Color-octet Contributions to Inelastic Heavy-quarkonium Production

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Abstract. Color-octet mechanism based on the nonrelativisctic QCD(NRQCD) factorization approach in inclusive heavy quarkonium production in high energy processes is reviewed. As phenomenological applications, we discuss charmonium production at HERA and Υ production associated with Weak gauge bosons at LHC.

1 Introduction

In high energy experiments, $J^{PC} = 1^{--}$ quarkonium states, such as the charmonium state J/ψ and the bottomonium state Υ, have been used as clean probes to study QCD. They provide an enormous suppression of the background due to their leptonic decay modes. For a long time, color singlet model(CSM)[1,2] has been a reasonable picture to describe heavy quarkonium production and decay. CSM allows a color-singlet heavy quark pair to form a quarkonium state with the same spectroscopic state $^{2S+1}L_J$. Factrization of short distance process from bound state formation is assumed due to the separation of the two scales govern them. The short distance process is calculated in perturbative QCD and wavefunction and its derivatives at the origin, which involve nonperturbative physics, are calculated within potential models or phenomenological anaysis.

In the middle of 1990's, serious discrepancies between several experimental results and CSM are found and this naive factorization approach was reexamined. For example, the dominant mechanism in large p_T J/ψ production at $p\overline{p}$ collisions, has been found to be parton fragmentations in the framework of CSM by Braaten and Yuan[3]. This fragmentation mechanism has been applied to various studies on the prompt charmonium production at Tevatron[4] and the CDF data on the prompted J/ψ production[5] qualitatively meet these theoretical predictions. This fragmentation picture in CSM was not enough. Measured ψ' production rate at CDF was 30 times larger than the theoretical prediction, which is the so-called ψ' anomaly[6], even after including parton fragmentation mechanism. Based on NRQCD, Braaten and Fleming proposed color-octet gluon fragmentation picture as a possible scenario to resolve this problem[7]. They included gluon fragmentation into color-octet $Q\overline{Q}$ pair in $^3S_1^{(8)}$ state followed by soft transition of this pair into physical quarkonium. This subprocess is not allowed in CSM where only the color-singlet $Q\overline{Q}$ pair with the same spectroscopic state($^3S_1^{(1)}$) as that of final quarkonium(J/ψ) can be hadronized into a physical quarkonium. As an effective field theory of QCD, NRQCD[8,9] was developed to describe the heavy quarkonium production and decay in rigorous way from the

first principle of QCD. In NRQCD, it is allowed to make a quarkonium state from various $Q\overline{Q}$'s with color and spin states which may not be the same as those of final quarkonium state. Among infinite number of channels, only a few channels dominates the soft transition process with the help of NRQCD velocity scaling rules[8,9]. Newly introduced nonperturbative NRQCD matrix elements should then be fixed from experimental data. Efforts are being made to extract the NRQCD matrix elements from experiments to test the universality.

This talk is organized as follows. We first review the basics on NRQCD in the analysis of inclusive production of heavy quarkonium. Then we discuss charmonium production at HERA and associate production of Υ and Waek gauge bosons at LHC.

2 NRQCD Basics

2.1 Lagrangian

By use of mass splitting of heavy quarkonia, one may assume the velocity v of the heavy quark inside the system is small and therefore one find the separation among the three important scales, heavy quark mass M, momentum in meson rest frame Mv and binding energy Mv^2 as

$$M \gg Mv \gg Mv^2 \quad \text{where} \quad v_b^2 \sim 0.1, \quad v_c^2 \sim 0.3. \tag{1}$$

NRQCD Lagrangian is obtained from full QCD by introducing untraviolet mo-

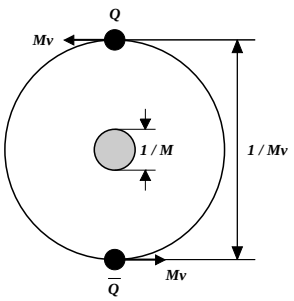

Fig. 1. Typical scales of a heavy quarkonium system.

mentum cutoff Λ that is order of M since the important nonperturbative physics involves momenta of order Mv or less. One can compensate the removal of the relativistic states by adding local interactions to the lagrangian order by order in $1/M$. Due to the decoupling of particle and antiparticle in this region, dynamics of heavy quark can be described in nonrelativistic Schrödinger field theory. Only the heavy quark part is modified from full QCD Lagrangian[8,9]:

$$\mathcal{L} \qquad = \mathcal{L}_{\text{light}} + \mathcal{L}_{\text{heavy}} + \delta\mathcal{L}, \tag{2}$$

$$\mathcal{L}_{\rm heavy} = \psi^\dagger \left(iD_t + \frac{\boldsymbol{D}^2}{2M} \right) \psi + \chi^\dagger \left(iD_t - \frac{\boldsymbol{D}^2}{2M} \right) \chi. \tag{3}$$

In LO($\delta\mathcal{L} = 0$), there is no spin-flip operator and this leads to *approximate* heavy quark spin symmetry(HQSS) of NRQCD. LO NRQCD Lagrangian naturally allow color-octet term via chromoelectric dipole (E1) transition which is included in $\boldsymbol{D}^2/(2M)$. The relativistic effects from full QCD are included in the correction term $\delta\mathcal{L}$. The correction term is composed of bilinear terms

$$\begin{aligned} \delta\mathcal{L}_{\rm bilinear} = & \frac{c_1}{8M^3} \left(\psi^\dagger (\mathbf{D}^2)^2 \psi \ - \ \chi^\dagger (\mathbf{D}^2)^2 \chi \right) + \cdots \\ & + \frac{c_4}{2M} \left(\psi^\dagger (g\mathbf{B} \cdot \boldsymbol{\sigma}) \psi \ - \ \chi^\dagger (g\mathbf{B} \cdot \boldsymbol{\sigma}) \chi \right), \end{aligned} \tag{4}$$

which describes further details on low energy physics and 4-fermion interaction terms:

$$\delta\mathcal{L}_{4-\rm fermion} = \sum_n \left[\frac{f_n(\Lambda)}{M^{d_n-4}} \psi^\dagger \Gamma_n \chi \chi^\dagger \Gamma_n' \psi + \frac{f_n^{EM}(\Lambda)}{M^{d_n-4}} \psi^\dagger \Gamma_n \chi |0\rangle\langle 0| \chi^\dagger \Gamma_n' \psi \right]. \tag{5}$$

The former represents the heavy quark pair annihilation into light hadrons while the latter describes electromagnetic annihilation in NRQCD. The short distance scale physics is included in the coefficient $f_n^{(EM)}$. The bilinear part includes all the higher dimensional operators comes from the expansion in heavy quark velocity v. Here we find the spin-flip operator $\boldsymbol{\sigma}$ in the chromomagnetic dipole (M1) transition.

2.2 Velocity Scaling Rules

Velocity scaling rule[8,9] classifies the importance of each terms in NRQCD interaction Lagrangian in powers of v_Q^2. For example, most important channels of J/ψ production can be classified as

$$\begin{aligned} & (c\overline{c})(^3S_1^{(8)}) \to J/\psi : (E1)^2 : v^4 \times (c\overline{c})(^3S_1^{(1)} \to J/\psi), \\ & (c\overline{c})(^1S_0^{(8)}) \to J/\psi : (M1)^1 : v^3 \times (c\overline{c})(^3S_1^{(1)} \to J/\psi), \\ & (c\overline{c})(^3P_J^{(8)}) \to J/\psi : (E1)^1 : v^4 \times (c\overline{c})(^3S_1^{(1)} \to J/\psi). \end{aligned} \tag{6}$$

Note that $^3P_J^{(8)}$ is further suppressed by v^2 in addition to E1 transition factor v^2 since the operator itself have covariant derivative. If we only consider long distance part, color singlet matrix element dominates color octet ones. Therefore color octet mechanism dominates color singlet channel only when the short distance coefficient for the octet channel is large enough to compensate the suppression in long distance factor.

2.3 Factorization and Matching in inculsive heavy quarkonium production

Factorization in inclusive heavy quarkonium production rate comes from the idea that the probability of forming bound state from a heavy quark pair produced in

short distance process is significant only if the corresponding production points are separated by a distance of order $1/M$ or less[9]. Then the production rate of heavy quark pair within a distance scale of order $1/M$ is factored out from the formation of bound state with distance scale of order $1/(Mv)$ or larger. The latter is accurately described by NRQCD. Vacuum expectation value of a four-quark operator describes the transition rate of the long distance process. As shown in Fig.2, the operator crerates heavy quark pair at a spacetime point

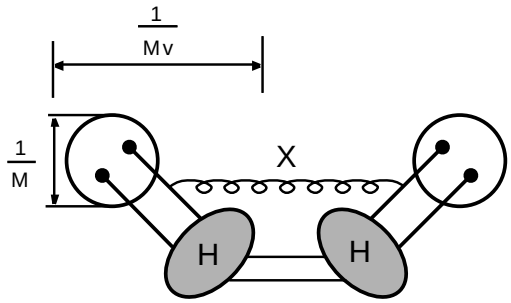

Fig. 2. Diagram representing the NRQCD color octet matrix element.

and propagates into the asymptotic future where the final state includes heavy quarkonium state, and then propagates back to the creation point. Factorization formula of inclusive quarkonium H production is then given by[9]

$$\sigma(H) \;=\; \sum_n \frac{F_n(\Lambda)}{M^{d_n-4}} \langle 0|\mathcal{O}_n^H(\Lambda)|0\rangle, \tag{7}$$

where F_n is the short distance coefficient, which is infrared- and collinear-finite, and $\mathcal{O}_n^H$ is the four-quark operator of inclusive production mentioned above. Factorization scale Λ is order of heavy quark mass M. Most important operators in 1^{--} quarkonium production are given by

$$\begin{aligned}
\mathcal{O}_1^H(^3S_1) &= \chi^\dagger\sigma^i\psi\left(a_H^\dagger a_H\right)\psi^\dagger\sigma^i\chi,\\
\mathcal{O}_8^H(^1S_0) &= \chi^\dagger T^a\psi\left(a_H^\dagger a_H\right)\psi^\dagger T^a\chi,\\
\mathcal{O}_8^H(^3S_1) &= \chi^\dagger\sigma^i T^a\psi\left(a_H^\dagger a_H\right)\psi^\dagger\sigma^i T^a\chi,\\
\mathcal{O}_8^H(^3P_0) &= \frac{1}{3}\chi^\dagger\sigma^i D^i T^a\psi\left(a_H^\dagger a_H\right)\psi^\dagger\sigma^j D^j T^a\chi,\\
a_H^\dagger a_H \quad &\equiv \sum_X\sum_{m_J}|H+X\rangle\langle H+X|,
\end{aligned} \tag{8}$$

where the sums are over the spin states of H and over all other final states. Scale dependence of each matrix elements is canceled after summing over all the contributions. Expanding the perturbative QCD amplitude by v, one can

find out the partial wave amplitudes with NRQCD operators. In this matching procedure, one can extract the short distance coefficients F_n.

3 Quarkonium production at HERA

After color-octet mechanism was applied to high p_T ψ' production via gluon fragmentation at Tevatron[7], studies on the J/ψ production including color-octet mechanism were activated. Cho and Leibovich considered a large class of color-octet diagrams which can contribute to the J/ψ production, below the region where the fragmentation is dominant, at hadron colliders[10]. The same approach have been used in inclusive photoproduction of J/ψ[11,12]. In these region where gluon fragmentation does not dominate, two more NRQCD color-octet matrix elements, $\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle$ and $\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle$, contribute significantly. Unfortunately, they appear in linear combination and this makes it difficult for one to determine their numerical values separately. Furthermore, the results obtained from Tevatron data[10] are not appropriate to explain photoproduction data[11,12]. The energy distribution of produced J/ψ is one of the most important measurable quantities in this process. While CSM is enough to explain lower z (z is J/ψ energy fraction of initial photon at lab frame) region($z < 0.8 \sim 0.9$) data[13,14] where color-octet contribution is suppressed, higher z region data was not well explained. Diverging behavior in higher z region contribution via color-octet mechanism seemed to be troublesome. However, Beneke, Rothstein and Wise showed that NRQCD expansion may lead to a breakdown near the boundaries of phase space[15]. Further analysis on this end point region dynamics would give more clear explanation on the J/ψ energy distribution in high z region. Fleming and Mehen[16] suggested the leptoproduction analysis to avoid the end point region ambiguity. In high Q^2 region in leptoproduction, the corrections come from the non-relativistic approximation of the quarkonium phase space become negligible[16]. They also predicted the polarization of J/ψ in leptoproduction. But the data sample is not sufficient to confirm it yet[17]. Recently, Kniehl and Kramer took into account HO QCD effects[18] due to the multiple emission of gluons, which had been estimated by Monte Carlo techniques[19]. As a consequence the excess of NRQCD prediction at z close to unity over the HERA data disappeared. So the complete NLO analysis on this process is called for.

4 $pp \to \Upsilon + W/Z + X$

The associated production of $W^{\pm}$ or Z^0 and a J/ψ has been studied previously, but only for J/ψ's with large transverse momentum, where the process is dominated by gluon fragmentation into J/ψ [20]. The differential cross sections for $W^{\pm} + J/\psi$ and $Z^0 + J/\psi$ peak at small transverse momentum of the J/ψ. Because the mass of the Υ is larger than that of the J/ψ by a factor of 3, the cross sections for $W^{\pm} + \Upsilon$ and $Z^0 + \Upsilon$ are much smaller than those for $W^{\pm} + J/\psi$ and

$Z^0 + J/\psi$. However the larger mass of the Υ makes it possible to observe the leptons from its decay, even if the Υ is produced at small transverse momentum. It is therefore possible to measure the total cross sections for $W^\pm + \Upsilon$ and $Z^0 + \Upsilon$.

Let us consider the production of $W^\pm/Z + \Upsilon$ in a hadron collider. The $2 \to 3$ parton processes that produce $W^+/Z + b\bar{b}$ are shown in Fig.3. The cross sections

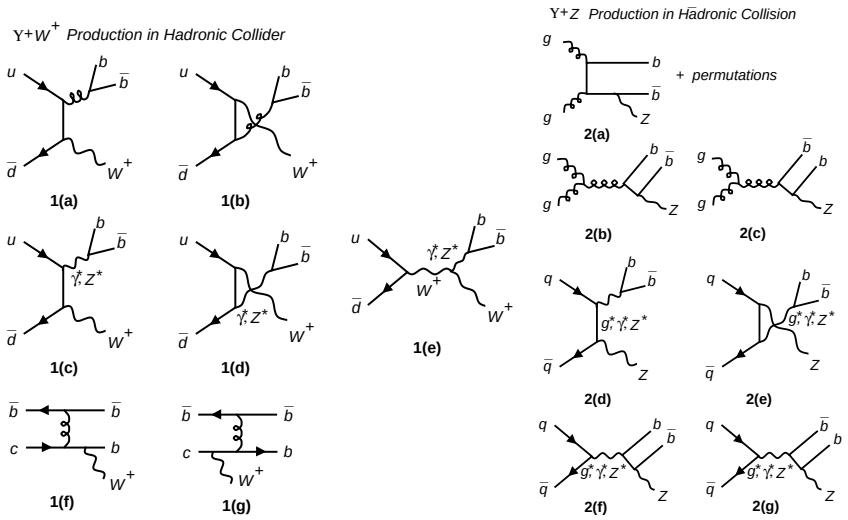

Fig. 3. $2 \to 3$ parton processes that produce $W^+/Z + b\bar{b}$.

for production of $W^\pm + \Upsilon$ and $Z^0 + \Upsilon$ in pp collisions at the LHC with center-of-mass energy 14 TeV is[21]

$$\sum_{\pm} \sigma(W^\pm + \Upsilon) = 10 \text{ fb} \, \frac{\sum B\langle \mathcal{O}_1(^3S_1)\rangle}{8 \text{ GeV}^3} + 4000 \text{ fb} \, \frac{\sum B\langle \mathcal{O}_8(^3S_1)\rangle}{0.4 \text{ GeV}^3}, \quad (9)$$

$$\sigma(Z^0 + \Upsilon) = 500 \text{ fb} \, \frac{\sum B\langle \mathcal{O}_1(^3S_1)\rangle}{8 \text{ GeV}^3} + 1300 \text{ fb} \, \frac{\sum B\langle \mathcal{O}_8(^3S_1)\rangle}{0.4 \text{ GeV}^3}. \quad (10)$$

where $\sum B\langle \mathcal{O}_{1,8}(^3S_1)\rangle$ includes the feed down processes from higher bottomium states as well as direct production of Υ. Their numerical values are estimated[21] as shown in the denominator. Leading order GRV-94 parton distributions are used and set the factorization and renormalization scales equal. We neglect the masses of the u, d, s, and c quarks, and we use the value 4.7 GeV for the b quark mass. The theoretical error due to higher order perturbative corrections can be estimated by varying the factorization and renormalization scales by a factor of 2 and is roughly 35%. The theoretical error due to the uncertainty in the b quark mass can be estimated by varying m_b by 0.25 GeV and is roughly 25%. With an integrated luminosity of 10 fb^{-1}, the number of events in the purely leptonic decay channels should be about 440 for $W^\pm + \Upsilon$ and about 70 for $Z^0 + \Upsilon$. Even

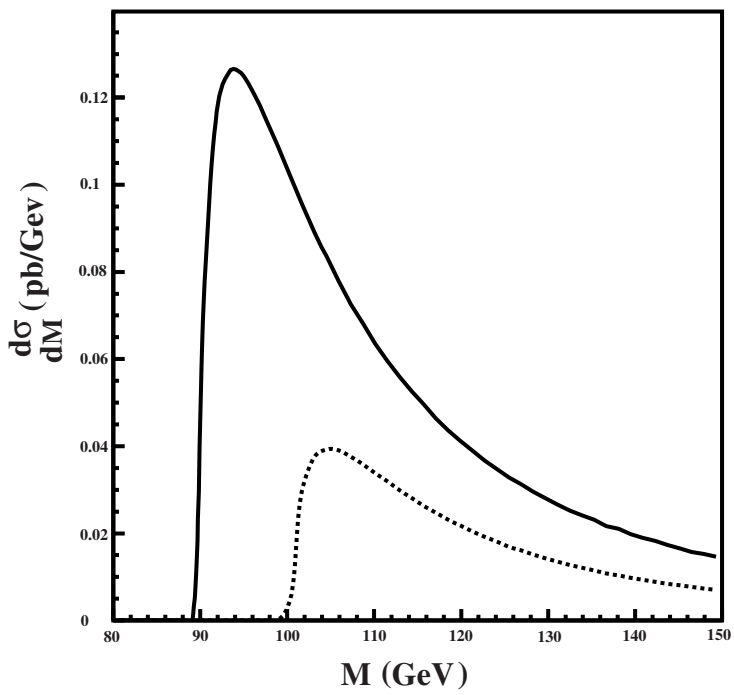

Fig. 4. The invariant mass distributions $d\sigma/dM_{W\Upsilon}$ (summed over $W^{\pm}$) and $d\sigma/dM_{Z\Upsilon}$ of $pp \to \Upsilon + W/Z + X$ at LHC.

after allowing for detector acceptances and efficiencies, there should be enough events to make these processes observable. In Figure 4, we plot the invariant mass distributions $d\sigma/dM_{W\Upsilon}$ (summed over $W^{\pm}$) and $d\sigma/dM_{Z\Upsilon}$. They peak at only a few GeV above the thresholds of 89.8 GeV for $W^{\pm}+\Upsilon$ and 100.6 GeV for $Z^0+\Upsilon$. The cross sections for $W^{\pm}+\Upsilon$ and $Z^0+\Upsilon$ are both dominated by the $\langle \mathcal{O}_8(^3S_1)\rangle$ term. While the color-singlet matrix element is accurately normalized by the leptonic decay width of the Υ, there is a large uncertainty in the normalization of the color-octet matrix element. The uncertainty in the value of $\sum B\langle \mathcal{O}_8(^3S_1)\rangle$ leads to a substantial uncertainty in the normalizations of the cross sections. However this uncertainty cancels in the ratio $\sum_{\pm} \sigma(W^{\pm}+\Upsilon)/\sigma(Z^0+\Upsilon)$, which is predicted to be about 3 at the Tevatron and about 2 at the LHC. If a significant deviation from this prediction is observed at the LHC, it might be evidence for

an additional contribution from a heavy particle that decays into $W^{\pm} + b\bar{b}$ or $Z^0 + b\bar{b}$.

The production of $W^{\pm} + \Upsilon$ and $Z^0 + \Upsilon$ provide lampposts under which one can look for new physics. The most promising possibility is to search for a charged Higgs via the decay $H^+ \to W^+ + \Upsilon$. The decay rate of the charged Higgs into $W + b\bar{b}$ is enhanced by the Yukawa coupling of the Higgs to a virtual top quark. If the mass of the charged Higgs is in the range between 140 GeV and $t\bar{b}$ threshold and if the Higgs mixing parameter $\tan\beta$ is small, then $W + b\bar{b}$ may be the largest single decay mode [22]. The decay rate of the charged Higgs into $W + \Upsilon$ was first calculated by Grifols, Gunion, and Mendez [23]. For small $\tan\beta$, the branching fraction $B(H^+ \to W^+ + \Upsilon)$ ranges from about 10^{-4} if the Higgs mass is just above the $W^+ + \Upsilon$ threshold to about 10^{-3} if the Higgs mass is just below the $t\bar{b}$ threshold.

In a hadron collider, most of the standard production mechanisms for a charged Higgs in the mass range below $t\bar{b}$ threshold involve the production of an additional very massive particle [24]. The standard production mechanisms for H^+ include $t\bar{t}$ production followed by the decay $t \to H^+ b$, $\bar{t}H^+$ production, $W^- H^+$ production, and $H^- H^+$ production. Because of the additional very massive particle, events in which a charged Higgs decays into $W + \Upsilon$ will be easily distinguished from $W + \Upsilon$ events produced by Standard Model processes. There is one potentially significant production process for a charged Higgs that could result in events that resemble Standard Model $W + \Upsilon$ events. That process is $qb \to q'bH^+$, which proceeds through a Feynman diagram that involves a virtual W and a virtual top quark [25].

5 Conclusion

Introduction of color-octet mechanism made it possible to explain the enormous surplus in unpolarized $\psi(1S, 2S)$ production at Tevatron. At HERA, still one can not definitely say whether NRQCD is working or not since NRQCD loses the predictive power in some kinematic region. High Q^2 leptoproduction of J/ψ proposed by Fleming and Mehen might give more concrete answer to this. Associate production of Υ and Weak gauge bosons at LHC might be a lamppost under which one can probe a charged heavy reasonance.

Within NRQCD, one can also predict the polarization[26] of heavy quarkonia. Polarization predictions on the direct $\psi^{(\prime)}$ at Tevatron are already known[27]. But the first experimenal result for polarized production at Tevatron would be that of prompt ψ which includes cascade effects and therefore one need to include the feeddown effect. Futher test on polarized quarkonium production at Tevatron will be one of the most important test of NRQCD in near future.

Acknowledgments. The author thanks organizers of this workshop for invitation and also thanks E. Braaten and S. Fleming for their enjoyable collaborations on the subject discussed in sec. 4. This work is supported in part by the Alexander von Humboldt Foundations.

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