Running in the Dark Sector

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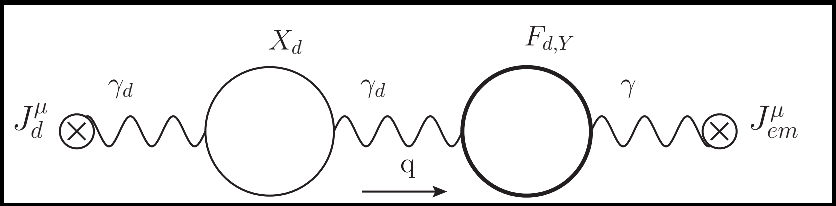
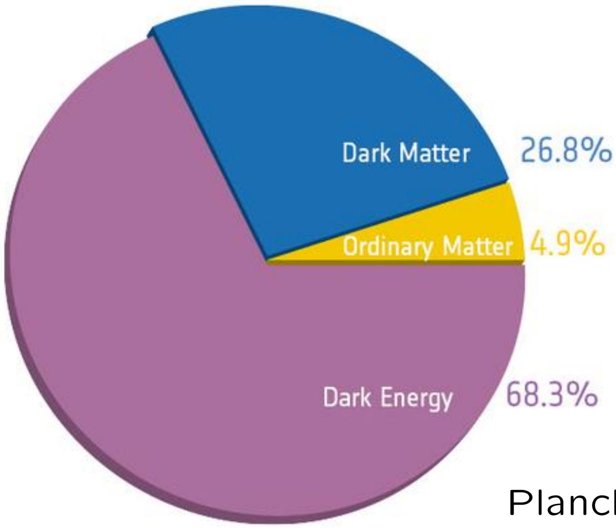


Based on: H.D. and W.J. Marciano, arXiv:1502.07383 [hep-ph]

11th Patras Workshop on Axions, WIMPs and WISPs

June 22-26, 2015, University of Zaragoza, Spain

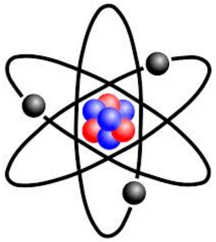
The Big Picture



Planck

- **Mostly "Dark" Universe**

- 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

Dark Forces

- Assume a "dark" sector $U(1)_d$

- Minimal extension that captures key physics
- Mediated by vector boson Z_d of mass m_{Z_d} coupling g_d
- Interaction with SM: dim-4 operator (portal) via *mixing*

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

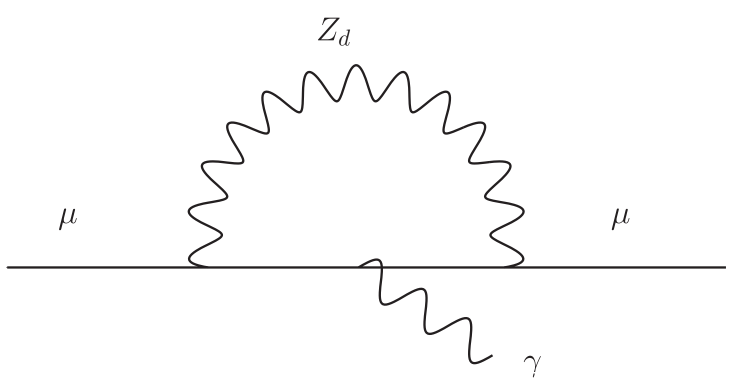
- DM interpretation of astrophysical data

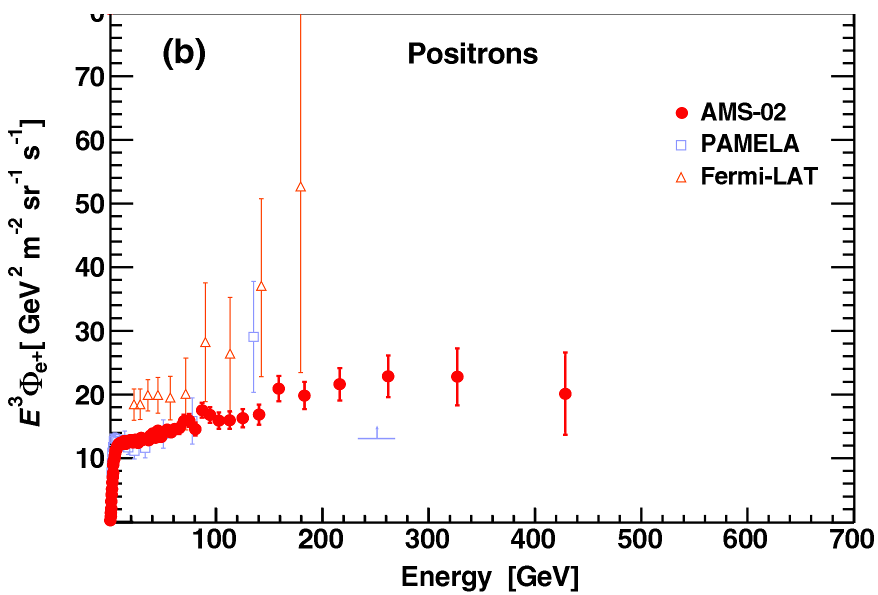
Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

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

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

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





AMS Collab., PRL 113, 121102 (2014)

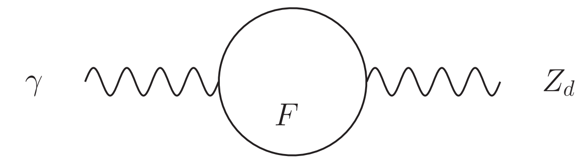
Dark Photon

- 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 $J^\mu_{em} = \sum_f Q_f \bar{f}\gamma^\mu f + \cdots$

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

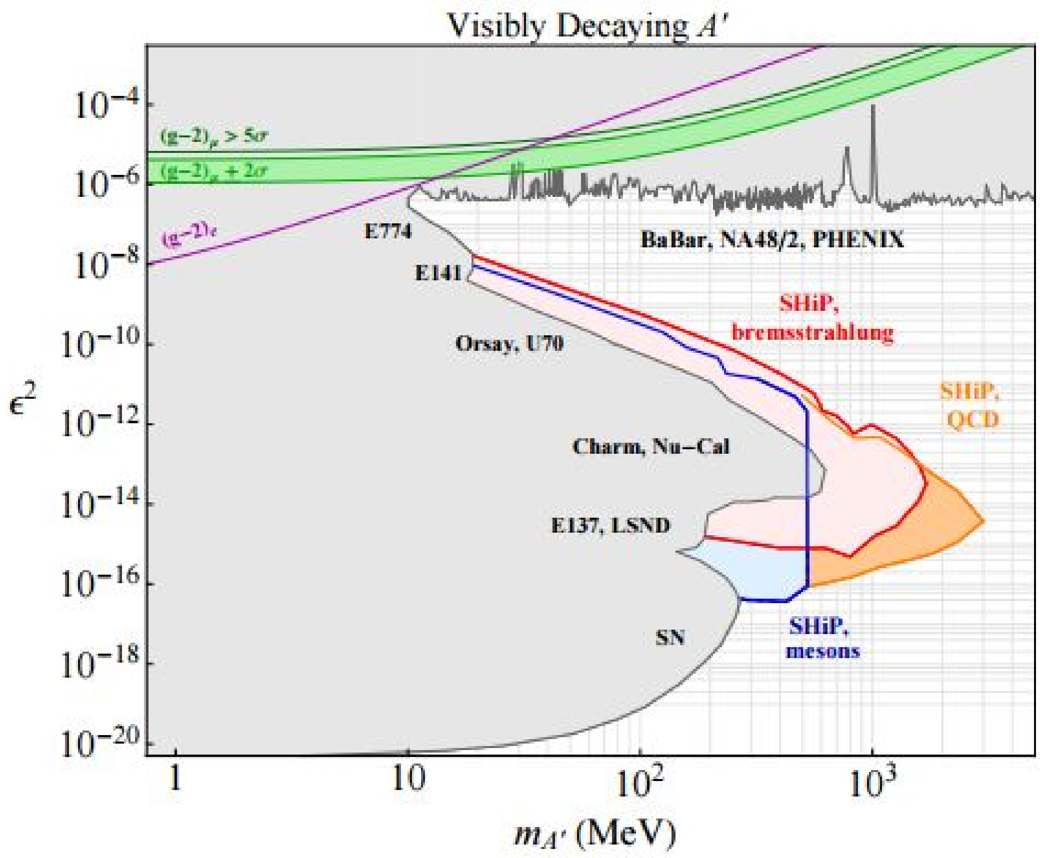
  - Like a photon, but ε-suppressed couplings: "dark" photon

- 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

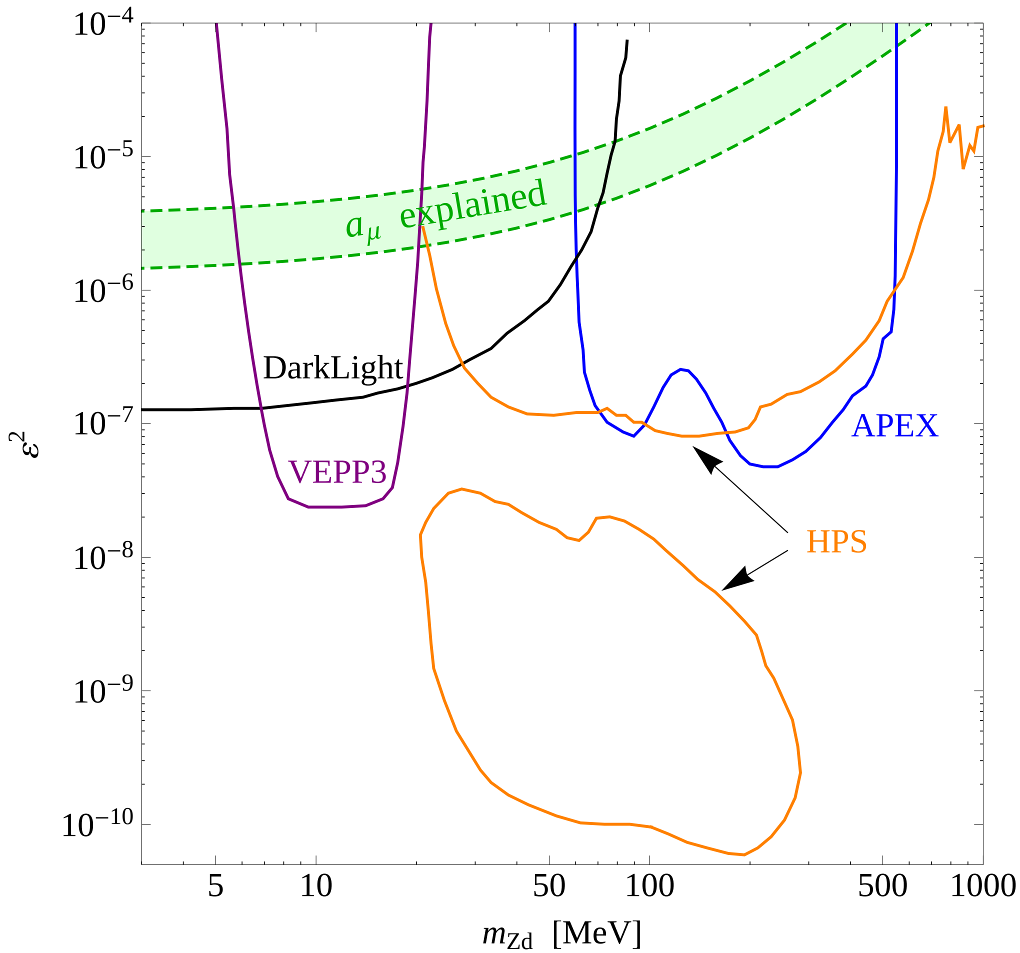
• An early experimental target: $g_\mu - 2$ parameter space



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

• Visibly decaying dark photon nearly ruled out as $g_\mu - 2$ explanation

Future prospects for dark photon searches



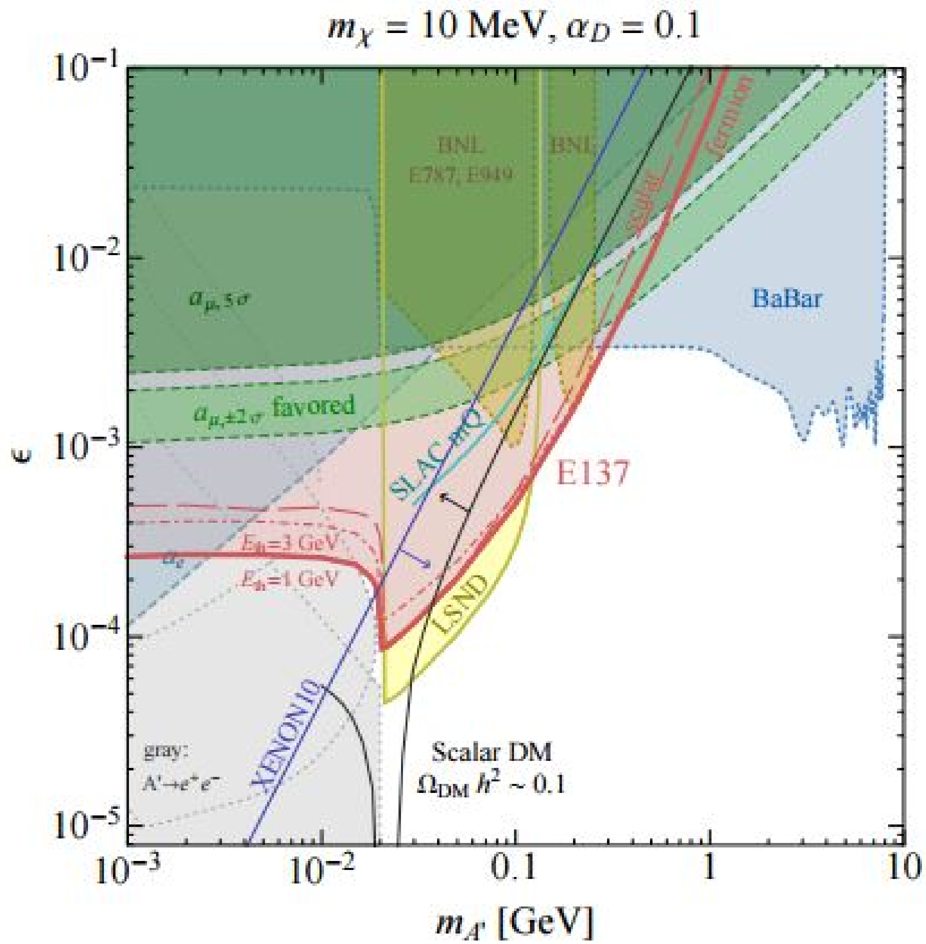
- VEPP3 independent of Z_d branching fractions
- HPS sensitivity to low ε via displaced vertex

“Invisible” Dark Photon

- Z_d essentially invisible if $\exists$ dark X (DM) with $m_X < m_{Z_d}/2$
  - Coupling to X with $g_d \lesssim 1$ versus $e\varepsilon \ll 1$ to SM $\Rightarrow$ Br$(Z_d \to X\bar{X}) \simeq 1$
  - $g_\mu - 2$ solution independent of dominant Z_d branching fraction

<u>Constraints</u>:

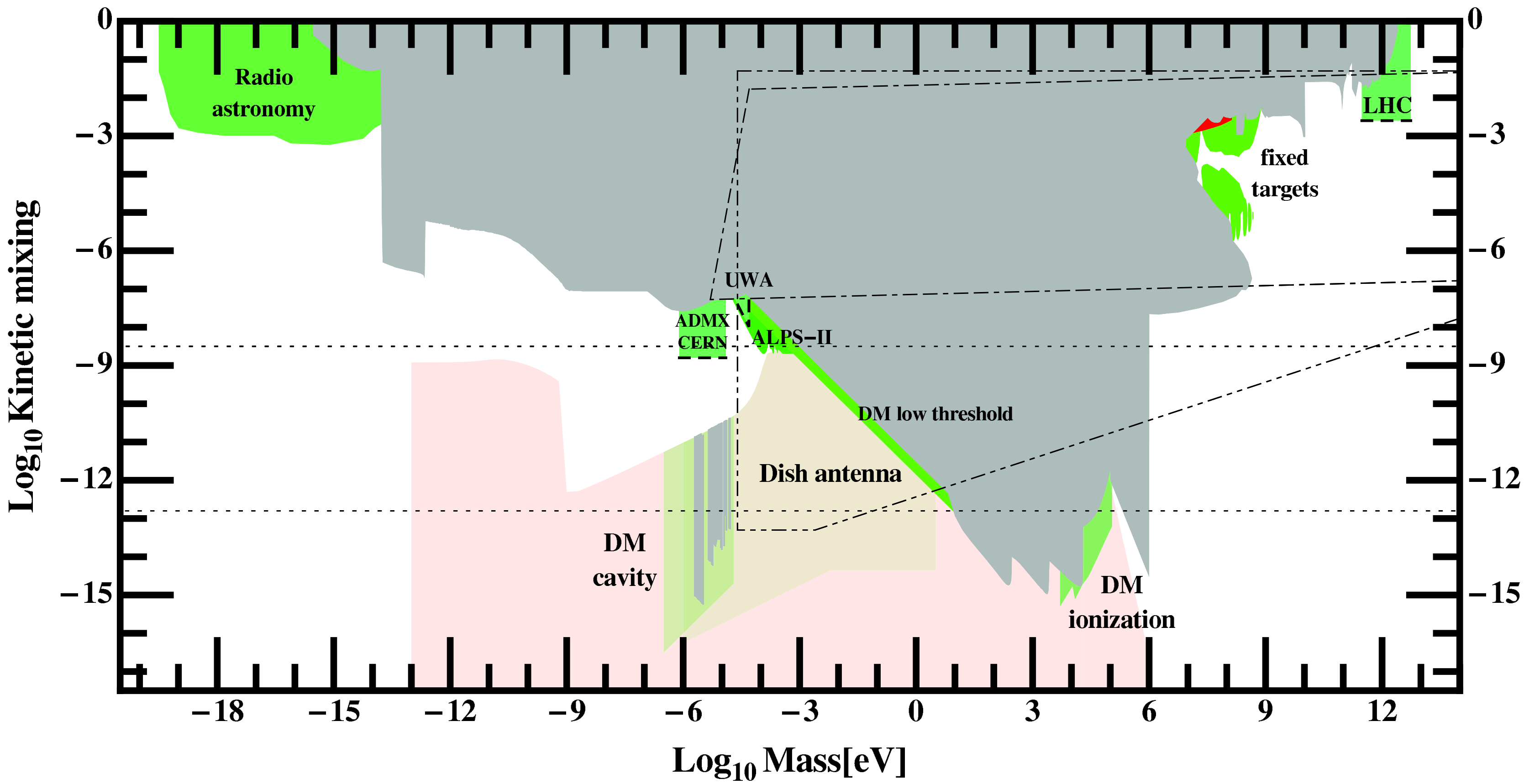
- BNL E787, E949: $K \to \pi +$ invisible
- SLAC Millicharge Experiment
  Diamond, Schuster, 2013
- LSND from $\pi^0 \to \gamma\, Z_d$
  deNiverville, Pospelov, Ritz, 2011
- SLAC beam dump E137
  Batell, Essig, Surujon, 2014
  - On-shell Z_d decay into DM: $\varepsilon^4 Q_d^2 \alpha_d$
  - Off-shell Z_d decay into DM: $\varepsilon^4 Q_d^4 \alpha_d^2$
  - Z_d “invisible” for $Q_d^2 \alpha_d \gtrsim \alpha\varepsilon^2$
- . . .



Batell, Essig, Surujon, 1406.2698

Much wider ranges have been considered

From K. Baker *et al.*, arXiv:1306.2841 [hep-ph]



- Gray: Dark ("hidden") photon ruled out
- Pink: Dark photon may be cold DM (misalignment mechanism)

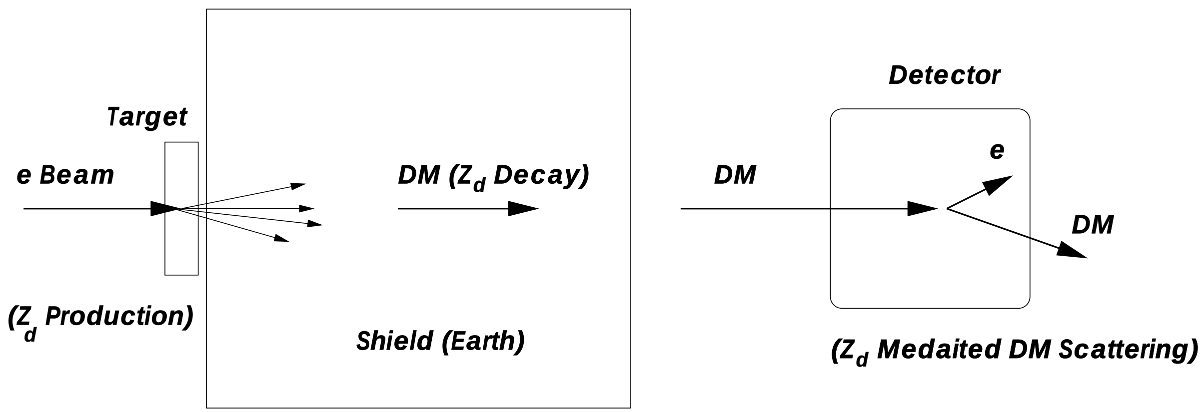
Nelson, Scholtz, 2011

Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald, 2012

Invisible Z_d and DM Production

- Possible production and detection of *DM beams* in experiments
- p or e on fixed target $\Rightarrow$ production of boosted Z_d (meson decays, bremsstrahlung,. . .)
- Z_d beam decays into DM which can be detected via Z_d exchange
- Event rate depends on α_d and ε, generally assumed to be constant

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



This talk: For $Q^2 \gg m^2_{Z_d}$, *running* of $\alpha_d(Q^2) \gtrsim$ few $\times$ 0.1 (and $\varepsilon^2 \propto \alpha_d$) could be significant, sensitive to dark sector spectrum below Q^2

HD, Marciano, 2015

See also Zhang, Li, Cao, Li, 2009; Sannino, Shoemaker, 2014 (non-Abelian gauge groups)

Light DM and Running Couplings

- Correct DM thermal relic density ($m_{Z_d} > m_X$)

$$\alpha_d \sim 0.02\, w \left(\frac{10^{-3}}{\varepsilon}\right)^2 \left(\frac{m_{Z_d}}{100 \text{ MeV}}\right)^4 \left(\frac{10 \text{ MeV}}{m_X}\right)^2$$

- $w \sim 10(1)$ for scalar (fermion) DM *E.g.*, Izaguirre, Krnjaic, Schuster, Toro, 1411.1404

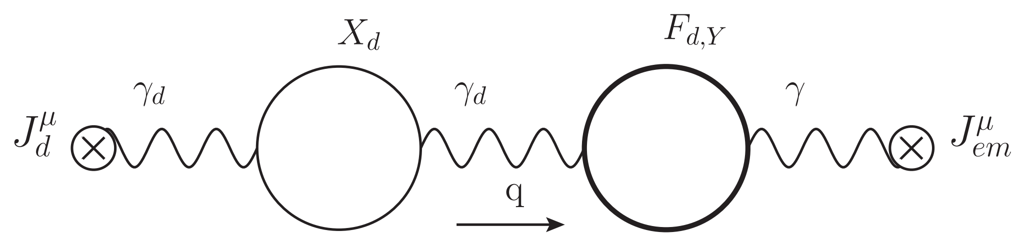
- Experiments can probe $\varepsilon \sim 10^{-4}$, corresponding to $\alpha_d \sim 1$

- $\alpha_d \sim 1 \oplus$ light DM with $m_X^2 \lesssim q^2 \Rightarrow$ significant $\alpha_d(q)$ running

- $m_X < m_{Z_d}/2$ for invisible DM while $q^2 \gtrsim m_{Z_d}^2$ can be typical

- Kinetic mixing naturally from loops: $\varepsilon^2 \propto \alpha\alpha_d \Rightarrow$ Running $\varepsilon(q)$

- F-loop $\to \varepsilon$; X-loop $\to$ running ($m_X \ll m_F$)



Numerical Analysis

- For $\alpha_d \sim 1$, higher order effects important

- 2-loop analysis, with n_F fermions and n_S scalars

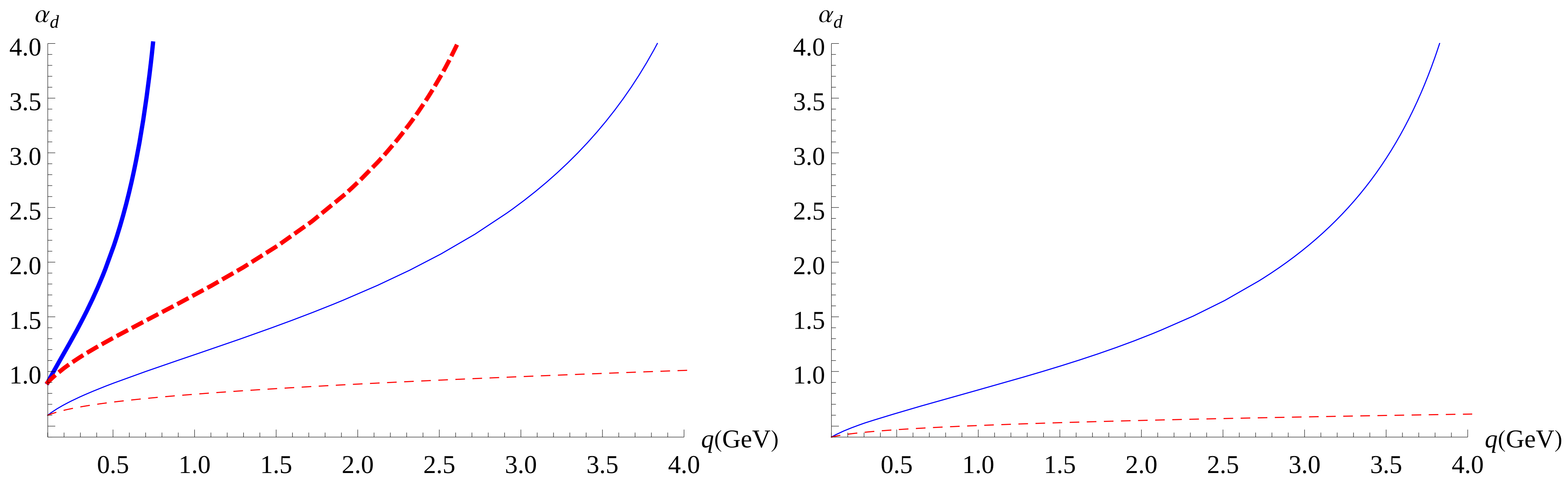
$$\boxed{\beta(\alpha_d) = \frac{\alpha_d^2}{2\pi}\left[\frac{4}{3}\left(n_F + \frac{n_S}{4}\right) + \frac{\alpha_d}{\pi}(n_F + n_S)\right]}$$

- $\beta(\alpha_d) \equiv \mu\, d\alpha_d/d\mu$

- Assume one light dark Higgs for $m_{Z_d} \neq 0$ ($n_S \geq 1$) throughout

- Expression for $\beta(\alpha_d)$: perturbative analysis unreliable for $\alpha_d \gtrsim \pi$

- Consider running above momentum transfer $q_0 \gtrsim m_{Z_d}$



The solid (dashed) curves correspond to a fermion (scalar) dark matter state, $q_0 = 0.1$ GeV ($m_{Z_d} \lesssim q_0$). Left: one DM state; thin (thick) curves correspond to $\alpha_d(q_0) = 0.6$ (0.9). Right: two DM states with $\alpha_d(q_0) = 0.4$. From H.D. and W.J. Marciano, 1502.07383 [hep-ph]

- Beam-dump or fixed target experiments: range for q of $\mathcal{O}$(GeV)
- Measurements sensitive to combined running of $\alpha_d(q)$ and $\varepsilon(q)$
- Probe number and type (spin) of low lying (below q^2) states

Measurement of q^2 Running

- General features of Z_d interactions suggest an approach

- Definitive statements depend on experimental details

- Consider on-shell Z_d production $\propto \varepsilon^2(m_{Z_d})$

- Detection cross section $\sigma_{\text{DM}} \propto \alpha_d(q)\varepsilon^2(q)$

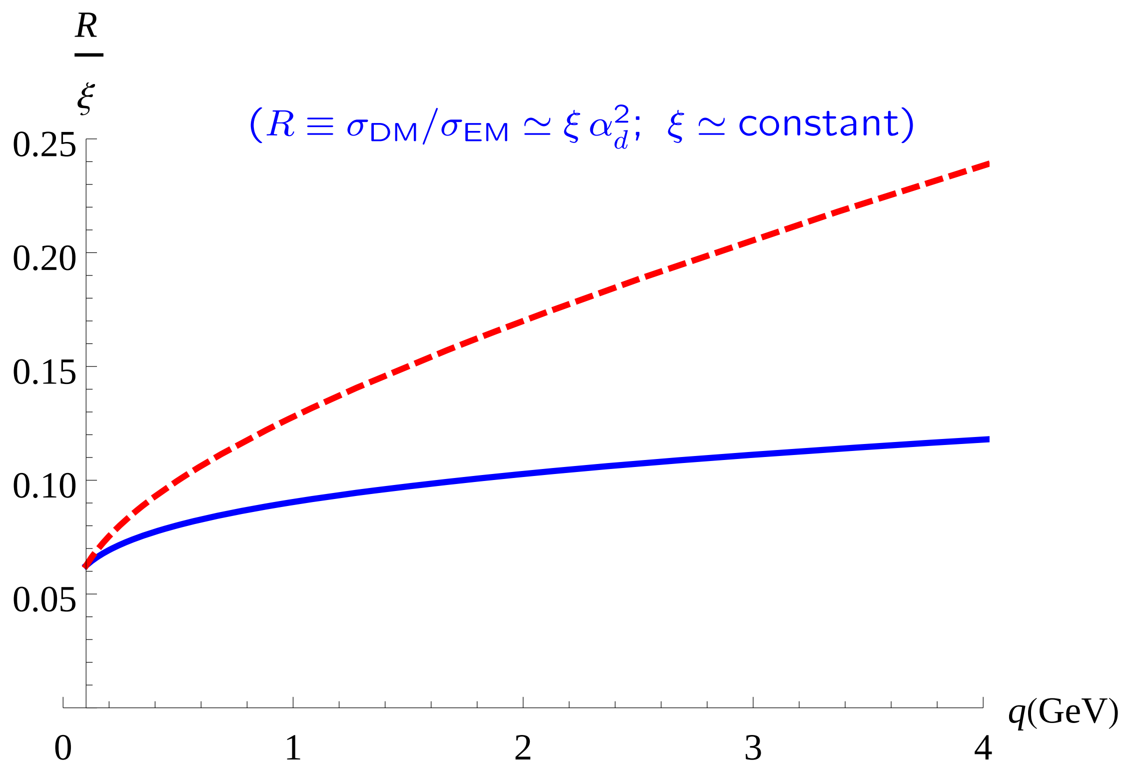
- Loop-induced kinetic mixing: $\varepsilon^2(q) \propto \alpha_d(q) \Rightarrow \sigma_{\text{DM}} \propto \alpha_d^2(q)$

- At $q \gtrsim m_{Z_d}$, DM interactions with nucleus similar to QED

- Normalize σ_{DM} to electron (or muon) $\sigma_{\text{EM}} \propto 1/q^2$ (well-understood, can be measured precisely)

$$R \equiv \sigma_{\text{DM}}/\sigma_{\text{EM}} \simeq \alpha_d \, \varepsilon^2/\alpha \simeq \xi \, \alpha_d^2 \qquad (\xi \simeq \text{constant})$$

Ignoring QED radiative corrections and $m_{Z_d} \neq 0$ propagator effects



Running of $R/\xi = \alpha_d^2$ with q, for one (solid) and two (dashed) light DM fermions and $\alpha_d(q_0) = 0.25$, $q_0 = 0.1$ GeV, and $m_{Z_d} \lesssim q_0$; a dark Higgs boson is included for both cases. From H.D. and W.J. Marciano, 1502.07383 [hep-ph]

• Running significant over $q \in [0.1, 4]$ GeV, the two cases quite distinct

• σ_{DM} falls like $1/q^2$, for $q \gtrsim m_{Z_d}$ (modulo α_d running)

• DM signal stronger for lower q^2, while potential backgrounds from ν-nucleus scattering more suppressed (optimal q range depends on experimental setup)

Astrophysical Sources

- Similar consideration could apply to lower energy scales

Example:

- Emission of very light Z_d from the Sun; $m_{Z_d} \sim 10^{-6}$ eV

- Z_d emission governed by $\varepsilon^2(m_{Z_d})$ An, Pospelov, Pradler, 2013; Redondo, Raffelt, 2013

- DM detector as helioscope: $q^2 \sim$ keV^2

- Dark photon absorption by detector atoms An, Pospelov, Pradler, 2013

- Absorption (ionization) in helioscope governed by $\varepsilon^2(q)$

- Event rate $\propto \varepsilon^2(m_{Z_d})\,\varepsilon^2(q)$

- $q/m_{Z_d} \sim 10^9$: running of $\varepsilon^2(q) \propto \alpha_d(q)$ can be significant

$m_{Z_d} = 10^{-6}$ eV, $q = 10^3$ eV, $n_F = 2$, $n_S = 1$ (mass $\sim m_{Z_d}$), $\alpha_d(m_{Z_d}) = 0.06$

$$\Rightarrow \varepsilon^2(q)/\varepsilon^2(m_{Z_d}) = \alpha_d(q)/\alpha_d(m_{Z_d}) \simeq 2.5$$

Theoretic Implications of a Landau Pole

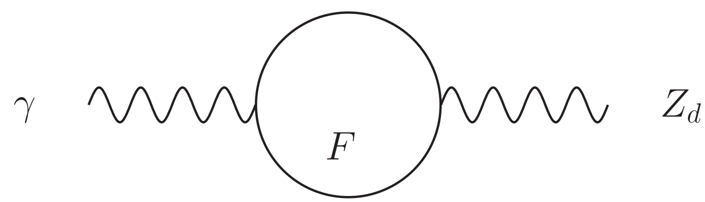
- Landau pole ($\alpha_d \gg 1$) at $q = q^*$ signals need for new physics

- Straightforward example: $U(1)_d \rightarrow SU(N)_d$

- Expect $\varepsilon = 0$ at $q = q^*$ [*e.g.*, no kinetic mixing for $SU(N)_d$]

- ε generated below q^* by loops of F with $Q_d Q_Y \neq 0$ and $m_F < q^*$

- Experimental constraints: $m_F \gtrsim 100$ GeV, since $Q_Y(F) \neq 0$



- Implies that q^* should be above the weak scale

- Running of $\alpha_d(q)$

$$\alpha_d(q_0) = \frac{\alpha_d(q^*)}{1 + \frac{2}{3\pi}\alpha_d(q^*)(n_F + n_S/4)\ln(q^*/q_0)}$$

- For $\ln(q^*/q_0) \gg 1$, low energy $\alpha_d(q_0)$ insensitive to $\alpha_d(q^*) \gtrsim 1$

$$\boxed{\alpha_d(q_0) \approx \frac{3\pi}{(2n_F + n_S/2)\ln(q^*/q_0)}}$$

- For $q_0 \approx 100$ MeV:

$q^* = 1\text{TeV} \Rightarrow \alpha_d(q_0) \lesssim 0.5/(n_F + n_S/4)$

$q^* = M_{\text{Planck}} \simeq 1.2 \times 10^{19}$ GeV $\Rightarrow \alpha_d(q_0) \lesssim 0.1/(n_F + n_S/4)$

- Typically implies the low energy upper bound $\alpha_d(q_0) \lesssim 0.5$

Concluding Remarks

- Dark sector may include new forces
- $U(1)_d$ mediated by a sub-GeV Z_d a simple and widely considered example

  DM model building, $g_\mu - 2$, . . .
- DM may be light and couple to SM via the $Z_d - \gamma$ kinetic mixing $\propto \varepsilon$

  Typically requires $\alpha_d \gtrsim 0.1$
- Light DM may be probed at fixed target experiments

  Production and detection mediated by Z_d
- Running of α_d and a loop-induced ε can be significant for $q^2 \gtrsim m_{Z_d}^2$
- Measuring $\alpha_d(q)$ and $\varepsilon(q)$ could probe the dark sector matter content

  Typical detection rate $\propto \alpha_d(q)\varepsilon^2(q)$ in dark beam experiments
- Theoretical considerations imply $\alpha_d \lesssim 0.5$ at low energies ($\sim m_{Z_d} \lesssim 0.1$ GeV)

  Assuming 1 or more dark fermions of mass $\lesssim m_{Z_d}$
- Similar considerations could apply to lower m_{Z_d} scales (stellar physics)