Dark Photons

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Abstract

Dark photon is a proposed new gauge boson that mediates the interaction between familiar Standard Model particle and dark sector particle, and between dark sector particles. In this report the origin, properties and experimental searches was discussed. The fixed target experiment NA48/2 and collider experiment LHCb were introduced as examples.

1 Introduction

The Standard Model (SM) is what achieved by far in particle physics researches, which studies the most fundamental constituents. Although it has succeeded in explaining physics phenomenons of familiar matter with validation from experiments, it is incomplete in various aspects, leading to searches of physics beyond the SM.

One of the important research field of physics beyond the SM is the search of dark sector. 71.4% of our universe is dark energy, 24% is dark matter, and the familiar matter we know only account for 4.6%[1]. The origin and physics of the dark matter and dark energy remains unexplained by the SM, which motivates extending the SM to include a "dark sector". Dark sector (also called hidden sector or uncharged sector [2]) is a collection of particles that are under gravitational interactions, but not other SM forces (strong, weak, and electromagnetic forces). Or say, the dark sector consists of fields with no SM gauge charges. [3]

The dark sector could explain some gaps in the Standard Model, like the existence of large amount of dark matter and their lack of interactions, origin of neutrino masses, baryon asymmetry, dynamics of galactic structure formation, photon charge radius, etc. [3] The theory of dark sector is also compatible with theories about supersymmetry breaking and mediation, as well as the theory of unifying the SM gauge groups at a high scale[2], these all motivate studies of the dark sector.

One of the possibilities of how dark sector particles couple to (interacts with) the SM particles is that it is done via an unknown force felt very weakly by the Standard Model particles. The force carrier is assumed to be massive dark photons (denoted by A'). In this report the concept and interaction of dark photon from other literature is investigated and some experimental attempts on detecting it is introduced.

2 Dark Photon

2.1 What is a Dark Photon

In the 70s and 80s, this idea of a new neutral spin-1 gauge boson was proposed by P. Fayet motivated by supersymmetry, although it was then studied outside this SUSY context as well. [4] During his research he proposed various possibilities: this new boson appears to be a gauge particle similar to that mediates electroweak interactions, but also mediate gravitational interactions like the (today still to be found) graviton and gravitino [5], it could be the fifth interaction apart from the four we are familiar with in the SM. He suggested to extend the $SU(3) \times SU(2) \times U(1)$ gauge by adding an extra $U(1)$ factor, which is responsible for spontaneous symmetry breaking, and this would require the new neutral gauge boson, which he called the U boson.

He also suggested various aspects of possible experiments to search for the U boson.[6] He suggested that the U boson could be produced directly in particle physics experiments despite its small gauge coupling constant. The type of experiments suitable for searching for it depend on its various properties like mass, the strength of its interaction, and parity character. Depending on its mass, it could be searched in "neutral-current phenomenology, e+e- annihilation, parity-violation in atomic physics, beam-dump experiments, rare decays of mesons", etc. Some of these ideas are being realized in current experimental particle physics research.

In a review article [3], recent developments in research about dark sector was summarized, including dark photons. The constituents and interactions of dark sector particles is unclear and poorly tested, as they are very different from the matter we are familiar with. The only known features are that dark sector particles are lack of strong or electromagnetic interactions, and that they are abundant.

It was proposed that dark sector interact with SM matter through "portal" interactions, and there are constraints on these portals from the symmetries of the SM. What couples to the SM via portals are one or several mediator particles in the dark sector. The spin and parity of the mediator particle decide whether it is a scalar ϕ, pseudoscalar a, fermion N, or vector A'. The dominant interaction portals are the vector portal (if the mediate particle is a vector A'), Higgs portal (mediate particle is scalar ϕ), neutrino portal (fermion N) and axion portal, with different mediator particles. The portal that has been mostly focused on is the vector portal, as it fits thermal models of light dark matter (LDM). In this scenario, the mediator particle is the dark photon, which is from an additional $U(1)_D$ gauge group.

In terms of gauge theory, the SM of particle physics describes strong, weak and electromagnetic interactions based on the $SU(3) \times SU(2) \times U(1)_Y$ symmetry group. This model is open to the possibility of becoming more complete by adding other gauge interactions, and this way of adding other gauge appears in many theoretical extensions of the SM, such as SUSY and string theory.

The photon we are familiar with is the force carrier and gauge boson of electromagnetic interaction, denoted by A. It is essentially electromagnetic field with $U(1)_Y$ gauge symmetry in the SM. Similarly, the dark photon is a vector field denoted by A', a gauge boson from an additional $U(1)_D$ gauge group, force carrier of a new force that is similar to the electromagnetic force in the SM. By this new force, the dark sector particles interact with the SM particles. Like the SM photon, dark photons couples (interacts) electromagnetically, but the coupling is suppressed by a factor of ϵ. [7]

2.2 Interaction and Properties [3]

One of the simplest model is that dark sector particles couple to SM particles via "kinetic mixing" , which is a phenomenon that produces an interaction between gauge bosons of two different gauge groups, as shown in figure 1.

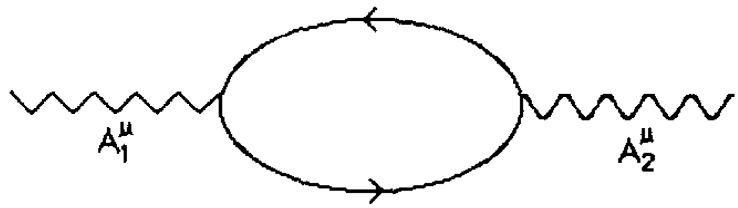


Figure 1. [8] Kinetic mixing. $A_1'^{\mu}$ and $A_2'^{\mu}$ are the two gauge fields.

In the model of dark photon, these two gauge groups are the SM $U(1)_Y$ gauge symmetry and the additional $U(1)_D$ gauge symmetry. [9]

The kinetic mixing is a term in the Lagrangian (which describes the dynamics of a system) expressed by:

$$L_{kin.mix} = \frac{1}{2}\epsilon F^{\mu\nu} F'_{\nu\mu} \tag{1}$$

where:

— F is the field strength tensor of the SM $U(1)_{em}$.

— F' is the field strength tensor of the dark $U(1)_D$.

— ϵ is the strength of the kinetic mixing, it is a very small dimensionless parameter between 10^{-5} and 10^{-2}, and is inversely related to the lifetime of A' [10].

The result of kinetic mixing is best understood in a specific basis. Then the interaction between the dark photon and SM particles are described by $L_{int} = \epsilon e A'_\mu J^\mu_{EM}$, where J^μ_{EM} is the familiar electromagnetic current, and e is the electric charge. This means the A' coupling to SM particles are proportional to e. This interaction is responsible for the production of dark photon in SM particle collisions and the decay of A' into SM particles.

As this is a interaction with very simple structure, it leads to very predictive theory. For example, the prediction of the braching ratios of A' decays.

There are two models about how A' decays: the "visible dark photon" model and the "invisible dark photon" model. In the visible dark photon model it is kinematically forbidden for dark photons to decay into dark sector particles. In this case, the branching ratio of the decay is shown in figure 2.

In the invisible dark photon model, the dark photon can decay into dark sector states. Then in the simplest case, the resultant dark sector particles cannot be seen by the standard particle detectors, thus called "invisible", although it is possible that some type of detectors would be sensitive to long-lived dark sector states. The invisible case could be distinguished if the branching ratios of the A' into the SM as shown in fig 2 is uniformly reduced. It could also be detected by using missing-mass or missing-momentum techniques.

It is also possible that A' could decay into mixed final states that contain both SM particles and dark sector particles, which adds difficulty in experimental searches, as some techniques, like the missing-mass technique, could be insensitive to some specific decay channels.

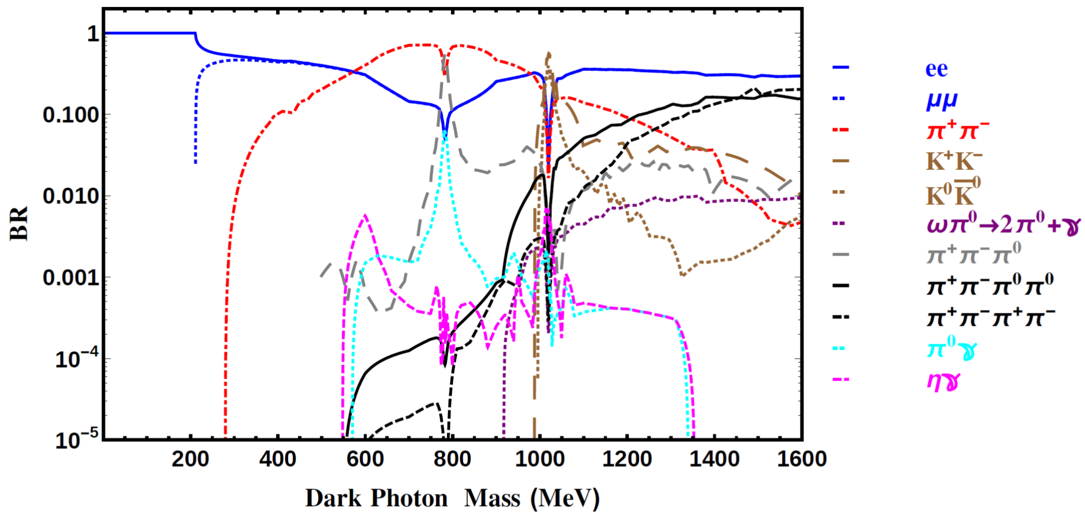


Figure 2. The branching ratios of the dark photon decay. [11]

2.3 Experimental Searches

The experimental searches can be categorized by ways of production and detection, they are summarized in the review article in 2016 [3]. The main ways of production are listed below, and the Feynman diagrams are shown in figure 3.

- Bremsstrahlung. $e^-Z \to e^-ZA'$, where Z is the nuclear charge. This is when an electron (or proton) collide on a fixed nuclear target. Example of experiments that use this method is HPS, APEX, DarkLight.
- Annilation. $e^+e^- \to \gamma A'$ This is better for searching invisible A' decay modes with missing-mass technique. This can be done in both fixed target and collider experiments.
- Meson decay. $\pi^0/\eta/\eta' \to \gamma A'$, $K \to \pi A'$, $\phi \to \eta A'$, etc. If A' do couple to quarks, this may produce low-mass A'. This production channel is favoured because there is a large meson production in hadronic environments.
- Drell-Yan $q\bar{q} \to A' \to (l^+l^- or h^+h^-)$.

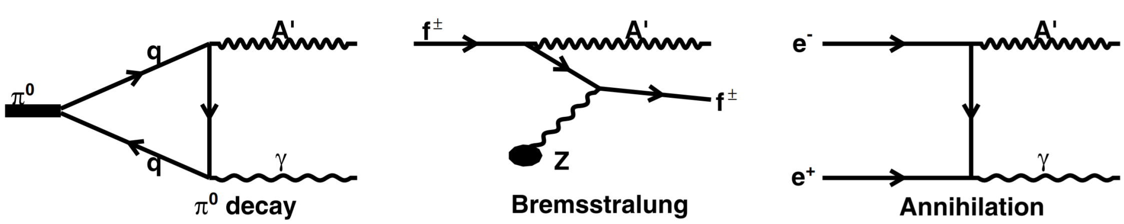


Figure 3. Feynman diagrams for different A' production channels. [12]

There are other ways of production used in experiments as well, like Higgsstrahlung, and in a lot of cases multiple ways of production are used.

In terms of detection, what method to use depends on ϵ and $m_{A'}$. The A' parameter plane is ϵ^2 versus $m_{A'}$, and the decay length of A' scales with $(\epsilon^2 m_{A'})^{-1}$. Some area in the parameter plane is excluded by experiments. Different ways of detection are listed below, and two experiments are introduced in the next part as examples.

- Bump hunt in visible final-state invariant mass. This is the case when they detect the mass of the final state particles that A' decays into: $A' \to l^+l^-$, $A' \to h^+h^-$.
- Bump hunt in missing-mass. This can be used in the case where A' could be invisible. From known initial state and reconstructed visible part of the final state, the A' can show up to be a bump in missing-mass distribution.
- Vertex detection. This is again in the visible decay mode when A' decay leptonically: $A' \to l^+l^-$. In this technique displacement of vertices is measured. As the decay length of A' scales with $(\epsilon^2 m_{A'})^{-1}$, having a long decay length requires ϵ. Searches with this method probes low ϵ area in the parameter plane.

The NA48/2 experiment [13]

The NA48/2 is an experiment at CERN, Geneva, where charged kaons (K^+K^-) are produced in the SPS proton synchrotron, and decays via $K^\pm \to \pi^0\pi^\pm$ and $K^\pm \to \pi^0\mu^\pm\nu$. The pions subsequently decays $(\pi^0 \to \gamma e^+e^-)$ and candidates of this decay were used to search for the dark photon. 1.69×10^7 candidates collected during 2003-2004 were analyzed, where there could be prompt A' produced by $\pi^0 \to \gamma A'$, and then decay $(A' \to e^+e^-)$. In this experiment only prompt dark photon decay (decay at the production point) was searched, as this is the assumption of the theoretical analysis.

The upper limit of the mass range that can be probed is limited because of the expected branching ratio $B(\pi^0 \to \gamma A') = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$. This equation means when $m_{A'}$ is as big as m_{π^0}, this decay process is kinematically suppressed. Thus this production channel give access to the A' mass in the range $2m_e < m_{A'} < m_{\pi^0}$, and in this range, the branching ratio of $A' \to e^+e^-$ is almost 1.

The production of K^+ and K^- is by protons colliding with a beryllium target. The produced kaon beams are focused, travel in vacuum and decay. Then there are drift chambers adding transverse momentum to the charged particles, and the plastice scintillator hodoscope, liquid krypton electromagnetic calorimeter, trigger system etc. detect various properties of the particles, identify them, select and collect data. Monte Carlo simulation was done with GEANT3 and the simulation was used when analyzing the data, like simulating the background from the $K^\pm \to \pi^\pm\pi^0\pi^0$ decay helped determining the mass range and the number of background events. In the end, the search of A' signal was performed in the mass range $9MeV/c^2 \leq m_{A'} < 120MeV/c^2$. The number of observed data events N_{obs}

and the background events N_{exp} as well as their uncertainties $\delta N_{obs}, \delta N_{exp}$ were determined, and the statistical significance of the A' signal was calculated for each mass with equation $Z = (N_{obs} - N_{exp})/\sqrt{(\delta N_{obs})^2 + (\delta N_{exp})^2}$, which never exceeded 3σ. This means there were no A' signal observed. And 90% confidence level exclusion limit was put on ϵ^2.

They also evaluated their sensitivity to the production channel $K^{\pm} \rightarrow \pi^{\pm} A'$, and decided that the sensitivity is not competitive compared with the result already obtained.

The result of the excluded region in the parameter plane is shown in fig 4 from the review article published in 2016.

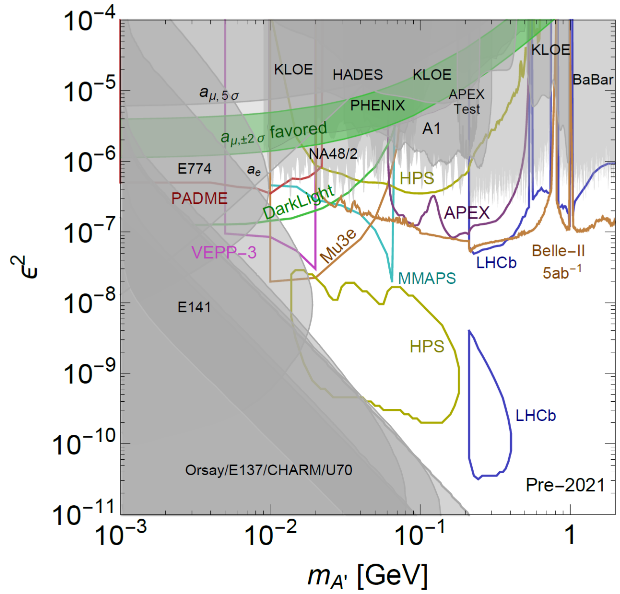


Figure 4. Summary of results from various experiments (shaded regions) and experiments that could deliver results before 2021. [3]

The LHCb experiment [7]

LHCb is also an experiment at CERN. In the LHCb, the searches were performed in proton-proton collisions with centre of mass ($\sqrt{s}$) 13 TeV and integrated luminosity 1.6 fb^{-1} by searching for mass bump from $A' \rightarrow \mu^+\mu^-$ decays. Multiple production channels were used.

Both prompt-like and long-lived A' was searched for. For prompt-like A' the search was performed in the mass range from the dimuon threshold (the lowest mass that a muon pair can have) to 70GeV, while for long-lived A' the range is in a much lower region: 214–350 MeV.

Assuming that the production mechanism of A' in proton-proton collision via kinetic $\gamma - A'$ mixing is similar to that of an off-shell photon γ^* with the same mass, the decay kinematics of them decaying into muon pairs $\mu^+\mu^-$ would be identical too. Thus equation 2 holds.

$$n_{ex}^{A'}[m(A'), \epsilon^2] = \epsilon^2 \left[\frac{n_{ob}^{\gamma^*}[m(A')]}{2\Delta m} \right] F[m(A')] \epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')] \quad (2)$$

where:

— $n_{ob}^{\gamma^*}[m(A')]$ is the observed yield of prompt $\gamma^* \to \mu^+\mu^-$ in a small interval $\pm\Delta m$ around $m(A')$.

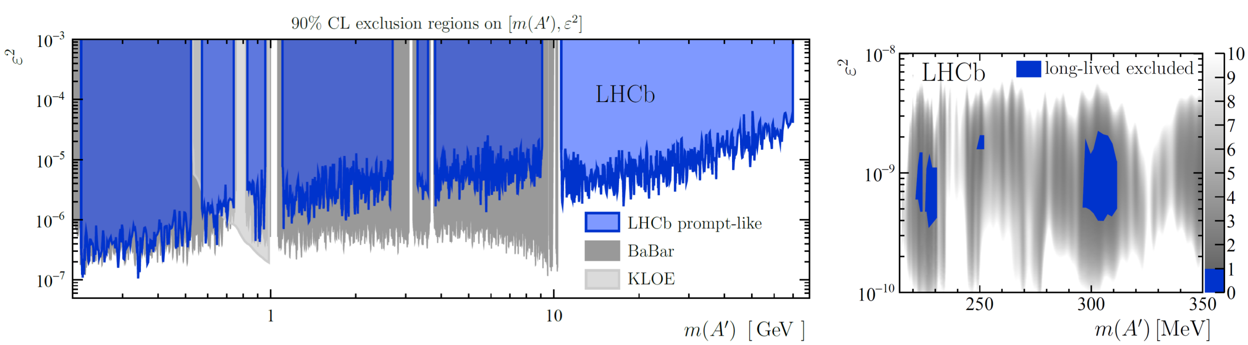
— $F[m(A')]$ is a function with known factors.

— $\epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')]$ is the ratio of $A' \to \mu^+\mu^-$ and $\gamma^* \to \mu^+\mu^-$ detection efficiencies.

In the prompt-like A' case, $\epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')]$ is close to 1 as experimentally the two decays are indistinguishable, and the observed yield $n_{ob}^{\gamma^*}[m(A')]$ can be normalized to $n_{ex}^{A'}[m(A'), \epsilon^2]$ to obtain constraints on ϵ^2

In the long-lived A' case, $\tau(A') \propto (m(A')\epsilon^2)^{-1}$ if A' mostly decay to visible final states. Thus the $A' \to \mu^+\mu^-$ decay can be constructed as displaced vertex if $m(A')\epsilon^2$ is small. In the experiment this displaced-vertex signature was used, and this experiment is the first to achieve sensitivity with this technique.

The events are selected by triggers, which consists of hardware trigger that use information from calorimeters and muon systems, and software trigger. The background could come from $\gamma^* \to \mu^+\mu^-$, misreconstruction, etc. Selection criteria of the candidates include requirements of the muon and A' having a certain range of pseudorapidity η, transverse momentum p_T (momentum that is transverse to the beam direction) and that topolotically they come from the primary vertex in the prompt-like A' search. The triggers are not yet efficient enough for low-mass, and there were no evidence of signal found, but some area of the parameter plane was excluded (shown in figure 5).



(a) prompt-like (b) long-lived

Figure 5. Area in blue are the regions excluded in the parameter plane at 90% credential level for prompt-like and long-lived A'.

3 Future prospects

Although current experiments have not found dark photon signals, there are various improvements could be done to help finding it in the future. In Run3 of the LHC (2021–2023) there would be higher luminosity, improved software trigger efficiency, hardware trigger would be removed. Larger region of the parameter space could be probed and the expected number of decay in low-mass region would be increased by a factor of 100–1000 [7]. Trigger schemes specifically optimized for dark sector searches could be built. For experiments using annihilation as production channel, it was proposed that building an asymmetric collider would cover a more extended range of mass. [3] Collider experiments could probe higher mass than fixed target experiments, a wider mass range could be probed in the future with higher energy. Searches could also be done with various future colliders.

4 Summary

Dark photon is a new gauge boson arise by adding an extra $U(1)_D$ gauge group to the $SU(3) \times SU(2) \times U(1)_Y$ symmetry group in the standard model. It is the force carrier of a force similar to the electromagnetic force in the SM. It is proposed to be the mediator between dark sector particles and a portal that dark sector particles could interact with SM particles. The interaction is via kinetic mixing.

There are two possible models of dark photon decay: the visible dark photon model, where the dark photon could decay into SM particles, and the invisible dark photon model, where they decay into dark sector particles. They could also decay into mixed final states that contain both the SM and dark sector particles.

There are various way that dark photon could possibly be produced and detected. There are various experiments looking for signals of dark photons, while no signals are found until today. But different regions in the parameter plane ϵ^2 vs $m_{A'}$ was excluded, and more experiments could be done to achieve better sensitivity and probe larger area in the future, and potentially unveil some of the mystery of dark matter.

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