Muon Anomaly & Dark Bosons

Based on work by:

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Dark Bosons

- **$U(1)_d$ gauge symmetry from the Dark Sector**
  *Dark Photon, U Boson, Secluded … **Dark Z** (Z_d)*

Astrophysics Motivation

Sommerfeld Enhancement (Dark Matter Annihilation)

Positron Excesses: $Z_d \rightarrow e^+e^-$, $\mu^+\mu^-$

Etc.

Interaction with our world:

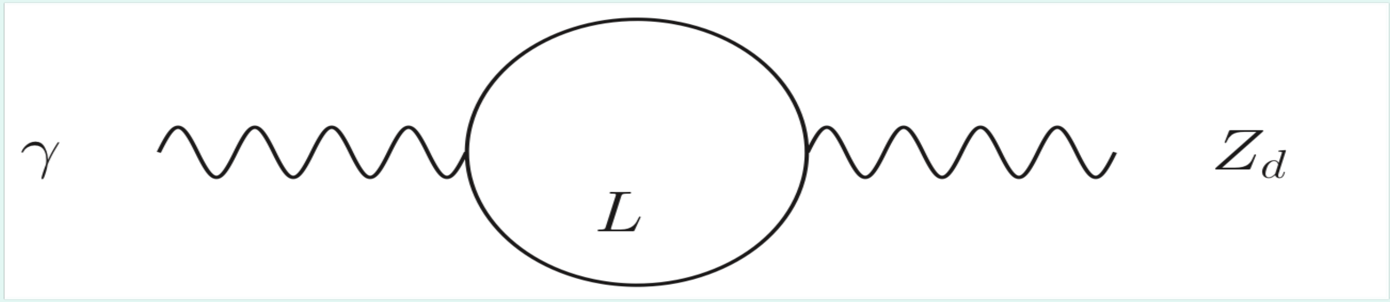
1) Kinetic Mixing $U(1)_Y x U(1)_d$ $\varepsilon e Z_d^{\mu} J_{\mu}^{em}$ $\varepsilon \approx \alpha/\pi \approx \underline{2x10^{-3}}$

2) Z-Z_d Mass Mixing $\varepsilon_Z g/2\cos\theta_W Z_d^{\mu} J_{\mu}^{NC}$

$\varepsilon_Z = m_{Zd}/m_Z \delta = O(m_{Zd}/m_Z)^2 \approx \underline{10^{-6}}$

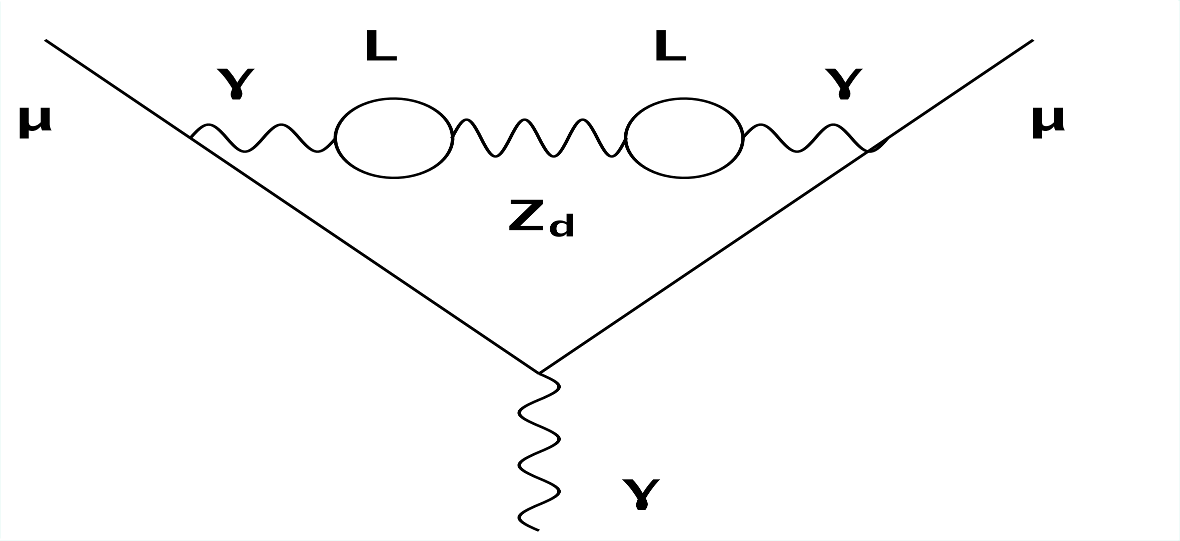
Example

One Loop gamma-Z_d Kinetic Mixing (Through Heavy Charged Leptons) That also carry $U(1)_d$ charge



Effective 3 loop g_μ-2 Diagram

$a_\mu^{Zd} = \alpha/2\pi\varepsilon^2 F(m_{Zd}/m_\mu)$, $F(0)=1$ solves g_μ-2 discrepancy for $\varepsilon^2 \approx 3\text{-}5\times10^{-6}$ & $m_{Zd} \approx 20\text{-}50$MeV (see figure)



Anomalous Magnetic Moments

$a_l=(g_l-2)/2 \quad l=e,\mu$

$a_e(\text{exp})=0.00115965218073(28)$ unc. 2.8×10^{-13}!

(Hanneke, Fogwell, Gabrielse: PRL 2008)

$a_e(\text{SM})=\alpha/2\pi-0.328478965579193\ldots(\alpha/\pi)^2$

$+1.181241456\ldots(\alpha/\pi)^3 -1.9097(20)(\alpha/\pi)^4$

$+9.16(58)(\alpha/\pi)^5\ldots +1.68\times10^{-12}(\text{had}) +0.03\times10^{-12}(\text{EW})$

Aoyama, Hayakawa, Kinoshita, & Nio 2012 Update

$\alpha^{-1}(^{87}\text{Rb})=137.035999037(91)$

Bouchendira et al. PRL. (2011)

$a_e(\text{exp}) - a_e(\text{theory}) = -1.06\ (0.82) \times 10^{-12}$

Overall Factor 10 Sensitivity Improvement!

Further Improvement? Factor of 2? More?

Muon Anomalous Magnetic Moment

Experimental E821 at BNL (2004 Final)

$a_\mu^{exp} \equiv (g_\mu\text{-}2)/2 = 116592089(54)_{stat}(33)_{sys}x10^{-11}$

$= 116592089(63)x10^{-11}$

Storage Ring being shipped to Fermilab

(Future Factor 4 Improvement Expected)

Standard Model Prediction

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Hadronic}$$

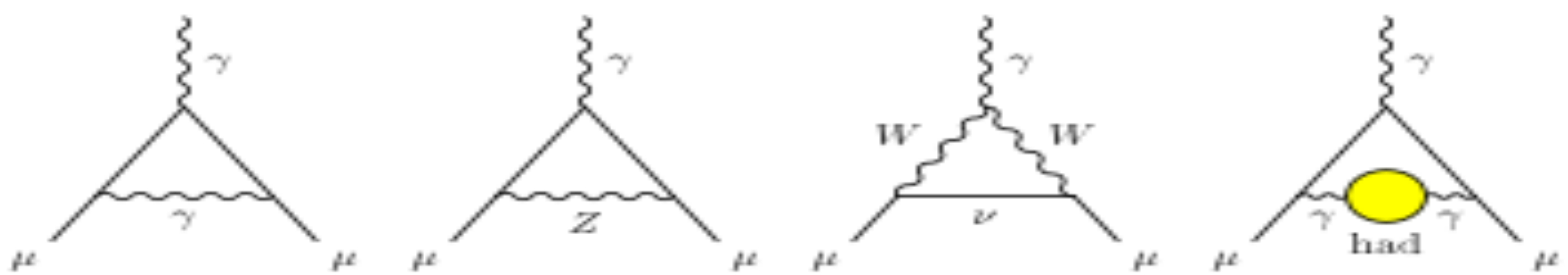


Figure 1: Representative diagrams contributing to a_μ^{SM}. From left to right: first order QED (Schwinger term), lowest-order weak, lowest-

QED Contributions:

- $a_\mu^{QED}=0.5(\alpha/\pi)+0.765857410(27)(\alpha/\pi)^2+$
  $24.05050964(43)(\alpha/\pi)^3+$
  $130.8794(63)(\alpha/\pi)^4+$
  $753.29(1.04)(\alpha/\pi)^5$ $+\ldots$ (5 loop Completed!)

2012 Update: Aoyama, Hayakawa, Kinoshita, & Nio

$\alpha^{-1}(^{87}Rb)=137.035999037(91)$

$a_\mu^{QED}=116584718.864(36)\times10^{-11}$ Very Precise!

Electroweak Loop Effects

a_μ^{EW}(1 loop)=194.8x10^{-11} original goal of E821

a_μ^{EW}(2 loop)=-40.3(1.0)x10^{-11} (Higgs Mass = 126GeV))

3 loop EW leading logs very small O(10^{-12})

- ***a_μ^{EW}=154(1)x10^{-11} Non Controversial***

- **Hadronic Contributions (HVP & HLBL)**

a_μ^{Had}(V.P.)^{LO}=6923(40)(7)x10^{-11} (Hoecker update 2010)

a_μ^{Had}(V.P.)^{NLO} = -98(1)x10^{-11}

a_μ^{Had}(LBL) = 105(26)x10^{-11} (Consensus?)

a_μ^{SM}=116591803(49)x10^{-11} (Future Improvement?)

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$=286(63)(49)x$10^{-11}$ (*3.6σ deviation!*)

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$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(80) \times 10^{-11}$ (*3.6σ!*)

This is a very large deviation!

$\Delta a_e = a_e^{exp} - a_e^{SM} = -106\ (82) \times 10^{-14}$ *(Note Sign)*

(A thousand times better measured than Δa_μ!)

But the muon is $(m_\mu/m_e)^2 \cong 40{,}000$ times more sensitive to New SD Physics

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Interpretations

Generic 1 loop SUSY Contribution:

$a_\mu^{SUSY} = (\text{sgn}\mu) 130 \times 10^{-11} (100\text{GeV}/m_{susy})^2 \tan\beta$

$\tan\beta \approx 3\text{-}40$, $m_{susy} \approx 100\text{-}500\text{GeV}$ *Some LHC Tension*

Other Explanations: ***Hadronic e^+e^- Data? HLBL (3loop)?***

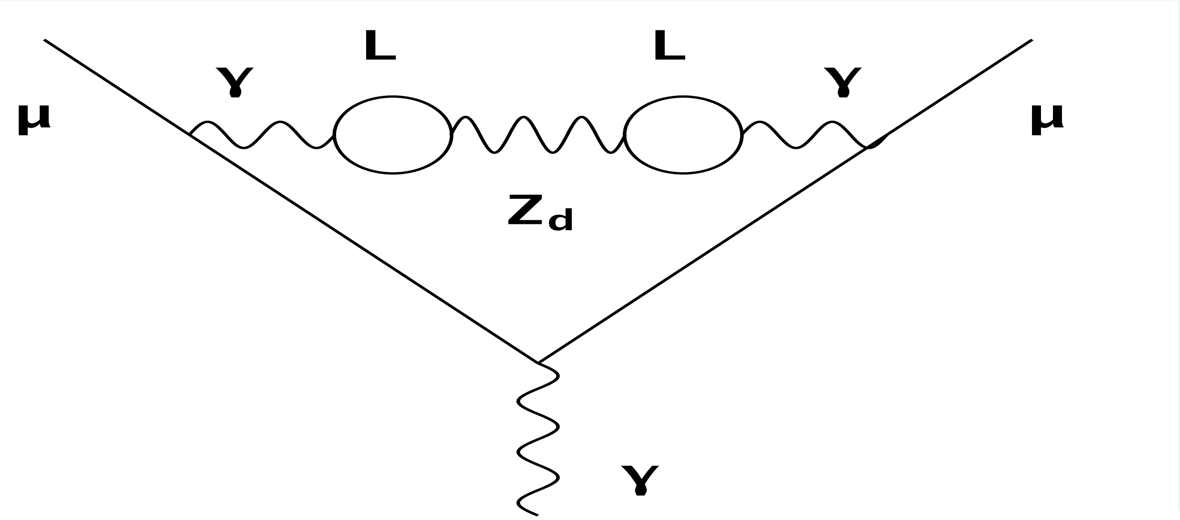
Multi-Higgs Models *(2 loop effects)*

Extra Dimensions<2TeV, Heavy Z', Dynamics…

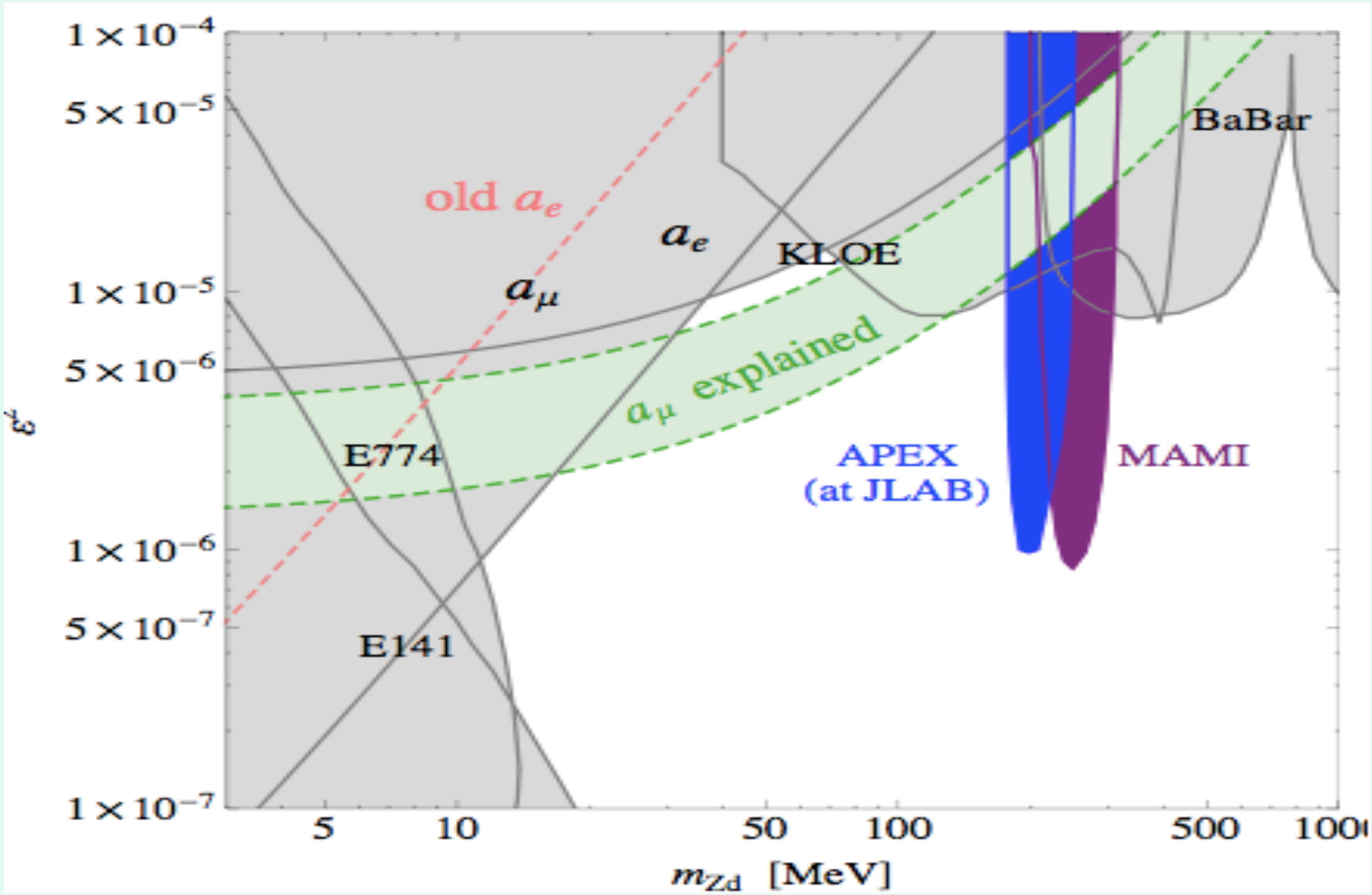
Light Higgs Like Scalar <10MeV?

* ***Dark Photons (Fayet, Pospelov…)***

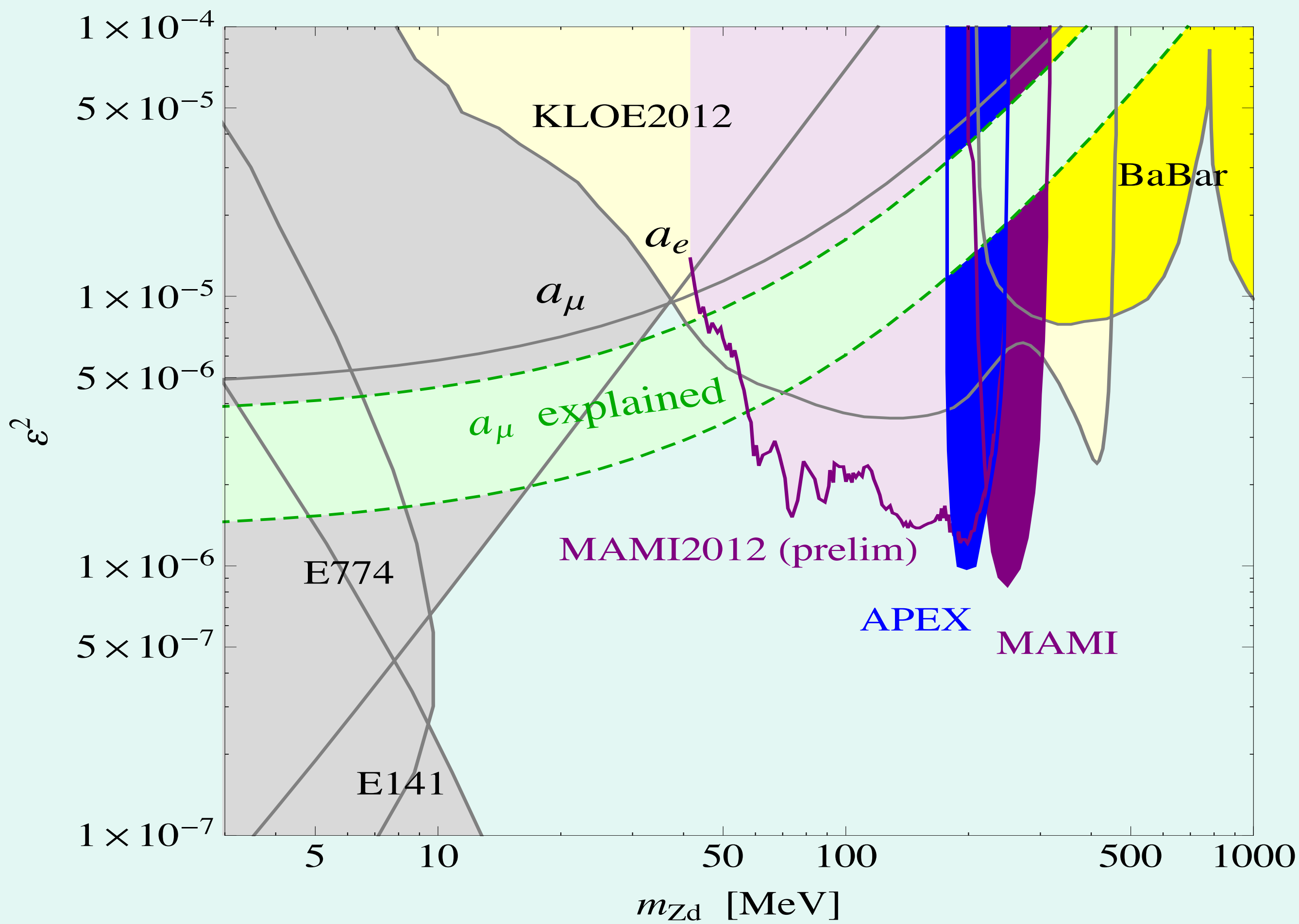
$a_\mu^{Zd}=\alpha/2\pi\varepsilon^2 F(m_{Zd}/m_\mu)$, $F(0)=1$ **solves g_μ-2 discrepancy for $\varepsilon^2\approx 3\text{-}5\times10^{-6}$ & $m_{Zd}\approx$20-50MeV (see figure)**



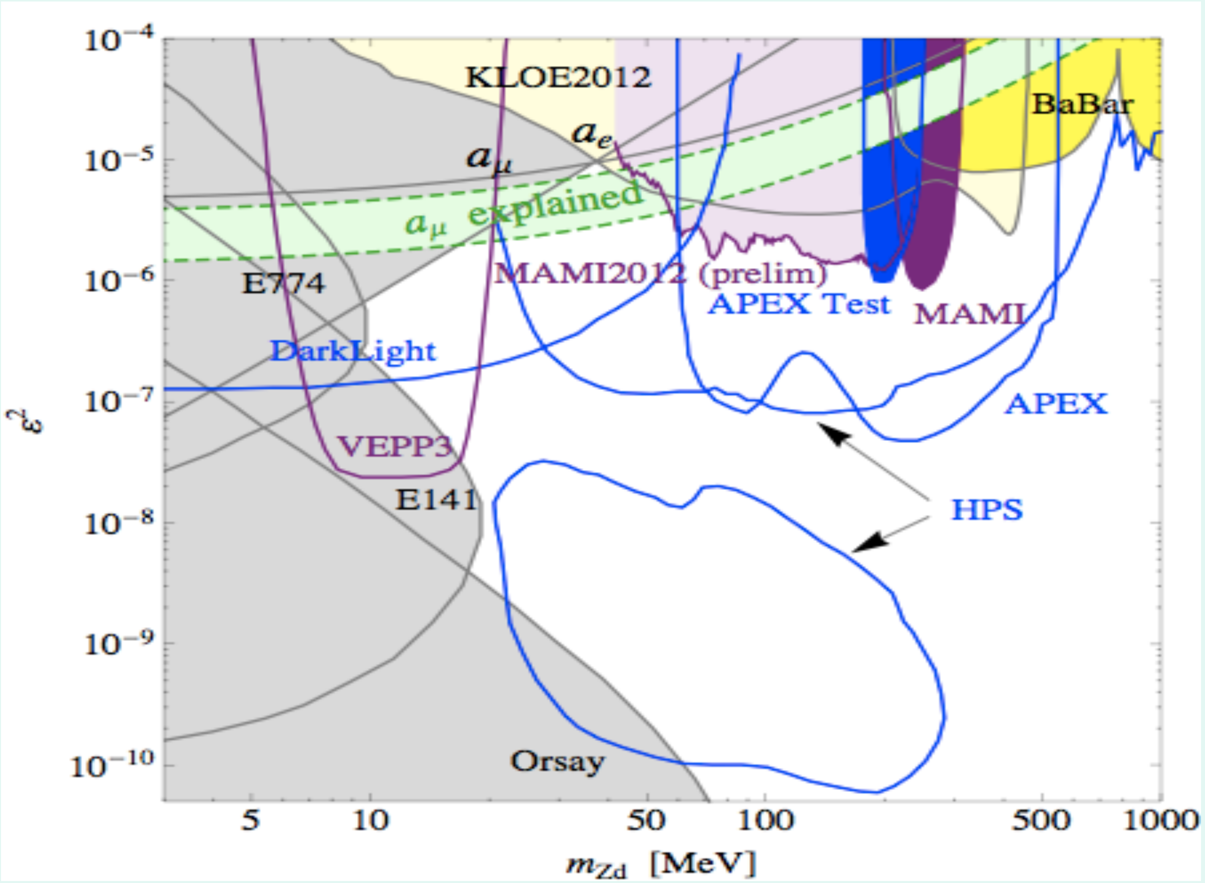
Old a_e vs New a_e (3 sigma bound)
(Davoudiasl, Lee & WJM)



Recent Updates➔20MeV-50MeV Left



Current Bounds & Future Dark Photon Sensitivity
Some Assume Br($Z_d \rightarrow e^+e^-$)=1



The Dark Photon g-2 Solution

20MeV$<m_{Zd}<$50MeV, *1.5x10$^{-3}<\varepsilon<$2.5x10^{-3}*

$SU(3)_C x SU(2)_L x U(1)_Y x U(1)_d$ kinetic Mixing

$L_{U(1)YxU(1)d} = -\frac{1}{4}(B_{\mu\nu}B^{\mu\nu} - 2\varepsilon/\cos\theta_W B_{\mu\nu}Z_d^{\mu\nu} + Z_{d\mu\nu}Z_d^{\mu\nu})$

$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad Z_{d\mu\nu} = \partial_\mu Z_{d\nu} - \partial_\nu Z_{d\mu}$

ε= potentially infinite counterterm or finite (calculable) loop effect

Remove ε by field redefinitions

$B_\mu \Rightarrow B_\mu + \varepsilon/\cos\theta_W Z_{d\mu}$ or in terms of γ & Z

$A_\mu \Rightarrow A_\mu + \varepsilon Z_{d\mu} \quad Z_\mu \Rightarrow Z_\mu + \varepsilon\tan\theta_W Z_{d\mu}$

$L_{int} = -e\varepsilon(J_\mu^{em} - 1/2\cos^2\theta_W J_\mu^{NC})\, Z_d^\mu$

Second term cancelled by Z-Z_d mass matrix diagonalization!

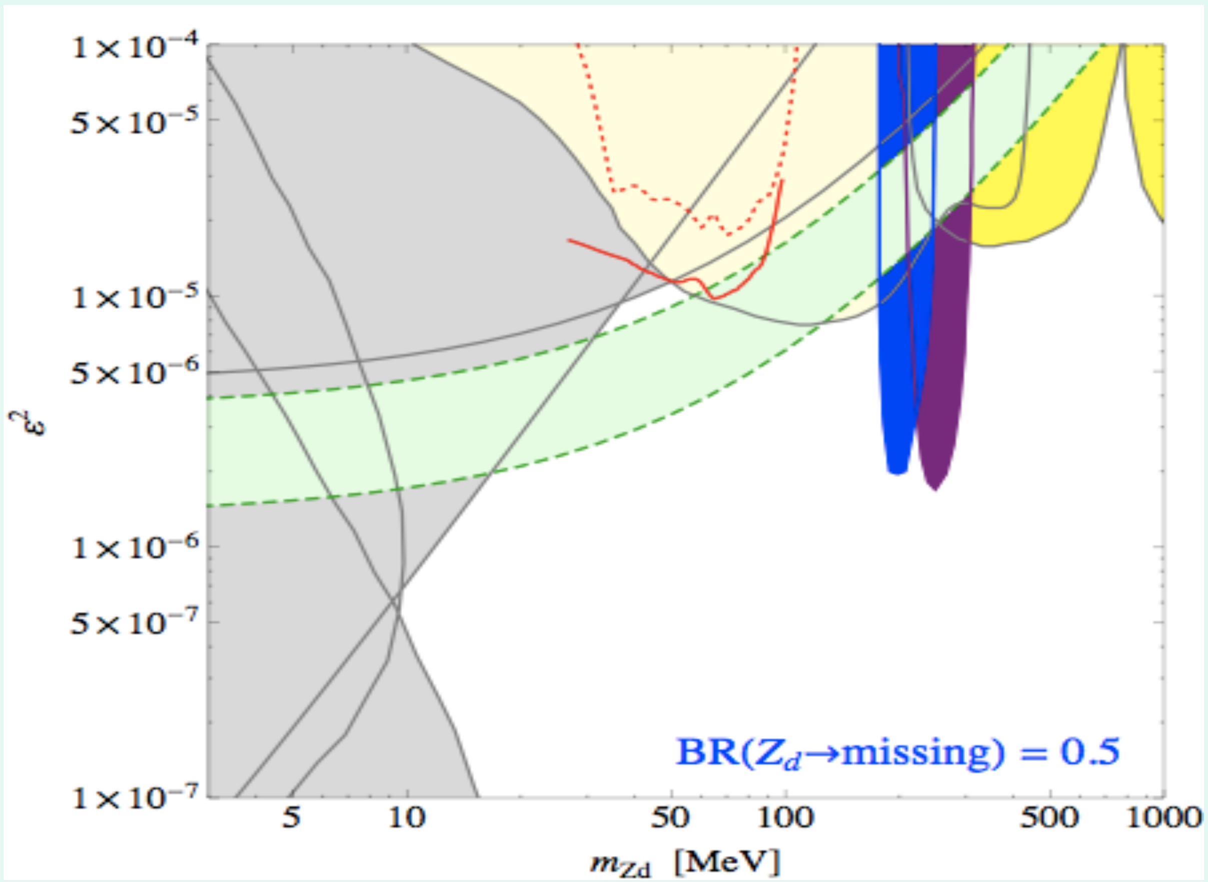
What if $Br(Z_d \rightarrow e^+e^-) < 1$?
, $Br(Z_d \rightarrow e^+e^-) + Br(Z_d \rightarrow \text{missing energy}) = 1$
For $m_{Zd} < 200\text{MeV}$

- **Pospelov**: Kinetic Mixing and $K^+ \rightarrow \pi^+ Z_d$

$BR(K^+ \rightarrow \pi^+ Z_d) = 8\times10^{-5}\varepsilon^2(m_{Zd}/100\text{MeV})^2$

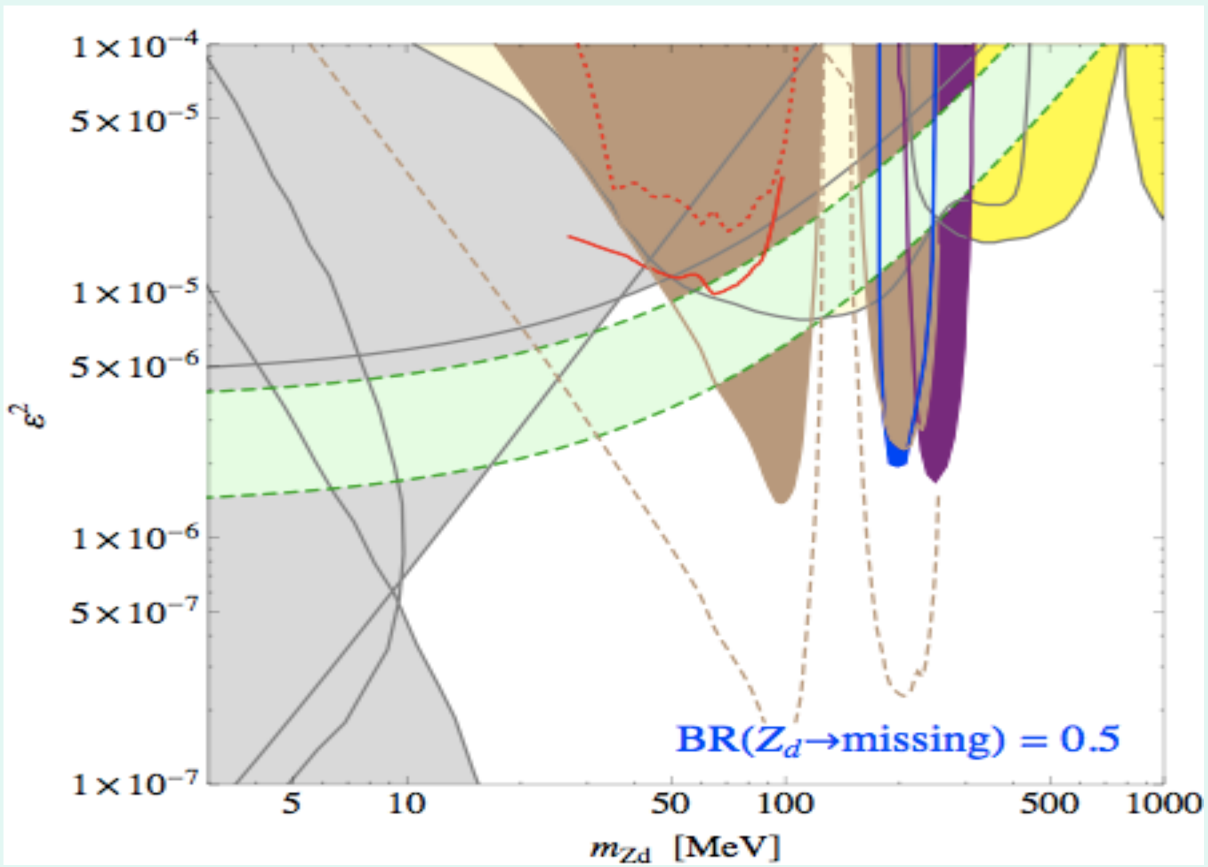
E787/949 at BNL sensitive to $BR(K^+ \rightarrow \pi^+ + \text{missing energy})$
down to 5×10^{-11} at $m_{Zd} = 100\text{MeV} \rightarrow \varepsilon < 8\times10^{-4}$!
For $BR(Z_d \rightarrow \text{missing energy}) = 1$

Combined with $Z_d \rightarrow e^+e^-$ constraints, leaves mainly
$20\text{MeV} < m_{Zd} < 50\text{MeV}$



1×10^{-4}
5×10^{-5}
1×10^{-5}
5×10^{-6}
1×10^{-6}
5×10^{-7}
1×10^{-7}
ε^2
5
10
50
100
500
1000
m_{Zd} [MeV]
BR($Z_d \to$missing) = 0.5

Combined $Z_d \rightarrow e^+e^-$ or missing energy
dashed lines correspond to E787/949 x 10



<u>*Summary*</u>

$\Delta a_e = a_e^{exp} - a_e^{SM} = -106(82) \times 10^{-14}$ (Recent Update)

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(80) \times 10^{-11}$ (*3.6σ discrepancy!*)

First Dark Photon Hint?: 20MeV<m_{Zd}<50MeV, *$\varepsilon \approx 2 \times 10^{-3}$*

Rare K ➔π+Z_d Z_d➔missing energy

ε^2xBR(Zd➔missing energy)~ 10^{-6} sensitivity

***Solidifies** **20MeV<m_{Zd}<50MeV**, $\varepsilon \approx 2 \times 10^{-3}$ constraint*

But Revolutionary Discovery Potential Remains!