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Leading-power $\psi(2S)$ production at large P_T with v^2 relativistic corrections

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We report on our study the impact of relativistic corrections to prompt $\psi(2S)$ production at high transverse momenta (P_T) at hadron colliders within nonrelativistic QCD (NRQCD). Our computation bears on Leading-Power (LP) factorisation in terms of Fragmentation Functions (FFs), valid at high P_T, including next-to-leading order (NLO) corrections to partonic cross sections, augmented by next-to-leading-logarithmic (NLL) resummation of collinear emissions through DGLAP evolution. We have performed a joint evolution of charm and gluon FFs with a complete analysis of short- and long-distance uncertainties. Relativistic corrections turn out to be very large for the gluon FF and moderate for the charm FF. Their inclusion brings our results into agreement with the ATLAS and CMS prompt data without the need to consider higher-order colour-octet contributions, particularly for $P_T \gtrsim 60$ GeV, where next-to-LP contributions are small. We have also studied the polar anisotropy, which is strongly affected by relativistic corrections to the gluon channel. We find that predictions are encouragingly close to the CMS prompt data up to $P_T = 100$ GeV. We also comment on the impact of relativistic corrections in the P_T range of the Tevatron. In a region where next-to-LP contributions should be important, we find that our results are very close to the CDF data.

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1. Introduction

Thanks to the extremely large luminosity and energy of the LHC, the CMS and ATLAS collaborations recently performed measurements [1, 2] of prompt $\psi(2S)$ production at transverse momenta P_T as large as thirty times their mass, to be specific up 140 GeV. These measurements significantly extend the Tevatron ones [3, 4] which uncovered a factor-30 discrepancy between the CDF data and the Colour Singlet Model [5–7] which was the most fashionable model at the time. This discrepancy, which is known as the "$\psi(2S)$ anomaly", triggered the introduction of the Colour-Octet Mechanism (COM) [8] encapsulated in NRQCD [9] which features a rigorous factorisation between Short-Distance Coefficients (SDCs) and Long-Distance Matrix Elements (LDMEs).

The recent ATLAS and CMS data are extremely important as they allow theorists to use Leading-Power (LP) factorisation and neglect next-to-LP (NLP) contributions. LP factorisation is cast in terms Fragmentation Functions (FFs) which can be computed in a variety of models in order to test them. Indeed, typically above 60 GeV for charmonia, LP terms in $d\sigma/dP_T^2$ will dominate as they scale as P_T^{-4}, while others terms scale at most as P_T^{-6}. Using LP factorisation exhibits the great asset to prevent the appearance of large radiative QCD corrections in Fixed-Order (FO) computations of the P_T dependence of quarkonium partonic cross sections. Presently, it remains problematic for the proposed quarkonium-production mechanisms to describe the wide variety of existing measurements [10–12]. In addition, it is not clear if missing high-order corrections could be responsible for some of these tensions. We nevertheless expect comparisons with high-P_T data to be more constraining, as the theory is more accurate, provided that measurements are precise enough and do not contain contributions from other sources.

It happens to be the case for both these high-statistic measurements as they bear on $\psi(2S)$ which does not suffer from feed down from higher states unlike the J/ψ dataset which, in the case the latest ATLAS measurement, extends up to 360 GeV. In practice, the most significant feed down to J/ψ is from χ_c decay which was also first measured by CDF in the mid nineties [13] and found to be about one third of the prompt J/ψ yield. It has been measured again at the LHC by ATLAS [2] was confirmed to be of this size up to $P_T = 25$ GeV. At higher P_T, it remains unknown and should be considered as a systematic uncertainty – significantly larger than the experimental J/ψ cross-section uncertainty– in particular owing to the complication in the theory description of P-wave production at large P_T.

At high P_T where one one can resort to LP factorisation, computing cross sections for $\mathcal{Q}$ production in NRQCD is further simplified with a second factorisation of the SDCs into perturbatively calculable FFs and the usual partonic cross sections from collinear factorisation [14]. NRQCD computations become more accurate at $P_T \gg M$ as they can readily account for the resummation of large logarithms of P_T/M appearing at higher order in α_s through collinear evolution.

We report here on the first impact study [15] of relativistic corrections to prompt hadroproduction of $\psi(2S)$ at large P_T. LP fragmentation from charm quarks c and gluons g are included. Evolution is performed in the so-called Variable-Flavour-Number Scheme (VFNS), which accounts for heavy-flavor threshold crossing, and by coupling the quark and gluon channels, up to next-to-leading logarithmic (NLL) accuracy, meaning that terms of order $\alpha_s^{n+1}\ln^n(P_T/M)$ are resummed. SDCs are evaluated up to NLO, i.e., $\mathcal{O}(\alpha_s^3)$. Relativistic corrections up to $\mathcal{O}(v^2)$, where v is the velocity of the c in the rest frame of the pair are systematically taken into account. NLO corrections ($O(\alpha_s^3)$) to the charm FF and $g \to \psi(2S)c\bar{c}$ contributions of the gluon FF are accounted for. Our results for the cross sections and the polar anisotropy are confronted to the latest prompt ATLAS and CMS data and happen to agree with them. Further comparisons with the CDF data at lower P_T, and FO results, are made and show a near agreement which corroborates the presence of Next-to-LP contributions.

2. Methodology

Up to M^2/P_T^2 corrections, the P_T-differential cross section, $d\sigma_{h_A h_B \to \mathcal{Q}X}/dP_T$, for the inclusive hadroproduction of a $\mathcal{Q}$ reads

$$\frac{d\sigma_{h_A h_B \to \mathcal{Q}X}}{dP_T} = \sum_{i,j,k} \int dx_i dx_j dz \, f_{i/h_A}(x_i;\mu_f) f_{j/h_B}(x_j;\mu_f) \frac{d\hat{\sigma}_{ij\to kX}}{dP_T}(x_i, x_j, z, P_T; \mu_f, \mu_R, \mu_F) D_{k/\mathcal{Q}}(z;\mu_F), \tag{1}$$

where $d\hat{\sigma}$ are the SDCs in the Zero-Mass VFNS, D, the FFs, f, the collinear Parton Distribution Functions (PDFs), $h_{A,B}$, the colliding hadrons, $x_{i/j}$, the momentum fractions of the incoming partons i and j relative to the parent hadrons, and z, the momentum fraction of $\mathcal{Q}$ relative to the fragmenting parton k. μ_f and μ_F are the scales at which the PDFs and FFs are, respectively, evaluated and μ_R is the renormalisation scale at which the strong coupling α_s in the SDCs is evaluated.

The NRQCD factorisation conjecture [9] is based on a double expansion in α_s and v and states that the FFs can be factorised at an inital scale μ_0 close to the quarkonium mass and can then be expressed by the product of a calculable SDCs and LDMEs. The NRQCD LDMEs account for the nonperturbative hadronisation of the intermediate heavy-quark-pair state $n = {}^{2S+1}L_J^{[C]}$ ($Q\bar{Q}[n]$) into the $\mathcal{Q}$ state.[1]

Specifically the NRQCD factorised FFs read

$$D_{k/\mathcal{Q}}(z,\mu_0) = \sum_{n,m,n_v} \frac{\alpha_s^m(\mu_{R_0})}{m_Q^3} d^{(m,n_v)}_{k/Q\bar{Q}[n]}(z,\mu_{R_0},\mu_0)\, v^{n_n+n_v} \langle \widetilde{O}^{\mathcal{Q}}_{n_v}(n)\rangle, \tag{2}$$

where the *absolute* power in α_s, m, and the *relative* order in v^2 of each transition, $n_n + n_v$, have been exposed. The relative suppression compared to the leading color-singlet (CS) contribution from ${}^3S_1^{[1]}$ is made explicit in Eq. (2) using the notation $\langle \widetilde{O}^{\mathcal{Q}}_{n_v}(n)\rangle = \langle O^{\mathcal{Q}}_{n_v}(n)\rangle / v^{n_n+n_v}$, where $\langle O^{\mathcal{Q}}_{n_v}(n)\rangle$ follows the definitions of Bodwin [16].[2]

The first relativistic corrections to ${}^3S_1^{[1]}$ are suppressed as v^2 ($n_n = 0$, $n_v = 2$). Contributions from Color-Octet (CO) states are suppressed by relative scaling v^{n_n} following the velocity scaling rules of NRQCD. Explicitly, for ${}^1S_0^{[8]}$, $n_n = 3$, for ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$, $n_n = 4$, etc. In addition, these transitions can receive higher relativistic corrections which are further suppressed by $n_v = 2, 4$, and so on. It is important to note that, at $O(v^4)$, the next-to-next-to-leading relativistic corrections

[1] ${}^{2S+1}L_J$ is the usual spectroscopic notation and $[C]$ is the color state.

[2] Note that the notation employed by Ma [17] differs from that of Bodwin [9], used here, by a factor of $2N_c$: $\langle O_0^{\mathcal{Q}}({}^3S_1^{[1]})\rangle = 2N_c \langle O^{\mathcal{Q}}({}^3S_1^{[1]})\rangle_{\text{Ma}}$.

to ${}^3S_1^{[1]}$ ($n_n = 0$, $n_v = 4$) mix with the leading ${}^3S_1^{[8]}$ contribution ($n_n = 4$, $n_v = 0$) [16]; CO contributions are in essence higher-order relativistic corrections.

CO LDMEs are not computable from first principles and are usually fitted to data. The issue is that CO LDMEs obtained from NLO fits often differ by more than an order of magnitude [10] and their values remain essentially unknown. On the contrary, the CS LDMEs can be computed by virtue of the vacuum saturation approximation [9] from potential models [18, 19] via the Schrödinger equations: $\langle \widetilde{O}_0^{\psi(2S)}({}^3S_1^{[1]})\rangle = 2N_c(2J+1)|R(0)|^2/4\pi + O(v^4)$. In addition, the Gremm-Kapustin relation [20] can be used to connect the CS LDME at relative order v^2 to that at relative order v^0 up to $O(v^2)$ corrections. This makes CS-based computations up to $O(v^2)$ significantly more predictive than CO-based ones up to $O(v^4)$.

Within our notation, the Gremm-Kapustin relation yields $\langle \widetilde{O}_2^{\psi(2S)}({}^3S_1^{[1]})\rangle = \langle \widetilde{O}_0^{\psi(2S)}({}^3S_1^{[1]})\rangle$ and to replace v^2 in Eq. (2) by its average value $\langle v^2\rangle$ evaluated as $(M-2m_Q)/m_Q \simeq (M^2 - 4m_Q^2)/(4m_Q^2)$, where m_Q is the heavy-quark mass . In our study, we fix $m_Q = m_c = 1.5$ GeV. Mass uncertainties are then encapsulated in variations of LDMEs and $\langle v^2\rangle$.

To proceed, we needed some FF NRQCD inputs at an initial scale μ_0 for the ${}^3S_1^{[1]}$ state. LO contributions to $D_{c/\psi(2S)}$ from $c \to \psi(2S)c$ have been computed at $O(\alpha_s^2)$ in Refs [21–23], and correspondingly for $\bar{c}$. The corresponding NLO corrections at $O(\alpha_s^3)$ have been computed in the unpolarised case [24], as well as their $O(v^2)$ corrections [25, 26]. When we refer to polarisation, we mean the polar anisotropy in the hadron centre-of-mass (or helicity) frame. As of now, the entire density matrix remains unknown for any contributions. LO contributions to $D_{g/\psi(2S)}$ from $g \to \psi(2S)gg$ at $O(\alpha_s^3)$, first computed in Ref. [27], have been recently analytically computed [17]. Their relativistic corrections have been computed up to $O(v^4)$ for the unpolarised case in Ref. [16] and up to relative $O(v^2)$ in the polarised case in Ref. [17]. All the above FF input up to $O(v^2)$ have been used in our study. In addition, we have considered contributions to the gluon channel from $g \to \psi(2S)c\bar{c}$ at $O(\alpha_s^3)$, $g \to \psi(2S)c\bar{c}$ derived by Feng *et al.* from $g \to B_c^\star c\bar{b}$ [28]. Finally, let us note that up to $O(\alpha_s^3)$, light quarks (u, d, s) FF at the initial scale vanish but they are dynamically generated through evolution. More details can be found in Ref. [15].

As what regards the $\mu_{f,F}$ dependence of PDFs and FFs in in Eq. (2), it is governed by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations , which for FFs read: $\mu_F^2 \frac{dD_{i/Q}}{d\mu_F^2}(z,\mu_F) = \sum_j P_{ji}(z,\alpha_s(\mu_F)) \otimes D_{j/Q}(z,\mu_F)$, where P_{ji} the are timelike splitting functions. `APFEL++` [29] is used to solve them at NLO accuracy and achieve NLL resummation of collinear logarithms. The FF initial conditions (see above) are processed by `APFEL++` to obtain their solution in the `LHAPDF` forma . For the PDFs, the CT18NLO set was used as well as the NLO SDCs $d\hat{\sigma}$ in Eq. (1) from `INCNLO1.4` . We have verified that the same results are obtained using `FMNLO`.

We have performed further checks with older results $\psi(2S)$ at moderate P_T, for instance the LL+LO LP ${}^3S_1^{[1]}$ FF studies made in the 90's [30–34] to be compared to CDF data, using both $D_{g/\psi(2S)}$ and $D_{c/\psi(2S)}$ at LO and evolved separately at LL. These found cross sections $O(30)$ times too small compared to the early Tevatron data [3]. Using the same setup, we reproduced the results of Refs. [32, 34]. We note, that in Ref. [31], massive SDCs were used for the charm channel so the comparison is not possible in particular in the CDF-data P_T range. At the time, no systematic studies of the theoretical uncertainty on $D_{g/\psi(2S)}$ and $D_{c/\psi(2S)}$ inputs were carried out and only central values of the input FF were used. We will come back to these later. We have also used two

J/ψ studies at the Tevatron for our benchmarking: one at NLL by Kniehl and Kramer in 1998 [35] and one by Qiao in 2003 [36].

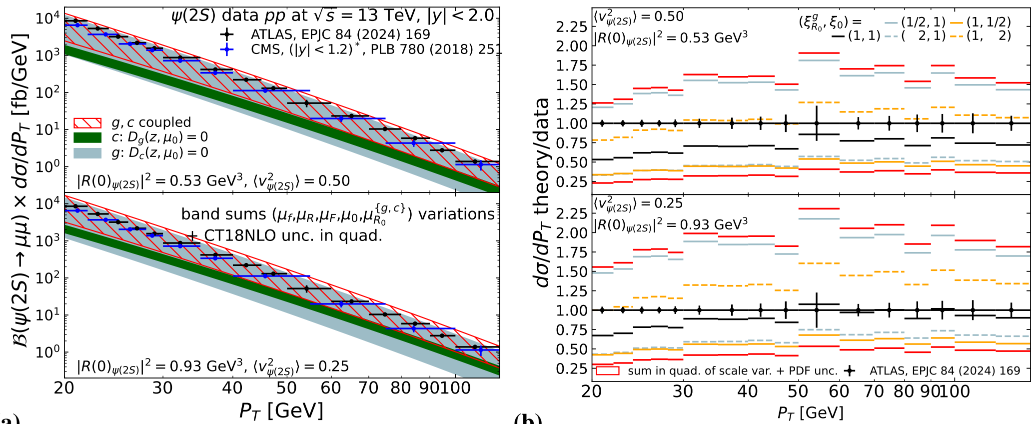
Let us now discuss the parameters of our computation. As previously mentioned, LDMEs (or $|R(0)|^2$) can be obtained from potential models up to $O(v^4)$ corrections. $|R(0)|^2 = 0.93$ GeV^3 for the Cornell potential [37], $|R(0)|^2 = 0.70$ GeV^3 for its variant of Ref. [19] and $|R(0)|^2 = 0.53$ GeV^3 for the Buchmüller-(Grunberg-)Tye potential [38] (See Ref. [18] for other values). Extractions from the very well measured and computed leptonic-decay are affected by very large QCD corrections starting from NNLO and we prefer to use indicative values from potential models despite their various results. In practice, a conservatively low value of $|R(0)|^2 = 0.53$ GeV^3 is chosen as a default and that from the Cornell potential, $|R(0)|^2 = 0.93$ GeV^3, as an alternate scenario. The other parameter to be chosen is $\langle v^2_{\psi(2S)}\rangle$. The Gremm-Kapustin relation tells us that it should be larger for $\psi(2S)$ than for J/ψ, yet with large uncertainties, owing to the ambiguity on m_c [39]. We take two realistic values 0.5 and 0.25 and combine them with the LMDE values discussed above avoiding taken them to be both large or both small. For α_s, we taken $\alpha_s^{1(2)\text{-loop}}(M_Z) = 0.135(0.118)$ for the pieces (SDCs or FFs) known at (N)LO. These correspond to the values obtained by the CT18 (N)LO fits. We note that $\alpha_s^{1\text{-loop}}(M_Z) = 0.135$ differs from the older value $\alpha_s^{1\text{-loop}}(M_Z) = 0.124$ used in Ref. [34].

3. Results

Before comparing data and v^2-improved cross sections, let us discuss the impact of the relativistic corrections to the N-th Mellin moment of the FFs, $\tilde{D}(N, \mu = P_T)$. Indeed, $d\sigma/dP_T \propto \tilde{D}(N, \mu = P_T) = \int_0^1 dz\, z^{N-1} D(z, \mu = P_T)$ with $N \sim 6$ for the LHC kinematics. In addition, at LL and neglecting off-diagonal splitting functions, the evolution in Mellin space is multiplicative via the factor $[\alpha_s(\mu_F)/\alpha_s(\mu_0)]^{\gamma(N)/\beta_0}$, where the anomalous dimension γ scales as $\gamma(N) \sim -\ln N$. In other words, if some corrections, relativistic or radiative, strongly affect the FF at their initial scale, these corrections will subsist when evolved to scales on the order of P_T.

Motivated by these observations, in 2012, Bodwin et al. focused their interest [16] on the relativistic corrections to $\tilde{D}_{g\to\psi(2S)gg}(N = 6.2, \mu_0 = 2m_c)$ and found the $O(v^2)$ ones to be as large as $O(15\langle v^2\rangle)$ but the phenomenological importance of these corrections was overlooked. With our FF inputs discussed above, evolving them at NLL in a coupled way with `APFEL++` and Mellin transforming them, we confirm that the v^2 enhancement of $\tilde{D}_{g\to\psi(2S)gg}(6, 100\text{ GeV})$ is $O(15\langle v^2\rangle)$. For the charm channel, i.e. $\tilde{D}_c(6, 100\text{ GeV})$, it is smaller, $O(0.8\langle v^2\rangle)$. The same holds for the first Mellin moments (i.e. the fragmentation probability), both for the gluon and charm channels, the v^2 enhancement for $\tilde{D}_{g\to\psi(2S)gg}(1, 100\text{ GeV})$ is $O(0.9\langle v^2\rangle)$, and for $\tilde{D}_c(1, 100\text{ GeV})$ is $O(0.24\langle v^2\rangle)$. We stress that the cross sections of Ref. [15] shown below have been obtained with a full computation, not by deriving $d\sigma/dP_T$ from $\tilde{D}(N, \mu = P_T)$. We refer them to as NLO+NLL predictions.

Figure 1a compares our NLO+NLL prompt $\psi(2S)$ P_T-differential cross section at $\sqrt{s} = 13$ TeV in the rapidity region $|y| < 2$ obtained first through coupled evolution (hatched red) and second separately with decoupled evolution (solid gray-blue for g and solid green for c) with the ATLAS data [2]. We also plotted the CMS data [1] rescaled by the ratio of the rapidity intervals ($\Delta y_{\text{ATLAS}}/\Delta y_{\text{CMS}}$). We note that both $|R(0)|^2 - \langle v^2\rangle$ sets (upper, lower) lead to a similar agreement with data for P_T above 60 GeV with a slightly larger relative charm contribution for the second



(a) (b)

Figure 1: (a) Prompt ATLAS and CMS $\psi(2S)$ $d\sigma/dP_T$ [1, 2] at $\sqrt{s}$ = 13 TeV compared to our results for coupled c & g (red), c (green), and g (gray-blue) channels. (b) Cross section ratio to ATLAS data. Solid and dashed curves show different scale choices and red curves show the combined scale and PDF uncertainty.

set. It worth noting that the charm component in green is harder owing to a slower evolution of the quark FF vs the gluon one. Finally we note that the ATLAS and CMS data get slightly less hard (i.e. decrease faster with P_T) above 60 GeV which partly explains the good agreement at high P_T.

Our results show a large uncertainty which is made more visible in Fig. 1b. Before discussing it, let us explain how we obtained it. For the central values of the renormalisation scales $\mu^g_{R_0}$ and $\mu^c_{R_0}$ of the input FF (D_g and D_c), we have taken $2m_c$. The same value is taken for the initial scale of the evolution, μ_0. For the SDCs, the central value for the renormalisation, initial-state factorisation, and final-state factorisation scales, $\mu_{R,f,F}$, are all P_T. We have then varied these scales about their central values, one scale at a time, by a factor of two. Explicitly, defining $\mu^{\{g,c\}}_{R_0} = \xi^{\{g,c\}}_{R_0} \cdot 2m_c$ with $\xi^{\{g,c\}}_{R_0} = (0.5, 1, 2)$ and $\mu_{R,f,F} = \xi_{R,f,F} \cdot P_T$ with $\xi_{R,f,F} = (0.5, 1, 2)$, only one ξ among $\xi^{\{g,c\}}_{R_0}$ and $\xi_{R,f,F}$ is varied between 0.5 or 2 while the other are set to 1. We have then combined the variations in quadrature along with the PDF uncertainties.

As is clear on Fig. 1b, the two largest scale uncertainties are those from $\mu^g_{R_0}$ (gray-blue) and from μ_0 (orange). Other uncertainties from the hard scales ($\mu_{f,F,R}$) and from the PDFs, are much smaller. All the details are given as supplementary material of [15]. The reason for the strong sensitivity on $\mu^g_{R_0}$ can simply be traced back that the fact that the corresponding FF $D_{g/\psi(2S)gg}$ is only known at LO and is proportional to the third power of $\alpha_S(\mu^g_{R_0})$. Varying $\mu^g_{R_0} \in \{m_c, 4m_c\}$ alone gives a factor 4 uncertainty since $\alpha_s(m_c)/\alpha_s(4m_c) \simeq 1.6$. We are surprised that this issue has not been addressed in the existing literature. Since $D_{c/\psi(2S)c}$ is known up to NLO [24], our cross section exhibits a notably reduced sensitivity on $\mu^c_{R_0}$.

In [15], we have also presented results for the polar anisotropy λ_θ which were not finalised at the time of the conference. These are in very good agreement with the CMS measurements extending to 100 GeV [40]. This lends strong support to the possibility that the data can indeed be described with solely the ${}^3S_1^{[1]}$ transition once v^2 corrections are taken into account.

Before concluding, we would like to briefly go back to the "CDF $\psi(2S)$ anomaly" which we have revisited with our up-to-date theory set up. We found that the central value of the LP $\psi(2S)$ cross section before the inclusion of the relativistic corrections increases by a factor of four after having (i) increased perturbative accuracy (SDCs at NLO and resummation at NLL) and (ii) updated input parameters, i.e., the radial wavefunction at the origin $|R(0)|^2$, the PDFs, and the α_s values. The corresponding results are shown by the hatched band in orange on Fig. 2a along with the CDF RUN-II data [4]. These are compared with results from [31, 34] rescaled with the appropriate value of $|R(0)|^2$ (in blue). One clearly sees that the LP results are not a factor 30 below the data as commonly believed. In addition, these results are associated with an uncertainty of at least a factor of five, which makes the gap with the CDF data possibly even smaller. As already discussed, the $\mu^g_{R_0}$ uncertainty alone is close to four. For reasons we ignore, such an uncertainty has been ignored in previous studies. We have also added to Fig. 2a a FO NLO (α_s^4) computation (gray band) [41, 42] which in essence comprises some NLP contributions and an approximated NNLO computation (red band) [43, 44] (up to α_s^5, dubbed NNLO*) which comprises some LP contributions. The LP and NNLO* results are in the same ball park while the NLO contribution might be relevant around 5 GeV. However, these results remain below the data. Fig. 2b shows the equivalent results to those for the LHC shown on Fig. 1a with the v^2 corrections and the same colour code. One observes that the LP contributions become compatible (within the large uncertainties) with the CDF Run-II data. It should however be clear that in this P_T range, NLP contributions are likely large. So far no computations of v^2 corrections to these NLP contributions has been made.

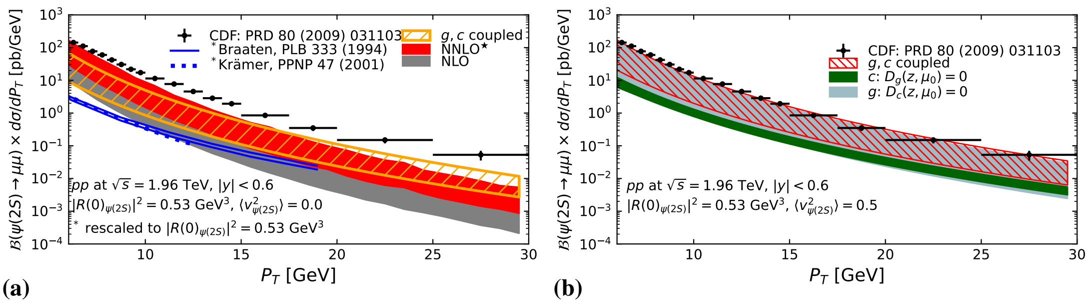


Figure 2: CDF Run-II data compared to (a) various computations w/o v^2 corrections: LP LO+LL (blue), LP NLO+NLL (orange), NLO (gray), NNLO* (red) and (b) our LP NLO+NLL with v^2 corrections.

4. Conclusion

We have reported on our study [15] of the $\mathcal{O}(v^2)$ relativistic corrections to $\psi(2S)$ production. Using our best knowledge of quarkonium FFs at the initial scale, evolving them at NLL with SDCs computed at NLO, performing a thorough investigation of theoretical uncertainties, from PDFs, FFs, and SDCs, we have found that the CMS and ATLAS data can described without the need to include higher-order relativistic corrections from, e.g., CO transitions. The uncertainty of our results remains large because one FF, that for $g \to \psi(2S)gg$, is still only known at LO. Besides the computation of the NLO correction to the (polarized) gluon FF, it remains to be investigated how the large $\mathcal{O}(v^2)$ CS corrections will impact existing $\mathcal{O}(v^{3,4})$ CO LDME determinations.

Although not reported here, our results for the polar anisotropy [15] are in near agreement with the CMS data. If, as one might speculate, the unknown NLO corrections to the gluon channel induce depolarisation, the agreement will be further improved.

Our results also underscore the need to improve our understanding of NLP corrections in the region $P_T < 60$ GeV, which is needed to address the Tevatron data are for which LP results are now reasonnably close from the CDF Run-II data. Finally we stress that the J/ψ case is more complex as it calls for a better understanding of χ_c production at large P_T, both from theory and experiments.

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