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Constraints on the χ_{c1} versus χ_{c2} polarizations in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$

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Abstract

The polarizations of promptly produced χ_{c1} and χ_{c2} mesons are studied using data collected by the CMS experiment at the LHC, in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$. The χ_c states are reconstructed via their radiative decays $\chi_c \to \text{J}/\psi\,\gamma$, with the photons being measured through conversions to e^+e^-, which allows the two states to be well resolved. The polarizations are measured in the helicity frame, through the analysis of the χ_{c2} to χ_{c1} yield ratio as a function of the polar or azimuthal angle of the positive muon emitted in the $\text{J}/\psi \to \mu^+\mu^-$ decay, in three bins of J/ψ transverse momentum. While no differences are seen between the two states in terms of azimuthal decay angle distributions, they are observed to have significantly different polar anisotropies. The measurement favors a scenario where at least one of the two states is strongly polarized along the helicity quantization axis, in agreement with nonrelativistic quantum chromodynamics predictions. This is the first measurement of significantly polarized quarkonia produced at high transverse momentum.

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*See Appendix B for the list of collaboration members

Quarkonium production is a benchmark for understanding how quarks combine into hadrons. The heaviness of c and b quarks makes it possible to describe the process in nonrelativistic quantum chromodynamics (NRQCD) [1–8], a framework valid when the quark velocities are small. This theory successfully described quarkonium cross sections measured [9] at high transverse momentum, p_{T}, by complementing the earlier color-singlet model [10, 11] with a superposition of several processes where the bound state originates from colored $\mathrm{Q\overline{Q}}$ pairs. In contrast to this complex model, the J/ψ, $\psi(2\mathrm{S})$, $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$, and $\Upsilon(3\mathrm{S})$ differential cross sections measured at central rapidity by ATLAS [12, 13] and CMS [14–16] have indistinguishable shapes as a function of p_{T}/M, where M is the meson mass [17, 18]. This universal momentum scaling pattern is also followed by the χ_{c1} and χ_{c2} states [19, 20]. The corresponding polarization measurements [21, 22] show that the five S-wave states are well compatible with being produced unpolarized, in contrast to the significant polarizations seen for the W and Z [23–30], Drell–Yan dileptons [31–36], and low-p_{T} quarkonia [37, 38]. The lack of polarization of high-p_{T} vector quarkonia was a long-standing challenge for NRQCD [39], until recent global-fit analyses [4, 40, 41] showed that cross sections and polarizations can be consistently described, unveiling a delicate compensation between terms in the factorization expansion [42]. Among the measurements mentioned above, one piece is clearly missing: the χ_{c1} and χ_{c2} polarizations. Contrary to what happens for the vector states, predicting the χ_{c1} and χ_{c2} polarizations is rather simple within NRQCD, where they are unequivocally determined by a single color-octet parameter, which can be extracted from the χ_{c2} to χ_{c1} cross section ratio. The analysis of the measured ratios [19, 20] provides a clear result: the polarizations of the two states should be opposite and almost maximal [43] (a result also reached in a parameter-free singlet-only model [44]). Finding that these P-wave states have similar polarizations (following the vector quarkonia in the polarizations, as in the cross sections) would be a challenge to NRQCD, where the two (necessarily different) singlet terms play a leading role.

This Letter reports the first measurement of the polarizations of promptly produced χ_{c1} and χ_{c2} mesons, using proton-proton (pp) data collected at the LHC by the CMS experiment at a center-of-mass energy of $\sqrt{s} = 8\,\mathrm{TeV}$, corresponding to an integrated luminosity of $19.1\,\mathrm{fb}^{-1}$. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A detailed description of the CMS detector, together with a definition of the coordinate system used and relevant kinematic variables, can be found in Ref. [45].

The event sample was collected with a two-level trigger system [46]. At level-1, custom hardware processors select events with two muons. The high-level trigger requires an opposite-sign muon pair of invariant mass 2.8–3.35 GeV, a dimuon vertex fit χ^2 probability larger than 0.5%, and a distance of closest approach between the two muons smaller than 0.5 cm. The trigger also requires that the dimuon has $p_{\mathrm{T}} > 7.9\,\mathrm{GeV}$ and rapidity $|y| < 1.25$. The offline reconstruction requires two oppositely charged muons matching those that triggered the detector readout. The muon tracks must pass high-purity track quality requirements [47], have $p_{\mathrm{T}} > 3.5\,\mathrm{GeV}$, $|\eta| < 1.6$, and fulfill the soft muon identification requirements [48], which imply, in particular, more than five hits in the silicon tracker, of which at least one is in the pixel layers. The muons are combined to form J/ψ candidates, which are kept for further processing if $|y| < 1.2$ and $8 < p_{\mathrm{T}} < 30\,\mathrm{GeV}$. Promptly produced J/ψ mesons are selected by requiring the distance between the dimuon vertex and the interaction point be smaller than 2.5 times its uncertainty.

The analysis uses $\chi_{\mathrm{c}} \to \mathrm{J}/\psi\,\gamma$ decays, with the J/ψ decaying to a dimuon. The photons are detected through their conversions to e^+e^- in the beam pipe and in the material of the silicon tracker, starting from two oppositely charged tracks, of which one has at least four tracker hits and the other at least three. The tracks must have a conversion vertex at least 1.5 cm away from the beam axis and a χ^2 probability of the kinematic fit imposing zero mass and a common vertex that exceeds 0.05%. A more detailed account of the reconstruction and selection procedures is given in Refs. [20, 49]. The photons must have $p_T > 0.4$ GeV and $|\eta| < 1.5$. If the distance along the beam axis between the dimuon vertex and the extrapolated photon trajectory is smaller than 5 mm, a χ_c candidate is formed through a kinematic fit of the dimuon-photon system, constraining the dimuon mass to the J/ψ mass [50], the dielectron mass to zero, and requiring that the two muons and the photon have a common vertex. Only χ_c candidates with a fit χ^2 probability larger than 1% and invariant mass between 3.2 and 3.75 GeV are kept in the evaluation of the χ_{c1} and χ_{c2} yields. After all selection criteria, around 103 000, 106 000, and 45 000 χ_c candidates are kept in the J/ψ p_T bins 8–12, 12–18, and 18–30 GeV, respectively.

The seemingly natural way to measure the χ_{c1} and χ_{c2} polarizations is to determine the angular distribution of the considered χ_c decay; in the present case, this means the distribution of the photon direction in the χ_c rest frame. However, that distribution depends not only on the χ_c angular momentum composition, but also, and possibly in a very significant way, on the (poorly known) contributions of photons with large orbital angular momentum ($J^\gamma > 1$). A cleaner determination of the χ_c polarization is obtained by measuring the dimuon angular decay distribution in the rest frame of the daughter J/ψ [51]. It is crucial to choose as polarization axis for the J/ψ decay not the J/ψ direction in the χ_c rest frame, as usually done in cascade decays, but rather any axis (center-of-mass helicity or Collins–Soper [52], for instance) defined in terms of the beam momenta in the J/ψ rest frame and ignoring its origin, as if it were observed inclusively. With the latter choice, the shape of the dimuon distribution represents an exact "clone" of the photon distribution in the χ_c rest frame, as it would be if it were undressed of its higher-order multipole contributions. This method provides, therefore, a full sensitivity to the angular momentum state of the χ_c, resulting in a (theoretically and experimentally) cleaner polarization measurement. The present analysis is performed in the center-of-mass helicity frame [53] and does not use the measured photon momentum, except to select, through the J/$\psi\,\gamma$ invariant mass distribution, the J/ψ mesons resulting from χ_{c1} or χ_{c2} decays. The dimuon angular decay distribution is parametrized with the function $1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi$, where ϑ and φ are the polar and azimuthal coordinates of the positive muon direction in the J/ψ rest frame, the system of axes being defined with z in the direction of the polarization axis and y perpendicular to the production plane. The χ_c angular momentum composition is encoded in the shape parameters λ_ϑ, λ_φ, and $\lambda_{\vartheta\varphi}$, whose values depend on the choice of polarization frame but must always be within certain physical domains [51], narrower than the parameter space of inclusive vector-particle production [54, 55]. The relation between the shape parameters and the polarization configuration depends on the quarkonium state. For example, $\lambda_\vartheta = +1$ indicates $J_z = \pm 1$ for the J/ψ, $J_z = 0$ for the χ_{c1}, and $J_z = +2$ for the χ_{c2}; conversely, states in the $J_z = 0$ angular momentum configuration lead to $\lambda_\vartheta = -1$ for the J/ψ, $\lambda_\vartheta = +1$ for the χ_{c1}, and $\lambda_\vartheta = -0.6$ for the χ_{c2}.

The measurement of the λ parameters implies knowing the shapes of the χ_{c1} and χ_{c2} differential cross sections as functions of $|\cos\vartheta|$ and φ, which crucially depend on the accuracy of the corrections of the muon and photon detection efficiencies. These efficiencies change by an order of magnitude in the low p_T bin covered by the present analysis and shape variations within their uncertainties lead to very different λ_ϑ values. Increasing the muon p_T threshold to avoid the turn-on region of the efficiency function would imply a strong reduction in the number of selected events and a smaller coverage of the $|\cos\vartheta|$ variable, effectively preventing the evaluation of λ_ϑ. Instead, the difference between the χ_{c1} and χ_{c2} polarizations, measured from the angular dependence of the χ_{c2}/χ_{c1} yield ratio, is essentially insensitive to the detection efficiencies, given that they cancel to a large extent in that ratio.

The $|\cos\vartheta|$ and φ dependences of the yield ratio are independently determined in three J/ψ p_T bins: 8–12, 12–18, and 18–30 GeV. For the study of possible azimuthal dependences of the χ_{c2}/χ_{c1} yield ratio, the events are split into subsamples corresponding to six equidistant φ bins between 0 and 90°. Folding φ into the first quadrant reduces the effect of the statistical fluctuations without any loss of information, given the four-fold φ symmetry that the angular distributions obey. For each p_T bin, the six J/$\psi\,\gamma$ invariant mass distributions are simultaneously fitted with an unbinned maximum likelihood fit. In the mass fit model, identical for all φ bins, each of the χ_{c1} and χ_{c2} signal peaks is represented by a double-sided Crystal Ball (CB) function [56], which complements a Gaussian core distribution with lower and upper power-law tails. The underlying combinatorial background, reflecting uncorrelated J/$\psi\,\gamma$ associations, is parametrized by an exponential function multiplied by a term that provides a low-mass turn-down, $(1 + \mathrm{erf}((m - \mu^{\mathrm{bg}})\,/\,\sigma^{\mathrm{bg}}))\,\exp(-m/\lambda^{\mathrm{bg}})$, where m is the J/$\psi\,\gamma$ invariant mass and μ^{bg}, σ^{bg}, and λ^{bg} are shape parameters. Although the results of this analysis are insensitive to the presence of a small peak reflecting the χ_{c0} decays, the fit model includes this background term, represented by a Breit–Wigner convolved with a Gaussian resolution function. To minimize fit instabilities, the χ_{c0} shape and yield parameters are determined from the corresponding parameters of the χ_{c1} term. The simultaneous fit has the advantage of reducing by a factor of six the number of free parameters defining the shapes of the signal and background mass models, by requiring that those parameters are independent of φ, an assumption validated by studies of simulated and measured event samples.

To study the polar angle dependence of the χ_{c2}/χ_{c1} yield ratio, 6, 7, or 5 $|\cos\vartheta|$ bins are considered, depending on the p_T bin. The $|\cos\vartheta|$ coverage is smaller in the lowest p_T bin (up to 0.45 instead of up to 0.625) because those events are the ones most affected by the single-muon p_T cut. Analogously to the procedure just described for the φ dimension, the χ_{c2}/χ_{c1} yield ratios are obtained as a function of $|\cos\vartheta|$ through a simultaneous fit of the J/$\psi\,\gamma$ invariant mass distributions. In this case, however, some of the shape parameters are not required to be independent of $|\cos\vartheta|$. More details can be found in Ref. [57].

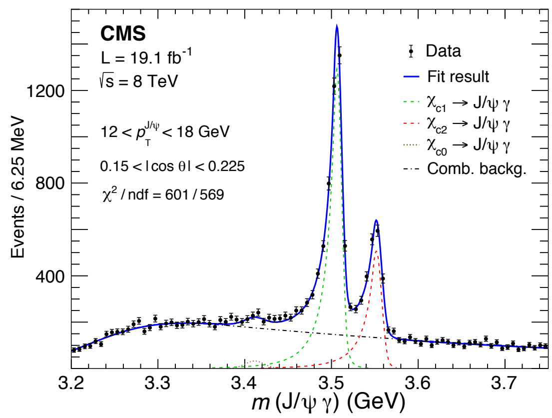

Figure 1: Example of a fitted J/$\psi\,\gamma$ invariant mass distribution, for the $0.15 < |\cos\vartheta| < 0.225$ bin, in the 12–18 GeV p_T bin. The vertical bars on the points indicate the statistical uncertainties. The lines show the various fit contributions.

Figure 1 shows one of the simultaneously fitted J/$\psi\,\gamma$ invariant mass distributions. The two signal peaks are well resolved, with widths around 6 MeV, consistent with the predictions from simulation. All of the fitted χ_c mass distributions show good fit qualities, as judged from the

χ^2 between the binned distributions and the fitted functions, the worst case giving $\chi^2 = 601$ for 569 degrees of freedom (ndf).

For each bin in J/ψ p_T and $|\cos\vartheta|$, or φ, the fitted J/$\psi\,\gamma$ invariant mass distributions provide functions reflecting the probability that an event of mass m is a χ_{c1} or a χ_{c2}. The χ_{c1} and χ_{c2} yields, corrected for acceptance and efficiencies, are then computed as the sums, over all events in that bin of J/ψ p_T and $|\cos\vartheta|$, or φ, of the product between the corresponding probabilities and the weights $1/\mathcal{A}_J(|\cos\vartheta|, \varphi, p_T)$, where $\mathcal{A}_J(|\cos\vartheta|, \varphi, p_T)$ are the acceptance times efficiency three-dimensional maps, independently evaluated for each χ_{cJ} state with large samples of simulated events. By correcting the detector acceptance and efficiency effects on an event-by-event basis, with weights depending on three dimuon observables ($|\cos\vartheta|$, φ, and p_T), this procedure is immune to integration biases affecting certain one-dimensional analyses [58]. Simulation studies have shown that, if the three-dimensional correction maps are sufficiently fine-grained, the results do not depend on the polarization scenario nor on the p_T distributions assumed in the simulation, and that all physically allowed differences between the χ_{c1} and χ_{c2} polarizations, in any frame, can be reliably determined from the dependences of the χ_{c2}/χ_{c1} yield ratios on $|\cos\vartheta|$ and φ.

The corrected ratios are reported in Tables A.1 and A.2 of Appendix A, and shown in Fig. 2, where it can be seen that the uncorrected and corrected values are almost identical, apart from normalization factors irrelevant for the determination of the polar and azimuthal anisotropies.

Several sources of potential systematic effects have been considered, by redoing the analysis with different inputs and comparing the obtained results with the nominal ones. The results are insensitive to variations of the thresholds used to reject the nonprompt contamination from b hadron decays, estimated to be around 5%, or events with a poor kinematic vertex fit quality in the reconstruction of the χ_c candidates. The fits of the mass distributions were redone using alternative options for the low- and high-mass tails of the double-sided CB functions, and by varying the combinatorial background description, both by changing the floating parameters of the nominal function and by using the alternative function $(x - x_0)^\lambda \exp(\nu(x - x_0))$, where ν is left free, λ is fitted to a constant, and $x_0 = 3.2\,\mathrm{GeV}$, a value determined in fits to the background-only mass distributions obtained by excluding the 3.37–3.6 GeV region. The sensitivity of the results to the acceptance and efficiency corrections was evaluated by redoing the analysis with maps computed with alternative single-muon and photon detection efficiencies, as well as with simulated samples generated with different p_T/M shapes for each of the two χ_c states. All effects lead to similar variations in the yields of the two states and cancel, to a large extent, in the χ_{c2}/χ_{c1} ratio, apart from a normalization shift that has no impact on the angular anisotropies. The total systematic uncertainties are less than 20% of the statistical ones.

The χ_{c2} to χ_{c1} yield ratios as a function of φ, shown in Fig. 2 (left), are compatible with being flat, excluding large differences in azimuthal anisotropy, as exemplified by the two curves compared to the data points in the second p_T bin. These curves represent the simplest conceivable polarization hypotheses leading to large azimuthal effects in the helicity frame: χ_{c1} and χ_{c2} have maximally different polar anisotropies in the Collins–Soper frame, corresponding to specific alignments of their angular momentum vectors along the collision direction ($J_z^{\chi_{c1}} = J_z^{\chi_{c2}} = 0$ and $J_z^{\chi_{c1}} = \pm 1$, $J_z^{\chi_{c2}} = \pm 2$, for the dotted and dash-dotted curve, respectively). In fact, the change from the Collins–Soper to the helicity quantization axis is almost a 90° rotation, transforming polarized distributions into azimuthally anisotropic ones. This uniform φ behavior confirms the choice of the helicity axis as the one that should reflect most closely the natural alignment of the angular momentum vector, maximizing the polar anisotropy effects.

In Fig. 2 (right) the measured $|\cos\vartheta|$ dependence of the χ_{c2}/χ_{c1} ratio is compared to the analytic

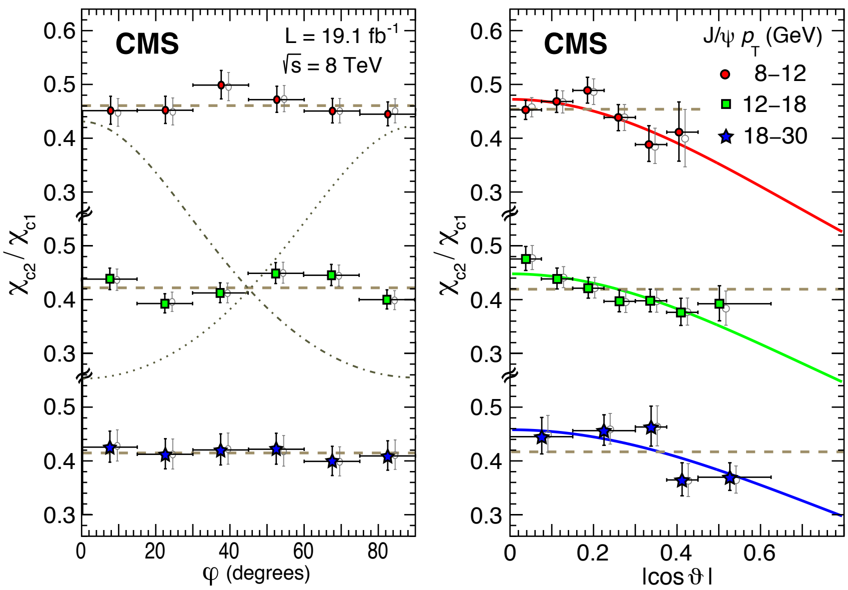

Figure 2: The χ_{c2}/χ_{c1} yield ratio vs. φ (left) and $|\cos\vartheta|$ (right), for the three J/ψ p_T bins. The grey markers (slightly shifted horizontally) show the values before acceptance and efficiency corrections, scaled vertically for an easier shape comparison. The vertical bars represent the statistical uncertainties and the horizontal bars the bin widths. The solid and dashed curves show, respectively, the NRQCD [43] and unpolarized scenarios. The dotted and dash-dotted curves illustrate maximally different natural polarizations in the Collins–Soper frame, leading to large differences in azimuthal anisotropy.

expression $(1 + \lambda_\vartheta^{\chi_{c2}} \cos^2\vartheta) / (1 + \lambda_\vartheta^{\chi_{c1}} \cos^2\vartheta)$. Two scenarios are considered. The unpolarized scenario, $\lambda_\vartheta^{\chi_{c1}} = \lambda_\vartheta^{\chi_{c2}} = 0$ independently of p_T, represented in Fig. 2 (right) by the dashed flat lines, gives a poor description of the data. A fit with free normalizations leads to $\chi^2/\text{ndf} = 31/15$, corresponding to a χ^2 probability of 0.9%. The NRQCD scenario [43], where $\lambda_\vartheta^{\chi_{c1}} = 0.72$, 0.65, and 0.56, and $\lambda_\vartheta^{\chi_{c2}} = -0.48$, -0.35, and -0.19, for the average p_T values in each of the three bins, agrees well with the data: $\chi^2/\text{ndf} = 13/15$, corresponding to $P(\chi^2) = 58\%$.

Figure 3 shows the polar anisotropy parameters $\lambda_\vartheta^{\chi_{c1}}$ and $\lambda_\vartheta^{\chi_{c2}}$ derived from the measured $|\cos\vartheta|$ dependence of the χ_{c2}/χ_{c1} ratio, combining the three p_T bins. The contours in the $\lambda_\vartheta^{\chi_{c1}}$ vs. $\lambda_\vartheta^{\chi_{c2}}$ plane are obtained by scanning the two λ_ϑ parameters and the three normalizations to evaluate the χ^2 profiles corresponding to the 68.3, 95.5, and 99.7% confidence levels. The unpolarized scenario ($\lambda_\vartheta^{\chi_{c1}} = \lambda_\vartheta^{\chi_{c2}} = 0$), as well as more than half of the physically allowed region, including all cases where $\lambda_\vartheta^{\chi_{c2}} \geq \lambda_\vartheta^{\chi_{c1}}$, are outside the 99.7% contour. In terms of specific pure angular momentum configurations, it can be seen that, in particular, the cases $J_z^{\chi_{c2}} = \pm 2$ and $J_z^{\chi_{c1}} = J_z^{\chi_{c2}} = \pm 1$ are strongly disfavored.

The correlation between the $\lambda_\vartheta^{\chi_{c1}}$ and $\lambda_\vartheta^{\chi_{c2}}$ parameters can be accurately expressed through a simple parametrization: $\lambda_\vartheta^{\chi_{c2}} = (-0.94 + 0.90\,\lambda_\vartheta^{\chi_{c1}}) \pm (0.51 + 0.05\,\lambda_\vartheta^{\chi_{c1}})$, $(-0.76 + 0.80\,\lambda_\vartheta^{\chi_{c1}}) \pm (0.26 + 0.05\,\lambda_\vartheta^{\chi_{c1}})$, and $(-0.78 + 0.77\,\lambda_\vartheta^{\chi_{c1}}) \pm (0.26 + 0.06\,\lambda_\vartheta^{\chi_{c1}})$, for the three consecutive p_T bins. These expressions can be used for direct comparisons to theoretical scenarios.

Figure 4 shows, as a function of p_T/M of the J/ψ (equal on average to the p_T/M of the χ_{c1} and χ_{c2} mothers [17]), the $\lambda_\vartheta^{\chi_{c2}}$ values measured when $\lambda_\vartheta^{\chi_{c1}}$ is fixed to the predictions of the

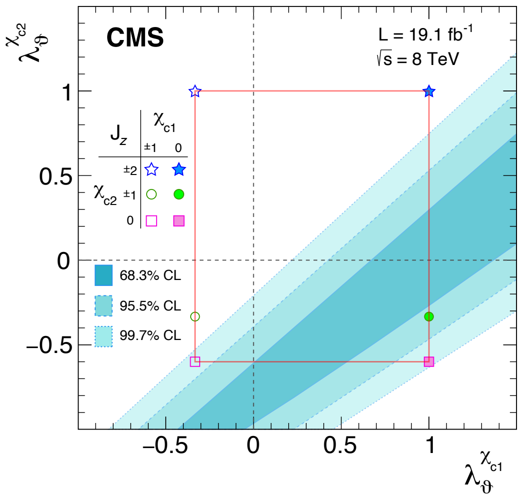

Figure 3: Two-dimensional $\lambda_\vartheta^{\chi_{c2}}$ vs. $\lambda_\vartheta^{\chi_{c1}}$ contours, at 68.3, 95.5, and 99.7% confidence levels (CL), measured combining the three J/ψ p_T bins. The physically allowed region (red rectangle) and six pure angular momentum configurations (markers) are also shown. The crossing of the two dashed lines represents the unpolarized case.

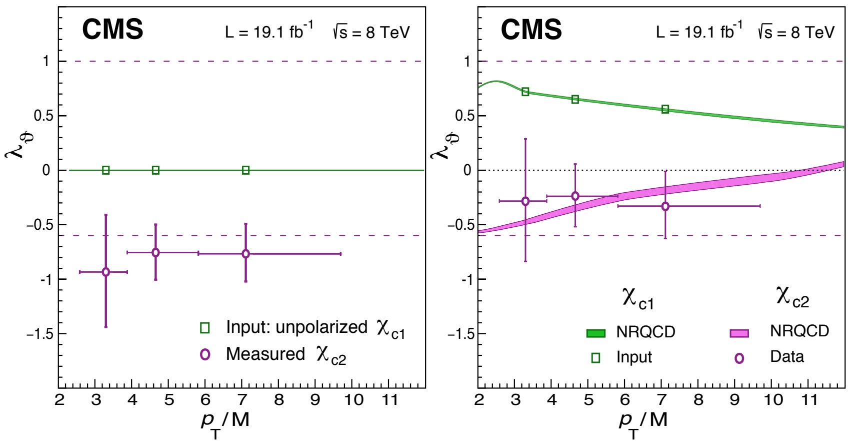

Figure 4: The $\lambda_\vartheta^{\chi_{c2}}$ values (circles) measured when the $\lambda_\vartheta^{\chi_{c1}}$ values (squares) are fixed to the unpolarized (left) or the NRQCD (right) scenarios (green curves), as a function of p_T/M of the J/ψ. The purple band on the right is the NRQCD prediction for $\lambda_\vartheta^{\chi_{c2}}$ [43], while in the unpolarized scenario $\lambda_\vartheta^{\chi_{c2}} = \lambda_\vartheta^{\chi_{c1}} = 0$. The markers are shown at the average p_T/M values in each bin, the vertical bars represent the total uncertainties, and the horizontal bars the bin widths. The dashed lines indicate the physically allowed range of $\lambda_\vartheta^{\chi_{c2}}$.

two scenarios already considered in Fig. 2. Setting $\lambda_\vartheta^{\chi_{c1}} = 0$ leads to $\lambda_\vartheta^{\chi_{c2}}$ values that are significantly different from zero. The NRQCD prediction is, instead, in good agreement with the measurement.

In summary, first experimental constraints on the polarizations of promptly produced χ_{c1} and χ_{c2} mesons have been obtained, using pp collisions at $\sqrt{s} = 8\,\text{TeV}$. The analysis uses the J/$\psi\,\gamma$ decay channel in three J/ψ p_T bins between 8 and 30 GeV. The measurement, made in the helicity frame, shows a significant difference between the polar anisotropy parameters $\lambda_\vartheta^{\chi_{c1}}$ and $\lambda_\vartheta^{\chi_{c2}}$, in agreement with the NRQCD prediction. This result is a new step in the experimental studies of quarkonium production and the first significant indication of kinematic differences between the various quarkonia.

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A Numerical values of the measured yield ratios

Table A.1: The ratio of the χ_{c2} to χ_{c1} yields, corrected for acceptance and efficiencies, vs. φ, in three J/ψ p_T ranges. The average φ values are also given.

J/ψ p_T (GeV)	φ (degrees)	$\langle\varphi\rangle$ (degrees)	χ_{c2}/χ_{c1}
8–12	0–15	7.8	$0.451^{+0.027}_{-0.025}$
	15–30	22.6	$0.452^{+0.026}_{-0.025}$
	30–45	37.6	$0.499^{+0.027}_{-0.026}$
	45–60	52.6	$0.472^{+0.025}_{-0.024}$
	60–75	67.6	$0.450^{+0.023}_{-0.022}$
	75–90	82.5	$0.445^{+0.023}_{-0.022}$
12–18	0–15	7.7	$0.438^{+0.021}_{-0.020}$
	15–30	22.5	$0.393^{+0.018}_{-0.017}$
	30–45	37.5	$0.412^{+0.019}_{-0.018}$
	45–60	52.4	$0.449^{+0.020}_{-0.019}$
	60–75	67.5	$0.445^{+0.020}_{-0.019}$
	75–90	82.5	$0.400^{+0.018}_{-0.017}$
18–30	0–15	7.6	$0.425^{+0.030}_{-0.028}$
	15–30	22.6	$0.412^{+0.028}_{-0.027}$
	30–45	37.5	$0.420^{+0.030}_{-0.028}$
	45–60	52.5	$0.421^{+0.030}_{-0.028}$
	60–75	67.6	$0.399^{+0.028}_{-0.026}$
	75–90	82.5	$0.409^{+0.028}_{-0.027}$

Table A.2: The ratio of the χ_{c2} to χ_{c1} yields, corrected for acceptance and efficiencies, vs. $|\cos\vartheta|$, in three J/ψ p_T ranges. The average $|\cos\vartheta|$ values are also given. Fitting these ratios to a flat function (unpolarized scenario) leads to $\chi^2/\text{ndf} = 7.2/5$, 13.5/6, and 10.3/4, respectively for the p_T ranges 8–12, 12–18, and 18–30 GeV; the corresponding values for the NRQCD prediction are 4.1/5, 4.9/6, and 4.2/4.

J/ψ p_T (GeV)	$\lvert\cos\vartheta\rvert$	$\langle\lvert\cos\vartheta\rvert\rangle$	χ_{c2}/χ_{c1}
8–12	0.000–0.075	0.037	$0.453^{+0.018}_{-0.018}$
	0.075–0.150	0.111	$0.468^{+0.021}_{-0.020}$
	0.150–0.225	0.185	$0.489^{+0.025}_{-0.024}$
	0.225–0.300	0.259	$0.439^{+0.024}_{-0.025}$
	0.300–0.375	0.332	$0.388^{+0.035}_{-0.031}$
	0.375–0.450	0.404	$0.411^{+0.056}_{-0.054}$
12–18	0.000–0.075	0.038	$0.476^{+0.023}_{-0.021}$
	0.075–0.150	0.113	$0.438^{+0.020}_{-0.019}$
	0.150–0.225	0.187	$0.421^{+0.020}_{-0.019}$
	0.225–0.300	0.262	$0.397^{+0.021}_{-0.019}$
	0.300–0.375	0.336	$0.398^{+0.022}_{-0.021}$
	0.375–0.450	0.409	$0.376^{+0.026}_{-0.024}$
	0.450–0.625	0.502	$0.392^{+0.033}_{-0.032}$
18–30	0.000–0.150	0.076	$0.445^{+0.036}_{-0.032}$
	0.150–0.300	0.225	$0.456^{+0.030}_{-0.027}$
	0.300–0.375	0.338	$0.463^{+0.039}_{-0.036}$
	0.375–0.450	0.412	$0.365^{+0.032}_{-0.030}$
	0.450–0.625	0.526	$0.370^{+0.027}_{-0.025}$

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60: Also at Ozyegin University, Istanbul, Turkey
61: Also at Izmir Institute of Technology, Izmir, Turkey
62: Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
63: Also at Marmara University, Istanbul, Turkey
64: Also at Milli Savunma University, Istanbul, Turkey
65: Also at Kafkas University, Kars, Turkey
66: Also at Istanbul Bilgi University, Istanbul, Turkey
67: Also at Hacettepe University, Ankara, Turkey
68: Also at Adiyaman University, Adiyaman, Turkey
69: Also at Vrije Universiteit Brussel, Brussel, Belgium
70: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
71: Also at IPPP Durham University, Durham, United Kingdom
72: Also at Monash University, Faculty of Science, Clayton, Australia
73: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
74: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
75: Also at Bingol University, Bingol, Turkey
76: Also at Georgian Technical University, Tbilisi, Georgia
77: Also at Sinop University, Sinop, Turkey
78: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
79: Also at Nanjing Normal University Department of Physics, Nanjing, China
80: Also at Texas A&M University at Qatar, Doha, Qatar
81: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea