Complete NLO study on the yield and polarization of Upsilon(1S,2S,3S) at the Tevatron and LHC

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Based on our work:
PRL112, 032001, 2014, B. Gong, L. P. Wan, J. X. Wang, H. F. Zhang and Y. Feng
and update with recent measurement on feeddown fraction of $\chi_b(nP)$ to $\Upsilon(nS)$

Introduction

- Perturbative and non-perturbative QCD, hadronization, factorization
- Color-singlet and Color-octet mechanism was proposed based on NRQCD since b and c-quark is heavy.
- Clear signal to detect J/ψ.
- heavy quarkonium production is a good place to testify these theoretical framework.
- J/ψ photoproduction at HERA
- J/ψ production at the B factories
- J/ψ production and polarization at the Tevatron
- J/ψ production at the LHC
- LO theoretical predication were given before more than 15 years
- NLO theoretical predications were given within last 5 years.
- It seems that the QCD NLO calculations can adequately describe the experimental data.
- But there are still many difficulties.

- color-singlet at QCD NLO:
  PRL98,252002 (2007), J. Campbell, F. Maltoni F. Tramontano
  PRL100,232001 (2008), B. Gong and J. X. Wang
- NRQCD at QCD NLO:
  PLB 673:197,2009, B. Gong X. Q. Li and J. X. Wang
  PRL 106, 042002,2011, Y.-Q. Ma, K. Wang, K.-T. Chao
  PRL 106, 022003,2011, M. Butenschoen, B. A. Kniehl
  PRL 108, 248004,2012,K.-T.Chao,Y.-Q.Ma,H.-S.Shao,K.Wang,Y.-J.Zhang
  PRL 108, 172002,2012, M. Butenschoen, B. A. Kniehl
  PRL 110, 042002,2013, B. Gong, L.-P. Wan, J. X. Wang and H. F. Zhang
  PRL 113, 022001 (2014) G. T. Bodwin, H. S. Chung, U. R. Kim and J. Lee,
- Relativistic Correction in NRQCD
  PRD 86, 094017 (2012) G. Z. Xu, Y. J. Li, K. Y. Liu and Y. J. Zhang
- New factorization scheme
  PRL 108, 102002 (2012), Z. B. Kang, J. W. Qiu and G. Sterman
  PRL 113, 142002 (2014), Y. Q. Ma, J. W. Qiu, G. Sterman and H. Zhang
- Many new measurements on p_t distribution of yield and polarization by CMS, Atalas, LHCb and Alice.

QCD Correction to prompt $J/\psi({}^3S_1^1,\ {}^1S_0^8,\ {}^3S_1^8,\ {}^3P_J^8)$ production

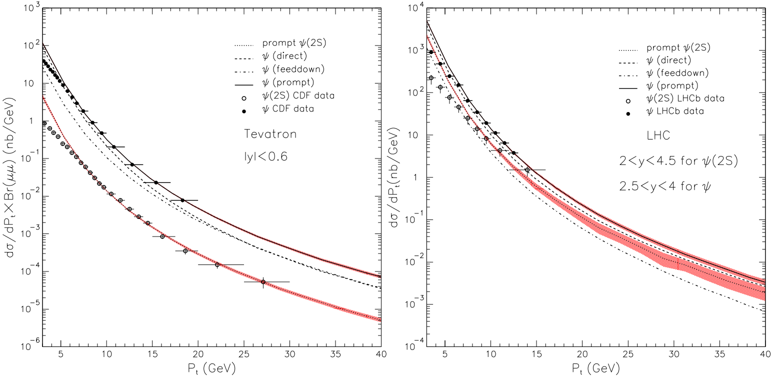


Figure: p_t distribution of prompt J/ψ and ψ' hadroproduction. The CDF and LHCb data are taken in the fitting.

PRL110, 042002, 2013, ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang

QCD Correction to $\psi'({}^3S_1^1,\ {}^1S_0^8,\ {}^3S_1^8,\ {}^3P_J^8)$ polarization

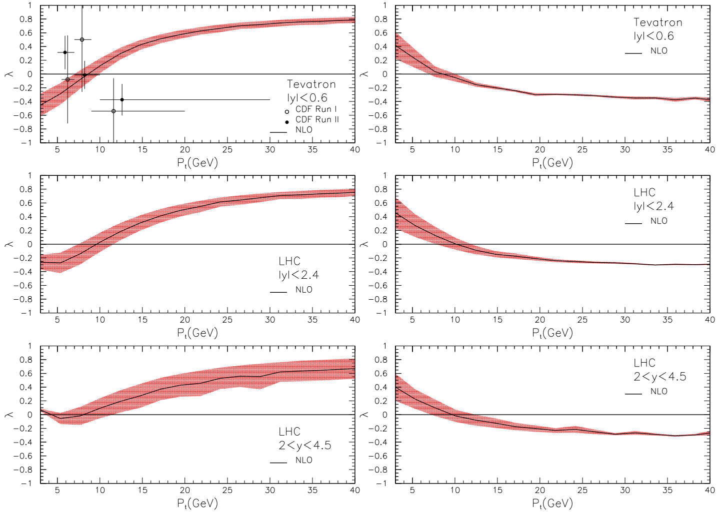


Figure: Polarization parameter λ of J/ψ' in helicity(left) and CS(right) frames.

PRL110, 042002, 2013, ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang

QCD Correction to $\chi_{cJ}({}^3P_J^1,\ {}^3S_1^8) \to J/\psi$ polarization

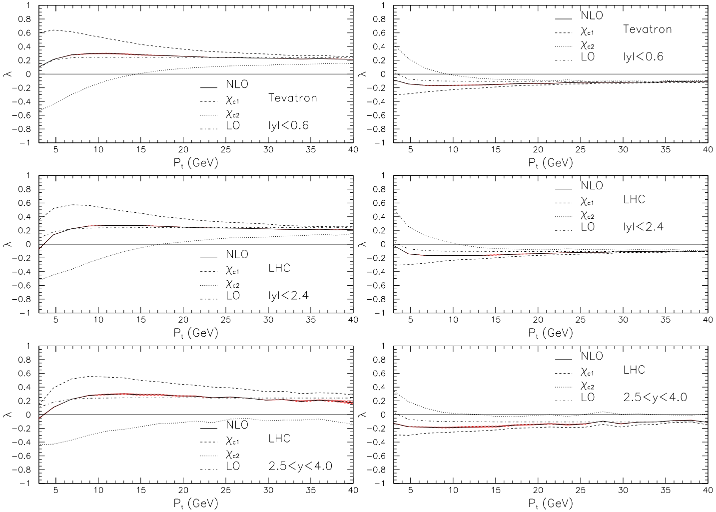


Figure: Polarization parameter λ of J/ψ in helicity(left) and CS(right) frames.

PRL1100420022013), ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang

QCD Correction to prompt $J/\psi(^3S_1^1,\ ^1S_0^8,\ ^3S_1^8,\ ^3P_J^8)$ polarization

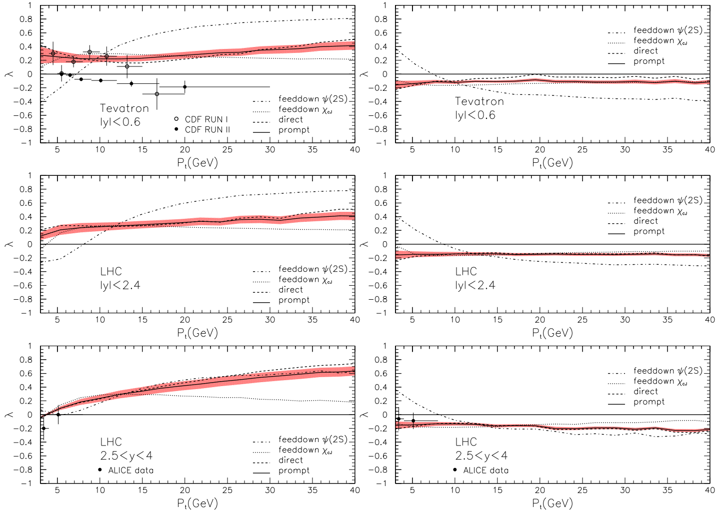


Figure: Polarization parameter λ of prompt J/ψ hadroproduction in helicity(left) and CS(right) frames.

PRL110, 042002, 2013, ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang

- The polarization puzzle is still not cleared solved. ....
  universality of NRQCD long-distance matrix elements
  Fix-order result is not good at small and large p_t region
  unphysics solution in large p_t, small p_t, for transverse or longitude polarization
  NRQCD factorization scale dependent problem.
  relativstic corrections
  freedom in fit,
- measurement on the $J/\psi + \gamma$ hadroproductioin can fix the freedom, talk by R. Li, this afternoon.

Based on NRQCD factorization scheme, the cross section of h hadroproduction is

$$\sigma[pp \to hx] = \sum \int dx_1 dx_2 G_p^i G_p^j \hat{\sigma}[ij \to (Q\bar{Q})_n x]\langle \mathcal{O}_n^h \rangle, \quad (1)$$

where p is either a proton or antiproton, the indices i, j run over all the partonic species and n represents the $Q\bar{Q}$ intermediate states (${}^3S_1 1$, ${}^3S_1 8$, ${}^1S_0 8$, ${}^3P_J 8$) for s-wave heavy quarkonium state, or (${}^3P_J 1$, ${}^3S_1 8$) for p-wave heavy quarkonium state. The short-distance contribution $\hat{\sigma}$ can be perturbatively calculated and the long-distance matrix elements (LDMEs) $\langle \mathcal{O}_n^h \rangle$ represent the nonperturbative QCD effects.
For FDCHQHP, In order to calculate the short-distance coefficient, two spin projection operators

$$\begin{aligned}
\Pi_0(P,p) &= \frac{1}{2\sqrt{2}E(E+m)}\left(\frac{1}{2}\not{P}+m+\not{p}\right)\frac{\not{P}+2E}{4E}\gamma_5\left(\frac{1}{2}\not{P}-m-\not{p}\right), \\
\Pi_1(P,p,\epsilon) &= \frac{-1}{2\sqrt{2}E(E+m)}\left(\frac{1}{2}\not{P}+m+\not{p}\right)\frac{\not{P}+2E}{4E}\not{\epsilon}\left(\frac{1}{2}\not{P}-m-\not{p}\right), \quad (2)
\end{aligned}$$

are implemented in for spin singlet and triplet intermediate states, where m is the mass of heavy quark, P is the momentum of quarkonium, $p = (p_Q - p_{\bar{Q}})/2$ is the "relative momentum" between heavy quark pair, and $E \equiv \sqrt{m^2 - p^2}$ can be regarded as half of the "mass" of quarkonium.
the heavy quarkonium polarization parameters λ_θ, $\lambda_{\theta\phi}$, λ_ϕ is defined as

$$\lambda_\theta = \frac{\mathrm{d}\sigma_{11} - \mathrm{d}\sigma_{00}}{\mathrm{d}\sigma_{11} + \mathrm{d}\sigma_{00}}, \lambda_{\theta\phi} = \frac{\sqrt{2}\mathrm{Re}\mathrm{d}\sigma_{10}}{\mathrm{d}\sigma_{11} + \mathrm{d}\sigma_{00}}, \lambda_\phi = \frac{2\mathrm{d}\sigma_{1,-1}}{\mathrm{d}\sigma_{11} + \mathrm{d}\sigma_{00}},$$

where $d\sigma_{S_z S_z'}$ is the spin density matrix of heavy quarkonium hadroproduction.

This package includes

- 6 channels
- 76 sub-processes
- almost 2 millions lines Fortran codes in total.

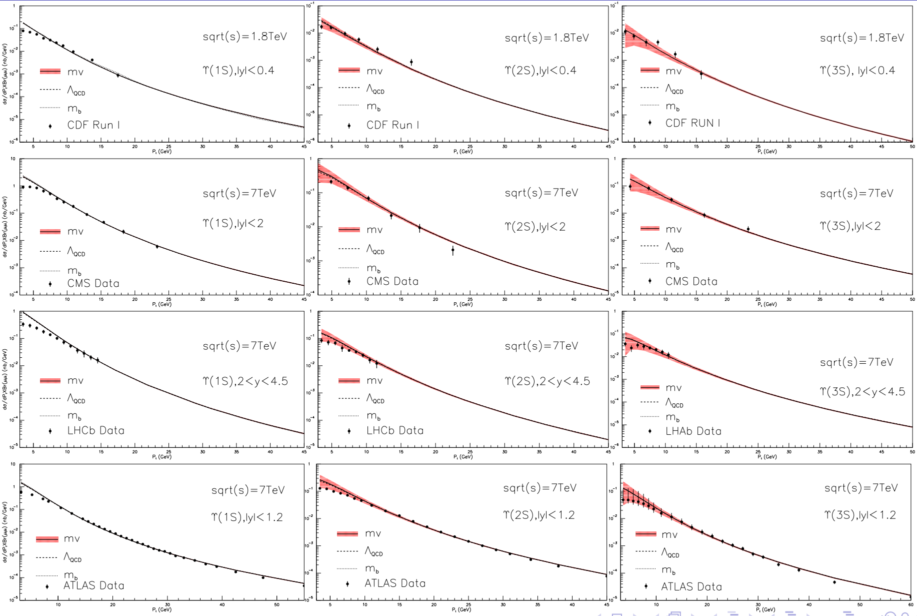
It can be run in paralleled mode with more than hundren thousands cpu with high efficiency.

STATES	LO sub-process	number of Feynman diagrams	NLO sub-process	number of Feynman diagrams
${}^3S_1^{(1)}$	$g+g \to (Q\bar{Q})_n + g$	6	$g+g \to (Q\bar{Q})_n + g$(one-loop)	128
			$g+g \to (QQ)_n + g + g$	60
			$g+g \to (QQ)_n + Q + Q$	42
			$g+g \to (QQ)_n + q + \bar{q}$	6
			$g+q(\bar{q}) \to (QQ)_n + g + q(\bar{q})$	6
${}^1S_0^{(8)}$(also ${}^3P_J^8$)	$g+g \to (Q\bar{Q})_n + g$	(12,16,12)	$g+g \to (Q\bar{Q})_n + g$(one-loop)	(369,644,390)
or	$g+q(\bar{q}) \to (QQ)_n + q(\bar{q})$	(2,5,2)	$g+q(\bar{q}) \to (QQ)_n + q(\bar{q})$(one-loop)	(61,156,65)
${}^3S_1^{(8)}$	$q+\bar{q} \to (Q\bar{Q})_n + g$	(2,5,2)	$q+\bar{q} \to (Q\bar{Q})_n + g$(one-loop)	(61,156,65)
or			$g+g \to (QQ)_n + g + g$	(98,123,98)
${}^3P_J^1$			$g+g \to (Q\bar{Q})_n + q + \bar{q}$	(20,36,20)
			$g+q(\bar{q}) \to (QQ)_n + g + q(\bar{q})$	(20,36,20)
			$q+\bar{q} \to (QQ)_n + g + g$	(20,36,20)
			$q+\bar{q} \to (QQ)_n + q + \bar{q}$	(4,14,4)
			$q+\bar{q} \to (Q\bar{Q})_n + q' + q'$	(2,7,2)
			$q+q \to (QQ)_n + q + q$	(4,14,4)
			$q+q' \to (QQ)_n + q + q'$	(2,7,2)

Table: The sub-processes for heavy quarkonium $c\bar{c}$ and $b\bar{b}$ prompt production at LO and NLO.

- recent measurement by the CMS collaboration at the LHC
- $m_b \sim 3m_c$ measns the perturbative QCD expansion in bottomium case is better than charmonium case.
- For heavy quark Q velocity v_Q at quarkonium rest frame, $v_b^2 \sim 0.1$ and $v_c^2 \sim 0.3$, it measns that nonrelativistic expansion in bottomium case is better than charmonium case.
- logarithm term $ln(m_Q/p_t)$ plays important role later, i.e. $p_t = 30$ GeV for $J/\psi \sim p_t = 3x30$ GeV for Υ.
- Can we expect better desciption of experimental measurement on $\Upsilon(1S, 2S, 3S)$ by NLO NRQCD calculation?
- Much more numerical calculation and more long-distance matrix parameters needed to be fixed from fit.

QCD Correction to $\Upsilon(1S, 2S, 3S)$ production



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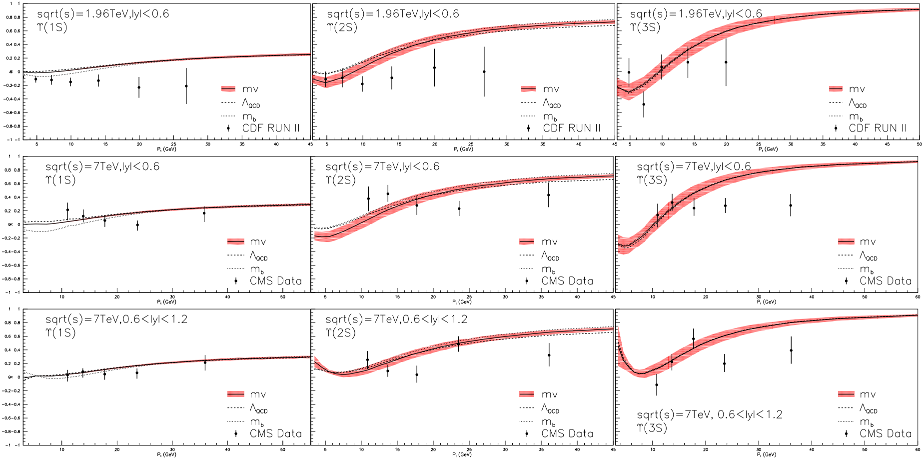
QCD Correction to $\Upsilon(1S, 2S, 3S)$ polarization



PRL112, 032001, 2014, arXiv:1305.0748, by Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang

Figure: Polarization parameter λ of prompt $\Upsilon(1S, 2S, 3S)$ hadroproduction in helicity frame

- The ratio of differential cross sections of $\chi_{b2}(1P)$ to $\chi_{b1}(1P)$ V. Khachatryan *et al.* (CMS Collaboration), arXiv:1409.5761 [hep-ex].
- The fractions of $\Upsilon(mS)$ $(m = 1, 2, 3)$ production from $\chi_b(nP)$ $(n = 1, 2, 3)$ feeddown contributions Aaij *et al.* (LHCb Collaboration), arXiv:1407.7734 [hep-ex].
- Updated fit has been presented by Hao Han, Yan-Qing Ma, Ce Meng, Hua-Sheng Shao, Yu-Jie Zhang, Kuang-Ta Chao in arXiv:1410.8537

Updated Fit on $\Upsilon(1S, 2S, 3S)$ production and polarization

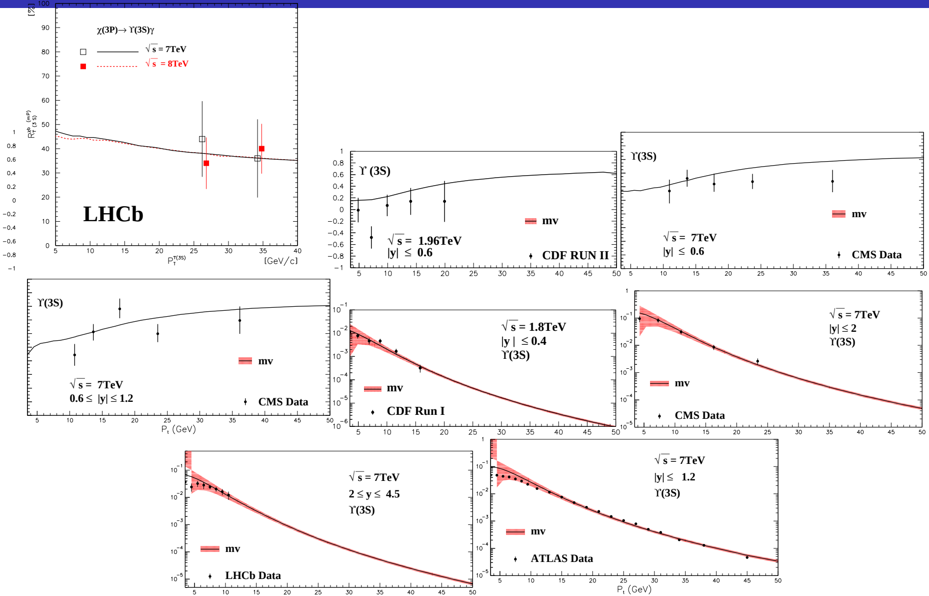


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Figure: Polarization parameter λ of prompt $\Upsilon(1S, 2S, 3S)$ hadroproduction in helicity frame

Summary

- The prediction on the polarization of prompt J/ψ hadroproduction is archived at QCD NLO, but polarization puzzle is still unclear.
- The study on $J/\psi + \gamma$ production at the LHC show that there are still problem in the previous fits to explain J/ψ production. The experimental measurements on it are needed to clarify the situation.
- For Υ, our results can explain the measurements on the transverse momentum distribution of producation rate very well, and for the polarizations of $\Upsilon(1S, 2S, 3S)$, they are in (good, good, bad) agreement with recent CMS measurement, but still have some distance from the CDF measurement.
- recent LHCb measurement on feeddown fraction of $\chi_b(nP)$ to $\Upsilon(nS)$ show that the predications is too large, but this problem can be solved by an updated fit.
- By considering the $\chi_b(3P)$ feeddown, which is measured by LHCb, the CMS measurement on $\Upsilon(3S)$ polarization can be explained by QCD NLO calculation in NRQCD.

Thank you!