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Hadroproduction of $\Upsilon(nS)$ above the $B\bar{B}$ thresholds and implications for $Y_b(10890)$

Ahmed Ali*
Deutsches Elektronen-Synchrotron DESY, Hamburg 22607, Germany

Christian Hambrock†
Institut für Physik, Technische Universität Dortmund, Dortmund 44221, Germany

Wei Wang‡
Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, Bonn 53115, Germany

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Based on the nonrelativistic QCD factorization scheme, we study the hadroproduction of the bottomonium states $\Upsilon(5S)$ and $\Upsilon(6S)$. We argue to search for them in the final states $\Upsilon(1S, 2S, 3S)\pi^+\pi^-$, which are found to have anomalously large production rates at $\Upsilon(5S)$. The enhanced rates for the dipionic transitions in the $\Upsilon(5S)$ energy region could, besides $\Upsilon(5S)$, be ascribed to $Y_b(10890)$, a state reported by the Belle Collaboration, which may be interpreted as a tetraquark. The LHC/Tevatron measurements are capable of making a case in favor of or against the existence of $Y_b(10890)$, as demonstrated here. Dalitz analysis of the $\Upsilon(1S, 2S, 3S)\pi^+\pi^-$ states from the $\Upsilon(5S)/Y_b(10890)$ decays also impacts directly on the interpretation of the charged bottomonium-like states, $Z_b(10600)$ and $Z_b(10650)$, discovered by Belle in these puzzling decays.

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As a multiscale system, heavy quarkonium states provide a unique laboratory to explore the interplay between perturbative and nonperturbative effects of QCD. Due to their nonrelativistic nature, these states allow the application of theoretical tools that can simplify and constrain the analyses of nonperturbative effects. The commonly accepted method is nonrelativistic QCD (NRQCD) [1], which adopts a factorization ansatz to separate the short-distance and long-distance effects. Since the bottom quark is approximately three times heavier than the charm quark, it is expected that the expansion in $\alpha_s(\mu)$, where μ is a scale of $O(m_b)$, and v^2, with v as the velocity of the heavy quark in the hadron, which also is a NRQCD expansion parameter, will converge much faster for the bottomonium states. Consequently, great progress has been made in the past few years on the hadronic production of $\Upsilon(1S, 2S, 3S)$ [2]. On the experimental side, the production rates and polarization have been measured at the Tevatron [3–5] and at the LHC [6–8]. Theoretical attempts to explain these data have been independently performed by several groups with the inclusion of the next-to-leading-order QCD corrections [9–16].

Experimental and theoretical studies performed at hadron colliders have so far been limited to the $\Upsilon(1S, 2S, 3S)$ bound states, since they all lie below the $B\bar{B}$ threshold and hence have sizable leptonic branching fractions. Above the $B\bar{B}$ threshold, however, the leptonic branching ratios of the higher bottomonium states become very small, as a consequence of which these states have not been seen so far in hadronic collisions. But, if the anomalously large decay widths of $O(1)$ MeV in the final states $\Upsilon(1S, 2S, 3S)\pi^+\pi^-$, reported by Belle a few years ago [17,18], are to be ascribed to the decays of the $\Upsilon(5S)$, then these final states are also promising for the detection of the $\Upsilon(5S)$ in experiments at the Tevatron and the LHC [19]. Arguing along similar lines, the rescattering mechanism which enhances the dipionic partial widths in the $\Upsilon(5S)$ decays is also likely to yield similar enhancements in the rates for the corresponding transitions in the $\Upsilon(6S)$ decays [20], which then could also be measurable in hadronic collisions. In this paper, we derive the hadroproduction cross sections for $\Upsilon(5S)$ and $\Upsilon(6S)$ in $p\bar{p}(p)$ collisions using the NRQCD framework, supplemented by the subsequent decays into $\Upsilon(1S, 2S, 3S)\pi^+\pi^-$.

The enhanced rates for the dipionic transitions in the $\Upsilon(5S)$ energy region could, however, also be ascribed to $Y_b(10890)$, a state reported by the Belle Collaboration [17,18], which is tentatively interpreted as a tetraquark [21–24]. In that case, one expects a smaller cross section for the hadroproduction of $Y_b(10890)$ than for a genuine $b\bar{b}$ bound state. At the same time, as there are no tetraquark states expected to lie in the $\Upsilon(6S)$ region, there would be no plausible grounds to expect a measurable yield in the $(\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-)\pi^+\pi^-$ final states from the decays of $\Upsilon(6S)$. Since exotic states in the charm sector have been successfully searched for in the $(J/\psi, \psi')\pi^+\pi^-$ final states not only at the e^+e^- colliders, but also in

*ahmed.ali@desy.de
†christian.hambrock@tu-dortmund.de
‡Corresponding author.
weiwang@hiskp.uni-bonn.de

hadroproduction in experiments at the Tevatron [25] and the LHC [26,27], the proposed measurements at hadron colliders in the final states $(\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-)\pi^+\pi^-$ could open new avenues in the search and discovery of the exotic four-quark states in the bottom sector. In particular, there exist three candidates to date, namely the states labeled $Y_b(10890)$, $Z_b(10610)$ and $Z_b(10650)$, with the last two observed by Belle last year [28]. If the exotic state $Y_b(10890)$ is not confirmed, we have nonetheless demonstrated a new way to explore the bottomonia above the $B\bar{B}$ threshold, which would supplement the study of $\Upsilon(1S, 2S, 3S)$ in hadronic collisions. First steps in that direction were recently reported by the CMS Collaboration [29].

The cross section for the hadroproduction process $p\bar{p}(p) \to \Upsilon + X$ (we will leave X implicit in the following) is given by

$$\sigma_N(p\bar{p}(p) \to \Upsilon + X) = \int dx_1 dx_2 \sum_{i,j} f_i(x_1) f_j(x_2) \hat{\sigma}(ij \to \langle \bar{b}b\rangle_N + X)\langle O[N]\rangle, \tag{1}$$

where i, j denotes a generic parton inside a proton/antiproton; $f_a(x_1)$, $f_b(x_2)$ are the parton distribution functions (PDFs), which depend on the fractional momenta $x_i (i = 1, 2)$ (an additional scale dependence is suppressed here); and Υ denotes a generic bottomonium state above the $B\bar{B}$ threshold for which we consider $\Upsilon(5S)$ and $\Upsilon(6S)$ in this paper. We adopt the CTEQ 6 PDFs [30] in our numerical calculations. $\langle O[N]\rangle$ are the long-distance matrix elements (LDMEs). N denotes all the quantum numbers of the $b\bar{b}$ pair, which we label in the form ${}^{2S+1}L_J^c$ (color c, spin S, angular momentum L, and total angular momentum J), and $\hat{\sigma}$ denotes the partonic cross section.

The normalized cross sections, in which the LDMEs are factored out, are defined by $\tilde{\sigma}_N \equiv \sigma_N/\langle O[N]\rangle$. The transverse momentum distribution is then given by

$$\frac{d\sigma_N}{dp_t} = \sum_{i,j} \int J dx_1 dy f_i(x_1, \mu_f) f_j(x_2, \mu_f) \frac{d\hat{\sigma}_N}{dt} \langle O[N]\rangle, \tag{2}$$

where y is the rapidity of Υ, p_t is the transverse momentum, and J is the Jacobian factor.

The leading-order partonic processes for the S-wave configurations are

$$\begin{aligned} g(p_1)g(p_2) &\to \Upsilon[{}^3S_1^1](p_3) + g(p_4), \\ g(p_1)g(p_2) &\to \Upsilon[{}^1S_0^8, {}^3S_1^8](p_3) + g(p_4), \\ g(p_1)q(p_2) &\to \Upsilon[{}^1S_0^8, {}^3S_1^8](p_3) + q(p_4), \\ q(p_1)\bar{q}(p_2) &\to \Upsilon[{}^1S_0^8, {}^3S_1^8](p_3) + g(p_4). \end{aligned} \tag{3}$$

These differential partonic cross sections, which are needed in Eq. (2), have been calculated in fixed-order perturbation theory in the literature. For the color singlet (CS), one has (see for instance Ref. [15])

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{5\pi^2\alpha_s^3[\hat{s}^2(\hat{s}-1)^2 + \hat{t}^2(\hat{t}-1)^2 + \hat{u}^2(\hat{u}-1)^2]}{216 m_b^5 \hat{s}^2(\hat{s}-1)^2(\hat{t}-1)^2(\hat{u}-1)^2}. \tag{4}$$

The normalized Mandelstam variables are defined as

$$\hat{s} = \frac{(p_1+p_2)^2}{4m_b^2}, \qquad \hat{t} = \frac{(p_1-p_3)^2}{4m_b^2}, \qquad \hat{u} = \frac{(p_1-p_4)^2}{4m_b^2}, \tag{5}$$

with $m_b \simeq 4.75$ GeV. The factorization scale μ_f is chosen as $\mu_f = \sqrt{4m_b^2 + p_t^2}$. The partonic cross sections for the color octet (CO) have been calculated in Refs. [11,31]. The K factor for the CS contribution has been calculated for the process $p\bar{p}(p) \to \Upsilon(1S)$ in Ref. [15], which we have employed for the numerical calculations presented here. It is assumed that the K factor is not sensitive to $\sqrt{s}$. The CO contributions are taken at LO, since the NLO corrections, which have also been calculated for $p\bar{p}(p) \to \Upsilon(1S)$, are small [11].

Using these inputs, we show the transverse momentum distributions $d\tilde{\sigma}/dp_t$ in Fig. 1 for the processes $pp \to \Upsilon(5S)$ at the LHC with $\sqrt{s} = 7$ TeV in the transverse momentum range 3 GeV $< p_t <$ 50 GeV, where $\log(p_t/m_{\Upsilon(5S)})$ is not large enough to necessitate the resummation of the logarithms [32–34]. The integrated normalized cross sections $\tilde{\sigma}_N$ are given in Table I.

For the long-distance part, we need nonperturbative input. The CS LDMEs are given by the radial wave function at the origin and can be extracted from the partial e^+e^- widths via the van Royen–Weisskopf formula. Using the Particle Data Group values [35] for the leptonic partial widths as input, and $m_{\Upsilon(5S)} = 10876$ MeV, $m_{\Upsilon(6S)} = 11019$ MeV, we find at NLO $|R(0)|^2_{\Upsilon(5S)} = 2.37\ \mathrm{GeV}^3$ and $|R(0)|^2_{\Upsilon(6S)} = 1.02\ \mathrm{GeV}^3$. The radial wave function at the origin, $R(0)$, is related to the LDME via $\langle O^{H3}S_1^1\rangle = 3|R(0)|^2/(4\pi)$.

The CO LDMEs can only be extracted from the experimental data on differential distributions. This has been done for the $\Upsilon(1S, 2S, 3S)$ states by fitting the data on $\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-$. We do not have the corresponding nonperturbative input for $\Upsilon(5S, 6S)$ at the current stage. Once the p_t distributions in these states have been measured, the CO matrix elements can be extracted from a NRQCD-based analysis of the data.

For this work, we attempt an estimate for $\Upsilon(5S)$ and $\Upsilon(6S)$ by adopting the full range from no CO contribution (lower bound) to the LDMEs estimated from $\Upsilon(3S)$ (upper bound). Generically, it is believed that the contribution of the CO LDMEs in the hadroproduction of the $\Upsilon(nS)$ decreases as the principal number n increases. Hence, our predicted range can be viewed as conservative. We

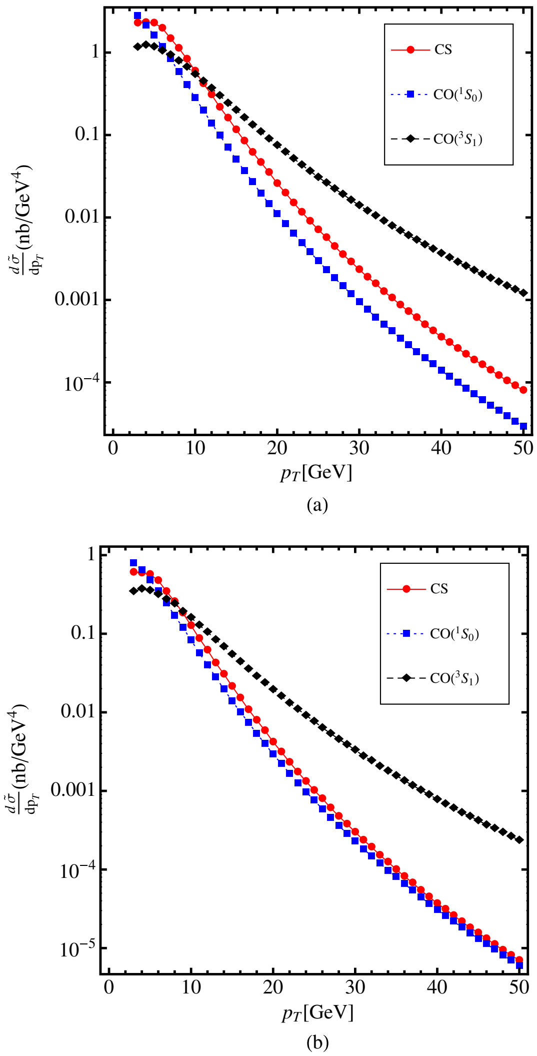

FIG. 1 (color online). Individual contributions ($^3S_1^1$ solid lines, $^3S_1^8$ dashed lines, $^1S_0^8$ dotted lines; CO contributions are multiplied by 10^{-2}) for the normalized transverse momentum distributions $d\tilde{\sigma}/dp_t$ (explained in the text) for the process $pp \to \Upsilon(5S)$ at the LHC with (a) $\sqrt{s} = 7$ TeV for $|y| < 2.5$ and (b) $2 < |y| < 4.5$. (The corresponding curves for $\Upsilon(6S)$ are almost identical on a logarithmic plot.) The p_t integrated values are given in Table I.

extract the values from data on $pp \to \Upsilon(3S)$ by the CMS Collaboration [8] for $p_t > 3$ GeV. The advantage of using the estimates from $\Upsilon(3S)$ is the negligibility of feed-down contributions of higher lying states, which is, for example, present in $\Upsilon(1S, 2S)$ and makes the extraction somewhat more biased. We find $\langle O^H\,{}^1S_0^8\rangle = (-0.95 \pm 0.38)10^{-2}$ GeV^3 and $\langle O^H\,{}^3S_1^8\rangle = (3.46 \pm 0.21)10^{-2}$ GeV^3 and obtain good agreement with the data with $\chi^2/\text{d.o.f.} = 4.3/5$, depicted in Fig. 2 (left-hand). Our findings are in agreement with Ref. [16]. There is a small discrepancy of 1.2σ with $\langle O^H\,{}^3S_1^8\rangle = (2.71 \pm 0.13)10^{-2}$ GeV^3, which may be due to the fact that in Ref. [16], P-wave contributions are also considered, which can account for the

TABLE I. Integrated normalized cross sections $\tilde{\sigma}_N$, shown in Fig. 1 (in units of nb/GeV^3; CO channels are multiplied by 10^{-2}) for the processes $p\bar{p}(p) \to \Upsilon(5S, 6S)$, assuming a transverse momentum range 3 GeV $< p_t <$ 50 GeV. The rapidity range $|y| < 2.5$ has been assumed for the Tevatron experiments (CDF and D0) at 1.96 TeV, and for the LHC experiments (ATLAS and CMS) at 7, 8 and 14 TeV; the rapidity range $2.0 < y < 4.5$ is used for the LHCb.

		$\Upsilon(5S)$			$\Upsilon(6S)$	
	$^3S_1^1$	$^3S_1^8$	$^1S_0^8$	$^3S_1^1$	$^3S_1^8$	$^1S_0^8$
Tevatron	2.72	1.73	1.75	2.54	1.66	1.60
LHC 7	13.25	9.49	9.06	12.44	9.16	8.32
LHCb 7	3.13	2.78	2.65	2.93	2.67	2.43
LHC 8	15.35	11.15	10.57	14.41	10.75	9.73
LHCb 8	3.80	3.35	3.17	3.56	3.22	2.92
LHC 14	27.62	21.15	18.76	25.98	20.48	17.30
LHCb 14	7.99	6.91	6.45	7.50	6.67	5.92

smaller value. Refitting the data has several advantages; we can account for large error correlations, shown in Fig. 2 (right-hand), of the LDMEs and get a consistent framework from the extraction to the final theory prediction. Certainly, the measurement of the $\Upsilon(5S)$ transitions will also strongly improve the estimates for the $\Upsilon(6S)$ by getting further information about the LDMEs of the higher-lying states.

For the exclusive production processes $p\bar{p}(p) \to \Upsilon(5S, 6S) \to (\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-)\pi^+\pi^-$, we combine the results from the cross sections discussed earlier and the branching ratios for the $\Upsilon(nS)$ decays, which are listed in Table II. Note that in this table, the branching fractions of $\Upsilon(5S) \to \Upsilon(1S, 2S, 3S)\pi^+\pi^-$ are taken from the experimental data, and thus no model dependence is introduced. For the estimate for the branching ratio of $\Upsilon(6S)$, we rely on the rescattering model [20], as the Belle anomaly seen in the $\Upsilon(5S)$ decays can be well explained. In this model, the $\Upsilon(6S) \to \Upsilon(1S, 2S, 3S)\pi^+\pi^-$ channels are also expected to have partial widths of about 1 MeV. Possible variations in the estimates of the off-mass-shell effects due to different parametrizations are neglected,

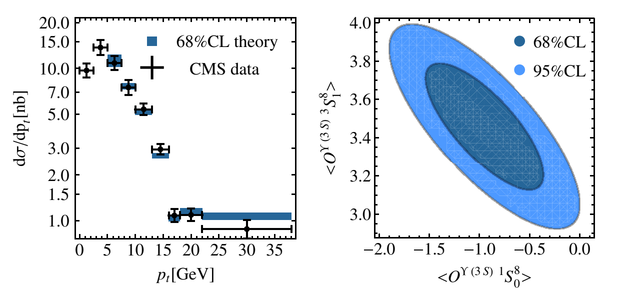

FIG. 2 (color online). Estimates of the LDMEs for $\Upsilon(3S)$ by fitting data on $\Upsilon(3S) \to \mu^+\mu^-$ by the CMS Collaboration [8] with $p_t > 3$ GeV. The fit is shown to the left, while the error correlation of the parameters is shown to the right.

TABLE II. Branching ratios for $\Upsilon(5S)$ and $\Upsilon(6S)$. All input values are taken from the PDG [35], except for the $\Upsilon(6S)$ entries, which are estimated from the scattering model [20].

$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-)$	$(0.53 \pm 0.06)\%$
$\mathcal{B}(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)$	$(0.78 \pm 0.13)\%$
$\mathcal{B}(\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-)$	$(0.48 \pm 0.18)\%$
$\mathcal{B}(\Upsilon(6S) \to \Upsilon(1S)\pi^+\pi^-)$	$\approx 0.4\%$
$\mathcal{B}(\Upsilon(6S) \to \Upsilon(2S)\pi^+\pi^-)$	(0.4–1.2)%
$\mathcal{B}(\Upsilon(6S) \to \Upsilon(3S)\pi^+\pi^-)$	(1.2–2.5)%
$\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$	$(2.48 \pm 0.05)\%$
$\mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-)$	$(1.93 \pm 0.17)\%$
$\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)$	$(2.18 \pm 0.21)\%$

as we do not expect them to be large. Again, we remain on the conservative side by adding the errors on the branching ratios linearly for the upper and lower bounds.

The total cross sections for the processes $p\bar{p}(p) \to \Upsilon(5S, 6S) \to (\Upsilon(nS) \to \mu^+\mu^-)\pi^+\pi^-$ $(n = 1, 2, 3)$ in pb at the Tevatron ($\sqrt{s} = 1.96$ TeV) and the LHC ($\sqrt{s} =$ 7, 8, 14 TeV), assuming the rapidity intervals described in Table I, are given in Table III. They are the principal results derived in this paper and deserve a number of comments. In calculating the cross sections, we have included the next-to-leading-order contributions by rescaling the available results for the process $p\bar{p}(p) \to \Upsilon(1S)$ [15]. Fixing the center-of-mass energy and the rapidity interval, the cross sections for each of the six processes $pp(\bar{p} \to \Upsilon(5S, 6S) \to (\Upsilon(nS) \to \mu^+\mu^-)\pi^+\pi^-$ $(n = 1, 2, 3)$ are bounded in an interval spanning roughly 1 order of magnitude, mainly due to our current ignorance of the CO matrix elements for the $\Upsilon(5S)$ and $\Upsilon(6S)$. We note that the cross sections increase by an order of magnitude in going from the Tevatron ($p\bar{p}$; $\sqrt{s} = 1.96$ TeV) to the LHC (pp; $\sqrt{s} =$ 14 TeV), with the cross sections at 8 TeV [with the currently highest luminosity of about 20 $(\mathrm{fb})^{-1}$] typically of $O(1)$ pb for the ATLAS and the CMS experimental setups. Thus, the estimates presented here offer achievable targets for future experimental searches.

Recently, the CMS Collaboration has presented the search for a new bottomonium state, denoted as X_b, decaying to $\Upsilon(1S)\pi^+\pi^-$, based on a data sample corresponding to an integrated luminosity of 20.7 fb^{-1} at $\sqrt{s} =$ 8 TeV [29]. No evidence is found for X_b, and the upper limit at a confidence level of 95% on the production cross section of X_b times the decay branching fraction of $X_b \to \Upsilon(1S)\pi^+\pi^-$ is set to be

$$\frac{\sigma(pp \to X_b \to \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-)} < 0.02, \tag{6}$$

where the stated upper bound corresponds to the X_b mass around 10.876 GeV.

Using the current experimental data on the $\sigma(pp \to \Upsilon(2S))$, we can convert the above ratio to absolute cross sections and compare them with our results. Since the masses of $\Upsilon(2S)$ and X_b are close, it may be a good approximation to assume that the ratio given in Eq. (6) is insensitive to the kinematics cuts. Using the CMS result at $\sqrt{s} = 7$ TeV in Ref. [8],

$$\sigma(pp \to \Upsilon(2S)X)\mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 1.55 \text{ nb}, \tag{7}$$

we get

$$\sigma(pp \to X_b \to \Upsilon(1S)\pi^+\pi^-)\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) < 7.1 \text{ pb}, \tag{8}$$

where the ranges $3 \text{ GeV} < p_t < 50 \text{ GeV}$ and $|y| < 2.4$ have been used. Identifying X_b with $\Upsilon(5S)$, the above upper bound is larger than our predictions by a factor of $\mathcal{O}(10)$. With increased luminosity, the next round of experiments at the LHC will reach the required experimental sensitivity. We also note that the current CMS analysis is based on a stiff cut on p_t ($p_t > 13.5$ GeV). Lowering this cut will help significantly in the discovery of X_b [$\Upsilon(5S)$ or Y_b].

There are two competing scenarios, which can be explored in the future data analysis:

(i) Experiments are able to establish the signals in the processes $p\bar{p}(p) \to \Upsilon(5S, 6S) \to (\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-)\pi^+\pi^-$, in approximate agreement with the estimates presented here, based on the rescattering formalism. This would then extend the application of the NRQCD techniques to the yet unexplored sectors $\Upsilon(5S)$ and $\Upsilon(6S)$ in hadroproduction. Note that the estimates can be easily adopted for any other scenario which relies on the anomaly coming from $\Upsilon(5S)$. In this case also, one expects $\Upsilon(6S)$ to reflect the enhanced branching ratios to $\Upsilon(nS)\pi^+\pi^-$, as seen in the decays of $\Upsilon(5S)$. Any such scenario will be tested as well. Changing the estimated branching ratio, listed in Table II, is straightforward.

(ii) Experiments are able to establish only the process $p\bar{p}(p) \to \Upsilon(5S) \to (\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-)\pi^+\pi^-$, but not $p\bar{p}(p) \to \Upsilon(6S) \to (\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-)\pi^+\pi^-$, which, in our opinion, would speak against the rescattering mechanism and strengthen the case of $Y_b(10890)$ as the source of the anomalous dipion transitions [21–24]. In this case, experiments would provide a calibration of the cross section for the exotic hadron $Y_b(10890)$—certainly a valuable piece of information in this unexplored QCD sector.

Once enough data are available, one could undertake a Dalitz analysis of the $\Upsilon(1S, 2S, 3S)\pi^+\pi^-$ final states to determine the origin of the charged tetraquark states $Z_b(10610)$ and $Z_b(10650)$, discovered by the Belle Collaboration [28] along similar lines. In this regard, we wish to point out that recently a charged four-quark state, $Z_c(3900)$, has been discovered by the BESIII Collaboration [36], confirmed by Belle [37], in the decays $Y(4260) \to Z_c(3900)^\pm\pi^\mp \to J/\psi\pi^+\pi^-$, where $Y(4260)$ is an exotic $c\bar{c}$ state [2], possibly a tetraquark [24,38]. Another

TABLE III. Total cross sections for the processes $p\bar{p}(p) \to \Upsilon(5S, 6S) \to (\Upsilon(nS) \to \mu^+\mu^-)\pi^+\pi^-$ ($n = 1, 2, 3$) in pb at the Tevatron ($\sqrt{s} = 1.96$ TeV) and the LHC ($\sqrt{s} = 7$, 8, 14 TeV), assuming the rapidity intervals described in Table I. The error estimates are from the variation of the central values of the CO LDMEs and the various decay branching ratios; see text.

	$\Upsilon(5S)$			$\Upsilon(6S)$		
	$n = 1$	$n = 2$	$n = 3$	$n = 1$	$n = 2$	$n = 3$
Tevatron	[0.18, 0.98]	[0.18, 1.35]	[0.09, 1.03]	[0.06, 0.57]	[0.04, 1.38]	[0.15, 3.26]
LHC 7	[0.86, 5.26]	[0.86, 6.74]	[0.44, 5.56]	[0.29, 3.13]	[0.21, 7.57]	[0.72, 17.9]
LHCb 7	[0.20, 1.48]	[0.20, 1.89]	[0.10, 1.56]	[0.07, 0.89]	[0.05, 2.16]	[0.17, 5.13]
LHC 8	[0.99, 6.17]	[0.99, 7.89]	[0.51, 6.52]	[0.34, 3.67]	[0.25, 8.87]	[0.83, 21.0]
LHCb 8	[0.25, 1.78]	[0.25, 2.28]	[0.13, 1.88]	[0.08, 1.08]	[0.06, 2.61]	[0.20, 6.19]
LHC 14	[1.79, 11.7]	[1.79, 14.9]	[0.92, 12.3]	[0.61, 7.02]	[0.45, 17.0]	[1.50, 40.2]
LHCb 14	[0.52, 3.70]	[0.52, 4.74]	[0.27, 3.91]	[0.18, 2.25]	[0.13, 5.43]	[0.43, 12.9]

charged four-quark state $Z_c(4025)$ was found in $e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$ at $\sqrt{s} = 4.26$ GeV by the BESIII Collaboration [39]. These observations indirectly support the interpretation that $Z_b(10610)$ and $Z_b(10650)$ are likewise the decay products of the exotic state $Y_b(10890)$. We note that $Z_c(3900)$ is also found in the analysis based on CLEO data [40]. These charmonium-like states can be accessed at hadron colliders in the final state $J/\psi^{(\prime)}\pi^+\pi^-$.

Using the available NRQCD results, we have explored the hadroproduction of bottomonium states above the $B\bar{B}$ threshold at the LHC and the Tevatron. The large branching fractions for the decays $\Upsilon(5S) \to \Upsilon(1S, 2S, 3S)\pi^+\pi^-$, observed by Belle [17,18], offer an opportunity to access the $\Upsilon(5S)$ in hadronic collisions. Attributing the large enhancement in the dipionic transitions at the $\Upsilon(5S)$ to the rescattering phenomenon [20], very similar dipionic rates are expected for the $\Upsilon(6S)$ decays, which we have also worked out and can easily be generalized for other scenarios. By the above computations, with results shown in Table III, we have shown that the experiments at the LHC have in principle the sensitivity to detect the bottomonium states $\Upsilon(5S)$ and $\Upsilon(6S)$, extending significantly their current experimental reach, and exploring thereby also the nature of the exotic states $Y_b(10890)$, $Z_b(10600)$ and $Z_b(10650)$, discovered in e^+e^- annihilation experiments. As the observed decay widths for $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ show an anomalous enhancement by 2 orders of magnitude, and our estimates presented in Table III are uncertain by at most an order of magnitude, the rescattering mechanism as the source of this enhancement can be tested. Once the p_t spectrum of the $\Upsilon(5S)$ is measured, the data will be precise enough to unambiguously pin down the nature of the resonance, $\Upsilon(5S)$ or Y_b. Our lower bounds presented in Table III put the measurement of the $\Upsilon(5S)$ within reach of the next round of experiments at the LHC.

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