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NLO NRQCD disfavors the interpretation of $X(3872)$ as $\chi_{c1}(2P)$

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Abstract

We study $\chi_{c1}(2P)$ inclusive hadroproduction at next-to-leading order (NLO), both in α_s and v^2, within the factorization formalism of nonrelativistic quantum chromodynamics (NRQCD), including the color-singlet ${}^3P_1^{[1]}$ and color-octet ${}^3S_1^{[8]}$ $c\bar{c}$ Fock states as well as the mixing of the latter with the ${}^3D_1^{[8]}$ state. Assuming the recently discovered $X(3872)$ hadron to be the $J^{PC} = 1^{++}$ charmonium state $\chi_{c1}(2P)$, we perform a fit to the cross sections measured by the CDF, CMS, and LHCb Collaborations. We either obtain an unacceptably high value of χ^2, a value of $|R'_{2P}(0)|$ incompatible with well-established potential models, or an intolerable violation of the NRQCD velocity rules. We thus conclude that NLO NRQCD is inconsistent with the hypothesis $X(3872) \equiv \chi_{c1}(2P)$.

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During the past decade, a series of charmonium or charmonium-like X, Y, Z states were discovered (for a recent review, see Ref. [1]). The $X(3872)$ state is one of the most interesting among them. It was discovered in 2003 by the Belle Collaboration at KEKB in B meson decays [2], and confirmed shortly afterwards by the BaBar Collaboration at SLAC PEP-II [3]. It was also observed by the CDF [4] and D0 [5] Collaborations in $p\bar{p}$ collisions at the Tevatron Fermilab. Ever since its discovery, many theoretical group have tried to interpret its nature, which has remained mysterious to date, and it is an urgent task of great importance and broad interest to solve this notorious puzzle of hadron spectroscopy. Typical options include conventional charmonia [6], $D^{*0}\overline{D}^{0}/D^{0}\overline{D}^{*0}$ molecules [7], and tetraquarks [8]. However, none of them can provide a convincing description of all the experimental measurements. After analyzing the dipion mass spectrum in $X(3872) \to J/\psi + \pi^+\pi^-$, only two options for its J^{PC} property are left, either 1^{++} or 2^{-+} [9].[a] In $p\bar{p}$ and pp collisions, most of the $X(3872)$ mesons are produced promptly rather than through decays of b hadrons [11, 12]. The study of $X(3872)$ prompt production provides complementary information on its nature. In Ref. [13], the cross section of $X(3872)$ was estimated under the assumption that it is a loosely-bound $D^{*0}\overline{D}^{0}/D^{0}\overline{D}^{*0}$ molecule, and the upper bound of the theoretical calculation was found to be much smaller than the CDF measurement [4, 11]. Later, Artoisenet and Braaten [14] pointed out that the upper bound of this prediction can be rendered consistent with the Tevatron data [4, 5, 11] by properly taking into account rescattering effects. They also used the NRQCD factorization approach [15] to interpret $X(3872)$ prompt production at the Tevatron [4, 5, 11] and presented predictions for the LHC. However, their predictions significantly exceed the new measurements reported by the CMS [12] and LHCb [16] Collaborations. In their charmonium interpretation [14], $X(3872)$ is assumed to be a 1^{++} state that is dominantly produced via the color-octet $c\bar{c}$ Fock state ${}^3S_1^{[8]}$, and the short-distance coefficients are calculated at leading order (LO). Note that, at first sight, the mass value 3.872 GeV seems too low for a $\chi_{c1}(2P)$ candidate, but color-screening effects together with coupled-channel effects may draw its mass down towards 3.872 GeV [17].

Recent NRQCD analyses have revealed that NLO corrections play a key role in explaining the J/ψ [18] and $\chi_{cJ}(1P)$ [19] yields measured at the Tevatron and the LHC. Under the

[a] Very recently, the LHCb Collaboration [10] established the assignment $J^{PC} = 1^{++}$, which, however, still lacks independent confirmation.

assumption that $X(3872)$ is the 1^{++} charmonium state $\chi_{c1}(2P)$, it is then natural to ask if its prompt production rates may be explained upon including NLO corrections. The main goal of our work is to answer this question. To this end, we shall first calculate the cross section of inclusive $\chi_{c1}(2P)$ hadroproduction at NLO in NRQCD and then check if its free parameters can be adjusted so as to yield a satisfactory description of the available prompt $X(3872)$ hadroproduction data [4, 11, 12, 16].

Owing to the factorization theorems of the QCD parton model and NRQCD [15], the inclusive $\chi_{c1}(2P)$ hadroproduction cross section is evaluated from

$$d\sigma(AB \to \chi_{c1}(2P) + X) = \sum_{i,j,n} \int dx dy \, f_{i/A}(x) f_{j/B}(y) \times \langle \mathcal{O}^{\chi_{c1}(2P)}[n] \rangle d\sigma(ij \to c\overline{c}[n] + X), \tag{1}$$

where $f_{i/A}(x)$ are the parton distribution functions (PDFs) of hadron A, $\langle \mathcal{O}^{\chi_{c1}(2P)}[n] \rangle$ are the long-distance matrix elements (LDMEs), and $d\sigma(ij \to c\overline{c}[n] + X)$ are the partonic cross sections. Working in the fixed-flavor-number scheme, i and j run over the gluon g and the light quarks $q = u, d, s$ and anti-quarks $\overline{q}$. The system X always contains one hard parton at LO and is taken to be devoid of heavy flavors, which may be tagged and vetoed experimentally. The contribution due to final states in which X comprises an open $c\bar{c}$ pair is found to be suppressed by one order of magnitude [20]. At LO in the relative velocity v of the bound c and $\bar{c}$ quarks in the charmonium rest frame, only the states $n = {}^3P_1^{[1]}, {}^3S_1^{[8]}$ contribute [15]. We evaluate the NLO corrections, which are of relative orders $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(v^2)$.

In our $\mathcal{O}(\alpha_s)$ calculation, all singularities are canceled analytically. The ultraviolet divergences are removed by renormalizing the parameters α_s and m_c and the wave functions of the external lines. Specifically, we work in the on-shell scheme, except for α_s, which is treated in the $\overline{\text{MS}}$ scheme. The infrared singularities are canceled similarly as described in Ref. [21]. Notice that the inclusion of the ${}^3S_1^{[8]}$ contribution is indispensable in order to obtain an IR finite result. We thus recover the notion that the color-singlet model is not a complete theory. By the same token, the dependencies of $\langle \mathcal{O}^{\chi_{c1}(2P)}[n] \rangle$ and $d\sigma(ij \to c\overline{c}[n] + X)$ on the NRQCD factorization scale μ_Λ only cancel after summation over n. The $\mathcal{O}(v^2)$ corrections involve the additional $\langle \mathcal{P}^{\chi_{c1}(2P)}({}^3P_1^{[1]}) \rangle$, $\langle \mathcal{P}^{\chi_{c1}(2P)}({}^3S_1^{[8]}) \rangle$, and $\langle \mathcal{P}^{\chi_{c1}(2P)}({}^3S_1^{[8]}, {}^3D_1^{[8]}) \rangle$ LDMEs of the respective local four-fermion operators of mass dimension eight [15] and may be evaluated from tree-level diagrams of $c\bar{c}$ hadroproduction similarly as for hadronic quarkonium

decays [22].

We now describe the choices of input for our NLO NRQCD calculation. We take the charm-quark mass to be $m_c = 1.5$ GeV and use 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 [23], which comes with asymptotic scale parameter $\Lambda_{\rm QCD}^{(4)} = 326$ MeV. We choose the $\overline{\rm MS}$ renormalization, factorization, and NRQCD scales to be $\mu_r = \mu_f = \xi m_T$ and $\mu_\Lambda = \eta m_c$, where $m_T = \sqrt{p_T^2 + 4m_c^2}$ is the $\chi_{c1}(2P)$ transverse mass, and independently vary ξ and η by a factor of two up and down about their default values $\xi = \eta = 1$ to estimate the scale uncertainty. To LO in v, we have [15]

$$\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]}) \rangle = (2J+1)\frac{3C_A}{2\pi}|R'_{2P}(0)|^2, \tag{2}$$

where $C_A = N_c = 3$, $J = 1$ is the total angular momentum of the $\chi_{c1}(2P)$ meson and $R_{2P}(r)$ is its radial wave function, which may be calculated using models for the QCD potential of the charm quark. Adopting frequently used potential models with different choices of parameters, $|R'_{2P}(0)|^2$ is found to range from 0.076 GeV^5 to 0.183 GeV^5 [24]. As the default for our fits, we adopt the value $|R'_{2P}(0)|^2 = 0.102$ GeV^5 obtained using the Buchmüller-Tye potential [25]. To compare theoretical predictions with the experimental data, we also need to know the branching fraction (BR) of the decay mode $X(3872) \to J/\psi + \pi^+\pi^-$ used to identify the $X(3872)$ meson. It has not been determined yet, but the lower bound BR $> 2.6\%$ has been established at 90% C.L. [26]. Furthermore, the upper bound BR $< 9.3\%$ was derived at 90% C.L. using constrains from some other decay channels [14]. In our fits, we use BR $= 2.6\%$.

Based on the measurements by the CDF Collaboration [4, 11], at center-of-mass energy $\sqrt{s} = 1.96$ TeV, the prompt production cross section of $X(3872)$ mesons with rapidity $|y| < 0.6$ and transverse momentum $p_T > 5$ GeV is estimated to be [13, 14]

$$\sigma_{\rm CDF}^{\rm prompt}(p\bar{p} \to X(3872) + X){\rm BR} = (3.1 \pm 0.7)\ {\rm nb}. \tag{3}$$

At LHC, prompt $X(3872)$ production was first measured by the CMS Collaboration [12], at $\sqrt{s} = 7$ TeV, with the result

$$\sigma_{\rm CMS}^{\rm prompt}(pp \to X(3872) + X){\rm BR} = (1.06 \pm 0.19)\ {\rm nb}, \tag{4}$$

for $|y| < 1.2$ and 10 GeV $< p_T <$ 30 GeV. They also presented a p_T distribution [12]. The LHCb Collaboration also measured $X(3872)$ production at $\sqrt{s} = 7$ TeV, but did not

TABLE I: Results of our $\mathcal{O}(\alpha_s)$ NLO NRQCD fits to the measured p_T distribution of prompt $X(3872)$ production [12] and the integrated cross section of Eq. (3) including or excluding the result of Eq. (5). In the one-parameter case, $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle$ is determined by the potential model of Ref. [25], while it is a fit parameter in the two-parameter case. We adopt BR = 2.6%.

	One-parameter fit		Two-parameter fit	
	w/ LHCb data	w/o LHCb data	w/ LHCb data	w/o LHCb data
$\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle$ [GeV^5]	0.438	0.438	$0.100^{+0.050}_{-0.050}$	$0.190^{+0.092}_{-0.094}$
$\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3S_1^{[8]})\rangle$ [GeV^3]	$(3.84^{+0.28}_{-0.24}) \times 10^{-3}$	$(4.30^{+0.30}_{-0.26}) \times 10^{-3}$	$(2.95^{+0.54}_{-0.58}) \times 10^{-3}$	$(3.36^{+0.56}_{-0.66}) \times 10^{-3}$
χ^2/d.o.f.	$79.1/5 = 15.8$	$16.7/4 = 4.18$	$4.26/4 = 1.07$	$0.63/3 = 0.21$

discriminate between b-hadron and prompt sources [16]. Averaging the CDF and CMS measurements of the non-prompt fraction, $(16.1 \pm 4.9 \pm 2.0)\%$ [4, 11] and $(26.3 \pm 2.3 \pm 1.6)\%$ [12], respectively, we estimate the LHCb prompt cross section to be

$$\sigma^{\rm prompt}_{\rm LHCb}(pp \to X(3872) + X){\rm BR} = (4.26 \pm 1.23)\ {\rm nb}, \tag{5}$$

for $2.5 < y < 4.5$ and 5 GeV $< p_T <$ 20 GeV.

In the following, we perform a NLO NRQCD test of the hypothesis that the $X(3872)$ hadron is the $\chi_{c1}(2P)$ charmonium state. Since $X(3872)$ production via feed-down of heavier charmonia has not been observed, we assume for the time being prompt production to be approximately exhausted by direct production. In fact, charmonia heavier than the $X(3872)$ hadron have sufficient phase space above the open charm production threshold and preferably decay to pairs of D mesons so as to evade the kinematic constraint of $c\bar{c}$ bound state formation. To start with, we neglect the $\mathcal{O}(v^2)$ corrections, which will be studied in a second step. We are thus led to fit Eq. (1), which depends on the parameters $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle$ and $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3S_1^{[8]})\rangle$, to the experimental data of prompt $X(3872)$ production [4, 11, 12, 16]. We consider four options altogether. On the theoretical side, we either fix $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle = 0.438$ GeV^5 by the potential model of Ref. [25], or fit it along with $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3S_1^{[8]})\rangle$. In the latter case, we actually take $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle{\rm BR}$ and $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3S_1^{[8]})\rangle{\rm BR}$ to be fit parameters. On the experimental side, we either include the LHCb result [16] of Eq. (5) in the fit along with the CDF result [4, 11] of Eq. (3) and the CMS measurement of the p_T distribution [12], which includes four data points, or we exclude it. In order to avoid double counting, we always exclude the CMS result [12] of Eq. (4) from the fit.

The results of the four fits are summarized in Table I, and their goodness may be conveniently assessed from Fig. 1. In the two-parameter case, the quoted values of $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle$ and $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3S_1^{[8]})\rangle$ correspond to our default value BR = 2.6%. When Eq. (5) is excluded from the fit, $\sigma^{\rm prompt}_{\rm LHCb}$BR is a genuine prediction. The uncertainties are estimated by adding in quadrature the errors of experimental origin resulting from the fits using our default NLO NRQCD results and those due the variations of the scale parameters ξ and η.

The one-parameter fit including the LHCb data point of Eq. (5) has d.o.f. = 5 degrees of freedom and yields $\chi^2 = 79.1$, so that $\chi^2/\text{d.o.f.} = 15.8$ is intolerably large suggesting that the experimental data is poorly described by only adjusting $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3S_1^{[8]})\rangle$. This is also evident from the upper left panel in Fig. 1. We observe that χ^2 rapidly increases with $|R'_{2P}(0)|^2$ and BR. For $|R'_{2P}(0)| = 0.076$ GeV^5 and BR = 2.6%, we obtain the best value $\chi^2 = 37.5$, which is still unacceptably large, while for $|R'_{2P}(0)|^2 = 0.183$ GeV^5 and BR = 9.3%, χ^2 is around 5000. We also notice that the NLO NRQCD result greatly overshoots the LHCb data point although it is included in the fit. Excluding it from the fit mildly increases the central values of the fit results and their errors, but significantly reduces χ^2, by almost a factor of five. The NLO NRQCD prediction for Eq. (5) is then $(14.21^{+3.41}_{-2.83})$ nb, so that the theory band overshoots the LHCb result by almost six experimental standard deviations.

The two-parameter fit including the LHCb data point of Eq. (5) works nicely, yielding $\chi^2/\text{d.o.f.} = 1.07$. Specifically, we have $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle\text{BR} = (2.60^{+1.30}_{-1.30}) \times 10^{-3}$ GeV^5 and $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3S_1^{[8]})\rangle\text{BR} = (7.67^{+1.40}_{-1.51}) \times 10^{-5}$ GeV^3. From BR $> 2.6\%$ at 90% C.L. [26], we thus derive the 90% C.L. upper bound $|R'_{2P}(0)|^2 < (2.33 \pm 1.16) \times 10^{-2}$ GeV^5, which undershoots the smallest known potential model result, 0.076 GeV^5 [24], by more than 4σ and whose central value is more than a factor of three smaller than the latter. Conversely, if we choose $|R'_{2P}(0)|^2$ within the ballpark of potential model calculations, then the upper bound on BR is around three times smaller than the lower bound 2.6% [26]. Also the LHCb data point is nicely described by the fit. Excluding it from the fit appreciably increases the central values and errors of the fit results and pushes $\chi^2/\text{d.o.f.}$ far below unity, to 0.21. Specifically, we find $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle\text{BR} = (4.94^{+2.39}_{-2.44}) \times 10^{-3}$ GeV^5 and $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3S_1^{[8]})\rangle\text{BR} = (8.74^{+1.46}_{-1.72}) \times 10^{-5}$ GeV^3. However, the NLO NRQCD prediction for Eq. (5) now reads $(8.04^{+1.42}_{-1.56})$ nb, so that the theory band overshoots the LHCb result by almost two experimental standard deviations.

We now study the influence of the $\mathcal{O}(v^2)$ corrections on top of the $\mathcal{O}(\alpha_s)$ ones. We first

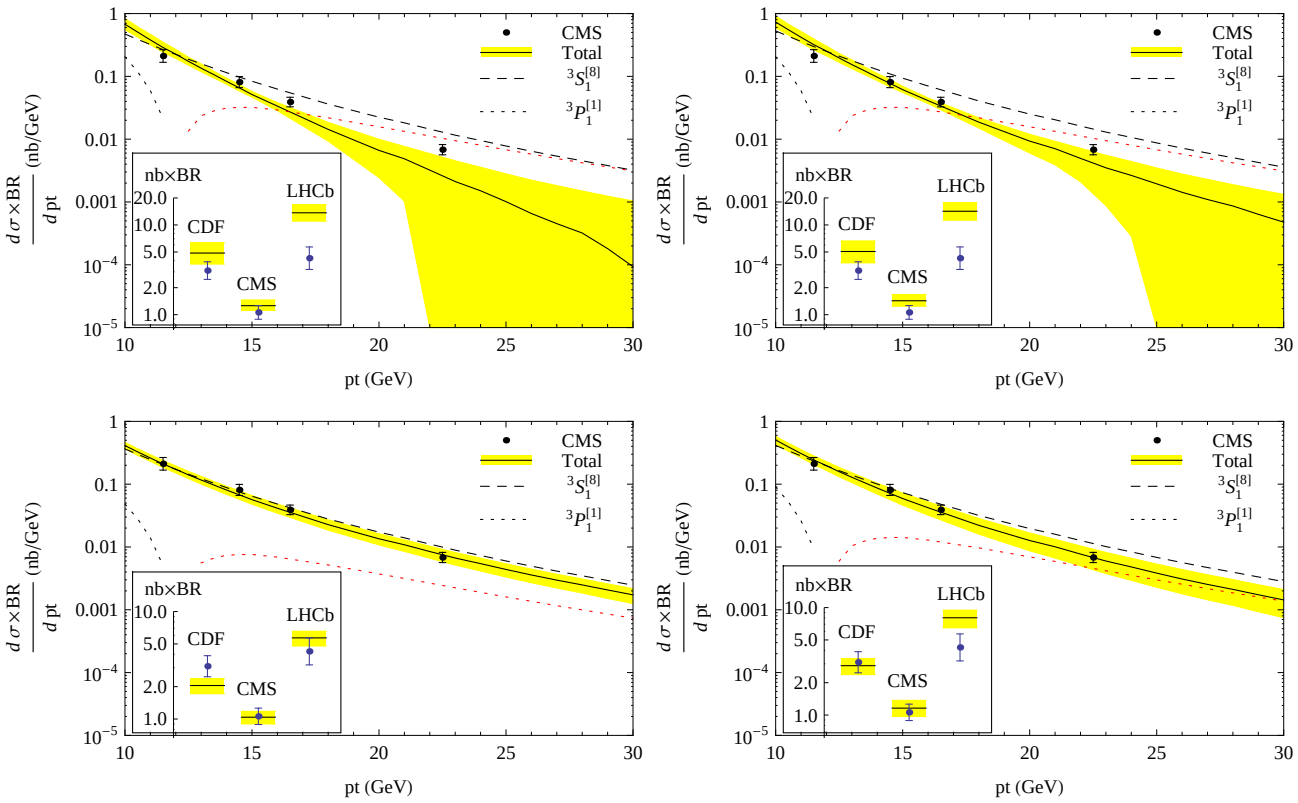

FIG. 1: The prompt $X(3872)$ production cross sections measured by the CDF [4, 11], CMS [12], and LHCb [16] Collaborations are compared with NLO NRQCD results based on one-parameter (upper row) or two-parameter (lower row) fits including (left column) or excluding (right column) the LHCb data point of Eq. (5) [16]. Dotted, dashed, and solid lines represent the $^3P_1^{[1]}$ and $^3S_1^{[8]}$ contributions and their sum, respectively. Red lines denote negative values, familiar from Refs. [18, 19]. Yellow bands indicated the uncertainties in the total results.

observe that, in the kinematic range of our fits, the additional contributions to Eq. (1) proportional to $\langle\mathcal{P}^{\chi_{c1}(2P)}(^3S_1^{[8]})\rangle$ and $\langle\mathcal{P}^{\chi_{c1}(2P)}(^3S_1^{[8]},{}^3D_1^{[8]})\rangle$ have p_T dependencies that match the one of the contribution proportional to $\langle\mathcal{O}^{\chi_{c1}(2P)}(^3S_1^{[8]})\rangle$ within a few percent, so that these three LDMEs cannot be determined individually. We thus account for the $\mathcal{O}(v^2)$ corrections by replacing $\langle\mathcal{O}^{\chi_{c1}(2P)}(^3S_1^{[8]})\rangle$ with $\mathcal{M}_8 = \langle\mathcal{O}^{\chi_{c1}(2P)}(^3S_1^{[8]})\rangle + c_1\langle\mathcal{P}^{\chi_{c1}(2P)}(^3S_1^{[8]})\rangle/m_c^2 + c_2\langle\mathcal{P}^{\chi_{c1}(2P)}(^3S_1^{[8]},{}^3D_1^{[8]})\rangle/m_c^2$, with $c_1 = -1.06 \pm 0.03$ and $c_2 = 0.73 \pm 0.02$. As in the one-parameter fit above, we fix $\langle\mathcal{O}^{\chi_{c1}(2P)}(^3P_1^{[1]})\rangle = 0.438$ GeV^5 [25]. The fit to the CDF [4, 11], CMS [12], and LHCb [16] data then yields $\langle\mathcal{P}^{\chi_{c1}(2P)}(^3P_1^{[1]})\rangle/m_c^2 = (0.517 \pm 0.059)$ GeV^5 and $\mathcal{M}_8 = (5.71 \pm 0.32) \times 10^{-3}$ GeV^5 with χ^2/d.o.f. $= 2.91/4 = 0.73$. I.e. the fit

is excellent, but the hierarchy $(\langle \mathcal{P}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle/m_c^2)/\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle = \mathcal{O}(v^2)$ predicted by the NRQCD velocity scaling rules [15] is strongly violated. On the other hand, if we assume that $\langle \mathcal{P}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle/m_c^2 = v^2\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle$ with $v^2 = 0.3$, then we obtain $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle \mathrm{BR} = (3.39 \pm 1.25) \times 10^{-3}$ GeV^5 with $\chi^2/\mathrm{d.o.f.} = 4.06/4 = 1.02$. This corresponds to $|R'_{2P}(0)|^2 < (3.03 \pm 1.12) \times 10^{-2}$ GeV^5 at 90% C.L., which falls more than 4σ below the smallest known potential model result, 0.076 GeV^5 [24],

In conclusion, we tested the hypothesis that the $X(3872)$ hadron, whose nature is remaining undetermined even a decade after its discovery, is a pure $\chi_{c1}(2P)$ charmonium state, by fitting all available data of prompt $X(3872)$ production, from the CDF [4, 11], CMS [12], and LHCb [16] Collaborations, at NLO in α_s and v^2 within the effective quantum field theory of NRQCD endowed with the factorization theorem proposed by Braaten, Bodwin, and Lepage [15]. NRQCD factorization, which is arguably the only game in town among the candidate theories of heavy-quarkonium production and decay, has recently been impressively consolidated at NLO by global analyses of the world data of J/ψ inclusive production (for a review, see Ref. [27]). Assuming the color-singlet LDME $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle$ to be in the ballpark of well-established potential models [24] and imposing the lower bound on the BR of $X(3872) \to J/\psi + \pi^+\pi^-$ quoted by the Particle Data Group [26], we find that the pure $\chi_{c1}(2P)$ assignment to the $X(3872)$ hadron is strongly disfavored. If the $\mathcal{O}(v^2)$ corrections are neglected, the goodness of the fit is unacceptably poor, and if they are included, the NRQCD velocity scaling rules [15] are strongly violated. The tension may be somewhat relaxed by excluding the LHCb data point [16] from the fit, which is, however, unmotivated and unsatisfactory, the more so as this challenges the CDF [4, 11] and CMS [12] measurements of the non-prompt $X(3872)$ BR.

If we assume that the $X(3872)$ hadron is a quantum-mechanical superposition of the $\chi_{c1}(2P)$ meson and a $D^{*0}\overline{D}^0/D^0\overline{D}^{*0}$ molecule and that the prompt production rate of the latter is negligible because of its minuscule binding energy, then our two-parameter fit including the LHCb data point [16] (see Table I) allows us to convert the bounds $|R'_{2P}(0)|^2 > 0.076$ GeV^5 [24] and BR $> 2.6\%$ [26] into the bound $|\langle \chi_{c1}(2P)|X(3872)\rangle|^2 < (31 \pm 15)\%$ on the probability of encountering the $\chi_{c1}(2P)$ component in the $X(3872)$ state. If we also include $\mathcal{O}(v^2)$ corrections and enforce the proper scaling of $\langle \mathcal{P}^{\chi_{c1}(2P)}({}^3P_1^{[1]})\rangle/m_c^2$ with v^2, then we have $|\langle \chi_{c1}(2P)|X(3872)\rangle|^2 < (40 \pm 15)\%$. Despite concerted experimental and theoretical endeavors during the past decade, the quest for the ultimate classification of the $X(3872)$

resonance remains one of the most tantalizing puzzles of hadron spectroscopy at the present time.

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Note added. After submission, a preprint [28] appeared, in which $X(3872)$ hadroproduction is studied at NLO in α_s by performing a two-parameter fit to the CMS data [12] and verifying consistency with the CDF data point [4]. In our notation, the fit results of Ref. [28] are $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3P_1^{[1]}) \rangle = (0.17 \pm 0.07)$ GeV^5 and $\langle \mathcal{O}^{\chi_{c1}(2P)}({}^3S_1^{[8]}) \rangle = (3.34 \pm 1.69) \times 10^{-3}$ GeV^3 with $\chi^2/\text{d.o.f.} = 0.52/2 = 0.26$, nicely confirming the corresponding results in the rightmost column of Table I.

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