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] (to appear in PRD)
- arXiv:1205.2709 [hep-ph] (to appear in PRL)

8th Patras Workshop, Chicago and Fermilab, July 18-22, 2012

Light Vector Particles

Motivation

- 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

Interactions

- 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 $\varepsilon\, e X^\mu J_\mu^{em}$

- Intensity frontier searches Bjorken, Essig, Schuster, Toro, 2009

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 $\boxed{\boldsymbol{\xi \simeq \varepsilon_Z}}$ $(\varepsilon \simeq 0)$.

- Dark Z fermion couplings:

$$\boxed{\boldsymbol{\mathcal{L}}_{\text{int}} = \left[-\mathbf{e}\boldsymbol{\varepsilon}\mathbf{J}^{\mathbf{em}}_{\boldsymbol{\mu}} - \frac{\mathbf{1}}{\mathbf{2}}(\mathbf{g}/\cos\boldsymbol{\theta}_{\mathbf{W}})\,\boldsymbol{\varepsilon}_{\mathbf{Z}}\mathbf{J}^{\mathbf{NC}}_{\boldsymbol{\mu}} \right] \mathbf{Z}^{\boldsymbol{\mu}}_{\mathbf{d}}}$$

$$J_\mu^{em} = \sum_f Q_f \bar{f}\gamma_\mu f$$

$$J_\mu^{NC} = \sum_f (T_{3f} - 2Q_f \sin^2\theta_W)\bar{f}\gamma_\mu f - T_{3f}\bar{f}\gamma_\mu\gamma_5 f$$

- **Aspects of Dark Z phenomenology**

- Relation to $(g-2)_\mu$ anomaly.
- Parity violation: atomic, ee and ep scattering.
- Flavor: emission of Z_d in rare K and B decays.
- **Higgs** at the LHC, in particular $H \to Z Z_d$.

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

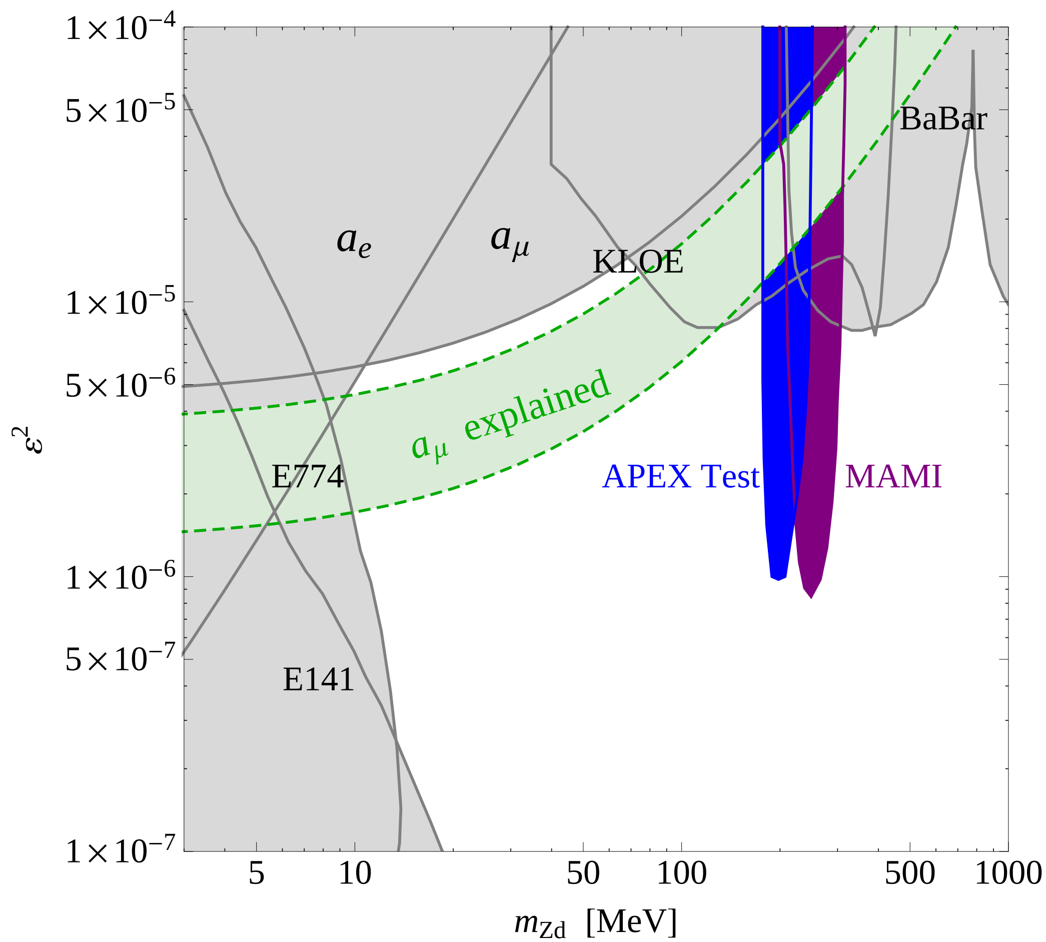
Aside

- Z_d coupling to neutral current from kinetic mixing: $\varepsilon \tan\theta_W \frac{m_{Z_d}^2}{m_Z^2}$.
- Largely negligible compared to the mass mixing effect.

The Muon $g-2$

- $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 287(80) \times 10^{-11}$
- Kinetic mixing: $\Delta a_\mu^{Z_d}(\text{vector}) = \frac{\alpha}{2\pi}\varepsilon^2 F_V\left(m_{Z_d}/m_\mu\right)$ $F_V(0,\infty) = 1, 0$
- Right sign; 10 MeV $\lesssim m_{Z_d} \lesssim$ 500 MeV and $10^{-6} \lesssim \varepsilon^2 \lesssim 10^{-4}$.

Adapted from R. D. McKeown, arXiv:1109.4855 [hep-ex]



- Additional vector coupling for $\delta \neq 0$:

$$\varepsilon^2 \to \left(\varepsilon + \varepsilon_Z \frac{1-4\sin^2\theta_W}{4\sin\theta_W\cos\theta_W}\right)^2 \simeq (\varepsilon + 0.02\varepsilon_Z)^2 \Rightarrow \text{Can be ignored.}$$

- Axial-vector contribution:

$$\Delta a_\mu^{Z_d}(\text{axial}) = -\frac{G_F m_\mu^2}{8\sqrt{2}\pi^2}\delta^2 F_A\left(m_{Z_d}/m_\mu\right) \simeq -117 \times 10^{-11}\delta^2 F_A\left(m_{Z_d}/m_\mu\right)$$

$F_A(0,\infty) = 1, 5/3$

Also negligible for $\delta^2 \lesssim 0.1$ (atomic parity violation).

$\Rightarrow$ $(g-2)_\mu$ explanation dominated by kinetic mixing.

Parity Violation

- 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 $\sin^2\theta_W \to \kappa_d \sin^2\theta_W$

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

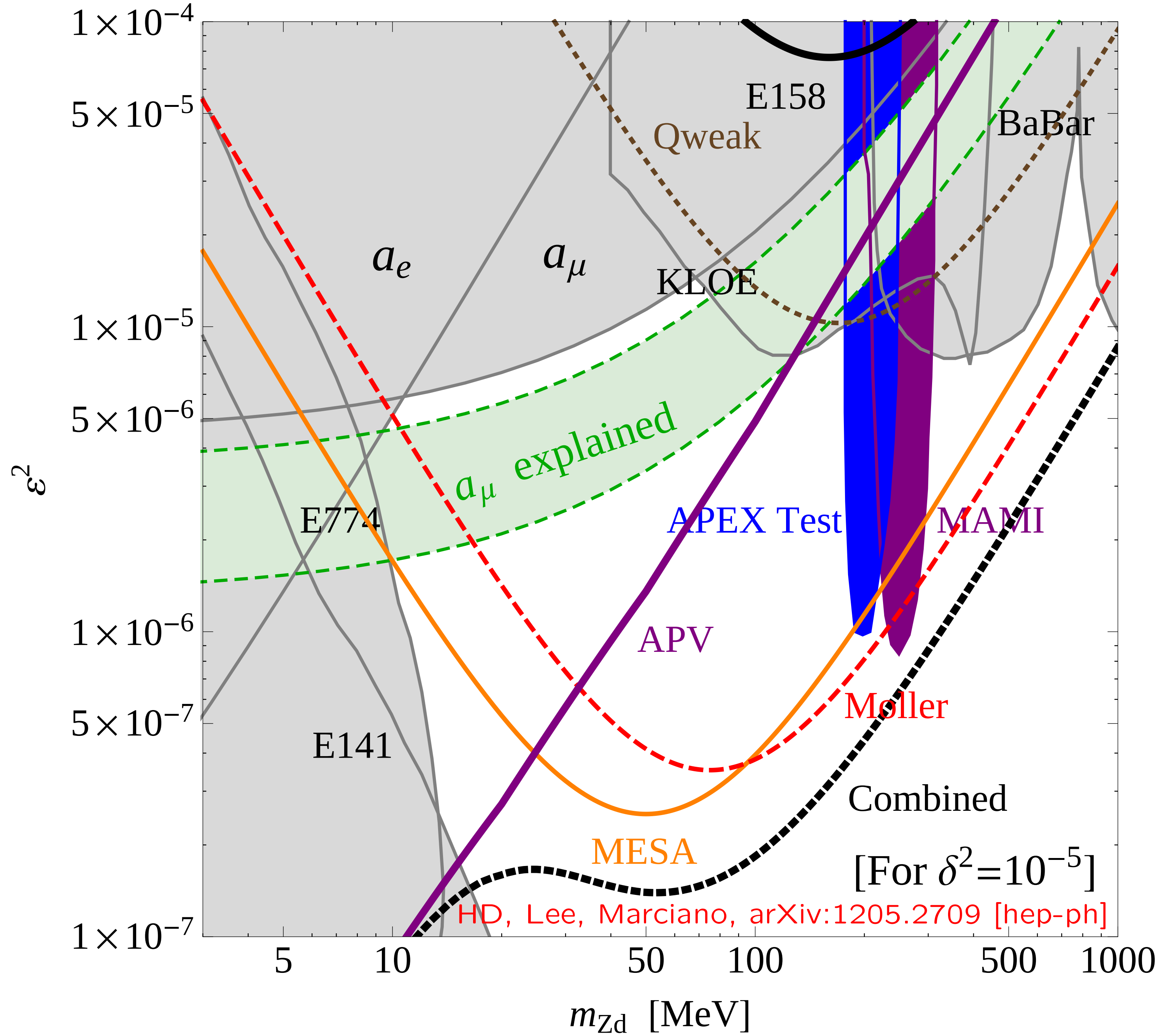
- Atomic parity violation (APV)

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

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

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

- Mainly sensitive to κ_d.



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1×10^{-7}
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500
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m_{Zd} [MeV]
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Qweak
BaBar
a_e
a_μ
KLOE
a_μ explained
E774
APEX Test
MAMI
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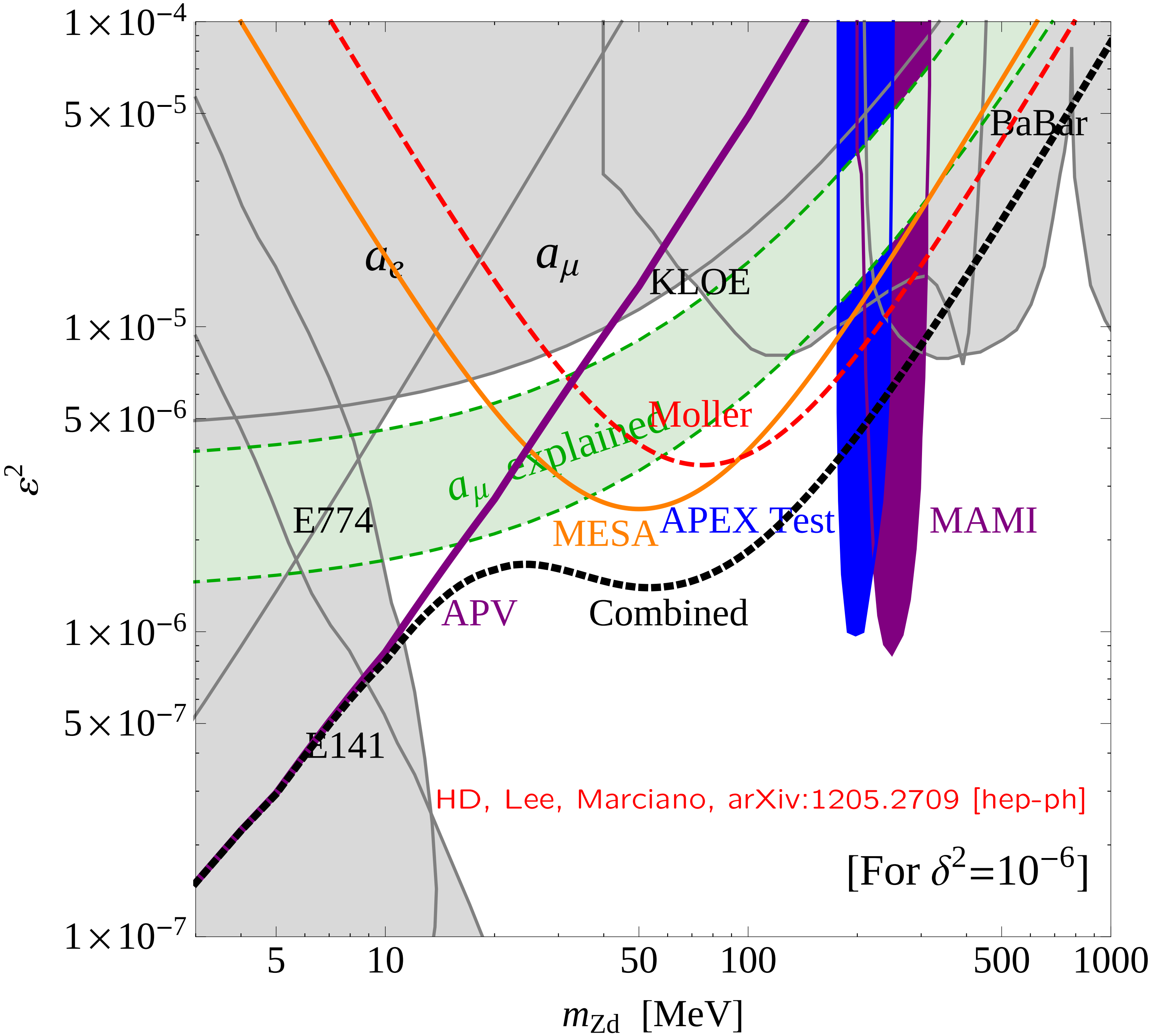
Moller
E141
Combined
MESA
[For δ^2=10^{-5}]
HD, Lee, Marciano, arXiv:1205.2709 [hep-ph]



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m_{Zd} [MeV]
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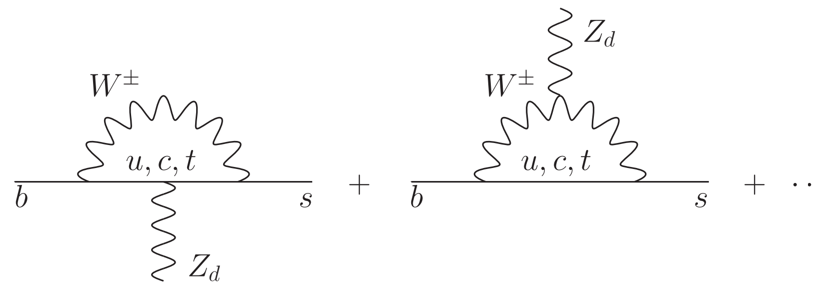
[For $\delta^2=10^{-6}$]

Rare K and B Decays



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

- Goldstone equivalence theorem (GET):

axion $\leftrightarrow$ 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

Batell, Pospelov, Ritz, 2009; Freytsis, Ligeti, Thaler, 2009

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

- Ignore kinetic mixing, due to mostly suppressed effect.

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

- $m_{Z_d} \ll m_K$:

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

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

- $m_{Z_d} \ll m_B$:

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

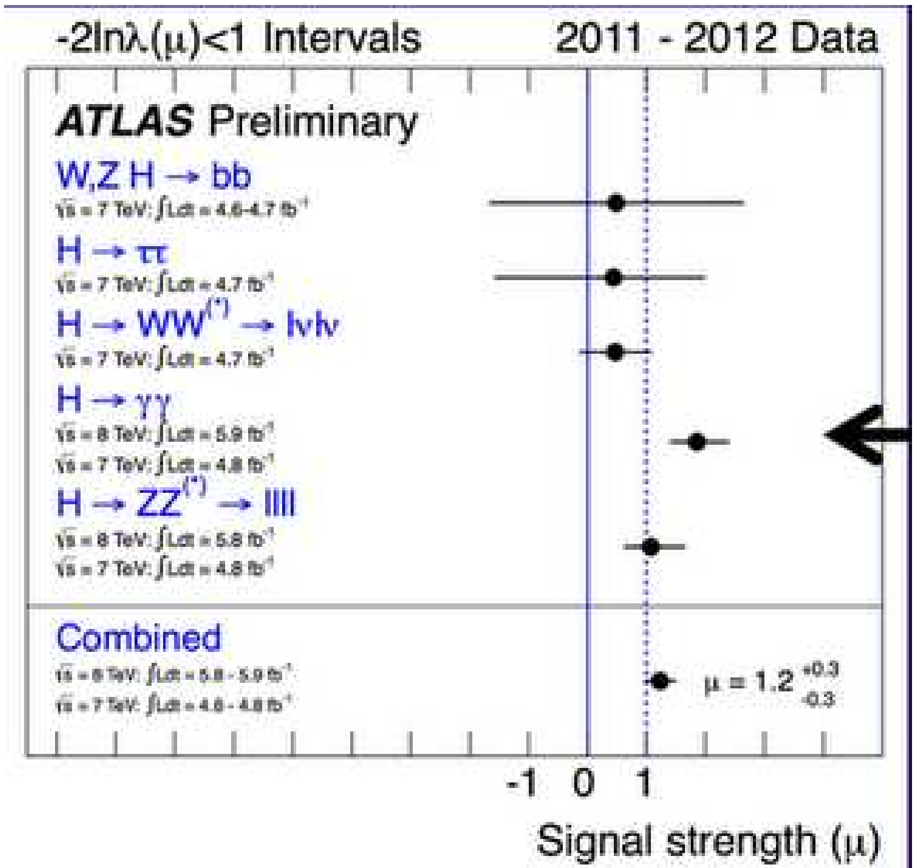
$$\boldsymbol{\delta \lesssim 0.001/\sqrt{\mathrm{BR}(Z_d \to \ell^+\ell^-)} \quad ; \quad \delta \lesssim 0.01/\sqrt{\mathrm{BR}(Z_d \to \text{missing energy})}}$$

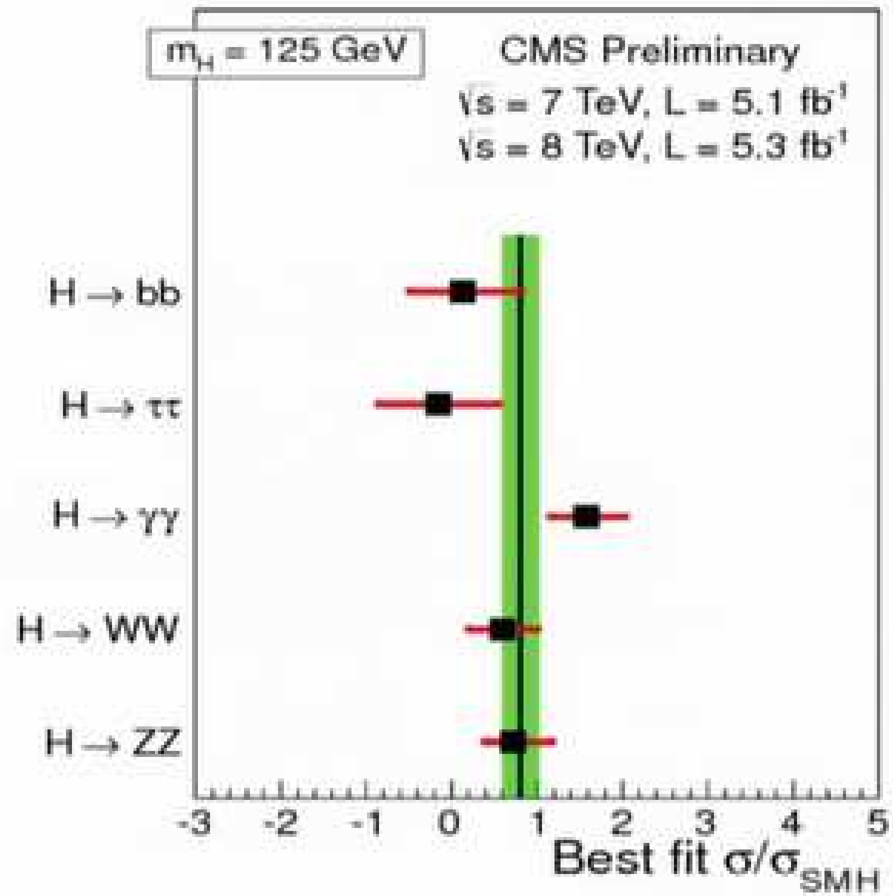
- $\frac{\mathrm{BR}(Z_d \to e^+ e^-)}{\mathrm{BR}(Z_d \to \nu\bar{\nu})} \simeq \frac{1}{6} + \frac{1}{2}\left(\frac{\varepsilon}{\varepsilon_Z}\right)^2$

Higgs-like state discovered by ATLAS and CMS!

- $m_H \sim 125$ GeV

- **Is it the SM Higgs?**





Higgs Decays

The new state may open a window to the dark sector:

- $H \to ZZ_d$

- 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.

- $\Gamma(H \to ZZ^* \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-) \simeq 1.8 \times 10^{-6} \frac{G_F}{8\sqrt{2}\pi} m_H m_W^2$
- $\Gamma(H \to ZZ_d \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-) \simeq 7 \times 10^{-3} \frac{G_F}{8\sqrt{2}\pi} m_H^3 \delta^2 \mathrm{BR}(Z_d \to \ell_2^+\ell_2^-)$

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

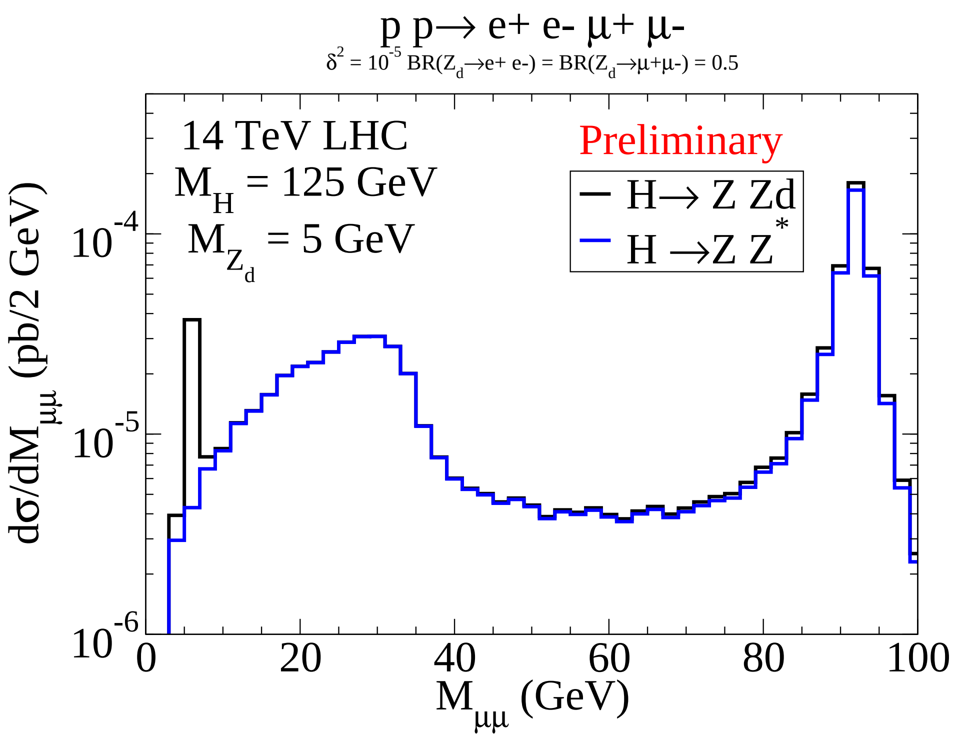
$$\boldsymbol{\frac{\Gamma(H\to ZZ_d\to\ell^+\ell^-+\not{E})}{\Gamma(H\to ZZ^*\to\ell^+\ell^-+\not{E})} \simeq (1/3) \times 10^4\delta^2\mathrm{BR}(Z_d \to \not{E})}$$

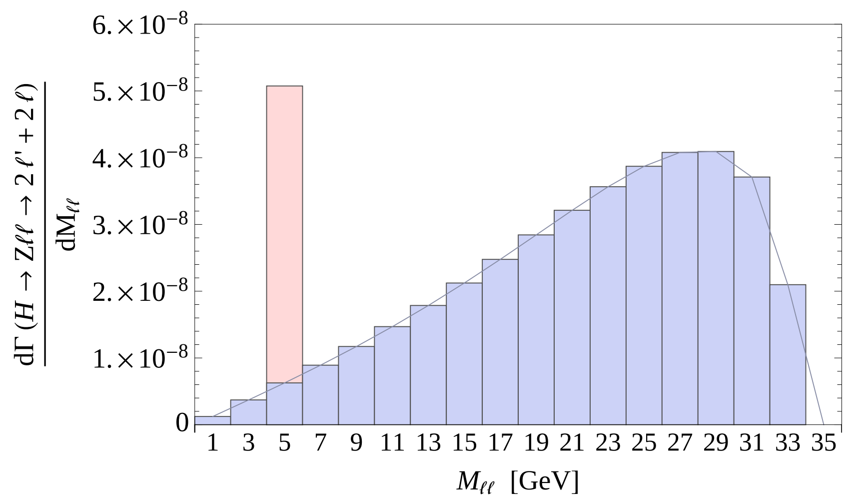
LHC Prospects

- $m_{Z_d} = 5$ GeV and $\delta^2 \text{BR}(Z_d \to \ell^+\ell^-) = 10^{-5}$.
- 3σ evidence: $N_H \sim 10^6$ (current sample $\sim$ few hundred thousand).

⋆ 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.





H.D., Lee, Lewis, Marciano, work in progress

A 2HDM Realization:

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

- *Singelt* H_d and H_2 carry 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 $\to$ 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	$\delta \lesssim 0.02 - 0.001\ (0.0003)$	$m_\pi^2 < m_{Z_d}^2 \ll m_B^2$.
$H \to ZZ_d$	$\delta \lesssim (0.003 - 0.001)$	$m_{Z_d}^2 \ll (m_H - m_Z)^2$.