Search for Dark Photon Decay in Radiative Processes

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Abstract

Among the diverse theories describing the interaction between the Dark Sector and SM particles, in this article, an analysis of the possible production of the dark photon and subsequent decay channel: $A' \to \mu^+\mu^-$ s has been conducted. The mode of production of the dark photon is through e^+e^- collision at 10.56 GeV in the Belle-II experiment and the analysis is focussed on setting bounds on the ϵ interactions strength parameter for the decay of a dark sector photon into two standard model leptons. The results are obtained using MC simulation and a sensitivity study for future searches at Belle II is performed where we can expect 1000 fb^{-1} expected luminosity from the experiment in the future and the limits for the parameter of interest are in the 10^{-3} $- 10^{-4}$ range.

1 Introduction

Dark matter constitutes of approximately 85% of the total mass of the universe [1], and is called so due to the fact that it is generally believed to not interact with electromagnetic radiation and is only detected by its gravitational effects. As the theory of the dark sector is not within the bounds of the Standard Model of particle physics, in case of non-Weakly Interacting Massive Particle dark matter, we must examine a theoretical dark sector gauge boson - the dark photon, which may interact with the standard model $U(1)_Y$ gauge group. According to [6] we can write the lagrangian for such an interaction as:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{g}{2}F'^{\mu\nu}F_{\mu\nu}$$

Here F and F' are the field strength tensors for the SM and dark sector $U(1)$ gauge groups. The ϵ parameter in the kinetic mixing term between the two gauge bosons is called the mixing strength, examining which is the goal of this article.

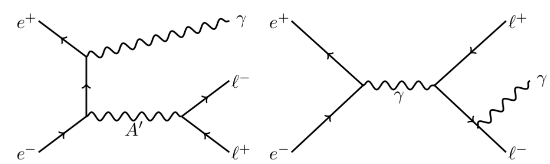

Figure 1: The tree-level Feynman diagrams [8] for the Signal and Background processes in the study. Left: Relevant mode of Dark Photon signal production at a B-factory experiment like Belle-II, where an on-shell A' dark photon and relevant leptons l are produced. Right: Primary background process with same end-state as the signal. For our study, l^+l^- is the muon $\mu^+\mu^-$

In a collider experiment, the primary variable we can measure is the total cross-section of a process. For the channel: $A' \to l^+l^-$, with the interaction of the form $\epsilon\bar{\psi}\Gamma^\mu A'_\mu\psi$, we obtain the cross section [5]:

$$\sigma = k\epsilon^2 \cdot (1-a)\left[b\cdot\Theta - \cos\theta_{max} + \cos\theta_{min}\right]$$

Where:

$$k = \frac{2\pi\alpha^2}{E_{CM}^2},\ a = \frac{m_{A'}^2}{E_{CM}^2},\ b = 1 + \frac{2a}{(1-a)^2}$$

$$\Theta = \log\left(\frac{(1+\cos\theta_{max})(1-\cos\theta_{min})}{(1+\cos\theta_{min})(1-\cos\theta_{max})}\right)$$

Here, $\alpha = 1/137$ is the electromagnetic fine structure constant, $E_{CM} = 10.58\ GeV$ is the center–of–mass (CM) energy of the e^+e^- collision at Belle-II, $\theta_{max} = 155°$ and $\theta_{min} = 12°$ define the angular acceptance of the Electromagnetic Calorimeter, and $m_{A'}$ is the mass of the dark photon which we consider over a certain range. One of the important conclusions from this expression is the fact that the cross-section varies with the square of ϵ. This allows us to set bounds on the parameter in the space of mixing strength and mass range of the dark photon.

2 Signal and Background Selection

The simulation of events is performed using the `basf2` [3] [7] software framework. For our study of a muon end state, signals were generated using MadGraph5. The signals were of 0.4, 0.6, 0.8, 1.0, 2.0, 4.0, 6.0, 8.0 and 9.0 GeV dark photon invariant mass, as lower masses favour decay of A' into a dielectron end state and become redundant for the way the analysis is performed.

For the background data, the primary final state is $\mu^+\mu^-\gamma$ which was collected from `/belle/collection/MC/MC15rd_mumu_exp20-26_4S_v2`. The MC equivalent luminosity for this collection is 699.235 fb^{-1} which was scaled down to 514 fb^{-1} to compare with the BaBar study [2] and also scaled up to 1000 fb^{-1} in order to predict how Belle-II results would look like in the future.

In order to reduce the background, the following cuts were made: The basf2 variable *dz* was fixed within a range, which means the distance of the point of closest approach of the vertex track from the point interaction was less than 5 cm. Also the variable *dr*, which is the transverse distance with respect to interaction point for a vertex was taken to be less than 2 cm. This reduces the chance of misidentifying the event vertex. The transverse momentum, *pt* and the centre of mass energy of the photon E_γ, were restricted to be > 2 GeV as we are not working with lower energies for the muon final state thus this reduces the number of fake tracks. The polar angle θ_γ for the Photon was also restricted to be in the CDC acceptance range which is roughly between 17° to 150°. For both the muons, *MuonID* was arbitrarily taken to be > 0.6 for selection and the $\chi^2 > 0$ criteria was provided after fitting the vertex to the event. The major cut which reduces the background is on the polar angle of the dark photon itself. We restricted it to be between 10° and 165° as it was seen that the polar angle for the signal events never exceeded those limits. A figure is provided below to see how the background and signal $\theta_{A'}$ variable compares after the cut is made.

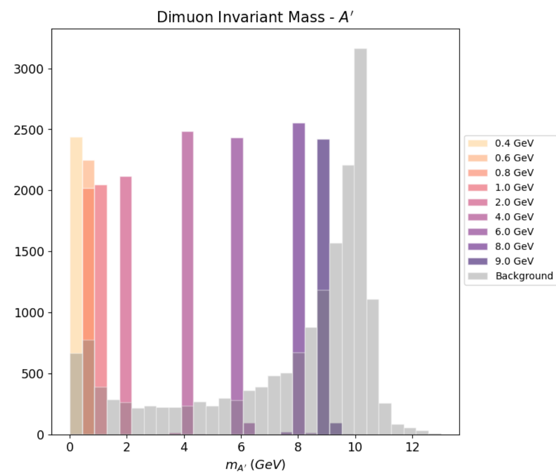

Figure 2: The dimuon invariant mass distribution is shown for chosen dark photon signal mass hypotheses and the background selected in the relevant mass range

A few of the selection cuts made were from a previous BaBar study for the e^+e final state [2]. The study selected events containing two oppositely charged tracks and a single photon with a center of mass energy greater than 0.2 GeV. If there are additional low-energy photons, they are allowed as long as their energies in the laboratory frame, do not exceed 0.2 GeV. To meet the identification criteria, at least one track must be recognized as an electron, or both tracks must be identified as muons. The muon helicity angle is defined as the angle between the muon and the CM frame in the A' rest frame and it was taken to be less than 0.95. To minimize the contribution from radiative Bhabha events, they also impose restrictions on the cosine of the polar angles of the positron and electron in the CM frame. The positron's polar angle must be larger than -0.5, while the electron's polar angle must be less than 0.5. Subsequently, the study fit the $\gamma l^+ l^-$ system, where the center-of-mass energy of the candidate is constrained to be within the beam energy spread, and the tracks are required to originate from the interaction point within its spread. Finally, they set a requirement that the χ^2 of the fit should be less than 30 (for 8 degrees of freedom).

A superimposed plot is provided for the signal and background after arbitrarily rescaling the background in the following figure:

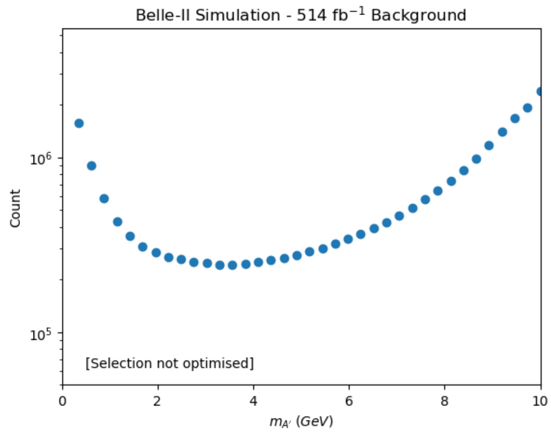

Figure 3: Selected background in the region, the plot here is logarithmically scaled along the Y-axis and from the distribution we can see that ISR was not taken into consideration.

The signal efficiencies were then extracted and from the plot we can see that the efficiencies follow a certain trend for different mass regions.

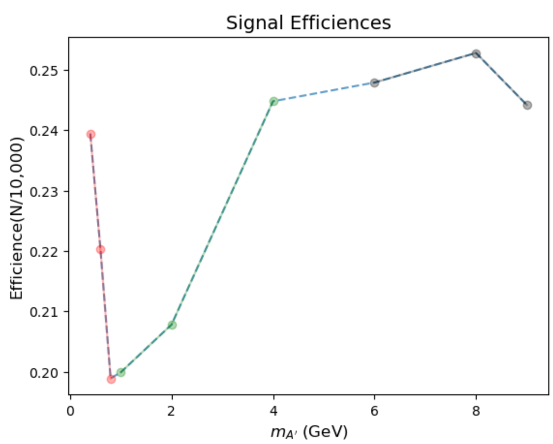

Figure 4: Selection efficiencies rapidly drop in the 0.4 to 0.8 GeV region and show an opposite trend for 1 to 4 GeV invariant masses and plateau after the 6 GeV region around roughly 25% efficiency

3 Offline Analysis

In order to proceed, we need to extract the upper limit of signal points (N_{sig}), we need for a specific luminosity. To obtain this, we have taken ϵ to be in the range of 5×10^{-4} to 3×10^{-3} along with the previously mentioned mass array and calculated the expected cross-section (σ). For a given luminosity (L), and signal efficiency (ε) we have,

$$\sigma = \frac{N_{sig}}{\varepsilon L}$$

In the space of the mixing strength and mass, for each point the value of N_{sig} is determined and the signal is scaled according to the number. This was done for $L = 514\ fb^{-1}$ and $L = 1000\ fb^{-1}$ values. Initially the background set had a luminosity of $699.235\ fb^{-1}$, which was again scaled up and down to the two values of L.

The first goal of the offline analysis after signal and background selection is completed is to fit the signal with a double-sided crystal ball function as the PDF using `zfit` software [4]. All the fits that follow are performed using `zfit` as it works in synchronisation with the `hepstats` which will be used to actually determine the limits of ϵ. The double-sided crystall ball function was chosen instead of the commonly used double-Gaussian as it can model the decaying tails of the signal to a greater accuracy. The double sided crystal ball function has parameters μ and σ which model the peak and α_i and n_i which define the decay of the tails on both sides of the peak. The function itself is defined as follows in `/pdf/zfit.pdf.DoubleCB.html`:

$$f(x;\mu,\sigma,\alpha_L,n_L,\alpha_R,n_R) = \begin{cases} A_L \cdot (B_L - \frac{x-\mu}{\sigma})^{-n}, & \text{for } \frac{x-\mu}{\sigma} < -\alpha_L \\ \exp(-\frac{(x-\mu)^2}{2\sigma^2}), & -\alpha_L \leqslant \text{for} \frac{x-\mu}{\sigma} \leqslant \alpha_R \\ A_R \cdot (B_R - \frac{x-\mu}{\sigma})^{-n}, & \text{for } \frac{x-\mu}{\sigma} > \alpha_R \end{cases}$$

$$A_{L/R} = \left(\frac{n_{L/R}}{|\alpha_{L/R}|}\right)^{n}_{L/R} \cdot \exp\left(-\frac{|\alpha_{L/R}|^2}{2}\right)$$

$$B_{L/R} = \frac{n_{L/R}}{|\alpha_{L/R}|} - |\alpha_{L/R}|$$

Figure 5: Fit function for signals

Certain considerations had to be taken into account when using `zfit` tools for fitting the signal including initialising the mean of the fit function to the exact chosen mass point and the standard deviation to the standard deviation of the signal invariant mass array. All other parameters were initialised as the default 1.

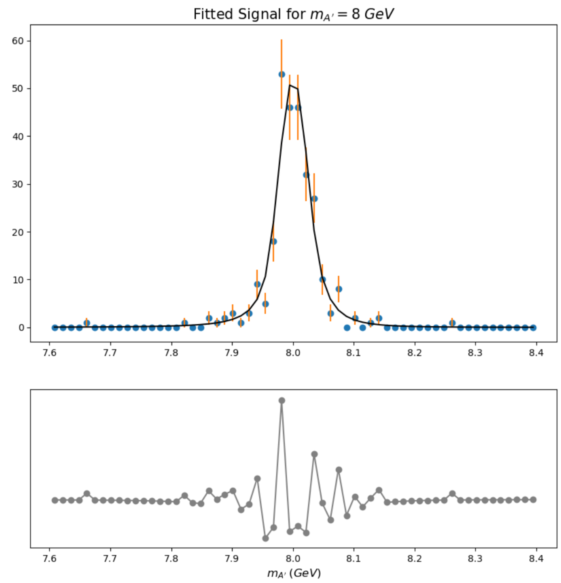

Figure 6: The signal for 8 GeV dark photon invariant mass fitted to the pdf and the error range of the fit

Initially, the background chosen was the MC simulation in MC15rd from DESY Confluence for the experiment 26, run 01968: `/mumu/mdst/sub00/mdst_000001_prod00027831_task251967000001.root` but, the signal size being too small, a region around the mean of the chosen signals (5% around the peak) and then fitted with an exponential PDF, and scaled up according to that PDF.

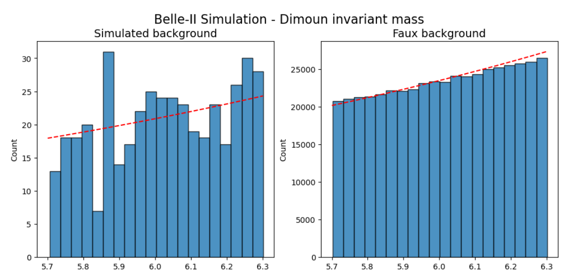

Figure 7: While considering the physics near the peak of an injected signal, there are not enough background points to eliminate statistical fluctuations and thus, we fit an exponential PDF to the background and generate a faux background with greater number of points in the region for analysis.

However, using `/belle/collection/MC/MC15rd_mumu_exp20-26_4S_v2`, we solved this issue and we could cut out neighbourhoods around the signal and fit them directly using an exponential PDF for further analysis.

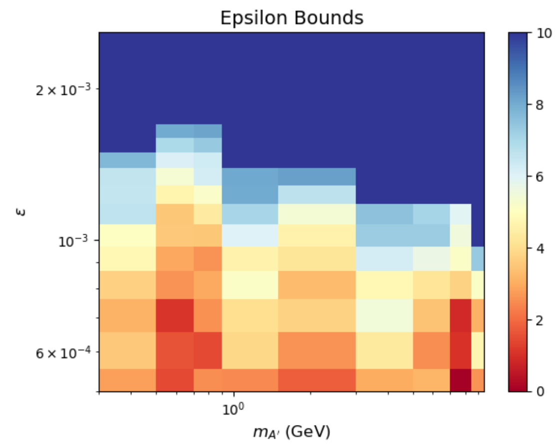

Figure 8: The colormap of significance values for 514 fb^{-1} of data. The plot has been logarithmically scaled along both the mass and mixing strength axis.

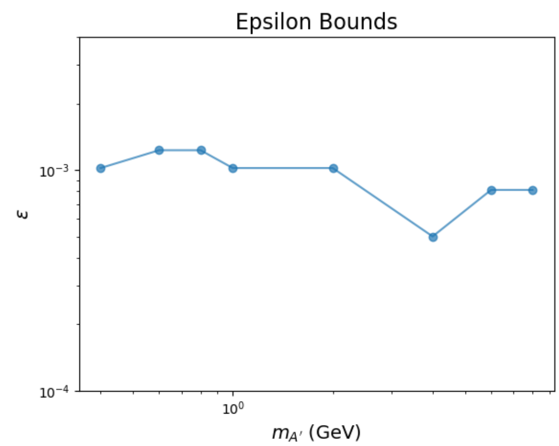

Figure 9: Lower bound of 5σ significance line over 0.4 - 9 GeV invariant dark photon mass. The simplest conclusion from this figure is that for 514 fb^{-1} data, the limit dwells around 10^{-3} in general and begins to lower for the higher mass range.

To find new physics, we must obtain the lowest values of ϵ for which we can get a 5σ fit for the signal in the data. So, the fit parameters extracted from the background and the signal were fixed and then a likelihood fit was performed on the combined data set of the signal and the background. The loss functions were changed to `ExtendedUnbinnedNLL` for the `zfit` package, then utilising `AsymptoticCalculator` from `hepstats.hypotests.calculators` and the `Discovery` function from the `hepstats.hypotests`, the p-values for the null hypothesis and significances were extracted along with signal and background yields in the space of mixing strength and invariant mass. A colormap of the significance values are provided from which we can obtain the lowest ϵ for each of the selected invariant mass points which give a significance $> 5\sigma$.

We also perform an upper limit analysis for the signal yield from the extended unbinned fit to extract the limits of ϵ to compare with previous studies. The module used here is `UpperLimit` from `hepstats.hypotests`. We obtain the expected signal yield in absence of tthe signals itself to set the bounds. If we inject signal, we can observe large deviations of the observed UL value from the expected UL value. We have used a confidence level of 90% for this calculation and obtained the signal yield for 20 experiments with values ranging from 0 to 25,000.

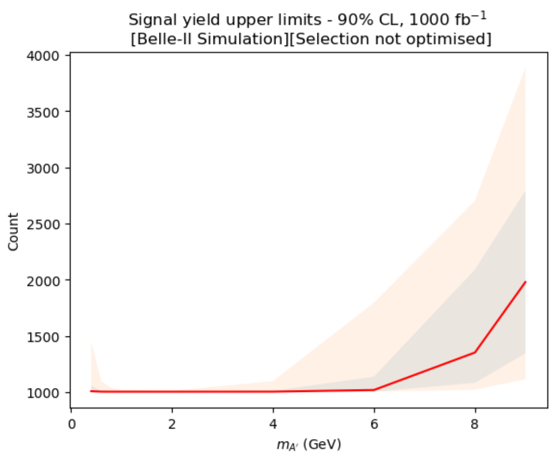

Figure 10: For comparison with [2] we plot the signal yield upper limits, noticing that up until 6 GeV dark photon mass, the line remains at an almost constant magnitude of 1133.

Hereon, in order to determine the upper limits of the mixing strength at 95% CL, the signal yield N_{sig} is converted back to the cross section and subsequently to the values of the mixing strength ϵ and plotted against similar anlysis done by other studies in one plot. We have plotted two limiting lines, one for 514 fb^{-1} in order to compare with [2] and another at 1000 fb^{-1} in order to predict what future Belle-II results may be observed.

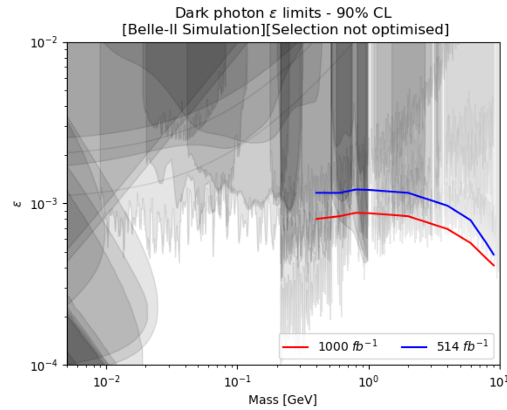

Figure 11: Upper limit (90% CL) on the mixing strength ϵ as a function of the dark photon mass in the range of 0.4 - 9 GeV.

4 Conclusion

To conclude, we conducted an investigation into the production of dark photons with masses between 0.4 GeV and 9 GeV and their subsequent decay into a dimuon state. The entire study is based on simulation in Belle-II software and we were able to establish upper limits on the mixing strength in the relevant interaction, in the range of 10^{-4} to 10^{-3}. These limits obtained are similar to those of previous searches including [2] and [8], also predicting how results would look like if a search was conducted using Belle-II experimental data at the luminosity of 1000 fb^{-1}. However, the results presented are based on very loose selection cuts in order to build the framework for such analysis and is a subject of further study for more conclusive results. All `Jupyter` notebooks are in `github.com/SahilSaha/DarkPhoton2023`.

References

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