Running in the Dark Sector

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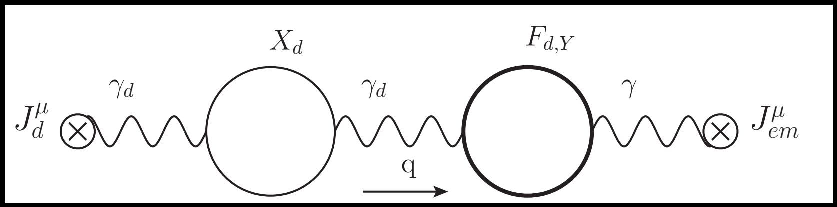

Based on: H.D. and W.J. Marciano, Phys. Rev. D **92**, no. 3, 035008 (2015)
[arXiv:1502.07383 [hep-ph]]

CERN-EPFL-Korea Theory Institute "New Physics at the Intensity Frontier"
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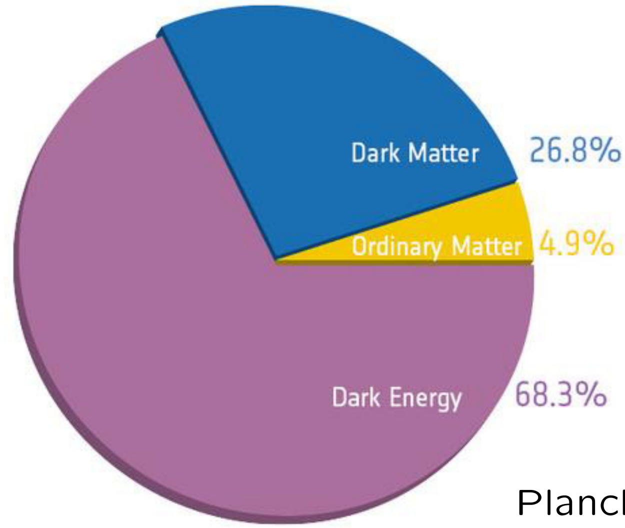
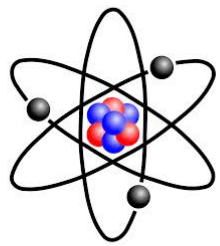
The Big Picture



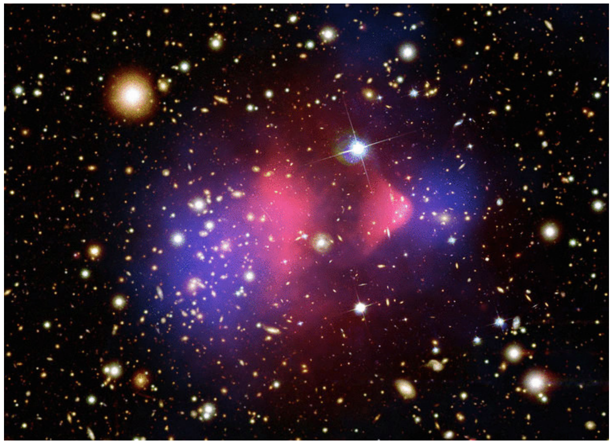
Planck

- **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*

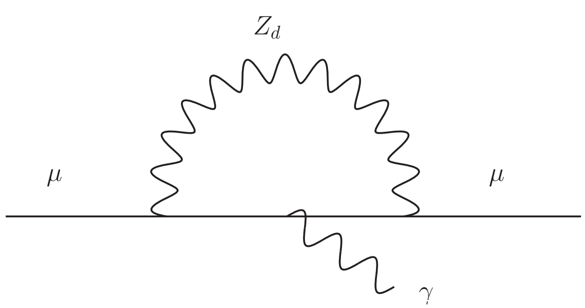
- $m_{Z_d} \lesssim 1$ GeV has been invoked in various contexts

- DM interpretation of astrophysical data

Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

- Explaining 3.5σ $g_\mu - 2$ anomaly: $\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 288(80) \times 10^{-11}$

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



- Model building (Asymmetric DM models,. . .)

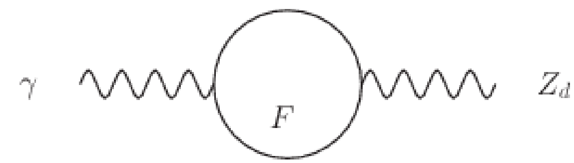
Dark Photon

- 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

$\Rightarrow$ Z_d couples to EM current: $\boxed{\mathcal{L}_{\text{int}} = -e\,\varepsilon\, J^\mu_{em} Z_{d\mu}}$ $J^\mu_{em} = \sum_f Q_f \bar{f}\gamma^\mu f + \cdots$

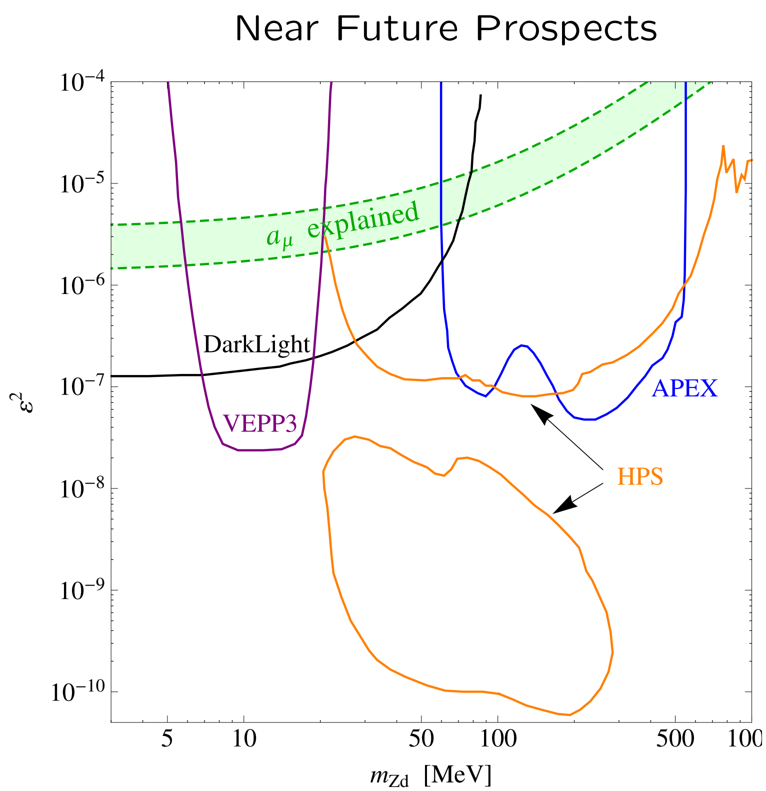
  - Like a photon, but ε-suppressed couplings: <u>"dark" photon</u>
  - Neutral current coupling suppressed by $m^2_{Z_d}/m^2_Z \ll 1$

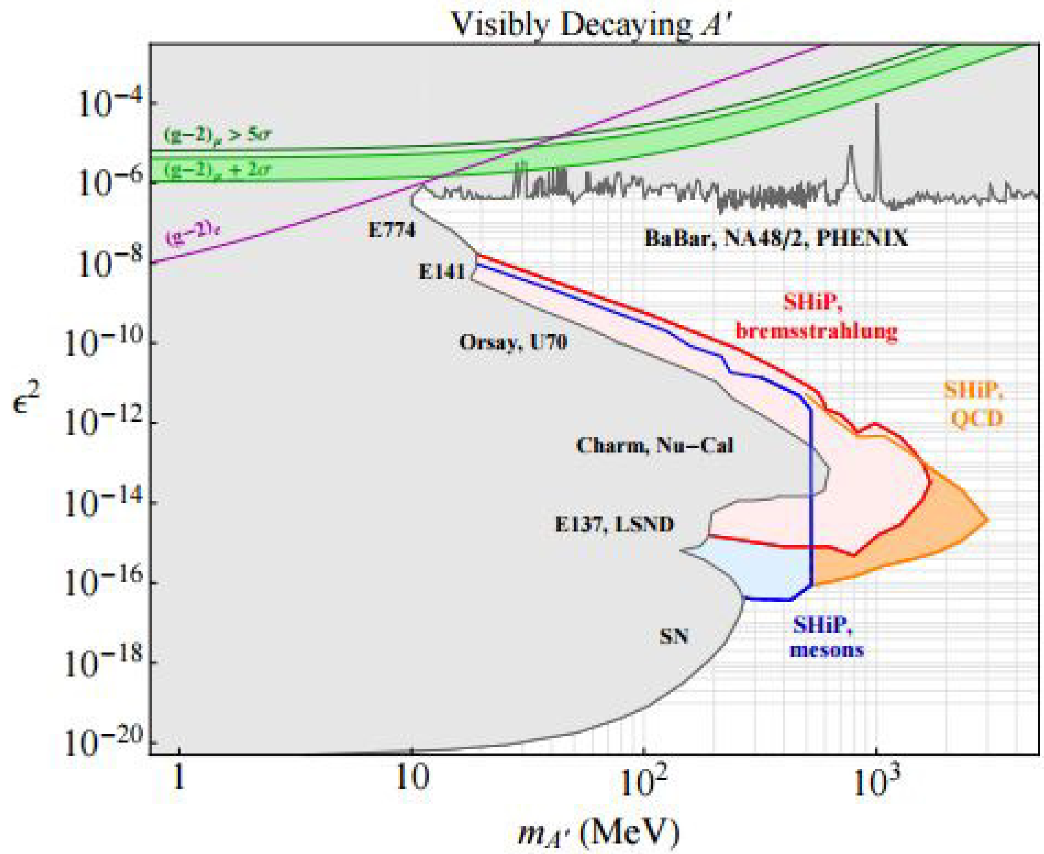
- Add Z-Z_d mass mixing $\to$ Z_d as "dark" Z HD, Marciano, Lee, 2012
  - "Dark" parity violation, rare meson and Higgs decays, . . .

- 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



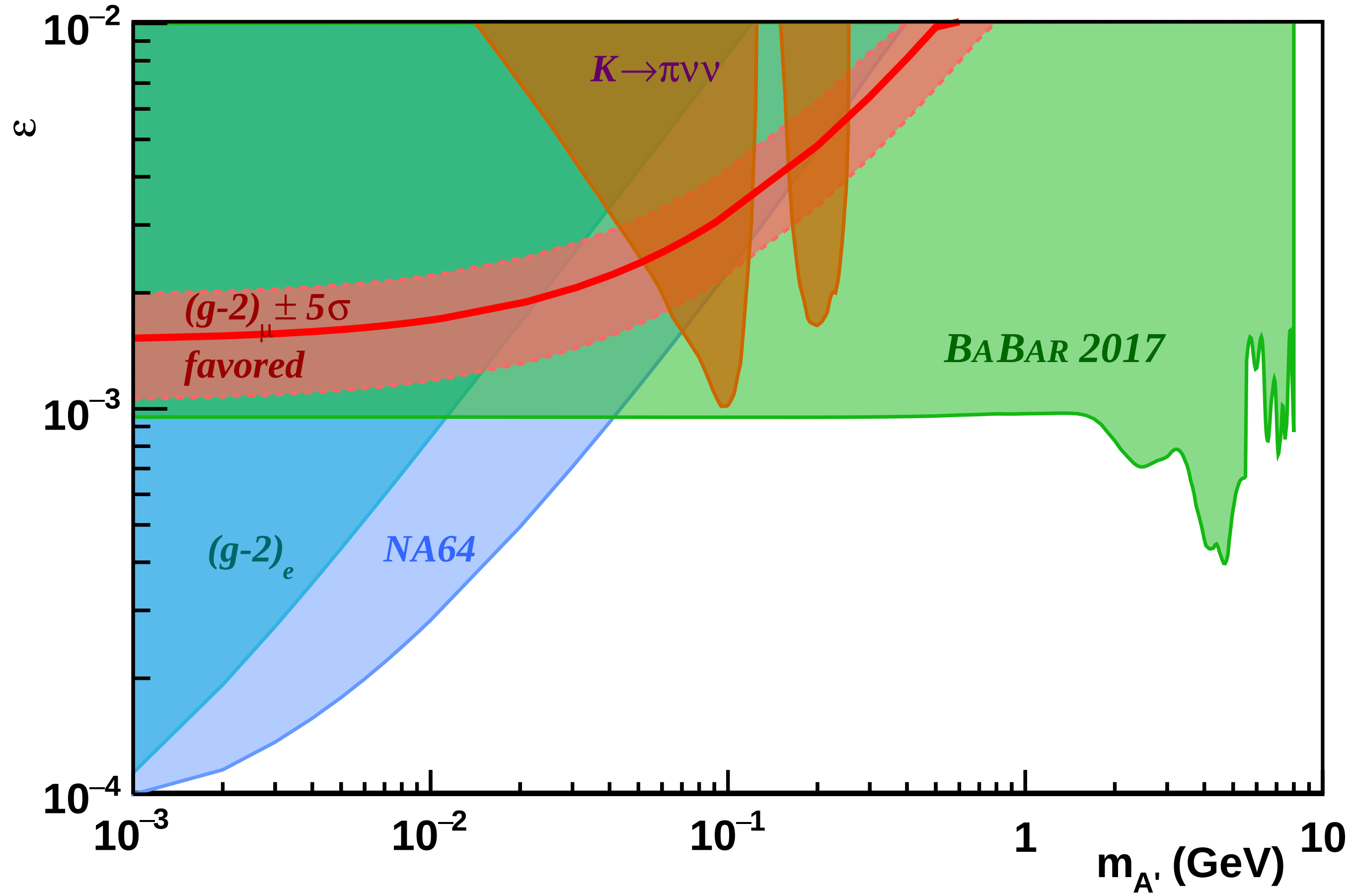


S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

GeV-scale visibly decaying Z_d basically excluded as $g_\mu - 2$ explanation

"Invisible" Dark Photon

- $\exists$ dark X with $m_X < m_{Z_d}/2$ and $Q_d g_d \gg e\varepsilon \Rightarrow \text{Br}(Z_d \to X\bar{X}) \simeq 1$



Recent 90% CL bound from Babar Collaboration, arXiv:1702.03327 [hep-ex]

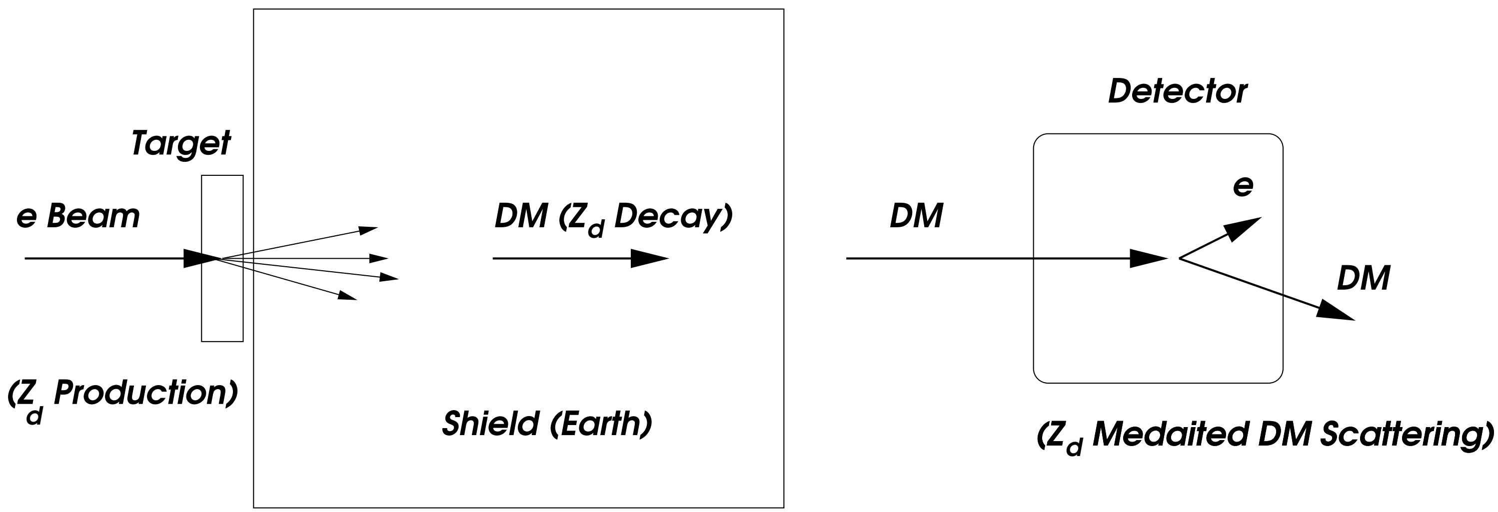
GeV-scale "invisible" dark photon $g_\mu - 2$ solution ruled out

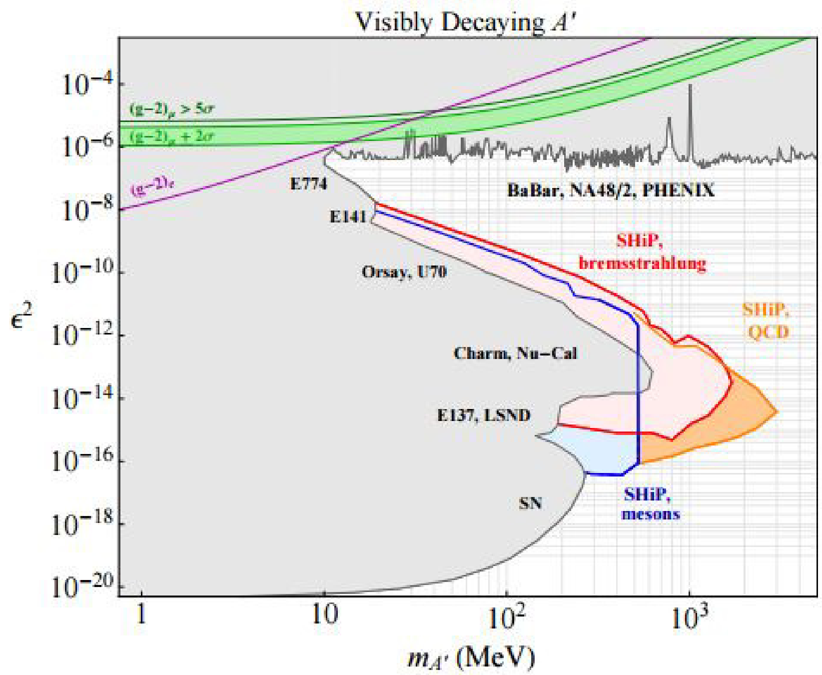
Invisible Z_d and DM Production

- 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 $\alpha_d \equiv g_d^2/(4\pi)$ and ε^2

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





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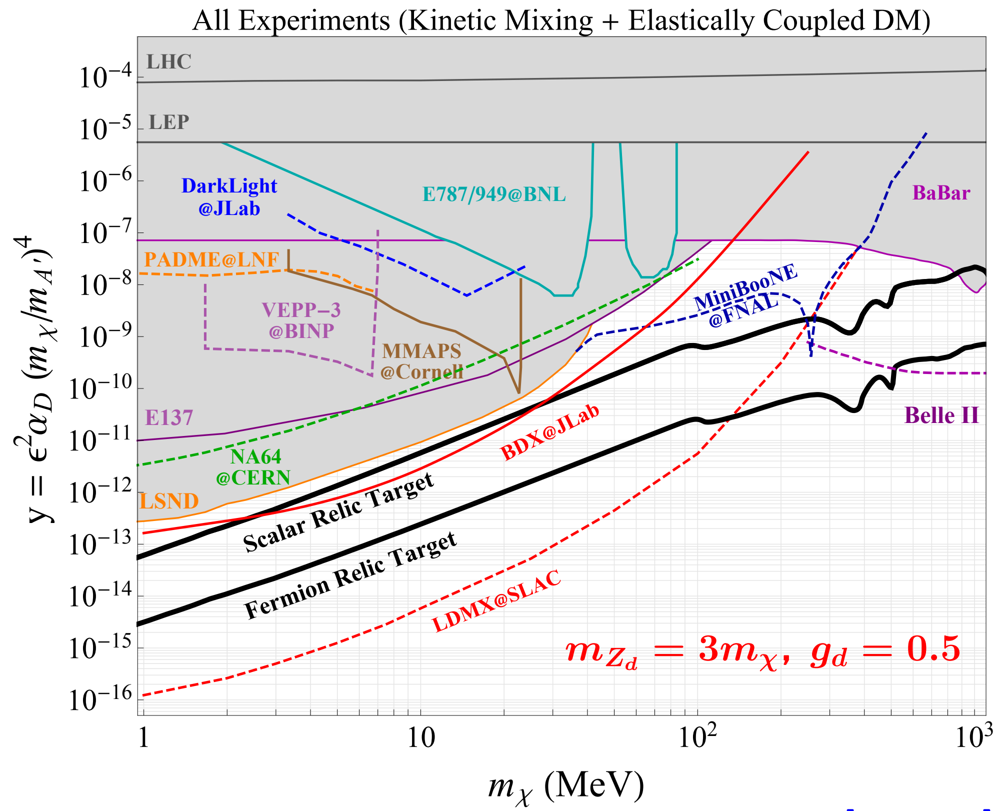


J. Alexander *et al.*, arXiv:1608.08632 [hep-ph]

- $(\alpha_d, \varepsilon^2)$ typically assumed <u>constant</u> over q^2 ranges of experiments

- <u>This talk</u>: For $q^2 \gg m_{Z_d}^2$, *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 ($m_{Z_d} > m_X$)

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

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

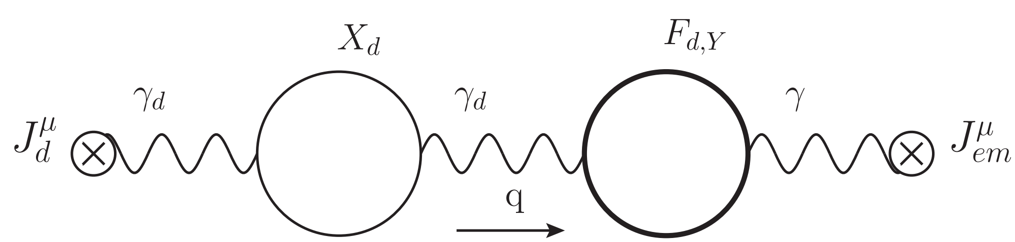
- Experiments can probe $\varepsilon \lesssim 10^{-4}$, corresponding to $\alpha_d \sim 1$

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

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

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

- Heavy F-loop $\rightarrow \varepsilon$; Light X-loop $\rightarrow$ running



Numerical Analysis

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

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

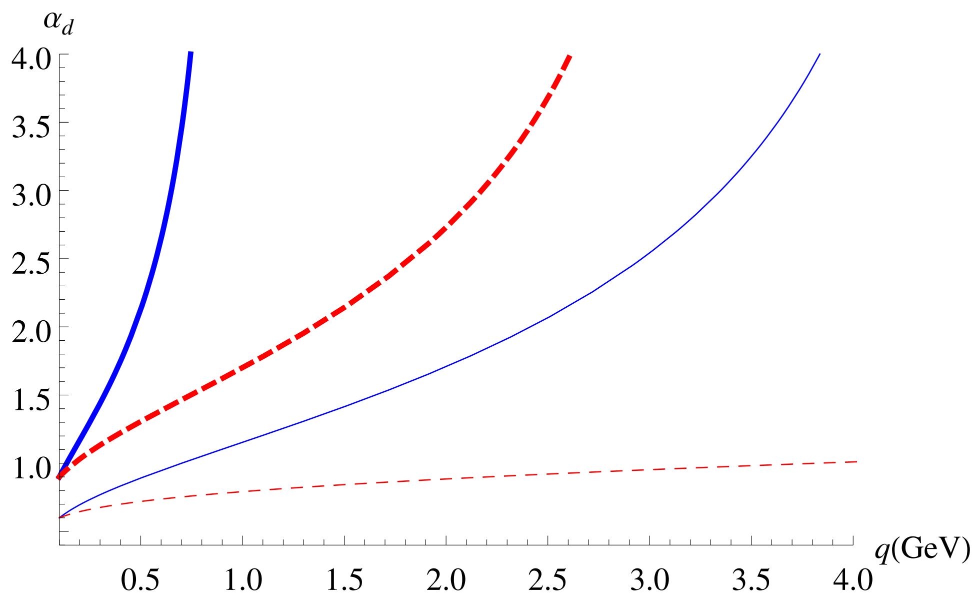
$$\boxed{\beta(\alpha_d) = \frac{\alpha_d^2}{2\pi}\left[\frac{4}{3}\left(n_F + \frac{n_S}{4}\right) + \frac{\alpha_d}{\pi}(n_F + n_S)\right]}$$

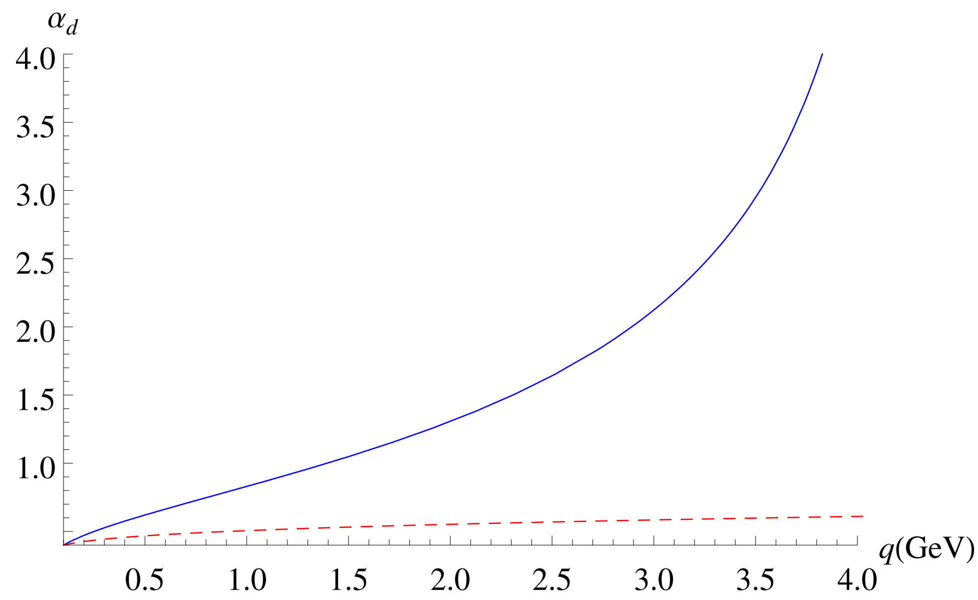
- $\beta(\alpha_d) \equiv \mu\, d\alpha_d/d\mu$

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

- Form of $\beta(\alpha_d)$ suggests 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 $\sigma_{\text{DM}} \propto \alpha_d(q)\varepsilon^2(q)$

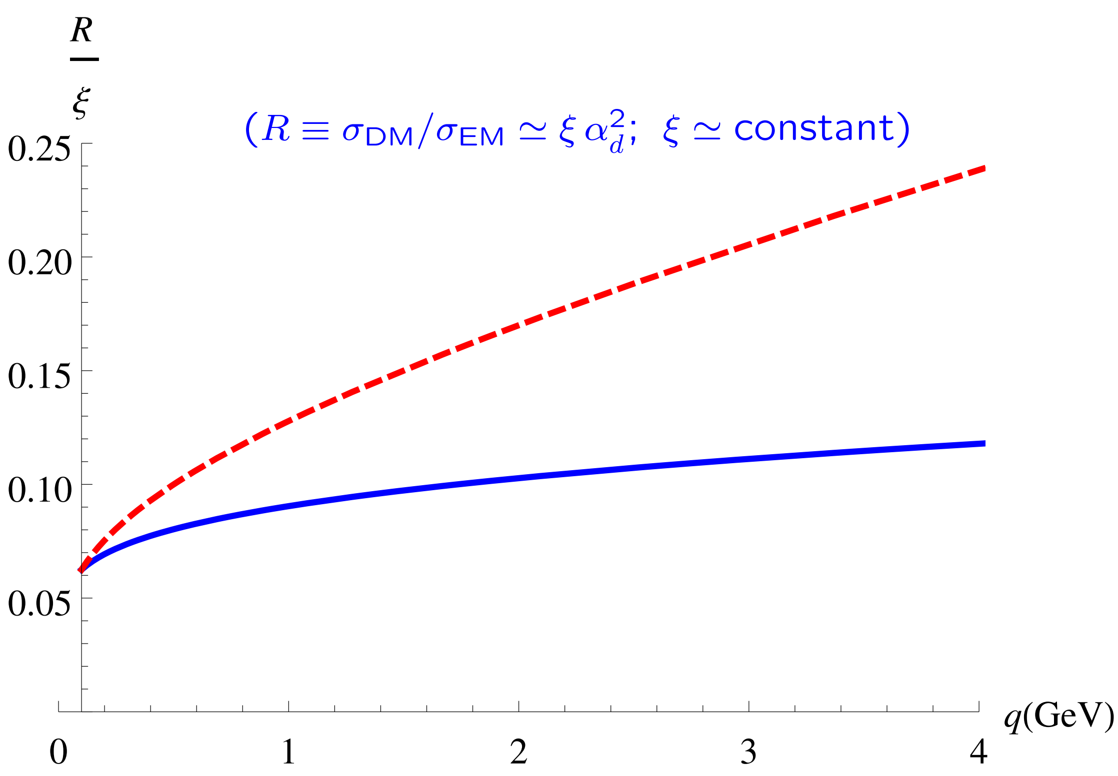
- Loop-induced kinetic mixing: $\varepsilon^2(q) \propto \alpha_d(q) \Rightarrow \boxed{\sigma_{\text{DM}} \propto \alpha_d^2(q)}$

- 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
- $\sigma_{\rm DM}$ 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: $q^2 \sim \mathrm{keV}^2$

- 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, $n_F = 1$, $n_S = 1$ (mass $\sim m_{Z_d}$), $\alpha_d(m_{Z_d}) = 0.06$

$$\Rightarrow \varepsilon^2(q)/\varepsilon^2(m_{Z_d}) = \alpha_d(q)/\alpha_d(m_{Z_d}) \simeq 1.5$$

Theoretic Implications of a Landau Pole

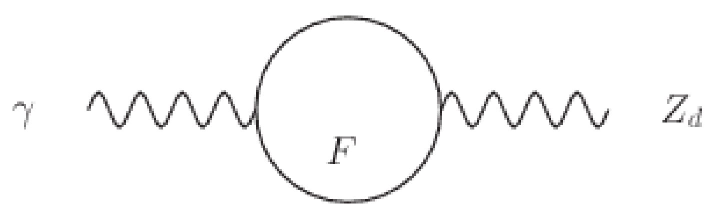
- Landau pole ($\alpha_d \gg 1$) at $q = q^*$ signals need for new physics

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

- 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 $\alpha_d(q^*) \gtrsim 1$

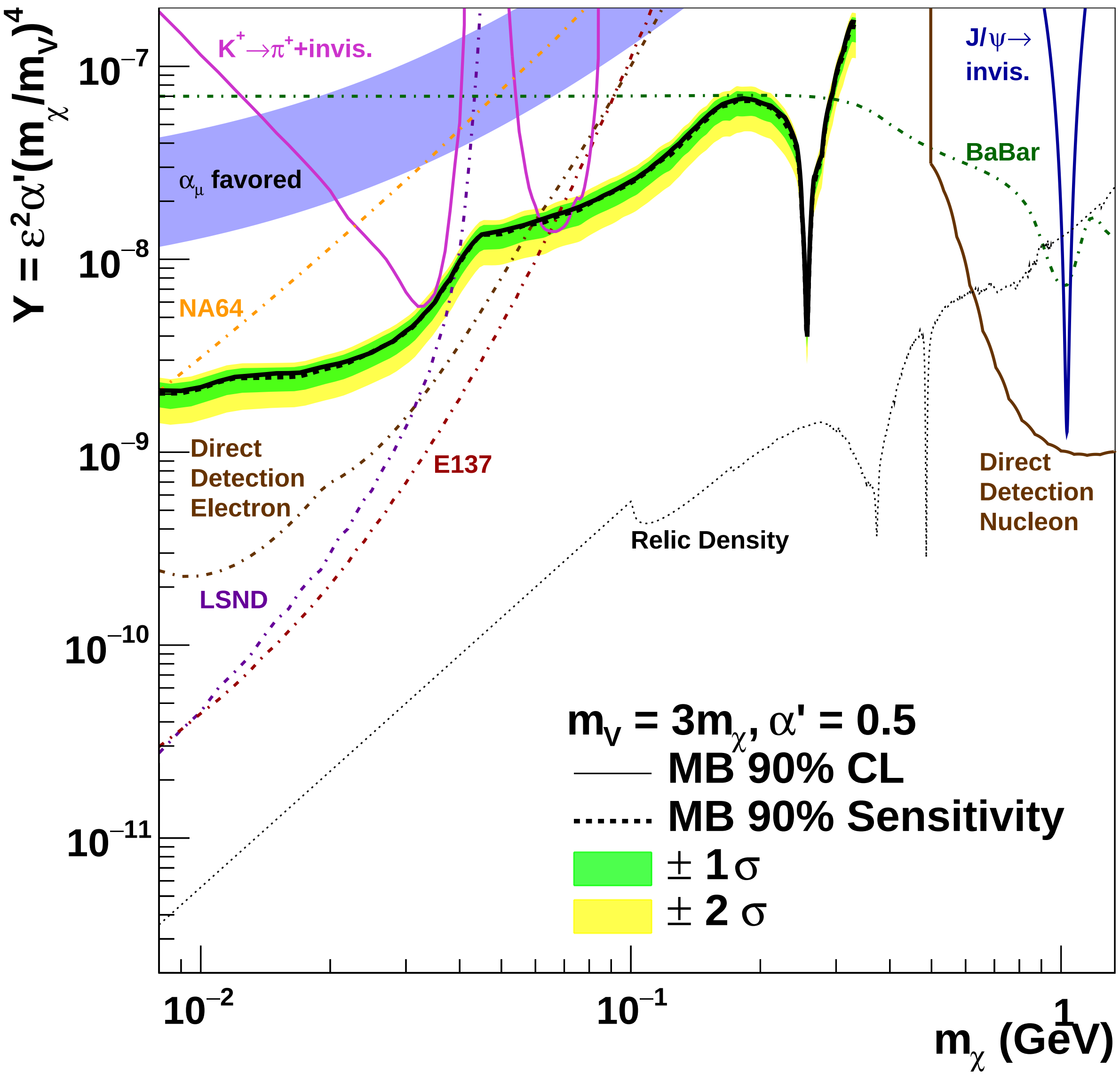
$$\boxed{\alpha_d(q_0) \approx \frac{3\pi}{(2n_F + n_S/2)\ln(q^*/q_0)}}$$

- 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 low energy upper bound $\boxed{\boldsymbol{\alpha_d(q_0) \lesssim 0.5}}$ $(q^* \gtrsim 1$ TeV$)$



From arXiv:1702.02688 [hep-ex] (MiniBooNE Collaboration)

"Dark Matter Search in a Proton Beam Dump with MiniBooNE"

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 $q^2 \gtrsim m^2_{Z_d}$
- 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)