

## Dark matter/new physics searches at BESIII

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Many new physics models beyond the Standard Model, motivated by the recent astrophysical anomalies, include the possibility of several new types of light weak-interacting particles. Typical models, such as Next-to-Minimal Supersymmetric Standard Model and Hidden Dark-sector Model, predict the light Higgs and dark bosons, respectively. The masses of these particles are expected to be a few GeV and thus making them accessible at BESIII. BESIII has recently explored the possibility of light Higgs and dark bosons in several decay modes using the data-sets collected at  $J/\psi$ ,  $\psi(3686)$  and  $\psi(3770)$  resonances. The  $J/\psi$  data have further utilized to search for invisible decays of light vector ( $V = \omega, \phi$ ) and pseudo-scalar ( $P = \eta, \eta'$ ) mesons via  $J/\psi \rightarrow VP$  decays. This report summarizes the recent results of the BESIII experiment on these new physics topics.

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## 1. Introduction

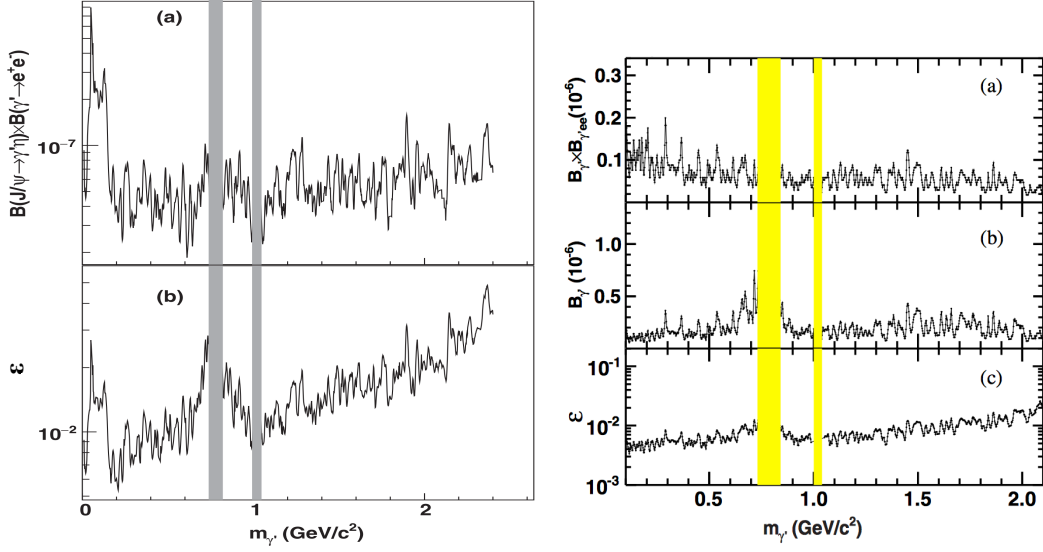
Many astrophysical observations strongly suggest the existence of dark matter [1], which nature is still mysterious in modern physics. Dark matter neither emits nor absorbs the electromagnetic radiation and its presence can only be inferred via gravity. New physics models beyond the Standard Model (SM) motivate a new type of ‘hidden dark-sector’ under which the WIMP like dark matter particles are charged via a new type of force carrier [2]. The corresponding gauge field can couple to the ordinary matter via “portals” [3], which could be scalar, pseudoscalar, vector or spin-1/2 fermions. The masses of these new particles are expected to be a few GeV to satisfy the constraints of recent experimental anomalies [1, 4], and thus making them accessible via high intensity electron-positron collider experiments, such as BESIII experiment. BESIII, an  $e^+e^-$  collider experiment running at tau-charm region, has collected a huge amount of data at several energy points between 2.0-4.6 GeV, including  $J/\psi$ ,  $\psi(3686)$  and  $\psi(3770)$  resonances, to study the light hadron spectroscopy and search for new physics beyond the SM. This report summarizes the recent results of the BESIII experiment related to the new physics/dark matter searches.

## 2. Search for dark photon

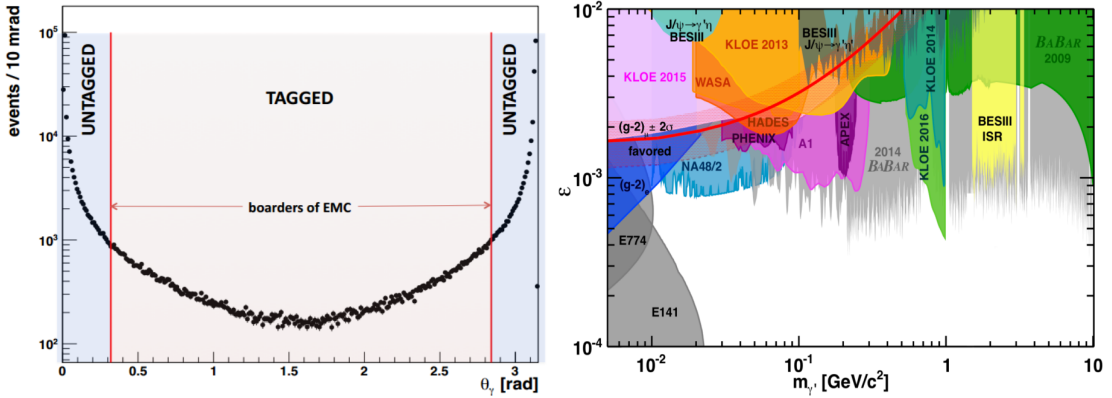
The dark photon ( $\gamma'$ ) is a new type of force carrier in the simplest scenario of an Abelian  $U(1)$  gauge field. It couples to the SM photon via kinetic mixing strength, defined as  $\varepsilon^2 = \alpha'/\alpha$ , where  $\alpha'$  and  $\alpha$  are the fine structure constants in the dark and SM sectors, respectively [2]. The mass of the  $\gamma'$  is expected to be a few GeV to satisfy the constraints of recent astrophysical anomalies [1], as well as the observed deviation in the muon anomalous magnetic moment up to the level of  $(3-4)\sigma$  between theory and experiment [4]. A series of experiments have performed the searches for  $\gamma'$  and reported only null results so far with an exclusion limit on  $\varepsilon$  to be below  $10^{-3}$  [5, 6].

BESIII has recently searched for di-electron decays of a  $\gamma'$  through  $J/\psi \rightarrow \gamma'\eta^{(\prime)}$  using 1.3 billion of  $J/\psi$  events, where  $\eta$  ( $\eta'$ ) is reconstructed from  $\eta \rightarrow \pi^+\pi^-\pi^0$ ,  $\pi^0 \rightarrow \gamma\gamma$  and  $\eta \rightarrow \gamma\gamma$  ( $\eta' \rightarrow \gamma\pi^+\pi^-$  and  $\eta' \rightarrow \eta\pi^+\pi^-$ ,  $\eta \rightarrow \gamma\gamma$ ) [7]. The search for a narrow  $\gamma'$  resonance is performed in the  $m_{e^+e^-}$  distribution of the data. But, we exclude the  $\omega$  and  $\phi$  mass regions in the  $m_{e^+e^-}$  spectrum from the  $\gamma'$  searches due to their resolutions are compatible with the  $\gamma'$  mass resolution. No evidence of  $\gamma'$  production is found. The 90% confidence level upper limits on product branching fractions  $\mathcal{B}(J/\psi \rightarrow \eta^{(\prime)}\gamma') \times \mathcal{B}(\gamma' \rightarrow e^+e^-)$  and  $\varepsilon$  are set to be up to the level of  $10^{-8}$  and  $10^{-3}$ , respectively, depending upon the  $\gamma'$  mass points (Figure 1).

BESIII has also performed the search for dark photon via initial-state-radiation (ISR) process  $e^+e^- \rightarrow \gamma_{ISR}\gamma'$ ,  $\gamma' \rightarrow l^+l^-$  ( $l = e, \mu$ ) using  $2.93 \text{ fb}^{-1}$   $\psi(3770)$  data [6]. This search uses an untagged photon method in which ISR photon is not detected in the BESIII electromagnetic calorimeter acceptance region (Figure 2 (left)). The background in this search is mainly dominated by the ISR processes of  $e^+e^- \rightarrow \gamma l^+l^-$  ( $l = e, \mu$ ). No any obvious enhancement above these backgrounds is seen in di-lepton invariant mass spectrum, and a 90% C.L. upper limit on  $\varepsilon$  is set in the mass range between 1.5 and 3.4  $\text{GeV}/c^2$ . The obtained upper limits in tested mass range are compatible with the BaBar measurement (Figure 2 (right)).



**Figure 1:** The 90% C.L. upper limits on the branching fractions  $\mathcal{B}(J/\psi \rightarrow \gamma \eta^{(\prime)}) \times \mathcal{B}(\gamma \rightarrow e^+ e^-)$  (top) and the kinetic mixing strength  $\epsilon$  (bottom). The left plots are for  $J/\psi \rightarrow \gamma \eta$  decay and right plots for  $J/\psi \rightarrow \gamma \eta'$  decay. The right hand side figure also shows the plot of 90% C.L. upper limit on  $\mathcal{B}(J/\psi \rightarrow \gamma \eta')$ .



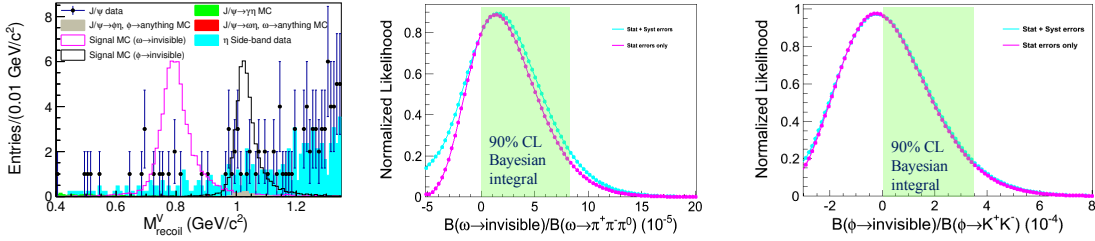
**Figure 2:** (Left) Polar angle ( $\theta_\gamma$ ) distribution of the ISR photon and (right) the 90% C.L. upper limits on  $\epsilon$  as a function of  $m_\gamma$  for various experimental measurements [5] including the BESIII [6, 7]. BESIII detector acceptance region for  $\theta_\gamma$  is [0.376, 2.765] radian. In untagged photon method, the ISR photon is required to be not detected in the EMC detection region.

### 3. invisible decays of light mesons

Neutrinos ( $\nu$ ) are the only invisible particles within the SM that don't interact with the particle physics detector. Only the four momenta of missing particles in a decay mode is used to infer the presence of this particle. Quarkonium, which is a composition of a quark ( $q$ ) and its own anti-quark ( $\bar{q}$ ), annihilates into a neutrino-pair rarely via virtual  $Z^0$  boson. The branching fractions of such a rare decays might enhance in the presence of light dark matter (LDM) particles. Ref. [8] predicts the branching fractions of the invisible  $\chi$  decays of various quarkonium states while assuming the same cross-section for the time reversed processes  $\sigma(q\bar{q} \rightarrow \chi\chi) \simeq \sigma(\chi\chi \rightarrow q\bar{q})$ . BaBar [9] and

BESII [10] experiments have set one of most stringent upper limits on the invisible decays of  $\Upsilon(1S)$  and  $J/\psi$  mesons, respectively, which are still above SM predictions. By using 225 million  $J/\psi$  events, BESIII has analyzed  $J/\psi \rightarrow \phi \eta$  decays and determined upper limits at 90% C.L. to be  $2.6 \times 10^{-4}$  for the ratio  $\frac{\mathcal{B}(\eta \rightarrow \text{invisible})}{\mathcal{B}(\eta \rightarrow \gamma\gamma)}$  and  $2.4 \times 10^{-2}$  for  $\frac{\mathcal{B}(\eta' \rightarrow \text{invisible})}{\mathcal{B}(\eta' \rightarrow \gamma\gamma)}$  [13].

The SM predicts  $\mathcal{B}(\omega \rightarrow \nu\bar{\nu}) = (2.79 \pm 0.05) \times 10^{-13}$  and  $\mathcal{B}(\phi \rightarrow \nu\bar{\nu}) = (1.67 \pm 0.02) \times 10^{-11}$  [11], but the presence of LDM may enhance the branching fractions  $\omega/\phi \rightarrow \chi\chi$  up to the level of  $10^{-8}$  [8]. BESIII has recently performed the search for invisible decays of  $\omega$  and  $\phi$  meson in  $J/\psi \rightarrow V\eta$  decays using 1.3 billion  $J/\psi$  events, where  $\eta$  is reconstructed by  $\pi^+\pi^-\pi^0$  with  $\pi^0 \rightarrow \gamma\gamma$  in the final state [12]. The mass recoiling against  $\eta$ ,  $M_{\text{recoil}}^V = \sqrt{(E_{\text{CM}} - E_{\pi^+\pi^-\pi^0})^2 - \vec{p}_{\pi^+\pi^-\pi^0}^2}$ , is used to search for invisible decays of  $\omega$  and  $\phi$  mesons (Figure 3 (left)). No evidence of the significant invisible signal events is observed, and the upper limits on the ratio of branchings at the 90% C.L. are measured to be  $\frac{\mathcal{B}(\omega \rightarrow \text{invisible})}{\mathcal{B}(\omega \rightarrow \pi^+\pi^-\pi^0)} < 8.0 \times 10^{-5}$  and  $\frac{\mathcal{B}(\phi \rightarrow \text{invisible})}{\mathcal{B}(\phi \rightarrow K^+K^-)} < 3.4 \times 10^{-4}$  using the Bayesian approach [14] (Figure 3 (middle and right)). The 90% C.L. upper limits on  $\mathcal{B}(\omega \rightarrow \text{invisible})$  and  $\mathcal{B}(\phi \rightarrow \text{invisible})$  also set to be less than  $7.2 \times 10^{-5}$  and  $1.7 \times 10^{-4}$ , respectively, for the first time using the world average values of  $\mathcal{B}(\omega \rightarrow \pi^+\pi^-\pi^0)$  and  $\mathcal{B}(\phi \rightarrow K^+K^-)$  [14].

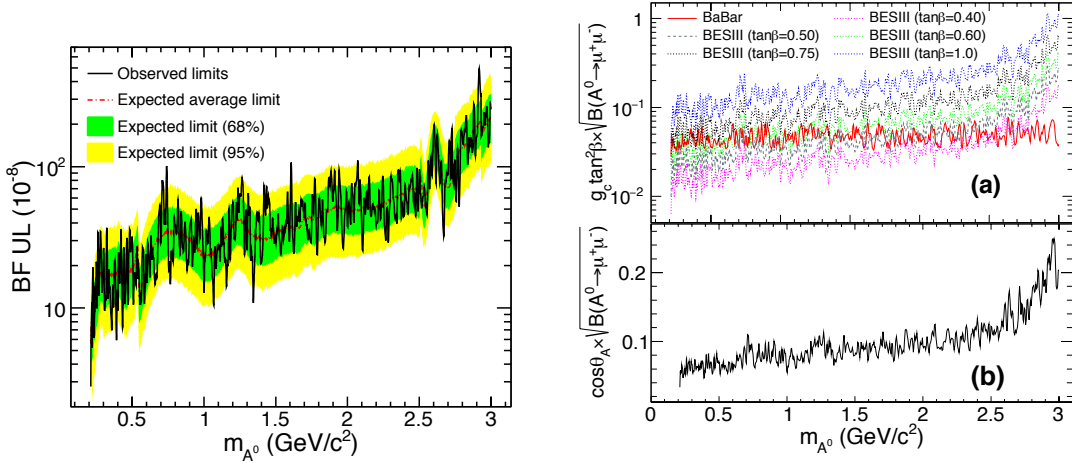


**Figure 3:** The  $M_{\text{recoil}}^V$  distribution for data (black dots with error bars), signal MC samples (pink and black histograms for  $\omega$  and  $\phi$  decays, respectively) and various expected backgrounds shown by various colored histograms (left), and the normalized likelihood versus  $\frac{\mathcal{B}(\omega \rightarrow \text{invisible})}{\mathcal{B}(\omega \rightarrow \pi^+\pi^-\pi^0)}$  (middle) and  $\frac{\mathcal{B}(\phi \rightarrow \text{invisible})}{\mathcal{B}(\phi \rightarrow K^+K^-)}$  (right) including the statistical uncertainty only (pink) and both systematic and statistical uncertainties (cyan).

#### 4. Search for a $CP$ -odd like Higgs boson

A light Higgs boson is predicted by many models beyond the SM including Next-to-Minimal Supersymmetric Model (NMSSM) [15]. The Higgs sector of the NMSSM contains seven Higgs bosons, among them there is a  $CP$ -odd light Higgs boson ( $A^0$ ) whose mass is expected to a few GeV. Such a low-mass Higgs boson can be accessible via  $J/\psi \rightarrow \gamma A^0$  using the data of BESIII experiment collected at  $J/\psi$  and  $\psi(3686)$  resonances [16]. Coupling of the Higgs field to the charm ‘c’ (bottom ‘b’) quark-pair ( $g_{b/c}$ ) is proportional to  $\cos \theta_A / \tan \beta$  ( $\cos \theta_A \tan \beta$ ), where  $\tan \beta$  is a standard SUSY parameter and  $\cos \theta_A (= |\sqrt{g_b g_c}|)$  is a mixing parameter between singlet and doublet components of the  $A^0$  [17, 18]. The branching fraction of  $J/\psi \rightarrow \gamma A^0$  is predicted to be in the range of  $10^{-9} - 10^{-7}$ , depending up on the  $A^0$  mass, coupling and the NMSSM parameters [17, 18]. By using 106 million  $\psi(3686)$  events, BESIII has previously set 90% C.L. upper limits on product branching fractions  $\mathcal{B}(J/\psi \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \gamma\gamma)$  to be in the range of  $(4 - 210) \times 10^{-7}$  depending upon the  $A^0$  mass point for  $m_{A^0} < 3.0 \text{ GeV}/c^2$  [21], where a  $J/\psi$  sample is selected by tagging a pion-pair from  $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$  transitions.

The search for  $A^0$  is also performed using 225 million  $J/\psi$  events collected at the  $J/\psi$  resonance by the BESIII detector [19]. The background is mainly dominated by the non-resonant component of  $e^+e^- \rightarrow \gamma\mu^+\mu^-$  process and the resonant components of  $J/\psi \rightarrow \rho\pi$  and  $J/\psi \rightarrow \gamma f$  ( $f = f_2(1270), f_0(1710)$ ) decays. We perform the search for a narrow resonance by performing the ML fit to the reduced mass distribution, defined  $m_{\text{red}} = \sqrt{m_{\mu^+\mu^-}^2 - 4m_\mu^2}$ , of data at 2035 mass points in the steps of 1-2 MeV/ $c^2$ , where  $m_{\mu^+\mu^-}$  is the di-muon invariant mass distribution and  $m_\mu$  is the nominal muon mass [14]. No evidence of  $A^0$  production is found at any  $m_{A^0}$  point. We set the 90% C.L. upper limits on product branching fractions  $\mathcal{B}(J/\psi \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \mu^+\mu^-)$  that vary in the range of  $(2.8 - 495.3) \times 10^{-8}$  for  $0.212 \leq m_{A^0} \leq 3.0$  GeV/ $c^2$  (Figure 4 (left)). This new result has five times improvement over the previous BESIII measurement [21]. The upper limit on  $g_b (= g_c \tan^2 \beta) \times \sqrt{\mathcal{B}(A^0 \rightarrow \mu^+\mu^-)}$  is also computed for different values of  $\tan \beta$  at 90% C.L. in order to compare this result with the BaBar measurement [20]. Our result is better than the BaBar measurement [20] in the low-mass region for  $\tan \beta \leq 0.6$  (Figure 4 (right)). The combined results of both BaBar and BESIII in term of  $\cos \theta_A \times \sqrt{\mathcal{B}(A^0 \rightarrow \mu^+\mu^-)}$ , which is independent of  $\tan \beta$ , reveal that the nature of the  $A^0$  is mostly singlet in nature.



**Figure 4:** The 90% C.L. upper limits on product branching fractions  $\mathcal{B}(J/\psi \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \mu^+\mu^-)$  (left),  $g_b (= g_c \tan^2 \beta) \times \sqrt{\mathcal{B}(A^0 \rightarrow \mu^+\mu^-)}$  for the BaBar [20] and BESIII [19] measurements (right top) and  $\cos \theta_A (= |\sqrt{g_b g_c}| \times \sqrt{\mathcal{B}(A^0 \rightarrow \mu^+\mu^-)})$  (right bottom) as a function of  $m_{A^0}$  including all the systematic uncertainties. In left hand side figure, the inner and outer bands include the statistical uncertainty only and contain 68% and 95% of the expected limits values that are computed using a large number of pseudoexperiments.

## 5. Summary

BESIII has performed the searches for di-lepton decays of light Higgs and dark bosons as well as invisible decays of light vector and pseudoscalar mesons using the data samples collected at  $J/\psi$ ,  $\psi(3686)$  and  $\psi(3770)$  resonances. No evidence of any significant signal events is found in these data-sets and set one of the stringent exclusion limits. These exclusion limits may constrain a large fraction of the parameters of the new physics models including the NMSSM and hidden

dark-sector. BESIII is performing the searches for new physics in several other decay modes too using the large data-sets collected at various energy points, including 10 billion  $J/\psi$  events that have recently collected by the BESIII detector, and we look forward to seeing more exciting results on the new physics topics in the near future.

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