The hadroproduction of $J/\psi+\gamma$ at the NLO

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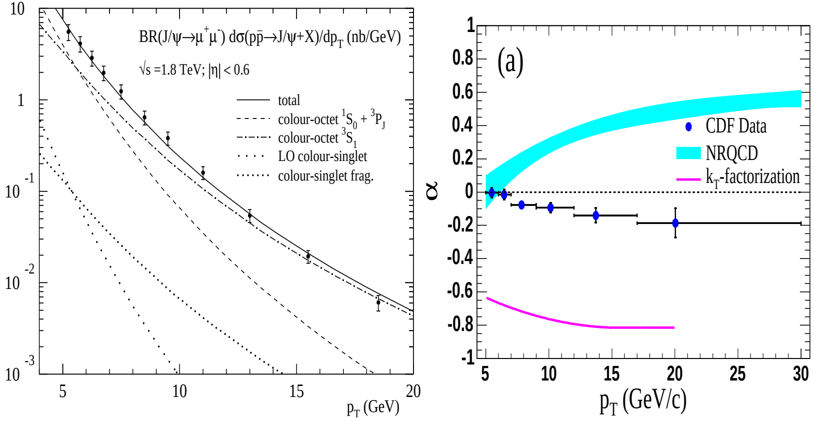
Introduction

- Heavy Quarkonium
  Two heavy quarks system, especially the J/ψ and Υ.
  The dilepton decay channel of them.
  The large heavy quark masses set a scale for perturbative calculation.
- color-singlet model
  Short distance part$\otimes$Long-distance matrix elements
- Shortcomings of color-singlet model
  Theoretically:Infrared divergence in study of P-wave Quarkonium decay at QCD NLO and relativistic correction for the decay of S-wave Quarkonium
  Experimentally: The $J/\psi(\psi')$ surplus problem at the Tevatron.

- NRQCD Factorization
  Effective theory based on QCD(G.T. Bodwin, L. Braaten, and G. P. Lepage, Phys. Rev. D51, 1125, 1995, hep-ph/9407339)
  Characteristic scales in heavy quark system: $M_Q >> M_Q v >> M_Q v^2$
- Factorization formula for the production of Quarkonium and the matching of coefficients.

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

$$A(Q\overline{Q} \to Q\overline{Q})\Big|_{\text{pert. QCD}} = \sum_n \frac{f_n}{m^{d_n-4}} \langle Q\overline{Q}|\mathcal{O}_n|Q\overline{Q}\rangle\Big|_{\text{pert. NRQCD}}$$



The p_t distribution of inclusive J/ψ production at Tevatron。(hep-ph/0106120,arXiv:0704.0638)

- Important progresses on the inclusive Heavy Quarkonium hadroproduction in recent years.
  1. The NLO correction to p_t distribution of heavy Quarkonium in CSM (Campbell et al 2007)
  2. The NLO result on the polarization distribution of heavy Quarkonium in CSM (Gong et al 2008)
  3. The NLO results including the contribution from ${}^3S_1^8$ and ${}^1S_0^8$ channels (Gong et al 2008).
  4. The complete NLO results on the p_t distribution of J/ψ in NRQCD. (Butenschoen et al 2011; Ma et al 2011)
  5. The complete NLO results on the polarization distribution of J/ψ in NRQCD. (Butenschoen et al 2011; Chao et al 2011)
  6. The results on polarization distribution of J/ψ and Υ with the feed-down contribution. (Gong 2013; 2014)

- The relevant works on the associate production of Heavy Quarkonium and a Boson.

  1. To investigate the gluon content of proton (Drees et al 1992; Doncheski et al 1994)

  2. To study the production mechanism of Quarkonium (Kim et al 1995;1997; Roy et al 1995; Mathews et al 1999; Kniehl et al 2002; Lansberg et al 2013)

  3. The NLO results on the Quarkonium+$Z^0(W^{\pm})$ (Li et al 2011; Mao et al 2011; Gong et al 2013)

  4. The NLO results on the Quarkonium+γ in CSM (Li and Wang 2009)

  5. The NNLO* results on the Quarkonium+γ in CSM (Lansberg 2009)

  6. To investigate the transverse dynamics and polarization of gluon in proton (den Dunnen et al 2014)

Motivation

- The extension of our study on hadroproduction of $J/\psi + \gamma + x$ in CSM in 2008.
  We investigate the process in CSM and found that the NLO QCD correction enhance the p_t distribution largely and change the theoretical prediction on polarization from transverse to longitudinal. To Compare the theoretical results with the experimental data a complete calculation in NRQCD is needed.
- To investigate the different sets of LDME and even to extract LDME from matching with the experimental data.
- The forthcoming study on $\Upsilon + \gamma + X$ will be helpful to study TMD factorization. (Lansberg 2014)

Our work

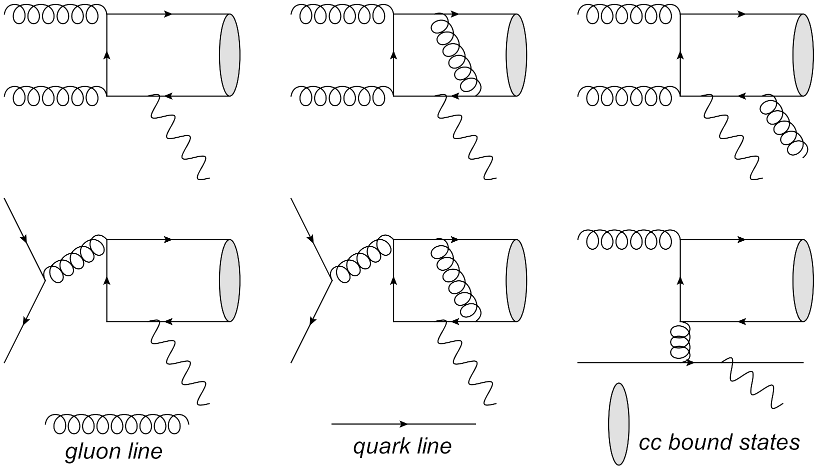
- We investigate the QCD NLO correction to $p + \bar{p} \rightarrow J/\psi + \gamma + X$ with following factorization formula:

$$\sigma(p + \bar{p} \rightarrow J/\psi + \gamma + X) = \sum_{i,j} \int dx_1 dx_2$$
$$\times \quad G_p^i(x_1) G_{\bar{p}}^j(x_2) \hat{\sigma}(ij \rightarrow (Q\bar{Q})_n + \gamma + X) \langle O_n^{J/\psi} \rangle.$$

- The relevant parton level processes:

$$LO\ and\ Virtual : g + g \rightarrow Q\bar{Q}[^3S_1^1, ^1S_0^8, ^3S_1^8, ^3P_J^8] + \gamma,$$
$$q + \bar{q} \rightarrow Q\bar{Q}[^3S_1^1, ^1S_0^8, ^3S_1^8, ^3P_J^8] + \gamma,$$

$$Real : g + g \rightarrow Q\bar{Q}[^3S_1^1, ^1S_0^8, ^3S_1^8, ^3P_J^8] + \gamma + g,$$
$$q + \bar{q} \rightarrow Q\bar{Q}[^1S_0^8, ^3S_1^8, ^3P_J^8] + \gamma + g,$$
$$q(\bar{q}) + g \rightarrow Q\bar{Q}[^3S_1^1, ^1S_0^8, ^3S_1^8, ^3P_J^8] + \gamma + q(\bar{q}).$$



The typical Feynman diagrams of this process.

- The infrared divergence in the ${}^3P_J^8$ parts. The soft divergence in real part of ${}^3P_J^8$ process are canceled by the virtual parts and absorbed by the redefinition of the LDMEs at NLO.
- The isolated photon scheme (Frixione 1998):

$$p_t^i \leq p_t^\gamma \frac{1-\cos R_{\gamma_i}}{1-\cos\delta_0} \quad \textit{for} \quad R_{\gamma_i} < \delta_0,$$
$$R_{\gamma i} = \sqrt{(\eta_i-\eta_\gamma)^2+(\phi_i-\phi_\gamma)^2}.$$

$\eta_{\gamma(i)}$: pseudorapidity of $\gamma(jet)$.
$\phi_{\gamma(i)}$: azimuthal angle of $\gamma(jet)$.
Here we take $\delta_0 = 0.7$

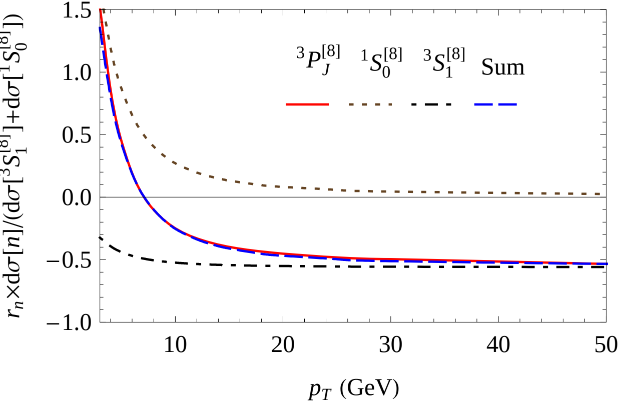
- the parameters

1.The wave functions at origin of J/ψ is extracted from its lepton decay with：

$$\Gamma_{ee} = (1 - \frac{16\alpha_s}{3\pi})\frac{4\alpha^2 e^2_{c(b)}}{M^2_{J/\psi}}|R_s^{J/\psi}|^2$$

$\Gamma_{ee}^{J/\psi} = 5.55\text{keV}$, α=1/137， $\alpha_s = \alpha_s^{2-loop}(2m_c)$.
2.The calculation of short distance coefficients：
m_c=1.4,1.5,1.6GeV The running of α_s： one-loop for the LO calculation； two-loop for the NLO calculation.
The scales are setting as:
$\mu_r = \mu_f = \mu_0 = \sqrt{(2m_c)^2 + p_t^2}$
α=1/128
The parton distribution function:CTEQ6L1 and CTEQ6M for LO and NLO calculation respectively.

- The linear correlation among the short distance coefficients of the three color octet channel (Ma et al 2011):



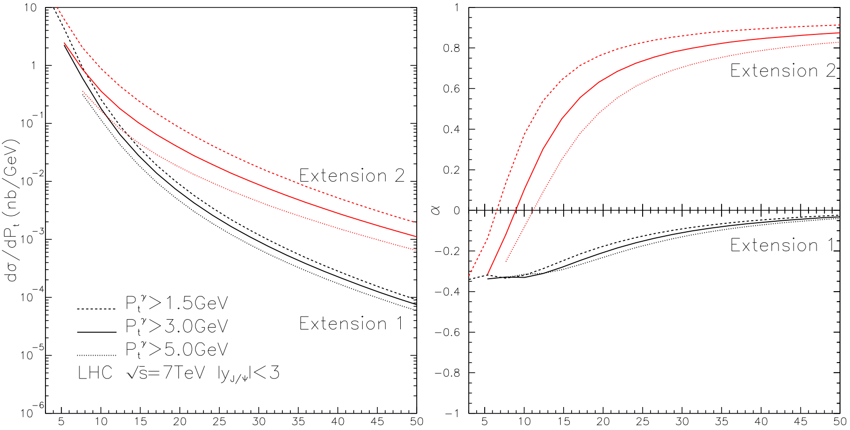
$$M_{0,r_0}^{J/\psi} = \langle O^{J/\psi}(^1S_0^8)\rangle + \frac{r_0}{m_c^2}\langle O^{J/\psi}(^3P_0^8)\rangle,$$

$$M_{1,r_1}^{J/\psi} = \langle O^{J/\psi}(^3S_1^8)\rangle + \frac{r_1}{m_c^2}\langle O^{J/\psi}(^3P_0^8)\rangle,$$

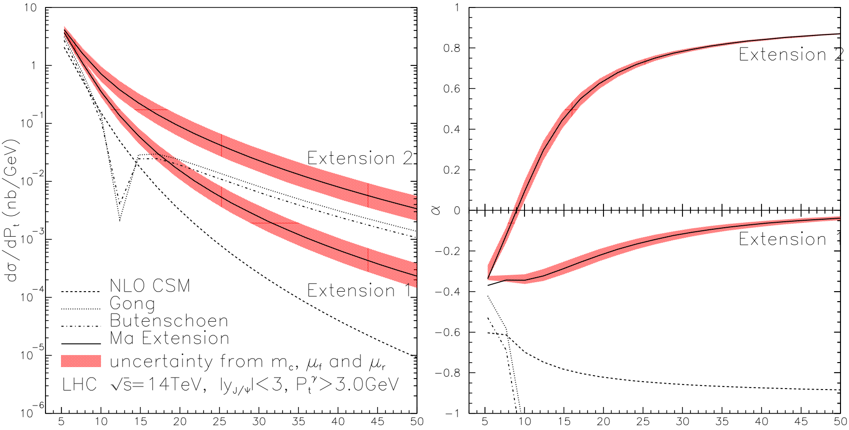
Table: The NRQCD LDMEs $\langle O^{J/\psi}(n)\rangle$ extracted by three groups at the NLO with $\langle O^{J/\psi}(^3S_1^1)\rangle$ =1.32 (1.16) GeV^3 used in the paper of Butenschoen (in the others). The NRQCD LDMEs in Ma extension1 and extension2 are determined from the combination extracted in the work of Ma (r_0=3.9, r_1=-0.56, $M_{0,r_0}^{J/\psi} = 0.074$ and $M_{1,r_1}^{J/\psi} = 0.0005$)

n	$^1S_0^8, \mathrm{GeV}^3$	$^3S_1^8, \mathrm{GeV}^3$	$^3P_0^8, \mathrm{GeV}^5$
Butenschoen,2011	0.0497	0.0022	-0.0161
Gong,2012	0.097	-0.0046	-0.0214
Chao,2012	0.089	0.0030	0.0126
Ma extension1	0.074	0.0005	0
Ma extension2	0	0.011	0.019

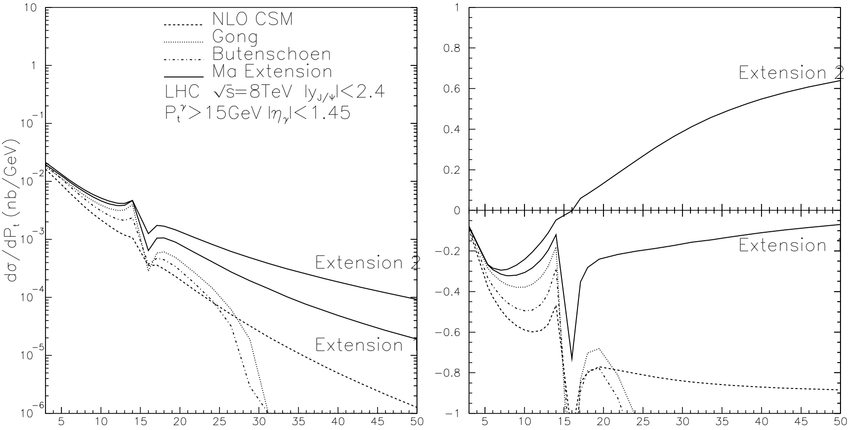
- The p_t distribution and the polarization of J/ψ for $J/\psi + \gamma$ production with different cuts on p_t^γ.



- The p_t distribution and the polarization of J/ψ for $J/\psi + \gamma$ production with different sets of LDMEs.



- The p_t distribution and the polarization of J/ψ for $J/\psi + \gamma$ production at the LHC with $\sqrt{s} = 8\,TeV$.



Conclusion

1. The $p + \bar{p} \to J/\psi + \gamma + X$ is investigated at the NLO in the framework of NRQCD and the color-octet channel plays an important role.
2. This process is sensitive to the LDME $\langle {}^3P_0^8 \rangle$. Therefore, the measurement of this process can be very helpful to fix the value of $\langle {}^3P_0^8 \rangle$ which has much flexibility at present.
3. This process can be investigated by using the present data sample collected at 8TeV LHC theoretically.

$$\text{Integrated luminosity}: \ 23fb^{-1}$$
$$\text{Photon reconstruction efficiency}: \ 0.7$$
$$Br(J/\psi \to \mu^+\mu^-) = 0.06$$
$$p_t^{J/\psi} = 17GeV: \ 960 \sim 1920 \text{ events}$$
$$p_t^{J/\psi} = 50GeV: \ 19 \sim 96 \text{ events}$$

Thanks