Associated production of heavy quarkonium

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Outline

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Introduction

- Heavy Quarkonium:
  The system consisted of two heavy quarks:Esp. J/ψ and Υ
- Main characteristics of the system:
  1.The dilepton decay channel of $^3S_1$ state.
  2.Large heavy quark masses set a scale for perturbative calculation.
- color-singlet model:
  Short distance part$\otimes$Long-distance matrix elements.
  Short-distance part: perturbative calculation
  Long-distance part: extracted from experimental or calculated from potential model
- Problems:
  Infrared divergence and the J/ψ surplus at the Tevatron.

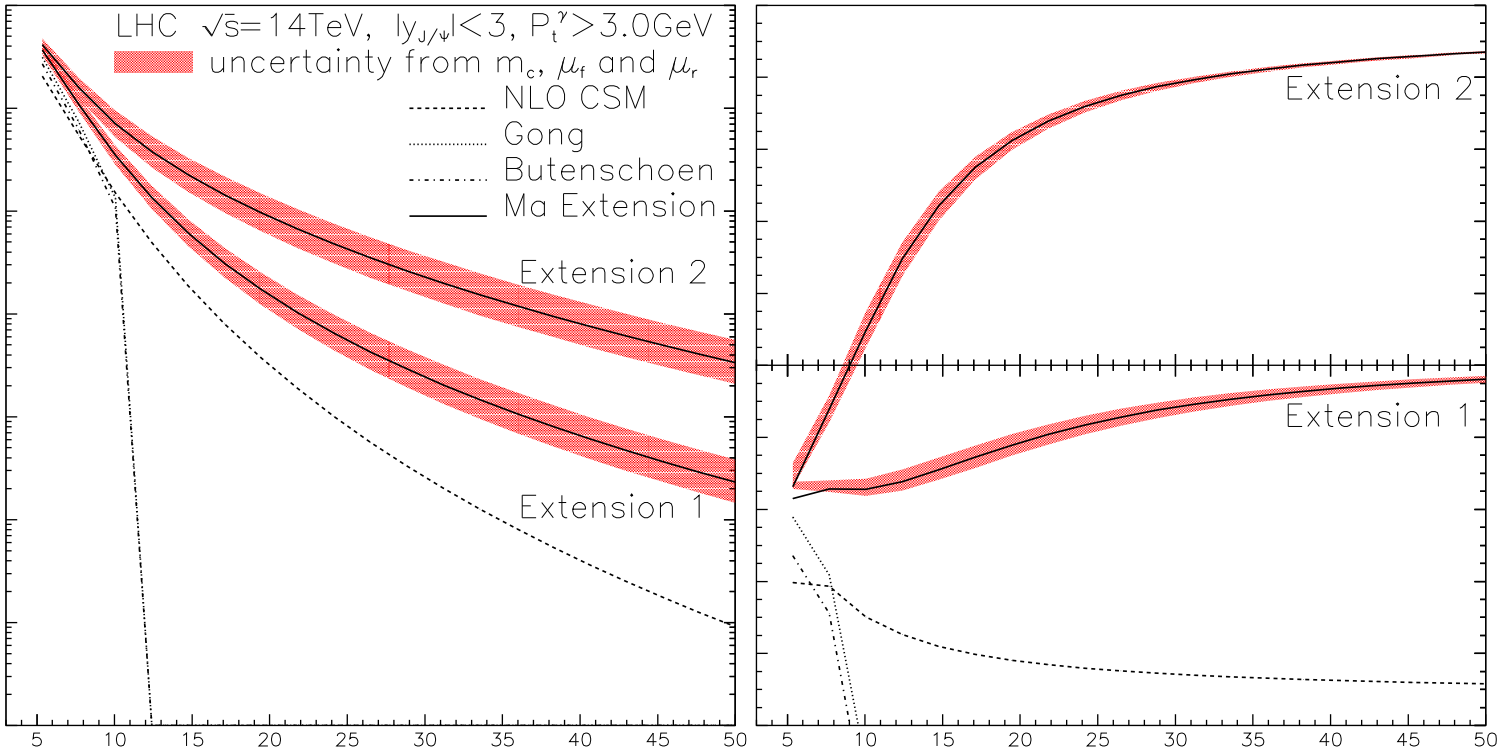
- NRQCD Factorization:
  Effective theory based on QCD(G.T. Bodwin, L. Braaten, and G. P. Lepage, Phys. Rev. D51, 1125, 1995)
  Characteristic scales in heavy quark system:
  $M_Q >> M_Q v >> M_Q v^2$
- Factorization formula for the production of Quarkonium and the matching of coefficients.

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

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

- Some important progresses related to our works.
  1. About 10 years ago, there are two groups had given the NLO correction to the yield and polarization on the inclusive production of heavy quarkonium in CSM.
  2. Recent years, three groups had calculate the complete NLO correction to the J/ψ inclusive production at the hadron collider and extracted the LDMEs of J/ψ. They used the different scheme and get different sets of LDMEs.
  3. As for the Υ cases, two groups had extracted different sets of LDMEs by using the different schemes that we will investigate below.
  4. Two years ago, we had given a complete study on the inclusive production of $J/\psi + \gamma + X$ and found that by using the different sets of LDMEs on J/ψ production the inconsistent predictions had been obtained.
  5. Also there had been some studies on the associated production of $J/\psi + Z^0(W^{\pm})$.

- Main results on $J/\psi + \gamma$(Phys. Rev. D 89, 114018)



This process is sensitive to the LDMEs.This process can be investigated by using the present data sample collected at 8TeV LHC theoretically: Integrated luminosity:$23fb^{-1}$;Photon reconstruction efficiency : 0.7;Br($J/\psi \to \mu^+\mu^-$)=0.06; $p_t^{J/\psi} \sim$ 17GeV, 960$\sim$1920 events; $p_t^{J/\psi} \sim$ 50GeV 19$\sim$96 events.

Motivation

- The extension of our study on hadroproduction of $\Upsilon + \gamma + x$ 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.
- Two years ago we get the complete results on $J/\psi + \gamma + X$ and reveal the problem on the universality of LDMEs. Maybe the $b\bar{b}$ system as a better non-relativistic system can give some positive support on the universality of LDMEs.
- To investigate the different sets of LDME that had been extracted by two groups with different schemes and even to extract LDMEs from matching with the experimental data.
- The study on $\Upsilon + \gamma + X$ as a background will be helpful to study TMD factorization.

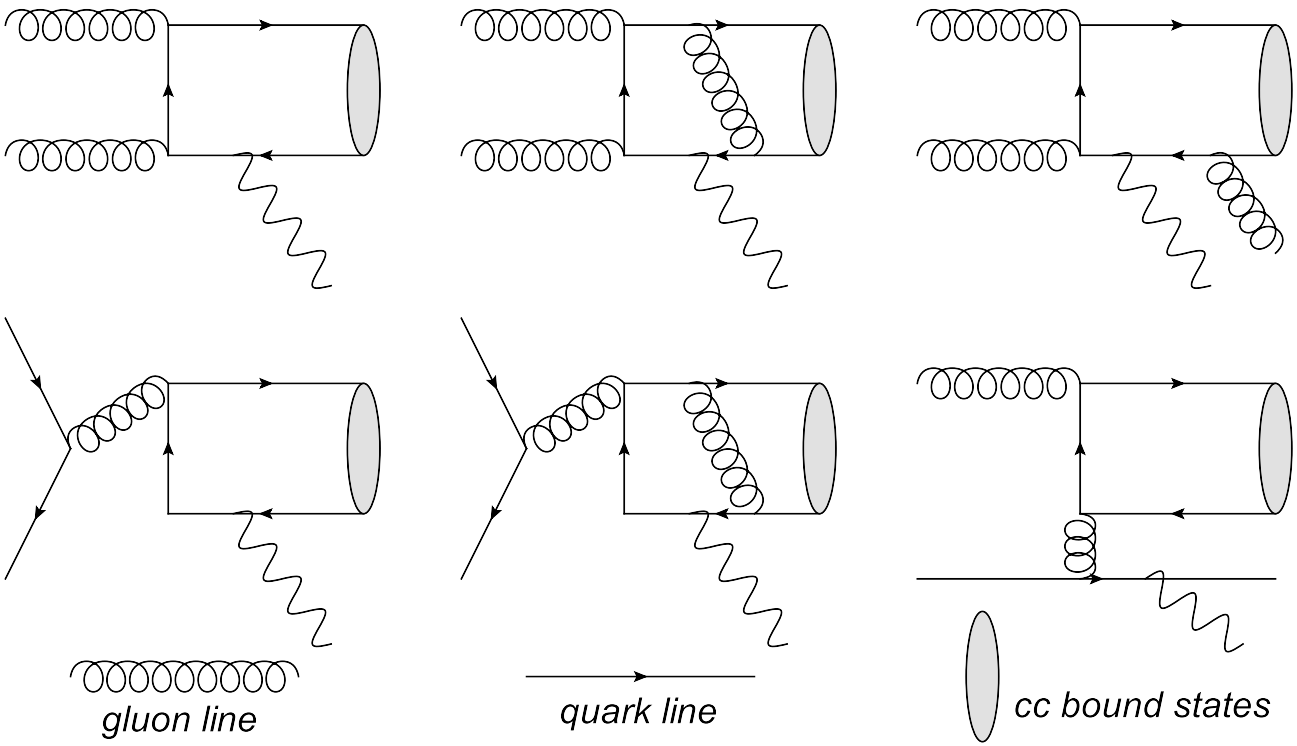
Our preliminary results on $\Upsilon + \gamma$

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

$$\sigma(p + \bar{p} \to \Upsilon + \gamma + X) = \sum_{i,j} \int dx_1 dx_2 \tag{1}$$
$$\times \quad G_p^i(x_1) G_{\bar{p}}^j(x_2) \hat{\sigma}(ij \to (Q\bar{Q})_n + \gamma + X) \langle O_n^{\Upsilon} \rangle.$$

- The relevant parton level processes:

$$g + g \to Q\bar{Q}[^3S_1^1, {}^1S_0^8, {}^3S_1^8, {}^3P_J^8] + \gamma, \tag{2}$$
$$g + g \to Q\bar{Q}[^3S_1^1, {}^1S_0^8, {}^3S_1^8, {}^3P_J^8] + \gamma + g, \tag{3}$$
$$q + \bar{q} \to Q\bar{Q}[^3S_1^1, {}^1S_0^8, {}^3S_1^8, {}^3P_J^8] + \gamma, \tag{4}$$
$$q + \bar{q} \to Q\bar{Q}[^1S_0^8, {}^3S_1^8, {}^3P_J^8] + \gamma + g, \tag{5}$$
$$q(\bar{q}) + g \to Q\bar{Q}[^3S_1^1, {}^1S_0^8, {}^3S_1^8, {}^3P_J^8] + \gamma + q(\bar{q}). \tag{6}$$



The Feynman diagrams of these process.

- The definition of polarization parameter in helicity frame:

$$\alpha(p_t) = \frac{d\sigma_{11}/dp_t - d\sigma_{00}/dp_t}{d\sigma_{11}/dp_t + d\sigma_{00}/dp_t}. \tag{7}$$

- The isolated photon scheme (Frixione 1998):

$$p_t^i \leq p_t^\gamma \frac{1-\cos R_{\gamma_i}}{1-\cos\delta_0} \quad \textit{for} \quad R_{\gamma_i} < \delta_0, \tag{8}$$

$$R_{\gamma i} = \sqrt{(\eta_i - \eta_\gamma)^2 + (\phi_i - \phi_\gamma)^2}. \tag{9}$$

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

- the parameters

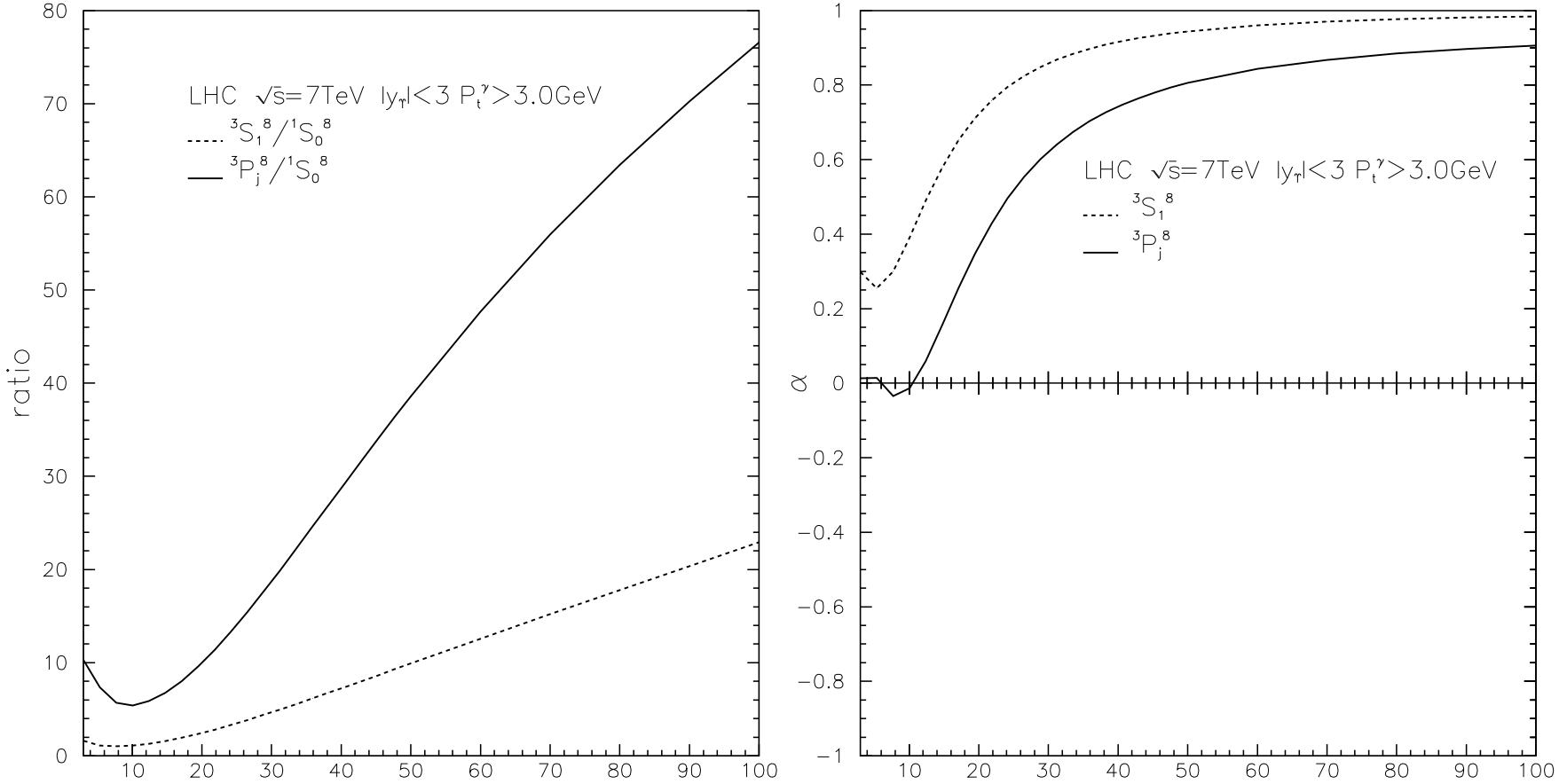
  1.The wave functions at origin of Υ is estimated by using the B-T potential model.

$$|R_\Upsilon(0)|^2 = 6.477 GeV^3;$$
$$\langle O(^3S_1^1)\rangle = \frac{(2J+1)2N_c}{4\pi}|R_\Upsilon(0)|^2$$

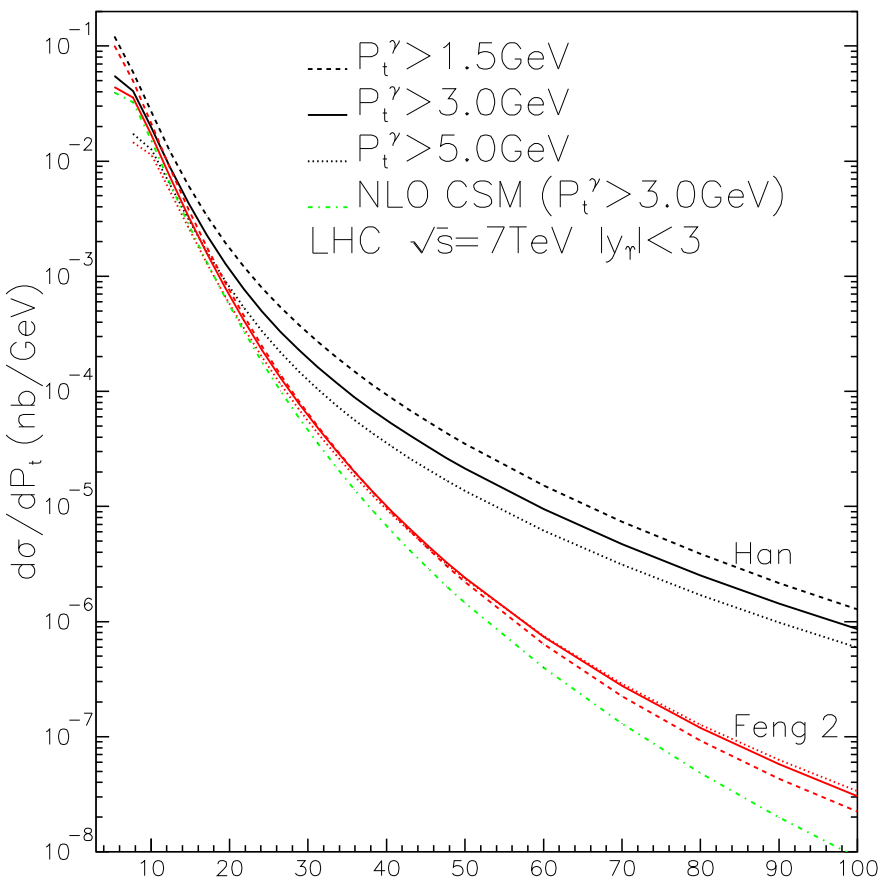
  2.The calculation of short distance coefficients
  m_b=4.63, 4.73 and 4.83GeV The running of $\alpha_s$one-loop for the LO calculationtwo-loop for the NLO calculation.
  The scales are setting as:
  $\mu_r = \mu_f = 0.5\mu_0, \mu_0$ and $2\mu_0, \mu_0 = \sqrt{(2m_b)^2 + p_t^2}$;$\alpha$=1/128
  $\mu_\Lambda = m_b$ or $\mu_\Lambda = m_b v \simeq$1.5GeV;
  $\sqrt{s}$ =7,14 and 8 TeV respectively.
  The parton distribution function:CTEQ6L1 and CTEQ6M for LO and NLO calculation respectively.

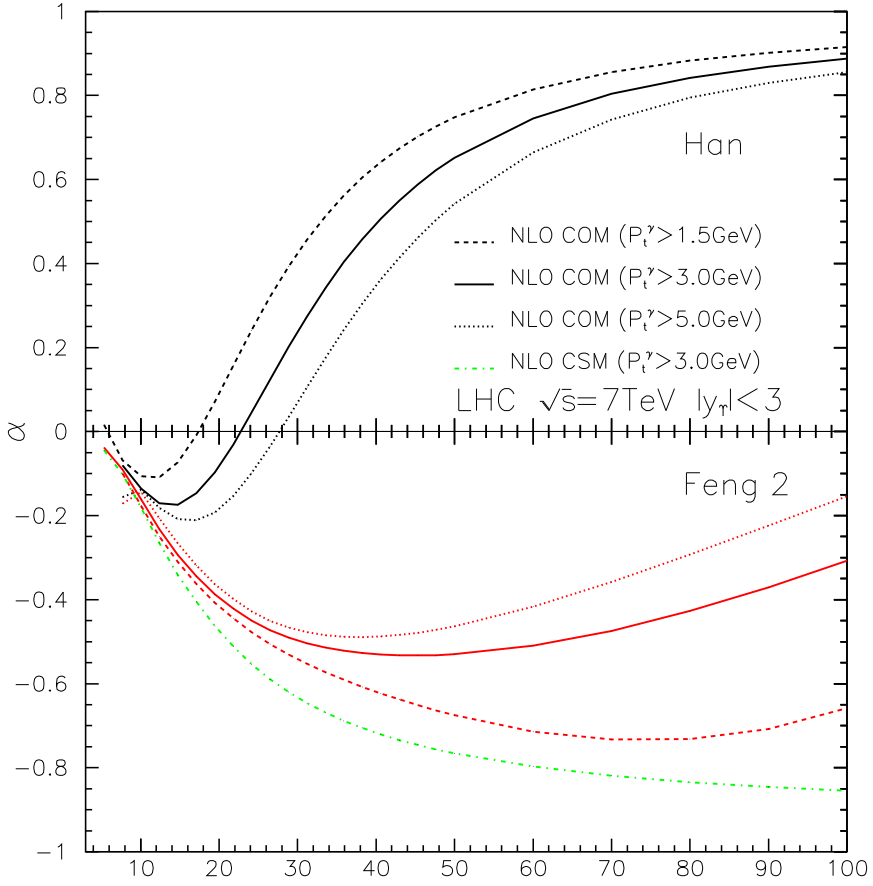
Table: The NRQCD LDMEs $\langle O^{\Upsilon}(n)\rangle$ extracted by two groups at the NLO with $\langle O^{\Upsilon}(^3S_1^1)\rangle$ =9.28 GeV^3.The other three color-octet LDMEs are listed as following.(LDMEs in unit of 10^{-2} GeV^3)

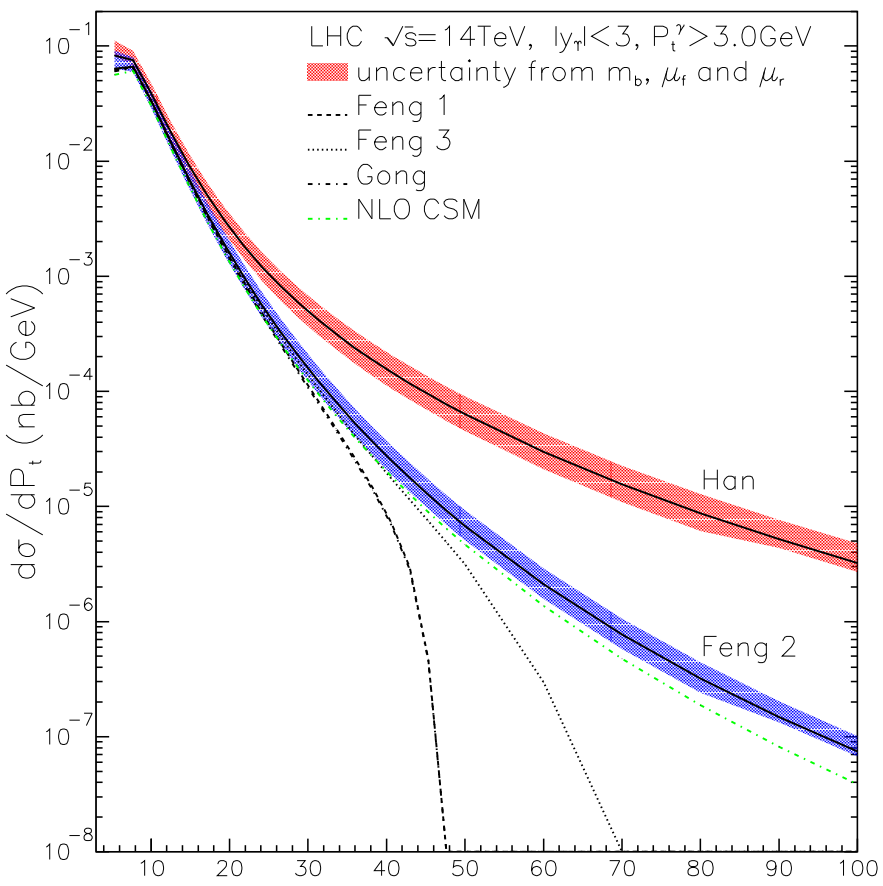
	$O(^1S_0^8)$	$O(^3S_1^8)$	$O(^3P_0^8)/m_b^2$	$P_t >$	μ_Λ
Han	0.017	2.97	3.83	15	m_b
Feng 1	13.6	0.61	-0.93	8	$m_b v$
Feng 2	10.1	0.73	-0.23	8	$m_b v$
Feng 3	11.6	0.47	-0.49	8	m_b
Gong	11.15	-0.41	-0.67	8	$m_b v$

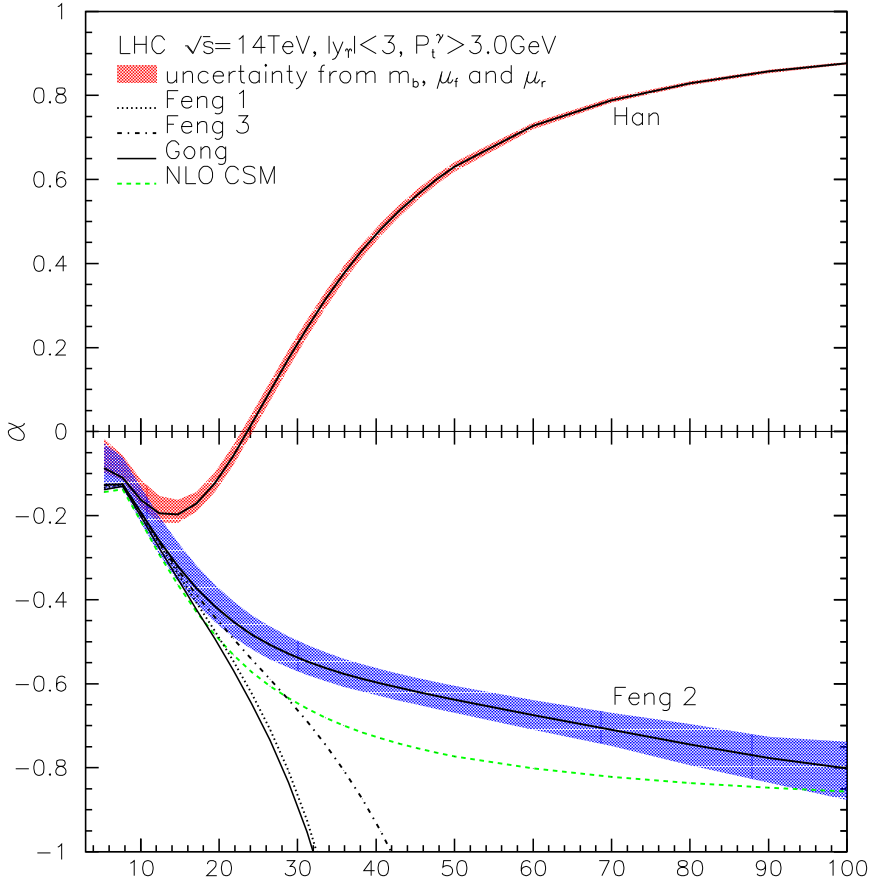


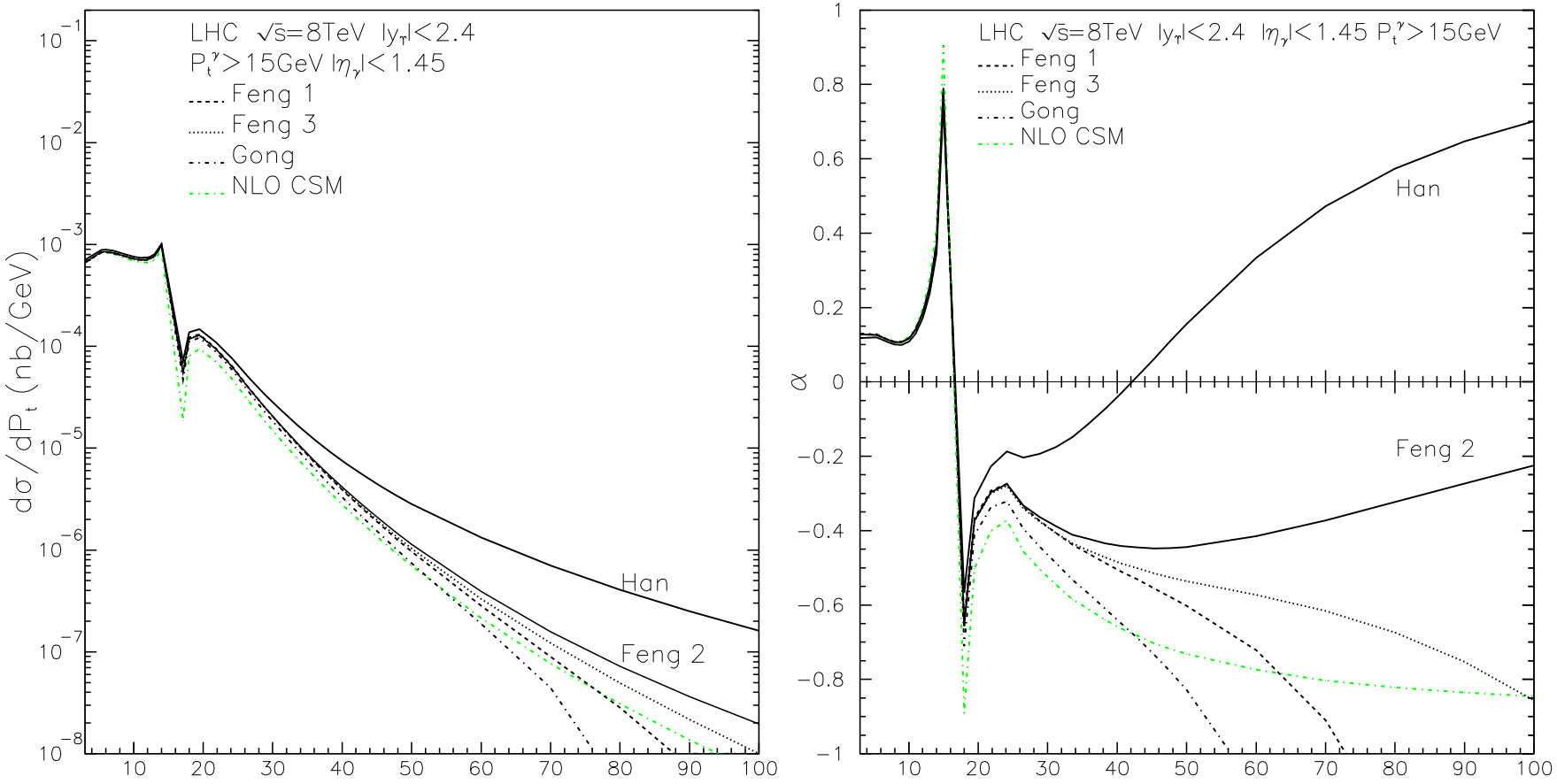
The ratio of $d\sigma(^3P_J^8)/d\sigma(^1S_0^8)$ and $d\sigma(^3S_1^8)/d\sigma(^1S_0^8)$ as functions of p_t(left). The polarization of the subprocesses(right).


$P_t^\gamma > 1.5$GeV
$P_t^\gamma > 3.0$GeV
$P_t^\gamma > 5.0$GeV
NLO CSM ($P_t^\gamma > 3.0$GeV)
LHC $\sqrt{s}=7$TeV $|y_\gamma|<3$
Han
Feng 2
$d\sigma/dP_t$ (nb/GeV)


Han
NLO COM ($P_t^\gamma > 1.5$GeV)
NLO COM ($P_t^\gamma > 3.0$GeV)
NLO COM ($P_t^\gamma > 5.0$GeV)
NLO CSM ($P_t^\gamma > 3.0$GeV)
LHC $\sqrt{s}=7$TeV $|y_\gamma|<3$
Feng 2
α


LHC √s=14TeV, |y_γ|<3, P_t^γ>3.0GeV
uncertainty from m_b, μ_f and μ_r
Feng 1
Feng 3
Gong
NLO CSM
Han
Feng 2
dσ/dP_t (nb/GeV)


LHC √s=14TeV, |y_γ|<3, P_t^γ>3.0GeV
uncertainty from m_b, μ_f and μ_r
Feng 1
Feng 3
Gong
NLO CSM
Han
Feng 2
α


LHC √s=8TeV |y_γ|<2.4
P_t^γ>15GeV |η_γ|<1.45
Feng 1
Feng 3
Gong
NLO CSM
Han
Feng 2
dσ/dP_t (nb/GeV)
α

Summary

1. The $p + \bar{p} \to \Upsilon + \gamma + X$ is investigated at the NLO in the framework of NRQCD which can give a well additional test on the LDMEs.
2. The available LDMEs can not give a consistent prediction on the p_t distribution and polarization distribution at the NLO.
3. This process can hardly be investigated by using the present data sample collected at 8TeV LHC theoretically.
4. Maybe it is necessary to include the feed-down contribution or some further contributions from other corrections or processes in comparing with the experiment results.