Dark Photons: Theory & Experimental Status

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Motivation

- Since the first cosmological evidence for dark matter, many searches for new physics in the HEP world have targeted it
- Dark matter/energy appear to make up the majority of matter in our universe $\implies$ it is important to probe
- **Particle dark matter** is the main candidate for dark matter searches at the LHC [1]

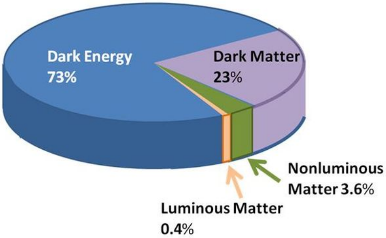

Figure 1: Dark energy + matter distribution

Dark Sectors

- A dark sector would consist of particles that have no interaction with the strong, weak, or EM forces.[2]
- Given that the SM describes only a subdominant component of the Universe's matter, it would not be surprising if a possible dark sector had itself a rich structure.
- The coupling to the SM would come through **new light weakly-coupled particles**, particles below the weak-scale interacting only feebly with matter

Dark Sectors: Interaction

According to Ref. [2], only a few well-motivated interactions are allowed by SM symmetries which provide **"portals"** into the dark sector from the SM sector. These are summarized as per Ref. [2] here:

Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu} \widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2) H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$

Figure 2: SM to Dark Sector coupling options

Dark Photons

- The minimal way of adding a sector containing dark photons (or more generally, dark gauge bosons) to the SM can be done by introducing a $U(1)$ gauge field
- Unfortunately, the specifics of the interaction between this field and the potential dark sector fields are practically unlimited
- Constraints only come from existing couplings, since there is no observational evidence beyond this
- One of the simplest and most frequently used methods of doing this is by introducing an abelian $U(1)$ gauge boson A', which couples weakly to electrically charged particles through some **kinetic mixing** with the photon.
- While A' is generally referred to as a dark photon, it can also be considered/called a dark boson under other formulations

Dark Photons: ϵ parameterization

- Kinetic mixing produces a parity-conserving interaction of the A'_μ to the electomagnetic current J^μ_{EM}, with some suppression ϵ relative to electron charge e.
- This term takes the form

$$\epsilon e A'_\mu J^\mu_{EM}$$

- The scaling parameter ϵ is not required to be small, since it is unsuppressed by any mass scale.
- Particular calculations for ϵ based on various models (preturbative calculations, large-volume effects, quantum loops, etc.) place the order of $\epsilon \sim 10^{-12} - 10^{-3}$
- Under all these formulations, the photon coupline to A' would provide the only non-gravitational window into the dark sector's existence, regardless of how complex the sector may be

Dark Photons: Mass Matrix Mixing

- A generalization of mixing comes from mass matrix mixing, parameterized by ϵ_Z, which accounts for mixing between the dark photon and the SM Z boson
- This allows a coupling with both the electromagnetic and weak neutral currents in the SM
- Additional lagrangian of interaction then becomes

$$\mathcal{L}_{int} = -\left(\epsilon e J_\mu^{\mathrm{EM}} + \epsilon_Z \frac{g}{2\cos\theta_W} J_\mu^{\mathrm{NC}}\right) Z_d^\mu$$

where we now refer to the dark photon as a Z-like boson Z_d^μ to emphasize Z-like properties

Dark Photon Search Regions: Current Data

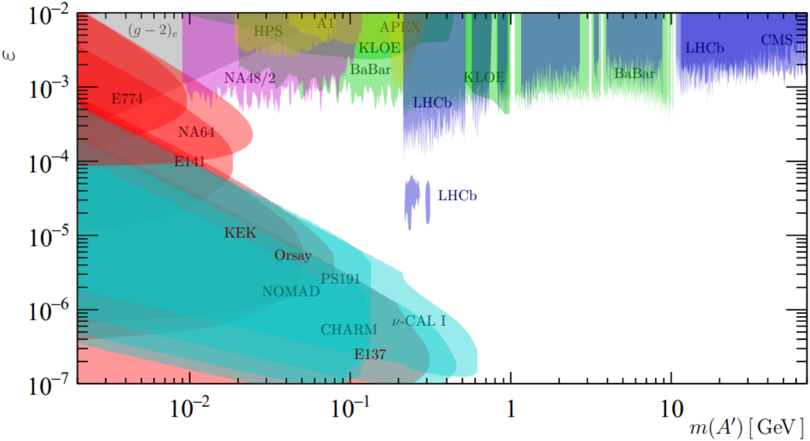

Figure 3: Current cnstraints on visible dark photon decays. Electron beam dumps shown in red, proton dumps in cyan, electron colliders in green, proton colliders in dark blue, meson decays in purple, and electron fixed targets in yellow. From Ref. [3]

Dark Photon Search Regions: Future Data

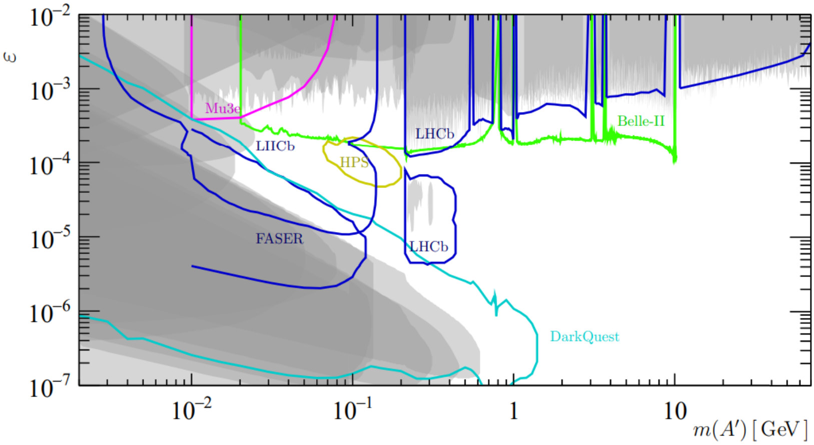

Figure 4: Same as previous slide, but with future sensitivities shown as dark lines. From Ref. [3]

Electron Beam Dump Experiments

- High intensity electron beams are dumped onto fixed targets
- Idea is to probe the weak couplings of dark photons
- Kinetic mixing could give rise to the emission of dark photons through a "dark bremsstrahlung effect" during electron-target scattering
- A detector is placed in the forward direction with a significant SM shield, to select highly boosted dark photons
- Dark photons could be decayed due to their decay into leptons (e^+e^- highest expected BR)
- A large decay length (0.1 - 1 meter) is needed for the photons to be observable after decays behind the shield & before the detector
- This constrains the search to large dark photon mass ($2m_e < m_{A'} < 500MeV$ and small ϵ ($10^{-7} \lesssim \epsilon 10^{-3}$)
- Several such experiments have been operated, setting limits as shown in the plots which precede this slide. These include E141 and E137 (SLAC), E774 (Fermilab), and experiments from KEK and Orsay.

Proton Beam Dump Experiments

- The setup for proton beam dump experiments is similar to that of electron beams
- The difference is that many more production processes exist, thus complicating analysis
- These experiments largely probed the same region as the electron beam dumps
- In the future, variations of SeaQuest will probe higher sensitivity regions by searching for $A' \to \mu^+\mu^-$ and $A' \to e^+e^-$ decays using a 120 GeV proton beam.

Electron Beam Fixed-Target Experiments

- Fixed target electron experiments target the region where A' is radiated off electrons that scatter on the target nuclei (usually with high Z)
- Again, radiative dark photons are produced by A' recoiling against the target nucleus i.e. through bremsstrahlung.
- Detection methods vary, but generally involve low-angle, movable, high resolutoin spectrometers searching for $A' \to e^+e^-$ decays [3].
- Sensitivity from these experiments isn't impressive yet.

e^+e^- Collider Experiments

- Predominant production mode is $e^+e^- \to A'\gamma$, where a dark photon replaces a normal one in the SM annihilation process.
- Backgrounds are dominated by $e^+e^- \to \updownarrow^+\updownarrow^-\gamma$ continuum, photon conversion in detector materials, and vector meson decays $(\omega, \phi, \psi, \Upsilon$ etc.)
- Background from photon conversion in detector material can be suppressed by good vertexing, rejecting events with verticies inconsistent with the primary interaction point.
- The BaBar experiment has provided good limits with this strategy, along with Belle II, and in the future, the FCC.
- In general, e^+e^- colliders provide one of the best probes for dark photon decays.

Hadron Ion Collider Experiments

- For the LHC, dominant production modes are from meson decays, meson-dark photon mixing, and Drell-Yan $q\bar{q} \rightarrow A'$
- As in electron colliders, backgrounds are SM vector meson decays and photon conversions.
- Results from LHCb and CMS have given the best limits on dark photon decays with mass $m_{A'} > 10 GeV$
- LHCb in particular is expected to provide excellent future constraints, which may allow inclusive searches for $A' \rightarrow e^+e^-$ decays
- LHC experiments also may soon include the ability to probe long-lived dark photons
- Particularly, FASER will be installed 480m downstream from the ATLAS interaction point, and has some decent expected sensitivity.

Meson/Lepton Decay Experiments

- NA48/2, an experiment at the SPS at CERN, searches particularly for $\pi^0 \to A'\gamma$ decays followed by decay to EP-production. These are world leading from prompt decays in the region of 10-100 MeV.
- Similarly, the Mu3e experiment at PSI will soon provide further sensitivity using stopped muons.

Outlook

- Dark photons are one of the simplest dark-sector models for dark matter, with a variety of theoretical possibilities for discovery
- Future searches for minimal dark photon models have the possibility to achieve good sensitivity
- Sensitivity is achieved in a variety of different experimental ways, which is useful because the parameter space is enormous
- More complicated dark-sector models (rich dark sectors) provide another, even larger search parameter space for future searches.

Questions?

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