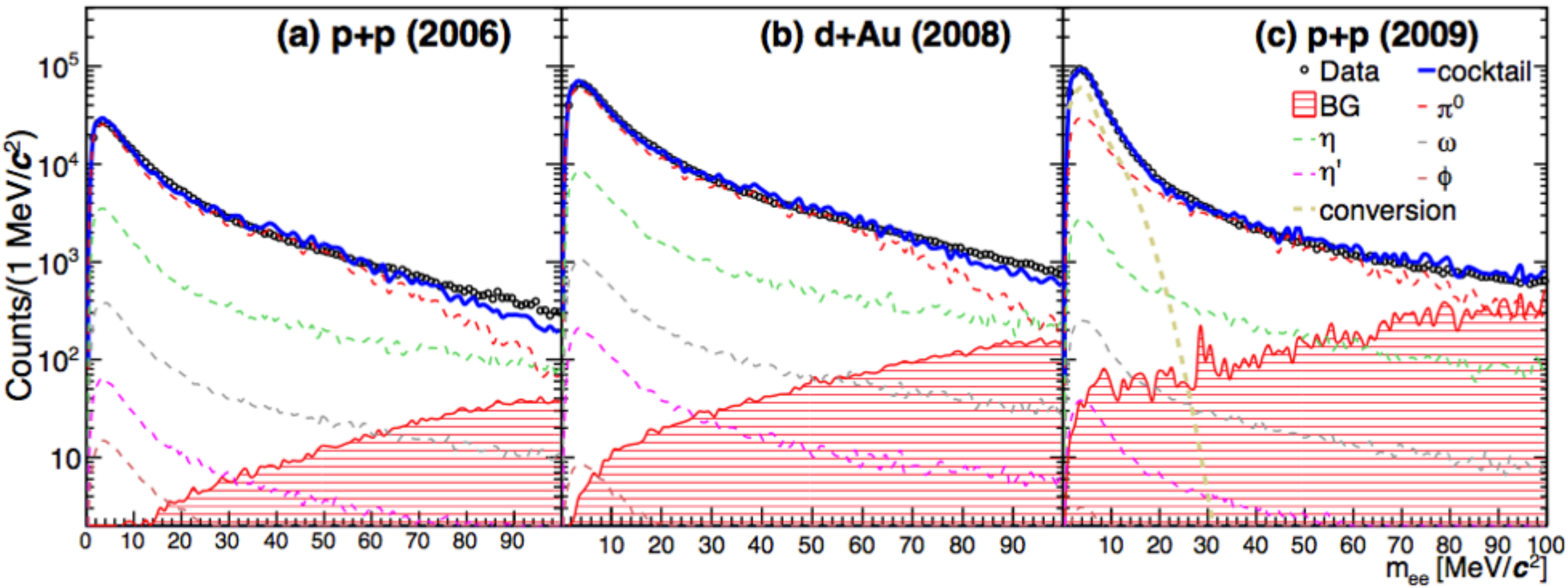
m_{ee} resolution found using Monte Carlo: 3.1 $\pm$ 0.09 MeV (expected width of dark photon peak)

e^+e^- pairs from in-detector conversion are rejected by kinematic cuts and by angle w.r.t. external magnetic field

This and others inform the correction to the predicted spectra:

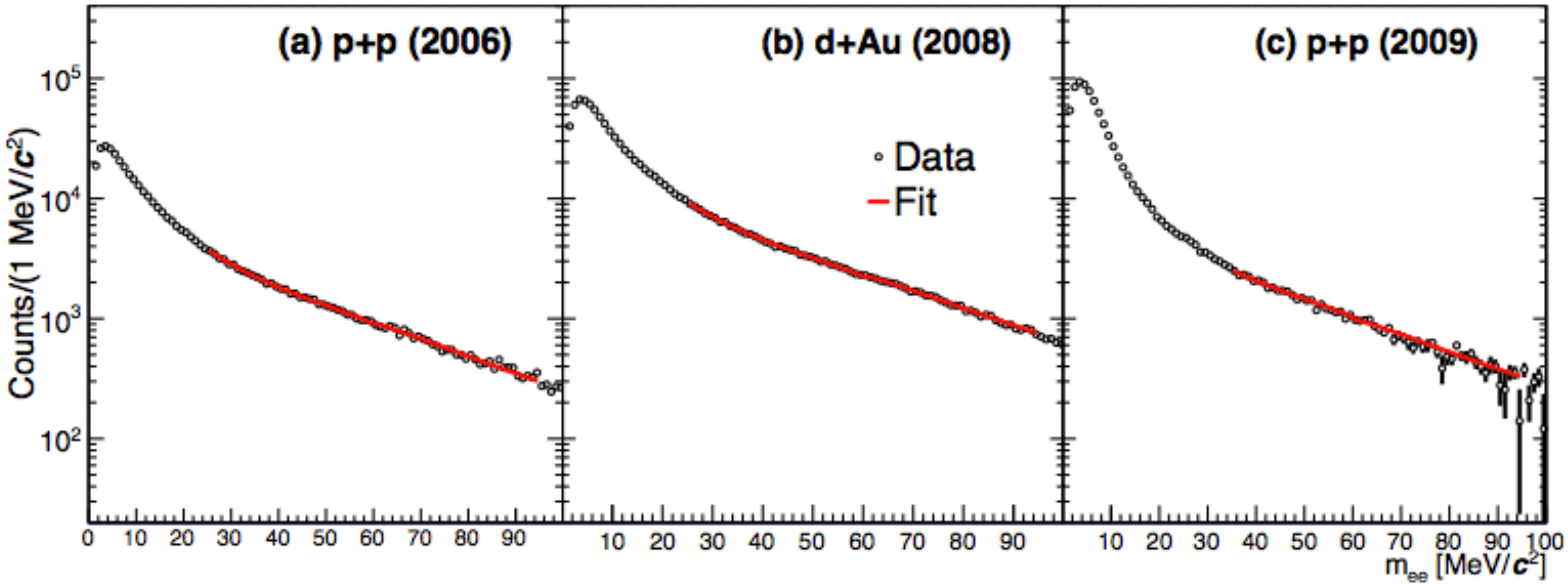
$$f(m_{ee}) = \frac{1}{m_{ee}} \times \left[\left(1 - \frac{m_{ee}^2}{m_{\pi^0}^2}\right)^3 + r_{\eta/\pi^0} \times \left(1 - \frac{m_{ee}^2}{m_\eta^2}\right)^3 \right] \times T_4(m_{ee})$$

More detector effects

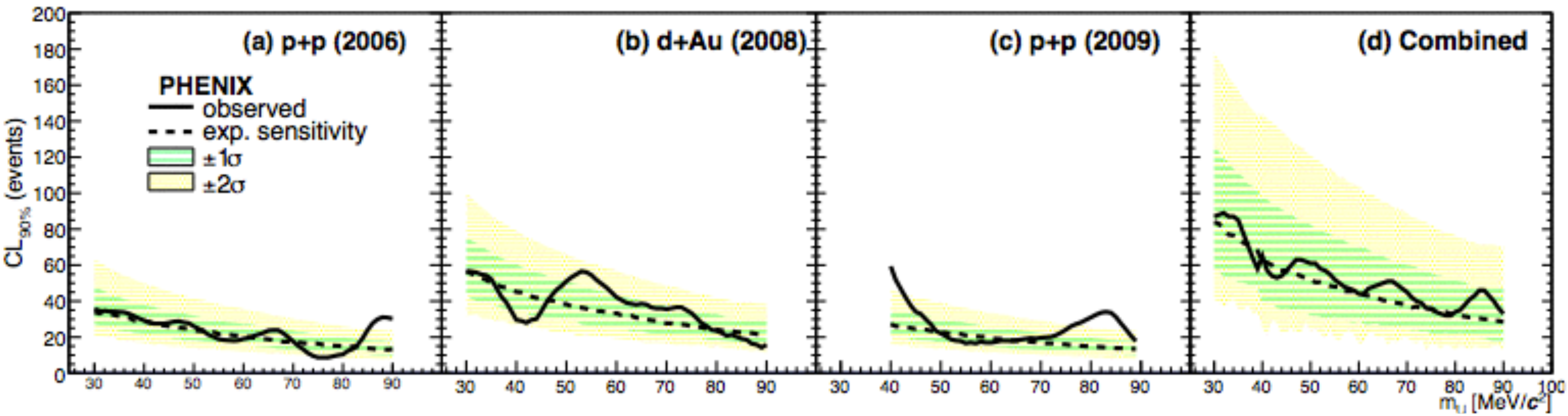


New Hadron-Blind Detector increased $\gamma \rightarrow e^+e^-$ conversion rates in 2009 $\Longrightarrow$ increased background

Fit results



(a) p+p (2006)
(b) d+Au (2008)
(c) p+p (2009)
Data
Fit
Counts/(1 MeV/c²)
m_ee [MeV/c²]



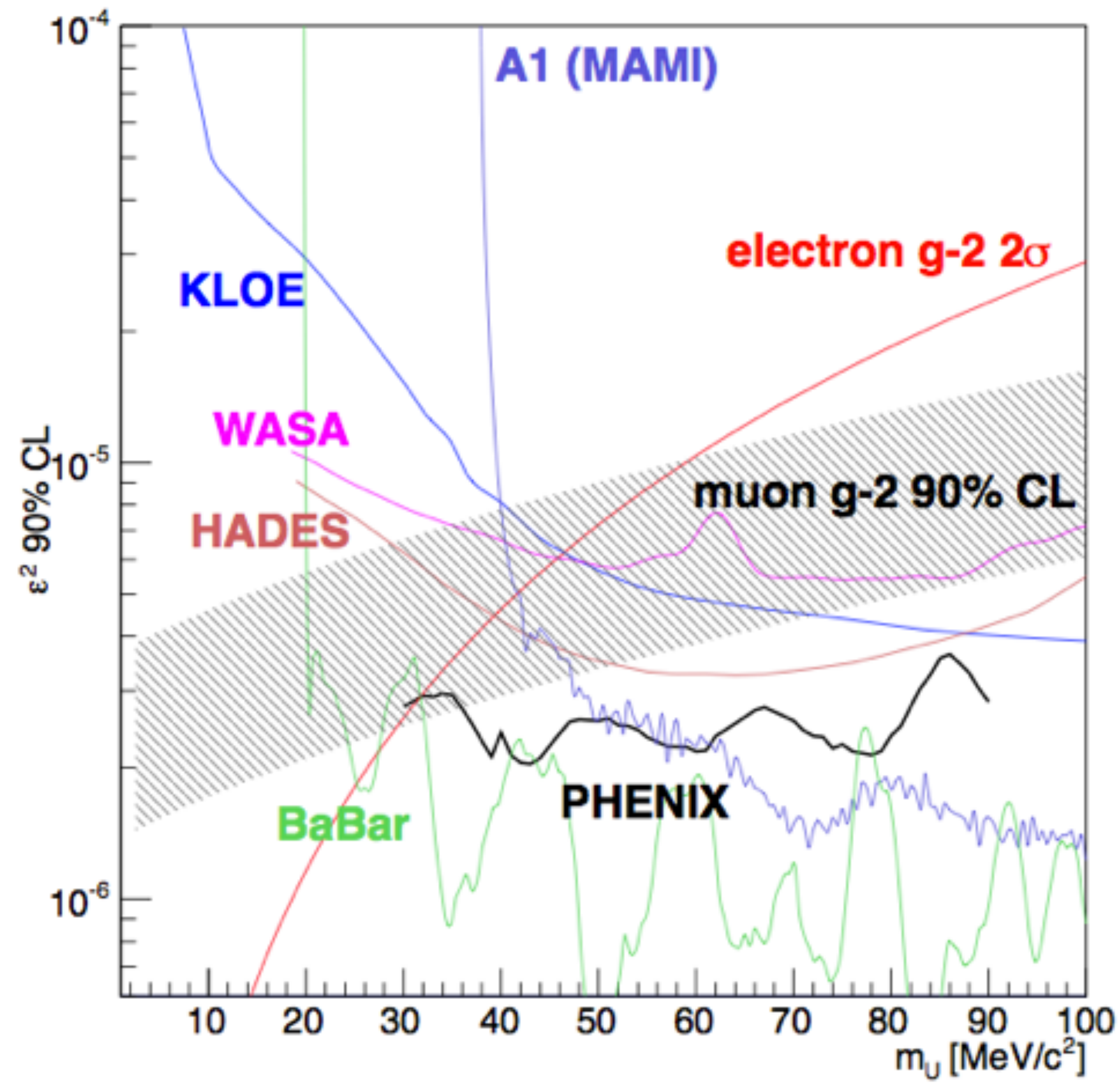
(a) p+p (2006)
(b) d+Au (2008)
(c) p+p (2009)
(d) Combined
PHENIX
observed
exp. sensitivity
±1σ
±2σ
CL90% (events)
m_U [MeV/c²]

Update to exclusion plot

Rules out most of the <100MeV dark photon parameter space.

Small bit left between 29 and 32 MeV

Note: BaBar excludes all the way out to 10 GeV



Conclusions

Dark photons are hypothesized to help solve the muon $g-2$ anomaly

PHENIX (and others) looked for mass peaks in e^+e^- invariant mass from three-body decays of π and η

No peaks were found, excluding dark photons from resolving the $g-2$ anomaly at 90% CL on almost all of the parameter space examined

References

[1] A. Adare *et al.* (PHENIX Collaboration), Phys. Rev. C **91**, 031901(R) (2015)

[2] C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C **40**, 100001 (2016)

[3] A. Czarnecki and W. Marciano, Phys. Rev. D **64**, 013014 (2001)