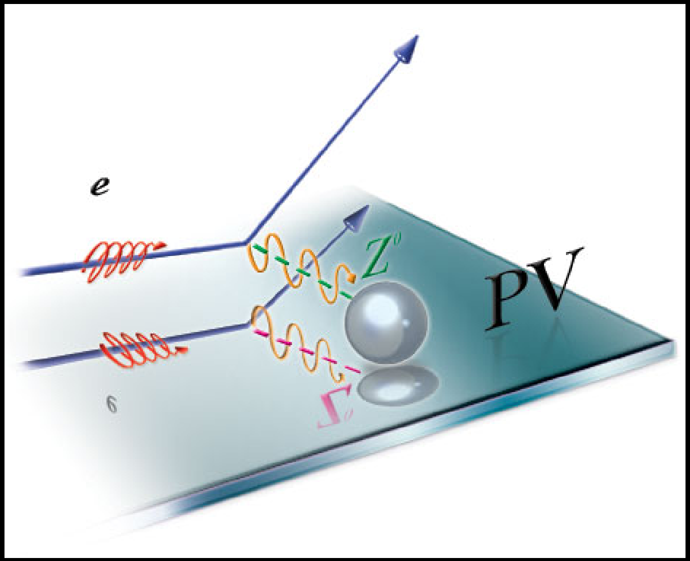
Dark Z and Parity Violation

Hooman Davoudiasl

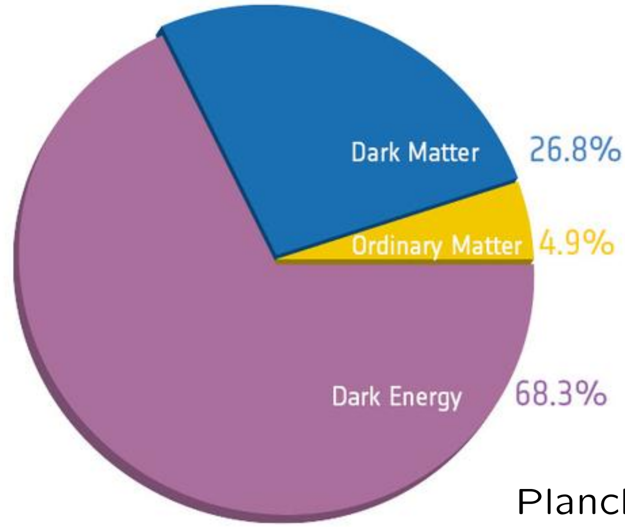
HET Group, Brookhaven National Laboratory



INTENSE ELECTRON BEAMS WORKSHOP

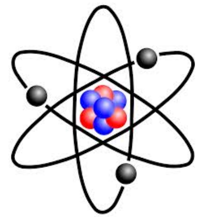
CORNELL UNIVERSITY, JUNE 17-19, 2015

- **Mostly "Dark" Universe**



Planck

- Known "visible" matter: $\sim 5\%$ of total



- Unknown dark matter (DM): $\sim 27\%$

  - Stable on cosmological time scales
  - Feeble interactions with ordinary matter
  - May be from a dark sector (no direct coupling to SM)
  - Analogy with SM: dark sector may contain matter and forces

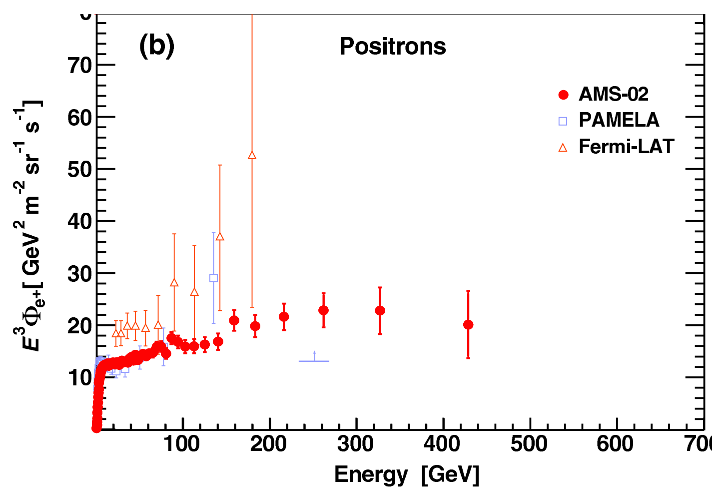
• Assume a “dark” sector force $U(1)_d$

- Minimal addition that captures key physics
- Mediated by vector boson Z_d of mass m_{Z_d} coupling g_d
- Interaction with SM via *mixing*

• $m_{Z_d} \lesssim 1$ GeV may be motivated

- DM interpretation of astrophysical data

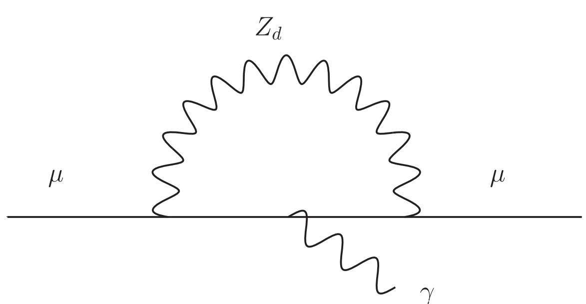
Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008



AMS Collab., PRL 113, 121102 (2014)

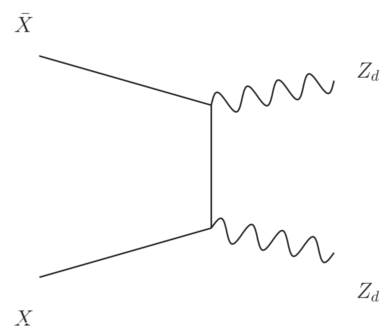
- May explain 3.6σ $g_\mu - 2$ anomaly

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 287(80) \times 10^{-11}$$



- $\Omega_{\rm visible}$ similar to $\Omega_{\rm DM}$

- GeV scale asymmetric DM models
- Efficient conjugate pair annihilation into light Z_d

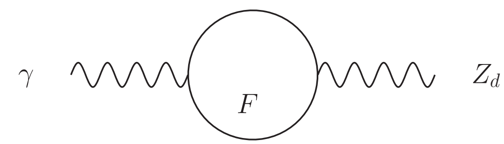


Dark Photon

- Kinetic mixing: Z_d of $U(1)_d$ and B of SM $U(1)_Y$ Holdom, 1986

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

$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$



  - 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 by $O(m^2_{Z_d}/m^2_Z) \ll 1$

- Active experimental program to search for dark photon

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

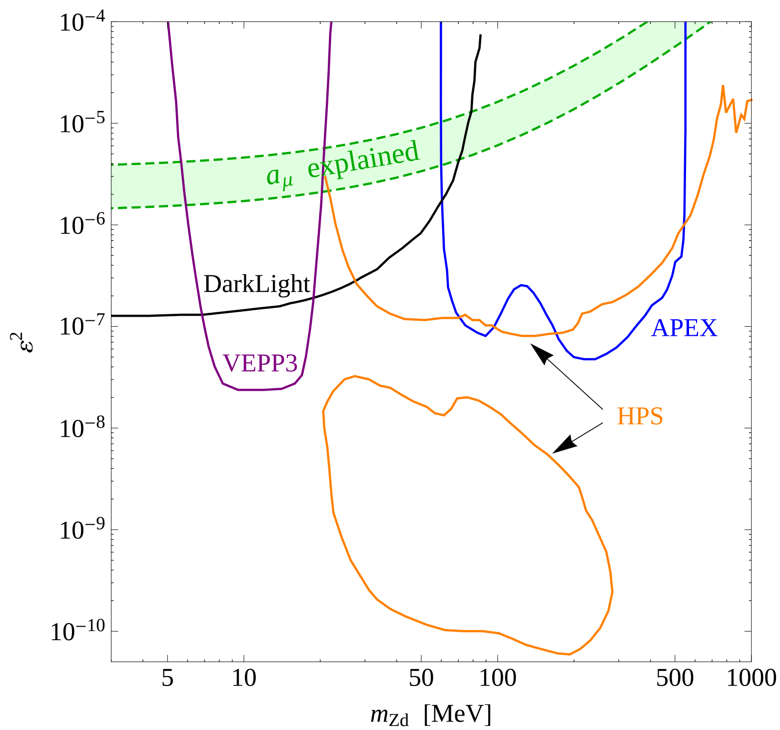
- An early experimental target: $g_\mu - 2$ parameter space

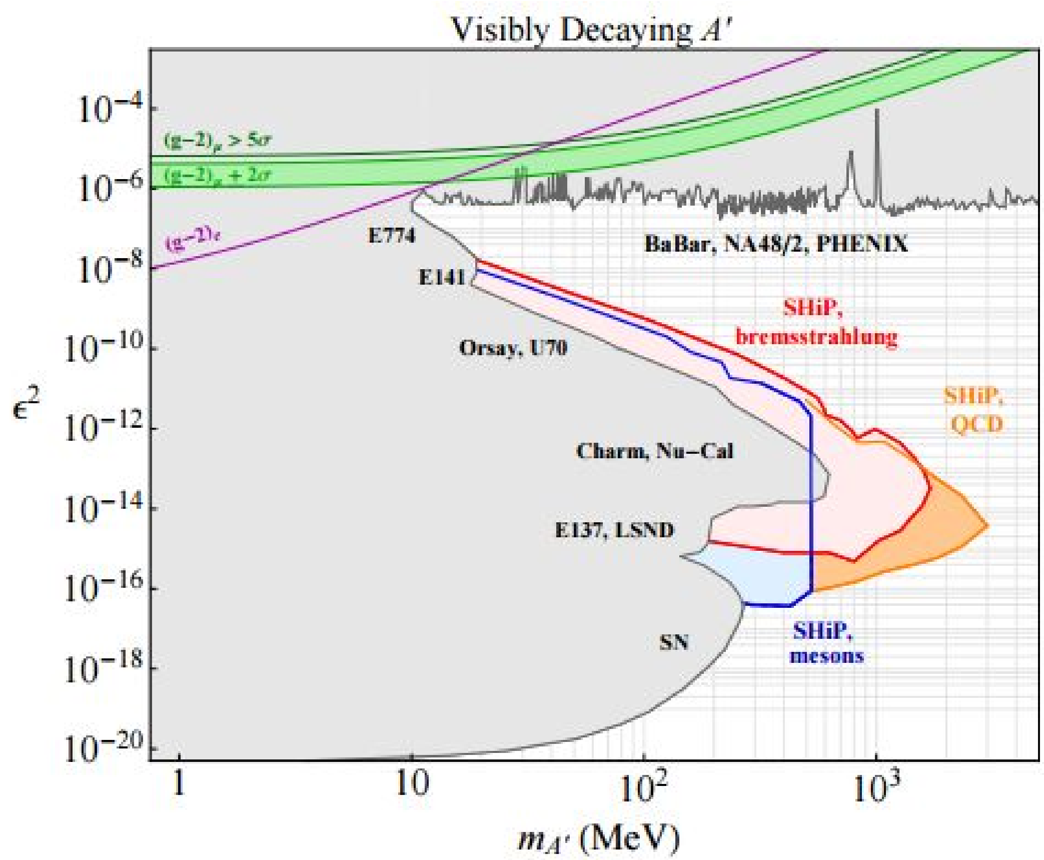
Fayet, 2007 (direct coupling) Pospelov, 2008 (kinetic mixing)

$\Delta a_\mu^{Z_d}(\text{vector}) = \frac{\alpha}{2\pi}\varepsilon^2 \int_0^1 dz \frac{2z(1-z)^2}{(1-z)^2+x^2 z}$

Leveille, 1978

Future Prospects





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

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

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)
  - Generally, also a dark sector Higgs particle H_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

- Additional dark Z phenomenology with mass-mixing

HD, Lee, Marciano, 2012

- "Dark" parity violation mediated by light Z_d
  - Atomic parity violation
  - Polarized electron scattering at low Q^2

$$|\delta| \lesssim 10^{-2} \qquad (\varepsilon \sim 2 \times 10^{-3},\ m_{Z_d} \sim 100 \text{ MeV})$$

- Longitudinal Z_d enhancement $\sim E/m_{Z_d}$
  - $Z_{d,\text{long}}$ with $m_{Z_d} \ll E$: Goldstone equivalence theorem
  - Effects from flavor physics: $K \to \pi Z_d$, $B \to K Z_d \to |\delta| \lesssim 10^{-3}$

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

  - High energy data, *e.g.* rare Higgs decay $H \to Z Z_d$ ($m_{Z_d} \ll m_Z$, on-shell Z_d)

1505.07645, ATLAS Collaboration

- 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:

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

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

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

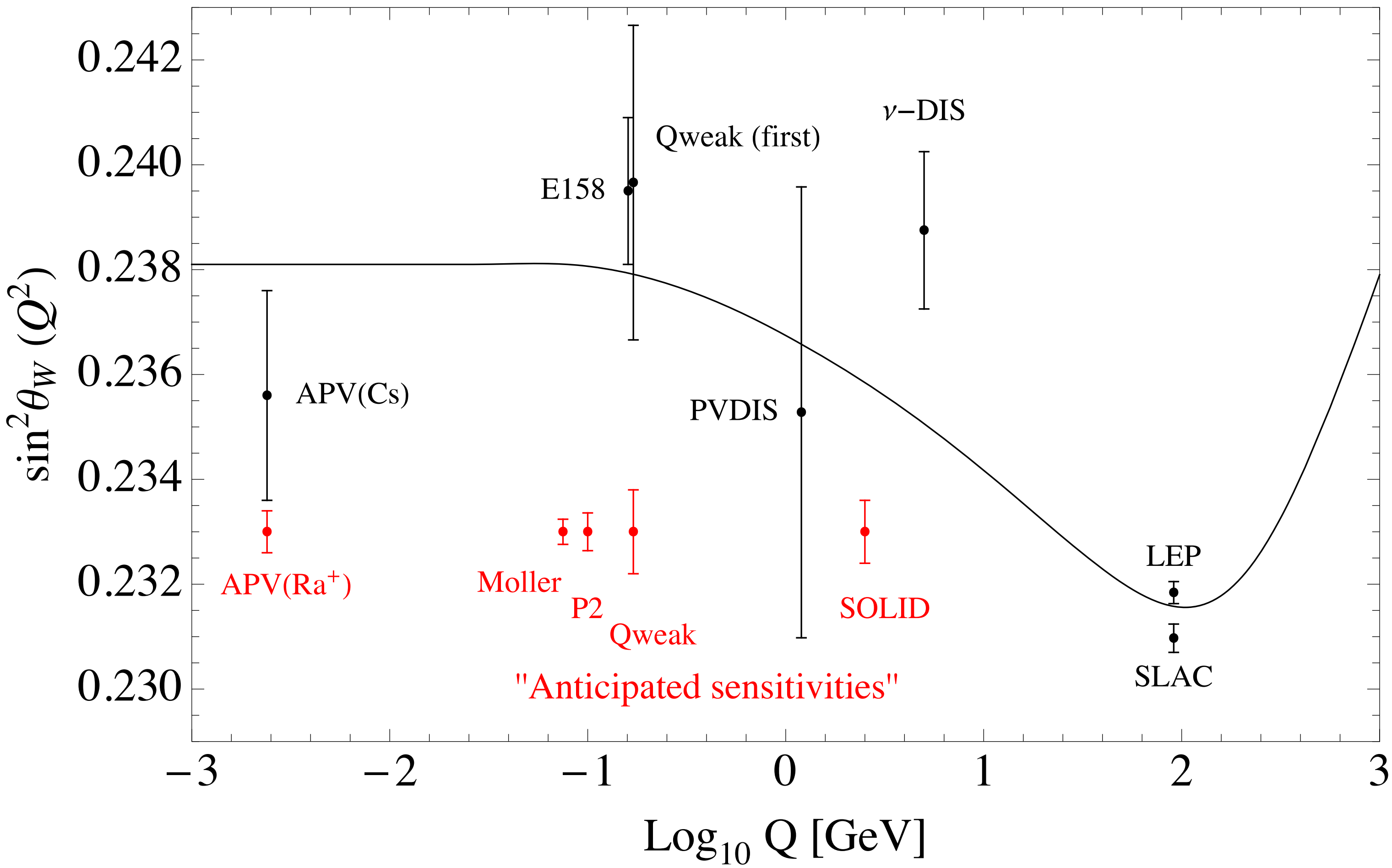
- Weighted average:

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

- Low Q^2 data $\Rightarrow \sim 1.8\,\sigma$ deviation

Current Results and Future Prospects

From HD, Lee, Marciano, work in progress



- Black curve: SM running   Marciano, Sirlin, 1981; Czarnecki, Marciano, 1996

$\sin^2\theta_W$ Deviation and Z_d

- Deviation: potential faint indication of new physics?

- Fit could be improved with a Z_d

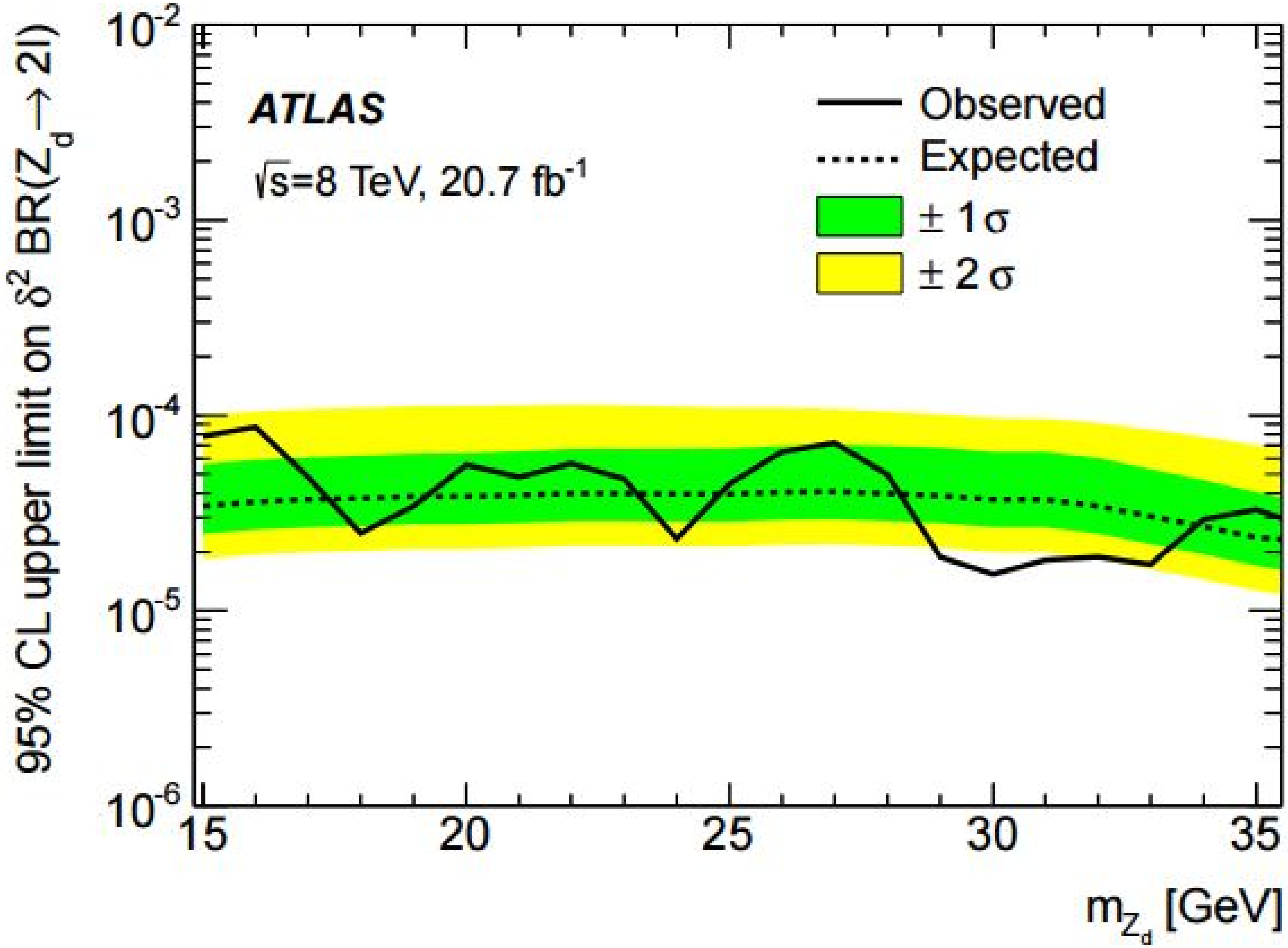
- NuTeV $\langle Q\rangle \simeq 5$ GeV: intermediate scale Z_d

- Let us consider the range $\sim 10-35$ GeV HD, Lee, Marciano, work in progress
  - Set $g_\mu - 2$ aside
  - Beyond reach of low energy direct search (flavor, fixed target, . . .)
  - Range motivated by rare Higgs decay $H \to ZZ_d$ kinematics

- EW precision constraints: $\varepsilon \lesssim 0.03$ *E.g.*, Curtin, Essig, Gori, Shelton, 2014

- Mass mixing $\delta' \equiv \delta + \varepsilon\,(m_{Z_d}/m_Z)\tan\theta_W$

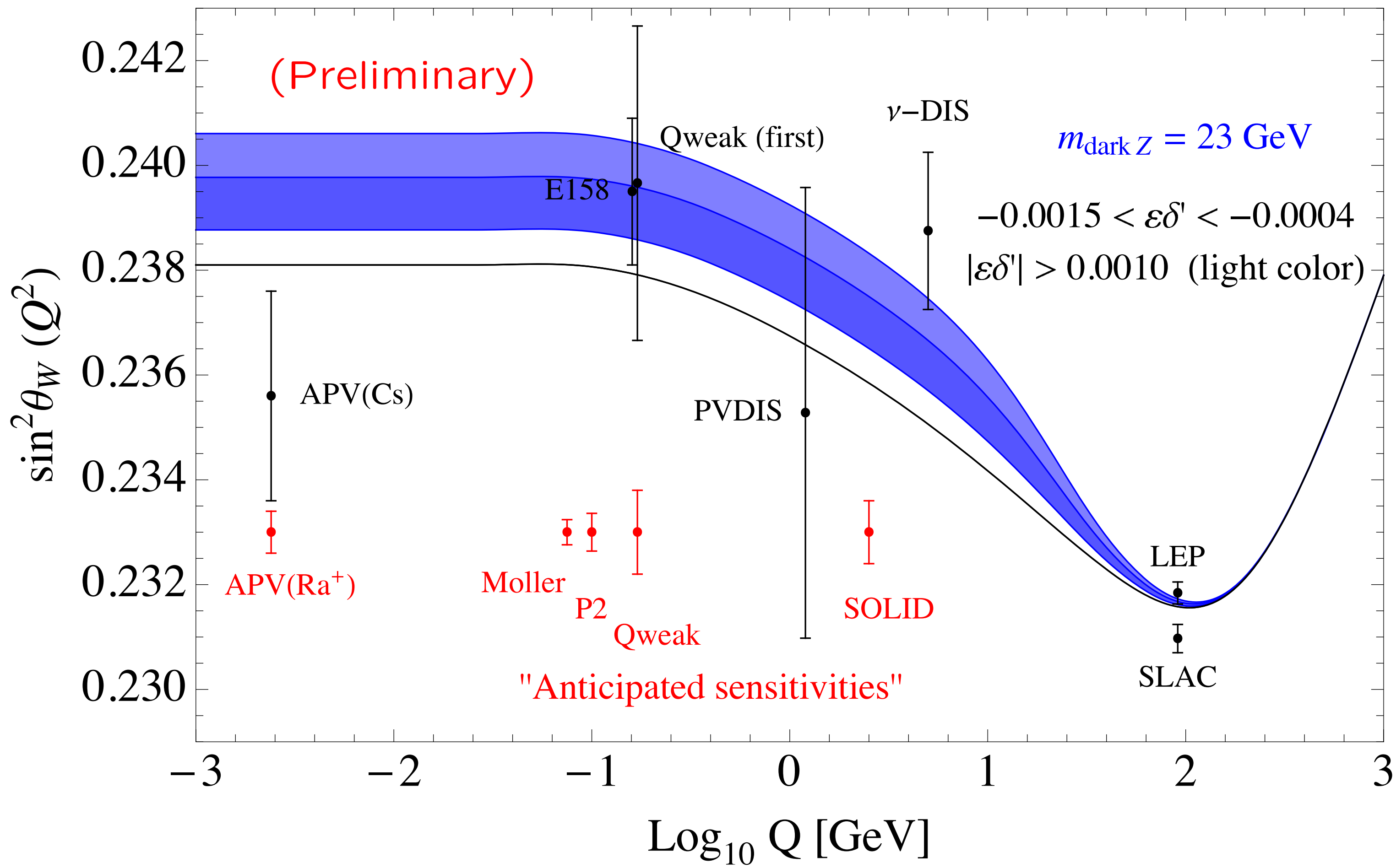
- $\delta'^2 \lesssim \frac{10^{-4}}{\mathrm{Br}(Z_d\to\ell^+\ell^-)}$ (at $2\,\sigma$) from $H \to ZZ_d$ search ATLAS, 2015



From G. Aad *et al.* [ATLAS Collaboration], arXiv:1505.07645 [hep-ex]

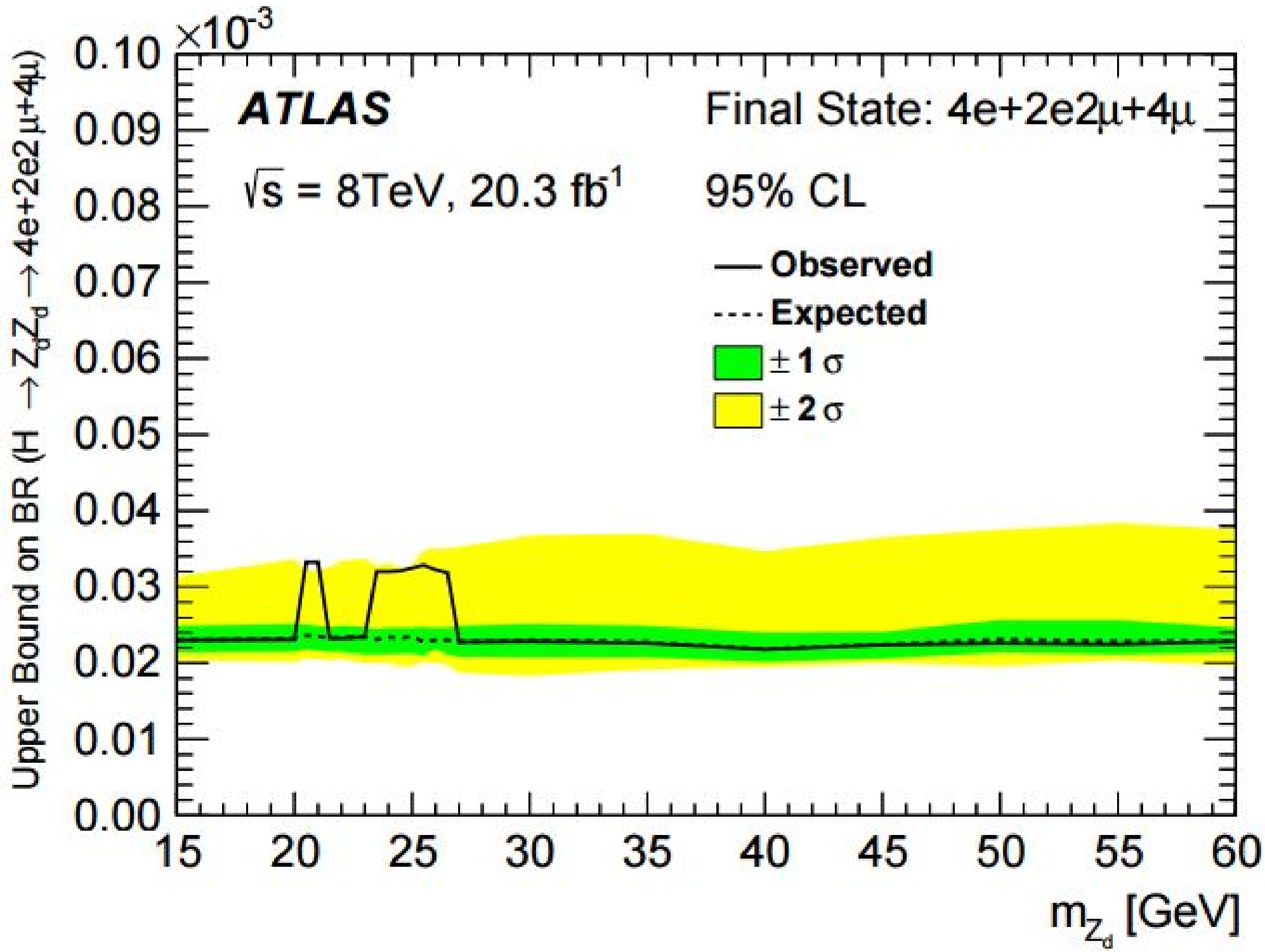
- $\text{Br}(\text{Z}_\text{d} \to \ell^+\ell^-) \sim 0.3$ for $\text{Br}(\text{Z}_\text{d} \to \text{SM}) = 1$
- Br may be $\ll 0.3$ if Z_d can decay into $U(1)_d$ charged (DM) states

HD, Lee, Marciano, work in progress



- $\varepsilon\delta' < 0$ 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

A tenuous hint from ATLAS $H \to Z_d Z_d$ search?



From G. Aad *et al.* [ATLAS Collaboration], arXiv:1505.07645 [hep-ex]

- Lower (higher) mass event from 4μ ($4e$); each 1.7 σ (local)
- Higgs mixing with a dark scalar (Higgs) with $Q_d \neq 0$

Concluding Remarks

- Dark sector may have its own forces, mediated by dark bosons
- Minimal example: Z_d from a $U(1)_d$
- The new bosons may be light, but weakly coupled to SM

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

- Mass-mixing with Z: dark Z
- New low energy source of parity violation
- Induces shift, as a function of Q^2, in $\sin^2\theta_W$
- Opportunities for polarized electron scattering experiments
- Potential correlated signals in rare Higgs decays
- Intermediate $m_{Z_d} \sim 10 - 35$ GeV an interesting target (deviations in $\sin^2\theta_W$)