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# Physics Analysis to Investigate the Nature of the X(3872) State at BESIII

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The Beijing Electron Spectrometer III (BESIII) experiment is located at the Institute of High Energy Physics (IHEP) in Beijing studying symmetric $e^+e^-$ collisions in the energy regime from 2 to 4.6 GeV. In this mass regime recently many new states have been observed which do not fit into the common picture of $c\bar{c}$ states. An example is the $X(3872)$, found by the Belle Collaboration in 2003 as an unexpected narrow state above the $D\bar{D}$ threshold. Due to its mass close to the $D\bar{D}^*$ threshold and its isospin violating decays, the $X(3872)$ could be interpreted as an exotic molecule. Until recently, the $X(3872)$ was only observed in B meson decays and hadron collisions. BESIII observed the decay of $X(3872) \to J/\psi\pi^+\pi^-$ in $e^+e^- \to \gamma X(3872)$ for the first time in the charm system.
To further investigate the still unknown nature of the $X(3872)$ state, a first Monte-Carlo study of the decay $e^+e^- \to \gamma X(3872)$ at center-of-mass energies at 4.260 GeV and 4.360 GeV with the subsequent radiative decay of $X(3872) \to J/\psi\gamma$ is presented here.

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## 1. Introduction

Charmonium, being built of $c\bar{c}$ quarks, is a bound system of the strong force, quantum chromodynamics (QCD). In principle QCD determines all meson properties such as masses, widths and decay rates, but its non-pertubative nature in the low energy region up to a few GeV makes an expansion in the strong coupling constant unusable. Therefore mostly models are used to describe the $c-\bar{c}$ potential, such as non-relativistic effective field theories. The precise measurement of the charmonium spectra via spectroscopy and the comparison to the predictions from theory are crucial for the understanding of QCD, since they can be used to probe the low energy non-perturbative region of QCD.

Until recently, the charmonium system and its fundamental role in the development of QCD was thought to be rather well understood, since most of the states below the open charm threshold were discovered and well described with models employing QCD-inspired potentials. Charmonium spectroscopy gained a lot of new attention with the discovery of the charmonium-like $X(3872)$ state by Belle in 2003 in the decay channel $B^{\pm} \to K^{\pm}X(3872) \to K^{\pm}J\psi\pi^{+}\pi^{-}$, which was confirmed by several other experiments [1]. By analysing the angular distribution of $X(3872)$ from B meson decays, LHCb determined its quantum numbers to be $1^{++}$ at a significance of 8.4 $\sigma$ [2]. The world average mass of the $X(3872)$ is $3871.68 \pm 0.17$ MeV/c$^2$, which is close to the mass of the $D^{*0}\bar{D}^{0}$ threshold: $m[X(3872)] - [m(D^{0*}) + m(\bar{D}^{0})] = -0.17 \pm 0.26$ MeV/c$^2$ [3]. The width of the state was measured to be very small with an upper limit of $\Gamma < 1.2$ MeV at 90% confidence level (C.L.) [3]. This corresponds to an unexpected long lifetime compared to conventional charmonium above the $D\bar{D}$ threshold. Together with the observed isospin violating decays $R_{\omega/\rho} = \Gamma(X \to J/\psi\omega)/\Gamma(X \to J/\psi\rho) = 0.8 \pm 0.3$ [3], this is the most intriguing fact making the $X(3872)$ an exotic candidate. Its apparent quantum numbers, mass and decay patterns make it unlikely to be a conventional charmonium candidate, and so far no consensual explanation has been found to explain all measured properties.

Another puzzling state is the $Y(4260)$, which was observed as an unexpected vector charmonium-like state in Initial State Radiation (ISR) production of $Y(4260) \to \pi^{+}\pi^{-}J/\psi$ by BABAR and confirmed by other experiments [4]. Another $J^{PC} = 1^{--}$ state, the $Y(4360)$, was found by BABAR in $\pi^{+}\pi^{-}\psi(2S)$ and confirmed by Belle [5]. No model predicted $1^{--}$ states close to those masses with widths of less than 100 MeV. Moreover both states do not show up in the inclusive hadron cross section (R-scan) measurement of such states as would be expected [6]. It is also worth to mention that the decay width $\Gamma(Y \to \pi^{+}\pi^{-}J/\psi)$ is an order of magnitude higher than expected for conventional vector charmonium states, since charmonium above the $D\bar{D}$ threshold dominantly decays into open charm final states [6].

Together with the recently discovered charged-charmonium like states such as the $Z(3900)^{\pm}$ and the $Z(4430)^{\pm}$ [7, 8, 9], this is known as the *XYZ puzzle* [10, 11]. Currently, the nature of these states is widely discussed in the physics community because those states are believed to be good candidates for a new exotic QCD-allowed form of matter like hybrids, tetraquarks or molecules [6].

Since the nature of these states still remains unknown, its interpretation demands much more experimental investigations and therefore they need to be investigated in other than the known decay processes to better understand their nature [12]. These proceedings presents a search for radiative transitions of $Y(4260)$ and $Y(4360)$ to the lower lying charmonium-like $X(3872)$ state, where the $X(3872)$ is reconstructed by its decay products $J/\psi$ and $\gamma$. Such investigations should help to clarify the existence of the radiative decay of $Y(4260) \to \gamma X(3872)$ as studied with a different final state $J/\psi\pi^+\pi^-$ by BESIII [12] which is of great interest for theorists [13].

## 2. Summary of previous BESIII results

Recently, BESIII published a search for the radiative decay process $e^+e^- \to \gamma X(3872) \to \gamma J/\psi\pi^+\pi^-$ [12]. For the first time the $X(3872)$ was observed in a radiative transition with a significance of $6.3\sigma$.

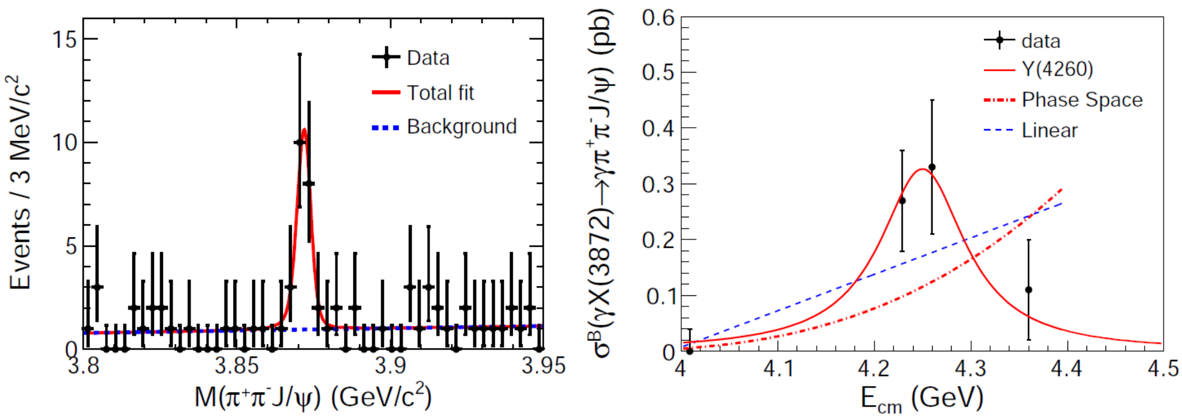


Figure 1: left: Fit of the $M(J/\psi\pi^+\pi^-)$ distribution, right: Fits to extracted $\gamma X(3872)$ cross section [12].

The fit result of BESIII gives a mass of $M(X(3872)) = 3871.9 \pm 0.7$ MeV/c$^2$ and $20.1 \pm 4.5$ signal events (compare to Figure 1 (left)). Table 1 gives a summary of determined signal parameters at different center-of-mass (CM) energies [12].

| $\sqrt{s}$(GeV) | $N^{obs}$ | $N^{up}$ | $\sigma^B \cdot \mathcal{B}$(pb) | $\sigma^{up} \cdot \mathcal{B}$(pb) |
|---|---|---|---|---|
| 4.009 | $0.0 \pm 0.5$ | $< 1.4$ | $0.0 \pm 0.4 \pm 0.01$ | $< 0.11$ |
| 4.229 | $9.6 \pm 3.1$ | - | $0.27 \pm 0.09 \pm 0.02$ | - |
| 4.260 | $8.7 \pm 3.0$ | - | $0.33 \pm 0.12 \pm 0.02$ | - |
| 4.360 | $1.7 \pm 1.4$ | $< 5.1$ | $0.11 \pm 0.09 \pm 0.01$ | $< 0.36$ |

Table 1: Summarized Results of cross section measurements of $\sigma^B[e^+e^- \to \gamma X(3872)] \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ from [12].

Figure 1 (right) shows the measured cross sections for the reaction $e^+e^- \to \gamma X(3872)$ and $X(3872) \to J/\psi\pi^+\pi^-$ at different CM energies from [12]. Three different functions are used to fit the data: a linear continuum function, a E1-transition phase space ($\propto E_\gamma^3$) term and the $Y(4260)$ resonance, where the parameters are fixed according to PDG [3] values. One can see that the $Y(4260)$ resonance describes the data better than the other options. However, the current statistics are not sufficient to rule out a continuum production $e^+e^- \to \gamma X(3872)$ of the $X(3872)$ and the existence of the radiative decay of $Y(4260)$ is still unclear [12]. If this decay could be confirmed, this would have important implications. Therefore additional decay models of $X(3872)$ have to be studied.

The branching ratio of:

$$\frac{\mathscr{B}(X(3872) \to \gamma J/\psi)}{\mathscr{B}(X(3872) \to J/\psi\pi^+\pi^-)},$$

according to previous measurements is $\sim \frac{1}{3}$ [14]. Due to the observation of $20.1 \pm 4.5$ signal events by BESIII in $X(3872) \to J/\psi\pi^+\pi^-$ [12] and comparable efficiencies, about seven events are expected for the $X(3872) \to \gamma J/\psi$ channel and will allow for a study of $e^+e^- \to \gamma X(3872) \to \gamma\gamma J/\psi$.

## 3. The BESIII detector

The BESIII detector is located at the Beijing Electron Postitron Collider II (BEPCII) collider with a design luminosity of $10^{33} cm^{-2}s^{-1}$ and CM energies from 2-4.6 GeV. The detector is a high performance general purpose detector with an onion-shell like structure. The innermost detector is a helium-gas based (60% He / 40 % $C_3H_8$) drift chamber (MDC) for charged-particle tracking and particle identification by $dE/dx$ ionization followed by a plastic scintillator time-of-flight (TOF) system and a CsI(Tl) electromagnetic calorimeter (EMC) for electron and photon detection. Those are surrounded by a super-conducting solenoid magnet with a field of 1 Tesla and the outermost detector for muon identification which is made of resistive-plate chambers. The momentum resolution for charged particles is 0.5% at 1 GeV/c and the energy resolution is 2.5% in the barrel and 5% in the endcap part for 1 GeV photons [15].

## 4. Analysis and Results

In this analysis a preliminary search for direct $X(3872)$ production in charmonium decays of exotic states $Y(4260), Y(4360)$ is performed using Monte Carlo (MC) simulations corresponding to data sets produced at CM energies of 4.230 GeV, 4.260 GeV and 4.360 GeV for the BESIII experiment. The optimization of event selection criteria and the estimation of the background are performed with these simulations. The decay of charmonium is modelled using the EvtGen package [16]. A GEANT4-based simulation software [17] is used for the geometric description of all BESIII subdetectors and to simulate the behaviour of traversing particles.

In order to determine the detection efficiency and to optimize the selection criteria for the present analysis, the exclusive decay $e^+e^- \to \gamma X(3872)$ with $X(3872) \to J/\psi\gamma$ is simulated at each CM energy point mentioned before. A phase space decay model is used to simulate the process

$e^+e^- \to \gamma X(3872)$ as well as $X(3872) \to J/\psi\gamma$, where the $J/\psi$ decays into $e^+e^-$ and $\mu^+\mu^-$ with identical branching ratios modelled with the VLL model [16]. Final State Radiation (FSR) effects associated with leptons are handled by PHOTOS [18]. Each MC sample contains 20000 events.

### 4.1 Event Selection

For this study the events of interest are $X(3872) \to J/\psi\gamma$ with $J/\psi$ being reconstructed from its decay into lepton pairs ($e^+e^-, \mu^+\mu^-$). Therefore all signal events should have two oppositely charged tracks with a total charge of zero and at least two neutral tracks corresponding to the two photons. Charged tracks are reconstructed from their MDC information, each track is required to originate from the interaction point with its point of closest approach to the beam axis within 10 cm of the interaction point in beam direction and within 1 cm in the direction perpendicular to the beam axis. Tracks are required to lie within the polar angle region of $|\cos\theta| < 0.93$ due to the geometrical acceptance of the BESIII detector.
Neutral particles are reconstructed from their EMC information. The deposited energy in the barrel ($|\cos\theta| < 0.8$) is required to be larger than 25 MeV and showers in the endcap EMC ($0.86 < |\cos\theta| < 0.92$) must have at least 50 MeV. Photons originally produced by Bremsstrahlung are rejected by the requirement that the angle between charged particles and a photon should be larger than $20^\circ$. To suppress electronic noise and energy deposits which are unrelated to the event, the EMC signal has to be within 0 to 700 ns after the collision.

Electrons and muons are separated by comparing the energy deposited in the EMC (Figure 2). Electrons are required to have $E_{EMC} > 1$ GeV and muons to have $E_{EMC} < 0.35$ GeV. The momentum measured by the MDC should be larger than 1 GeV for both type of particles.

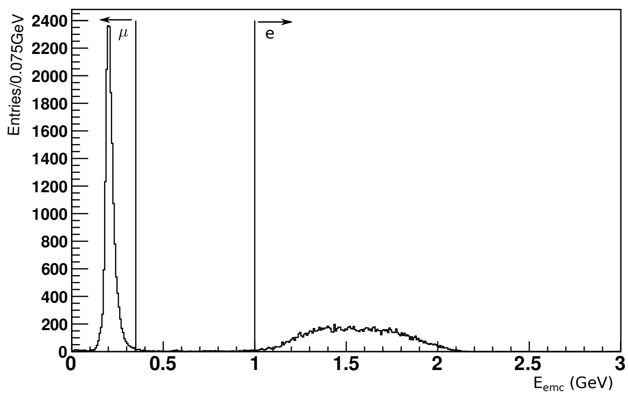


Figure 2: Lepton energy deposition in the EMC for signal MC at $\sqrt{s} = 4.260$ GeV. Cut lines are drawn to discriminate muons (left) and electrons (right).

A vertex fit is used to constrain the two charged particles in each final state to the same starting point. $J/\psi\gamma\gamma$ events are subject to a kinematic fit, employing the initial 4-momentum as constraints to improve the resolution. For events with more than two photons per event, the best combination corresponding to the smallest $\chi^2_{4C}$ is chosen. In the further event selection $\chi^2_{4C} < 60$ is required. The efficiency of the 4C fit is $85.7 \pm 0.2\%$, where the error is the binomial one taking into account the correlation of the selected and total events N [19].

In Figure 3, the $J/\psi$ invariant mass from MC samples at $\sqrt{s} = 4.260$ GeV is shown. The invariant mass spectrum is fitted with a double Gaussian function in order to extract parameters of the $J/\psi$ resonance. The fit results give a central value of 3.0998 GeV/c$^2$ for the mass and a width of $\sigma$ ~8.1 MeV/c$^2$.

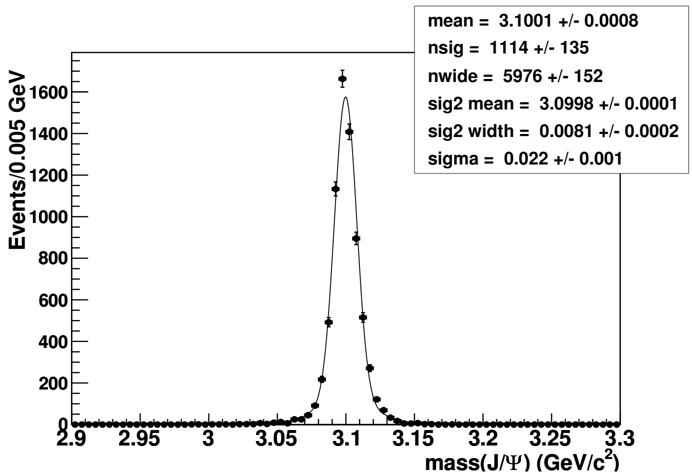


Figure 3: Invariant mass distribution of lepton pairs from MC simulation at $\sqrt{s} = 4.260$ GeV with a double Gaussian fit.

### 4.2 Background Contributions

To reject possible $e^+e^- \to \eta J/\psi$ background events, a $\eta$-veto condition of $|M(\gamma\gamma) - M_\eta| <$0.027 GeV/c$^2$ is used, corresponding to a 3 $\sigma$ region around the central mass value.

The Bhabha background $e^+e^- \to e^+e^-$ to this final state was also estimated using MC simulations. Bhabha studies were performed at $\sqrt{s} = 4.260$ GeV and the distribution of the momentum of the leptons is shown in left of Figure 4. As expected, the Bhabha background peaks at around 2 GeV/c compared to signal MC events which peak between 1.4 to 1.8 GeV/c as shown on the right side of Figure 4. To reject Bhabha background a total momentum cut of $1.2 < p_{lep} < 1.97$ GeV/c is used which also cuts about 8% of the signal MC events.

Bhabha events have a back-to-back topology with a polar angle distribution peaking at $\theta \sim 0°$, whereas signal MC events are equally distributed over the whole polar angle range. To further reject those events, the polar angle for electrons has to satisfy $\cos(\theta_{e^-}) \geq -0.6$ and for positrons $\cos(\theta_{e^+}) \leq 0.6$ is required. With this cut another 8% signal MC events are rejected.

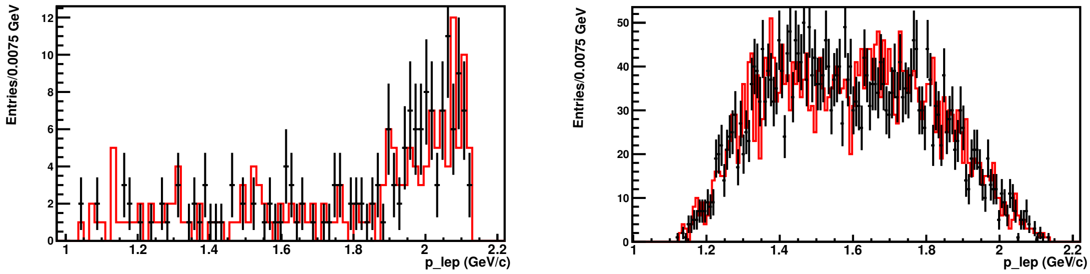


Figure 4: The momentum distribution of leptons from simulated Bhabha background (left) compared to exclusive signal MC (right) at $\sqrt{s} = 4.260$ GeV. Positively charged leptons are drawn in red, whereas the negatively charged ones are drawn in black.

In Figure 5 the spectrum of photon energy versus the polar angle for the higher energetic photons is shown for a signal MC simulation at 4.26 GeV after the kinematic fit. Here one can see that the maximal energy of the higher energetic photon is 0.8 GeV, therefore a cut is set to this maximum energy to suppress further background. This cut removes less than 0.1% of signal MC events with an efficiency of $99.9 \pm 0.7\%$.

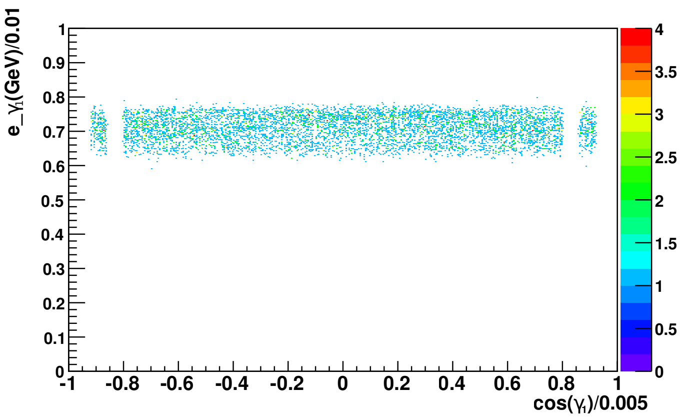


Figure 5: The polar angle of the higher energetic photon versus the energy of the photon is shown here for exclusive signal MC events at $\sqrt{s} = 4.260$ GeV.

### 4.3 Results

After applying all final selection criteria explained above, the detection efficiencies from exclusive MC simulations are 34.4% at $\sqrt{s} = 4.229$ GeV, 34.0% at $\sqrt{s} = 4.260$ GeV and 33.1% at $\sqrt{s} = 4.360$ GeV. The cutflow of the final event selection is summarized in Table 2.

With the final selection criteria, the $X(3872)$ signal simulated from exclusive MC is shown in Figure 6. Here the relation $m(J/\psi\gamma) - m(l^+l^-) + m(J/\psi)$ is used to cancel resolution effects of the leptons, where $m(J/\psi)$ is the PDG mass [3]. The invariant mass of both leptons including the $J/\psi$ mass cut is combined with the higher energetic photon from the kinematic fit to reconstruct the $X(3872)$ signal ($m(J/\psi\gamma_{\rm H})$).

| Cuts | $\sqrt{s} = 4.229$ GeV | $\sqrt{s} = 4.260$ GeV | $\sqrt{s} = 4.360$ GeV |
|---|---|---|---|
| total number | 20000 | 20000 | 20000 |
| Charged tracks | 16674 | 16648 | 16597 |
| Photon selection | 11839 | 11839 | 11946 |
| PID | 11378 | 11403 | 11504 |
| Vertex Fit | 11297 | 11328 | 11427 |
| 4C-Kinematic fit | 8903 | 8878 | 9051 |
| $\eta$ veto | 8431 | 8430 | 8686 |
| $p_{lep}$ cut | 7730 | 7736 | 7620 |
| $\cos_e$ cut | 7097 | 7098 | 6990 |
| $e_{\gamma 1} \leq 0.8$ cut | 7093 | 7091 | 6950 |
| $J/\psi$ cut | 6810 | 6799 | 6625 |
| Efficiency | 34.4% | 34.0% | 33.1% |

Table 2: The Cutflow for MC simulations

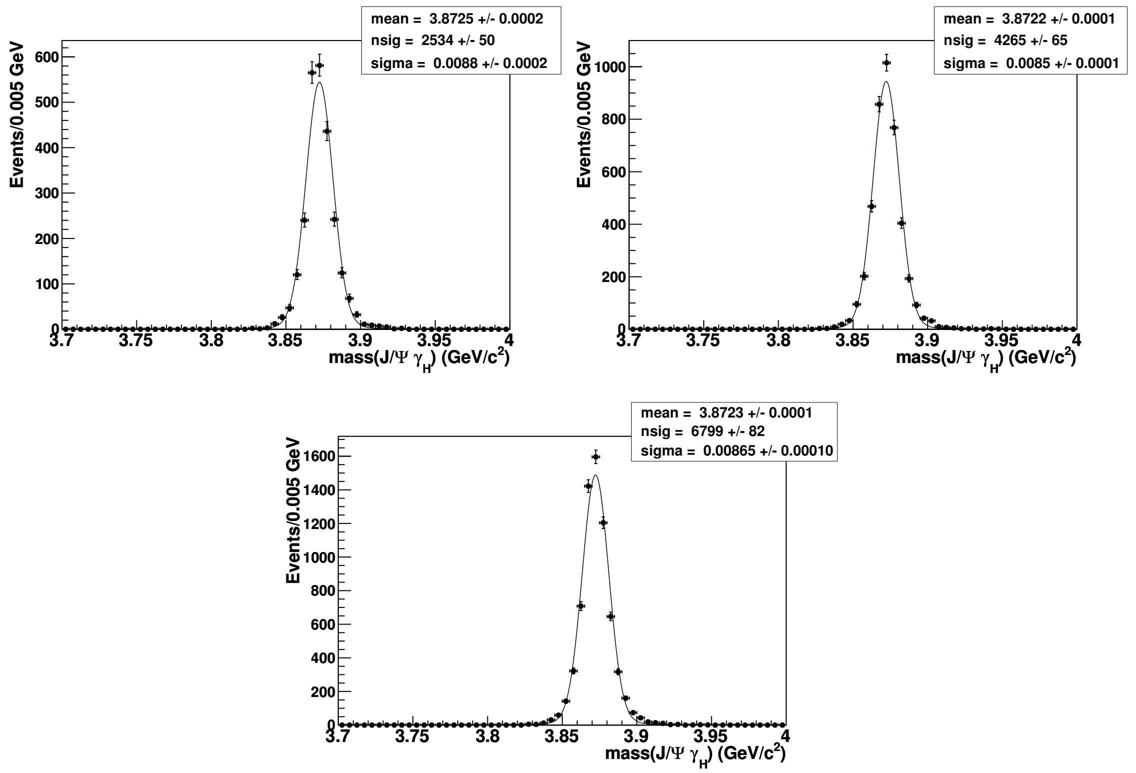


Figure 6: The $X(3872)$ signal from MC simulation at $\sqrt{s} = 4.260$ GeV after all cuts. In the top left plot the $J/\psi$ signal is reconstructed via electrons, whereas in the top right plot muons are used and the bottom plot shows the total signal. A fit is performed with a Breit-Wigner convolved with a Gaussian function to extract the resonance parameters of each signal.

The $X(3872)$ signal is fitted with a Breit-Wigner convolved with a Gaussian probability density function, to get the resonance parameters. The central value from the fit for the electron mode is

$m(X(3872)) = 3.8725 \pm 0.0002$ GeV/c$^2$ and its width is $\sigma = 8.8 \pm 0.2$ MeV/c$^2$, whereas the parameters for the muon mode are $m(X(3872)) = 3.8722 \pm 0.0001$ GeV/c$^2$ and $\sigma = 8.5 \pm 0.1$ MeV/c$^2$ for the width. The central value for the total sum is $m(X(3872)) = 3.8723 \pm 0.0001$ GeV/c$^2$ and its width is $\sigma = 8.65 \pm 0.1$ MeV/c$^2$. More detailed informations are given in [20].

## 5. Summary and Conclusions

Preliminary MC studies for $X(3872) \to J/\psi\gamma$ of CM energies at 4.230 GeV, 4.260 GeV and 4.360 GeV for the BESIII detector were performed. The detection efficiencies at those CM energies are obtained to be 34.4%, 34.0% and 33.1% respectively. From previous measurements of branching rations at different experiments as well the recently performed measurement of around 20 events in the $J/\psi\pi^+\pi^-$ final state by BESIII[12], about seven events are expected in data since the MC efficiency of both channels is comparable.

The observation or the absence of such a radiative transitions of $Y(4260)$ or $Y(4360)$ to $\gamma X(3872)$ will provide important information concerning the internal sub-structure and the connections between those exotic states. The observations of [12] strongly suggest the existence of the radiative transition process $Y(4260) \to \gamma X(3872)$ which could be another unseen decay mode of the $Y(4260)$ resonance, but further investigations are needed to confirm that the measured cross section follows the resonant contribution of the $Y(4260)$ line shape, as investigated therein. If the decay is confirmed, it seems very likely that the $X(3872)$ and the $Y(4260)$ have a common nature for example both being molecules as discussed in [21].

## References

[1] S. Choi et al. (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003), D. Acosta et al. (CDF Collaboration), Phys. Rev. Lett. **93**, 072001 (2004), V. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. **93**, 162002 (2004), B. Aubert et al. (BaBar Collaboration), Phys. Rev. **D71**, 071103 (2005)

[2] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. **110**, 222001 (2013)

[3] J. Beringer et al. (Particle Data Group), Phys. Rev. D **86**, 010001 (2012)

[4] B. Aubert et al. (BaBar Collaboration) (2008), hep-ex/0808.1543, C. Z. Yuan et al. (Belle Collaboration), Phys. Rev. Lett. **99**, 182004 (2007) Q. He et al. (CLEO Collaboration), Phys. Rev. **D 74**, 091104 (2006)

[5] B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 98, 212001 (2007), X. L. Wang et al. (Belle Collaboration), Phys. Rev. Lett. 99, 142002 (2007)

[6] N. Brambilla et al., Eur. Phys. J. **C71**, 1534 (2011)

[7] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. **110**, 252001 (2013), Z. Q. Liu et al. (Belle Collaboration), Phys. Rev. Lett. 110, 252002 (2013), T. Xiao et al., Physics Letters B 727, 366 (2013)

[8] S.-K. Choi et al. (Belle Collaboration), Phys. Rev. Lett. **100**, 142001 (2008), R. Aaij et al. (LHCb), hep-ex/1404.1903 (2014)

[9] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 111, 242001 (2013), R. Mizuk et al. (Belle Collaboration), Phys. Rev. D 78, 072004 (2008)

[10] P. G. Ortega, D. R. Entem and F. Fernandez, J. Phys. G: Nucl. Part. Phys., **40** 065107 (2013)

[11] X. Liu, hep-ph/1312.7408 (2013)

[12] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. **112**, 092001 (2014)

[13] F.-K. Guo et al., Phys. Lett. B **725**, 127 (2013)

[14] V. Bhardwaj et al. (Belle Collaboration), Phys. Rev. Lett. **107**, 091803 (2011), B. Aubert et al. (BaBar Collaboration), Phys. Rev. **D77**, 111101 (2008), B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. **102**, 132001 (2009)

[15] M. Ablikim et al., Nucl. Instrum. Meth. A **614**, 345 (2010).

[16] A. Ryd et al., EVTGEN-V00-11-07 (2005)

[17] Z. Deng et al., Chinese Phys. C 30, 371 (2006).

[18] P. Golonka, and Z. Was, Eur. Phys. J. C **45**, 97 (2006)

[19] M. G. Ullrich, Ph.D. thesis, Justus-Liebig-Universität Gießen (2013)

[20] Svende Annelies Braun, Analysis of the decay $e^+e^- \to \gamma X(3872) \to J/\psi\gamma\gamma$ at the BESIII experiment, Master-Thesis, Justus-Liebig-Universität Gießen (2014)

[21] E. Swanson, hep-ph/1401.3914