

Searching for Neutral State in the Rare Decay

$$J/\psi \rightarrow e^+ e^- \phi$$

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Abstract

We investigate the decay process $J/\psi \rightarrow e^+ e^- \phi$, where the relatively clean electromagnetic (EM) transitions dominate at leading order at the tree level, while hadronic contributions arise only through hadronic loop transitions. The branching ratio of $J/\psi \rightarrow e^+ e^- \phi$ was estimated to be approximately 2.28×10^{-8} where the hadronic effects are negligible compared to the EM contributions. The upper limit on the branching fraction was set to be $B(J/\psi \rightarrow e^+ e^- \phi) < 1.2 \times 10^{-7}$ by BESIII collaboration. In this paper, we investigate the existence of a neutral state such as dark photon and dark Z . Our analysis shows that the constraints on the dark photon and dark Z are stringent in the way that large enhancement to the SM branching ratio up to the present experimental limit is not possible. Therefore, observing a signal for the dark photon and dark Z in this decay channel is changeable.

Keywords

Rare Decays, Dark Matter, Hadrons

1. Introduction

High-intensity experiments enable precise tests of the Standard Model (SM) and the search for signs of new physics beyond the Standard Model (BSM). Rare decays are particularly useful in the low-energy regime, as SM contributions are suppressed, making anomalies potential indicators of BSM effects. Experiments like BEPCII/BESIII [1] and BELLE-II [2] [3] offer extensive data for studying such rare processes.

The decay $J/\psi \rightarrow e^+ e^- \phi$ serves as an example of a rare process measurable by

BESIII which sets upper limit on the branching fraction to be

$B(J/\psi \rightarrow e^+e^-\phi) < 1.2 \times 10^{-7}$ [4]. The dominant contribution comes from EM transitions via vector meson dominance [5], while sub-leading contributions arise from hadronic meson loops involving quark-gluon dynamics. Experimental data on radiative decays $J/\psi \rightarrow \gamma P$ and γS , $\phi \rightarrow \gamma P$ (where P and S are pseudoscalar and scalar mesons) help estimate hadronic contributions.

Results indicate hadronic effects are smaller than EM contributions, with significant intermediate states being η, η' (pseudoscalar) and $f_0(980)$ (scalar), while contributions from $\sigma(500)$ can be neglected due to weak couplings. This analysis provides insights into rare processes and potential traces of BSM physics.

Flavor-changing neutral currents (FCNCs) are powerful tools for exploring new physics (NP) and place strong constraints on extensions of the SM. The study in Ref. [6] focuses on FCNC processes in B and K decays to investigate models involving a light gauge boson. Specifically, it examines the dark $U(1)_D$ model, which predicts a dark photon or a dark Z (Z'), collectively referred to as Z_D [7]-[9].

The nature of Z_D depends on its interactions: kinetic mixing with the electromagnetic field produces a dark photon with vector couplings to SM fermions (except neutrinos), while mass mixing with SM gauge fields results in a dark Z . FCNC processes involving Z_D are loop-mediated, with significant effects in B decays due to the suppression of the GIM mechanism for up-type quarks, while D decays are less affected due to down-type quark loops.

Unlike heavy mediators, light mediators like Z_D lead to q^2 -dependent Wilson coefficients. Ref. [6] evaluates Z_D -mediated $b \rightarrow s \ell^+ \ell^-$ transitions for Z_D masses in the range $0.01 \text{ GeV} \lesssim M_{Z_D} \lesssim 2 \text{ GeV}$ [10]-[21], considering both on-shell and off-shell decays. Hadronic decays and invisible decays of Z_D (from interactions with dark sector particles) are included. Additionally, the study explores models where Z_D directly couples to muons and/or electrons, providing a detailed analysis of the rates and effects of these processes.

In this paper, we will be interested in probing dark photon and dark Z states via the decay channel $J/\psi \rightarrow e^+e^-\phi$. Constraints on the model parameters are taken from B_s mixing, $B_s \rightarrow \mu^+\mu^-$, $B \rightarrow K^{(*)}\nu\bar{\nu}$, Kaon decay and mixing, Radiative $K^+ \rightarrow \mu^+\nu_\mu Z_D$ decays, Radiative $\pi^+ \rightarrow \mu^+\nu_\mu Z_D$ decays, Atomic parity violation, Neutrino trident and CE ν NS, and Collider and other bounds. All these constraints were discussed in Ref. [6].

The paper is organized as follows: In Sec. 2, the general formalism of the dark symmetry $U(1)_D$ is discussed. In Sec. 3, we discuss the SM formalism and numerics to the decay process $J/\psi \rightarrow e^+e^-\phi$. The NP contribution is discussed in Sec. 4 and we summarize in Sec. 5.

2. Formalism

We consider Z_D as a gauge boson associated with the broken $U(1)_D$ symmetry of a dark sector, coupled to the SM via kinetic mixing with $U(1)_Y$ [7]. The gauge Lagrangian is given by [9]:

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z_D^{\mu\nu} - \frac{1}{4}Z_{D\mu\nu}Z_D^{\mu\nu},$$

where $B_{\mu\nu}$ and $Z_{D\mu\nu}$ are the field strength tensors for B and Z_D , ε is the kinetic mixing parameter, and θ_W is the weak mixing angle.

After diagonalizing the gauge sector [9] [22], Z_D acquires an induced coupling to the SM electromagnetic current, leading to the dark photon model. To leading order in ε , the interaction is:

$$\mathcal{L}_D^{\text{em}} \supset e\varepsilon Z_D^\mu J_\mu^{\text{em}} - ie\varepsilon \left[Z_D W^+ W^- \right],$$

where $\left[Z_D W^+ W^- \right]$ represents the interaction of Z_D with W^\pm bosons.

$$\begin{aligned} \left[Z_D W^+ W^- \right] &= \varepsilon_{Z_D}^\mu(k_1) \varepsilon_{W^+}^\nu(k_2) \varepsilon_{W^-}^\lambda(k_3) \\ &\times \left[(k_1 - k_2)_\lambda g_{\mu\nu} + (k_2 - k_3)_\mu g_{\nu\lambda} + (k_3 - k_1)_\nu g_{\lambda\mu} \right]. \end{aligned} \tag{1}$$

If $U(1)_D$ is broken by a scalar field charged under the SM, Z_D can mix with the SM Z boson via mass terms [8] [9]. The physical states are expressed as:

$$Z = Z^0 \cos \xi - Z_D^0 \sin \xi, \quad Z_D = Z^0 \sin \xi + Z_D^0 \cos \xi,$$

where ξ is the mass mixing angle. This interaction defines the dark Z model, with the Lagrangian:

$$\mathcal{L}_D^Z \supset \frac{g}{\cos\theta_W} \varepsilon_Z Z_D^\mu J_\mu^Z - ig \cos\theta_W \varepsilon_Z \left[Z_D W^+ W^- \right],$$

where $\varepsilon_Z = \frac{1}{2} \tan 2\xi$. If $U(1)_D$ is broken by SM singlet scalars, then $\varepsilon_Z = 0$, reducing the model to a dark photon.

We do not specify a Higgs sector for $U(1)_D$ breaking but focus on the general mass mixing. The free parameters are the mixing parameters ε and ε_Z , along with the mass of Z_D (M_{Z_D}). Updated constraints on these parameters are provided in recent studies.

In the relevant mass range, Z_D decays into lepton pairs and hadronic final states. While e^+e^- and $\nu\bar{\nu}$ decays are always kinematically allowed, the $\mu^+\mu^-$ channel is accessible only if $M_{Z_D} > 2m_\mu$. The decay widths for these processes are given by [6]:

$$\begin{aligned} \Gamma(Z_D \rightarrow \ell^+ \ell^-) &= \frac{e^2}{96\pi c_W^2 s_W^2 M_{Z_D}} \sqrt{1 - 4\frac{m_\ell^2}{M_{Z_D}^2}} \left[8c_W^2 s_W^2 \varepsilon^2 (2m_\ell^2 + M_{Z_D}^2) \right. \\ &\quad - 4c_W s_W (4s_W^2 - 1) \varepsilon \varepsilon_Z (2m_\ell^2 + M_{Z_D}^2) \\ &\quad \left. + \varepsilon_Z^2 (m_\ell^2 (16s_W^4 - 8s_W^2 - 1) + M_{Z_D}^2 (8s_W^4 - 4s_W^2 + 1)) \right], \end{aligned}$$

$$\Gamma(Z_D \rightarrow \nu\bar{\nu}) = \frac{e^2 M_{Z_D} \epsilon_Z^2}{96\pi c_W^2 s_W^2}. \tag{2}$$

where c_W and s_W are the cos and sin of the Weinberg angle, M_{Z_D} is the dark Z mass, m_ℓ is the lepton mass, ϵ and ϵ_Z are the kinetic mixing and mass mixing parameters.

Hadronic decays, however, cannot be calculated directly using perturbative QCD. Instead, the VMD model is employed to describe low-energy QCD [23]-[27]. Recent data-driven studies have calculated the hadronic decay widths of light $U(1)$ vector bosons [28]-[30]. For dark photons with couplings proportional to electric charge, the hadronic decay width can be expressed as:

$$\Gamma(Z_D \rightarrow \mathcal{H}) = \Gamma(Z_D \rightarrow \mu^+ \mu^-) \times \mathcal{R}_\mu^{\mathcal{H}},$$

where $\mathcal{R}_\mu^{\mathcal{H}} = \sigma(e^+ e^- \rightarrow \mathcal{H}) / \sigma(e^+ e^- \rightarrow \mu^+ \mu^-)$, measured experimentally [31]. At energies away from hadron resonances, $e^+ e^-$ annihilation gradually transitions to perturbative quark-pair production, with $\mathcal{R}_\mu^{\mathcal{H}} \approx N_c \sum_{f=u,d,s} (Q_{em}^f)^2 = 2$, where $N_c = 3$ is the color factor and Q_{em}^f is the fermion's electric charge.

For baryophilic dark photons, the hadronic decay width has been calculated by summing over various final states within the VMD framework [30]. This analysis is adapted to the vector coupling of the dark Z . For axial vector couplings, quark-level decays are used to estimate contributions to the hadronic width.

3. The EM Contribution to $J/\psi \rightarrow e^+ e^- \phi$

The leading EM contribution to $J/\psi \rightarrow e^+ e^- \phi$ for which the corresponding Feynman diagrams are shown in Figure 1 (Ref. [32]).

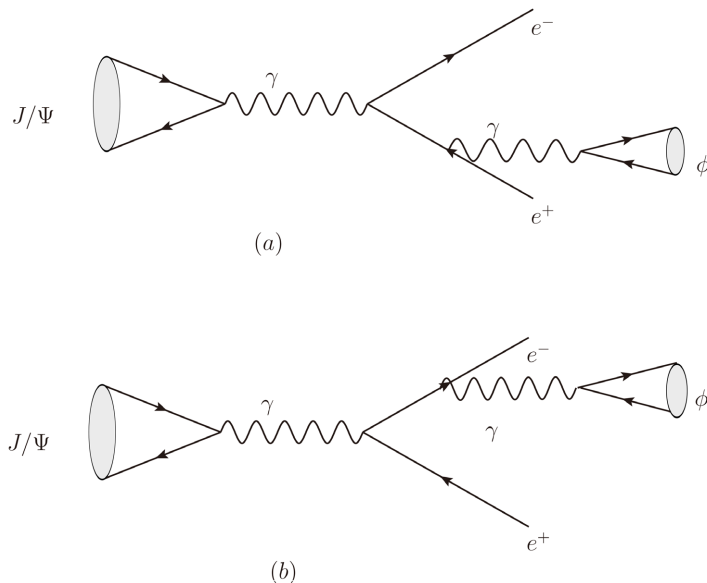


Figure 1. The EM transitions of $J/\psi \rightarrow e^+ e^- \phi$.

The decay $J/\psi \rightarrow \gamma\phi$ is forbidden by C -parity conservation unless new physics BSM exists to break this rule. However, when the photon is virtual and converts into an e^+e^- pair, the decay $J/\psi \rightarrow e^+e^-\phi$ becomes allowed and measurable.

Electromagnetic Contribution: The leading contribution is EM, as shown in **Figure 1**. The effective γ -vector meson couplings are calculated using VMD:

$$\langle J/\psi | \bar{c}\gamma^\nu c | 0 \rangle = g_{\psi\gamma} \epsilon_\nu^{*\nu}, \quad \langle \phi | \bar{u}\gamma^\mu u | 0 \rangle = g_{\phi\gamma} \epsilon_\phi^{*\mu},$$

where the couplings are

$$g_{\psi\gamma} = 0.150 \text{ GeV}^2, \quad g_{\phi\gamma} = 0.013 \text{ GeV}^2.$$

The EM transition amplitude is

$$\begin{aligned} \mathcal{M}_{EM} = \bar{u}(p_1) & \left[(-ie\gamma^\nu) \frac{p_2 + p_\phi + m_e}{(p_2 + p_\phi)^2 - m_e^2} (-ie\gamma^\mu) \right. \\ & \left. + (-ie\gamma^\mu) \frac{p_1 + p_\phi + m_e}{(p_1 + p_\phi)^2 - m_e^2} (-ie\gamma^\nu) \right] v(p_2) \frac{g_{\phi\gamma} \epsilon_\phi^\mu}{p_\phi^2} \frac{g_{\psi\gamma} \epsilon_\psi^{*\nu}}{p_\psi^2}. \end{aligned} \quad (3)$$

where p_1 and p_2 are the electron and positron momenta, p_ϕ and p_ψ are the ϕ and ψ momenta, $g_{\psi\gamma}$ and $g_{\phi\gamma}$ are the effective couplings of ϕ and ψ with the photon.

Hadronic Loop Contributions: Hadronic contributions via intermediate states ($f_0(980)$, η , η') are included. The effective couplings are:

$$\begin{aligned} g_{\psi f_0} &= 3.21 \times 10^{-5} \text{ GeV}, \quad g_{\phi f_0} = 3.03 \times 10^{-2} \text{ GeV}^{-1}, \\ g_{\psi\eta} &= 5.36 \times 10^{-4} \text{ GeV}^{-1}, \quad g_{\psi\eta'} = 1.28 \times 10^{-3} \text{ GeV}^{-1}. \end{aligned}$$

Decay Widths and Branching Ratios: The decay widths and branching ratios of $J/\psi \rightarrow e^+e^-\phi$ from EM and hadronic processes are summarized in **Table 1**, see Ref. [32]:

Table 1. The decay widths and branching ratios of $J/\psi \rightarrow e^+e^-\phi$ contributed from the EM and hadronic processes.

	EM	via $f_0(980)$	via η	via η'	Total
$\Gamma(J/\psi \rightarrow e^+e^-\phi)$ (keV)	2.12×10^{-6}	2.00×10^{-13}	7.2×10^{-11}	1.12×10^{-9}	2.12×10^{-6}
B.R.	2.28×10^{-8}	2.16×10^{-15}	7.75×10^{-13}	1.20×10^{-11}	2.28×10^{-8}

The EM process dominates, with a partial branching ratio of 2.28×10^{-8} . Hadronic loop contributions are suppressed by at least three orders of magnitude. The SM background is minimal, making this process a promising probe for BSM physics. The decay $J/\psi \rightarrow e^+e^-\phi$ is a rare process in the SM, dominated by the EM

contribution. Its suppression makes it an ideal candidate to explore potential BSM contributions.

4. Numerical Analysis

The branching ratio formula is given by

$$BR_{A/Z_D} = \frac{1}{\Gamma} \frac{1}{(2\pi i)^3 32M_{J/\psi}^3} \int_{(m_{12}^2)_{\min}}^{(m_{12}^2)_{\max}} \int_{(m_{23}^2)_{\min}}^{(m_{23}^2)_{\max}} |\mathcal{M}_{A/Z_D} + \mathcal{M}_{EM}|^2 dm_{23}^2 dm_{12}^2 \quad (4)$$

where the dark photon contribution to the decay process $J/\psi \rightarrow e^+ e^- \phi$ is

$$\begin{aligned} \mathcal{M}_A = & \bar{u}(p_1) \left[(-ie\epsilon\gamma^\nu) \frac{p_2 + p_\phi + m_e}{(p_2 + p_\phi)^2 - m_e^2} (-ie\epsilon\gamma^\mu) \right. \\ & \left. + (-ie\epsilon\gamma^\mu) \frac{p_1 + p_\phi + m_e}{(p_1 + p_\phi)^2 - m_e^2} (-ie\epsilon\gamma^\nu) \right] v(p_2) \\ & i \left(\frac{\bar{P}_\phi^\mu \bar{P}_\phi^{\mu'}}{M_x^2} - \bar{g}^{\mu\mu'} \right) \times i \left(\frac{\bar{P}_\psi^\nu \bar{P}_\psi^{\nu'}}{M_x^2} - \bar{g}^{\nu\nu'} \right) \\ & \frac{1}{\bar{P}_\phi^2 - M_x^2 + i\Gamma_x M_x} \times \frac{1}{\bar{P}_\psi^2 - M_x^2 + i\Gamma_x M_x} \times (g_{\phi\gamma} \epsilon \epsilon_\phi^{\mu'}) (g_{\psi\gamma} \epsilon \epsilon_\psi^{\nu'}) \end{aligned} \quad (5)$$

where M_x is the dark photon mass. The dark Z_D contribution is

$$\begin{aligned} \mathcal{M}_{Z_D} = & (g_L + g_R) \frac{g_{W\gamma}}{e} \epsilon_Z P_\psi (\bar{\epsilon}^*)^{\nu'} (g_L + g_R) \frac{g_{\phi\gamma}}{e} \epsilon_Z P_\phi \bar{\epsilon}^{\mu'} \\ & \times \frac{i \left(\frac{\bar{P}_\psi^\nu \bar{P}_\psi^{\nu'}}{M_x^2} - \bar{g}^{\nu\nu'} \right)}{\bar{P}_\psi^2 - M_x^2 + i\Gamma_x M_x} \frac{g}{2C_W} \bar{u}(P_1, m_e) \\ & \times \left(V^\mu \epsilon_Z \frac{\bar{\gamma} \cdot \bar{P}_1 + \bar{\gamma} \cdot \bar{P}_\phi + m_e}{(\bar{P}_1 + \bar{P}_\phi)^2 - m_e^2} V^\nu \epsilon_Z \right. \\ & \left. + V^\nu \epsilon_Z \frac{\bar{\gamma} \cdot \bar{P}_2 + \bar{\gamma} \cdot \bar{P}_\phi + m_e}{(\bar{P}_2 + \bar{P}_\phi)^2 - m_e^2} V^\mu \epsilon_Z \right) v(P_2, m_e) \\ & \times \frac{i \left(\frac{\bar{P}_\phi^\mu \bar{P}_\phi^{\mu'}}{M_x^2} - \bar{g}^{\mu\mu'} \right)}{\bar{P}_\phi^2 - M_x^2 + i\Gamma_x M_x} \frac{g}{2C_W}. \end{aligned} \quad (6)$$

with

$$V^\mu = \frac{1}{2} \frac{g}{c_W} \left(g_L \gamma^\mu (1 - \gamma^5) + g_R \gamma^\mu (1 + \gamma^5) \right),$$

$$E_2(m_{12}^2) = \frac{\sqrt{m_{12}^2}}{2},$$

$$E_3(m_{12}^2) = \frac{M_{J/\psi}^2 - m_{12}^2 - M_\phi^2}{2\sqrt{m_{12}^2}}$$

$$\begin{aligned}
(m_{23}^2(m_{12}^2))_{(\max)} &= (E_2(m_{12}^2) + E_3(m_{12}^2))^2 \\
&\quad - \left(\sqrt{E_2(m_{12}^2)^2 - m_e^2} - \sqrt{E_3(m_{12}^2)^2 - M_\phi^2} \right)^2 \\
(m_{23}^2(m_{12}^2))_{(\min)} &= (E_2(m_{12}^2) + E_3(m_{12}^2))^2 \\
&\quad - \left(\sqrt{E_2(m_{12}^2)^2 - m_e^2} - \sqrt{E_3(m_{12}^2)^2 + M_\phi^2} \right)^2 \\
(m_{12})_{(\max)} &= (M_{J/\psi} - M_\phi)^2 \\
(m_{12}^2)_{(\min)} &= 4m_e^2
\end{aligned}$$

where ε_ψ^V and ε_ϕ^H are the polarization vectors of J/ψ and ϕ , respectively, and $g_{\psi\gamma}$ and $g_{\phi\gamma}$ are the corresponding couplings for J/ψ and ϕ to a virtual photon, respectively. M_x is the Z_D mass, $m_{ij}^2 = p_{ij}^2$ where p_1 and p_2 are the momenta of the electron and positron, E_1 and E_2 are the energy of the electron and positron, $g_L = \left(1 - \frac{1}{2} + s_W^2\right)$, and $g_R = s_W^2$.

We computed the contribution of the dark photon, dark Z_D , and both states together to the decay channel $J/\psi \rightarrow e^+e^-\phi$ with $\varepsilon = 1 \times 10^{-3}$ and $\varepsilon_Z = 0$, $\varepsilon = 0$ and $\varepsilon_Z = 2 \times 10^{-3}$, $\varepsilon = 1 \times 10^{-3}$ and $\varepsilon_Z = 2 \times 10^{-3}$, respectively. The M_x value taken in the range of $2m_\mu$ to $M_B - M_K$, the range used in Ref. [6]. In this range, we avoid the J/ψ and ϕ masses to avoid the mixing effect between the dark boson and these hadronic states.

The contribution of the dark boson to the decay channel is almost negligible, as shown in the graphs, because of the stringent constraints on the model parameters $(\varepsilon, \varepsilon_Z)$. The stringent constraints on ε_Z [6] come from $B_s^0 - \bar{B}_s^0$ mixing, COHERENT neutrino scattering data, APV measurements for $\varepsilon = 0.0001, 0.001, 0.01$ with M_{Z_D} in the range of 0.01 - 1 GeV. The stringent constraints on ε [6] come from LHCb dark photon searches, APV measurements for $\varepsilon_Z = 0.0001$ and 0.001 with M_{Z_D} in the range of 0.01-1 GeV. The parameters are restricted to $\varepsilon \leq 0.001$ and $\varepsilon_Z \leq 0.002$. Therefore, probing down the two states of dark photon and dark Z_D in the decay channel $J/\psi \rightarrow e^+e^-\phi$ is not possible because of the strong constraints on the model parameters. These results are valuable to the scientific community to be aware of, so that no further investigation to be done in this direction. This by itself is a value will be added to the scientific community. It is impossible for the results to be tested in the future super tau-charm factory. Even though, the study introduces a value by closing up the search in this direction because of the stringent constraints on the model parameters, as discussed above.

Several alternative decay channels can be explored to probe the dark photon and dark (Z_D), each offering complementary insights. Rare B -meson decays,

such as $B \rightarrow K^{(*)} \ell^+ \ell^-$, $B \rightarrow \pi \ell^+ \ell^-$, and $B \rightarrow \ell^+ \ell^- \nu \nu$, are particularly sensitive due to their suppression in the SM and potential new physics contributions. Similarly, rare kaon decays like $K^+ \rightarrow \pi^+ \nu \nu$ and $K_L \rightarrow \pi^0 \ell^+ \ell^-$ are sensitive to dark sector particles. In the charmonium sector, modes such as $J/\psi \rightarrow \gamma + X$ and $J/\psi \rightarrow \ell^+ \ell^- + \phi$ allow for testing invisible or exotic final states. Tau decays, including $\tau \rightarrow \mu \nu_\tau \nu_\mu + Z_D$ and $\tau \rightarrow \ell + \gamma + Z_D$, are also promising due to the tau's mass and complex decay patterns. Furthermore, electron-positron annihilation channels, such as $e^+ e^- \rightarrow Z_D + \gamma$ and $e^+ e^- \rightarrow \ell^+ \ell^- Z_D$, offer clean experimental signatures, while hadronic decays like $\phi \rightarrow \eta Z_D$ and $\rho \rightarrow \pi Z_D$ utilize vector meson dominance. Higgs decays ($h \rightarrow ZZ_D$ or $h \rightarrow Z_D Z_D$) and direct dark photon decays ($Z_D \rightarrow \ell^+ \ell^-$ or $Z_D \rightarrow \nu \nu$) further expand the search across different mass and energy scales. Collectively, these channels provide diverse opportunities to explore the dark sector and refine constraints on Z_D and dark Z parameters.

5. Conclusion

In conclusion, we have analyzed the decay process $J/\psi \rightarrow e^+ e^- \phi$, where EM transitions dominate at leading order with negligible contributions from hadronic loops. The branching ratio was estimated to be approximately 2.28×10^{-8} , consistent with the dominance of EM effects. The BESIII collaboration has set an experimental upper limit of $B(J/\psi \rightarrow e^+ e^- \phi) < 1.2 \times 10^{-7}$. We explored the potential existence of new physics contributions, such as a dark photon or a dark Z , in this decay channel. Our findings indicate that constraints on these hypothetical particles are stringent, making significant enhancements to the SM branching ratio within the current experimental limit unlikely. Therefore, investigating the two states of the dark photon and dark Z_D in the decay channel $J/\psi \rightarrow e^+ e^- \phi$ is not feasible due to the stringent constraints on the model parameters. The parameter space that is considered $\varepsilon \leq 0.001$, $\varepsilon_Z \leq 0.002$, and dark boson mass with $2\mu : (M_B - M_K)$. Therefore, while this decay channel remains a useful probe for new physics, detecting signals for the dark photon or dark Z in this context appears challenging. Alternative decay channels can be explored to probe the dark photon and dark (Z_D) such as the decays of rare B -meson, kaon, charmonium, tau, exotic Higgs, as well as direct dark boson decays.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendix: Kinematics

In this paper we calculate the decay process in Fig. 1 in the rest frame of the decaying particle J/ψ where its momentum is given by $P = (M_{J/\psi}, 0, 0, 0)$, where for the other particles are $P_1 = P_{e^-}$, $P_2 = P_{e^+}$, and $P_3 = P_\phi$. The scalar multiplication of the momenta are given as follows

$$\begin{aligned} P_1 \cdot P_2 &= \frac{1}{2}(m_{12}^2 - 2m_e^2), \\ P_2 \cdot P_3 &= \frac{1}{2}(m_{23}^2 - m_e^2 - m_\phi^2), \\ P_1 \cdot P_3 &= \frac{1}{2}(M_{J/\psi}^2 - m_{12}^2 - m_{23}^2 + m_e^2), \\ P \cdot P_1 &= P_1^2 + P_1 \cdot P_2 + P_1 \cdot P_3, \\ P \cdot P_2 &= P_2^2 + P_1 \cdot P_2 + P_2 \cdot P_3, \text{ and} \\ P \cdot P_3 &= P_3^2 + P_1 \cdot P_3 + P_2 \cdot P_3, \end{aligned}$$

where $P^2 = M_{J/\psi}^2$, $P_1^2 = m_e^2$, $P_2^2 = m_e^2$, and $P_3^2 = m_\phi^2$. $m_{12}^2 = (P_1 + P_2)^2 = (P - P_3)^2$, $m_{23}^2 = (P_2 + P_3)^2 = (P - P_1)^2$, and $m_{13}^2 = (P_1 + P_3)^2 = (P - P_2)^2$. Also, $m_{12}^2 + m_{23}^2 + m_{13}^2 = M_{J/\psi}^2 + m_1^2 + m_2^2 + m_3^2$. The kinematical equations of the energy and momentum of this frame of reference are

$$\begin{aligned} E_1 &= \frac{M_{J/\psi}^2 + m_1^2 - m_{23}^2}{2M_{J/\psi}}, \\ E_2 &= \frac{M_{J/\psi}^2 + m_2^2 - m_{13}^2}{2M_{J/\psi}}, \\ E_3 &= \frac{M_{J/\psi}^2 + m_3^2 - m_{12}^2}{2M_{J/\psi}}, \\ P_1 &= \frac{\lambda^{1/2}(s, m_1^2, m_{23}^2)}{2M_{J/\psi}}, \\ P_2 &= \frac{\lambda^{1/2}(s, m_2^2, m_{13}^2)}{2M_{J/\psi}}, \\ P_3 &= \frac{\lambda^{1/2}(s, m_3^2, m_{12}^2)}{2M_{J/\psi}}, \end{aligned} \quad (7)$$

where $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz$. The differential decay rate will be calculated using this equation

$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M_{H_1}^3} |\bar{M}|^2 dm_{12}^2 dm_{23}^2, \quad (8)$$

with

$$|\bar{M}|^2 = \sum_{spin} |M_{SM} + M_{NP}|^2 = \sum_{spin} |M_\gamma + M_Z + M_X|^2, \quad (9)$$

The limits of the kinematical variables.

$$\begin{aligned}(m_1 + m_2)^2 &\leq m_{12}^2 \leq (M_{J/\psi} - m_3)^2, \\(m_2 + m_3)^2 &\leq m_{23}^2 \leq (M_{J/\psi} - m_1)^2, \\(m_1 + m_3)^2 &\leq m_{13}^2 \leq (M_{J/\psi} - m_2)^2.\end{aligned}\tag{10}$$