Testing QCD Fragmentation Mechanism on Heavy Quarkonium Production at the LHC

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

Introduction

- Perturbative QCD is successful to describe large momentum transfer processes.
- Quark hadronization is in non-perturbative range.
- For heavy quarkonium
  - Color-singlet mechanism: straightforward from pQCD
  - Color-octet mechanism: introduced to describe the discrepancy at the Tevatron
  - Clear signal to be detected due to its dilepton decay mode.
- But there are still many difficulties.
  - J/ψ production at the B factories
  - J/ψ polarization at the Tevatron
- NLO corrections are important.
  - Double charmonium production at the B factories

- 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:
  - parton distributions in the initial hadrons
  - partonic part
  - parton fragmentation into final state hadron
- 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)
- For heavy quarkonium, NRQCD, fragmentation functions calculable perturbatively.

The fragmentation function of charm into J/ψ

According to the fragmentation mechanism, we have

$$\begin{aligned} & d\sigma[e^+e^- \to J/\psi(p) + X] \\ = & \sum_i \int dz d\sigma[e^+e^- \to i(p/z) + X, \mu_F] D_{i\to J/\psi}(z, \mu_F) + \mathcal{O}\left(\frac{m_c}{\sqrt{s}}\right). \end{aligned}$$

(There is a sum over all possible parton i)

Up to NLO in α_s, and focuses on the $c\bar{c}$ channel:

$$\begin{aligned} & \frac{d\sigma[e^+e^- \to J/\psi c\bar{c} + X]}{dE_{J/\psi}} \\ = & \; 2\int \frac{dE_c}{E_c} \frac{d\sigma[e^+e^- \to c\bar{c}X]}{dE_c} \times D_{c\to J/\psi}\left(\frac{E_{J/\psi}}{E_c}\right), \end{aligned}$$

where $\mu_F = 3m_c$ is chosen and $D_{c\to J/\psi}(z) = D_{\bar{c}\to J/\psi}(z)$ has been used.

Contribution via fragmentation of light quarks and gluons are higher order in α_s, thus only charm quarks and anti-quarks remain in the sum over parton i.

The fragmentation function at the QCD LO

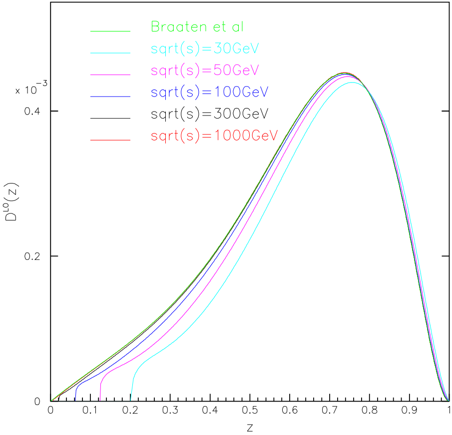
At LO in α_s, we have $z = 2E_{J/\psi}/\sqrt{s}$, then

$$\begin{aligned} \frac{d\sigma^{LO}[e^+e^- \to J/\psi c\bar{c}]}{dE_{J/\psi}} &= \frac{4}{\sqrt{s}}\sigma^{LO}[e^+e^- \to c\bar{c}] \times D^{LO}_{c\to J/\psi}(z) \\ D^{LO}_{c\to J/\psi}(z) &= \frac{1}{\sigma^*_{c\bar{c}}}\frac{d\sigma^{LO}[e^+e^- \to J/\psi c\bar{c}]}{dE_{J/\psi}} \\ \sigma^*_{c\bar{c}} &\equiv 4\sigma^{LO}[e^+e^- \to c\bar{c}]/\sqrt{s}. \end{aligned}$$

When $\sqrt{s}/m_c \to \infty$, it is easy to obtain

$$\begin{aligned} \sigma^*_{c\bar{c}} &= \frac{64\pi\alpha^2}{9s^{3/2}} \\ D^{LO}_{c\to J/\psi}(z) &= \frac{8\alpha_s(2m_c)^2|R_s(0)|^2}{27\pi m_c^3} \times \frac{z(1-z)^2(16-32z+72z^2-32z^3+5z^4)}{(2-z)^6} \end{aligned}$$

Exactly same as the one obtained from Z_0 decay by E. Braaten, K. Cheung and T. C. Yuan, PhysRevD.48, 4230.



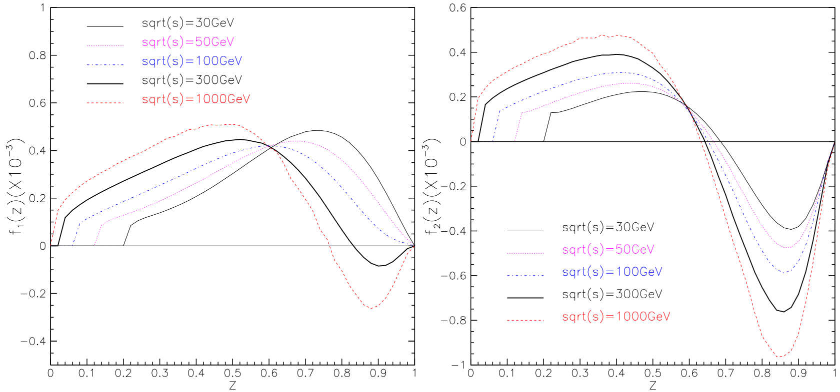
LO Fragmentation function of charm into J/ψ with $\mu_r = 2m_c$.

As shown in the figure, numerical approach with $\sqrt{s} = 30, 50, 100, 300, 1000$ GeV shows good coincidence with the analytic result.

The fragmentation function at the QCD NLO

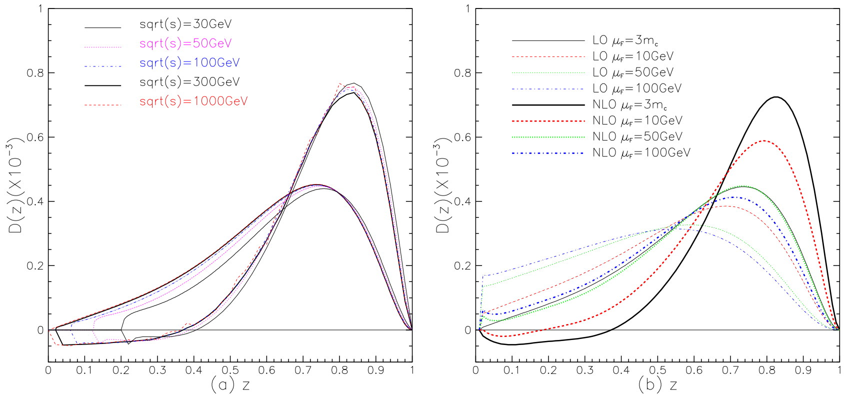
$$
\begin{aligned}
&\frac{d\sigma^{NLO}[e^+e^- \to J/\psi c\bar{c}]}{dE_{J/\psi}} \\
= \quad & 2\int \frac{dE_c}{E_c} \frac{d\sigma^{NLO}[e^+e^- \to c\bar{c}]}{dE_c} \times D^{NLO}_{c\to J/\psi}\left(\frac{E_{J/\psi}}{E_c}\right) \\
= \quad & 2\int \frac{dE_c}{E_c} \frac{d\sigma^{LO}[e^+e^- \to c\bar{c}]}{dE_c} \times D^{NLO}_{c\to J/\psi}\left(\frac{E_{J/\psi}}{E_c}\right) \\
+ \quad & 2\int \frac{dE_c}{E_c} \frac{d\sigma^{NLO}[e^+e^- \to c\bar{c}] - d\sigma^{LO}[e^+e^- \to c\bar{c}]}{dE_c} \times D^{LO}_{c\to J/\psi}\left(\frac{E_{J/\psi}}{E_c}\right) + \mathcal{O}(\alpha_s^4). \qquad (1)
\end{aligned}
$$

$$
\begin{aligned}
D^{NLO}_{c\to J/\psi}(z) \quad &= \quad f_1(z) - f_2(z) \\
f_1(z) \quad &\equiv \quad \frac{1}{\sigma^*_{c\bar{c}}} \frac{d\sigma^{NLO}[e^+e^- \to J/\psi c\bar{c}]}{dE_{J/\psi}}, \quad \sigma^{NLO*} \equiv \sigma^{NLO} - \sigma^{LO} \\
f_2(z) \quad &\equiv \quad \frac{2}{\sigma^*_{c\bar{c}}} \int \frac{dE_c}{E_c} \frac{d\sigma^{NLO*}[e^+e^- \to c\bar{c}]}{dE_c} \times D^{LO}_{c\to J/\psi}\left(\frac{E_{J/\psi}}{E_c}\right)
\end{aligned}
$$



Behavior of $f_1(z)$ and $f_2(z)$ with different $\sqrt{s}$ with $\mu_F = 3m_c$.

Obvious $\sqrt{s}$ dependence is seen.



Left: the fragmentation functions of charm quark fragment into J/ψ at QCD NLO.
Right: the Altarelli-Parisi evolution of the fragmentation functions.
Strong dependence on $\sqrt{s}$ in $f_1(z)$ and $f_2(z)$ cancels and limit without $\sqrt{s}$ dependence is seen.
The one with $\sqrt{s} = 1000\ \mathrm{GeV}$ is a bit unstable because of large number cancelation between $f_1(z)$ and $f_2(z)$.
(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. (1) 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 full 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.

The fragmentation function can be applied 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, $t \to \Upsilon + W^+ + b$, we have

$$\Gamma^{LO}_{t\to\Upsilon+X} = \Gamma^{LO}_{t\to b+X} \int dz D^{LO}_{b\to\Upsilon}(z) = 30.9 \text{ KeV}. \tag{2}$$

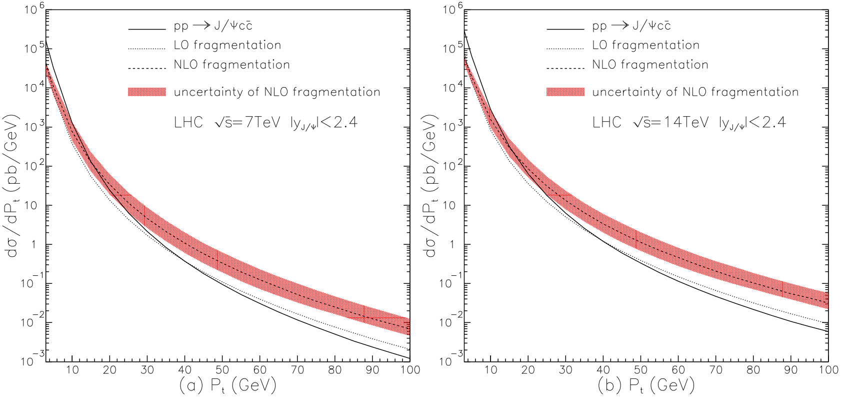
And the two corresponding NLO results are

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

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

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.

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



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

Summary

- $c \to J/\psi$ fragmentation function is obtained at QCD NLO level for the first time.
- The results for J/ψ production in z^0 decay via fragmentation agree with the one from the full calculation at NLO level.
- The results for Υ production in top quark decay via fragmentation does not agree with its full calculation at the NLO.
- Our predictions for p_t distribution of J/ψ production associated with a charm or anti-charm jet supply the first chance to test the fragmentation mechanism on heavy quarkonium production at the LHC.

Thank you!