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Cross sections of inclusive $\psi(2S)$ and $X(3872)$ production from b-hadron decays in pp collisions and comparison with ATLAS, CMS, and LHCb data

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Abstract

We study the cross sections for the inclusive production of $\psi(2S)$ and $X(3872)$ hadrons in pp collisions at the LHC at two different center-of-mass energies and compare them with experimental data obtained by the ATLAS, CMS, and LHCb Collaborations.

PACS: 12.38.Bx, 12.39.St, 13.85.Ni, 14.40.Nd

1 Intoduction

Some time ago, Paolo Bolzoni and two of us calculated the cross section for the inclusive production of J/ψ and $\psi(2S)$ mesons originating from decays of B mesons produced in $p\bar{p}$ collisions with center-of-mass energy $\sqrt{S} = 1.96$ TeV at the Fermilab Tevatron and in pp collisions with $\sqrt{S} = 7$ TeV at the CERN LHC at next-to-leading order (NLO) in the framework of the general-mass variable-flavor number scheme (GM-VFNS) in connection with nonrelativistic-QCD (NRQCD) factorization [1]. In Ref. [1], the transverse momentum (p_T) distributions of such nonprompt J/ψ mesons measured by the CDF II [2, 3], CMS [4, 5], LHCb [6, 7], ATLAS [8], and ALICE [9] Collaborations were found to be very well described by our predictions, with respect to both absolute normalization and line shape. Similarly, the p_T distributions of $\psi(2S)$ nonprompt production measured by CDF II [3], CMS [5], and LHCb [7] were rather well described by our calculations.

In 2003, a narrow charmonium-like state was discovered in exclusive $B^+ \to J/\psi K^+\pi^+\pi^-$ decays by the BELLE Collaboration [10]. The subsequent development was described in detail in publications by CMS [11] and ATLAS [12], where the first measurements of $X(3872)$ at the LHC were reported, and in two review articles [13, 14].

In 2017, ATLAS published measurements of the $\psi(2S)$ and $X(3872)$ cross sections in pp collisions at $\sqrt{S} = 8$ TeV, for both prompt and nonprompt production [12]. Both the $\psi(2S)$ and $X(3872)$ hadrons were detected via their decays to $J/\psi\pi^+\pi^-$. The experimental results for prompt production were found to be in agreement with predictions of nonrelativistic QCD (NRQCD) factorization [15, 16, 17]. The $\psi(2S)$ nonprompt production cross section was compared with FONLL predictions [18] and also found to agree very well with the ATLAS data [12].

Also the cross section of $X(3872)$ nonprompt production measured by ATLAS [12] was compared with theory. Specifically, the nonprompt $\psi(2S)$ production cross section evaluated in the FONLL scheme was rescaled by the ratio of branching fractions[1]

$$R_B = \frac{\mathrm{Br}(B \to X(3872) + X)\mathrm{Br}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathrm{Br}(B \to \psi(2S) + X)\mathrm{Br}(\psi(2S) \to J/\psi\pi^+\pi^-)}\,, \tag{1}$$

which was evaluated using the result $\mathrm{Br}(B \to X(3872) + X)\mathrm{Br}(X(3872) \to J/\psi\pi^+\pi^-) = (1.9 \pm 0.8) \times 10^{-4}$ extracted in Ref. [20] from Tevatron data [21] and the values $\mathrm{Br}(B \to \psi(2S) + X) = (3.07 \pm 0.21) \times 10^{-3}$ and $\mathrm{Br}(\psi(2S) \to J/\psi\pi^+\pi^-) = 0.3446 \pm 0.0030$ quoted by the Particle Data Group [22] to give

$$R_B^{[20]} = 0.18 \pm 0.08\,. \tag{2}$$

This led to an overestimation of the ATLAS data by a large factor, increasing with p_T from about 4 to about 8 [12].

[1]Notice that Eq. (1) implies a summation over the various B-hadron species and that the tacitly assumed universality of R_B is based on the assumption that the B-hadron fragmentation functions (FFs) are process independent, as they should by the factorization theorem [19].

We observe that the value of R_B in Eq. (2) is a factor of 5 larger than the one measured by ATLAS in a two-lifetime fit [12],

$$R_B^{\rm 2L} = (3.57 \pm 0.348) \times 10^{-2}. \tag{3}$$

If this lower value had been used instead of the larger value based on Ref. [20], the differential cross section $d\sigma/dp_T$ of $X(3872)$ nonprompt production calculated in the FONLL framework would have been in approximate agreement with the ATLAS measurement [12]. We are not aware of an explanation for the discrepancy between the two values of R_B.

The $\psi(2S)$ and $X(3872)$ processes considered here differ in the mechanisms of both production from B-hadron decay and decay to $J/\psi\pi^+\pi^-$. The $\psi(2S)$ meson is a pure $c\bar{c}$ state, whereas the $X(3872)$ hadron is believed to be a quantum-mechanical mixture of the pure $c\bar{c}$ state $\chi_{1c}(2P)$ and a $D^0\bar{D}^{*0}$ molecule, which is predominantly produced via its $\chi_{1c}(2P)$ component [15, 16, 17]. These differences are reflected in the fact that R_B is so different from unity. The value of R_B could be predicted from purely theoretical considerations, *e.g.*, on the basis of effective field theories derived from QCD in combination with hadron models. However, this would reach beyond the scope of this work. Instead, we adopt here a more heuristic approach to R_B, based on the interpretation of experimental data.

In the present work, we shall present the results of an alternative calculation of $d\sigma/dp_T$ for $\psi(2S)$ nonprompt production in the kinematic range relevant for the CMS [11] and ATLAS [12] measurements, based on the GM-VFNS. The calculation of $d\sigma/dp_T$ for a fixed rapidity (y) range was described in detail in Ref. [1], which is based on the earlier analysis [23] based on the zero-mass variable-flavor-number scheme (ZM-VFNS), where bottom is included among the massless quark flavors. An alternative GM-VFNS approach, in the SACOT-m_T scheme, was described in Ref. [24], but cross sections of J/ψ or $\psi(2S)$ production have not yet been calculated in that scheme.

2 Results

We start by considering $\psi(2S)$ nonprompt hadroproduction. Its theoretical treatment in the GM-VFNS was described in Ref. [1]. Without any additional assumptions, we thus obtain the results for the differential cross section $d\sigma/(dp_T dy)$ at $\sqrt{S} = 8$ TeV, averaged over the rapidity range $|y| < 0.75$, which are presented for $10 < p_T < 70$ GeV in Fig. 1(a) and compared with the ATLAS data [12]. We adopt the choices of renormalization and (unified) factorization scales, μ_R and μ_F, from our recent analysis of $B^{\pm}$-meson hadroproduction at the LHC [25] by setting $\mu_R = \xi\mu_T$ and $\mu_F = 0.49\mu_T$, with $\mu_T = \sqrt{p_T^2 + 4m_b^2}$ and $m_b = 4.5$ GeV, and varying ξ between 0.5 and 2 about its default value 1 to estimate the theoretical uncertainty. We use set CT14nlo [26] of parton distribution functions (PDFs) and the B-meson fragmentation functions (FFs) from Ref. [27]. As in the ATLAS analysis [12], we include the B^+, B_s^0, and Λ_b^0 hadrons and their antiparticles [28] taking into account the respective $b \to B$-hadron branching fractions as given in Ref. [22]. Here, we select the

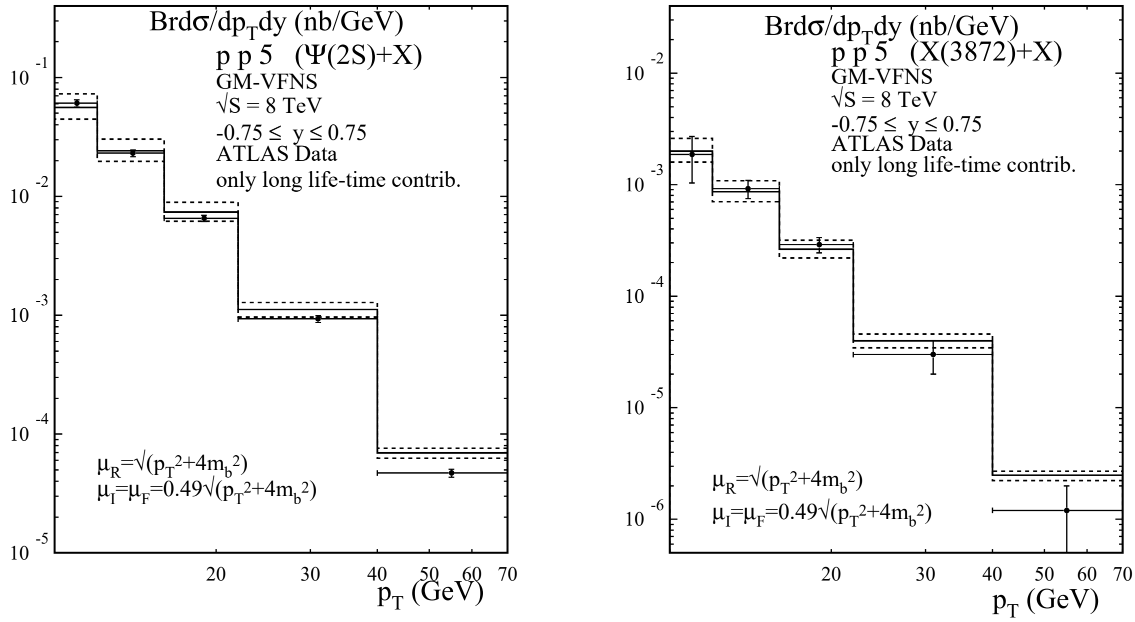

Figure 1: Double differential cross sections times branching fractions for (a) $\psi(2S)$ (left) and (b) $X(3872)$ (right) nonprompt hadroproduction at $\sqrt{S} = 8$ TeV, averaged over y in the region $|y| \leq 0.75$, as a function of p_T. The solid points with error bars represent the ATLAS data [12]. The solid and the upper and lower dashed histograms represent our NLO GM-VFNS predictions for $\xi = 1, 0.5, 2$, respectively.

ATLAS dataset corresponding to the long-lifetime contribution determined by the two-lifetime fit, where the short-lifetime contribution is attributed to the $B_c \to \psi(2S) + X$ decay. The data corresponding to the one-lifetime fit are quite similar, except that the cross sections in the first two p_T bins are slightly larger. We observe from Fig. 1(a) that the agreement between experiment and theory is quite good, except for the uppermost p_T bin.

We now turn to $X(3872)$ nonprompt hadroproduction. We convert our results for $\psi(2S)$ nonprompt hadroproduction shown in Fig. 1(a) to the $X(3872)$ case by including the R_B^{2L} ratio listed in Eq. (3). In Fig. 1(b), we compare the outcome with the respective ATLAS data, again for the two-lifetime fit [12]. The ATLAS data for the single-lifetime fit are somewhat larger in the first two p_T bins. We emphasize that the value of R_B^{2L} in Eq. (3) comes from the same experimental analysis as the cross sections $d\sigma/dp_T$ of inclusive $\psi(2S)$ and $X(3872)$ production, albeit from a different observable, namely from the ratio of long-lived $X(3872)$ to long-lived $\psi(2S)$ production rates with additional information from the p_T dependencies [see Fig. 4(b) in Ref. [12]]. Of course, one would like to have this information also from an independent experiment—for example from $\psi(2S)$ and $X(3872)$ production in e^+e^- annihilation. Unfortunately such information is not available yet.

The quality of agreement between data and theoretical predictions is similar for $\psi(2S)$ and $X(3872)$ production. It would be interesting to perform a comparative analysis of $\psi(2S)$ and $X(3872)$ production in e^+e^- annihilation. After all, the R_B ratio should not depend on the production mechanism.

Our results for $X(3872)$ nonprompt hadroproduction shown in Fig. 1(b) were obtained using the value of R_B^{2L} given in Eq. (3). To obtain a cross-check, we determine R_B by fitting our theory prediction to the ATLAS data [12] for the five p_T bins, assuming Gaussian errors. We thus obtain

$$R_B^{\mathrm{ATLAS}} = \left(3.41 \pm 0.37 \begin{array}{c} +0.63 \\ -0.56 \end{array} \right) \times 10^{-2}\,, \tag{4}$$

where the first error is propagated from the experimental data and the second errors are due to the uncertainty of the theory prediction from ξ variations as explained above. This value agrees within errors with the value given in Eq. (3) obtained from the two-lifetime fit in Ref. [12]. Its central value is slightly smaller and its error somewhat larger than in Eq. (3). We conclude that the determinations of R_B from the two-lifetime fit and from the cross-section analyses by ATLAS are consistent with each other.

To obtain yet another check of our assumption that the R_B value in Eq. (3) [12] is realistic, we use it for a comparison with the inclusive cross section $d\sigma/dp_T$, integrated over $|y| < 1.2$, of nonprompt $X(3872)$ production measured by the CMS Collaboration at $\sqrt{S} = 7$ TeV [11]. In Ref. [11], this cross section was not reported directly, but it can be calculated in four p_T bins from the prompt $X(3872)$ cross section times branching ratio (Table 7 in Ref. [11]) and the $X(3872)$ nonprompt fraction (Table 6 in Ref. [11]). Since both measurements have rather large uncertainties, the same is true also for the nonprompt cross section, but this should be sufficient for the sake of an approximate cross-check. In Ref. [11], CMS used as a benchmark their earlier measurement of the inclusive cross section of nonprompt $\psi(2S)$ production, also at $\sqrt{S} = 7$ TeV and for $|y| < 1.2$, but with a different p_T binning [5]. In Ref. [1], we compared these data with our prediction, which came as a continuous function in p_T. We now repeat this comparison adopting the very p_T binning from Ref. [5] and present the outcome in Fig. 2. The good agreement which is evident from Fig. 2 reassures us that our prediction of nonprompt $\psi(2S)$ production serves as a useful starting point for generating a prediction of nonprompt $X(3872)$ production.

We thus proceed by adjusting the p_T binning according to Ref. [11] and including the R_B value from Eq. (3). In Fig. 3(a), the outcome is compared with the inclusive cross section of nonprompt $X(3872)$ production extracted from Ref. [11] as explained above. We find satisfactory agreement within the rather large experimental errors, albeit not as good as for the ATLAS data [12] in Fig. 1(b). However, our predictions do not deviate more than 2 standard deviations from the CMS data [11]. It is obvious that there is no room for a discrepancy by a factor between 4 and 8 as claimed in Ref. [12]. The $\pm 10\%$ uncertainty in the R_B value in Eq. (3), which is not included in Fig. 3(a), does not affect this conclusion.

In turn, we may now use the CMS data [11] for an independent determination of R_B, just

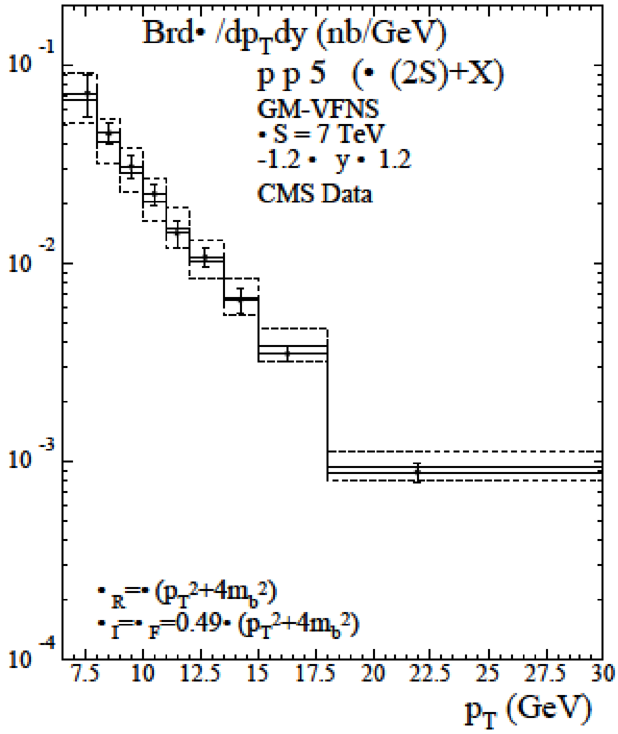

Figure 2: Double differential cross section times branching fraction for $\psi(2S)$ nonprompt hadroproduction at $\sqrt{S} = 7$ TeV, averaged over y in the region $|y| \leq 1.2$, as a function of p_T. The solid points with error bars represent the CMS data [5]. The solid and the upper and lower dashed histograms represent our NLO GM-VFNS predictions for $\xi = 1, 0.5, 2$, respectively.

as we did above with the ATLAS data [12]. We thus find

$$R_B^{\mathrm{CMS}} = \left(1.89 \pm 0.32 \begin{array}{c} +0.38 \\ -0.33 \end{array}\right) \times 10^{-2} \,. \tag{5}$$

As expected from Fig. 3(a), this result is smaller than the one in Eq. (3) from the two-lifetime fit in the ATLAS publication [12] and the one in Eq. (4) from matching our $\psi(2S)$ predictions to the ATLAS $X(3872)$ data [12]. For a consistency check, we compare the CMS $X(3872)$ data [11] with our predictions evaluated with the R_B value fitted to these data in Fig. 3(b), to find good agreement as expected.

We also simultaneously fit R_B to the nonprompt $X(3872)$ data from ATLAS [12] and CMS [11]. This is possibly problematic because the experimental (first) errors of R_B in Eqs. (4) and (5) from the individual fits do not overlap. In other words, the agreement of the underlying ATLAS [12] and CMS [11] data, gauged with respect to our universal NLO GM-VFNS predictions, is marginal. In fact, the combined fit to the $N = 9$ experimental data points yields a minimum χ^2 of $\chi^2_{\min} = 14.70$. Following a recommendation by the

Particle Data Group [22], we thus rescale the original Gaussian error of 0.24 with the enhancement factor $\sqrt{\chi^2_{\min}/(N-1)} = 1.36$. We so obtain

$$R_B^{\text{ATLAS+CMS}} = \left(2.54 \pm 0.33 \begin{array}{c} +0.49 \\ -0.43 \end{array}\right) \times 10^{-2}\,, \tag{6}$$

where the theoretical (second) error is determined as in Eqs. (4) and (5).

Finally, it is interesting to compare our results to recent data from the LHCb Collaboration on the dependence on the charged-particle multiplicity N of nonprompt $\psi(2S)$ and $X(3872)$ production, with subsequent decays to $J/\psi\pi^+\pi^-$, in pp collisions at $\sqrt{S} = 8$ TeV [29].[2] The study of the $X(3872)$ to $\psi(2S)$ ratio of nonprompt production cross sections as a function of N may help to shed light on the nature of the exotic $X(3872)$ state [30]. This ratio, which we identify with R_B, as we do in this paper, is presented in Fig. 4 of Ref. [29] for five intervals $[N_{\min}, N_{\max}]$ with weighted centers N. The results [31] are compiled in Table 1. We observe from Table 1 a slight increase of R_B with N, which is, however, not

[2]In Ref. [29], the $X(3872)$ hadron is denoted $\chi_{c1}(2S)$, an identification that was found to be disfavored through a dedicated NLO NRQCD analysis of prompt $X(3872)$ hadroproduction [15, 17].

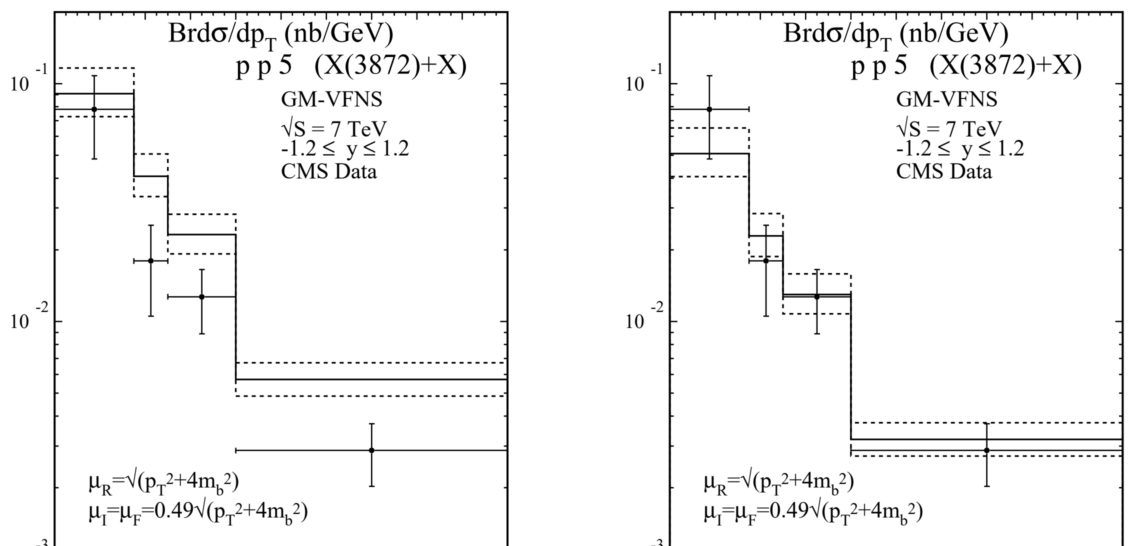

Figure 3: Differential cross sections times branching fractions for $X(3872)$ nonprompt hadroproduction at $\sqrt{S} = 7$ TeV, integrated over y in the region $|y| \leq 1.2$, as a function of p_T. The solid points with error bars are extracted from the CMS data [11]. The solid and the upper and lower dashed histograms represent our NLO GM-VFNS predictions for $\xi = 1, 0.5, 2$, respectively. The theoretical predictions were evaluated using the R_B values in (a) Eq. (3) (left) and (b) Eq. (5) (right).

$N_{\min}$	$N_{\max}$	N	$R_B \times 10^2$
0	40	30.8	$2.65 \pm 1.32 \pm 0.20$
40	60	50.3	$3.17 \pm 0.60 \pm 0.24$
60	80	69.3	$3.47 \pm 0.71 \pm 0.26$
80	100	88.8	$4.43 \pm 1.20 \pm 0.32$
100	200	118.3	$5.33 \pm 1.59 \pm 0.39$

Table 1: R_B for five different bins of charged-particle multiplicity N as measured by the LHCb Collaboration in pp collisions at $\sqrt{S} = 8$ TeV. The first and second errors are the uncorrelated and correlated uncertainties, respectively. The data are presented in Fig. 4 of Ref. [29].

statistically significant. As discussed in Ref. [29], a linear fit to these data points, without considering the correlated systematic uncertainty, gives a positive slope that is consistent with zero within 1.6 standard deviations. For this reason, it appears to be reasonable to fit a horizontal line to these data points. Specifically, we perform three fits using the uncorrelated uncertainties: one to the central data points, and one each to the central data points shifted up and down by their correlated uncertainties. We then take the upward and downward shifts of the central value to be the error due to the correlated uncertainties, which, in want of the correlation matrix, represents a conservative estimate. This yields

$$R_B^{\mathrm{LHCb}} = (3.48 \pm 0.39 \pm 0.26) \times 10^{-2}\,, \tag{7}$$

where the first and second errors stem from the uncorrelated and correlated uncertainties, respectively. The fit to the unshifted data points yields a χ^2 per degree of freedom as low as $\chi^2/4 = 0.67$, providing *a posteriori* a convincing justification for the zero-slope hypothesis. The value in Eq. (7) is in excellent agreement with the two-lifetime fit from ATLAS [12].

In Ref. [30], the LHCb data of prompt and nonprompt $X(3872)$ hadroproduction [29] were jointly fitted to a model, assuming that R_B is independent of N, as we do. Among other things, this yielded

$$R_B^{[30]} = (3.24 \pm 0.29) \times 10^{-2}\,, \tag{8}$$

which is consistent with our fit result in Eq. (7).

For the reader's convenience, we summarize in Table 2 the various values for R_B discussed in this paper.

3 Summary

We updated our prediction of the inclusive cross section of nonprompt $\psi(2S)$ hadroproduction at NLO in the GM-VFNS [1] and validated it by comparison with ATLAS [12] and CMS [5] data. From this, we obtained an analogous prediction for nonprompt $X(3872)$

Name	$R_B \times 10^2$	Source
$R_B^{[20]}$	18 ± 8	Extracted from CDF II data [21] in Ref. [20]
R_B^{2L}	3.57 ± 0.348	ATLAS [12]
R_B^{LHCb}	$3.48 \pm 0.39 \pm 0.26$	Extracted from LHCb data [29] here
$R_B^{[30]}$	3.24 ± 0.29	Extracted from LHCb data [29] in Ref. [30]
R_B^{ATLAS}	$3.41 \pm 0.37\ ^{+0.63}_{-0.56}$	Our fit to ATLAS data [12]
R_B^{CMS}	$1.89 \pm 0.32\ ^{+0.38}_{-0.33}$	Our fit to CMS data [11]
$R_B^{\mathrm{ATLAS+CMS}}$	$2.54 \pm 0.33\ ^{+0.49}_{-0.43}$	Our joint fit to ATLAS [12] and CMS [11] data

Table 2: Summary of the different R_B determinations discussed in this article.

hadrons by including the appropriate ratio R_B of branching fractions. In turn, this enabled us to determine R_B by fitting to ATLAS [12] and CMS [11] data of nonprompt $X(3872)$ production. This also provided us with a useful test bed to assess determinations of R_B by other authors [12, 20, 29, 30]. Our findings support the results for R_B obtained by ATLAS [12] and LHCb [29, 30], which undershoot a previous result [20] by a factor of about 1/5.

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References

[1] P. Bolzoni, B. A. Kniehl and G. Kramer, "Inclusive J/ψ and $\psi(2S)$ production from b-hadron decay in $p\bar{p}$ and pp collisions," Phys. Rev. D **88** (2013) 074035 [arXiv:1309.3389 [hep-ph]].

[2] D. Acosta *et al.* (CDF Collaboration), "Measurement of the J/ψ meson and b-hadron production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1960$ GeV," Phys. Rev. D **71** (2005) 032001 [arXiv:hep-ex/0412071 [hep-ex]].

[3] T. Aaltonen *et al.* (CDF Collaboration), "Production of $\psi(2S)$ mesons in $p\bar{p}$ collisions at 1.96 TeV," Phys. Rev. D **80** (2009) 031103(R) [arXiv:0905.1982 [hep-ex]].

[4] V. Khachatryan *et al.* (CMS Collaboration), "Prompt and non-nrompt J/ψ production in pp nollisions at $\sqrt{s} = 7$ TeV," Eur. Phys. J. C **71** (2011) 1575 [arXiv:1011.4193 [hep-ex]].

[5] S. Chatrchyan *et al.* (CMS Collaboration), "J/ψ and $\psi(2S)$ production in pp collisions at $\sqrt{s} = 7$ TeV," JHEP **02** (2012) 011 [arXiv:1111.1557 [hep-ex]].

[6] R. Aaij *et al.* (LHCb Collaboration), "Measurement of J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV," Eur. Phys. J. C **71** (2011) 1645 [arXiv:1103.0423 [hep-ex]].

[7] R. Aaij *et al.* (LHCb Collaboration), "Measurement of $\psi(2S)$ meson production in pp collisions at $\sqrt{s}$=7 TeV," Eur. Phys. J. C **72** (2012) 2100 [Erratum: Eur. Phys. J. C **80** (2020) 49] [arXiv:1204.1258 [hep-ex]].

[8] G. Aad *et al.* (ATLAS Collaboration), "Measurement of the differential cross-sections of inclusive, prompt and non-prompt J/ψ production in proton–proton collisions at $\sqrt{s} = 7$ TeV," Nucl. Phys. B **850** (2011) 387 [arXiv:1104.3038 [hep-ex]].

[9] B. Abelev *et al.* (ALICE Collaboration), "Measurement of prompt J/ψ and beauty hadron production cross sections at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV," JHEP **11** (2012) 065 [arXiv:1205.5880 [hep-ex]].

[10] S. K. Choi *et al.* (Belle Collaboration), "Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays," Phys. Rev. Lett. **91** (2003) 262001 [arXiv:hep-ex/0309032 [hep-ex]].

[11] S. Chatrchyan *et al.* (CMS Collaboration), "Measurement of the $X(3872)$ production cross section via decays to $J/\psi\pi^{+}\pi^{-}$ in pp collisions at $\sqrt{s} = 7$ TeV," JHEP **04** (2013) 154 [arXiv:1302.3968 [hep-ex]].

[12] M. Aaboud *et al.* (ATLAS Collaboration), "Measurements of $\psi(2S)$ and $X(3872) \to J/\psi\pi^{+}\pi^{-}$ production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," JHEP **01** (2017) 117 [arXiv:1610.09303 [hep-ex]].

[13] A. Ali, J. S. Lange and S. Stone, "Exotics: Heavy pentaquarks and tetraquarks," Prog. Part. Nucl. Phys. **97** (2017) 123 [arXiv:1706.00610 [hep-ph]].

[14] N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C.-P. Shen, C. E. Thomas, A. Vairo and C.-Z. Yuan, "The XYZ states: Experimental and theoretical status and perspectives," Phys. Rept. **873** (2020) 1 [arXiv:1907.07583 [hep-ex]].

[15] M. Butenschoen, Z.-G. He and B. A. Kniehl, "Next-to-leading-order nonrelativistic QCD disfavors the interpretation of $X(3872)$ as $\chi_{c1}(2P)$," Phys. Rev. D **88** (2013) 011501(R) [arXiv:1303.6524 [hep-ph]].

[16] C. Meng, H. Han and K.-T. Chao, "$X(3872)$ and its production at hadron colliders," Phys. Rev. D **96** (2017) 074014 [arXiv:1304.6710 [hep-ph]].

[17] M. Butenschoen, Z.-G. He and B. A. Kniehl, "Deciphering the $X(3872)$ via its Polarization in Prompt Production at the CERN LHC," Phys. Rev. Lett. **123** (2019) 032001 [arXiv:1906.08553 [hep-ph]].

[18] M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason and G. Ridolfi, "Theoretical predictions for charm and bottom production at the LHC," JHEP **10** (2012) 137 [arXiv:1205.6344 [hep-ph]].

[19] J. C. Collins, "Hard-scattering factorization with heavy quarks: A General treatment," Phys. Rev. D **58** (1998) 094002 [hep-ph/9806259].

[20] P. Artoisenet and E. Braaten, "Production of the $X(3872)$ at the Tevatron and the LHC," Phys. Rev. D **81** (2010) 114018 [arXiv:0911.2016 [hep-ph]].

[21] G. Bauer (CDF II Collaboration), "The $X(3872)$ at CDF II," Int. J. Mod. Phys. A **20** (2005) 3765 [arXiv:hep-ex/0409052 [hep-ex]].

[22] P. A. Zyla *et al.* (Particle Data Group), "Review of Particle Physics," Prog. Theor. Exp. Phys. **2020** (2020) 083C01.

[23] B. A. Kniehl and G. Kramer, "Inclusive J/ψ and $\psi(2S)$ production from B decay in $p\bar{p}$ collisions," Phys. Rev. D **60** (1999) 014006 [arXiv:hep-ph/9901348 [hep-ph]].

[24] I. Helenius and H. Paukkunen, "Revisiting the D-meson hadroproduction in general-mass variable flavour number scheme," JHEP **05** (2018) 196 [arXiv:1804.03557 [hep-ph]].

[25] M. Benzke, B. A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, "B-meson production in the general-mass variable-flavour-number scheme and LHC data," Eur. Phys. J. C **79** (2019) 814 [arXiv:1907.12456 [hep-ph]].

[26] S. Dulat, T.-J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump and C.-P. Yuan (CTEQ-TEA Collaboration), "New parton distribution functions from a global analysis of quantum chromodynamics," Phys. Rev. D **93** (2016) 033006 [arXiv:1506.07443 [hep-ph]].

[27] B. A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, "Finite-mass effects on inclusive B-meson hadroproduction," Phys. Rev. D **77** (2008) 014011 [arXiv:0705.4392 [hep-ph]].

[28] V. Kartvelishvili (ATLAS Collaboration) (private communication).

[29] R. Aaij *et al.* (LHCb Collaboration), "Observation of Multiplicity Dependent Prompt $\chi_{c1}(3872)$ and $\psi(2S)$ Production in pp Collisions," Phys. Rev. Lett. **126** (2021) 092001 [arXiv:2009.06619 [hep-ex]].

[30] E. Braaten, L.-P. He, K. Ingles, and J. Jiang, "Production of $X(3872)$ at high multiplicity," Phys. Rev. D **103** (2021) L071901 [arXiv:2012.13499 [hep-ph]].

[31] J. M. Durham (private communication).