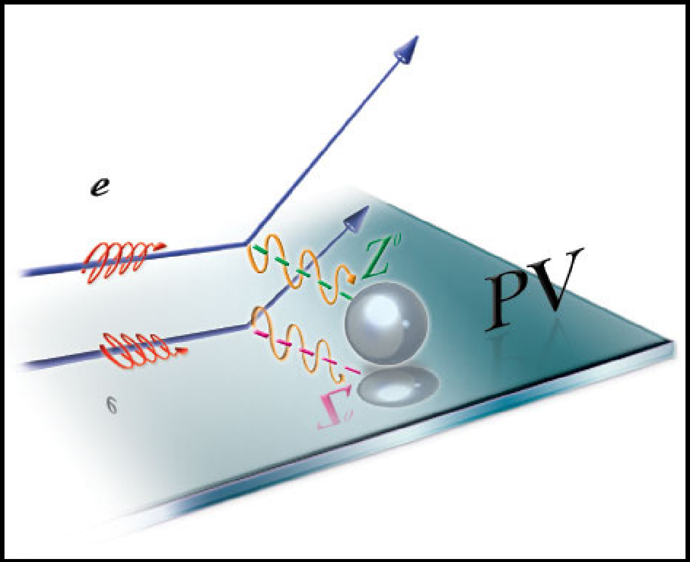
Parity Violation and Rare Higgs Decays from a Dark Force

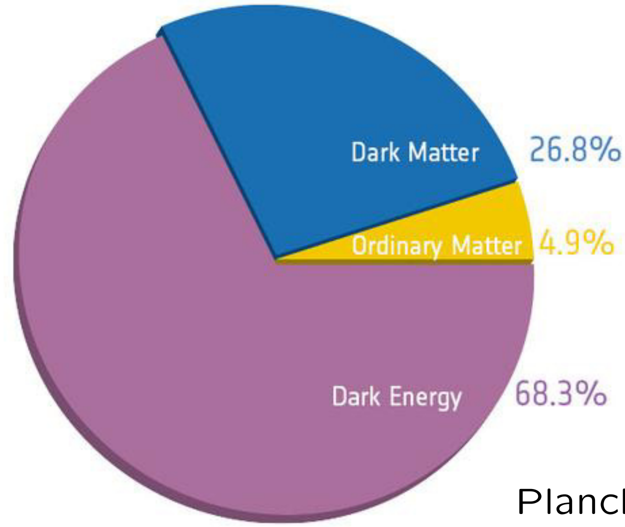
Hooman Davoudiasl

HET Group, Brookhaven National Laboratory



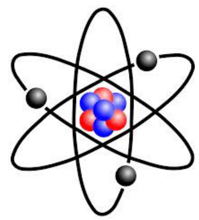
22nd International Spin Symposium, UIUC, September 25-30, 2016

- **The Universe is mostly "dark"**

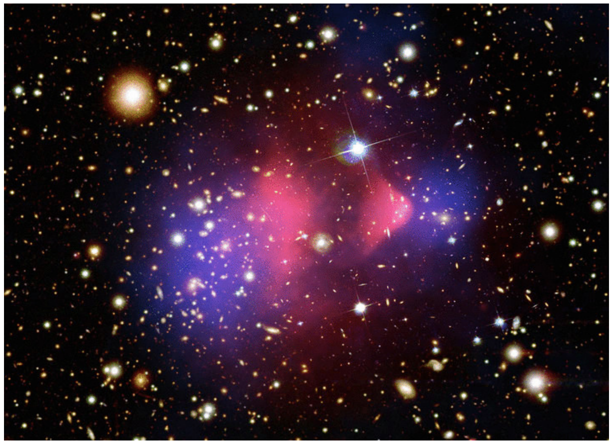


Planck

- Ordinary "visible" matter $\sim 5\%$



- Dark matter (DM) $\sim 27\%$



Basics:

- Stable on cosmological time scales
- Feeble interactions with ordinary matter

Possibility:

- May be from a dark sector (no direct coupling to SM)
- Analogy with SM: dark sector may contain matter and forces

This talk:

- Consider "dark" forces mediated by light new bosons

- Could allow DM interpretation of some astrophysical data
Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

- May explain 3.5σ $g_\mu - 2$ anomaly

$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 288(80) \times 10^{-11}$

- Minimal scenario: dark $U(1)_d$ force (dark photon/Z)

- Mediated by vector boson Z_d with coupling g_d

- Interaction with SM via *mixing*

- $g_\mu - 2$, dark parity violation, rare Higgs decays, . . .

- A "dark" singlet Higgs ϕ is generally assumed to break $U(1)_d$

- May have suppressed couplings to SM fermions

- Can be an alternative (additional) source of $g_\mu - 2$

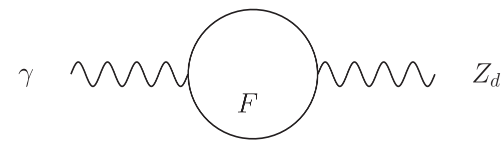
- Potentially measurable μ EDM ("dark" T violation), rare K decays, . . .

Dark Photon

- Kinetic mixing: $Z_{d\mu}$ of $U(1)_d$ and B_μ of SM $U(1)_Y$ Holdom, 1986

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_{\mathbf{W}}}\mathbf{B}_{\mu\nu}\mathbf{Z}_{\mathbf{d}}^{\mu\nu} - \frac{1}{4}\mathbf{Z}_{\mathbf{d}\mu\nu}\mathbf{Z}_{\mathbf{d}}^{\mu\nu} \qquad (X_{\mu\nu} \equiv \partial_\mu X_\nu - \partial_\nu X_\mu)$$

  - May be loop induced: $\varepsilon \sim e g_d/(4\pi)^2 \lesssim 10^{-3}$



- Remove cross term, via field redefinition
  - $B_\mu \to B_\mu + \frac{\varepsilon}{\cos\theta_W} Z_{d\mu}$
  - Z-Z_d mass matrix digonalization

- After redefinition, Z_d couples to EM current $J^\mu_{em} = \sum_f Q_f \bar{f}\gamma^\mu f + \cdots$

$$\boxed{\mathcal{L}_{\text{int}} = -e\,\varepsilon\, J^\mu_{em} Z_{d\mu}}$$

  - Like a photon, but ε-suppressed couplings: "dark" photon

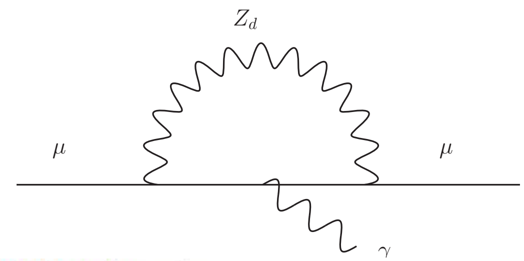
- Neutral current coupling suppressed further by $O(m_{Z_d}/m_Z) \ll 1$

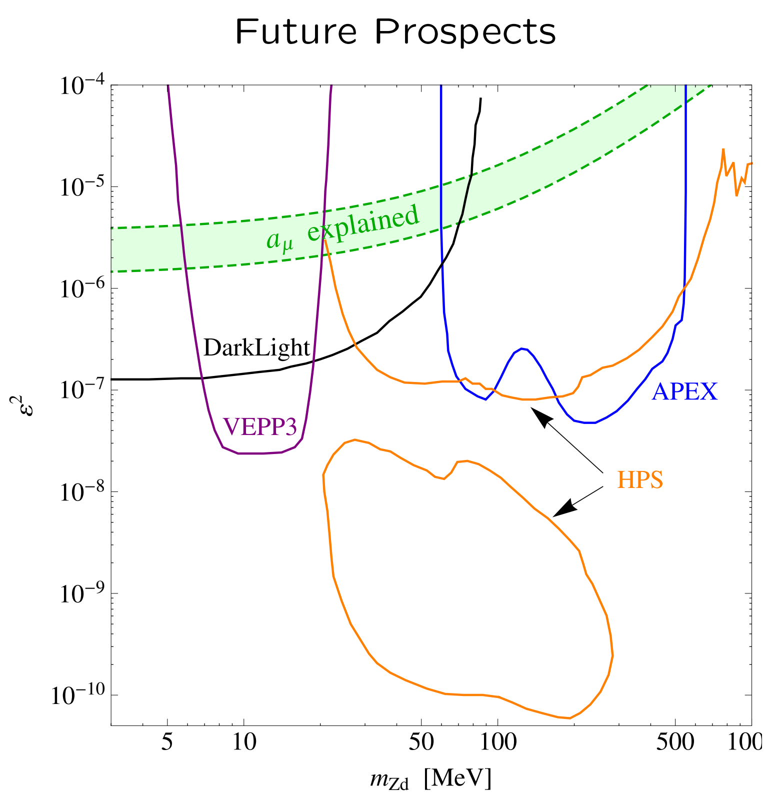
- Active experimental program to search for dark photon

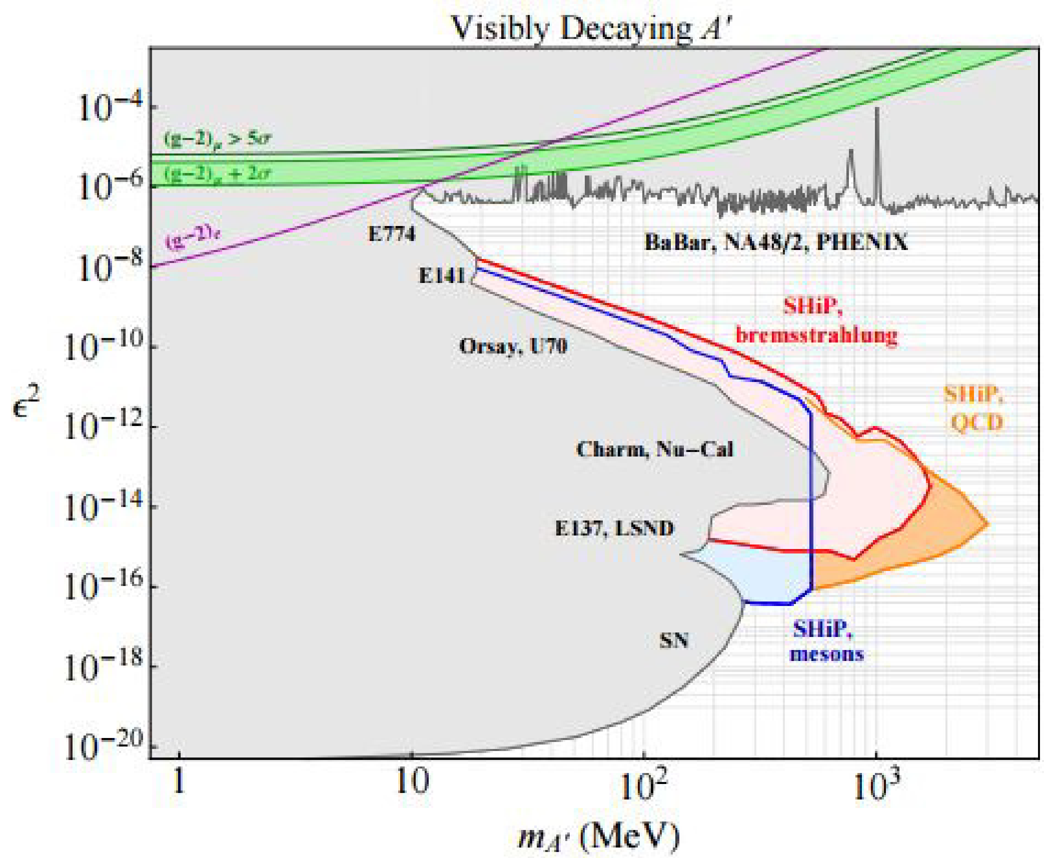
Pioneering work by Bjorken, Essig, Schuster, Toro, 2009

- An early experimental target: $g_\mu - 2$ parameter space

Fayet, 2007 (direct coupling)   Pospelov, 2008 (kinetic mixing)







S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

Visibly decaying Z_d nearly ruled out as $g_\mu - 2$ explanation

- Dark photon may be "invisible" if $\exists$ dark X with $m_X < m_{Z_d}/2$
- X could be DM, coupled to Z_d with $g_d \gg e\varepsilon$: Br$(Z_d \to X\bar{X}) \simeq 1$
- $g_\mu - 2$ solution independent of dominant Z_d branching fraction

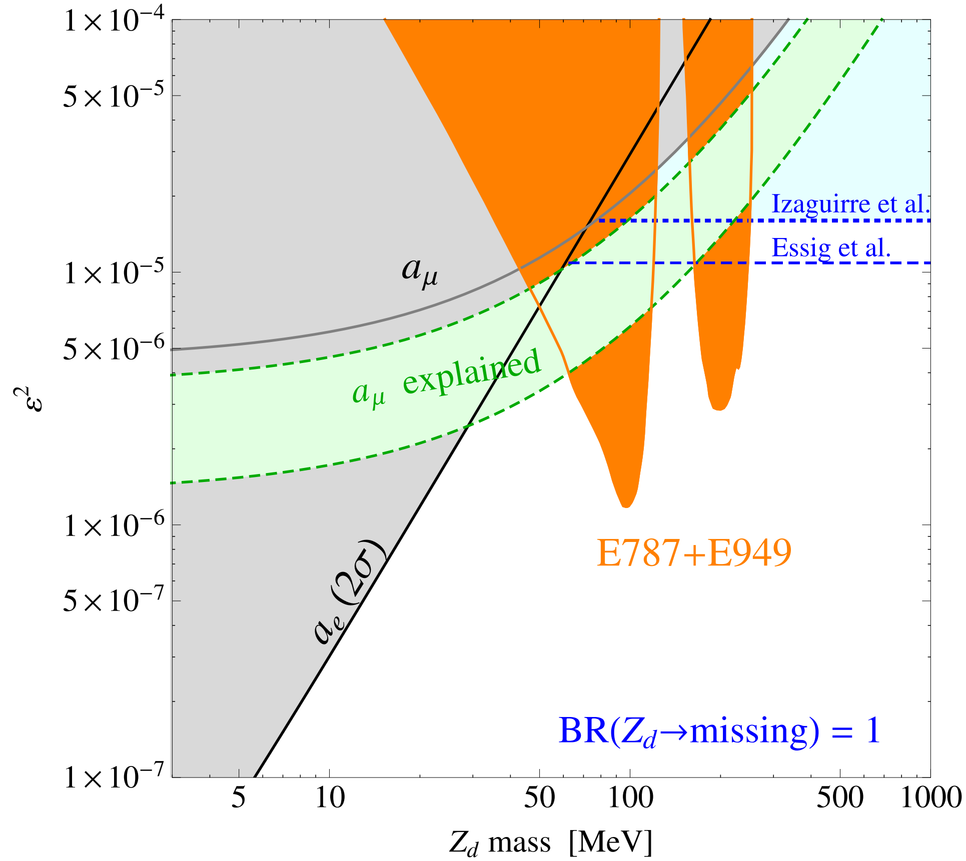
Constraints:

- Dashed lines: BaBar

Izaguirre, Krnjaic, Schuster, Toro, 2013
Essig, Mardon, Papucci, Volansky, Zhong, 2013

- Avoid beam dump bounds: $\alpha_d \lesssim 10^{-4}$
- E787+E949: $K \to \pi +$ nothing

HD, Lee, Marciano, Phys. Rev. D **89**, (2014)



- Possible production and detection of *DM beams* in experiments

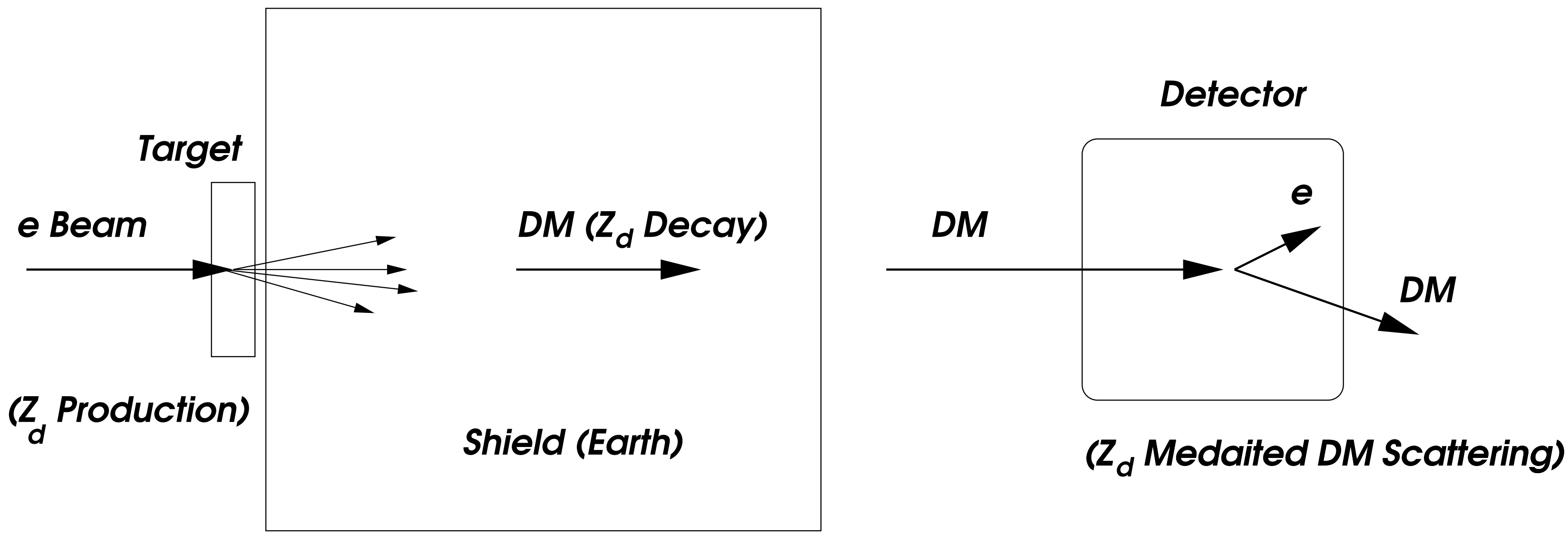
- p or e on fixed target $\Rightarrow$ production of Z_d (meson decays, bremsstrahlung,. . .)

Batell, Pospelov, Ritz, 2009 (p beam); Izaguirre, Krnjaic, Schuster, Toro, 2013 (e beam dump)

- Relativistic Z_d beam decays into DM particles

- DM interactions with detector via Z_d exchange

Example:



Dark Z

HD, Lee, Marciano, 1203.2947

- Z_d may also have mass mixing with SM Z

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

$$\boxed{\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta}$$

$\delta \ll 1$ a model-dependent parameter

- M_0 leads to Z-Z_d mixing angle ξ given by: $\tan 2\xi \simeq 2\frac{m_{Z_d}}{m_Z}\delta = 2\varepsilon_Z$
- Induced interactions with kinetic and mass mixing

$$\mathcal{L}_{\text{int}} = \left(-e\varepsilon J_\mu^{em} - \frac{g}{2\cos\theta_W}\varepsilon_Z J_\mu^{NC}\right) Z_d^\mu$$

$J_\mu^{NC} = \sum_f (T_{3f} - 2Q_f \sin^2\theta_W)\bar{f}\gamma_\mu f - T_{3f}\bar{f}\gamma_\mu\gamma_5 f$; $T_{3f} = \pm 1/2$ and $\sin^2\theta_W \simeq 0.23$

- Neutral current coupling of Z_d like a Z, suppressed by ε_Z: "dark" Z

Notation: Z_d dark photon or dark Z, depending on the context

A Concrete Dark Z Model

- Mass mixing can naturally occur in a 2HDM

- Type I 2HDM: H_1 and H_2, where only H_1 has $Q_d \neq 0$
  - $U(1)_d$ as protective symmetry for FCNCs instead of the usual $\mathbb{Z}_2$
  - SM fermions only couple to H_2 (SM-like); $\langle H_i \rangle = v_i$
  - Generally, also a dark sector Higgs particle ϕ with $\langle \phi \rangle = v_d$

$$m_Z \simeq \frac{g}{2\cos\theta_W}\sqrt{v_1^2 + v_2^2} \quad \text{and} \quad m_{Z_d} \simeq g_d Q_d \sqrt{v_d^2 + v_1^2}$$

- With $\tan\beta = v_2/v_1$ and $\tan\beta_d = v_d/v_1$ we get

$$\varepsilon_Z \simeq (m_{Z_d}/m_Z)\cos\beta\cos\beta_d \Rightarrow \delta \simeq \cos\beta\cos\beta_d$$

- H_1 has $Q_Y Q_d \neq 0$ $\rightarrow$ generally also expect kinetic mixing

Dark Z Phenomenology

HD, Lee, Marciano, 2012

- "Dark" parity violation [independent of $\text{Br}(\text{Z}_\text{d} \to \text{visible})$]

Polarized electron scattering, atomic parity violation, ...

- Flavor physics ($m_{Z_d} < m_{\text{meson}}$)

- Longitudinal Z_d enhancement $\sim E/m_{Z_d}$

$\{\text{Br}(\text{K}^+ \to \pi^+ \text{Z}_\text{d})_\text{long} \simeq 4 \times 10^{-4}\delta^2 \quad ; \quad \text{Br}(\text{B} \to \text{KZ}_\text{d})_\text{long} \simeq 0.1\delta^2\} \to |\delta| \lesssim 10^{-3}$

- Rare Higgs decays, *e.g.* $H \to ZZ_d$ (on-shell Z_d) ATLAS Collaboration, 2015

- In 2HDM realization there could be other signals

- Dominant $H^\pm \to W^\pm Z_d$ (tree-level) for $m_{H^\pm} \lesssim m_t$

HD, Marciano, Ramos, Sher, 2014
Lee, Kong, Park, 2014

Dark Z and Parity Violation

- Low Q^2 $(< m_{Z_d}^2)$ parity violation from Z-Z_d mixing

- Z_d effects can be parameterized by HD, Lee, Marciano, 2012

$$G_F \to \rho_d G_F \quad \text{and} \quad \sin^2\theta_W \to \kappa_d \sin^2\theta_W$$

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

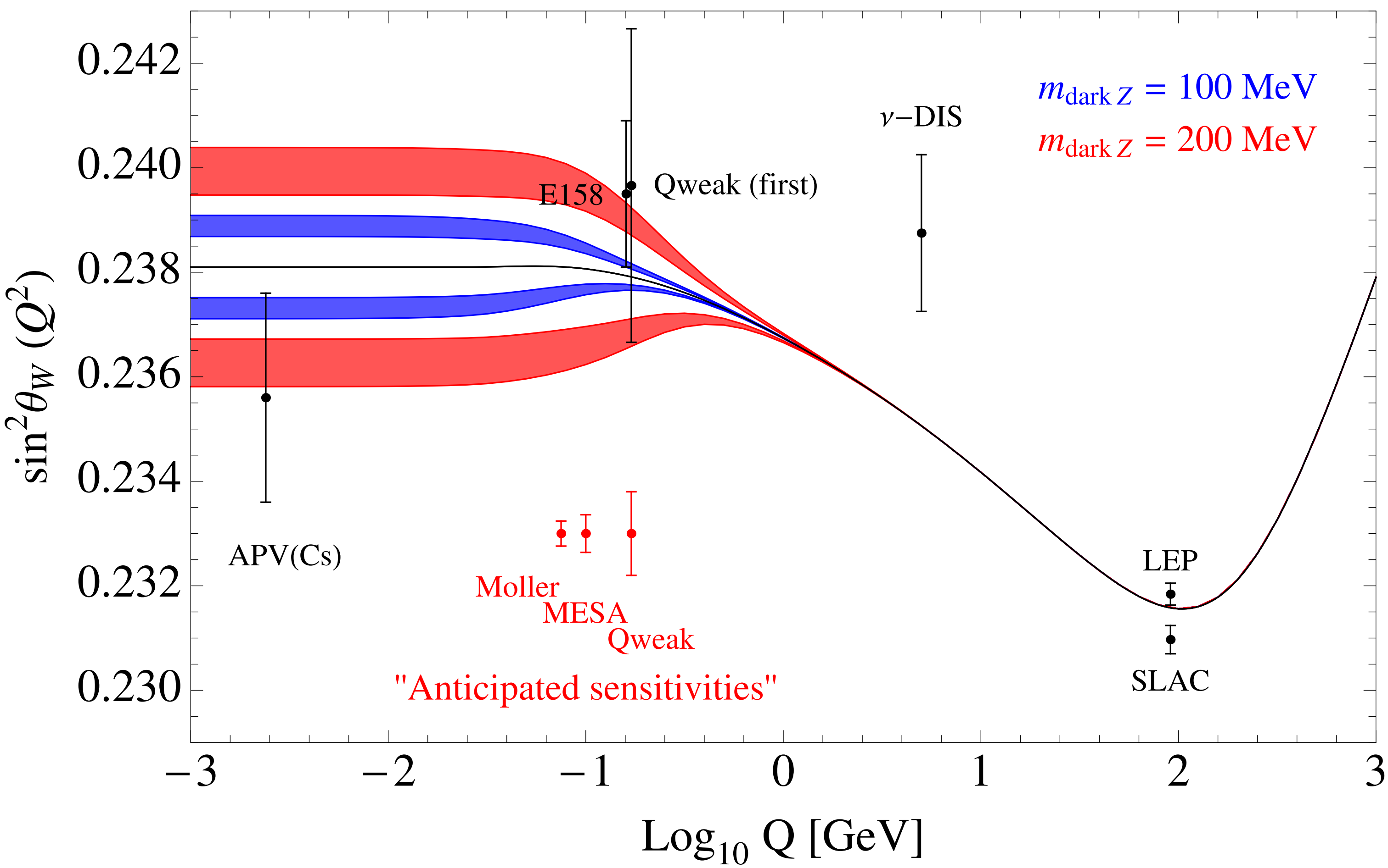
- Leads to variation of $\sin^2\theta_W$ with Q^2:

$$\boxed{\Delta \sin^2\theta_W(Q^2) = -\varepsilon\delta \frac{m_Z}{m_{Z_d}} \sin\theta_W \cos\theta_W f\left(Q^2/m_{Z_d}^2\right)}$$

$$f\left(Q^2/m_{Z_d}^2\right) = 1/(1 + Q^2/m_{Z_d}^2)$$

Running of $\sin^2\theta_W$ with Q^2

From HD, Lee, Marciano, Phys. Rev. D **89**, no. 9, 095006 (2014)



- Black curve: SM running Marciano, Sirlin, 1981; Czarnecki, Marciano, 1996
- Z_d parameters: $|\varepsilon| \sim |\delta| \sim$ few $\times\, 10^{-3}$ (for $g_\mu - 2$)
- Two branches corresponding to $\varepsilon\delta$ sign ambiguity ($\Delta \sin^2\theta_W \propto \varepsilon\delta$)

Rare Higgs Decay $H \to ZZ_d$

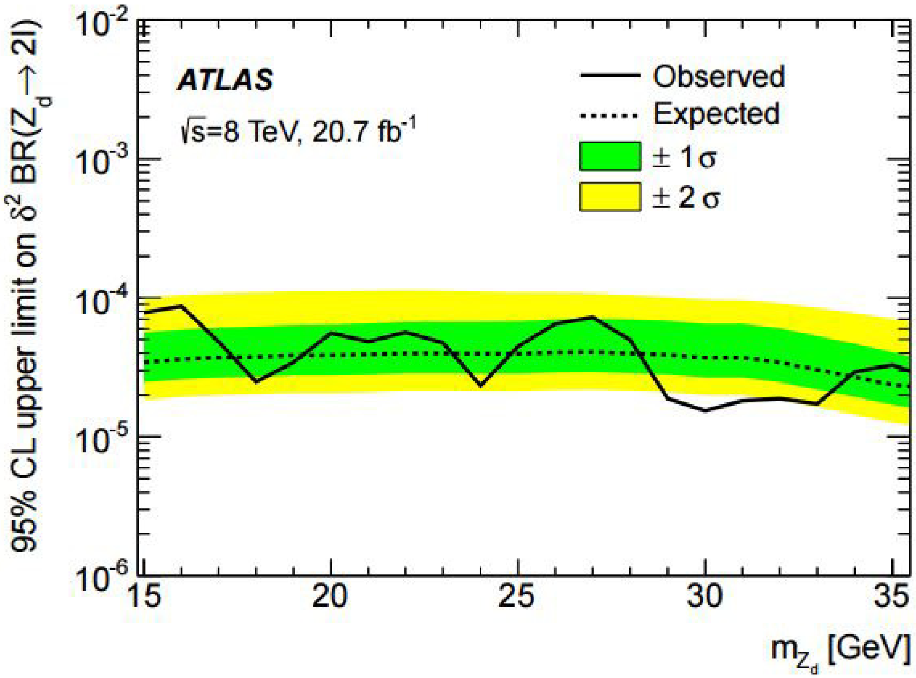
- ATLAS search for $m_{Z_d} > 15$ GeV (no lepton jets)
- Non-negligible m_{Z_d}: $\delta' \equiv \delta + \varepsilon\,(m_{Z_d}/m_Z)\tan\theta_W$
- $\mathrm{Br}(H \to ZZ_d) \approx (16-18)\delta'^2$
- EW precision constraints: $\varepsilon \lesssim 0.03$

Hook, Izaguirre, Wacker, 2010

Curtin, Essig, Gori, Shelton, 2014

- $\delta'^2 \lesssim \dfrac{10^{-4}}{\mathrm{Br}(Z_d \to \ell^+\ell^-)}$ (at 2σ)
  - $\mathrm{Br}(Z_d \to \ell^+\ell^-) \sim 0.3$ for $\mathrm{Br}(Z_d \to \mathrm{SM}) = 1$
  - Br $\ll 0.3$ if $Z_d \to$ dark states
- $|\varepsilon\delta'| \lesssim 0.0008$

(Allowing some cancellation with δ')



From G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **92**, no. 9, 092001 (2015)

Measurements of $\sin^2\theta_W$

E.g., Kumar, Mantry, Marciano, Souder, 1302.6263

- SM Prediction (EW fit): $\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.23124(12)$

- Cs APV: $\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.2283(20)$ at $\langle Q\rangle \simeq 2.4$ MeV

- E158 (Moller): $\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.2329(13)$ at $\langle Q\rangle \simeq 160$ MeV

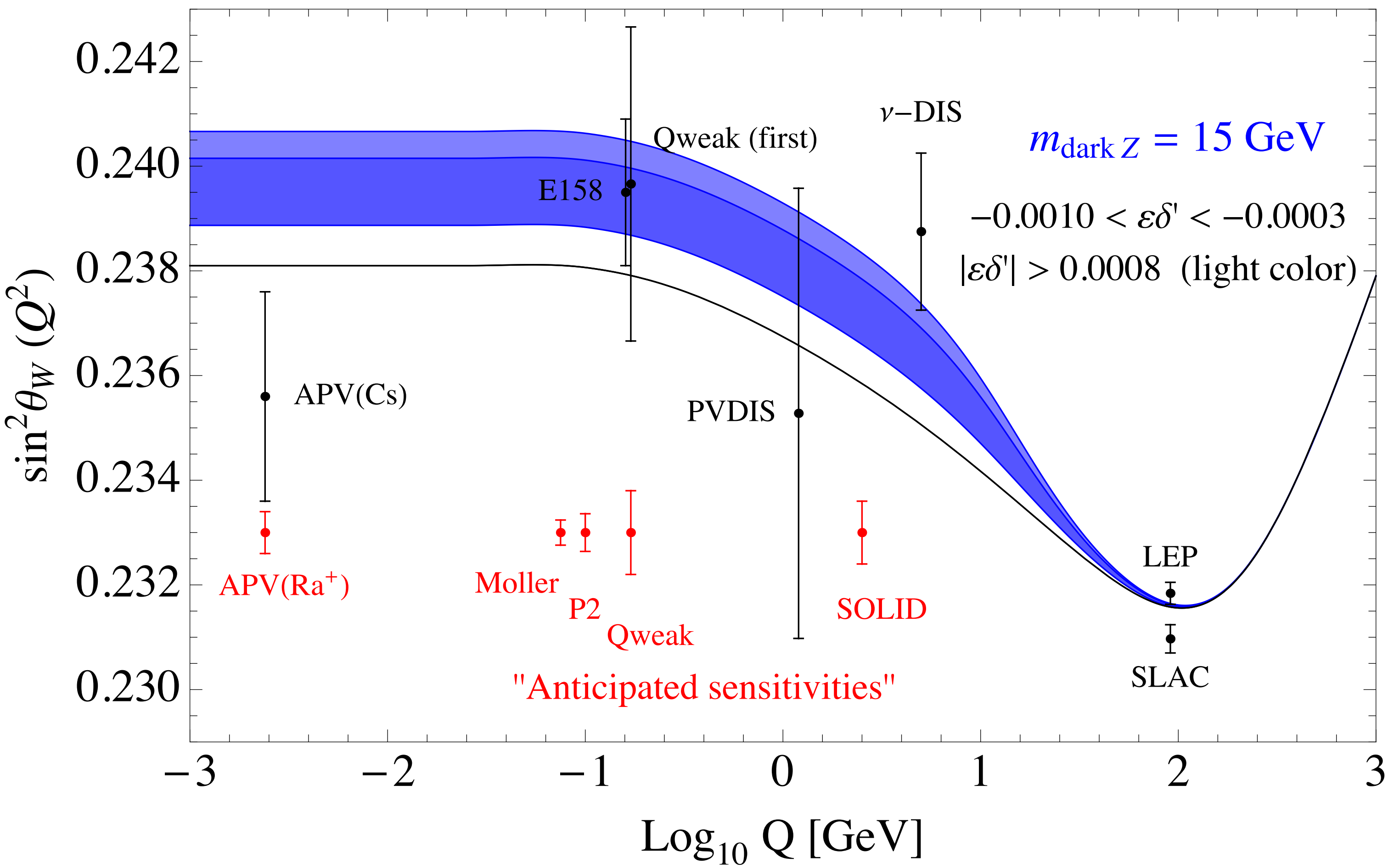
- NuTeV ($\nu_\mu N$): $\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.2356(16)$ at $\langle Q\rangle \simeq 5$ GeV

- Low Q^2 weighted average:

$$\langle\sin^2\theta_W(m_Z)_{\overline{\rm MS}}\rangle = 0.2328(9) \to \Delta\sin^2\theta_W \approx 0.0016(9)$$

- $\Delta\sin^2\theta_W \approx -0.42\,\varepsilon\,\delta'\,(m_Z/m_{Z_d})$ HD, Lee, Marciano, 2015

From HD, Lee, Marciano, Phys. Rev. D **92**, no. 5, 055005 (2015)



- $\varepsilon\delta' < 0$ range corresponds to 1 σ band for $\sin^2\theta_W$ deviation
- The upper region of the band: tension with constraints
- Interesting implications for planned experiments at different Q^2
- Near future: Q_{weak} results can shed further light on this scenario

Concluding Remarks

- Dark sector may have its own forces, mediated by dark bosons
- Z_d from a $U(1)_d$
- Dark Higgs ϕ, possibly associated with $U(1)_d$ breaking

- Kinetic mixing: dark photon
- Simple extension that could address $g_\mu - 2$; $m_{Z_d} \lesssim 1$ GeV

- Mass-mixing with Z: dark Z
- New low energy source of parity violation: $\Delta \sin^2 \theta_W(Q^2)$
- Opportunities for polarized electron scattering experiments
- Potential correlated signals in *rare Higgs decays*