Search for a light Higgs-like boson $A^0$ in $J/\psi$ radiative decays

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Using a data sample containing $1.06 \times 10^8 \psi'$ events collected with the BESIII detector at the BEPCII electron-positron collider, we search for a light Higgs-like boson $A^0$ in the process $\psi' \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow \gamma A^0, A^0 \rightarrow \mu^+ \mu^-$. Particles of this type are predicted in the next-Minimal supersymmetric extension of the Standard Model. The HyperCP experiment observed three anomalous $\Sigma^+ \rightarrow p\mu^+ \mu^-$ events, with $\mu^+ \mu^-$ masses clustered around $213.3 \pm 0.5$ MeV/c$^2$. In this analysis, we find no evidence for any $\mu^+ \mu^-$ mass peak between the mass threshold and 3.0 GeV/c$^2$. We set 90% confidence level upper limits on the product branching fractions for $J/\psi \rightarrow \gamma A^0, A^0 \rightarrow \mu^+ \mu^-$ that range from $4 \times 10^{-7}$ to $2.1 \times 10^{-5}$, depending on the mass of $A^0$, for $M(A^0) < 3.0$ GeV/c$^2$. Only one event is seen in the mass region below 255 MeV/c$^2$ and this has a $\mu^+ \mu^-$ mass of $213.3 \pm 0.5$ MeV/c$^2$ and the product branching fraction upper limit $5 \times 10^{-7}$.

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A light Higgs-like scalar boson $A^0$ is predicted in the next-Minimal supersymmetric extension of the Standard Model [12]. Sensitive searches for the $A^0$ are important and can be helpful for a better understanding of the Higgs mechanism and supersymmetry. The HyperCP experiment [4] observed three anomalous $\Sigma^+ \rightarrow \mu^+\mu^-$ events with $\mu^+\mu^-$ invariant mass clustered around 214.3 MeV/c², and these have been interpreted as possible evidence for a scalar boson with mass 214.3 MeV/c² that decays into a $\mu^+\mu^-$ pair. The BaBar [7, 8], CLEO [9], and Belle [10] experiments have searched for $A^0$ production in various channels and found no evidence for a signal.

For an $A^0$ boson with mass below the $\tau$-pair threshold the decay $A^0 \rightarrow \mu^+\mu^-$ is expected to be more prominent than $A^0 \rightarrow e^+e^-$ because the mass of muon is much larger than that of the electron. We use the process $\psi^+ \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$ to search for an $A^0$ with the BESIII detector [11] at the BEPCII electron-positron collider [12].

BESIII is a double-ring $e^+e^-$ collider with a design peak luminosity of $10^{33}$ cm⁻²s⁻¹. The BESIII detector is based on a large 1 Tesla solenoid magnet and covers 93% of the total 4$\pi$ solid angle surrounding the $e^+e^-$-collision point with four major detection systems: (1) A small-cell, helium-based main drift chamber (MDC) with a peak luminosity of $10^{33}$ cm⁻²s⁻¹. The BESIII detector is based on a large 1 Tesla solenoid magnet and covers 93% of the total 4$\pi$ solid angle surrounding the $e^+e^-$-collision point with four major detection systems: (1) A small-cell, helium-based main drift chamber (MDC) with 43 layers that provide an average single-hit resolution of 135 μm, charged-particle momentum resolution of 0.5% at 1 GeV/c, and a $dE/dx$ resolution that is better than 6%. (2) An electromagnetic calorimeter (EMC) consisting of 6240 CsI(Tl) crystals configured in a cylindrical structure (barrel) and two endcaps. The energy resolution for 1.0 GeV $\gamma$-rays is 2.5% in the barrel and 5% in the endcaps, and the position resolution is 6 mm in the barrel and 9 mm in the endcaps. (3) A time-of-flight system (TOF) constructed of 5-cm-thick plastic scintillators, with 176 pieces of 2.4 m long counters arranged in a two layer barrel and 96 fan-shaped counters in the endcap regions. The barrel (endcap) time resolution of 80 ps (110 ps) provides $2\sigma K/\pi$ separation for momenta up to $\sim 1.0$ GeV/c. The muon identification is provided by 1000 m² of Resistive Plate Chambers (RPCs) that are interspersed in the magnet’s iron flux return (MUC). Nine barrel and eight endcap layers provides 2 cm position resolution for penetrating particles.

The analysis is based on $1.06 \times 10^8$ events collected at the peak of the $\psi'$ resonance. The number of $\psi'$ events was determined by counting inclusive hadronic events as described in Ref. [13] with an estimated uncertainty of 4%. Monte Carlo (MC) events are simulated with the GEANT4 program [14] and experimentally determined resolutions of the wires and counters in the detector.

For the event selection, we first require two positive and two negative charged tracks and at least one good photon. We also use $\mu$ identification information, veto $\pi^0$s and apply kinematic constraints.

Candidate photons are energy clusters in the EMC that: (1) are within the fiducial region of the EMC ($|\cos \theta_{\gamma}| < 0.8$ for the barrel and 0.86 < $|\cos \theta_{\gamma}| < 0.92$ for the endcaps); (2) are more than 20 degrees away from the extrapolated position of the closest charged track; (3) have a pulse time that is consistent with being produced together with the charged track candidates.

Charged track candidates are required to originate from the interaction point, $V_{xy} = \sqrt{V_x^2 + V_y^2} < 1$ cm, $|V_z| < 10$ cm, where $V_x, V_y, V_z$ are the $x, y, z$ coordinates of the point of closest approach to the interaction point. The tracks are also required to be within the polar angle region $|\cos \theta| < 0.93$.

Candidate muons are charged tracks in the active area of the barrel MUC ($|\cos \theta| < 0.75$) with: momentum higher than 0.7 GeV/c; energy deposition in the EMC between 0.15 GeV and 0.26 GeV; $E/p$ (EMC energy over MDC momentum) less than 0.5; at least three associated hit layers in the MUC. For tracks in the momentum range 0.8 GeV/c < $p$ < 1.15 GeV/c, the MUC penetration depth is required to be greater than (70−40) cm ($p$ in GeV/c); for tracks with $p$ > 1.15 GeV/c, the penetration depth is required to be more than 41 cm. Tracks with momentum bigger than 0.8 GeV/c are removed if the fit to the MUC hits either fails or gives a poor fit result.

If there are multiple photons with energy larger than 25 MeV, we reject the event if any pair of these photons has an invariant mass within 40 MeV/c² of $m_{\mu\gamma}$. For the multi-photon events that remain, the $\gamma$ with the highest energy is selected as the photon used in the analysis. The pair of oppositely charged tracks with recoil mass closest to the $J/\psi$ mass is assigned as the $\pi^+$ and $\pi^-$ and the other two tracks as the $\mu^+$ and $\mu^-$. At least one of the tracks assigned as a $\mu$ is required to satisfy the muon candidate criteria. We select events with a $\pi^+\pi^-$ recoil mass in the range between 3.092 GeV/c² and 3.102 GeV/c² and perform a 4-constraint energy-momentum conserving kinematic fit using the selected $\gamma$ and four charged tracks. We require $\chi^2 < 40$ and $M(\mu^+\mu^-) < 3.02$ GeV/c².

The $A^0$ particle is expected to have a narrow width. Simulations where the width of $A^0$ is set to zero and the mass is set at 71 different values that range from 0.212 GeV/c² to 3.0 GeV/c² indicate that the selection efficiency varies between 28% and 18%, depending on the mass of $A^0$.

The $\mu^+\mu^-$ mass distribution of selected data events is shown in Fig. 1(a). Over the entire mass range, from threshold to 3.0 GeV/c², there is no evident narrow peak. Below 255 MeV/c² there is only one event, with $\mu^+\mu^-$ invariant mass of 213.3 MeV/c². The expected mass resolution of $A^0$ is about 0.2 MeV/c² for $M(A^0)$ at 213.3 MeV/c² and the major backgrounds in this region come from $\psi' \rightarrow \pi^+\pi^- J/\psi, \psi' \rightarrow \gamma\pi^+\pi^-$. The expected number of background events in the mass region
near 213.3 MeV/c^2 is about 0.2/MeV/c^2; the observation of one event in this region is consistent with that background level.

To set upper limits on the production rates for different masses, we do unbinned maximum likelihood fits to the \( \mu^+ \mu^- \) invariant mass spectrum where the mass of the \( A^0 \) peak is restricted to be within a series of 5 MeV/c^2 wide bins. In each fit, we use a MC-determined shape for the \( A^0 \) signal and for the background shape we use a polynomial. Bayesian upper limits on the signal yield in each 5 MeV/c^2 bin are determined. Figure 2 shows a typical fit (at 2.43 GeV/c^2) and likelihood distribution as a function of the signal yield with the 90% C.L. upper limit value indicated by an arrow.

We use different fit ranges, polynomial background shapes of different orders, different MC signal shapes for different \( A^0 \) mass values as signal shapes to estimate the fit-related systematic error on the signal yield in each mass interval. The resulting 90% C.L. upper limits on the number of signal events for all the mass intervals are shown in Fig. 1(b).

The systematic errors in the \( J/\psi \rightarrow \gamma A^0, A^0 \rightarrow \mu^+ \mu^- \) product branching fraction measurement are summarized in Table I; these include contributions from tracking, particle identification, photon selection, kinematic fit, \( \pi^+ \pi^- \) recoil mass requirement, and \( \pi^0 \) veto. The uncertainty of the number of \( \psi' \) events is 4% \[13\] and that of the \( \psi' \rightarrow \pi^+ \pi^- J/\psi \) branching fraction is 1.2% \[13\].

TABLE I: The individual contributions to the total relative systematic error in the product branching fraction measurement.

| Source                 | Error |
|------------------------|-------|
| Tracking efficiency    | 4.0   |
| Particle identification| 2.5   |
| Kinematic fit          | 3.2   |
| \( \gamma \) efficiency| 1.0   |
| \( \pi^+ \pi^- \) recoil mass| 1.2 |
| \( \pi^0 \) veto       | 2.0   |
| Number of \( \psi' \) s| 4.0   |
| \( B(\psi' \rightarrow \pi^+ \pi^- J/\psi) \) | 1.2   |
| Total                  | 7.5   |

The uncertainty due to data-MC difference in the charged tracking efficiency is 1% per track and added linearly. This is determined from samples of \( J/\psi \rightarrow \rho \pi \) and \( J/\psi \rightarrow \rho \rho \pi^+ \pi^- \) events. In this analysis, there are four charged tracks and the relative systematic error is 4%.

The uncertainties due to \( \mu \) identification (PID) is determined from studies of a sample of radiative muon pair events that contain one photon. The \( \mu \) PID efficiency for one track is about 65% (during the data taking, the MUC end cap detectors were not functioning). The difference in \( \mu \) PID efficiency between data and MC is less than 4% per track. Since we require only one muon to satisfy the identification criteria, the PID related systematic error is less than 2.5%.

The systematic uncertainty associated with the kinematic fit is determined by applying a similar kinematic fit to MC and data samples of \( \psi' \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow \pi^+ \pi^- \pi^0, \pi^0 \rightarrow \gamma \gamma \) events. In the event selection for this study, if there are more than two candidate \( \gamma \) we use the most energetic \( \gamma \) together with the one that has the best 1C fit to \( \pi^0 \rightarrow \gamma \gamma \). From data-MC differences for these events, the systematic error associated with the kinematic fit is determined to be 3.2%.

The systematic error associated with the \( \pi^0 \) veto is studied with samples of \( \psi' \rightarrow \gamma \chi_c \rightarrow \gamma \phi \phi \rightarrow \gamma 2(K^+K^-) \) and \( \psi' \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow \gamma f_2 (1270), f_2 (1270) \rightarrow \pi^+ \pi^- \) events from both MC simulation and data. From \( \psi' \rightarrow \gamma \chi_c \rightarrow \gamma \phi \phi \), we determine the effect of the \( \pi^0 \) veto cut on the efficiency. For the second sample, we fit the \( \pi^+ \pi^- \) mass spectrum to get the number of \( f_2 (1270) \rightarrow \pi^+ \pi^- \) events with and without the \( \pi^0 \) veto cut. Data and MC efficiency differences for the \( \pi^0 \) veto are found to be less than 1.7% from the first channel and less than 2.0% from the second channel. We use 2% as the systematic error due to the \( M(\gamma \gamma) \) requirement.

The systematic error caused by the \( \pi^+ \pi^- \) recoil mass requirement is analyzed with the sample of \( \psi' \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow \mu^+ \mu^- \) in data and MC simulation. From the numbers of events with and without the recoil mass requirement we determine data and MC efficiency difference to be less than 1.2%.

The systematic errors are summarized in Table I. Assuming the errors from all sources are independent, the total error is determined from the quadrature sum to be 7.5 percent.

We determine the upper limit on the branching fractions of \( J/\psi \rightarrow \gamma A^0, A^0 \rightarrow \mu^+ \mu^- \) from the relation

\[
B < \frac{Nsig(UL)/\varepsilon}{N(\psi') \times B(\psi' \rightarrow \pi^+ \pi^- J/\psi) \times (1 - \sigma)},
\]

where \( Nsig(UL) \) is the upper limit on the number of signal events in each \( M(\mu^+ \mu^-) \) bin after consideration of the mass fitting systematic errors shown in Fig. 1(b); \( \varepsilon \) is the \( A^0 \)-mass-dependent selection efficiency determined from MC simulation; \( N(\psi') = 1.06 \times 10^8 \) is the number of \( \psi' \) events \[13\] and \( B(\psi' \rightarrow \pi^+ \pi^- J/\psi) = (33.6 \pm 0.4)\% \) is the PDG world average \[13\]. The upper limit is increased by a factor of \( 1/(1 - \sigma) \), where \( \sigma \) is the total systematic error (7.5%) to give a conservative result. The resulting \( B(J/\psi \rightarrow \gamma A^0) \times B(A^0 \rightarrow \mu^+ \mu^-) \) ranges from \( 4 \times 10^{-7} \) for \( A^0 \) mass threshold to \( 2.1 \times 10^{-5} \) for \( M(A^0) \) near 3.0 GeV/c^2, and is shown in Fig. I(c). The branching fraction upper limit is less than \( 10^{-6} \) for all \( M(A^0) \) values below 0.36 GeV/c^2, and is less than \( 10^{-5} \) for all masses below 2.79 GeV/c^2.
FIG. 1: (a) The $\mu^+\mu^-$ invariant mass spectrum for the selected $\psi' \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \gamma \mu^+\mu^-$ events; (b) 90% confidence level (C.L.) upper limits on the number of signal events ($N_{\text{sig UL}}$) as a function of the $\mu^+\mu^-$ invariant mass; (c) upper limits on the branching fractions ($\text{BF UL}$) of $J/\psi \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$ at the 90% C.L.

FIG. 2: (a) A fit of the invariant mass spectrum $M(\mu^+\mu^-)$ in the 5 MeV/$c^2$ wide interval at 2.43 GeV/$c^2$ showing the total fit result and the background-subtracted signal and (b) the likelihood distribution as a function of the signal yield. The arrow in (b) is the position of the 90% C.L. upper limit on the signal yield.

In summary, we have searched for a Higgs-like boson $A^0$ at BESIII. No evidence is observed and upper limits on the product branching fractions for $J/\psi \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$ range from $4 \times 10^{-7}$ to $2.1 \times 10^{-5}$, depending on the mass of the $A^0$, are established. These limits are more stringent than previous experimental results. Only one event is observed in the low mass region below 255 MeV/$c^2$, with a $\mu^+\mu^-$ mass of 213.3 MeV/$c^2$. For $M(A^0) < 255$ MeV/$c^2$, including the 214.3 MeV/$c^2$ mass value of the anomalous HyperCP $\Sigma^+ \rightarrow p \mu^+\mu^-$ events, the product branching fraction upper limit is $5 \times 10^{-7}$ at the 90% C.L.

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