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Deciphering the $X(3872)$ via its Polarization in Prompt Production at the CERN LHC

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Based on the hypothesis that the $X(3872)$ exotic hadron is a mixture of $\chi_{c1}(2P)$ and other states and that its prompt hadroproduction predominately proceeds via its $\chi_{c1}(2P)$ component, we calculate the prompt-$X(3872)$ polarization at the CERN LHC through next-to-leading order in α_s within the factorization formalism of nonrelativistic QCD, including both the color-singlet ${}^3P_1^{[1]}$ and color-octet ${}^3S_1^{[8]}$ $c\bar{c}$ Fock states. We also consider the polarization of the J/ψ produced by the subsequent $X(3872)$ decay. We predict that, under ATLAS, CMS, and LHCb experimental conditions, the $X(3872)$ is largely longitudinally polarized, while the J/ψ is largely transversely polarized. We propose that the LHC experiments perform such polarization measurements to pin down the nature of the $X(3872)$ and other X, Y, Z exotic states with nonzero spin.

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The discovery of the $X(3872)$ by Belle in 2003 [1], which soon afterward was confirmed by CDF [2], D0 [3], and BaBar [4], triggered the renaissance of hadron spectroscopy. Ever since then, many charmonium or charmonium-like states, named X, Y, Z, were discovered, and numerous theoretical studies were devoted to reveal their nature. We refer to Refs. [5, 6] as the latest reviews of experimental results and theoretical approaches, respectively. Among the X, Y, Z hadrons, the $X(3872)$ is the top highlighted state. CDF [7] and LHCb [8] have established the $J^{PC} = 1^{++}$ quantum numbers of the $X(3872)$, and the very precise world average of its mass is $m_X = 3871.69 \pm 0.17$ MeV [9]. On the theory side, however, we are still far away from a convincing, overall picture to explain all the measurements. The popular models on the market include charmonium [10], $D^{*0}\bar{D}^0/D^0\bar{D}^{*0}$ molecule [11], tetraquark [12], hybrid [13], or some quantum-mechanical mixtures thereof; see, e.g., Ref. [14] for reviews. At hadron colliders, the $X(3872)$ is most frequently produced promptly, as has been observed by CDF [2, 15] at the Fermilab Tevatron and by LHCb [16], CMS [17], and ATLAS [18] at the CERN LHC. Besides mass spectrum and decay modes, prompt production provides a complementary source of information on the nature of the $X(3872)$. For example, in our previous work [19], we showed that the pure $\chi_{c1}(2P)$ option of the $X(3872)$ can be excluded by analyzing its prompt hadroproduction rates in the framework of nonrelativistic-QCD (NRQCD) factorization [20], and we predicted the $\chi_{c1}(2P)$ component to be around 30% under the assumption that the $X(3872)$ state is a quantum mechanical mixture of a $\chi_{c1}(2P)$ and a $D^{*0}\bar{D}^0/D^0\bar{D}^{*0}$ molecule as proposed in Ref. [21]. The study of $X(3872)$ prompt production within NRQCD factorization was pioneered by Artoisenet and Braaten [22], who considered the color octet (CO) contribution, due to the $c\bar{c}$ Fock state ${}^3S_1^{[8]}$, at leading order (LO). Prompt $X(3872)$ hadroproduction was also studied in the molecular picture, and the cross section was found to greatly undershoot CDF data [23]. Although this problem could be remedied [24] by properly taking into account the rescattering mechanism [22], it is still under debate if the molecular picture can adequately describe all the experimental data [25]. Very recently, $X(3872)$ plus soft-pion production has been proposed to settle this issue [26].

Despite a concerted experimental and theoretical endeavor during the past decade, the quest for the ultimate classification of the $X(3872)$ and other X, Y, Z states remains one of the most tantalizing challenges of hadron spectroscopy at the present time. Since the total spin of the $X(3872)$ is 1, rather than 0, its polarization in prompt production is expected to be rather sensitive to its production mechanism and its internal structure. Moreover, the $X(3872)$ has a considerable branching fraction to decay into the J/ψ. Under the assumption that the total spin of the charm quark pair is preserved during the decay process, the polarization of the J/ψ from the decay of the prompt $X(3872)$ will help us to analyze the role of the $c\bar{c}$ pair inside the $X(3872)$. To decipher the as-yet inscrutable nature of the $X(3872)$, we thus propose in this Letter to measure at the LHC its polarization and that of the J/ψ that springs from it. Working in NRQCD factorization at next-to-leading order (NLO) in α_s, we provide here, for the first time, the respective theoretical predictions under the likely assumption that the prompt hadroproduction of the $X(3872)$ proceeds predominately via the $\chi_{c1}(2P)$ component of its wave function at short distances. By doing so, we correct a reproducible error, common to existing literature on the NLO NRQCD treatment of P-wave heavy-quark pair polarization, related to the implementation of phase space slicing [27, 28].

The observation that NRQCD factorization at NLO fails to yield a coherent description of the world data on J/ψ yield and polarization [27, 29] may not affect our present analysis. In contrast to the χ_{cJ} case relevant here, the color singlet (CS) contribution to direct J/ψ hadroproduction has not yet unfolded its leading power, proportional to $1/p_T^4$, at NLO [30]. This will only happen at next-to-next-to-leading order, where a new dominant CS production channel will open up, which will dynamically create an enhancement that is likely to exceed the parametric $O(\alpha_s)$ by orders of magnitude, with the potential to reconcile the J/ψ world data with NRQCD factorization. Furthermore, the ${}^3P_J^{[8]}$ CO channel, which contributes to S, but not P wave quarkonium production, is potentially very sensitive to next-to-next-to-leading-order corrections, owing to a cancellation between LO and NLO corrections [27, 31]. Finally, the J/ψ polarization problem [27, 29] is reduced to a tolerable level if one takes the point of view that data with $p_T < 10$ GeV should be disregarded to suppress contributions violating NRQCD factorization [32], the more so if the leading logarithms in p_T^2/m_c^2 are resummed [33].

Adopting the collinear parton model of QCD and NRQCD factorization, the spin density matrix of the differential cross section of prompt $X(3872)$ hadroproduction can be evaluated as

$$d\sigma_{ij}(AB \to X(3872) + \text{anything}) = \sum_{k,l,n} \int dxdy\, f_{k/A}(x) \times f_{l/B}(y)\, d\hat{\sigma}_{ij}(kl \to c\overline{c}[n] + \text{anything})\, \langle \overline{\mathcal{O}}^{X(3872)}[n] \rangle, \quad (1)$$

where $f_{k/A}(x)$ is the density function (PDF) of parton k with longitudinal-momentum fraction x inside hadron A, $d\hat{\sigma}_{ij}(kl \to c\overline{c}[n] + \text{anything})$ with $i,j = 0, \pm 1$ is the spin density matrix element of the respective partonic cross section, and $\langle \overline{\mathcal{O}}^{X(3872)}[n] \rangle = \langle \mathcal{O}^{\chi_{c1}(2P)}[n] \rangle |\langle \chi_{c1}(2P)|X(3872)\rangle|^2$, with $\langle \mathcal{O}^{\chi_{c1}(2P)}[n] \rangle$ being the long-distance matrix element (LDME) of the $c\overline{c}$ Fock state n inside the $\chi_{c1}(2P)$ and $\langle \chi_{c1}(2P)|X(3872)\rangle$ being the overlap of the physical $X(3872)$ and $\chi_{c1}(2P)$ wave functions. At LO in v^2, where v is the relative velocity in the motion of the $c\overline{c}$ pair, we have $n = {}^3P_1^{[1]}, {}^3S_1^{[8]}$, where ${}^{2S+1}L_J$ refers to the spectroscopic notation and the label in brackets indicates CS and CO configurations. The evaluation of $d\hat{\sigma}_{ij}(kl \to c\overline{c}[n] + \text{anything})$ at NLO in NRQCD proceeds as in Ref. [27] upon the correction mentioned above. The production of polarized J/ψ's via the feed down of promptly hadroproduced $X(3872)$'s may be treated in one sweep, adopting the formalism outlined in Ref. [34]. NLO NRQCD polarization studies for promptly hadroproduced χ_{c1}'s and χ_{c2}'s may be found in Refs. [33, 35].

The polarizations of the $X(3872)$ and J/ψ can be measured by analyzing the angular distributions of their decay products. The J/ψ is easily reconstructed by its decay to a lepton pair l^+l^-, and the distribution in the

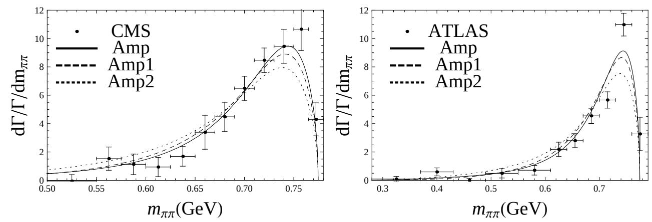

FIG. 1: The $m_{\pi\pi}$ distributions of $\Gamma(X(3872) \to J/\psi\pi^+\pi^-)$ measured by CMS [17] (left panel) and ATLAS [18] (right panel), normalized to unity across the experimental $m_{\pi\pi}$ ranges, are compared with our theoretical predictions based on $A_{\mu_1}^1$ (dashed lines), $A_{\mu_1}^2$ (dotted lines), and their linear combination in Eq. (4) with fitted value of g (solid lines).

polar angle θ of the l^+ flight direction in the J/ψ rest frame reads [36]

$$W_\psi(\theta) \propto 1 + \lambda_\theta^\psi \cos^2\theta, \quad (2)$$

where the polarization parameter $\lambda_\theta^\psi = (\sigma_{11}^\psi - \sigma_{00}^\psi)/(\sigma_{11}^\psi + \sigma_{00}^\psi)$ takes the values $0, \pm 1$ if the J/ψ is unpolarized and totally transversely or longitudinally polarized, respectively. The definition of θ depends on the choice of coordinate frame. The helicity (HX) frame, in which the polar axis is chosen to point along the J/ψ flight direction in the center-of-mass (c.m.) frame of the collision, and the Collins-Soper frame, in which the polar axis is defined as the bisector of the two beam directions [37], are most frequently used experimentally. For definiteness, we will use the HX frame throughout this Letter. The counterpart of Eq. (2) for the $X(3872)$ is not yet available and will be derived in the following. So far, all $X(3872)$ events of prompt hadroproduction have been reconstructed through the $J/\psi\pi^+\pi^-$ decay channel. CMS [17] and ATLAS [18] found that almost all the $\pi^+\pi^-$ pairs originate from ρ vector meson decay. Because of this ρ dominance, the partial decay amplitude of $X(3872) \to J/\psi\pi^+\pi^-$ can be approximated by

$$\mathcal{M}(X(3872) \to J/\psi\pi^+\pi^-) = \mathcal{A}_\mu(X(3872) \to J/\psi\rho) \times (-g^{\mu\nu} + p_\rho^\mu p_\rho^\nu/m_\rho^2)\mathrm{BW}_\rho(p_\rho^2)\mathcal{A}_\nu(\rho \to \pi^+\pi^-), \quad (3)$$

where p_ρ is the four-momentum of the intermediate ρ, m_ρ is its mass, and $\mathrm{BW}_\rho(p_\rho^2)$ is its propagator in Breit-Wigner form. As is well known [38], we have $\mathcal{A}^\mu(\rho \to \pi^+\pi^-) = f_{\rho\pi\pi}(p_{\pi^+}^\mu - p_{\pi^-}^\mu)$, where $f_{\rho\pi\pi}$ is a hadronic coupling constant. On the other hand, CPT conservation and Lorentz covariance restrict $\mathcal{A}_\mu(X(3872) \to J/\psi\rho)$ to be a linear combination of $\mathcal{A}_\mu^1 = \varepsilon_{\mu\alpha\beta\gamma}\epsilon_X^\alpha \epsilon_\psi^{*\beta} p_\rho^\gamma/m_\rho$ and $\mathcal{A}_\mu^2 = \varepsilon_{\mu\alpha\beta\gamma}\epsilon_X^\alpha \epsilon_\psi^{*\beta} p_\psi^\gamma/m_\psi$, if the J/ψ and ρ are in the

S-wave channel.[1] We thus make the ansatz

$$\mathcal{A}_\mu(X(3872) \to J/\psi\rho) \propto \mathcal{A}_\mu^1 + g\mathcal{A}_\mu^2, \qquad (4)$$

with the relative-weight factor g to be fitted to experimental data. Adopting the masses $m_X = 3.8717$ GeV, $m_\psi = 3.0969$ GeV, $m_\rho = 0.7753$ GeV, $m_{\pi^\pm} = 0.1396$ GeV, and the total decay width $\Gamma_\rho = 0.1491$ GeV from Ref. [9], using the functional form $\mathrm{BW}_\rho(p_\rho^2) = (p_\rho^2 - m_\rho^2 + i\Gamma_\rho\sqrt{p_\rho^2 - 4m_\pi^2})^{-1}$, and integrating out the $\pi^+\pi^-$ phase space numerically, we find the $X(3872)$ decay distribution, $W_X(\theta)$, to have the same form as in Eq. (2), with θ now being the polar angle of the J/ψ flight direction in the $X(3872)$ rest frame, and the polarization parameter therein to be

$$\lambda_\theta^X = \frac{f(1-R)}{2-f+R}, \qquad (5)$$

where $R = \sigma_{00}^X/\sigma_{11}^X$ and $f = (-0.56 + 1.28g + 3.12g^2)/(13.7 + 30.6g + 18.2g^2)$. Finally, we determine g by fitting to the distributions of the $X(3872) \to J/\psi\pi^+\pi^-$ partial decay width in the $\pi^+\pi^-$ invariant mass $m_{\pi\pi}$, normalized to unity, as measured by CMS [17] in the range $0.5 < m_{\pi\pi} < 0.78$ GeV and by ATLAS [18] in the range $0.28 < m_{\pi\pi} < 0.79$ GeV. We thus obtain $g = -0.51 \pm 0.10$ with $\chi^2/\mathrm{d.o.f.} = 35.3/22 = 1.60$. The goodness of the fit can also be judged from Fig. 1, which also contains the predictions evaluated with either A_μ^1 or A_μ^2 alone. The latter results are somewhat worse, yielding χ^2/d.o.f. values of $45.9/23 = 2.00$ and $80.0/23 = 3.48$, respectively. Other realistic functional forms of $\mathrm{BW}_\rho(p_\rho^2)$ yield very similar results, albeit with slightly larger χ^2/d.o.f. values. Inserting our fit result for g in Eq. (5) and setting in turn $\sigma_{00}^X = 0$ and $\sigma_{11}^X = 0$, we obtain the allowed corridor $-0.066 \le \lambda_\theta^X \le 0.141$, where the lower bound $f/(2-f)$, upper bound $-f$, and 0 correspond to totally transversely, totally longitudinally, and unpolarized $X(3872)$'s, respectively. Our result for $W_X(\theta)$ is new. We caution the reader that the functional form of f depends on the $\pi^+\pi^-$ phase space integrated over, so that λ_θ^X does depend on the experimental acceptance cuts applied. This must be taken into account in the extraction of polarization parameters from experimental data of $X(3872) \to J/\psi\pi^+\pi^-$.

In our NLO NRQCD calculations, we use the on-shell mass $m_c = 1.5$ GeV and the two-loop formula for $\alpha_s^{(n_f)}$ with $n_f = 4$ active quark flavors. As for the proton PDFs, we adopt the CTEQ6M set [39], which comes with asymptotic scale parameter $\Lambda_{\mathrm{QCD}}^{(4)} = 326$ MeV. We choose the $\overline{\mathrm{MS}}$ renormalization, factorization, and NRQCD scales to be $\mu_r = \mu_f = \xi m_T$ and $\mu_\Lambda = \eta m_c$, respectively, where $m_T = \sqrt{p_T^2 + 4m_c^2}$ is the transverse mass, and independently vary ξ and η by a factor of 2 up and down about their default values $\xi = \eta = 1$ to estimate the scale uncertainty.

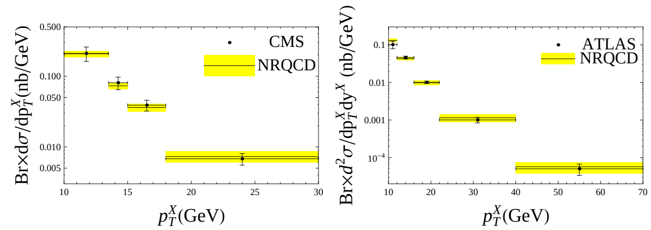

FIG. 2: The differential cross sections of prompt $X(3872)$ production as measured by CMS [17] (left panel) and ATLAS [18] (right panel) are compared with our NLO NRQCD results based on the new fit (solid lines). The yellow bands indicate the theoretical uncertainties.

The branching fraction $\mathcal{B}$ of $X(3872) \to J/\psi\pi^+\pi^-$ is not yet known, so that we can only determine the products $\langle\overline{\mathcal{O}}^X[n]\rangle\mathcal{B}$. In our previous fit [19], we included CDF [2, 15], LHCb [16], and CMS [17] data of prompt $X(3872)$ hadroproduction. Here, we perform an update by also including the recent ATLAS data [18]. We obtain $\langle\overline{\mathcal{O}}^X[^3P_1^{[1]}]\rangle\mathcal{B} = 0.34^{+0.12}_{-0.15} \times 10^{-2}$ GeV^5 and $\langle\overline{\mathcal{O}}^X[^3S_1^{[8]}]\rangle\mathcal{B} = 0.83^{+0.12}_{-0.16} \times 10^{-4}$ GeV^3, in good agreement with both our previous two-parameter fits [19], including and excluding the LHCb [16] data, lying in between them. The fit quality is excellent, with $\chi^2/\mathrm{d.o.f.} = 7.25/9 = 0.81$. This is also evident from Fig. 2, where the cross sections of $X(3872)$ prompt hadroproduction, differential in p_T^X, as measured by CMS [17] and ATLAS [18] are compared with our NLO NRQCD results. Also the integrated cross sections $\sigma^{\mathrm{prompt}}(p\overline{p} \to X(3872) + \mathrm{anything})\mathcal{B} = (3.1 \pm 0.7)$ nb and $\sigma^{\mathrm{prompt}}(pp \to X(3872) + \mathrm{anything})\mathcal{B} = (4.26 \pm 1.23)$ nb measured by CDF [2, 15] and LHCb [16] are compatible with our respective NLO NRQCD results, (2.2 ± 0.8) nb and (5.8 ± 1.5) nb. Here and in the following, the theoretical uncertainties are evaluated by combining the scale and fit errors in quadrature. Excluding the CDF [2, 15] and LHCb [16] data from our fit and so imposing the cut $p_T > 10$ GeV, we obtain $\langle\overline{\mathcal{O}}^X[^3P_1^{[1]}]\rangle\mathcal{B} = 0.38^{+0.16}_{-0.20} \times 10^{-2}$ GeV^5 and $\langle\overline{\mathcal{O}}^X[^3S_1^{[8]}]\rangle\mathcal{B} = 0.86^{+0.13}_{-0.19} \times 10^{-4}$ GeV^3, with $\chi^2/\mathrm{d.o.f.} = 3.83/7 = 0.55$. Adopting these fit results instead would have an insignificant effect on the predictions below.

Imposing the 90%-C.L. lower bound $\mathcal{B} > 3.2\%$ [9], we derive the upper bounds $\langle\overline{\mathcal{O}}^X[^3P_1^{[1]}]\rangle < 0.11^{+0.038}_{-0.047}$ GeV^5 and $\langle\overline{\mathcal{O}}^X[^3S_1^{[8]}]\rangle < 2.6^{+0.38}_{-0.50} \times 10^{-3}$ GeV^3. Since the factor $|\langle\chi_{c1}(2P)|X(3872)\rangle|^2$ cancels in the ratio $r = m_c^2\langle\overline{\mathcal{O}}^X[^3S_1^{[8]}]\rangle/\langle\overline{\mathcal{O}}^X[^3P_1^{[1]}]\rangle$, we can also extract valuable

[1] The D-wave channel contribution is greatly suppressed by the factor $(|\vec{p}_\rho|/m_X)^2$ and may safely be neglected.

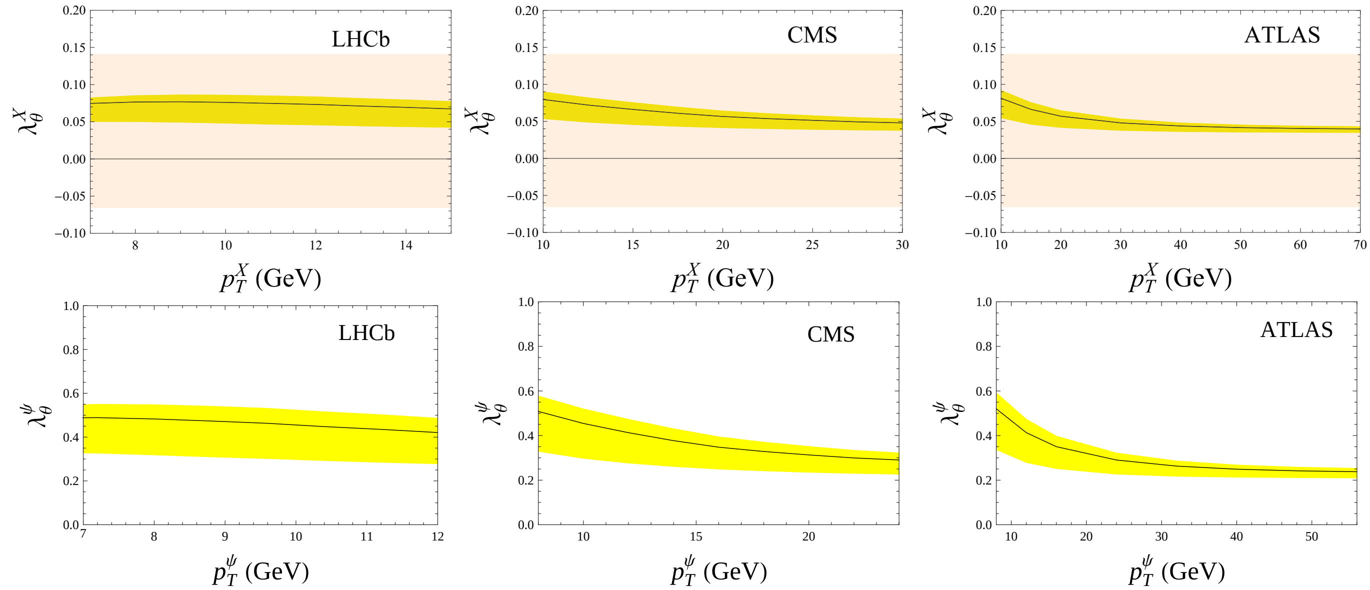

FIG. 3: p_T^X dependence of λ_θ^X (upper row) and p_T^ψ dependence of λ_θ^ψ (lower row) in the HX frame for prompt $X(3872)$'s decaying to $J/\psi\pi^+\pi^-$ for the LHCb (left), CMS (middle), and ATLAS (right) setups. The shaded or pink bands indicate the allowed corridor for λ_θ^X.

information on the $\chi_{cJ}(2P)$ LDMEs,

$$r = \frac{m_c^2\langle\mathcal{O}^{\chi_{c1}(2P)}[^3S_1^{[8]}]\rangle}{\langle\mathcal{O}^{\chi_{c1}(2P)}[^3P_1^{[1]}]\rangle} = \frac{m_c^2\langle\mathcal{O}^{\chi_{cJ}(2P)}[^3S_1^{[8]}]\rangle}{\langle\mathcal{O}^{\chi_{cJ}(2P)}[^3P_J^{[1]}]\rangle}, \quad (6)$$

where we have exploited heavy-quark spin symmetry relations valid to LO in v^2 among the LDMEs for $J = 0, 1, 2$. This will in turn allow for new predictions of $\chi_{cJ}(2P)$ hadroproduction. In this connection, it is interesting to observe that our central value $r = 0.055$ is consistent with the result for the $\chi_{cJ}(1P)$ case found in Ref. [40], 0.045 ± 0.010.

With our new LDMEs, we are now in a position to predict λ_θ^X and λ_θ^ψ at NLO in NRQCD. We consider three LHC setups as for pp c.m. energy $\sqrt{S}$ and $X(3872)$ rapidity y^X, corresponding to LHCb [16], CMS [17], and ATLAS [18] experimental conditions: (i) $\sqrt{S} = 7$ TeV and $2.0 < y^X < 4.5$; (ii) $\sqrt{S} = 7$ TeV and $|y^X| < 1.2$; and (iii) $\sqrt{S} = 8$ TeV and $|y^X| < 0.75$. In Fig. 3, λ_θ^X is presented as a function of p_T^X for these three setups. From there, we observe that the line shapes are very similar for the three setups and that λ_θ^X ranges between 0.04 and 0.10, which is in the upper part of the allowed corridor. Thus, on the basis of our hypothesis, the $X(3872)$ is predicted to be predominantly longitudinally polarized in all three setups, which is now up to experimental verification. Unfortunately, a reliable extraction of the $X(3872)$ polarization from the measurement of λ_θ^X is hampered by the narrowness of its allowed corridor, which necessitates high experimental precision. We note that Eq. (5) is restricted to the decay channel $X(3872) \to J/\psi\pi^+\pi^-$ and so is Fig. 3. However, the reader can easily extract the process independent quantity R from Fig. 3 using the relationship $R = (1 + 15.2\,\lambda_\theta^X)/(1 - 7.09\,\lambda_\theta^X)$ following from Eq. (5) with our fit value of g. R is found to monotonically fall with increasing p_T^X, from about 5 at $p_T^X = 10$ GeV down to its asymptotic value of about 2.2. Fortunately, the experimental disadvantage of λ_θ^X may be circumvented by measuring λ_θ^ψ for the J/ψ from $X(3872)$ decay instead. In fact, λ_θ^ψ is much more sensitive to the J/ψ polarization than λ_θ^X is to the $X(3872)$ polarization. Figure 3 also shows λ_θ^ψ as a function of p_T^ψ for the three setups. From there, we observe that the J/ψ is predicted to be largely transversely polarized, especially in the lower p_T^ψ range, where $\lambda_\theta^\psi \gtrsim 0.5$. Throughout the full p_T^ψ range considered, λ_θ^ψ is so distinctly separated from zero that this should be well discernible experimentally with reasonable statistics.

In the molecular picture, $X(3872)$ is a loosely bound S-wave state of $D^{*0}\bar{D}^0 + c.c.$ Since D^0 ($\bar{D}^0$) is a pseudoscalar, all the information on the $X(3872)$ polarization is carried by the D^{*0} ($\bar{D}^{*0}$) vector. At hadron colliders, prompt D^{*0}'s ($\bar{D}^{*0}$'s) arise from the nonperturbative evolution of perturbatively produced c's ($\bar{c}$'s), and we are not aware of a mechanism that leads to polarized D^{*0}'s ($\bar{D}^{*0}$'s). In fact, this argument is supported by several experimental measurements of D^{*0} ($\bar{D}^{*0}$) polarization in e^+e^- annihilation at different c.m. energies, for example by ARGUS [41]. We thus infer that, in the molecular picture, the prompt $X(3872)$'s would be unpolarized and so would the J/ψ's from their decays.

We now argue that the proposed $X(3872)$ and J/ψ polarization measurements are feasible using the LHC signal events already on tape by now and thus are not subject to delay by the ongoing Long Shutdown 2, which will impede proton physics before May 2021. CMS managed to perfom a full-fledged $\psi(2S)$ polarization measurement using $262\,\mathrm{k}\ \psi(2S) \to \mu^+\mu^-$ events in the range $14 < p_T^{\psi'} < 50$ GeV and $|y^{\psi'}| < 1.2$ [42]. On the other hand, they collected $11.91\,\mathrm{k}\ X(3872) \to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$ events in almost the same kinematic range, $10 < p_T^X < 50$ GeV and $|y^X| < 1.2$, using an integrated luminosity of 4.8 fb^{-1} [17]. At present, the integrated luminosity accumulated by CMS is 29.3 fb^{-1} from run 1 and 160 fb^{-1} from run 2 [43]. Assuming that acceptance and efficiency have been approximately steady during the data taking periods, this translates into $11.91\,\mathrm{k} \times 29.3/4.8 = 72.7\,\mathrm{k}$ and $397\,\mathrm{k}$ prompt $X(3872)$ events waiting to be analyzed with regard to their $X(3872)$ and J/ψ polarizations. The data sample from run 2 alone is more than 50% more copious than the one underlying the ψ' polarization measurement [42] and should thus conveniently allow for the proposed polarization measurements. A similar conclusion can be drawn for LHCb on the basis of Refs. [16, 44].

In summary, we studied the prompt hadroproduction of the mysterious $X(3872)$ and its subsequent decay to $J/\psi\pi^+\pi^-$ in the NRQCD factorization framework [20] at NLO in α_s, under the likely assumption that the creation of the $X(3872)$ proceeds chiefly through the $\chi_{c1}(2P)$ component of its short-distance wave function. We updated our previous fits of the $X(3872)$ LDMEs [19] by including the latest ATLAS data [18], scoring an excellent goodness, as low as $\chi^2/\mathrm{d.o.f.} = 0.81$ (see also Fig. 2). This also allowed us to predict the CO to CS LDME ratio of the $\chi_{cJ}(2P)$'s. Exploiting our fit results, we presented the first predictions of the polarization parameters λ_θ^X and λ_θ^ψ, in the HX frame for LHCb-, CMS-, and ATLAS-like setups. These imply that the $X(3872)$ and J/ψ polarizations are largely longitudinal and transverse, respectively. Comparing the sizes of available LHC data sets on the $X(3872)$ prompt yield with those on the ψ' polarization, we concluded that meaningful measurements of λ_θ^X and λ_θ^ψ should be feasible already now, during the LHC Long Shutdown 2. While the reliable interpretation of such measurements of λ_θ^X will be aggravated by the fact that the theoretically allowed λ_θ^X window is only 0.21 wide, there is no such limitation for λ_θ^ψ. Our predictions are distinctly different from those of the molecular picture [11], in which the $X(3872)$ and J/ψ vectors are expected to be both unpolarized, as we argued on the basis of Ref. [41]. Their experimental verification would simultaneously confirm both the validity of NLO NRQCD for χ_{cJ} polarization and the $\chi_{c1}(2P)$ dominance hypothesis in $X(3872)$ prompt production. Should the $\chi_{c1}(2P)$ be discovered distinguishably from the $X(3872)$, then the $\chi_{c1}(2P)$ dominance hypothesis could be tested, regardless of the validity of NRQCD factorization, by comparing the J/ψ polarizations measured in $\chi_{c1}(2P)$ and $X(3872)$ decays. We conclude by urging the LHC collaborations to extract λ_θ^X and λ_θ^ψ from available and future prompt-$X(3872)$ data and to perform similar analyses also for other X, Y, Z states with nonzero spin, which will allow us to distinguish between different models and so to take a major step in pinning down the nature of the X, Y, Z states.

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