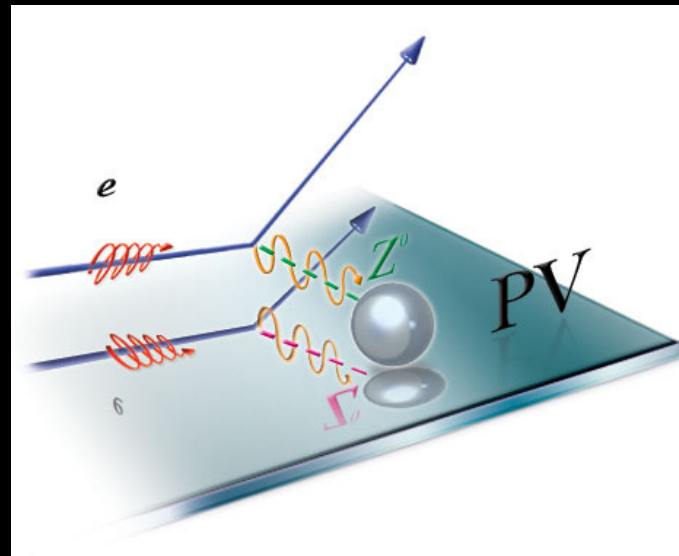


Dark Parity Violation and Rare Higgs Decays

Hooman Davoudiasl

HET Group, Brookhaven National Laboratory

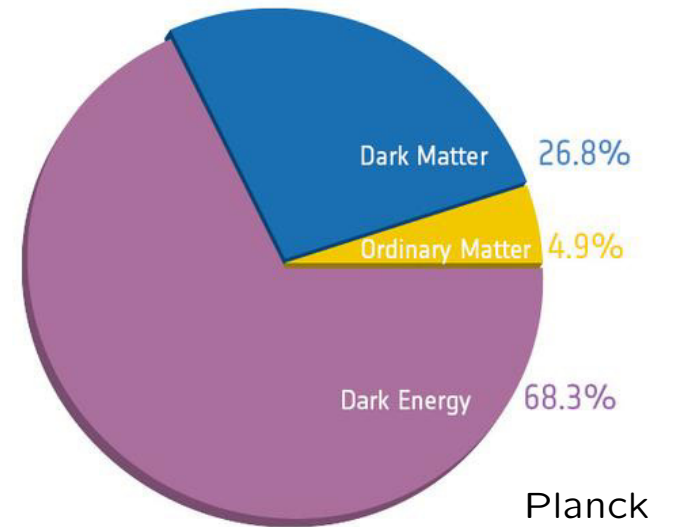
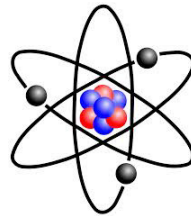


Workshop at ECT*, Trento, Italy

August 1-5, 2016

- The Universe is mostly “dark”

- Ordinary “visible” matter $\sim 5\%$



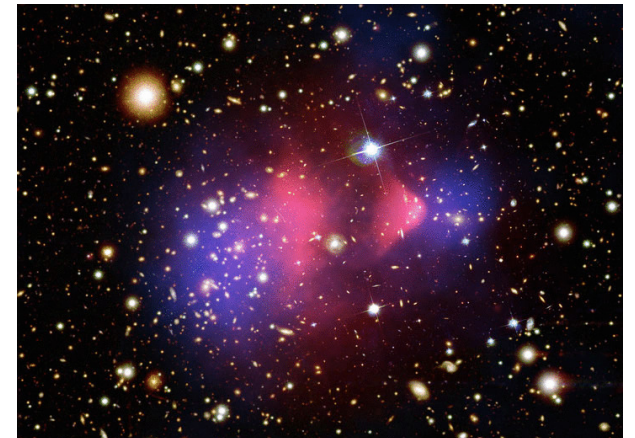
- Dark matter (DM) $\sim 27\%$

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

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

- 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 $U(1)_d$

- Possible 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, ...

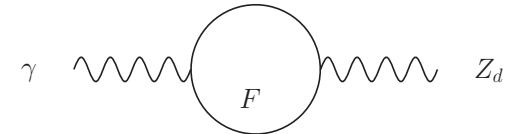
Dark Photon

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

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

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

- May be loop induced: $\varepsilon \sim eg_d/(4\pi)^2 \lesssim 10^{-3}$
- Remove cross term, via field redefinition
 - $B_\mu \rightarrow B_\mu + \frac{\varepsilon}{\cos \theta_W} Z_{d\mu}$
 - Z - Z_d mass matrix diagonalization
- After redefinition, Z_d couples to EM current $J_{em}^\mu = \sum_f Q_f \bar{f} \gamma^\mu f + \dots$



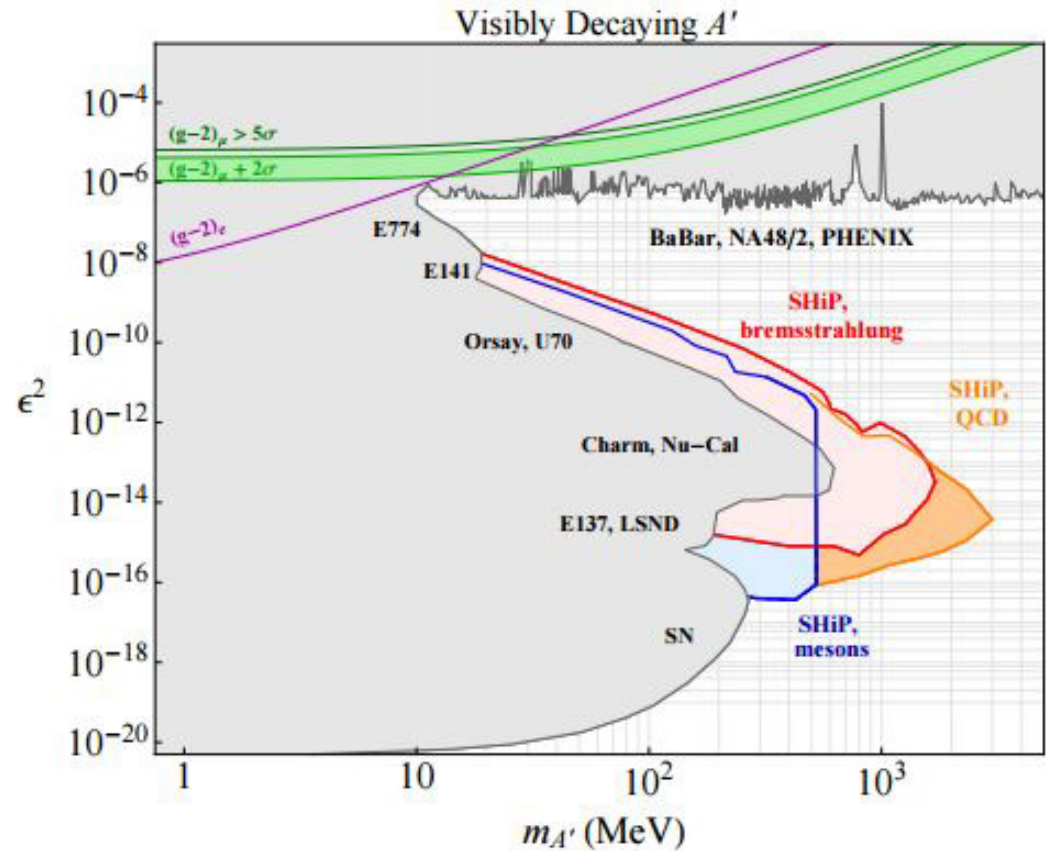
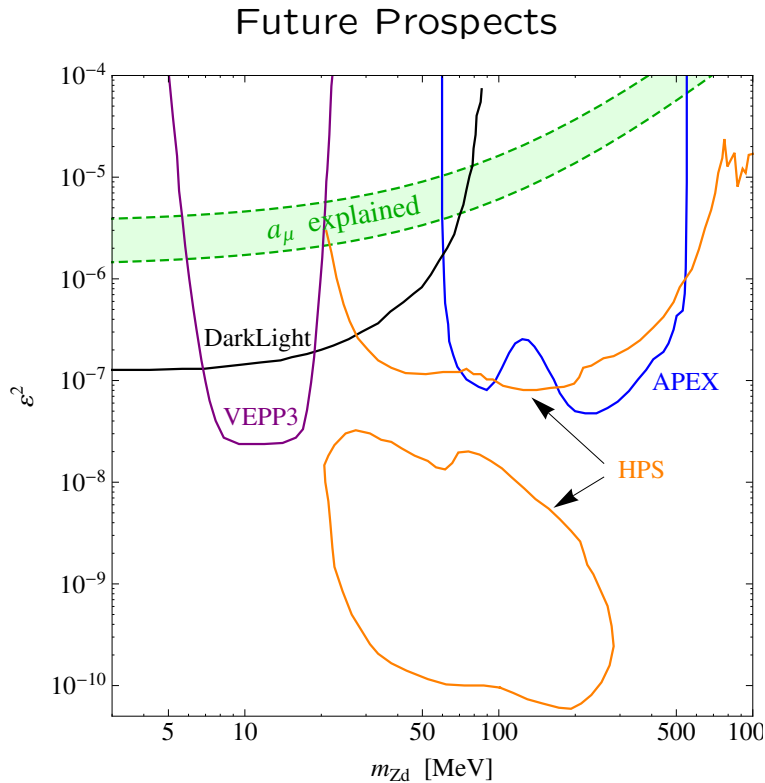
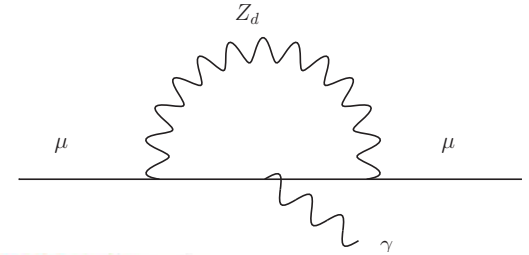
$$\mathcal{L}_{\text{int}} = -e \varepsilon J_{em}^\mu Z_{d\mu}$$

- 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

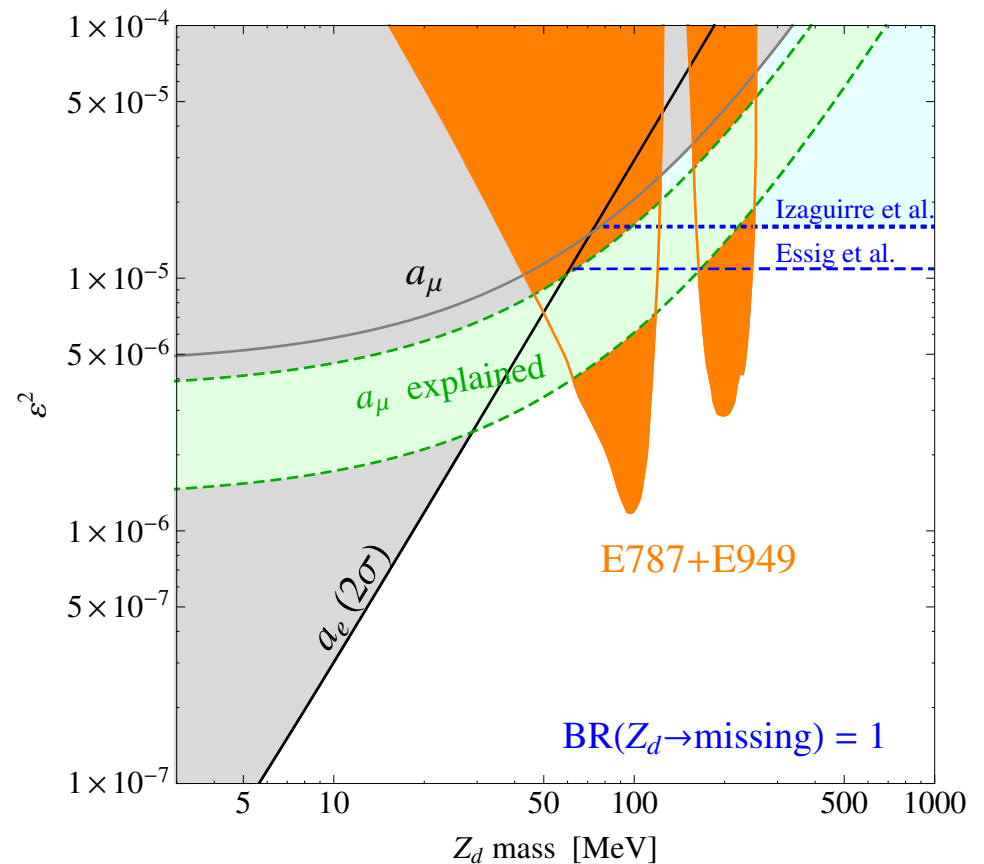
- Dark photon may be “invisible” if \exists dark X with $m_X < m_{Z_d}/2$
- X could be DM, coupled to Z_d with $g_d \gg e\epsilon$: $\text{Br}(Z_d \rightarrow X\bar{X}) \simeq 1$
- $g_\mu - 2$ solution independent of dominant Z_d branching fraction

Constraints:

- Dashed lines: BaBar
Izaguirre, Krnjaic, Schuster, Toro, 2013
Essig, Mardon, Papucci, Volansky, Zhong, 2013

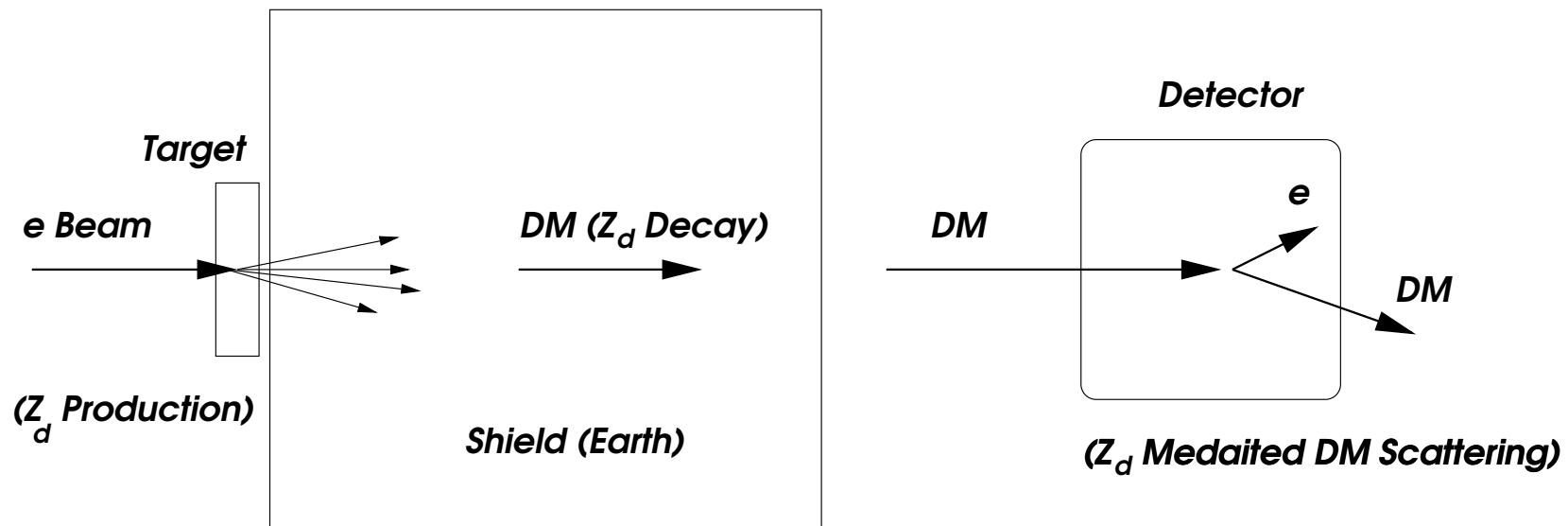
- Avoid beam dump bounds: $\alpha_d \lesssim 10^{-4}$
- E787+E949: $K \rightarrow \pi + \text{nothing}$

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

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

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

- 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 $\text{Br}(Z_d \rightarrow \text{visible})$]

Polarized electron scattering, atomic parity violation, ...

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

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

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

- Rare Higgs decays, e.g. $H \rightarrow Z Z_d$ ($m_{Z_d} \ll m_Z$, on-shell Z_d) [ATLAS Collaboration, 2015](#)

- In 2HDM realization there could be other signals

- Dominant $H^\pm \rightarrow W^\pm Z_d$ (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](#)

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

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

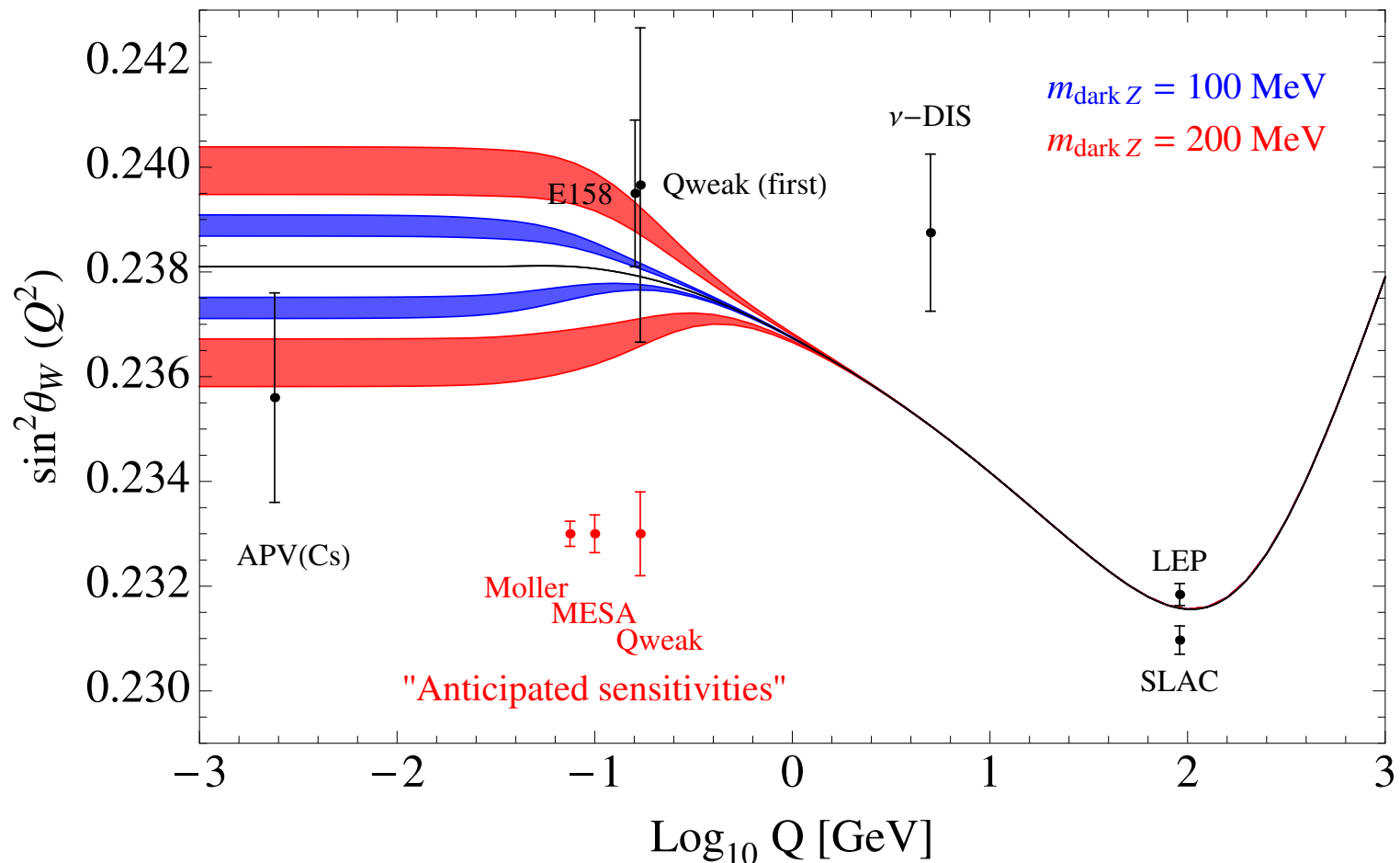
- Leads to variation of $\sin^2 \theta_W$ with Q^2 :

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

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

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: $|\varepsilon| \sim |\delta| \sim \text{few} \times 10^{-3}$ (for $g_\mu - 2$)
- Two branches corresponding to $\varepsilon\delta$ sign ambiguity ($\Delta \sin^2 \theta_W \propto \varepsilon\delta$)

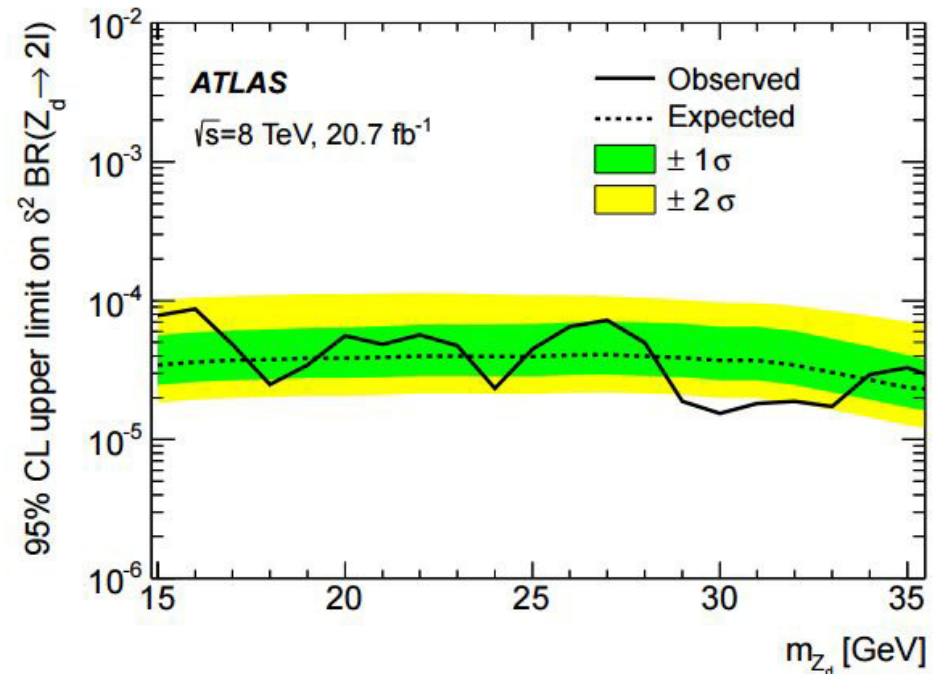
Rare Higgs Decay $H \rightarrow ZZ_d$

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

Hook, Izaguirre, Wacker, 2010

Curtin, Essig, Gori, Shelton, 2014

- $\delta'^2 \lesssim \frac{10^{-4}}{\text{Br}(Z_d \rightarrow l^+l^-)}$ (at 2σ)
- $\text{Br}(Z_d \rightarrow l^+l^-) \sim 0.3$ for $\text{Br}(Z_d \rightarrow \text{SM}) = 1$
- $\text{Br} \ll 0.3$ if $Z_d \rightarrow$ 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 $\sin^2 \theta_W$

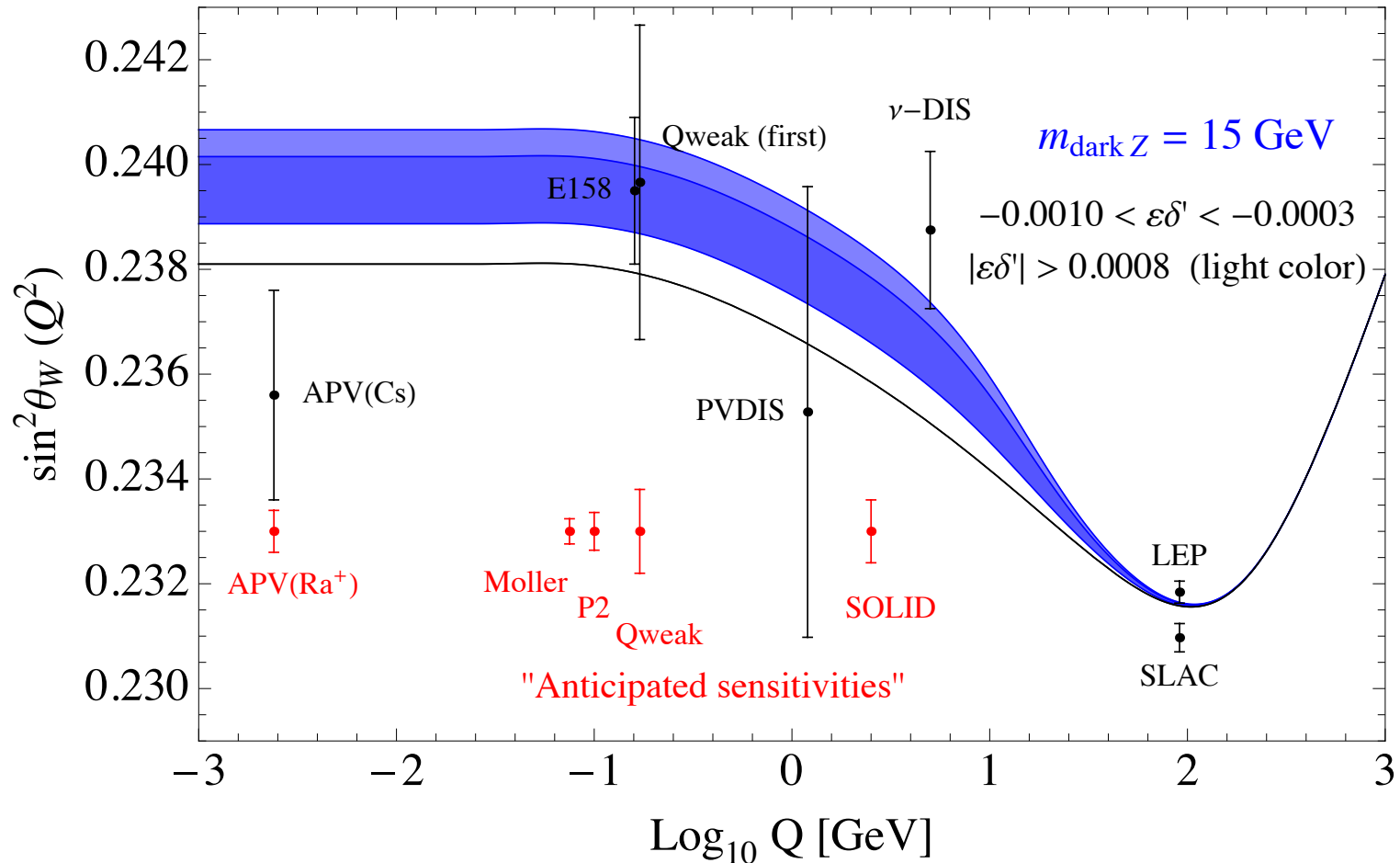
E.g., Kumar, Mantry, Marciano, Souder, 1302.6263

- SM Prediction (EW fit): $\sin^2 \theta_W(m_Z)_{\overline{MS}} = 0.23124(12)$
- Cs APV: $\sin^2 \theta_W(m_Z)_{\overline{MS}} = 0.2283(20)$ at $\langle Q \rangle \simeq 2.4$ MeV
- E158 (Moller): $\sin^2 \theta_W(m_Z)_{\overline{MS}} = 0.2329(13)$ at $\langle Q \rangle \simeq 160$ MeV
- NuTeV ($\nu_\mu N$): $\sin^2 \theta_W(m_Z)_{\overline{MS}} = 0.2356(16)$ at $\langle Q \rangle \simeq 5$ GeV
- Low Q^2 weighted average:

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

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

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

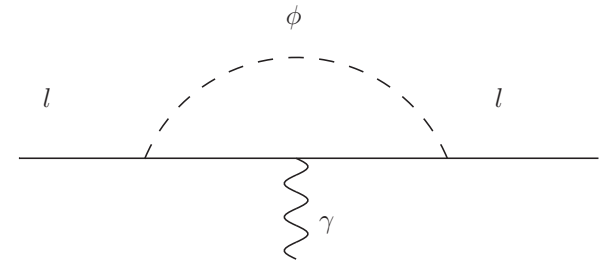


- $\epsilon\delta' < 0$ range corresponds to 1σ band for $\sin^2 \theta_W$ deviation
- The upper region of the band: tension with constraints
- Interesting implications for planned experiments at different Q^2
- Near future: Q_{weak} results can shed further light on this scenario

Moments from a Dark Higgs

Chen, HD, Marciano, Zhang, 2015

- Consider a GeV scale “dark” Higgs ϕ as main source of $g_\mu - 2$
- Potentially associated with $U(1)_d$ breaking
- Effective coupling of ϕ with leptons:



$$\mathcal{L}_{\phi\ell\ell} = -\phi\bar{\ell}\left(\lambda_S^\ell + i\lambda_P^\ell\gamma_5\right)\ell$$

- $\ell = e, \mu, \tau$, and λ_S^ℓ (λ_P^ℓ) CP-even (odd) dark Yukawa coupling
- Can be induced by heavy vector-like fermions (integrated out at low energies)
- Various experimental implications:
 - Direct probes: bump hunting in μ decay and capture, K decay including a μ
 - Potentially observable muon EDM $\lesssim 10^{-23}$ e cm [See also Geng and Ng, 1989](#)
 - Possible lepton flavor violating decays, deviation in $\text{BR}(H \rightarrow \mu^+\mu^-)_{\text{SM}}$
 - Extension to quarks: $\mathcal{L}_{\phi qq} = -\phi\bar{q}\left(\lambda_S^q + i\lambda_P^q\gamma_5\right)q \rightarrow$ Nucleon EDMs

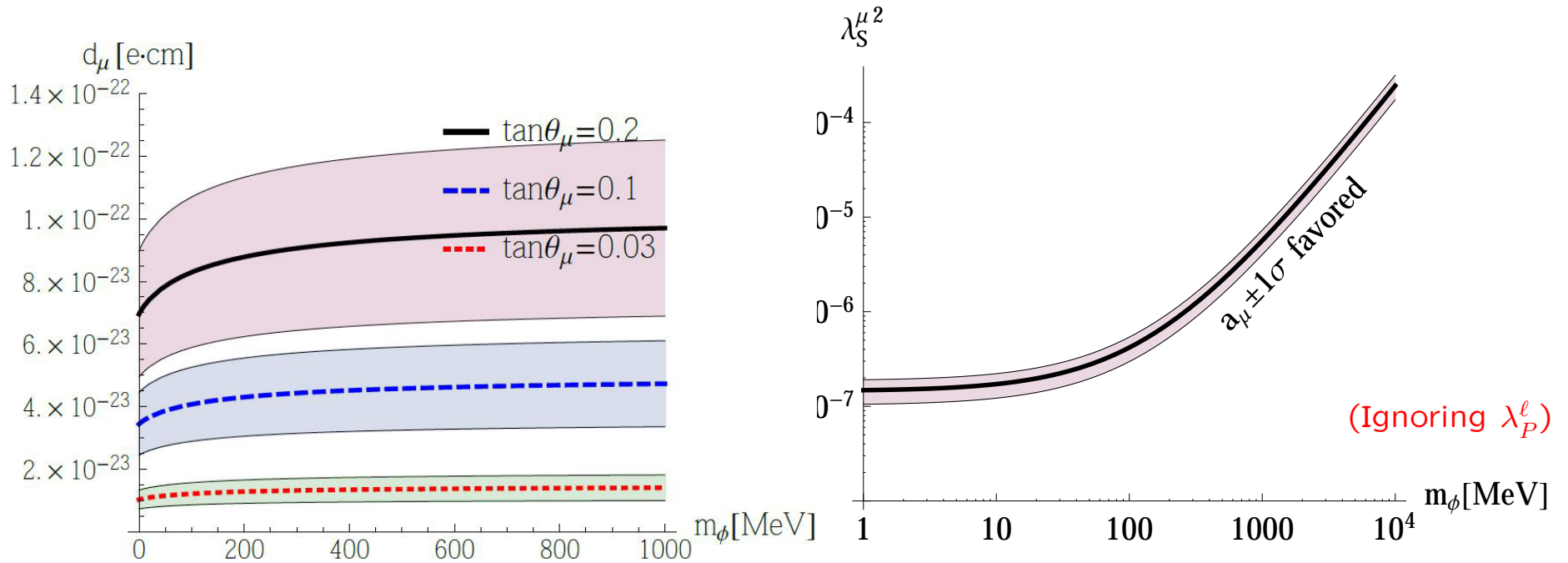


Figure: Muon EDM for various values of CP violating phase, assuming Δa_μ within one σ of measured $g_\mu - 2$; $\tan\theta_\ell = \lambda_P^\ell/\lambda_S^\ell$.

- Current bound $|d_\mu| < 1.8 \times 10^{-19} e \cdot \text{cm}$ Muon (g-2) Collaboration, 2008
- μ storage ring proposals: d_μ with sensitivity $10^{-24} \sim 10^{-25} e \cdot \text{cm}$ Semertzidis et al., 2000, 2003
- Assuming $\lambda_{S,P}^\ell \propto m_\ell$, for $m_\phi \in [10, 1000]$ MeV we get $d_e \sim 10^{-29} - 10^{-28} e \cdot \text{cm}$
- Current bound: $|d_e| < 8.7 \times 10^{-29} e \cdot \text{cm}$ ACME Collaboration, 2013

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*
- Dark Higgs: suppressed induced coupling to muons (fermions)
 - Possible alternative (additional) origin of $g_\mu - 2$
 - Direct low energy probes: μ decay and capture, Kaon decay including μ
 - Potentially observable muon EDM