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Measurements of $h_c(^1P_1)$ in ψ' Decays

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We present measurements of the charmonium state $h_c(^1P_1)$ made with 106M ψ' events collected by BESIII at BEPCII. Clear signals are observed for $\psi' \to \pi^0 h_c$ with and without the subsequent radiative decay $h_c \to \gamma\eta_c$. First measurements of the absolute branching ratios $\mathcal{B}(\psi' \to \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$ and $\mathcal{B}(h_c \to \gamma\eta_c) = (54.3 \pm 6.7 \pm 5.2)\%$ are presented. A statistics-limited determination of the previously unmeasured h_c width leads to an upper limit $\Gamma(h_c) < 1.44$ MeV (90% confidence). Measurements of $M(h_c) = 3525.40 \pm 0.13 \pm 0.18$ MeV/c^2 and $\mathcal{B}(\psi' \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c) = (4.58 \pm 0.40 \pm 0.50) \times 10^{-4}$ are consistent with previous results.

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Although the charmonium family of mesons composed of a charmed quark and its own antiquark ($c\bar{c}$) has been studied for many years, knowledge is sparse on the singlet state $h_c(^1P_1)$. The only known production mode of h_c from other charmonium decays is $\psi' \to \pi^0 h_c$, but its branching ratio has not been previously measured. For the decay chain $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$, the absolute branching ratio of $h_c \to \gamma\eta_c$ also has not previously been measured. Their measurements will allow the test of isospin violation mechanisms in charmonium hadronic transitions and guide refinements of theoretical methods in the charmonium region. Early predictions for the properties of the h_c are found in Refs. [1, 2]. More recently, Kuang [3] considered the effect of $S-D$ mixing and predicted $\mathcal{B}(\psi' \to \pi^0 h_c) = (0.4 - 1.3) \times 10^{-3}$, and gave estimates of $\mathcal{B}(h_c \to \gamma\eta_c) = 88\%$ and $\Gamma(h_c) = (0.51 \pm 0.01)$ MeV for perturbative QCD (PQCD) and $\mathcal{B}(h_c \to \gamma\eta_c) = 41\%$ and $\Gamma(h_c) = (1.1 \pm 0.09)$ MeV with nonrelativistic QCD (NRQCD). Godfrey and Rosner have predicted $\mathcal{B}(h_c \to \gamma\eta_c) = 38\%$ [4]. A recent unquenched lattice QCD analysis [5] included a prediction of the width $\Gamma(h_c \to \gamma\eta_c) = (0.601 \pm 0.055)$ MeV.

Information about the spin-dependent interaction of heavy quarks can be obtained from precise measurement of the $1P$ hyperfine mass splitting $\Delta\ M_{hf} \equiv \langle M(1^3P)\rangle - M(1^1P_1)$, where $\langle M(1^3P_J)\rangle = (M(\chi_{c0}) + 3M(\chi_{c1}) + 5M(\chi_{c2}))/9 = 3525.30 \pm 0.04$ MeV/c^2 [6] is the spin-weighted centroid of the ^3P_J mass and $M(1^1P_1)$ is the mass of the singlet state h_c. A non-zero hyperfine splitting may give indication of nonvanishing spin-spin interactions in charmonium potential models [7].

This Letter reports first results from the BESIII experiment at the BEPCII storage ring [8, 9] on the production and decay of the h_c at the ψ' resonance. We study distributions of mass recoiling against a detected π^0 to measure $\psi' \to \pi^0 h_c$ both inclusively and in events tagged as $h_c \to \gamma\eta_c$ by detection of the $E1$ transition photon. Combining inclusive and $E1$-tagged yields, we determine for the first time the branching ratio for $\psi' \to \pi^0 h_c$ and that for the $E1$ transition $h_c \to \gamma\eta_c$, as well as the h_c width. We also measure the product branching ratio for the chain $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ and the h_c mass, confirming previous results.

The CLEO Collaboration first observed the h_c in the cascade process $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ in both inclusive and exclusive measurements [10], and later improved the h_c mass determination [11] with more data. They average their measurements in [11] to obtain $M(h_c) = (3525.20 \pm 0.18 \pm 0.12)$ MeV/c^2. The E835 experiment [12] scanned antiproton energy and observed $p\bar{p} \to h_c \to \gamma\eta_c$. Recently, CLEO reported evidence for the decay $h_c \to \pi^+\pi^-\pi^+\pi^-\pi^0$ with indications that the width for h_c multihadronic decays is comparable to that for the radiative transition to η_c [13].

BEPCII is a two-ring e^+e^- collider designed for a peak luminosity of 10^{33} cm$^{-2}s^{-1}$ at a beam current of 0.93 A. The cylindrical core of the BESIII detector consists of a helium-gas-based drift chamber (MDC), a plastic scintillator Time-of-Flight system (TOF), and a CsI(Tl) Electromagnetic Calorimeter (EMC), all enclosed in a superconducting solenoidal magnet providing a 1.0-T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identifier modules (MU) interleaved with steel. The charged particle and photon acceptance is 93% of 4π, and the charged particle momentum and photon energy resolutions at 1 GeV are 0.5% and 2.5%, respectively.

We perform the analysis on a data sample consisting of $(1.06 \pm 0.04) \times 10^8$ ψ' decays [14]. An independent sample of 42.6 pb^{-1} at 3.65 GeV is used to determine continuum ($e^+e^- \to q\bar{q}$) background. We measure h_c production by selecting events consistent with $\psi' \to \pi^0 h_c$

(momentum $p(\pi^0) \simeq 84$ MeV/c) and fitting the distribution of masses recoiling against the π^0. The yield of $\psi' \to \pi^0 h_c, h_c \to \gamma\eta_c$ is determined with the same technique on events containing a ~ 500 MeV photon.

We model BESIII with a Monte Carlo (MC) simulation based on Geant4 [15, 16]. EvtGen [17] is used to generate $\psi' \to \pi^0 h_c$ events with an h_c mass of 3525.28 MeV/c^2 [11] and a width equal to that of the χ_{c1} (0.9 MeV). The $E1$ transition $h_c \to \gamma\eta_c$ (assumed branching ratio 50%) is modeled with EvtGen, with an angular distribution in the h_c frame of $1 + \cos^2\theta$. Other h_c decays are simulated by PYTHIA [17]. The η_c decay parameters are set to Particle Data Group values [6], with known modes simulated by EvtGen and the remainder by PYTHIA. Backgrounds are studied with a sample of ψ' generated by KKMC [18] with known decays modeled by EvtGen and other modes generated with Lundcharm [17].

Charged tracks in BESIII are reconstructed from MDC hits. To optimize the momentum measurement, we select tracks in the polar angle range $|\cos\theta| < 0.93$ and require that they pass within ±10 cm of the interaction point in the beam direction and within ±1 cm in the plane perpendicular to the beam. Electromagnetic showers are reconstructed by clustering EMC crystal energies. Efficiency and energy resolution are improved by including energy deposits in nearby TOF counters. Showers used in selecting $E1$-transition photons and in π^0 reconstruction must satisfy fiducial and shower-quality requirements. Showers in the barrel region ($|\cos\theta| < 0.8$) must have a minimum energy of 25 MeV, while those in the endcaps ($0.86 < |\cos\theta| < 0.92$) must have at least 50 MeV. Showers in the region between the barrel and endcap are poorly reconstructed and are excluded. To eliminate showers from charged particles, a photon must be separated by at least 10° from any charged track. EMC cluster timing requirements suppress electronic noise and energy deposits unrelated to the event. Diphoton pairs are accepted as π^0 candidates if their reconstructed mass satisfies $120 < M_{\gamma\gamma} < 145$ MeV/c^2, approximately equivalent to 1.5 (2.0) standard deviations on the low-mass (high-mass) side of the mass distribution. A 1-C kinematic fit with the π^0 mass constrained to its nominal value is used to improve the energy resolution.

Candidate events must have at least two charged tracks, with at least one passing the fiducial and vertex cuts. For selection of inclusive π^0 events we demand at least two photons passing the above requirements, with at least three photons for $E1$-tagged candidate events. To suppress continuum background, the total energy deposition in the EMC must be greater than 0.6 GeV. Background events from $\psi' \to \pi^+\pi^- J/\psi$ and $\pi^0\pi^0 J/\psi$ are suppressed by requiring that the $\pi^+\pi^-$ ($\pi^0\pi^0$) recoil mass be outside the range 3097 ± 7 MeV/c^2 (3097 ± 15 MeV/c^2).

To improve the signal-to-noise ratio, photons used in signal π^0 candidates must be in the barrel and have energies greater than 40 MeV. For the inclusive analysis, π^0 candidates are excluded if either daughter photon can make a π^0 with another photon in the event. Figure 1 shows the inclusive π^0 recoil mass spectra after applying the above selection criteria. For the $E1$-tagged selection (Fig. 1 (a)), we require one photon in the energy range $465 - 535$ MeV, demanding that it not form a π^0 with any other photon in the event. Because $E1$-tagged events have reduced background, we keep them even if daughter photons can be used in more than one π^0 combination, choosing the candidate with the minimum 1-C fit χ^2. Events with more than one π^0 in the $3.500-3.555$ GeV/c^2 recoil-mass region are excluded.

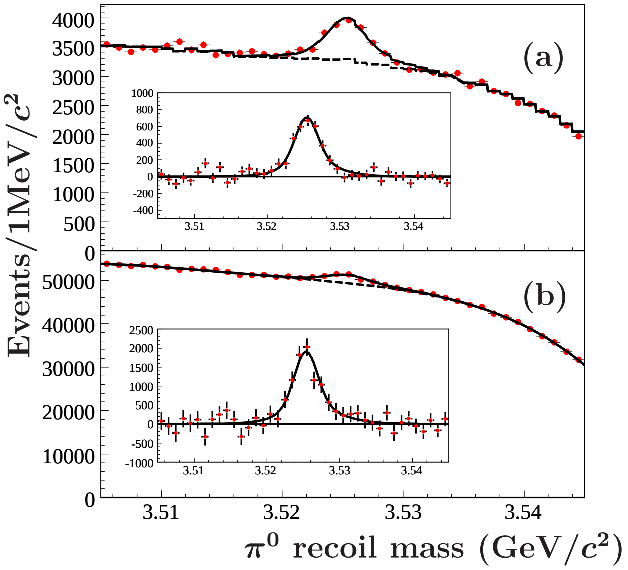

FIG. 1. (a) The π^0 recoil mass spectrum and fit for the $E1$-tagged analysis of $\psi' \to \pi^0 h_c, h_c \to \gamma\eta_c$; (b) the π^0 recoil mass spectrum and fit for the inclusive analysis of $\psi' \to \pi^0 h_c$. Fits are shown as solid lines, background as dashed lines. The insets show the background-subtracted spectra.

The π^0 recoil mass spectra (Fig. 1) are fitted by an unbinned maximum likelihood method. Because of its lower background, the $E1$-tagged fit is used to extract the mass and width of the h_c, which are then fixed for the inclusive fit. For the $E1$-tagged fit, the signal is parameterized as a Breit-Wigner function with the mass and width free, convoluted with a detector resolution function obtained from MC simulation. The background shape is obtained from the π^0 recoil mass spectrum with no photons in the signal region of $400 - 600$ MeV and at least one good photon in the signal-free region below 400 MeV and above 600 MeV. The upper and lower limits of the accepted ranges were varied to assess possible systematic uncertainty. The results of this fit are a yield of $E1$-tagged h_c decays of $N^{E1} = 3679 \pm 319$ and h_c parameters $M(h_c) = 3525.40 \pm 0.13$ MeV/c^2 and $\Gamma(h_c) = 0.73 \pm 0.45$ MeV, where the errors are statistical. The fit quality assessed with the binned distribution of Fig. 1(a) is $\chi^2/d.o.f. = 33.5/36$ (p-value 58.8%), and the statistical significance of the h_c signal is 18.6σ. The fit of the inclusive π^0 spectrum in Fig. 1 (b) is performed similarly, except that the h_c mass and width are fixed and the background is described by a 4th-order Chebychev polynomial with all parameters free. The fit result for the inclusive h_c yield is $N^{inc} = 10353 \pm 1097$, with $\chi^2/d.o.f. = 24.5/34$ (p-value 88.4%) and 9.5σ statistical significance. The insets of Fig. 1 show the π^0 recoil-mass spectra with the fitted backgrounds subtracted.

The product branching ratio $\mathcal{B}_1(\psi' \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c)$ depends on the number of ψ' decays in the sample and the yield and detection efficiency for $E1$-tagged events (ϵ_{12}), as given by Eq. (1):

$$\mathcal{B}_1 \times \mathcal{B}_2 = \frac{N^{E1}}{\epsilon_{12} \times N(\psi')}. \tag{1}$$

The efficiency, determined with the signal MC, is $\epsilon_{12} = 7.57\%$. The branching ratios for the inclusive process $\mathcal{B}_1(\psi' \to \pi^0 h_c)$ and for the $E1$ transition $\mathcal{B}_2(h_c \to \gamma\eta_c)$ are related to the inclusive yield N^{inc} and the efficiencies for selecting h_c decays to $\gamma\eta_c$ (ϵ_1^{E1}) and to other final states (ϵ_1^{had}), as given by Eq. (2):

$$\mathcal{B}_1 = \frac{N^{inc}}{(\epsilon_1^{E1}\mathcal{B}_2 + \epsilon_1^{had}(1-\mathcal{B}_2)) \times N(\psi')}. \tag{2}$$

The detection efficiencies are $\epsilon_1^{E1} = 12.89\%$ and $\epsilon_1^{had} = 10.02\%$, respectively.

Using the numbers obtained above, we find $\mathcal{B}_1 = (8.4 \pm 1.3) \times 10^{-4}$, $\mathcal{B}_2 = (54.3 \pm 6.7)\%$, and $\mathcal{B}_1 \times \mathcal{B}_2 = (4.58 \pm 0.40) \times 10^{-4}$, where the errors are statistical only.

Systematic uncertainties for our measurements are summarized in Table I. Dominant sources are the treatment of the background in the recoil-mass fits and imperfect modeling of photon and π^0 detection in BESIII.

For the inclusive measurements, we explore sensitivity to the background parameterization by changing the order of the Chebychev polynomial from 4 to 5 and by considering alternative fitting functions based on MC simulations. For the $E1$-tagged measurements, alternative background shapes are obtained by varying the photon-energy boundaries defining the signal-free sample. Systematic uncertainties are set based on the largest changes observed in the measured quantities for all alternative backgrounds. The uncertainty due to the choice of the fitting range is evaluated by changing from 3505−3545 MeV/c^2 to 3500−3540 MeV/c^2 and 3510−3545 MeV/c^2.

Our analysis depends on accurate simulation of the detector response for shower energy measurements. The calibration uncertainty in the photon-energy scale is estimated to be ±0.4% by studying $\psi' \to \gamma\chi_{c1,2}$ and radiative Bhabha events. Studies of the energy spectra for photons in radiative ψ' decays show the energy resolution to be larger in data than MC by 4% for $\psi' \to \gamma\chi_{c1}$ and 2% for $\psi' \to \gamma\chi_{c2}$. We estimate systematic uncertainties due to the energy measurement by determining the changes in results after adjusting the photon response accordingly. We also did more extensive studies allowing for correlations among the different effects by simultaneously varying the energy scale, energy resolution, reconstructed position, and error matrix of the photon measurement. These studies gave a somewhat larger uncertainty for the h_c mass. The maximum observed change in the h_c mass is 0.13 MeV/c^2, which we take as its systematic uncertainty due to the energy measurement.

We estimate the uncertainty in simulating the $E1$-photon selection efficiency with $e^+e^- \to \gamma e^+e^-$ events, studying the ratio E_{meas}/E_{exp} of measured to expected photon energy, where E_{exp} is determined from the e^+e^- recoil energy. Comparing this ratio between data and MC provides a smearing function that is used as an alternative to the standard line shape. This modification results in a 2% change in the efficiency for $E1$-photon selection, and associated systematic uncertainties are obtained by varying ϵ_{12} by ±2%.

The photon detection efficiency and resolution also enter through the uncertainty in the reconstruction efficiency of the π^0 selection, which was determined to be ±3% by analyzing $\psi' \to \pi^0\pi^0 J/\psi, J/\psi \to l^+l^-$ in data and MC. Systematic errors are obtained by varying the efficiencies ϵ_1^{E1}, ϵ_1^{had} and ϵ_{12} simultaneously by ±3%. The efficiency uncertainty due to the simulation of the number of π^0s, which is mainly generator dependent, is estimated by a comparison between data and MC for ψ' decays, which we assume behave similarly to h_c decays. Variations in the efficiencies ϵ_1^{E1}, ϵ_1^{had} and ϵ_{12} are determined by the equation $\Delta\epsilon = \sum \epsilon_i \times \Delta N_i^{\pi^0}$, where $\Delta\epsilon$ denotes the difference between the efficiencies from data and MC simulations, ϵ_i is the efficiency when $N_{\pi^0} = i$ in the event, and $\Delta N_i^{\pi^0}$ is the relative difference for $N_{\pi^0} = i$. The systematic errors are obtained by simultaneously varying ϵ_1^{E1}, ϵ_1^{had} and ϵ_{12} by $\Delta\epsilon_1^{E1}$, $\Delta\epsilon_1^{had}$ and $\Delta\epsilon_{12}$.

Other sources of systematic uncertainties are found to be small. The uncertainty in the efficiency of the requirement on the number of charged tracks arises from uncertainty in simulating h_c decays and in modeling charged-particle detection. We find that 9% of simulated $h_c \to \gamma\eta_c$ events and 5.5% of other h_c decays fail the requirement on the number of charged tracks. For generic ψ' decays we find relative differences between data and MC in the corresponding efficiencies to be less than 10%. Assuming similar consistency for h_c decays, we simultaneously vary ϵ_{12} and ϵ_1^{E1} by 9% × 10%=0.9%, and ϵ_1^{had} by $5.5\% \times 10\% = 0.55\%$ to estimate the resulting systematic uncertainty in the branching ratios. Systematic uncertainties associated with the requirements to suppress ψ' to J/ψ hadronic transitions are shown to be negligible for all measurements by varying the excluded recoil-mass range. The ±4% uncertainty in the number of ψ' in our sample makes a small contribution to the overall uncertainty for the measured branching ratios. Uncertainty in the ψ' mass has negligible effect. Assumptions for the η_c mass and width in signal simulations affect detection efficiencies through the $E1$-photon energy. Associated systematic uncertainties are set by varying these parameters within errors, recalculating efficiencies, and determining

TABLE I. Summary of systematic errors.

Source	$M(h_c)$(MeV/c^2)	$\Gamma(h_c)$(MeV)	$\mathcal{B}_1(10^{-4})$	$\mathcal{B}_1 \times \mathcal{B}_2(10^{-4})$	$\mathcal{B}_2$(%)
Background shape and fit range	0.11	0.23	0.4	0.22	4.4
Energy scale, position reconstruction and 1-C fit	0.13	0.06	0.5	0.10	2.1
Energy resolution	0.00	0.15	0.2	0.03	1.0
Background veto	0.05	0.03	0.0	0.03	0.3
π^0 efficiency	0.00	0.00	0.3	0.14	0.0
$E1$ photon efficiency	0.00	0.00	0.0	0.10	1.2
Number of π^0	0.00	0.00	0.6	0.35	0.6
Number of charged tracks	0.00	0.00	0.1	0.06	0.1
$N(\psi')$	0.00	0.00	0.4	0.19	0.0
$M(\psi')$	0.03	0.02	0.0	0.00	0.0
$M(\eta_c)$ and $\Gamma(\eta_c)$	0.00	0.00	0.0	0.01	0.3
Total systematic error	0.18	0.28	1.0	0.50	5.2

the maximum changes in the branching ratios.

We treat all sources of systematic uncertainty as uncorrelated and combine in quadrature to obtain the overall systematic uncertainties and the following results: $M(h_c) = 3525.40 \pm 0.13 \pm 0.18$ MeV/c^2, $\Gamma(h_c) = 0.73 \pm 0.45 \pm 0.28$ MeV ($<$ 1.44 MeV at 90% confidence), $\mathcal{B}(\psi' \to \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$, $\mathcal{B}(\psi' \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c) = (4.58 \pm 0.40 \pm 0.50) \times 10^{-4}$, and $\mathcal{B}(h_c \to \gamma\eta_c) = (54.3 \pm 6.7 \pm 5.2)\%$. In all cases the first errors are statistical and the second systematic. Our measurements of $\mathcal{B}(\psi' \to \pi^0 h_c)$ and $\mathcal{B}(h_c \to \gamma\eta_c)$ and information about the h_c width are the first experimental results for these quantities. The determinations of $M(h_c)$ and $\mathcal{B}(\psi' \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c)$ are consistent with published CLEO results [11] and of comparable precision.

Comparing our results for $h_c \to \gamma\eta_c$ to the $E1$ radiative transitions $\chi_{c1} \to \gamma J/\psi$, we find that the branching ratio $\mathcal{B}(h_c \to \gamma\eta_c)$ is consistent with the PDG value for $\mathcal{B}(\chi_{c1} \to \gamma J/\psi) = (36.0 \pm 1.9)\%$ [6]; the total widths $\Gamma(\chi_{c1})$ and $\Gamma(h_c)$ are also consistent. Our result for $\mathcal{B}(h_c \to \gamma\eta_c)$ is close to the prediction of Ref. [4] (38%) and the NRQCD prediction of Ref. [3] (41%). The branching ratio $\mathcal{B}(\psi' \to \pi^0 h_c)$ is consistent with the prediction of Ref. [3] ($(0.4 - 1.3) \times 10^{-3}$), and the total width $\Gamma(h_c)$ is consistent with the predictions of Refs. [3] and [5]. We find the $1P$ hyperfine mass splitting to be $\Delta\ M_{hf} \equiv \langle M(1^3P)\rangle - M(1^1P_1) = -0.10 \pm 0.13 \pm 0.18$ MeV/c^2, consistent with no strong spin-spin interaction.

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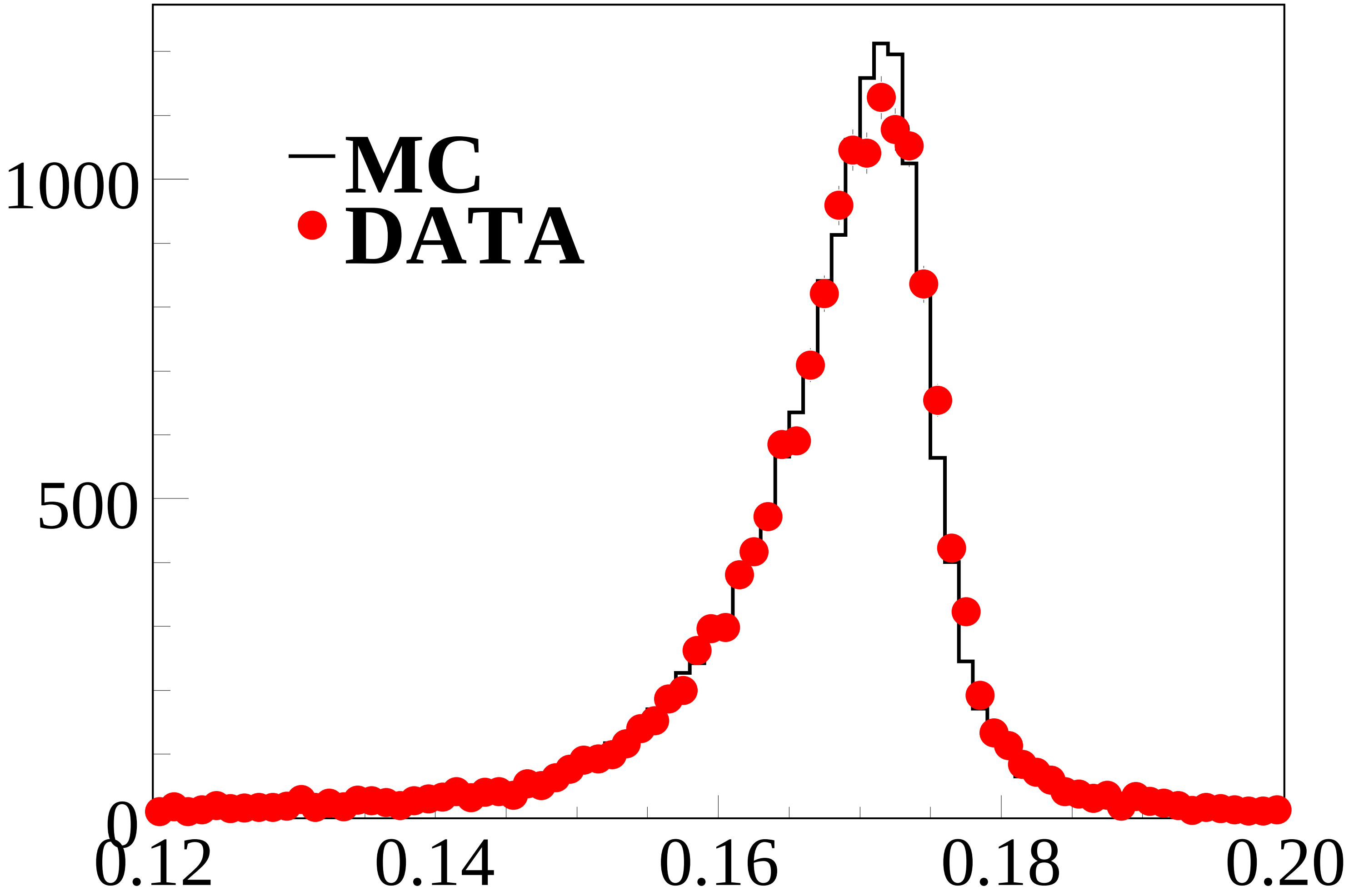
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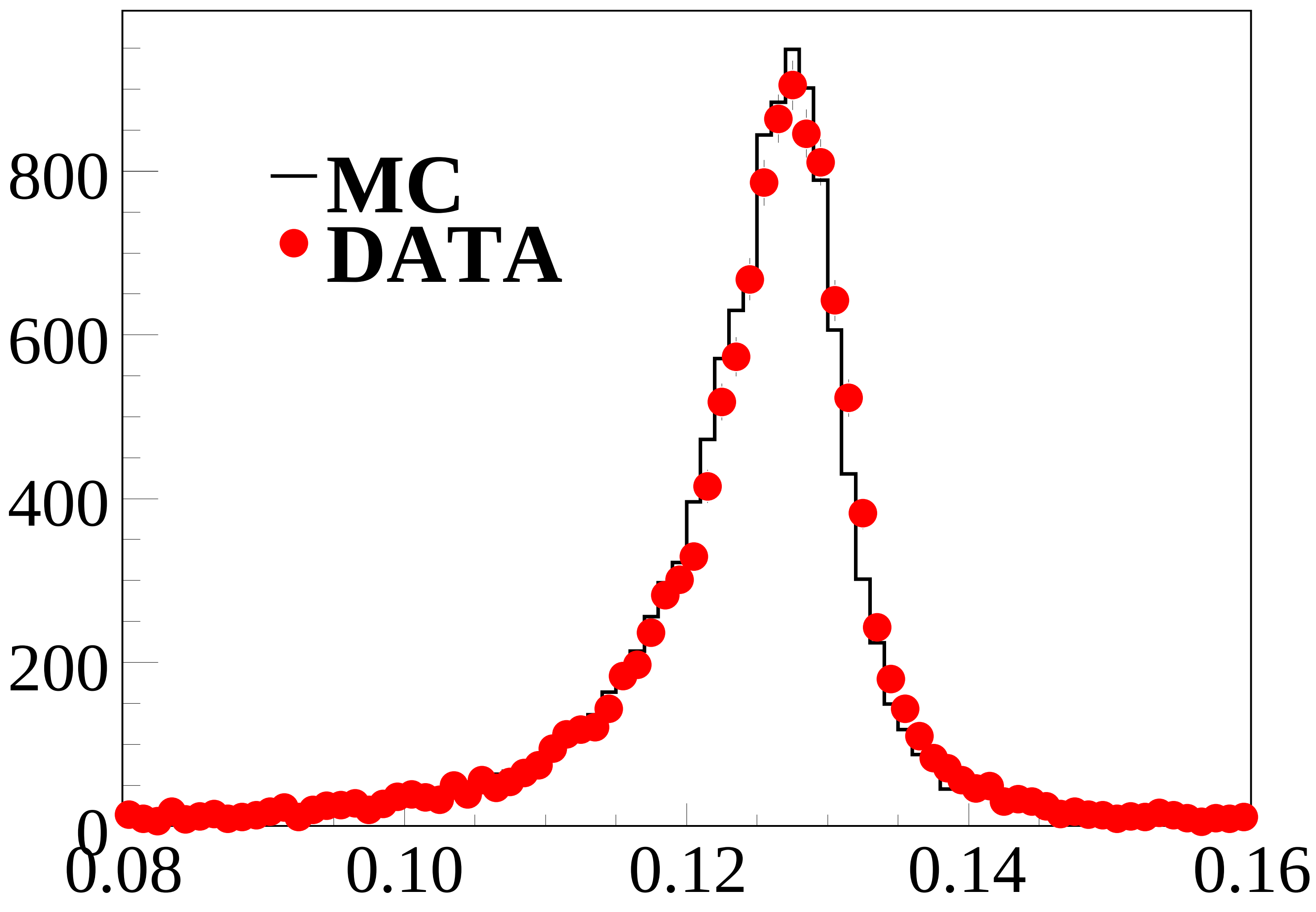
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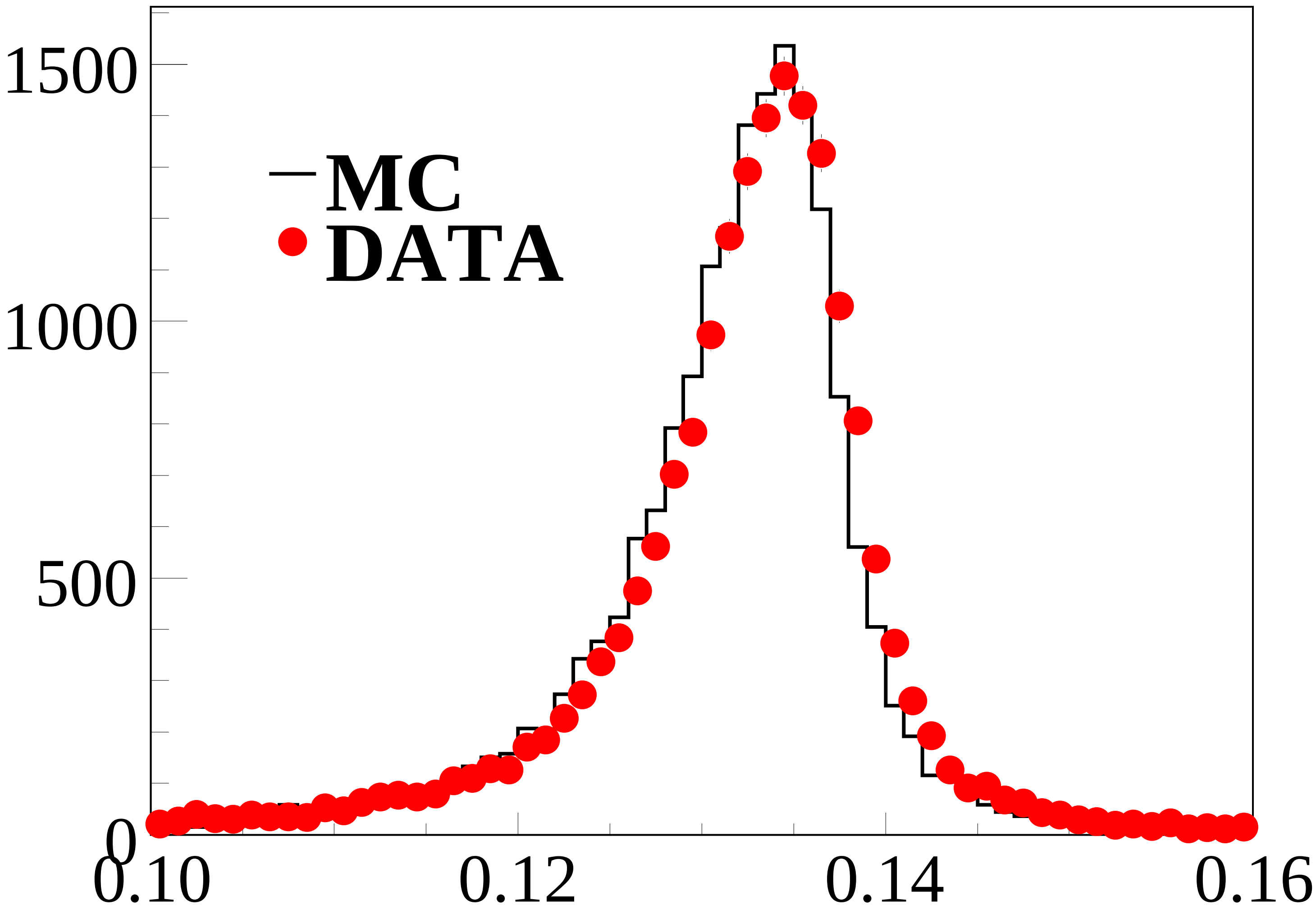
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