As good probe for people to understand both the perturbative and non-perturbative aspects of QCD, the production of heavy quarkonium in high energy processes has attracted considerable attention in recent years (see [1] for reviews).

Within the framework of an effective field theory non-relativistic QCD (NRQCD) [2], the orders of magnitude discrepancies between experimental data measured by the CDF Collaboration [3] and the color-singlet mechanism (CSM) theoretical predictions were well resolved by the color-octet states still dominates transverse polarization of J/ψ at sufficient large transverse momentum (pt) is in bad agreement with the almost unpolarized results measured by CDF collaboration [3, 7]. To reveal the J/ψ production mechanism, recently much theoretical effort has been made and some substantial progress has been achieved. At Hadron collider, the next-to-leading order (NLO) QCD corrections for conventional J/ψ production gg → J/ψg in the CSM are calculated in Ref. [8].

It is reported in Ref. [10] that the polarization for the conventional J/ψ production via the CSM turns from much transverse at leading-order (LO) into much longitudinal at NLO, while the J/ψ produced via \( 1S_0^{(8)} \) and \( 3S_1^{(8)} \) color-octet states still dominates transverse polarization at large pt at NLO [11]; it is argued in Ref. [12] that the s-channel cut contribution may be a possible solution to the J/ψ production puzzle. At e⁺e⁻ collider, the NLO QCD corrections [13] to e⁺e⁻ → J/ψcc and e⁺e⁻ → J/ψggg in the CSM can well resolve the large discrepancies between the experimental data and LO theoretical prediction. Some other attempts may be found in Ref. [14]. Even with these recent significant theoretical progresses, the challenge to our understanding of the heavy quarkonium production mechanism is still exist.

Since J/ψ(1−−) can couple with a photon, pp(p) → γ*(J/ψ) + X with J/ψ from a virtual photon γ* fragmentation. Our calculations show it’s pt distribution at NLO will be larger than that of the conventional J/ψ production from the color-singlet mechanism at NLO when pt > 26 (35) GeV at the Tevatron (LHC) and reach about 6 (10) times of the conventional one when pt = 50 (100) GeV at the Tevatron (LHC), in spite of a suppression factor (α/αs)² that is associated with the QED and QCD coupling constants. In addition, it also has large impact on the pt distribution of J/ψ polarization in large pt region. Therefore, it is an important mechanism for J/ψ production at large pt region especially for the LHC.

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where $p$ is either a proton or antiproton. The short distance part $\hat{σ}$ represents the partonic production of $c\bar{c}$ with quantum number $n$. And $\langle O^{\mu\nu}_n \rangle$ is the non-perturbative long distance matrix elements that parametrize the transition of the $c\bar{c}$ pair into $J/\psi$.

At LO, there are two partonic processes:

\[ B_1: \quad g(p_1) + q(p_2) \rightarrow J/\psi(p_3) + q(p_4), \]
\[ B_2: \quad q(p_1) + \bar{q}(p_2) \rightarrow J/\psi(p_3) + g(p_4), \]

where $q$ represents all possible light quark $u, d, s$ and anti-quark $\bar{u}, \bar{d}, \bar{s}$. The typical Feynman diagrams are shown in Fig. 1. The partonic tree level results of the two processes for certain light $q$ are trivial and given as:

\[
\frac{d\hat{σ}_1}{dt} = \frac{2\pi^2\alpha_s^2 c_q^2 c_{\bar{q}}^2 \langle O^1_{J/\psi} \rangle ((1-s)^2 + (1-u)^2)}{3m_t^2 s^2}, \quad su,
\]
\[
\frac{d\hat{σ}_2}{dt} = \frac{2\pi^2\alpha_s^2 c_q^2 c_{\bar{q}}^2 \langle O^1_{J/\psi} \rangle ((1-u)^2 + (1-t)^2)}{3m_t^2 s^2}, \quad ut, \quad (2)
\]

with $s = \frac{(p_1 + p_2)^2}{4m_c^2}$, $t = \frac{(p_1 - p_3)^2}{4m_c^2}$, $u = \frac{(p_1 - p_4)^2}{4m_c^2}$, $m_c$ is the mass of charm quark.

The NLO correction is of $\alpha_s^3\alpha_s^2$ order. It contains the virtual(V) part and the real(R) part. At this order, the $^{3}S_{1}^{(1)}$ state could couple to one photon or one photon and two gluons. Only the one photon diagrams have kinematic enhancement at large $p_t$ region, for which the representative ones are displayed in Fig.1. And they also form a gauge-invariant subset. At present, we drop the contribution of the diagrams with $c\bar{c}$ pair coupling to three gauge bosons. The complete NLO corrections and their interference with full QCD processes will be discussed in further work.

There are 19 fragmentation diagrams among all 33 NLO virtual correction diagrams for each Born process including the counter term diagrams. And the partonic virtual corrections for the differential cross section are:

\[
\frac{d\hat{σ}^V}{dt} \propto 2\text{Re}(M^B M^V^*). \quad (3)
\]

The ultraviolet (UV) and infrared (IR) divergences will appear in the calculation of $M^{V*}$. $D = 4 - 2\epsilon$ dimensional regularization is applied in all the calculations. We adopt the same renormalization scheme as in Ref. [20].

The Coulomb singularity is isolated by the small relative velocity $v$ and then is absorbed by the long-distance matrix element. The IR divergences will disappear when including the real corrections.

There are a few subprocesses in the real corrections. We divided them into seven categories below:

\[ gg \rightarrow J/\psi q\bar{q}, \quad q\bar{q} \rightarrow J/\psi gg, \quad \bar{q}q \rightarrow J/\psi q\bar{q}, \quad q\bar{q}' \rightarrow J/\psi q\bar{q}', \quad \bar{q}q' \rightarrow J/\psi q\bar{q}', \quad \bar{q}q(\bar{q}) \rightarrow J/\psi gg(\bar{q}), \]

where $q, q'$, $(\bar{q}, \bar{q}')$ denote light quark (anti-quark) with different flavors. For all these processes, there will be soft and collinear poles in the phase space integration. We separate them in $D$ dimensions for coherence using the two-cutoff phase space slicing method[21], in which the phase space is partitioned into three parts, the soft region, hard collinear region and hard non-collinear region by two small parameters: $\delta_s$, the soft cutoff and $\delta_c \ll \delta_s$ the collinear cutoff. Then the real corrections turn to be:

\[
σ^R = σ^S + σ^{HC} + σ^{HC}_{add} + σ^{HC}, \quad (4)
\]

where $σ^{S,a}$ is the contribution of soft region including soft divergences and is calculated analytically in the limit of the soft gluon. Note that the soft poles are all associated with light quarks or gluons, for only the one photon fragmentation diagrams are considered. $σ^{HC}$ from the hard collinear region contains collinear singularities which are also factorized out in D-dimensions. The initial state collinear poles are absorbed into the redefinition of the parton distribution function (PDF) (traditionally called mass factorization[22]). Here a scale dependent PDFs with $\overline{MS}$ convention[21] are used. After the redefinition of PDF, there will be an additional part $σ^{HC}_{add}$ left. The final state collinear poles together with the soft ones will cancel that of the virtual corrections, i.e. $σ^{HC} + σ^V$ is finite. And the cancellation is also completed analytically. The last part $σ^{HC}$ is finite and computed numerically.

To obtain the $p_t$ distribution of the $J/\psi$ production and polarization, the integral variables are transformed from $dz_2dt$ to $Jdp_tdy$. Then we have:

\[
\frac{dσ}{dp_t} = \int Jdx_1dyG_α(x_1, \mu_f)G_β(x_2, \mu_f) \frac{d\hat{σ}}{dt}. \quad (5)
\]

where $y$ is the rapidity of $J/\psi$ in the laboratory frame and $\mu_f$ is the factorization scale. And the polarization parameter $α$ is defined by:

\[
α(p_t) = \frac{dσ_T/dp_t - 2αL/dp_t}{dσ_T/dp_t + 2αL/dp_t}. \quad (6)
\]

To calculate $α(p_t)$, the $J/\psi$ polarization vectors $ε(λ)$ are kept through our calculation which makes the calculation

\[ \text{a Thereafter } \hat{σ} \text{ represents the corresponding partonic cross section.} \]
become more complicated. And the expression of the polarized \( J/\psi \) partonic differential cross section could be explicitly written as:

\[
\frac{d\sigma}{dt} = a \epsilon(t) \epsilon^*(t) + \sum_{i,j=1,2} a_{i,j} p_i \cdot \epsilon(t) p_j \cdot \epsilon^*(t),
\]

where \( \lambda = T_1, T_2, L \). \( \epsilon(T_1), \epsilon(T_2) \) and \( \epsilon(L) \) are the two transverse polarization vectors and the longitudinal one for \( J/\psi \) respectively. Meanwhile, the sum over polarizations of the other particles is done in D-dimensions. One could find that \( a \) and \( a_{i,j} \) will be finite if the virtual and real corrections are properly dealt as mentioned before.

To ensure the validity of our results, we also checked the gauge invariance by replacing the gluon polarization vectors with its momenta in the numerical calculation.

In the numerical calculations, the CTEQ6L1 and CTEQ6M PDFs are used and the corresponding fitted values \( \alpha_s(M_Z) = 0.130 \) and \( \alpha_s(M_Z) = 0.118 \) are used for LO and NLO predictions respectively. QED coupling constant \( \alpha = 1/128 \) and \( m_c = M_{J/\psi}/2 \approx 1.5 \text{GeV} \) are chosen.

The long distance matrix element \( \langle \mathcal{O}^{J/\psi}_1 \rangle = 1.35 \text{GeV}^3 \) is extracted from the leptonic decay of \( J/\psi \) at QCD NLO level. The renormalization scale \( \mu_r \) and factorization scale \( \mu_F \) are used as \( \mu_r = \mu_F = \mu_0 = \sqrt{(2m_c)^2 + p_t^2} \). The two phase space cutoffs \( \delta_t = 10^{-3} \) and \( \delta_c = \delta_t/50 \) are chosen, and the invariance for different values of \( \delta_t \) and \( \delta_c \) is obviously observed within the error tolerance. All the results are restricted to the NRQCD applicable domain \( p_t > 3 \text{ GeV} \), and \( |y_{J/\psi}| < 3 \) for the LHC, \( |y_{J/\psi}| < 0.6 \) for the Tevatron.

The numerical results for the photon fragmentation \( J/\psi \) production are presented in Fig. 2 and 3. For comparison, the plots for the conventional \( J/\psi \) production from the CSM at NLO are also shown in the two figures, and they will be referred as the conventional one in the following statement. The curves in Fig. 2.a show that the scale dependence is well improved at NLO at both the Tevatron and LHC, and the QCD corrections enhance the total cross section about 30% ~ 40% for our default choice of scale \( \mu_r = \mu_F = \mu_0 \). From Fig. 2.b, it is clear that the \( p_t \) distribution of \( J/\psi \) production for the new mechanism at NLO is comparable to the conventional one at middle \( p_t \) range \( (p_t \approx 20 \text{GeV}) \), and is larger than the conventional one as \( p_t > 26 \text{GeV} \), and reaches about 6 times of the conventional one when \( p_t = 50 \text{ GeV} \). The similar results for the LHC are shown in Fig. 2.c. The \( p_t \) distribution for the new one at NLO is larger than the conventional one as \( p_t > 35 \text{ GeV} \) and reaches about 10 times of the conventional one at \( p_t = 100 \text{ GeV} \). The \( p_t \) distribution of \( J/\psi \) polarization at the Tevatron and LHC are shown in Fig. 3. As can be seen from both the Tevatron and LHC results, because of \( J/\psi \) from photon fragmentation, the polarization parameter \( \alpha \) at LO is positive and turn close to 1 quickly when \( p_t \) increase. And its QCD corrections only make \( \alpha \) slightly lower down. It has been given in Ref. [10] that the \( J/\psi \) polarization at NLO is mainly longitudinal for the conventional one. When the contributions for the new one and conventional one are combined, \( \alpha \) is negative at low \( p_t \) region, and the photon fragmentation contribution to \( \alpha \) becomes more and more important as \( p_t \) increase. It makes \( \alpha \) go from negative to positive gradually.

In summary, we have suggested a new mechanism for \( J/\psi \) production at hadron colliders, \( pp(\bar{p}) \rightarrow \gamma^*(J/\psi) + X \), with \( J/\psi \) from photon fragmentation and calculated the \( J/\psi \) hadroproduction from this mechanism up to QCD NLO at the Tevatron and LHC. Although the obtained total cross section is small, its contribution has large impact on the \( p_t \) distribution of \( J/\psi \) production and polarization in large \( p_t \) region. The results show that the \( p_t \) distribution for the new production mechanism at NLO is larger than that of the conventional \( J/\psi \) production from the CSM at NLO when \( p_t > 26 \) (35) \text{GeV} at the
FIG. 3: The $p_t$ dependence of the polarization parameter $\alpha$ for $J/\psi$ production at Tevatron(left) and LHC (right).

Tevatron (LHC) and reach about 6 (10) times of the conventional one when $p_t = 50$ (100) GeV at the Tevatron (LHC), in spite of a suppression factor $(\alpha/\alpha_s)^2$. In addition, the $p_t$ distribution of $J/\psi$ polarization changes from longitudinal to transverse as $p_t$ increased by adding the new contribution to the conventional one. It is closer to the experimental result than the conventional one. In the future ATLAS and CMS experiments at LHC, the measured $p_t$ distributions of $J/\psi$ production and polarization can be extended to much larger $p_t$ region with its 14 TeV center-of-mass energy and high luminosity. Therefore it is a important mechanism for $J/\psi$ production at large $p_t$ region especially for the LHC.

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