Dark Z gauge boson

mostly based on the work with H. Davoudiasl and W. Marciano
(arXiv:1203.2947, arXiv:1205.2709)

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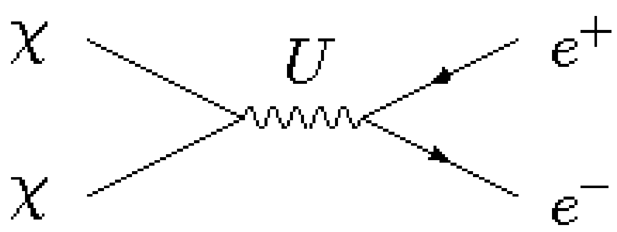
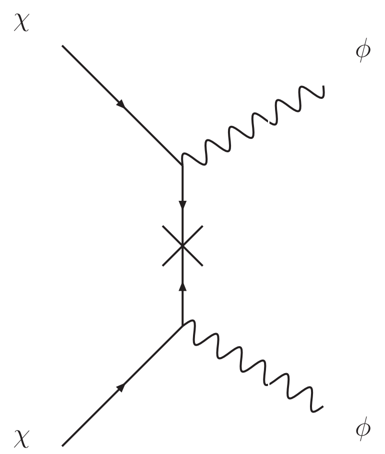
It is a light Z′ ($m_{Z'} \approx O(1)$ GeV)

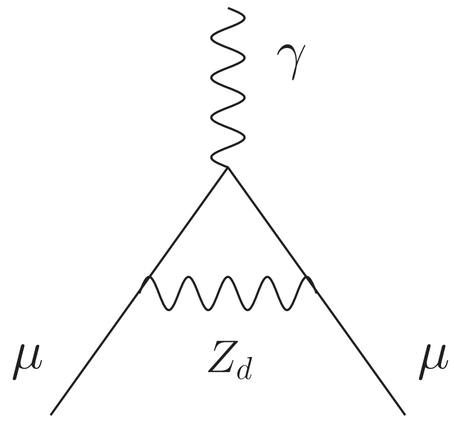
Typical motivations of light Z′ are from DM explanations of excess in the astrophysical signals from our galactic center.

DM annihilation with "GeV-scale gauge boson" can explain anomalies such as

(1) 511 keV gamma-ray (INTEGRAL) [Fayet 2004]
(2) Positron excess (ATIC, PAMELA) [Arkani-Hamed, Finkbeiner, Slatyer, Weiner 2008]







Also, $(g-2)_\mu$ anomaly can be explained. [Fayet 2007; Pospelov 2008]

Cf. Many pioneering works on light Z′ (called "U boson") in a rather general setup was done [by P. Fayet since 1980].

Light Z' is one of the New Physics scenario that can be tested with existing (and upcoming) Low-E experimental facilities (at JLab, Mainz, etc).

We consider very weakly interacting Z' in roughly "10 MeV $< m_{Z'} <$ 10 GeV".

We start from "Dark Photon" (well-established model) and extend it to "Dark Z".

Outline

1. Dark Photon (brief review)

2. Dark Z

3. Implications for Parity-Violating Experiments

4. Implications for Rare Meson Decays

5. Implications for Higgs Physics

1. Dark Photon

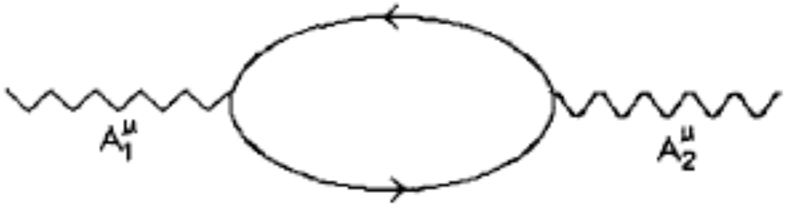
Secluded U(1)

Consider "Dark U(1)" or "Secluded U(1)" which may interact with DM or Hidden sector particles. SM particles have zero charges.

Z′ couples to SM particles through kinetic mixing of $U(1)_Y$ & $U(1)'$. [Holdom 1986]

$$\mathcal{L} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}\hat{B}_{\mu\nu}\hat{Z}'^{\mu\nu} - \frac{1}{4}\hat{Z}'_{\mu\nu}\hat{Z}'^{\mu\nu}$$

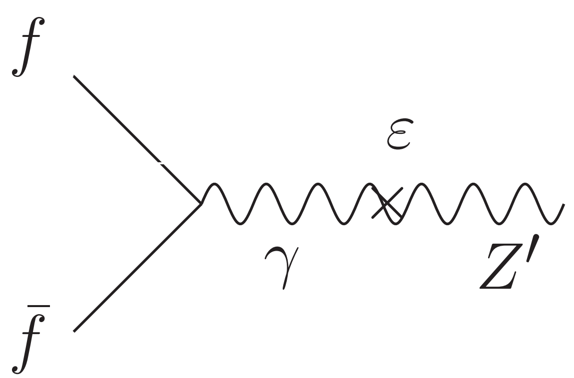
Expected size of kinetic mixing from loops of heavy fermions: $\varepsilon \sim (g_Y g_{Z'})/(16\pi^2) \lesssim 10^{-3}$



Dark Photon

Typical phenomenology of the U(1)$_Y$ & U(1)′ kinetic mixing is carried out in the setup that Z′ couples only to EM Current (vector coupling).

$$\mathcal{L}_{\rm int} = -\varepsilon\, e J^\mu_{em} Z'_\mu \qquad\qquad J^\mu_{em} = Q_f \bar{f}\gamma^\mu f$$



$: \ \varepsilon\, e Q_f$

(coupling) = ε (photon coupling)
Thus, named as "Dark Photon"

Puzzling at the first glance since $\quad B = \cos\theta_W A - \sin\theta_W Z$

Higgs structure matters

Dark Photon is justified in the simple Higgs structure

"SM Higgs doublet + Higgs singlet"

(Higgs singlet to break U(1)′ and give a mass to Z′)

Z-Z′ kinetic mixing part is cancelled by Z-Z′ mass mixing (which is "induced by kinetic mixing") at leading order, and leaves γ-Z′ mixing only.

$$\hat{B} = B + \frac{\varepsilon}{\cos\theta_W} Z' + \mathcal{O}(\varepsilon^2)$$

$$\hat{Z}' = Z' + \mathcal{O}(\varepsilon^2)$$

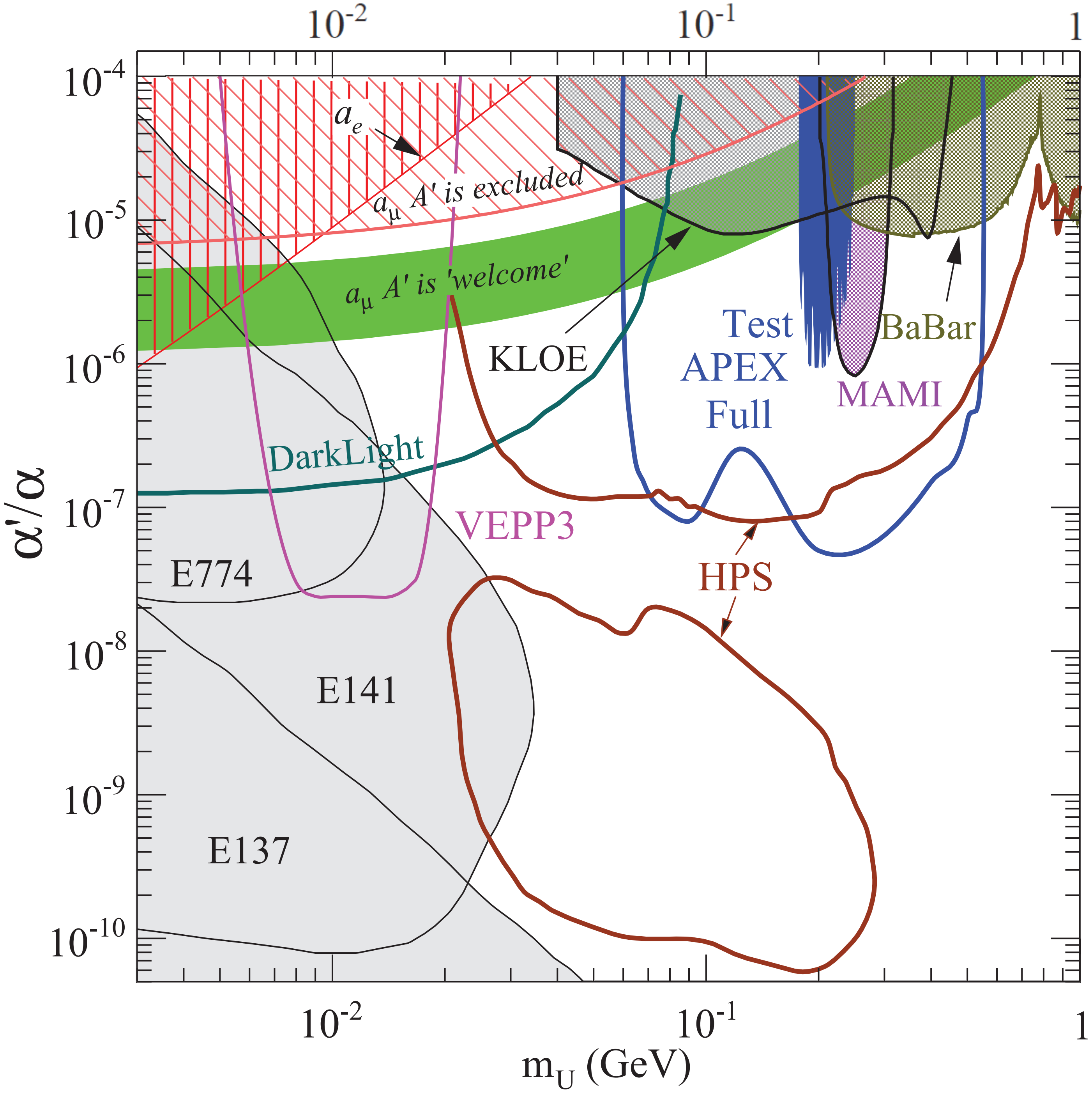
$$\rightarrow \mathcal{L}_{ZZ'} = \left(\frac{1}{2} \frac{g}{\cos\theta_W} \frac{\varepsilon g'}{\cos\theta_W} v^2 \right) Z Z'$$

Z′ coupling to weak Neutral Current (containing axial coupling) appears only at the higher order of ε, and it can be neglected in most cases (for $\varepsilon < 10^{-3}$).

Caveat: Z-Z′ mass mixing is sensitive to the Higgs sector.

(We will use this to introduce "Dark Z" which couples to NC later.)

Typical implications for Dark Photon (or light Z′)

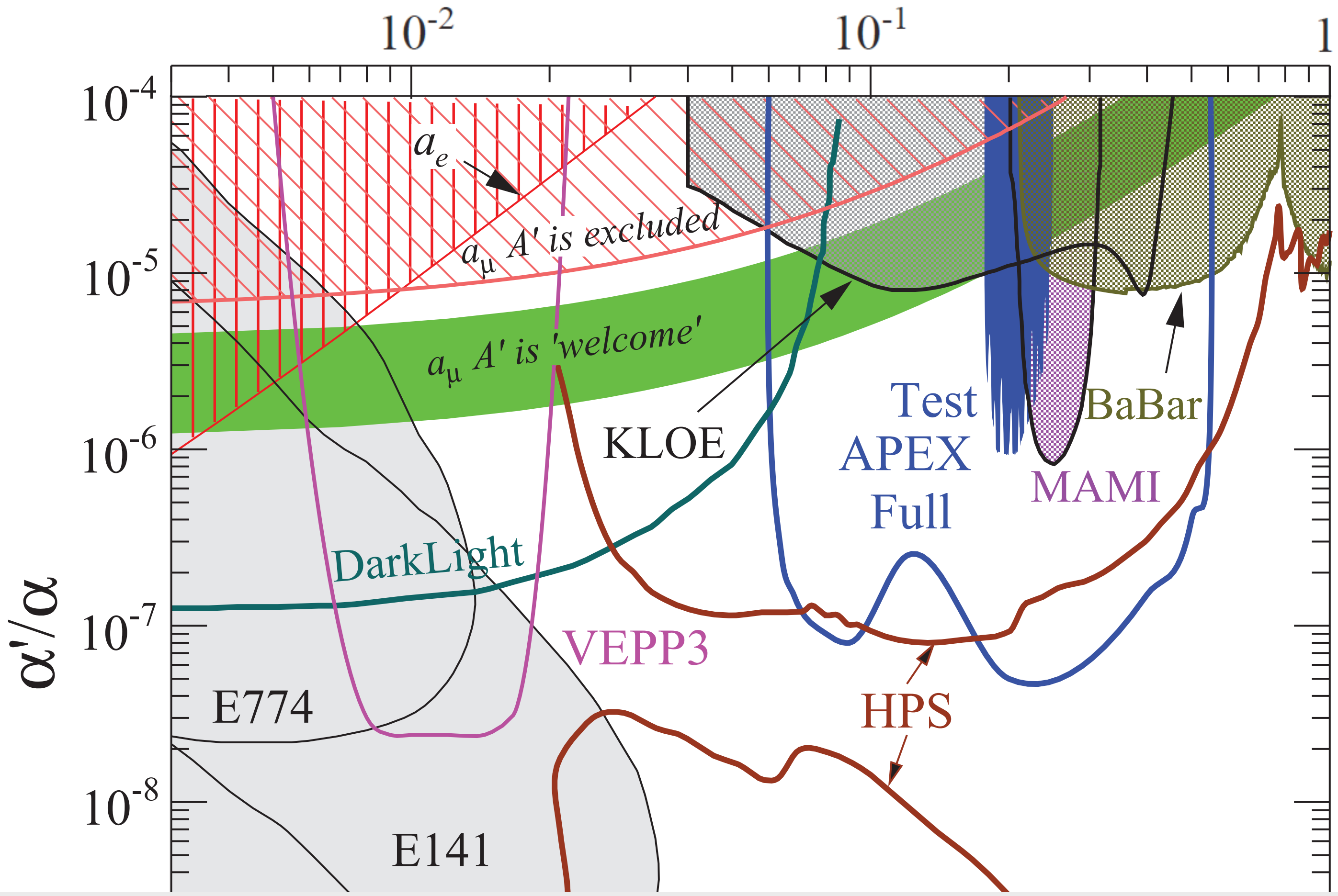


Numerous studies of Dark Photon phenomenology

[Pospelov, Ritz (2008)]
[Reece, Wang (2009)]
[Bjorken, Essig, Schuster, Toro (2009)]
[Freytsis, Ovanesyan, Thaler (2009)]
and many more ...

Constraints/Sensitivity in the ($m_{Z'}$, ε^2) plane [from R. McKeown (arXiv:1109.4855)]

Typical implications for Dark Photon (or light Z′)



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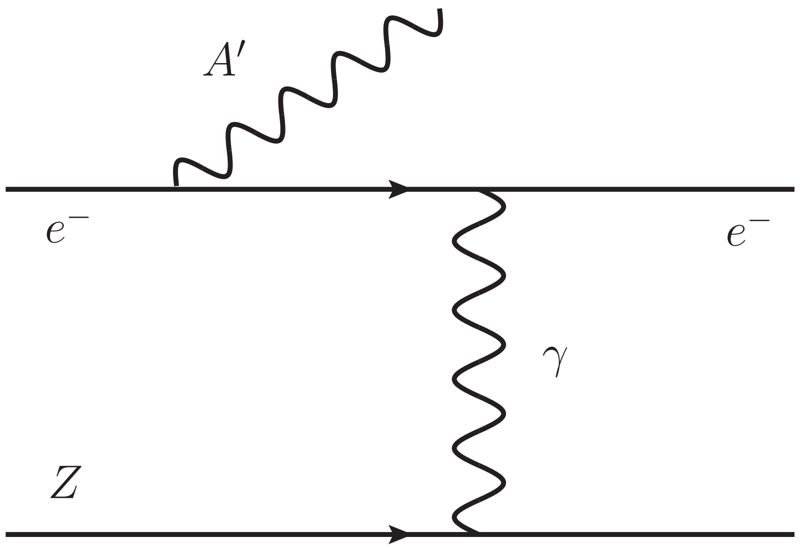
1. g-2 (for electron, muon)
   (Deviation in muon g-2 [green band] can be an early hint of Dark Photon.)

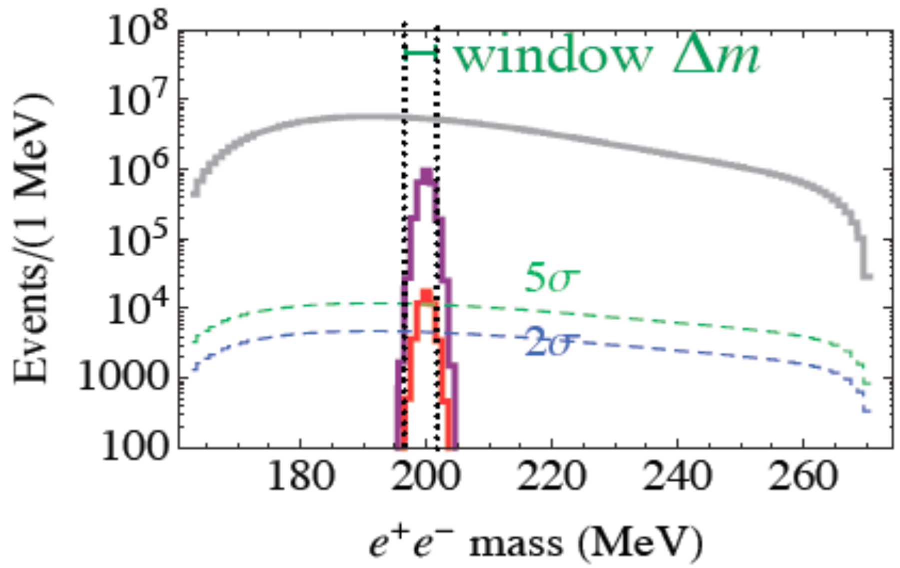
2. Electron beam-dump experiments (E137, E141 at SLAC; E774 at Fermilab)

3. $\Upsilon(3S) \to \gamma\, Z' \to \gamma\, \mu^+\mu^-$ (BaBar); $\phi \to \eta\, Z' \to \eta\, \ell^+\ell^-$ (KLOE in Italy)

5. Fixed target experiments: New experiments designed for Dark Photon search
   (APEX at JLab; MAMI at Mainz; ...)

Example: A′ Experiment (APEX) at JLab





[Essig, Schuster, Toro, Wojtsekhowski (2009)]

New Fixed target experiment designed for direct Dark Photon detection.

($Z' \to e^+e^-$ narrow resonance search)

Ongoing and proposed experiments for direct Dark Photon detection:

(1) MAMI (at Mainz in Germany)
(2) HPS (at JLab)
(3) DarkLight (at JLab)
(4) VEPP3 (at Budker in Russia)

Hunting for this little particle (light Z′) is becoming a big industry.

2. Dark Z

General Higgs sector

Consider the same setup as Dark Photon case (kinetic mixing), but with a more general Higgs sector.

The Z-Z′ mass mixing matrix (with $m_{Z'} \ll m_Z$) can be written as, in ε=0 limit,

$$M^2_{ZZ'} \simeq m_Z^2 \begin{pmatrix} 1 & -\varepsilon_Z \\ -\varepsilon_Z & m^2_{Z'}/m^2_Z \end{pmatrix}$$

with Z-Z′ mixing angle about the same to $\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta$
where δ is a small model-dependent quantity.

We do not specify the Higgs sector, but it can be realized with, for example, 2HDM (type-I) with U(1)′ instead of $\mathbf{Z}_2$.

- H_1 w/ zero U(1)′ charge → SM fermions couple to only this Higgs.
- H_2 w/ nonzero U(1)′ charge → It breaks U(1)′.
- (+ optional Higgs singlet H_d)

$$\delta = \sin\beta \sin\beta_d \quad (\text{with } \tan\beta \equiv v_2/v_1 \ , \ \ \tan\beta_d \equiv v_2/v_d)$$

Dark Z

Now, the Z′ couples to EM Current (∝ ε: kinetic mixing) as well as the weak Neutral Current (∝ ε_Z: Z-Z′ mass mixing).

$$\mathcal{L}_{\rm int}^{\rm SM} = -eJ^{\mu}_{em}A_{\mu} - (g/\cos\theta_W)J^{\mu}_{NC}Z_{\mu}$$

$$\mathcal{L}_{\rm int}^{Z'} = -\left[\varepsilon\, eJ^{\mu}_{em} + \varepsilon_Z\,(g/\cos\theta_W)J^{\mu}_{NC}\right]Z'_{\mu}$$

$$J_{\mu}^{NC} = (\frac{1}{2}T_{3f} - Q_f\sin^2\theta_W)\bar{f}\gamma_{\mu}f - \frac{1}{2}T_{3f}\bar{f}\gamma_{\mu}\gamma_5 f$$

To emphasize the difference from Dark Photon (coupling only to EM Current), we refer our Z′ to "Dark Z". (In ε→0 limit, Z′ couples only to Neutral Current.)

New features due to Neutral Current

Since Dark Z couples to weak Neutral Current (containing axial coupling), it implies some new features that Dark Photon (vector coupling only) do not show.

(i) Parity violation

(ii) Enhancement from Goldstone boson equivalence theorem (boosted Dark Z)

(iii) Coupling to electrically neutral particles (such as neutrinos)

We explore implications for Low Q^2 parity violation, rare meson decays, Higgs physics in this talk.

3. Implications for Parity-Violating Experiments

Dark Z effects on Neutral Current experiments

Dark Z effect comes to the "Neutral Current phenomenology" as

$$G_F \to \left(1 + \delta^2 \frac{1}{1 + Q^2/m_{Z'}^2}\right) G_F$$

$$\sin^2\theta_W \to \left(1 - \varepsilon\delta \frac{m_Z}{m_{Z'}} \frac{\cos\theta_W}{\sin\theta_W} \frac{1}{1 + Q^2/m_{Z'}^2}\right) \sin^2\theta_W$$

Unless ε is very small, it is more sensitive to Weinberg angle shift (which depends on both δ and ε) at Low Q^2 (momentum transfer).
(For $Q^2 \gg m_{Z'}^2$, the effect is negligible.)

"Low Q^2 parity-violating experiments (measuring Weinberg angle)" seem to be a right place to look: Atomic parity violation, Polarized electron scattering experiments.

Low Q^2 Parity-Violating Experiments

Atomic Parity Violation (Weak nuclear charge $Q_W(Z,N) \simeq -N+Z(1-4\sin^2\theta_W)$):

$Q_W(^{133}Cs) = -73.16(35)$ in Cesium Experiment [C. Wieman et al. 1985-1988]

$Q_W(^{133}Cs) = -73.16(5)$ in SM

in good agreement.

Polarized Electron Scattering (Left-Right asymmetry $A_{LR} = \sigma_L - \sigma_R / \sigma_L + \sigma_R$):

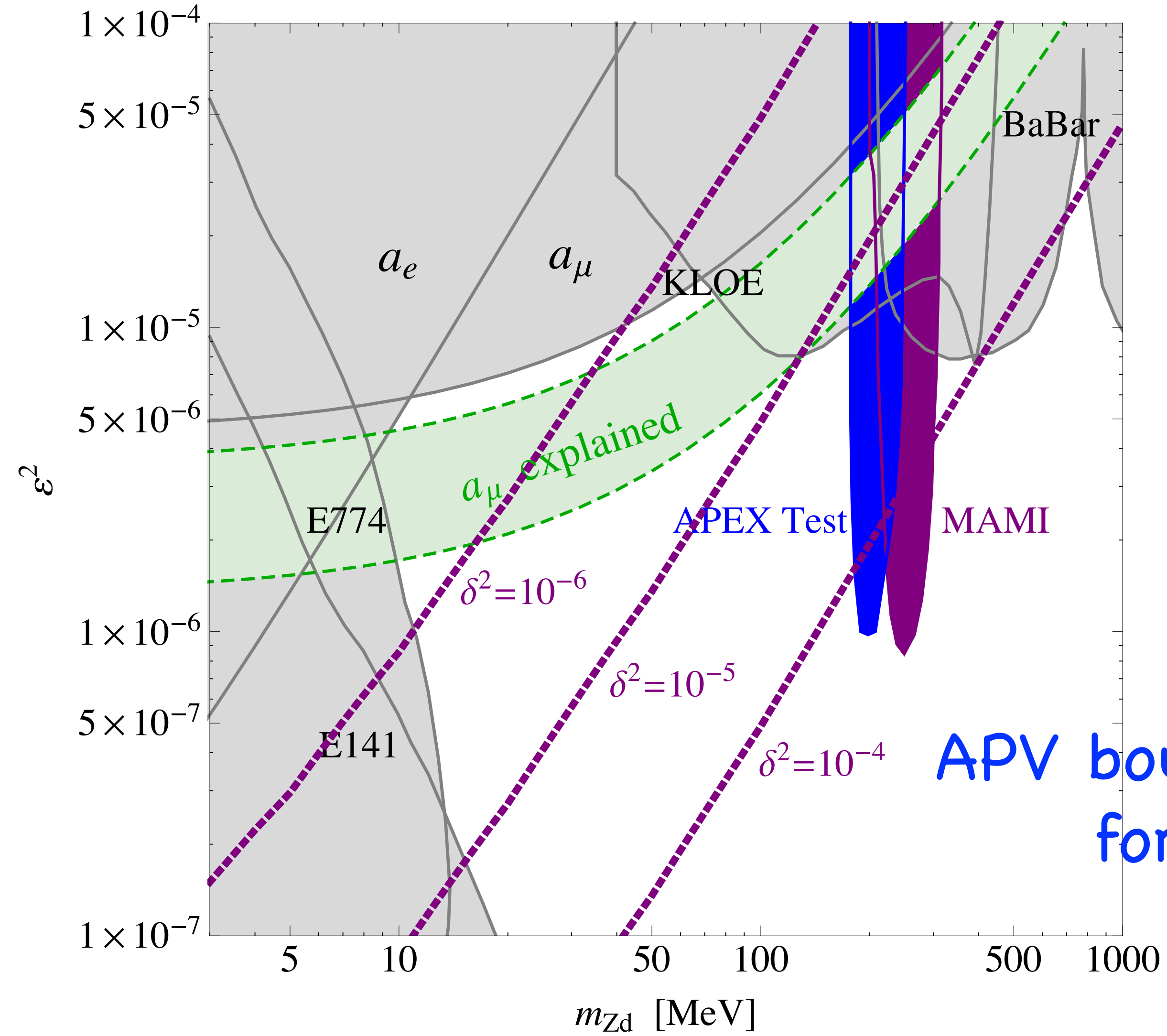
$\sin^2\theta_W(m_Z)=0.2329(13)$ SLAC E158 (e^-e^- Moller scattering; $Q \approx 160$MeV) (2005)

$\sin^2\theta_W(m_Z)=0.23125(16)$ at Z-pole average

in good agreement.

$$\Delta \sin^2\theta_W \simeq -0.42\varepsilon\delta \frac{m_Z}{m_{Z'}} f(Q^2/m_{Z'}^2)$$

Bounds from APV experiments



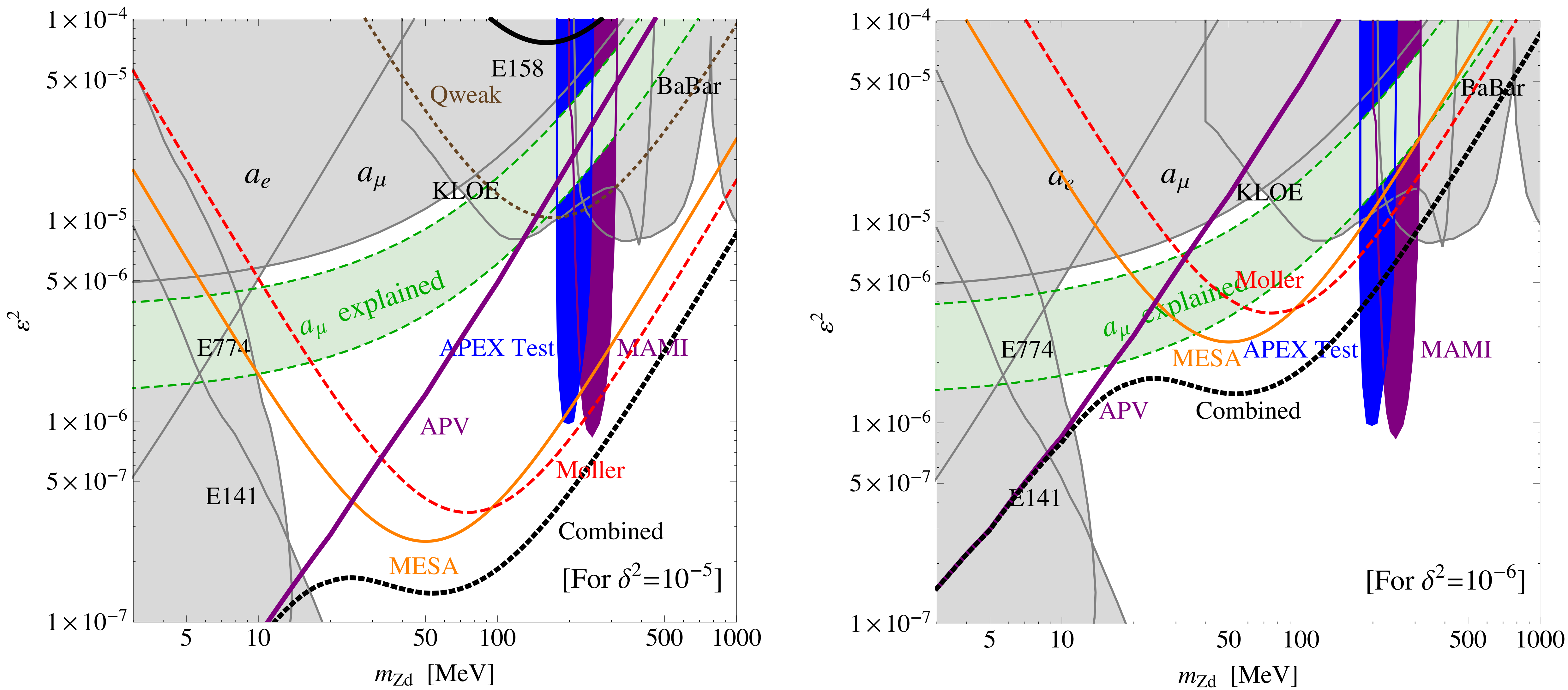
APV bounds in ($m_{Z'}$, ε^2) for a few δ^2

If we assume the muon anomaly (Δa_μ) is due to Dark Z (green band: roughly $\varepsilon^2 \approx 10^{-6}$–$10^{-4}$, $m_{Z'} \approx 10$–500 MeV region),

APV (no deviation) gives bounds $\delta^2 < 2\times10^{-5}$.   (curves in 90% CL)

Can polarized electron scattering test Z′ explanation to Δa_μ for smaller $\delta^2 = 10^{-5}$, $\delta^2 = 10^{-6}$?

Polarized electron scattering experiments

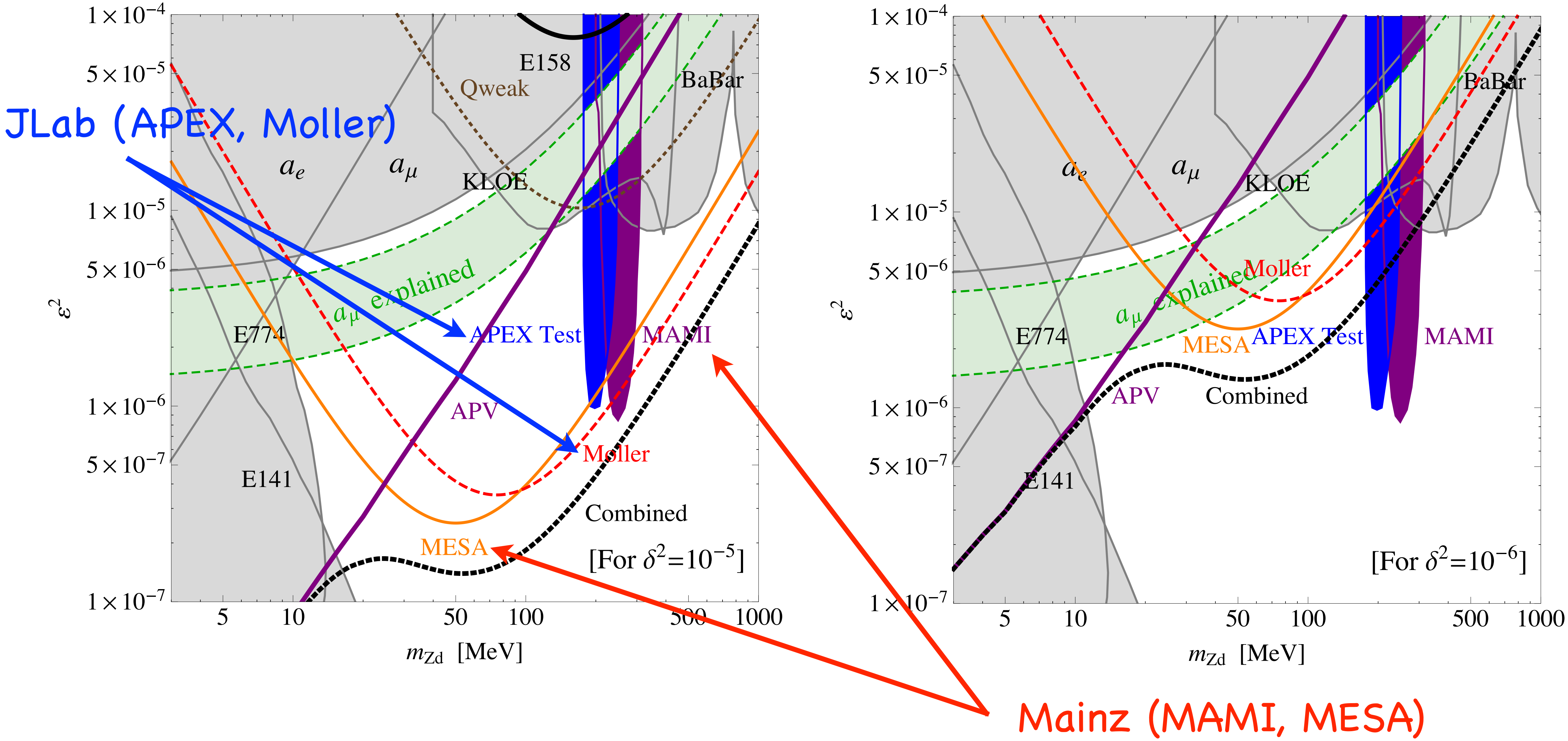


SLAC E158 and JLab Qweak (ongoing) bounds are weak, but proposed similar experiments (Moller at JLab, MESA at Mainz), combined with APV result, can test Dark Z explanation of Δa_μ up to $\delta^2 = 10^{-6}$. (curves in 90% CL)

If Dark Z is there, it will result in $\sin^2\theta_W$ shift.

(Ex) ($m_{Z'}$=75GeV, ε^2=10^{-5}) point will give $\Delta\sin^2\theta_W$ = 0.0015 (for δ^2=4×10^{-6}) that can be measured by Moller, MESA with 5σ CL.

Polarized electron scattering experiments



Direct Dark Photon search places (JLab, Mainz) are also running complementary polarized electron scattering experiments that can be used for Dark Z search.

4. Implications for Rare Meson Decays

Goldstone boson equivalence theorem

Textbook example in SM [Peskin, Schroeder]: Consider top decay width ($t \to bW$).

Naive expectation is $\Gamma(t \to bW) \sim g^2 m_t$

In reality, $\Gamma(t \to bW) \sim g^2 m_t \left(\frac{m_t}{m_W}\right)^2 \approx Y_t^2\, m_t \quad (\text{for } m_t \gg m_W)$

(larger than a naive expectation because of large Y_t)

Boosted W gets longitudinally polarized, and its production is that of associated Goldstone boson (pseudoscalar part of Higgs), up to $O(m_W^2/m_t^2)$.

Goldstone boson equivalence theorem (GBET):
(gauge boson emission/absorption) in High-E limit ≈ (associated pseudoscalar emission/absorption)

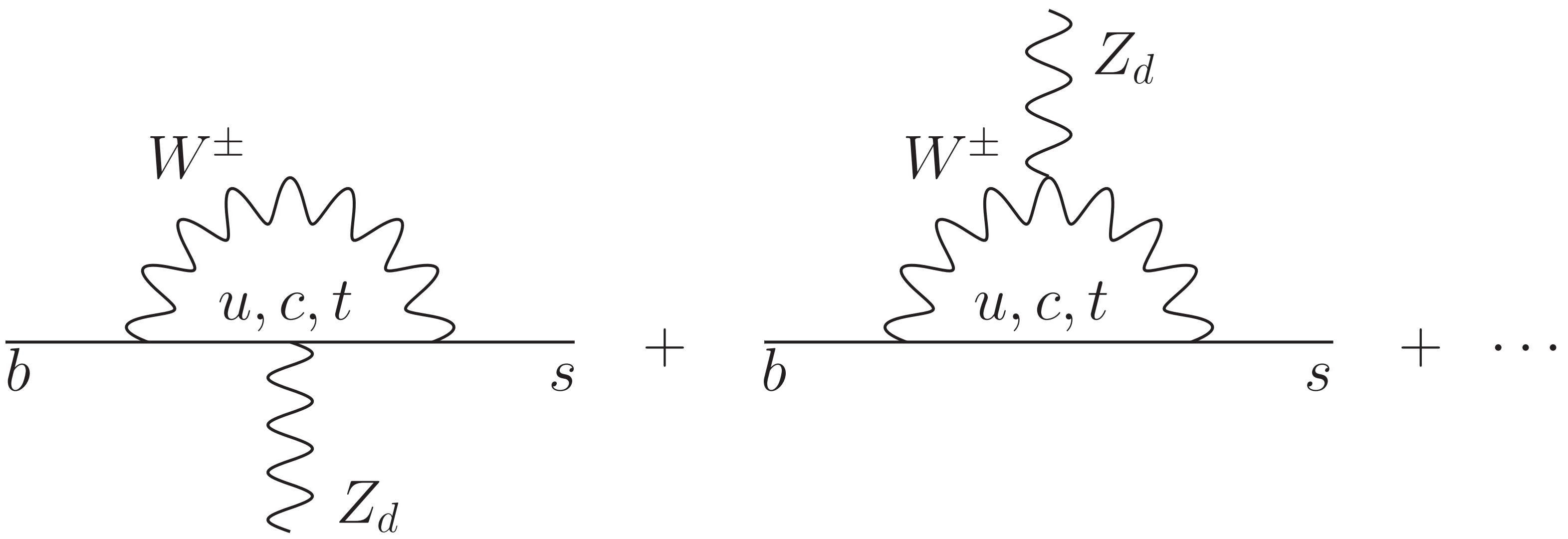
If the latter has larger coupling, the gauge boson production is enhanced.

Rare meson decays

Expect similar effect in rare meson decays into Dark Z:

$K \to \pi Z'$, $B \to K Z'$ (2-body decays)

$b \to s Z'$:
(FCNC through loop)



For $m_{Z'} << m_K, m_B$, Dark Z is boosted (longitudinally polarized), and GBET tells us

(Z′ production) ≈ (Axion production)

Cf. Decaying branching ratio is not axion-like.

$BR(Z' \to ee) = BR(Z' \to \mu\mu)$ (up to phase space)

Rare meson decays

We adopt existing calculation on s-d-Axion, b-s-Axion coupling as a good approx. [Hall, Wise 1981] [Frere, Vermaseren, Gavela 1981] [Freytsis, Ligeti, Thaler 2009]

$$\mathrm{BR}(K^+ \to \pi^+ Z')|_{\mathrm{longitudinal}} \simeq 4 \times 10^{-4}\, \delta^2$$

$$\mathrm{BR}(B \to K Z')|_{\mathrm{longitudinal}} \simeq 0.1\, \delta^2 \quad [\text{large } m_t \text{ and } V_{tb}]$$

Systematic studies on rare B decays to light Hidden sector particles (Dark Photon, RH neutrino, Axion, Higgs singlet) were done by [Batell, Pospelov, Ritz (2009)]. It shows that Dark Photon (vector coupling) case may not be large (for typical size of $\varepsilon \lesssim 10^{-3}$).

$$\mathrm{BR}(B \to K Z') \sim 6 \times 10^{-7}\, \varepsilon^2 \quad (\text{for } m_{Z'} \simeq 1\ \mathrm{GeV})$$

$K \to \pi Z'$

Compare to the experimental values (which agree to the SM expectation)

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

to get bounds

$$|\delta| < 0.01/\sqrt{\mathrm{BR}(Z' \to e^+ e^-)}$$
$$|\delta| < 0.001/\sqrt{\mathrm{BR}(Z' \to \text{missing energy})}$$

In the future, with enough data and fine bins, $Z' \to \ell^+ \ell^-$ ($\ell = e, \mu$) can give a bump in the dilepton invariant mass plot.

(Caveat: Acceptance cuts are used in experimental values. For example, $M_{ee} > 140$ MeV to avoid $\pi \to ee\gamma$ Dalitz decay BKG.)

$B \to K\ Z'$

Similarly, from B decay results, we get

$$|\delta| < 0.001/\sqrt{\mathrm{BR}(Z' \to e^+e^-)}$$
$$|\delta| < 0.01/\sqrt{\mathrm{BR}(Z' \to \text{missing energy})}$$

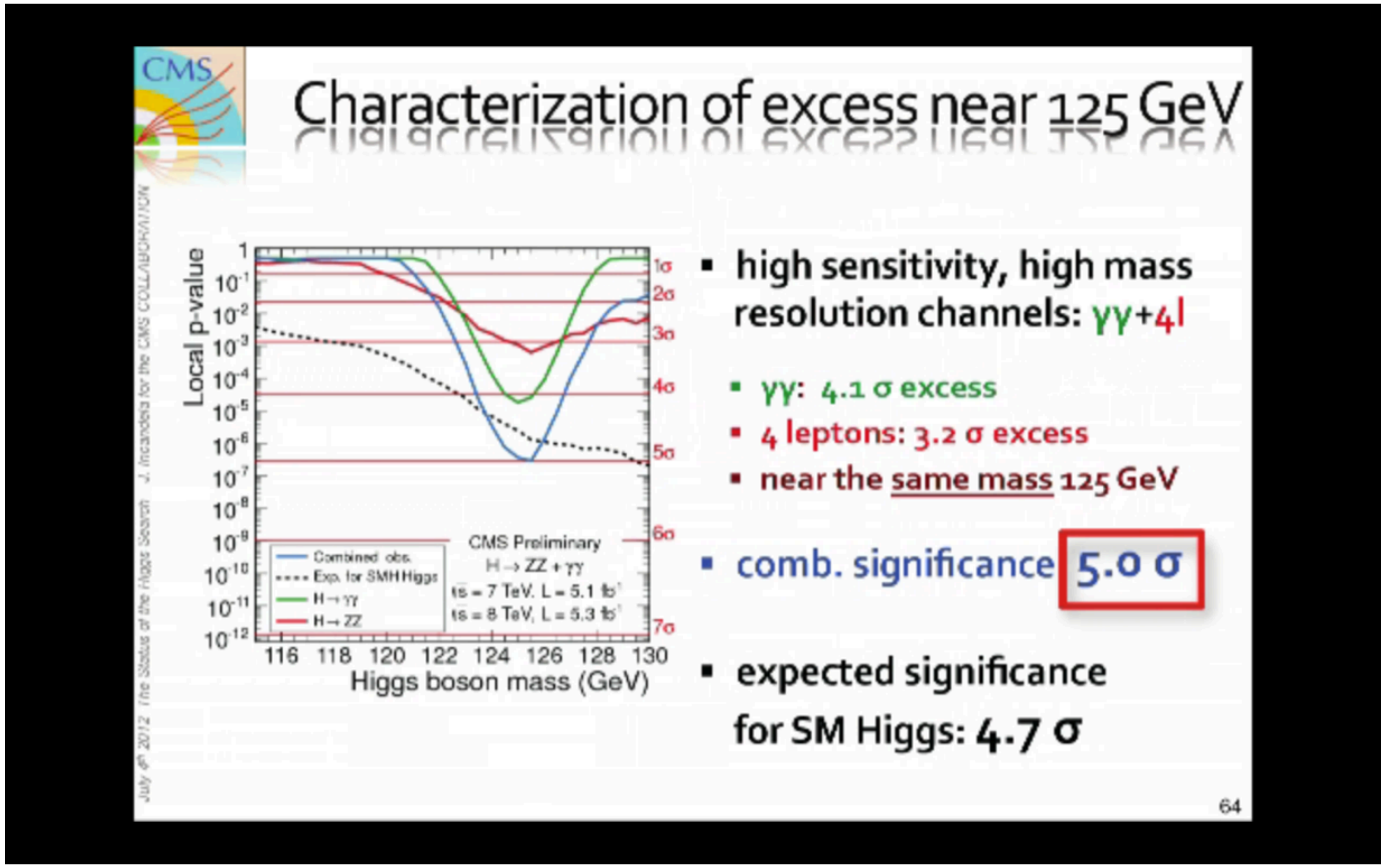
Overall, rare K and B meson decays provide, depending on Z′ BR,

$|\delta| < 0.01\text{–}0.001$ (for $m_{Z'} \ll m_K, m_B$).

5. Implications for Higgs Physics

(Dark Z implications for LHC experiments)

Higgs (or something similar) was discovered.



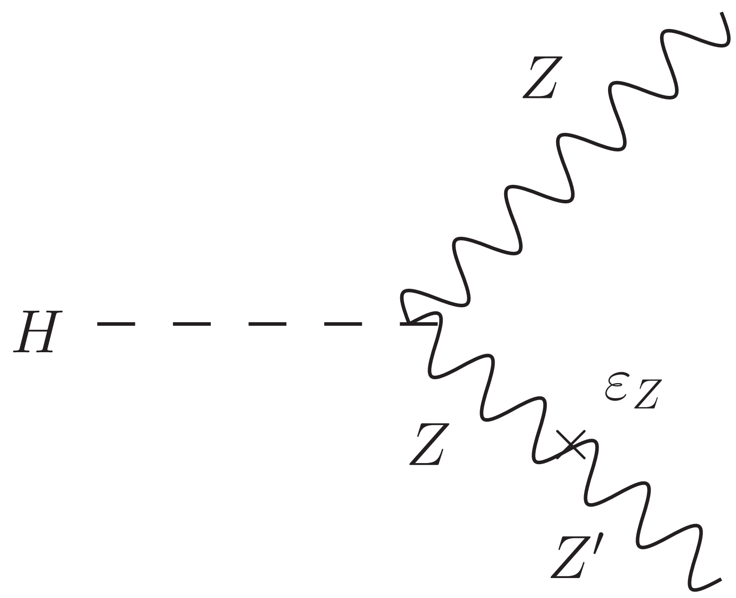
By both ATLAS and CMS
(July 4, 2012)

mass = 125–126 GeV
5σ C.L. ($\gamma\gamma$ and 4ℓ combined)

About time to do precision Higgs study.
We consider the SM-like Higgs decay into light Z' particle at the LHC.

Higgs → Z Z′

For Dark Photon (kinetic mixing only), Z-Z′ net mixing vanishes, but for Dark Z, it does not.



(HZZ′ coupling) = ε_Z (HZZ coupling)

Yet, it may not look promising. $$\frac{\Gamma(H \to ZZ')}{\Gamma(H \to ZZ)} \sim \varepsilon_Z^2 = \left(\delta \, \frac{m_{Z'}}{m_Z}\right)^2 ?$$

But, GBET provides an enhancement.

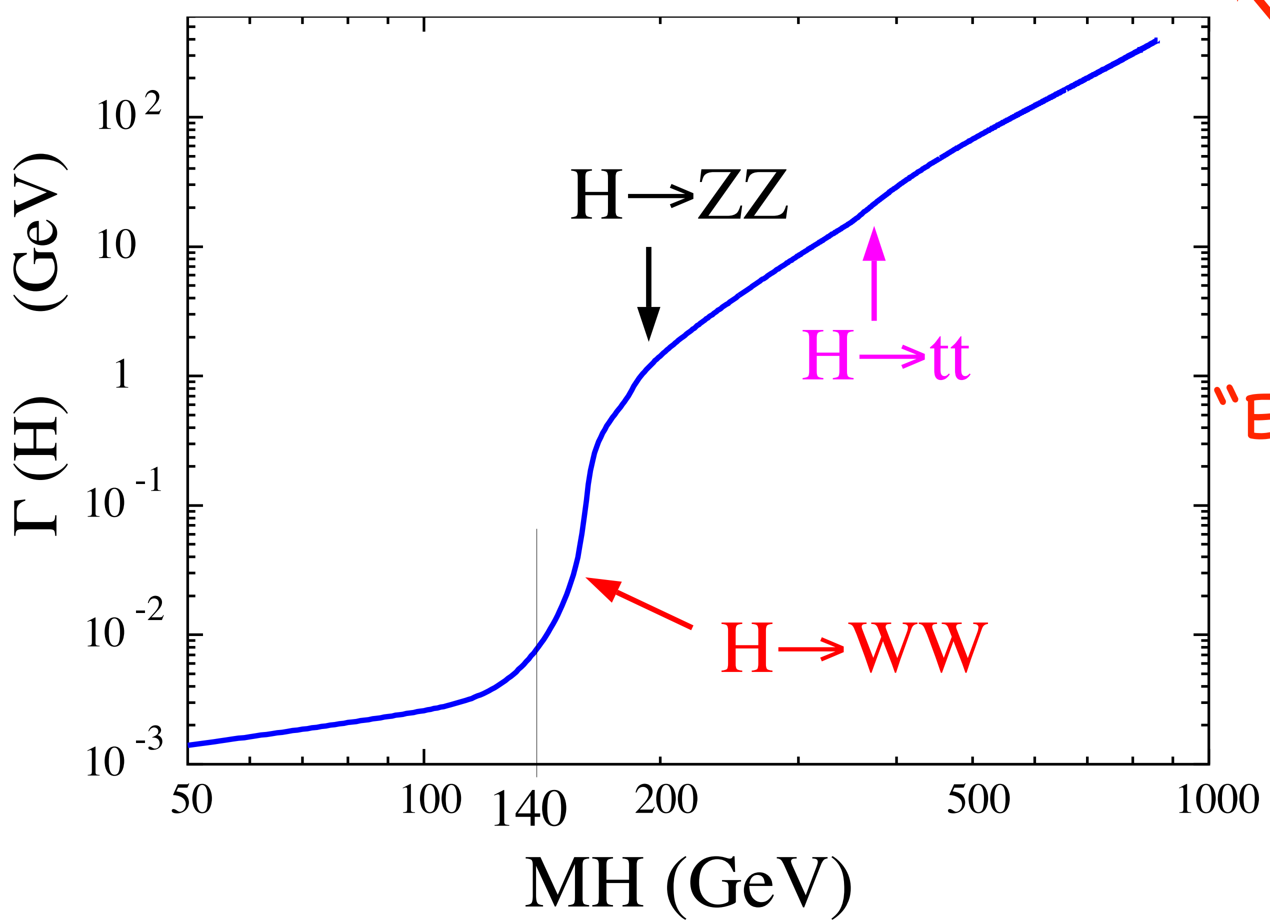
Goldstone boson equivalence theorem in SM Higgs decay

In the SM, if Higgs is heavy enough, its decay into WW, ZZ completely dominate the BR and grows as m_H^3. It is because W, Z are boosted (longitudinally polarized), and GBET provides enhancement.

$$\Gamma(H \to W_T W_T) \sim g^2 \frac{m_W^2}{m_H}$$

$$\Gamma(H \to W_L W_L) \sim g^2 \frac{m_W^2}{m_H} \left(\frac{m_H}{m_W} \right)^4 = g^2 \frac{m_H^3}{m_W^2}$$

"Huge" enhancement



GBET effect: (E/m_V)

"Enhancement is larger for smaller mass"

GBET enhancement is larger for light Z′ than Z.

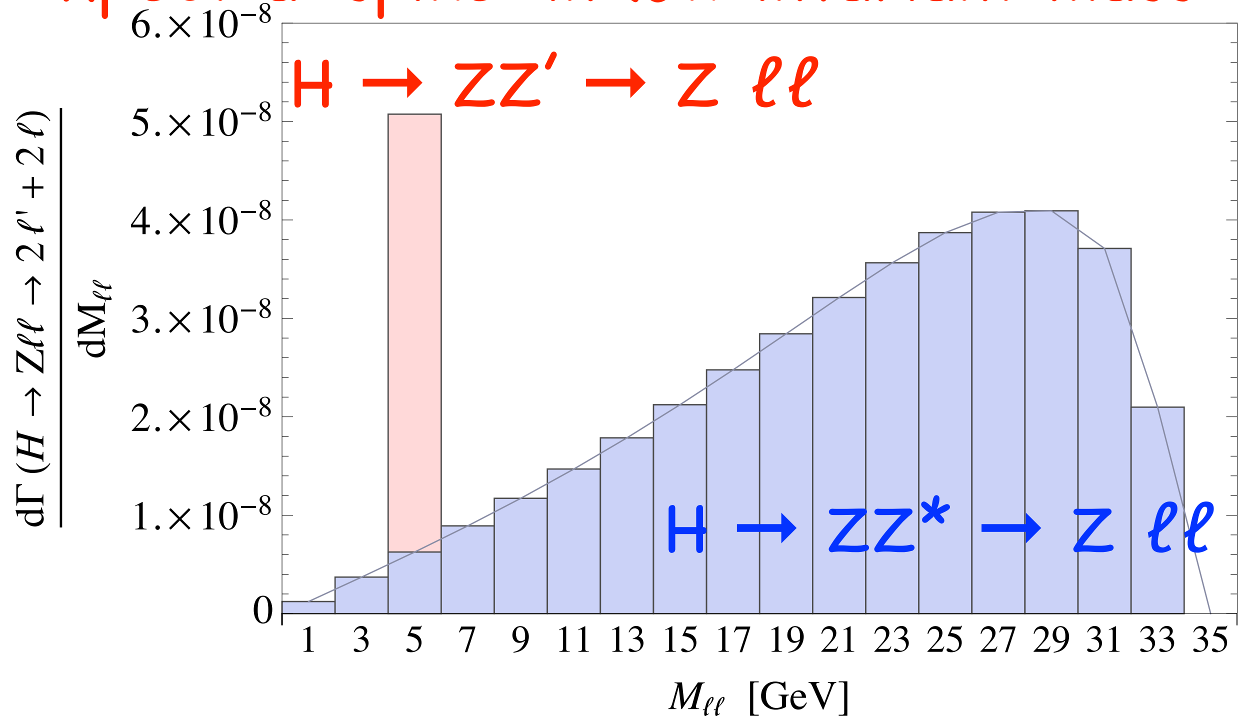
$$\Gamma(H \to ZZ) \sim \frac{1}{m_H}\left(\frac{m_H}{m_Z}\right)^2\left(\frac{m_H}{m_Z}\right)^2 (g_Z m_Z)^2 = \left(g_Z^2\frac{m_H^3}{m_Z^2}\right)$$

$$\Gamma(H \to ZZ') \sim \frac{1}{m_H}\left(\frac{m_H}{m_Z}\right)^2\left(\frac{m_H}{m_{Z'}}\right)^2 (\varepsilon_Z g_Z m_Z)^2 = \left(g_Z^2\frac{m_H^3}{m_Z^2}\right)\delta^2$$

Dark Z with a very weak coupling can affect High-Energy collider experiments.

Higgs → ZZ′ → 4-leptons

Expect a "spike" in low invariant mass



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

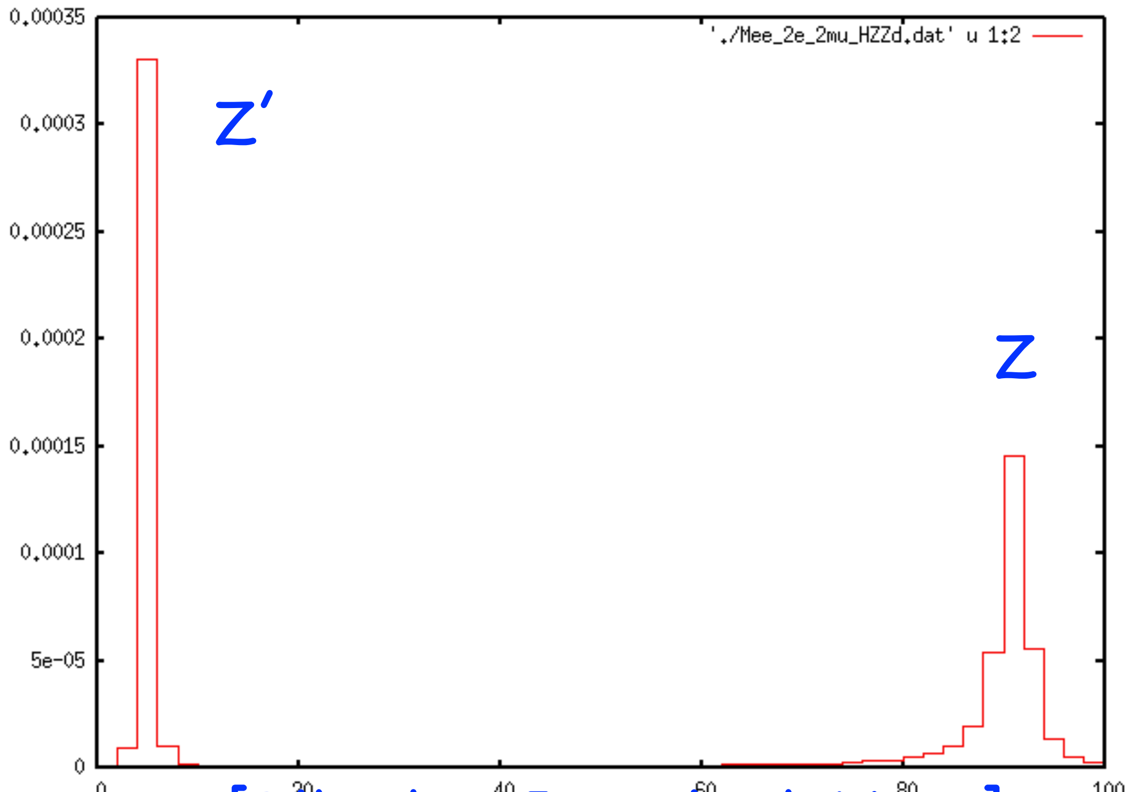
$$\frac{\Gamma(H \to Z Z_d)}{\Gamma_H^{\mathrm{SM}}(125\ \mathrm{GeV})} \simeq 16 \times \delta^2$$

[Dilepton invariant mass from H → ZZ* (or ZZ′) → Z ℓℓ]

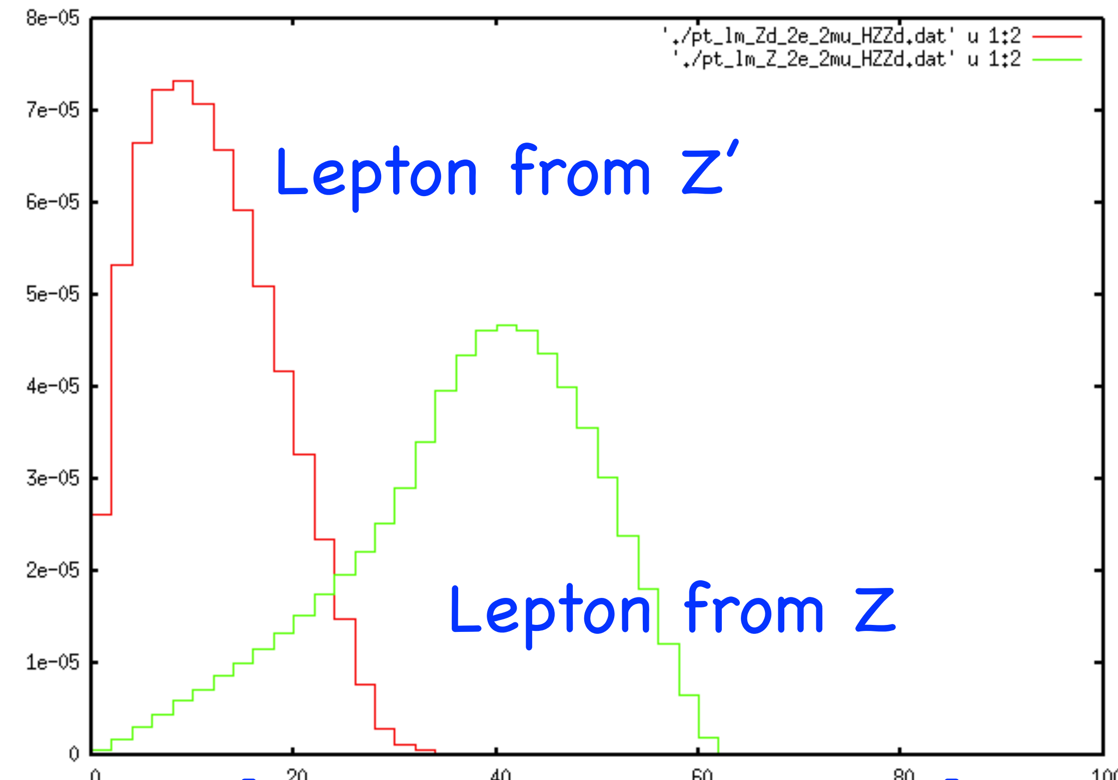
Superficial analysis (ZZ′, ZZ* only) for SM-like Higgs with $\delta^2 \mathrm{BR}(Z' \to \ell\ell) = 10^{-5}$. With $m_{Z'}$=5GeV, bin-size=2GeV, it requires 10^6 Higgs to see 3σ of ZZ′ over ZZ* in 4-lepton channel.

Monte Carlo Simulation (Higgs → ZZ′ → 4-leptons)

[Preliminary]



[Dilepton Invariant Mass]



[Lepton pT distribution]

(pT spread to large values due to boosted Z′)

Typical 4-lepton search at ATLAS/CMS [$H \to ZZ^{(*)}$]: Impose $M_{\ell\ell} \gtrsim$ 15-20 GeV to reduce BKG (such as $Z\gamma^*$).

But "$M_{\ell\ell} \sim$ several GeV" could be a sweet spot for Light Z′ bump hunting.

Monte Carlo analysis for feasibility study is underway [with I. Lewis at BNL].

Summary

Summary

In the dark/secluded U(1)′ picture (SM particles have zero charges), it can still communicate with the SM through kinetic mixing $U(1)_Y \times U(1)'$.

Z′ coupling depends on details of Higgs sector.
(i) Dark Photon: couples to EM Current (simplest Higgs case)
(ii) Dark Z: couples to Neutral Current as well (more general case)

Dark Z is a natural way to introduce axial coupling to "Dark Photon"-related study.

New features of Dark Z: Low-E parity violation, Enhancement from Goldstone boson equivalence theorem, ...

In hunting for a light and weakly-interacting Z′ (motivated from DM), various Low-E experiments (APEX, Moller, B-factories, ...) and High-E experiments (LHC, ...) are all relevant.

- Thank you -

Backup Slides

Dark Z lifetime

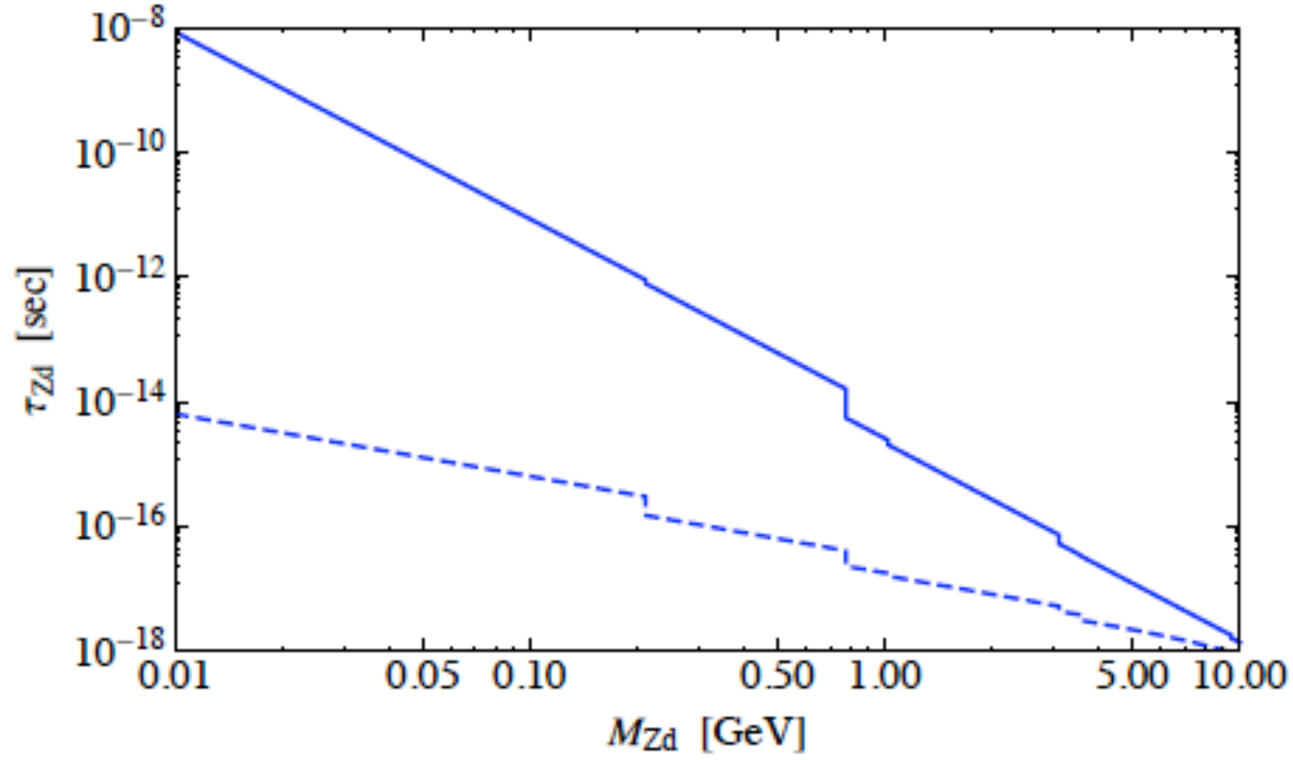


FIG. 2: Z_d lifetime with Z_d mass for $\delta^2 = 10^{-4}$ with $\varepsilon = 0$ (solid blue curve) and $\varepsilon = 2 \times 10^{-3}$ (dashed blue curve) cases. We take ρ, ϕ, J/ψ, Υ masses as the representative threshold for decays to mesons.

$$\mathcal{L}_{\rm int}^{Z'} = -\left[\varepsilon\, e J^{\mu}_{em} + \varepsilon_Z\,(g/\cos\theta_W) J^{\mu}_{NC}\right] Z'_{\mu}$$

SM Higgs BR (m_H = 125 GeV)

H Decay Channel	Branching Ratio
$b\bar{b}$	0.578
WW^*	0.215
gg	0.086
$\tau^+\tau^-$	0.063
$c\bar{c}$	0.029
ZZ^*	0.026
$\gamma\gamma$	2.3×10^{-3}
$Z\gamma$	1.5×10^{-3}
$H \to ZZ^* \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$	1.2×10^{-4}
$H \to ZZ^* \to \ell^+\ell^-\nu\bar{\nu}$	3.6×10^{-4}

TABLE I: Standard Model Higgs decay branching ratios for $m_H = 125$ GeV ($\Gamma_H \simeq 4.1$ MeV) from Ref. [51].

Bounds

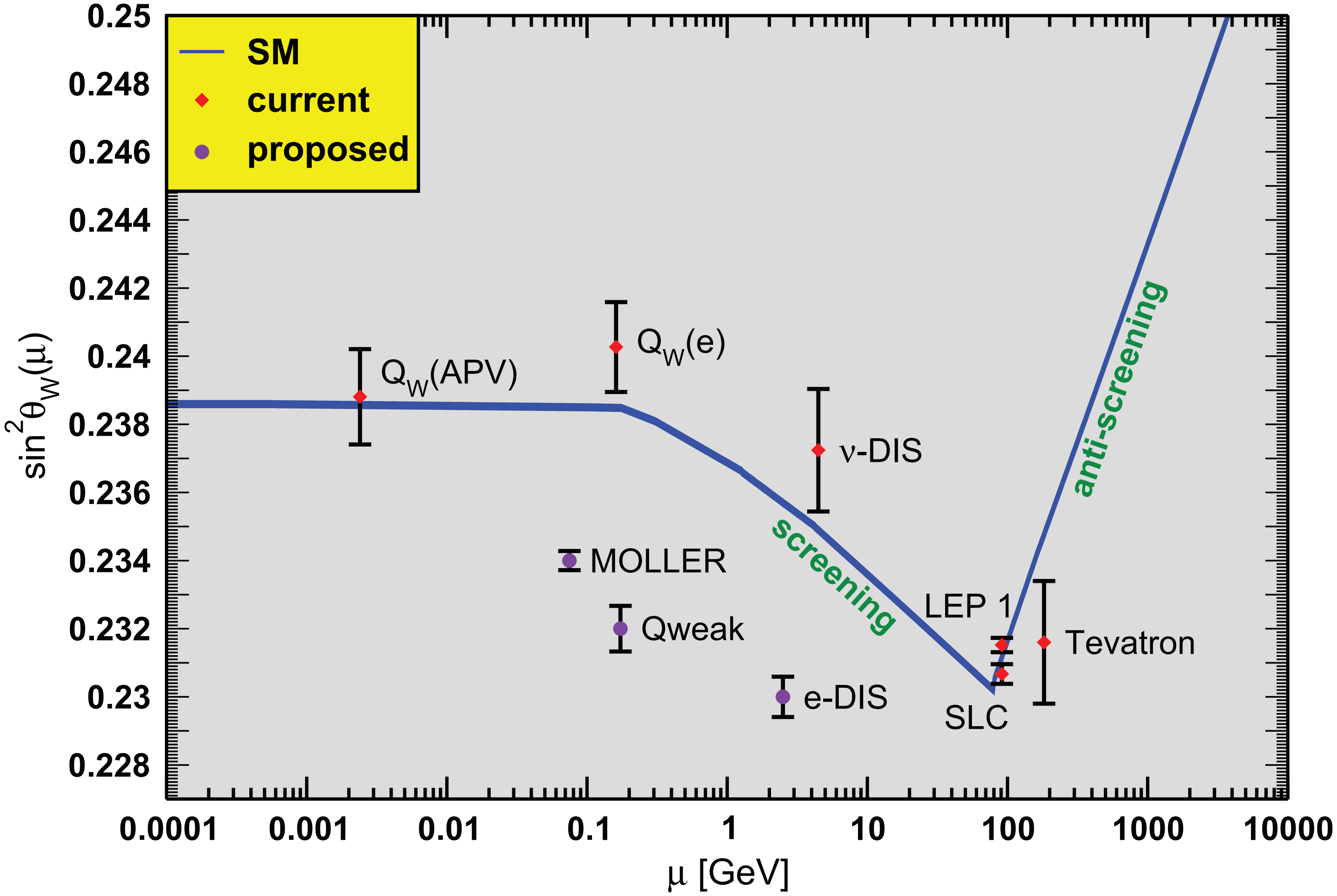
Process	Current (future) bound on δ	Comment
Low Energy Parity Violation	$\lvert\delta\rvert \lesssim 0.08 - 0.01\ (0.001)$	Fairly independent of m_{Z_d}. Depends on ε.
Rare K Decays	$\lvert\delta\rvert \lesssim 0.01 - 0.001\ (0.0003)$	$m_\pi^2 < m_{Z_d}^2 \ll m_K^2$. Depends on BR($Z_d$).
Rare B Decays	$\lvert\delta\rvert \lesssim 0.02 - 0.001\ (0.0003)$	$m_\pi^2 < m_{Z_d}^2 \ll m_B^2$. Depends on BR($Z_d$). Some mass gap ~ 3 GeV.
$H \to ZZ_d$	$\lvert\delta\rvert \lesssim (0.003 - 0.001)$	$m_{Z_d}^2 \ll (m_H - m_Z)^2$. Depends on BR($Z_d$) and background.

TABLE II: Rough ranges of current (future) constraints on δ from various processes examined along with commentary on applicability of the bounds. These processes have negligible sensitivity to pure kinetic mixing effects.

Experiment	$\langle Q\rangle$	$\sin^2\theta_W(m_Z)$	Bound on dark Z (90% CL)
Cesium APV	2.4 MeV	0.2313(16)	$\varepsilon^2 < \frac{39\times10^{-6}}{\delta^2}\left(\frac{m_{Z_d}}{m_Z}\right)^2 \frac{1}{K(m_{Z_d})^2}$
E158 (SLAC)	160 MeV	0.2329(13)	$\varepsilon^2 < \frac{62\times10^{-6}}{\delta^2}\left(\frac{(160\ \mathrm{MeV})^2+m_{Z_d}^2}{m_Z\, m_{Z_d}}\right)^2$
Qweak (JLAB)	170 MeV	±0.0007	$\varepsilon^2 < \frac{7.4\times10^{-6}}{\delta^2}\left(\frac{(170\ \mathrm{MeV})^2+m_{Z_d}^2}{m_Z\, m_{Z_d}}\right)^2$
Moller (JLAB)	75 MeV	±0.00029	$\varepsilon^2 < \frac{1.3\times10^{-6}}{\delta^2}\left(\frac{(75\ \mathrm{MeV})^2+m_{Z_d}^2}{m_Z\, m_{Z_d}}\right)^2$
MESA (Mainz)	50 MeV	±0.00037	$\varepsilon^2 < \frac{2.1\times10^{-6}}{\delta^2}\left(\frac{(50\ \mathrm{MeV})^2+m_{Z_d}^2}{m_Z\, m_{Z_d}}\right)^2$
Combined		±0.00021	$\varepsilon^2_{\mathrm{comb}} < \frac{1}{\sum_i(1/\varepsilon_i^2)}$

TABLE I: Existing and possible future constraints on dark Z from various parity violating experiments

Weinberg angle



$$\mathcal{L}_{\rm int} = -\frac{g}{2\cos\theta_W}\varepsilon_Z J_\mu^{NC'} Z_d^\mu$$

by the replacement $J_\mu^{NC'}(\sin^2\theta_W) = J_\mu^{NC}(\sin^2\theta'_W)$

$$\sin^2\theta'_W = \sin^2\theta_W - \frac{\varepsilon}{\varepsilon_Z}\cos\theta_W \sin\theta_W$$