Glueball searches using electron-positron annihilations with BESIII

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Abstract. Using a BESIII-data sample of $1.31 \times 10^9$ $J/\psi$ events collected in 2009 and 2012, the glueball-sensitive decay $J/\psi \rightarrow \gamma p\bar{p}$ is analyzed. In the past, an exciting near-threshold enhancement $X(p\bar{p})$ showed up. Furthermore, the poorly-understood properties of the $\eta_c$ resonance, its radiative production, and many other interesting dynamics can be studied via this decay. The high statistics provided by BESIII enables to perform a partial-wave analysis (PWA) of the reaction channel. With a PWA, the spin-parity of the possible intermediate glueball state can be determined unambiguously and more information can be gained about the dynamics of other resonances, such as the $\eta_c$. The main background contributions are from final-state radiation and from the $J/\psi \rightarrow \pi^0(\gamma\gamma)p\bar{p}$ channel. In a follow-up study, we will investigate the possibilities to further suppress the background and to use data-driven methods to control them.

1. Introduction
The discovery of the Higgs boson has been a breakthrough in the understanding of the origin of mass. However, this boson only explains 1% of the total mass of baryons. The remaining 99% originates, according to quantum chromodynamics (QCD), from the self-interaction of the gluons. The nature of gluons gives rise to the formation of exotic hadronic matter. In particular, massive hadrons that are purely made from massless gluons, glueballs, are considered to be the holy grail of QCD. Glueballs are predicted, but lack experimental verification. With its high resolution and acceptance, the Beijing Spectrometer (BES) III at the Beijing Electron Positron Collider (BEPC) II is an outstanding detector to search for glueballs. The BEPCII runs at a center-of-mass energy from 2 GeV to 4.6 GeV [1], an energy range where an abundance of glueballs are predicted by lattice QCD calculations [2, 3]. BESIII has collected the world’s largest sample of vector-meson charmonium data. Since charmonium mesons below the open-charm threshold decay mostly to gluons, BESIII can be seen as a real “glue factory”. BESIII has previously observed various exotic states of which some are glueball candidates [4, 5]. A BESIII-data sample of $1.31 \times 10^9$ $J/\psi$ events collected in 2009 and 2012 [6] is used for the analysis of the glueball-sensitive decay $J/\psi \rightarrow \gamma p\bar{p}$. With the most recent BESIII-data runs included, there will be even more than 10 billion $J/\psi$ events available!

2. The decay $J/\psi \rightarrow \gamma p\bar{p}$
The narrow and well-defined $J/\psi$ state is a $1^{--}$ state below the open-charm threshold, which makes radiative $J/\psi$ decays sensitive to glueballs. The $c\bar{c}$ annihilation in a radiative $J/\psi$ decay
couples dominantly to three gauge bosons, where one of these gauge bosons is required to be a photon. The detected photon makes it possible to scan various regions of the invariant mass of the resultant particles. The full spectrum of the $p\bar{p}$ invariant mass is shown in figure 1.

![Figure 1](image)

Figure 1. $p\bar{p}$ invariant mass for $J/\psi \rightarrow \gamma p\bar{p}$ [7]. The dashed blue line represents the phase-space contribution.

Figure 1 shows a spectacular near-threshold enhancement for the reaction $J/\psi \rightarrow \gamma p\bar{p}$, which is described in Refs. [8–10] as well. There is no similar effect seen in related decays like $J/\psi \rightarrow xp\bar{p}$ with $x = \omega, \pi, \eta$ and $\psi' \rightarrow xp\bar{p}$ with $x = \gamma, \pi, \eta$ [8–16]. However, in the decay $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$, a resonance is observed with properties consistent with expectations for a state that produces the enhancement in $J/\psi \rightarrow \gamma p\bar{p}$ [17]. In the high-mass region of figure 1, there is a clear $\eta_c$ peak visible around 3 GeV. More than 30 years after the discovery [18] of this lowest lying charmonium state, the knowledge of the $\eta_c$ is still relatively poor. Until now the measured exclusive decays cover less than two-thirds of its decay width, the mass and width have large uncertainties compared to those of other charmonium states and a distortion of the $\eta_c$ line shape has been pointed out in Refs. [19–21]. Finally, figure 1 shows an enhancement at an invariant mass of around 2.1 GeV. Thus far, this enhancement has not been studied yet. The aim is to get a better understanding of the full spectrum of the $p\bar{p}$ invariant mass and, especially, to get more information about the quantum numbers of the strong near-threshold enhancement.

### 3. The detector and Monte Carlo simulation

The BESIII experiment is a cylindrical detector which consists of a main drift chamber (MDC), a time-of-flight (TOF) detector, a CsI (Tl) electromagnetic calorimeter (EMC), a muon identifier and a superconducting magnet that provides a magnetic field with a strength of 1 T. BESIII has a nominal geometrical acceptance of 93% of 4π solid angle. The helium-gas based MDC measures the specific energy loss, $dE/dx$, with a resolution better than 6%. The transverse momentum resolution at 1 GeV is better than 0.5%. The EMC has an energy resolution of 2.5% (5%) in the barrel (end cap) region for 1 GeV electrons, positrons and photons. The TOF system has a timing resolution of 80 ps (110 ps) in the barrel (end caps) [21]. A more detailed description of BESIII and its subdetectors can be found in Ref. [22].

To determine the detector efficiency, optimize the event selection and estimate the backgrounds, an inclusive Monte Carlo (MC) sample of $1.225 \times 10^9 J/\psi$ events and generated exclusive MC samples will be used. The production of $J/\psi$ states are simulated by the MC generator KKMC [23], in which the effects of beam-energy spread and initial-state radiation are considered, and the event generator BesEvtGen [24] is used to generate subsequent $J/\psi$ decays. Known decays are generated by BesEvtGen using the branching fractions listed by the Particle Data Group (PDG) [19], and the remaining unknown decays are generated with LUNDCHARM [25].
4. Event selection

The $J/\psi \rightarrow \gamma p\bar{p}$ candidate events in this study are required to have two charged tracks with opposite charge and at least one photon. Charged tracks in the polar angle region $|\cos \theta| < 0.93$ are reconstructed from the MDC hits and will be discarded if the point of closest approach to the interaction point lies outside the region of $\pm 10 \text{ cm}$ along the beam direction and $1 \text{ cm}$ in the plane perpendicular to the beam direction. For each charged-track particle identification (PID) probability are determined with use of information from the TOF, the EMC and the muon identifier, and the ionization energy deposited in de MDC ($dE/dx$). Tracks that have a higher probability to be a kaon than a proton are discarded. To reconstruct photon candidates, the energy deposits in the EMC are clustered. Photon candidates with an angle smaller than $10^\circ$ will be measured and used to apply a background subtraction. Even without these further improvements, the significance of the decay $J/\psi \rightarrow \gamma p\bar{p}$ is already more than 300 $\sigma$.

In the low-mass $p\bar{p}$-invariant-mass region the mentioned prominent $X(p\bar{p})$ appears and in the high-mass region of the $p\bar{p}$-invariant-mass an expected $\eta_c$-peak is seen. In the MC dataset the enhancement around 2.1 GeV is not included, however, in the analyzed BESIII data a similar enhancement as the one in figure 1 is seen.

5. Analysis

Figure 2 shows the resulting $\sqrt{s}$ and $p\bar{p}$-invariant mass of the inclusive MC dataset. The main background components are given by $J/\psi \rightarrow \pi^0(\gamma\gamma)p\bar{p}$, where one of the two photons from the decay of $\pi^0$ is not detected, and $J/\psi \rightarrow p\bar{p}$, where a final-state radiation (FSR) photon is wrongly detected. The contributions of these backgrounds are shown in figure 2 in blue and green, respectively. In the shown MC dataset an attempt has been made to suppress background from a FSR photon by requiring $M_{\gamma p}^2 + M_{p\bar{p}}^2 < 2.16 \text{ GeV}^2$, where the limit is given by a significance optimization. In a follow-up study, we will employ other methods to further suppress the background. For example, studies are ongoing to optimize the cut of the angle between photon candidates to any charged track and to deploy multivariate analysis techniques to further suppress the background [26]. To account for the $\pi^0$ background, the decay $J/\psi \rightarrow \pi^0(\gamma\gamma)p\bar{p}$ will be measured and used to apply a background subtraction. Even without these further improvements, the significance of the decay $J/\psi \rightarrow \gamma p\bar{p}$ is already more than 300 $\sigma$.

6. Summary and outlook

Glueballs are interesting subjects to investigate and the strong and clean $J/\psi \rightarrow \gamma p\bar{p}$ decay is an ideal channel for these glueball studies. In the past, an exciting near-threshold enhancement showed up. In the BESIII analysis, the full event topology is reconstructed by identifying the photon, proton, and antiproton. This will allow us to perform a partial-wave analysis (PWA) of the reaction channel. In a PWA, the correlation between the momenta of final-state particles is fully exploited to determine the masses, widths and spin-parities of intermediate resonances. With a PWA, the spin-parity of the possible intermediate glueball state can be determined unambiguously. Previous PWAs of $J/\psi \rightarrow \gamma p\bar{p}$ only covered low-mass $p\bar{p}$-invariant-mass up to $M(p\bar{p}) \sim 2 \text{ GeV}$. In this mass region, FSI effects give a significant contribution [7]. In the mass-region $M(p\bar{p}) > 2 \text{ GeV}$, there is still a lot to be understood about the dynamics behind the enhancement around 2.1 GeV and about the properties and production mechanism of the $\eta_c$ resonance. The goal is thus to apply a full-fledged PWA, possibly extended with $NN$ FSI effects [27, 28] included near threshold. For the PWA, the software package PAWIAN (PArtial...
Figure 2. Results of the mentioned analysis of the channel $J/\psi \rightarrow \gamma p\bar{p}$ using an inclusive $J/\psi$ MC sample. The top panel (a) shows the reconstructed invariant mass of all final-state particles and the bottom panel (b) shows the reconstructed $p\bar{p}$-mass spectrum. The various contributions are indicated by the shaded areas and described in the legend.

Wave Interactive Analysis) [29] will be used. The BESIII-data sample currently used consist of $1.31 \times 10^9 J/\psi$ events collected in 2009 and 2012 [6]. Including data obtained from the most recent runtime in 2019, will allow us to analyze about $10^{10} J/\psi$ decays, thereby increasing the statistics significantly.

References
[1] Asner D M et al. 2008 arXiv e-prints (Preprint 0809.1869)
[2] Bali G S 2006 Int. J. Mod. Phys. A21 5610–5617 (Preprint hep-lat/0608004)
[3] Liu L, Moor G, Peardon M, Ryan S M, Thomas C E, Vilaseca P, Dudek J J, Edwards R G, Joo B and Richards D G (Hadron Spectrum) 2012 JHEP 07 126 (Preprint 1204.5425)
[4] Wang B 2018 Nuclear and Particle Physics Proceedings 294-296 63 – 69 ISSN 2405-6014 the
20th High-Energy Physics International Conference in Quantum Chromodynamics (QCD 17) URL http://www.sciencedirect.com/science/article/pii/S2405601418300336

[5] Yin J 2018 International Journal of Modern Physics: Conference Series 46 1860024 (Preprint https://doi.org/10.1142/S2010194518600248) URL https://doi.org/10.1142/S2010194518600248

[6] et al (the BESIII Collaboration) M A (BESIII) 2017 Chin. Phys. C41 013001 (Preprint 1607.00738)

[7] Ablikim M et al. (BESIII Collaboration) 2012 Phys. Rev. Lett. 108(11) 112003 URL https://link.aps.org/doi/10.1103/PhysRevLett.108.112003

[8] Bai J Z et al. (BES) 2001 Phys. Lett. B510 75–82 (Preprint hep-ex/0105011)

[9] Ablikim M et al. 2008 The European Physical Journal C 53 15–20 ISSN 1434-6052 URL https://doi.org/10.1140/epjc/s10052-007-0467-4

[10] Alexander J P et al. (CLEO Collaboration) 2010 Phys. Rev. D 82(9) 092002 URL https://link.aps.org/doi/10.1103/PhysRevD.82.092002

[11] Ablikim M et al. (BES Collaboration) 2009 Phys. Rev. D 80(5) 052004 URL https://link.aps.org/doi/10.1103/PhysRevD.80.052004

[12] Bai J Z et al. (BES) 2001 Phys. Lett. B510 75–82 (Preprint hep-ex/0105011)

[13] Ablikim M et al. 2008 The European Physical Journal C 53 15–20 ISSN 1434-6052 URL https://doi.org/10.1140/epjc/s10052-007-0467-4

[14] Ablikim M et al. (BESIII Collaboration) 2013 Phys. Rev. D 87(11) 112004 URL https://link.aps.org/doi/10.1103/PhysRevD.87.112004

[15] Ablikim M et al. (BESIII Collaboration) 2013 Phys. Rev. Lett. 110(2) 022001 URL https://link.aps.org/doi/10.1103/PhysRevLett.110.022001

[16] Ablikim M et al. (BESIII Collaboration) 2013 Phys. Rev. D 88(3) 032010 URL https://link.aps.org/doi/10.1103/PhysRevD.88.032010

[17] Ablikim M et al. (BES Collaboration) 2005 Phys. Rev. Lett. 95(26) 262001 URL https://link.aps.org/doi/10.1103/PhysRevLett.95.262001

[18] Partridge R et al. 1980 Phys. Rev. Lett. 45(14) 1150–1153 URL https://link.aps.org/doi/10.1103/PhysRevLett.45.1150

[19] Tanabashi M et al. (Particle Data Group) 2018 Phys. Rev. D 98(3) 030001 URL https://link.aps.org/doi/10.1103/PhysRevD.98.030001

[20] Mitchell R E et al. (CLEO) 2009 Phys. Rev. Lett. 102 011801 [Erratum: Phys. Rev. Lett.106,159903(2011)] (Preprint 0805.0252)

[21] Ablikim M et al. (BESII) 2012 Phys. Rev. Lett. 108 222002 (Preprint 1111.0398)

[22] Ablikim M et al. (BESIII) 2010 Nucl. Instrum. Meth. A614 345–399 (Preprint 0911.4960)

[23] S Jadach B W and Was Z 2001 Phys. Rev. D63 113009 (Preprint hep-ph/0006359)

[24] Lange D J 2001 Nucl. Instrum. Meth. A462 152–155

[25] RL Yang R P and Hong C 2014 Chin. Phys. 31 061301 URL http://stacks.iop.org/0256-307X/31/i=6/a=061301

[26] Isolabella T 2019 A machine learning approach to particle physics data analysis: the process J/ψ → γp URL http://fse.studenttheses.ub.rug.nl/20112/

[27] Dedonder J P, Loiseau B and Wycech S 2018 Phys. Rev. C 97(6) 065206 URL https://link.aps.org/doi/10.1103/PhysRevC.97.065206

[28] Kang X W, Haidenbauer J and Meiner U G 2015 Phys. Rev. D91 074003 (Preprint 1502.00880)

[29] URL https://panda-wiki.gsi.de/foswiki/bin/view/PWA/PawianPwaSoftware