Dark Z Implications for Parity Violation, Rare Meson Decays, and Higgs Physics

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Based on:

H. D., H.-S. Lee, and W. J. Marciano

- arXiv:1203.2947 [hep-ph]
- Work in progress

Pheno 2012, University of Pittsburgh

Light vector particles:

- Dark Matter interactions in the *hidden* sector

- Late annihilation rate of DM

Fayet, 2004; Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

- GeV-scale Asymmetric DM abundance

H.D., Morrissey, Sigurdson, Tulin, 2010

- $(g-2)_\mu$ anomaly   Fayet, 2007; Pospelov, 2008

- Often coupled via kinetic mixing: $\frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}X^{\mu\nu}$ Holdom, 1986

- "Dark photon" coupled through $\varepsilon\, e X^\mu J_\mu^{em}$

- **This talk: "Dark" Z** H.D., Lee, Marciano, arXiv:1203.2947 [hep-ph]

- Light vector $\boldsymbol{Z_d}$, mass-mixing with SM Z:

$$M_0^2 = m_Z^2 \begin{pmatrix} 1 & -\varepsilon_Z \\ -\varepsilon_Z & m_{Z_d}^2/m_Z^2 \end{pmatrix}$$

with $\boxed{\boldsymbol{\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta}}$ $(\delta \ll 1)$; Z-Z_d mixing angle $\boxed{\boldsymbol{\xi \simeq \varepsilon_Z}}$ $(\varepsilon \simeq 0)$.

- **Three Aspects of Dark Z phenomenology**

(I) Parity violation: atomic, ee and ep scattering.

(II) Flavor: emission of Z_d in rare K and B decays.

(III) Higgs at the LHC, in particular $H \to ZZ_d$.

- **We consider $10\ \mathrm{MeV} \lesssim m_{Z_d} \lesssim 10\ \mathrm{GeV}$.**

Parity Violation

- Dark Z fermion couplings: $\boldsymbol{\mathcal{L}}_{\text{int}} = \left[-e\varepsilon J_\mu^{em} - \frac{1}{2}(g/\cos\theta_W)\,\varepsilon_Z J_\mu^{NC}\right] Z_d^\mu$
- Parity violating amplitudes $\mathcal{M}_{NC}^{\text{PV}} = (G_F/2\sqrt{2})F(\sin^2\theta_W)$.
- $G_F \to \rho_d G_F$ and $\sin^2\theta_W \to \kappa_d \sin^2\theta_W$

$$\rho_d = 1 + \delta^2 \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2} \text{ and } \kappa_d = 1 - \frac{\varepsilon}{\varepsilon_Z}\delta^2 \frac{\cos\theta_W}{\sin\theta_W}\frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}$$

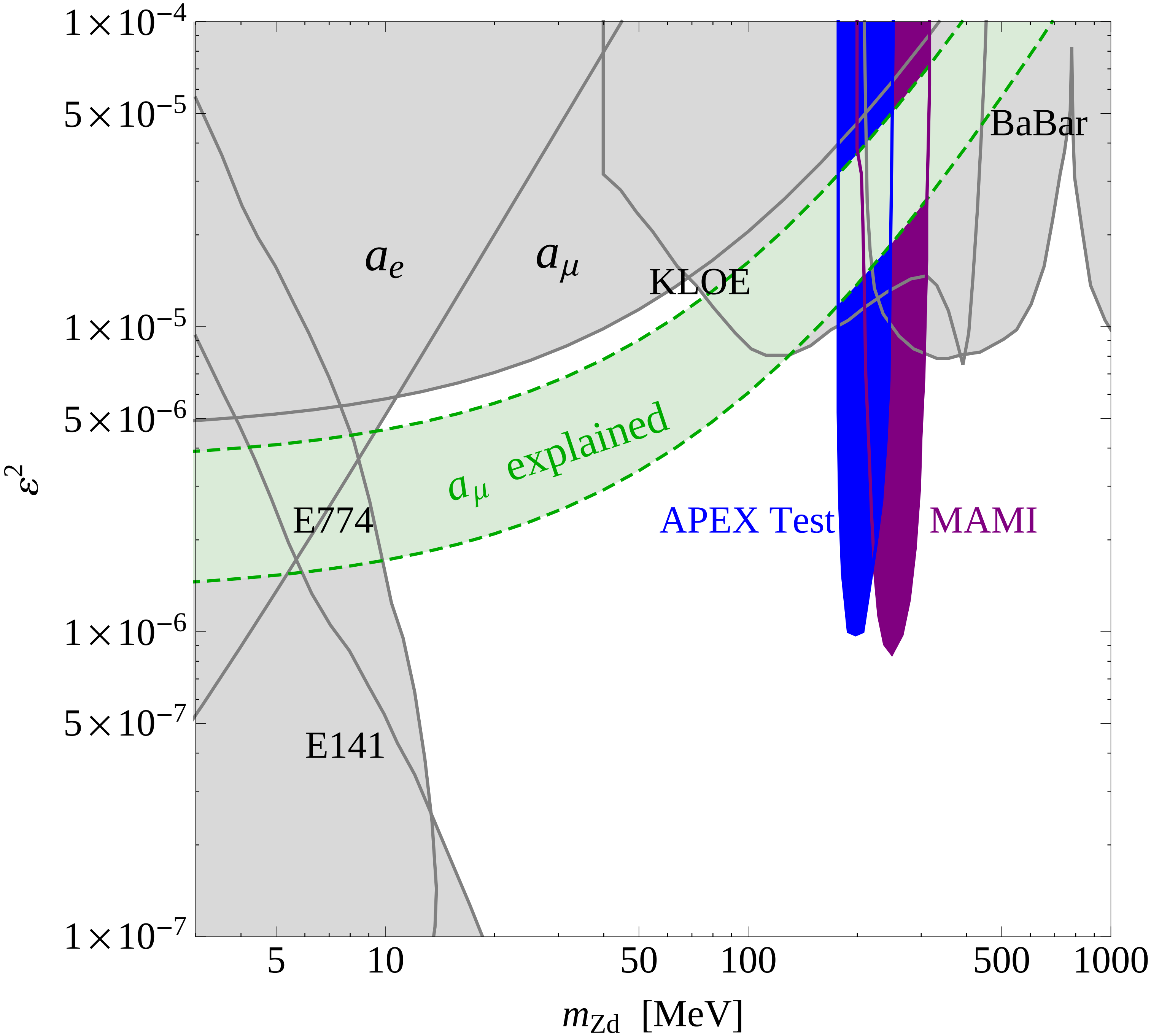
- Atomic parity violation (APV)

- $Q_W = -N + Z(1 - 4\sin^2\theta_W)$.
- $Q_W^{\text{SM}}({}^{133}_{55}\text{Cs}) = -73.16(5)$ and $Q_W^{\text{exp}}({}^{133}_{55}\text{Cs}) = -73.16(35)$.
- $Q_W^{\text{SM}} \to -73.16(1+\delta^2) + 220(\varepsilon/\varepsilon_Z)\delta^2\cos\theta_W\sin\theta_W$.

$$\Rightarrow \left|\delta^2\left(1 - 1.27\frac{\varepsilon}{\varepsilon_Z}\right)\right| \lesssim 0.006 \quad ; \quad \delta^2 \lesssim 0.006, \text{ for } \varepsilon \ll \varepsilon_Z$$

- Polarized electron scattering experiments: SLAC, JLAB, Mainz,. . . .

- Mainly sensitive to κ_d.



1×10^−4
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ε^2
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10
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100
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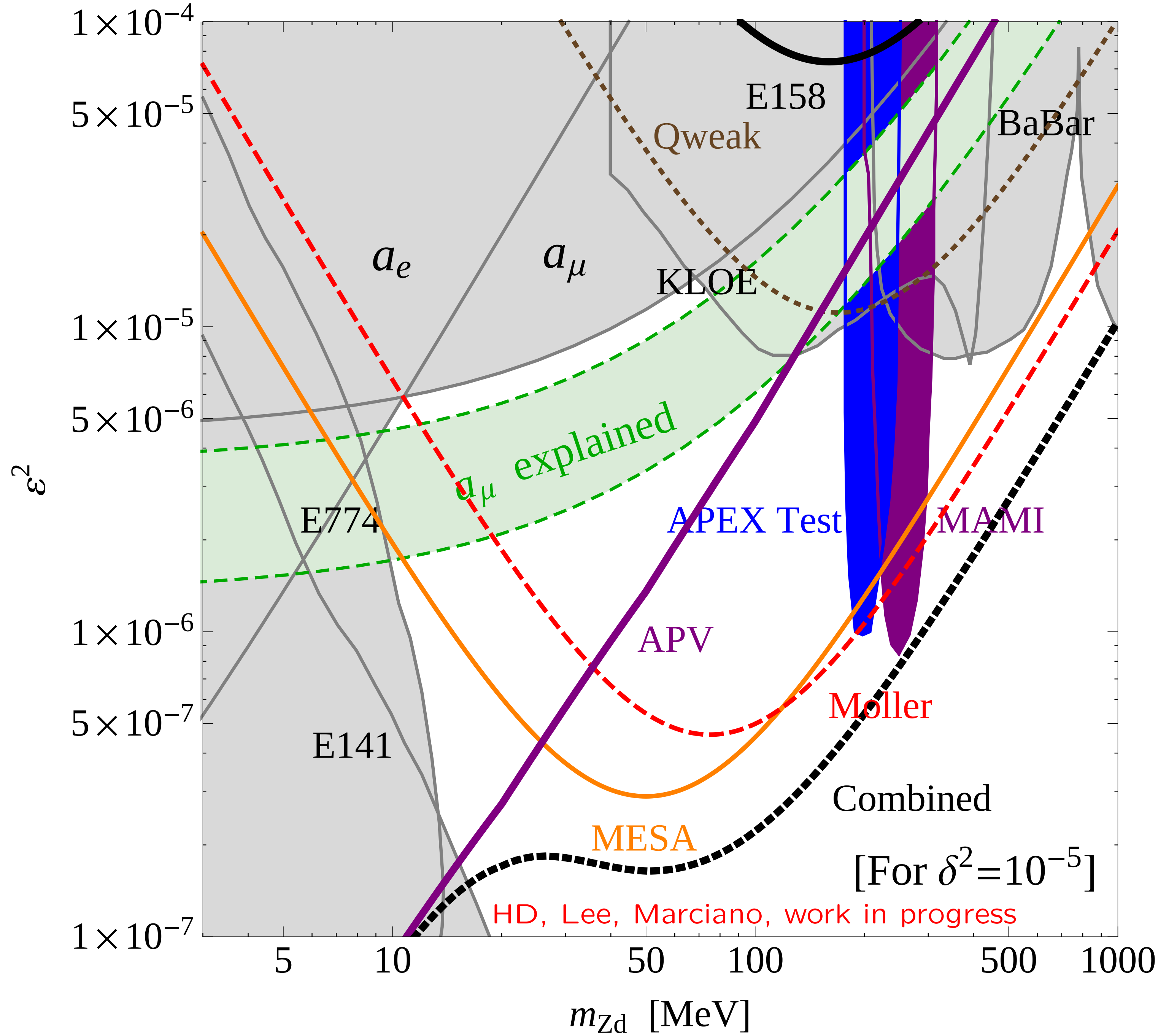
m_Zd [MeV]
a_e
a_μ
KLOE
BaBar
a_μ explained
E774
E141
APEX Test
MAMI



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a_μ
KLOE
a_μ explained
E774
APEX Test
MAMI
APV
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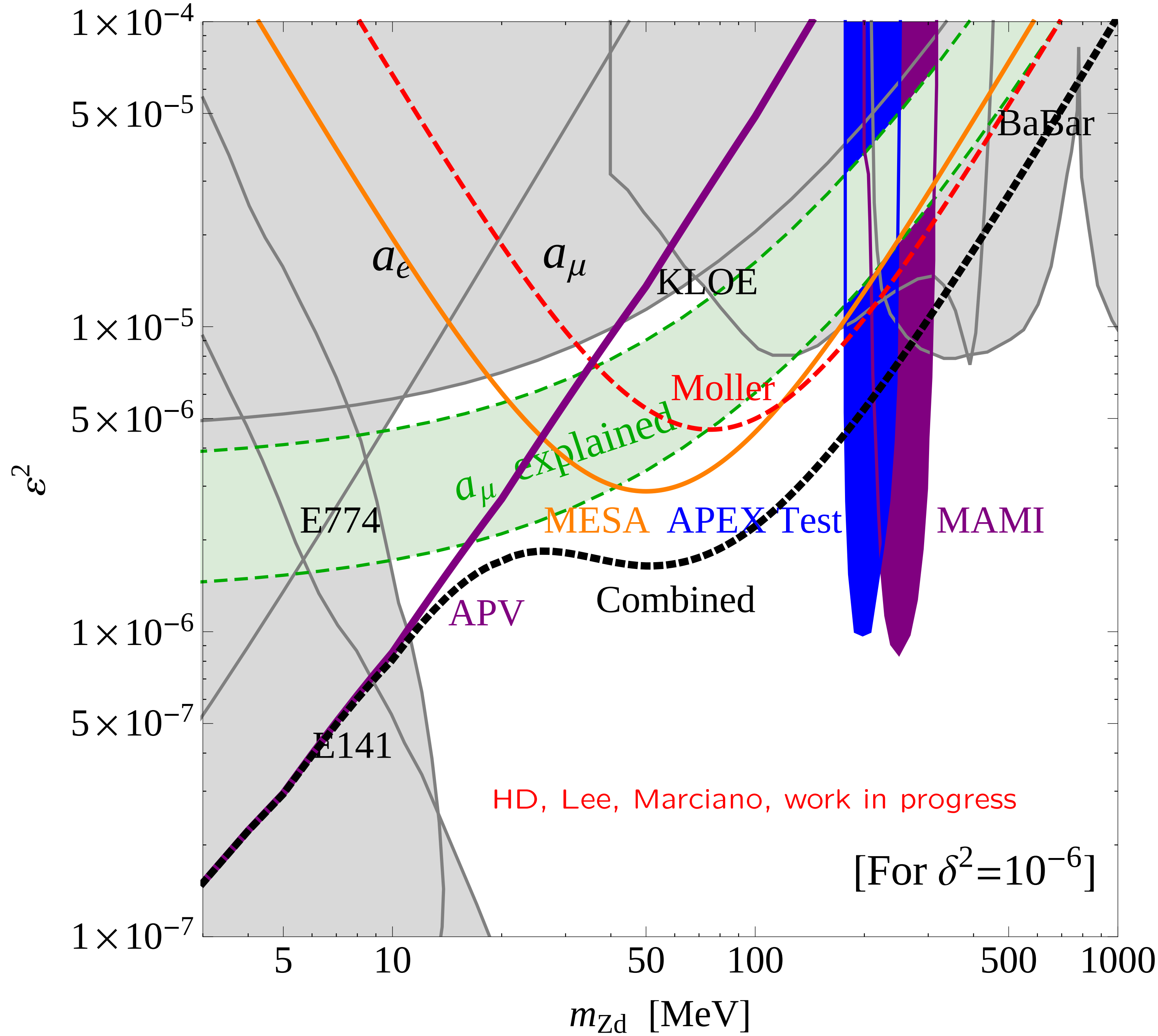
Combined
MESA
[For $\delta^2=10^{-5}$]
HD, Lee, Marciano, work in progress



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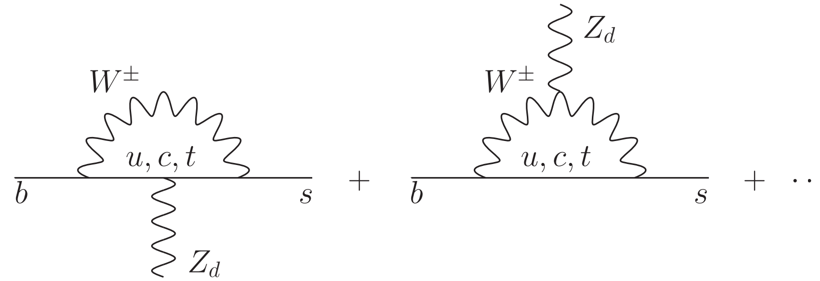
m_Zd [MeV]
a_e
a_μ
KLOE
BaBar
Moller
a_μ explained
E774
MESA
APEX Test
MAMI
APV
Combined
E141
HD, Lee, Marciano, work in progress
[For δ^2=10^−6]

Rare K and B Decays



- $m_{Z_d} \ll m_{K,B}$: longitudinal Z_d enhanced.

- Goldstone equivalence theorem (GET):

$$\text{axion} \leftrightarrow \text{longitudinal } Z_d$$

- Use $\bar{d}_L \gamma_\mu s_L \partial^\mu a$, $\bar{s}_L \gamma_\mu b_L \partial^\mu a$ to estimate $K \to \pi Z_d|_L$, $B \to K Z_d|_L$.

Hall and Wise, 1981; Frere, Vermaseren, and Gavela, 1981; Freytsis, Ligeti, Thaler, 2009

- Unlike axions, BR($Z_d \to e^+ e^-$) $\simeq$ BR($Z_d \to \mu^+ \mu^-$).

- Ignore kinetic mixing, due to suppressed effect:

BR($B \to K Z_d$) $\sim 6 \times 10^{-7} \varepsilon^2$ for $m_{Z_d} \simeq 1$ GeV. Batell, Pospelov, and Ritz, 2009

- Adapting 2HD axion results for estimates: Hall and Wise, 1981
- $\text{BR}(K^+ \to \pi^+ Z_d)_{\text{long}} \simeq 4 \times 10^{-4} \delta^2$
- $\text{BR}(B \to K Z_d)_{\text{long}} \simeq 0.1 \delta^2$

- $m_{Z_d} \ll m_K$:

$$\text{BR}(K^+ \to \pi^+ e^+ e^-)_{\text{exp}} = 3.00 \pm 0.09 \times 10^{-7}$$
$$\text{BR}(K^+ \to \pi^+ \mu^+ \mu^-)_{\text{exp}} = 9.4 \pm 0.6 \times 10^{-8}$$
$$\text{BR}(K^+ \to \pi^+ \nu \bar{\nu})_{\text{exp}} = 1.7 \pm 1.1 \times 10^{-10}$$

$$\boldsymbol{\delta \lesssim 0.01/\sqrt{\text{BR}(Z_d \to e^+ e^-)} \quad ; \quad \delta \lesssim 0.001/\sqrt{\text{BR}(Z_d \to \text{missing energy})}}$$

- $m_{Z_d} \ll m_B$:

$$\text{BR}(B \to K Z_d \to K \ell^+ \ell^-) < 10^{-7}$$
$$\text{BR}(B^+ \to K^+ \bar{\nu} \nu)_{\text{exp}} < 1.4 \times 10^{-5}$$

$$\boldsymbol{\delta \lesssim 0.001/\sqrt{\text{BR}(Z_d \to \ell^+ \ell^-)} \quad ; \quad \delta \lesssim 0.01/\sqrt{\text{BR}(Z_d \to \text{missing energy})}}$$

- $\frac{\text{BR}(Z_d \to e^+ e^-)}{\text{BR}(Z_d \to \nu \bar{\nu})} \simeq \frac{1}{6} + \frac{1}{2} \left(\frac{\varepsilon}{\varepsilon_Z} \right)^2$

Higgs Decays

- $H \to Z Z_d$
  - Relevance extends to $m_{Z_d} \gg m_{K,B}$.
  - Suppressed by $\varepsilon_Z^2 = (m_{Z_d}/m_Z)^2 \delta^2$.
  - *Enhanced* by $\sim (m_H/m_{Z_d})^2$ for longitudinal Z_d.

- Assume $m_H = 125$ GeV, motivated by LHC hints.
  - $\Gamma(H \to ZZ^* \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-) \simeq 1.8 \times 10^{-6} \frac{G_F}{8\sqrt{2}\pi} m_H m_W^2$
  - $\Gamma(H \to Z Z_d \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-) \simeq 7 \times 10^{-3} \frac{G_F}{8\sqrt{2}\pi} m_H^3 \delta^2 \mathrm{BR}(Z_d \to \ell_2^+ \ell_2^-)$

$$\frac{\Gamma(H \to Z Z_d \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-)}{\Gamma(H \to Z Z^* \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-)} \simeq 10^4 \delta^2 \mathrm{BR}(Z_d \to \ell_2^+ \ell_2^-)$$

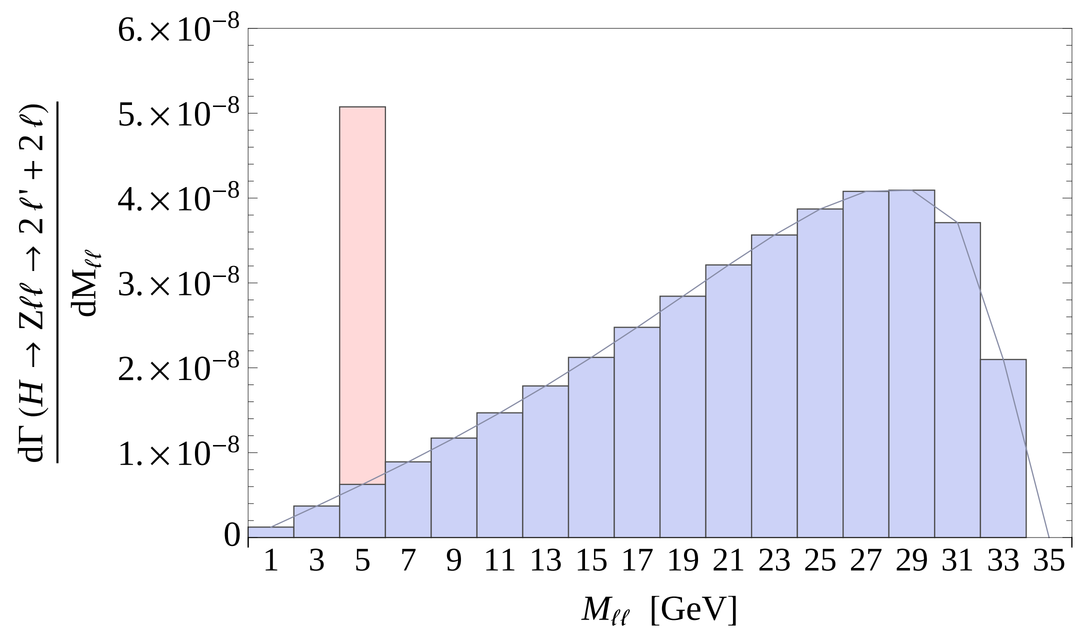
$$\frac{\Gamma(H \to Z Z_d \to \ell^+ \ell^- + \not{E})}{\Gamma(H \to Z Z^* \to \ell^+ \ell^- + \not{E})} \simeq (1/3) \times 10^4 \delta^2 \mathrm{BR}(Z_d \to \not{E})$$

LHC Prospects

- $m_{Z_d} = 5$ GeV and $\delta^2\text{BR}(Z_d \to \ell^+\ell^-) = 10^{-5}$.
- SM Higgs: $\sim 6.3 \times 10^{-9}$ GeV
- $H \to ZZ_d$: $\sim 4.5 \times 10^{-8}$ GeV
- 3σ evidence: $N_H \sim 10^6$ (current sample $N_H \sim 75000$).

⋆ Other reducible and irreducible backgrounds ignored for simple estimate.

⋆ ATLAS/CMS cuts for $H \to ZZ^*$: $M_{\ell\ell} \gtrsim 15$ GeV to avoid background.



A 2HDM Realization:

- SM $SU(2)$ doublets H_1 and H_2.

- *Singelt* H_d and H_2 carries dark charge under $U(1)_d$.

- $U(1)_d$ motivated to protect against FCNC effects in 2HDM.

- H_1 is SM-like (H) and H_2 is fermiophobic.

- m_{Z_d} from $\langle H_d \rangle = v_d$ and $\langle H_2 \rangle = v_2$.

- $\delta = \sin\beta \sin\beta_d$ with $\tan\beta = v_2/v_1$ and $\tan\beta_d = v_2/v_d$.

- SM-like H_1 for $\tan\beta \lesssim 1/3$.

Conclusions

- New physics may not (all) reside at $m_{\text{NP}} \gg m_W$.
- Support from DM considerations and a potential $(g-2)_\mu$ anomaly.
- Z_d vector particles at or below $\sim$ GeV.
- Contribution to m_{Z_d} from EWSB $\rightarrow$ PV, Flavor, Higgs decays.

Process	Current (future) bound on δ	Comment
Low Energy Parity Violation	$\delta \lesssim 0.08 - 0.01\ (0.001)$	Fairly independent of m_{Z_d}.
Rare K Decays	$\delta \lesssim 0.01 - 0.001\ (0.0003)$	$m_\pi^2 < m_{Z_d}^2 \ll m_K^2$.
Rare B Decays	$\delta \lesssim 0.02 - 0.001\ (0.0003)$	$m_\pi^2 < m_{Z_d}^2 \ll m_B^2$.
$H \rightarrow ZZ_d$	$\delta \lesssim (0.003 - 0.001)$	$m_{Z_d}^2 \ll (m_H - m_Z)^2$.