Testing QCD Fragmentation Mechanism on heavy quarkonium production at the LHC

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Based on our recently wrok: B. Gong, R. Li, J. X. Wang, arXiv:1102.0118 [hep-ph]

Introduction

- Perturbative and non-perturbative QCD, hadronization, factorization
- Color-singlet and Color-octet mechanism was proposed based on NRQCD since c-quark is heavy.
- Clear signal to detect J/ψ.
- heavy quarkonium production is a good place to testify these theoretical framework.
- But there are still many difficulties.
  - J/ψ photoproduction at HERA
  - J/ψ production at the B factories
  - J/ψ polarization at the Tevatron
- NLO corrections are important.
  - Double charmonium production at the B factories

Introduction

- QCD, successful theory, its fundamental ingredients, the quarks and gluons
- QCD factorization theorem, the dominant contribution to the cross section can be decomposed into three parts:
  - partonic part,
  - parton fragmentation into final state hadron
  - parton distributions in the initial hadrons.
- For light hadrons, fragmentation functions, p_T distribution of inclusive light-charged-particle production measured by the CDF shows significantly exceed on the theoretical prediction (Phys. Rev. Lett.104, 242001,2010 by S. Albino, B. A. Kniehl and G. Krameri).
- heavy quarkonium, NRQCD, fragmentation functions calculable perturbatively.

The fragmentation function of charm into J/ψ

According to the fragmentation mechanism, we generally have

$$d\sigma[e^+e^- \to J/\psi(p)+X] = \sum_i \int dz d\sigma[e^+e^- \to i(p/z)+X,\mu_F] D_{i\to J/\psi}(z,\mu_F)\,. \tag{1}$$

$$\frac{d\sigma[e^+e^- \to J/\psi c\bar{c}]}{dE_J/\psi} = \int \frac{dE_c}{E_c} \frac{d\sigma[e^+e^- \to c\bar{c}]}{dE_c} \times D_{c\to J/\psi}\left(\frac{E_J/\psi}{E_c}\right) + (c \leftrightarrow \bar{c})$$

$$= 2\int \frac{dE_c}{E_c} \frac{d\sigma[e^+e^- \to c\bar{c}]}{dE_c} \times D_{c\to J/\psi}\left(\frac{E_J/\psi}{E_c}\right) \tag{2}$$

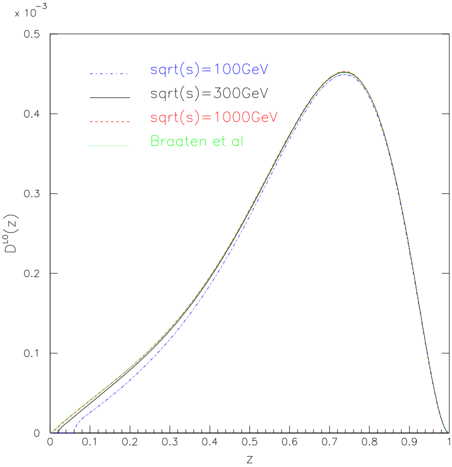
where $D_{c\to J/\psi}(z) = D_{\bar{c}\to J/\psi}(z)$ has been used.

The fragmentation function at the QCD leading-order

$$\frac{d\sigma^{LO}[e^+e^- \to J/\psi c\bar{c}]}{dE_J/\psi} = \frac{4}{\sqrt{s}}\sigma^{LO}[e^+e^- \to c\bar{c}] \times D_{c\to J/\psi}(z),\ z = 2E_J/\psi/\sqrt{s}. \tag{3}$$

Thus it's easy to exact the fragmentation function at LO in α_s:

$$D_{c\to J/\psi}(z) = \frac{1}{\sigma^*_{c\bar{c}}} \frac{d\sigma^{LO}[e^+e^- \to J/\psi c\bar{c}]}{dE_J/\psi},\ \sigma^*_{c\bar{c}} \equiv 4\sigma^{LO}[e^+e^- \to c\bar{c}]/\sqrt{s} \tag{4}$$



LO Fragmentation function of charm into J/ψ with $\mu_r = 2m_c$.
As shown in the figure, the result has little difference with the one given by E. Braaten, K. Cheung and T. C. Yuan, PhysRevD.48.4230 as $\sqrt{s}$ goes larger.

The fragmentation function at the QCD next-to-leading-order

$$
\begin{aligned}
& \frac{d\sigma^{NLO}[e^+e^- \rightarrow J/\psi c\bar{c}]}{dE_{J/\psi}} \\
= \quad & 2\int \frac{dE_c}{E_c} \frac{d\sigma^{NLO}[e^+e^- \rightarrow c\bar{c}]}{dE_c} \times D^{NLO}_{c\rightarrow J/\psi}\left(\frac{E_J/\psi}{E_c}\right) \\
= \quad & 2\int \frac{dE_c}{E_c} \frac{d\sigma^{LO}[e^+e^- \rightarrow c\bar{c}]}{dE_c} \times D^{NLO}_{c\rightarrow J/\psi}\left(\frac{E_J/\psi}{E_c}\right) \\
+ \quad & 2\int \frac{dE_c}{E_c} \frac{d\sigma^{NLO}[e^+e^- \rightarrow c\bar{c}] - \sigma^{LO}[e^+e^- \rightarrow c\bar{c}]}{dE_c} \times D^{LO}_{c\rightarrow J/\psi}\left(\frac{E_J/\psi}{E_c}\right) + \mathcal{O}(\alpha_s^4).
\end{aligned}
$$

$$
D^{NLO}_{c\rightarrow J/\psi}(z) \quad = \quad f_1(z) - f_2(z) \tag{5}
$$

$$
f_1(z) \quad \equiv \quad \frac{1}{\sigma^*_{c\bar{c}}} \frac{d\sigma^{NLO}[e^+e^- \rightarrow J/\psi c\bar{c}]}{dE_J/\psi}, \quad \sigma^{NLO*} \equiv \sigma^{NLO} - \sigma^{LO}
$$

$$
f_2(z) \quad \equiv \quad \frac{2}{\sigma^*_{c\bar{c}}} \int \frac{dE_c}{E_c} \frac{d\sigma^{NLO*}[e^+e^- \rightarrow c\bar{c}]}{dE_c} \times D^{LO}_{c\rightarrow J/\psi}\left(\frac{E_J/\psi}{E_c}\right) \tag{6}
$$

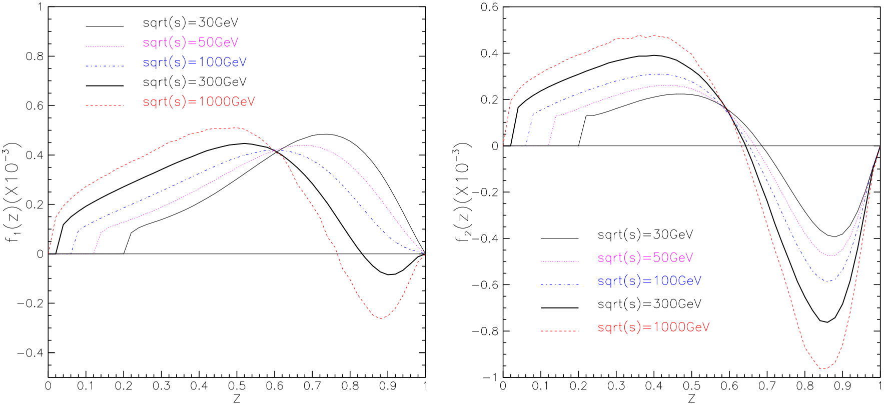


Figure: Behavior of $f_1(z)$ and $f_2(z)$ with $\mu_F = 3m_c$.

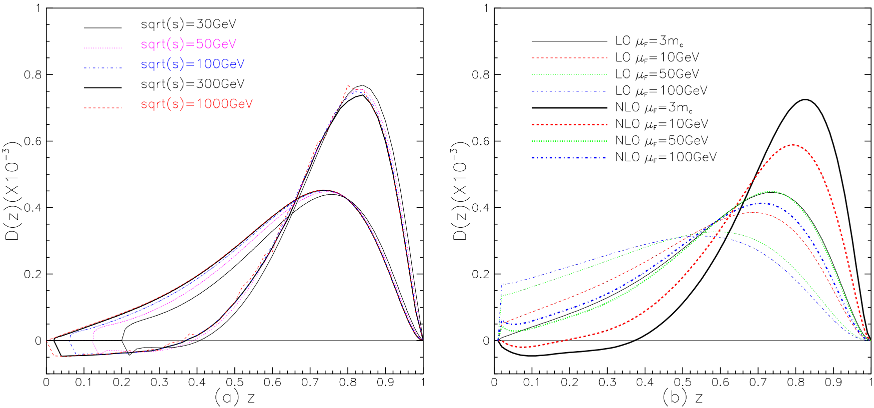


Figure: Left: the fragmentation functions of charm quark fragment into J/ψ at QCD next-to-leading order. Right: the Altarelli-Parisi evolution of the fragmentation functions. Bin Gong, Rong Li, Jian-Xiong Wang, arXiv:1102.0118 [hep-ph]

The decay width at LO is

$$\Gamma^{LO}_{J/\psi+X} = 2\Gamma^{LO}_{c+X} \int dz D^{LO}_{c\to J/\psi}(z) = 129 \text{ KeV}.$$

At NLO, there are two ways to calculate the decay width. One is described by Eq. 5 where the higher order term is neglected

$$\Gamma^{NLO}_{J/\psi+X} = 2\Gamma^{LO}_{c+X} \int dz D^{NLO}_{c\to J/\psi}(z) + 2\int dE_c dz \frac{d\Gamma^{NLO*}_{c+X}}{dE_c} D^{LO}_{c\to J/\psi}(z) = 136 \text{ KeV}.$$

The other one is to include the higher order term as

$$\Gamma^{NLO+}_{J/\psi+X} = 2\int dE_c dz \frac{d\Gamma^{NLO}_{c+X}}{dE_c} D^{NLO}_{c\to J/\psi}(z) = 141 \text{ KeV}.$$

Both the LO and NLO results are consistent with the fully NLO QCD calculation by R. Li and J. X. Wang in Phys. Rev. D.82:054006,2010, which gives 120 KeV at LO and 136 KeV at NLO with same parameters. The differences come from the fact that the limitation is not so well as the mass of Z^0 is not large enough to be treated as infinity.

To apply the fragmentation function to b quark case by substituting

$$m_c \leftrightarrow m_b, \quad n_f = 4 \leftrightarrow n_f = 5, \quad R_s^J/\psi(0) \leftrightarrow R_s^\Upsilon(0).$$

For the top quark decay, $t \longrightarrow \Upsilon + W^+ + b$, we have

$$\Gamma^{LO}_{t\longrightarrow\Upsilon+X} = \Gamma^{LO}_{t\longrightarrow b+X} \int dz D^{LO}_{b\longrightarrow\Upsilon}(z) = 30.9 \text{ KeV}. \tag{7}$$

And the two corresponding NLO results are

$$\Gamma^{NLO}_{t\longrightarrow\Upsilon+X} = \Gamma^{LO}_{t\longrightarrow b+X} \int dz D^{NLO}_{b\longrightarrow\Upsilon}(z) + \int dE_b dz \frac{d\Gamma^{NLO*}_{t\longrightarrow b+X}}{dE_b} D^{LO}_{b\longrightarrow\Upsilon}(z) = 40.0 \text{ KeV},$$

$$\Gamma^{NLO+}_{t\longrightarrow\Upsilon+X} = \int dE_b dz \frac{d\Gamma^{NLO*}_{t\longrightarrow b+X}}{dE_b} D^{NLO}_{b\longrightarrow\Upsilon}(z) = 39.7 \text{ KeV}.$$

Here we choose the same parameters as those used in the recent work by P. Sun, L. P. Sun and C. F. Qiao in Phys. Rev. D81:114035,2010. The corresponding LO and NLO results given by P. Sun et al are 26.8 and 52.3 KeV.

$$\sigma[pp \to J/\psi c\bar{c} + X] = \sum_{i,j=g,q,\bar{q}} \int dx_1 dx_2 dz f_{i/p}(x_1, \mu_f) f_{j/p}(x_2, \mu_f) d\hat{\sigma}[ij \to c\bar{c} + X, \mu_f, \mu_r, \mu_F] D_{c(\bar{c}) \to J/\psi}(z, \mu_F),$$

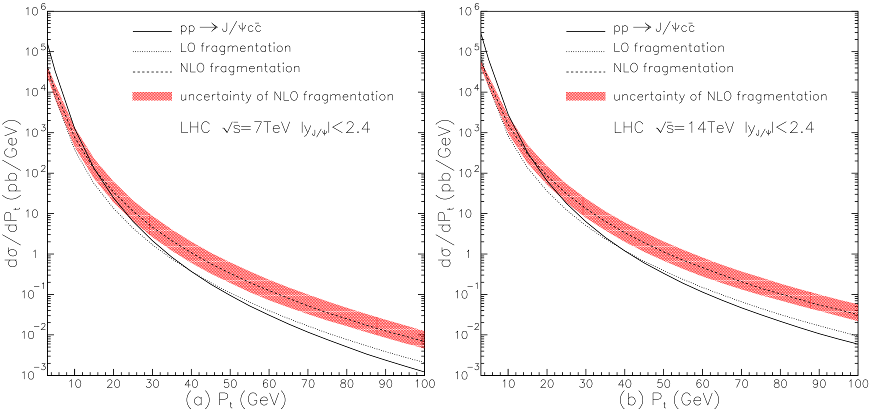


Figure: The theoretical prediction on p_t distribution of J/ψ production associated with a charm c ($\bar{c}$) jet at the LHC.

Summary

- $c \rightarrow J/\psi$ fragmentation function is obtained at NLO level for the first time.
- The results for J/ψ production in z^0 decay from the full calculation is agree with the result from $c \rightarrow J/\psi$ fragmentation function application at NLO level.
- The result from the applcation of the fragmentation function to b quark case in $t \rightarrow \Upsilon + W^+ + b + X$ does not agree with it's full calculation at the NLO.
- Our predication of the J/ψ transverse momentum distribution on J/ψ plus charm-jet signal supply the first chance to test the Fragmentation mechanism on Heavy Quarkonium production at the LHC.

Thank you!