QCD Correction to J/ψ Production at Different Energy Scales

Jian-Xiong Wang
Institute of High Energy, Chinese Academy of Science, Beijing

Charm 2010
The 4-th International Workshop on Charm Physics
Oct. 21-24, 2010, IHEP, Beijing, China

1 Introduction

2 J/psi production at the B factories
- double charmonium production
- Inclusive J/ψ production

3 the other
- J/ψ production in Z decay
- J/ψ production from Υ Decay

4 J/ψ production at the Tevatron and LHC
- QCD Correction to color-singlet J/ψ production
- QCD Correction to color-octet J/ψ production

5 J/ψ production at the HERA

6 Other New Progress

7 Summary

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.
  - Data on inelastic J/ψ photoproduction are adequately described by the color singlet channel alone at NLO
  - Double charmonium production at the B factories

$e^+e^- \to J/\psi + \eta_c$

Experimantal Data

BELLE: $\sigma[J/\psi + \eta_c] \times B^{\eta_c}[\geq 2] = (25.6 \pm 2.8 \pm 3.4)$ fb
BARAR: $\sigma[J/\psi + \eta_c] \times B^{\eta_c}[\geq 2] = (17.6 \pm 2.8^{+1.5}_{-2.1})$ fb
[Abe et al.(2002), Pakhlov(2004), Aubert et al.(2005)]

LO NRQCD Predictions

$2.3 \sim 5.5$ fb
[Braaten and Lee(2003), Liu et al.(2003), Hagiwara et al.(2003)]

$e^+e^- \to J/\psi + \eta_c$

Experimantal Data

BELLE: $\sigma[J/\psi + \eta_c] \times B^{\eta_c}[\geq 2] = (25.6 \pm 2.8 \pm 3.4)$ fb
BARAR: $\sigma[J/\psi + \eta_c] \times B^{\eta_c}[\geq 2] = (17.6 \pm 2.8^{+1.5}_{-2.1})$ fb
[Abe et al.(2002), Pakhlov(2004), Aubert et al.(2005)]

LO NRQCD Predictions

$2.3 \sim 5.5$ fb
[Braaten and Lee(2003), Liu et al.(2003), Hagiwara et al.(2003)]

NLO QCD corrections

$K \equiv \sigma^{NLO}/\sigma^{LO} \sim 2$
First given in PRL96, (2006) Y. J. Zhang, Y. J. Gao and K. T. Chao
Confirmed by the analytic result in PRD77, (2008), B. Gong and J. X. Wang

Relativistic corrections

$K \sim 2$
PRD67, (2007) E. Braaten and J. Lee
AIP Conf. Proc. (2007), G.T. Bodwin, D. Kang, T. Kim, J. Lee and C. Yu
PRD75, (2007), Z. G. He, Y. Fan and K. T. Chao
PRD77,(2008),G.T. Bodwin, J. Lee and C. Yu

$e^+e^- \to J/\psi + J/\psi$

Problem

LO NRQCD prediction indicates that the cross section of this process is large than that of $J/\psi + \eta_c$ production by a factor of 1.8, but no evidence for this process was found at the B factories.
PRL90, (2003) G. T. Bodwin, E. Braaten and J. Lee
PRD70, (2004), K. Abe, et al

$e^+e^- \to J/\psi + J/\psi$

Problem

LO NRQCD prediction indicates that the cross section of this process is large than that of $J/\psi + \eta_c$ production by a factor of 1.8, but no evidence for this process was found at the B factories.
PRL90, (2003) G. T. Bodwin, E. Braaten and J. Lee
PRD70, (2004), K. Abe, et al

NLO QCD corrections

- Greatly decreased, with a K factor ranging from $-0.31 \sim 0.25$ depending on the renormalization scale.
- Might explain the situation.

PRL100, (2008) B. Gong and J. X. Wang

LO NRQCD Predictions:

$$e^+e^- \to J/\psi + c\bar{c} \qquad 0.07 \sim 0.20\text{pb}$$
$$e^+e^- \to J/\psi + gg \qquad 0.15 \sim 0.3\text{pb}$$
$$e^+e^- \to J/\psi^{(8)}({}^3P_J, {}^1S_0) + g \qquad 0.3 \sim 0.8\text{pb}$$

PRL76,(1996), E. Braaten and Y. C. Chen, PLB577,(2003), K.Y. Liu, Z.G. He and K.T. chao, ...

Experimental Data:

$$\textit{BARAR} \quad \sigma[e^+e^- \to J/\psi + X] = (2.54 \pm 0.21 \pm 0.21)\ \text{pb}$$
$$\text{CLEO} \quad \sigma[e^+e^- \to J/\psi + X] = (1.9 \pm 0.20)\ \text{pb}$$
$$\text{BELLE} \quad \sigma[e^+e^- \to J/\psi + X] = (1.45 \pm 0.10 \pm 0.13)\ \text{pb}$$
$$\sigma[e^+e^- \to J/\psi + c\bar{c} + X] = (0.87^{+0.21}_{-0.19} \pm 0.17)\ \text{pb}$$

[Aubert et al.(2001), Aubert et al.(2005), Briere et al.(2004), Abe et al.(2002a), Abe et al.(2002)]

New BELLE Data

$$\sigma[e^+e^- \to J/\psi + X] = (1.17 \pm 0.02 \pm 0.07)\ \text{pb}$$
$$\sigma[e^+e^- \to J/\psi + c\bar{c}] = (0.74 \pm 0.08^{+0.09}_{-0.08})\ \text{pb}$$
$$\sigma[e^+e^- \to J/\psi + X_{\text{non}-c\bar{c}}] = (0.43 \pm 0.09 \pm 0.09)\ \text{pb}$$

[Pakhlov et al.(2009)]

Cross section at NLO for $e^+e^- \to J/\psi + gg$

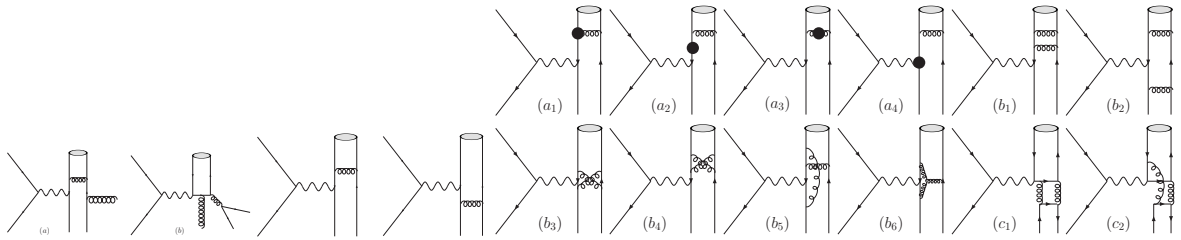
$$\sigma^{(1)} = \sigma^{(0)} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \left[a(\hat{s}) + \beta_0 \ln \left(\frac{\mu}{2m_c} \right) \right] \right\}$$

m_c(GeV)	$\alpha_s(\mu)$	$\sigma^{(0)}$(pb)	$a(\hat{s})$	$\sigma^{(1)}$(pb)	$\sigma^{(1)}/\sigma^{(0)}$
1.4	0.267	0.341	2.35	0.409	1.20
1.5	0.259	0.308	2.57	0.373	1.21
1.6	0.252	0.279	2.89	0.344	1.23

Consistent results from two group:
PRL102, (2009) Y. Q. Ma, Y. J. Zhang and K. T. Chao
PRL102, (2009) B. Gong and J. X. Wang

Relativistic Correction enchance results about a factor 1.3 from two group:
PRD81, (2010) Z. G. He, Y. Fan and K. T. Chao
PRD82, (2010). Y. Jia

$e^+e^- \to J/\psi + c\bar{c}$



$$\sigma^{(1)} = \sigma^{(0)} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \left[a(\hat{s}) + \beta_0 \ln\left(\frac{\mu}{2m_c}\right) \right] \right\}$$

m_c(GeV)	$\alpha_s(\mu)$	$\sigma^{(0)}$(pb)	$a(\hat{s})$	$\sigma^{(1)}$(pb)	$\sigma^{(1)}/\sigma^{(0)}$
1.4	0.267	0.224	8.19	0.380	1.70
1.5	0.259	0.171	8.94	0.298	1.74
1.6	0.252	0.129	9.74	0.230	1.78

Cross sections with different charm quark mass m_c with the renormalization scale $\mu = 2m_c$ and $\sqrt{s} = 10.6$ GeV.

The former result given by PRL98, (2007) Y. J. Zhang and K. T. Chao
confirmed by PRD80, (2009) B. Gong and J. X. Wang

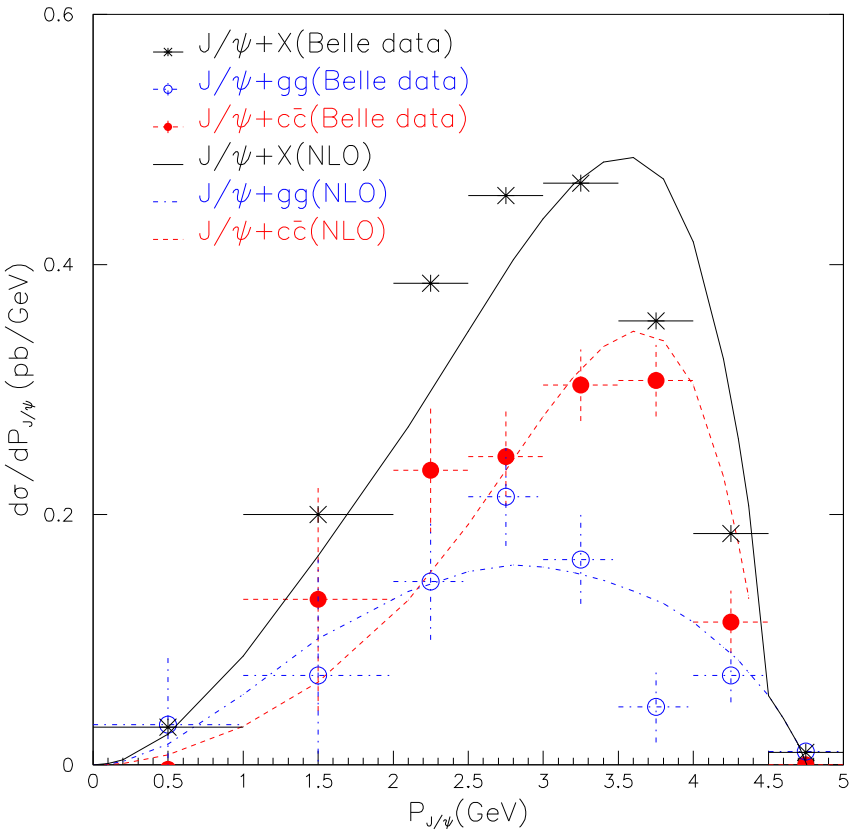
More about the scale and comparision with data

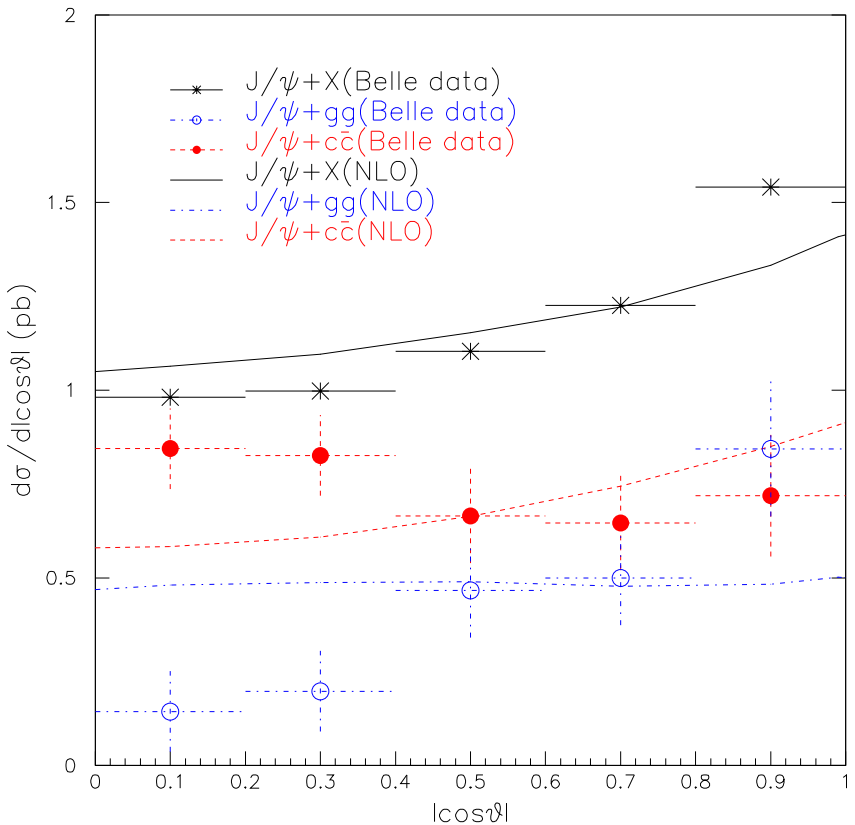
Use Brodsky, Lepage and Mackenzie (BLM) scale setting [Brodsky et al.(1983)]

$$\sigma^{(1)} = \sigma^{(0)}(\mu^*)[1 + \frac{\alpha_s(\mu^*)}{\pi} b(\hat{s})].$$

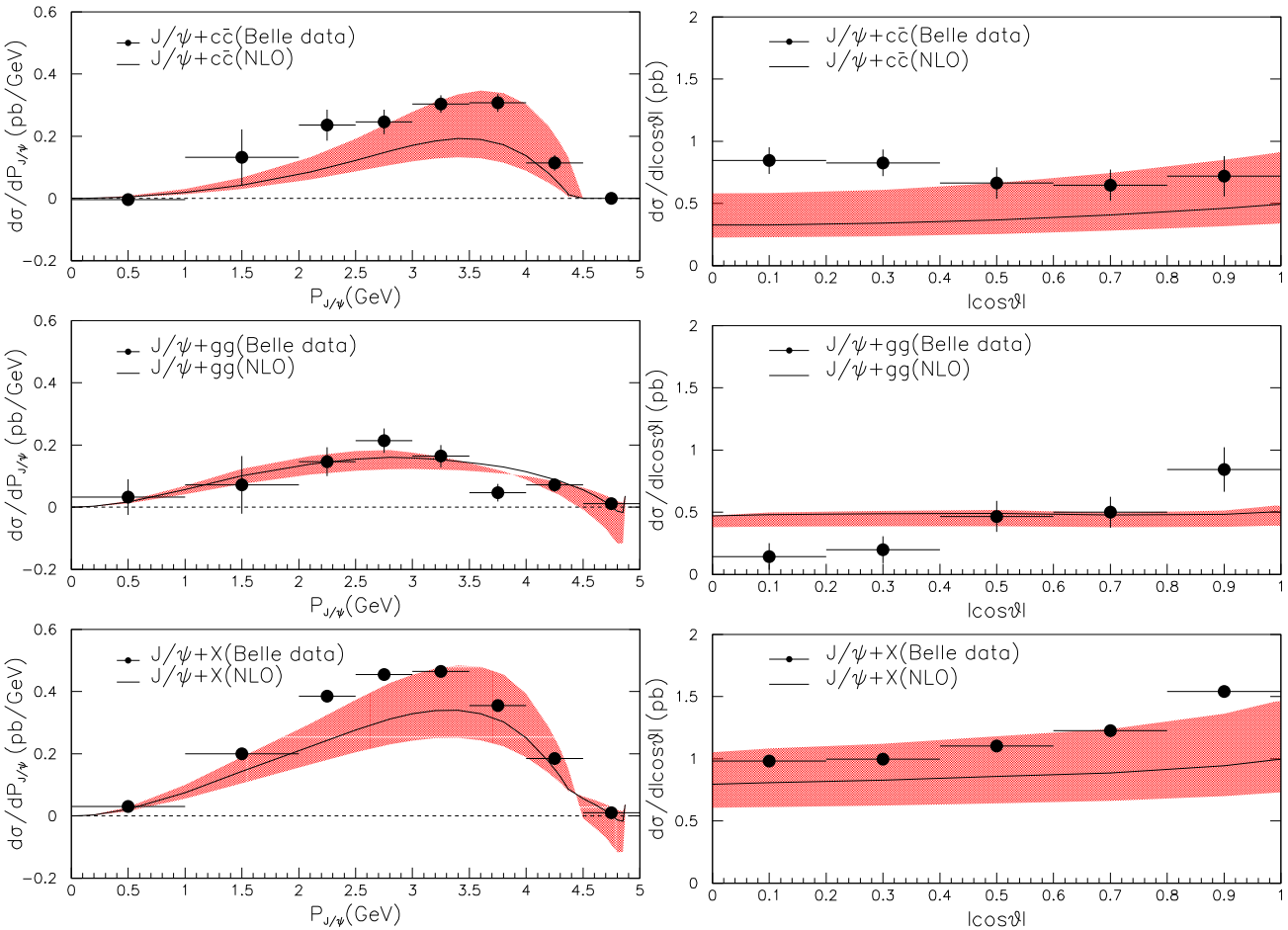
m_c(GeV)	$\alpha_s(\mu^*)$	$\sigma^{(0)}$(pb)	$b(\hat{s})$	$\sigma^{(1)}$(pb)	$\sigma^{(1)}/\sigma^{(0)}$	μ^*(GeV)
1.4	0.348	0.381	3.77	0.540	1.42	1.65
1.5	0.339	0.293	4.31	0.429	1.47	1.72
1.6	0.332	0.222	4.90	0.337	1.52	1.79

Cross sections with different charm quark mass m_c. The renormalization scale $\mu = \mu^* \sim m_c$.



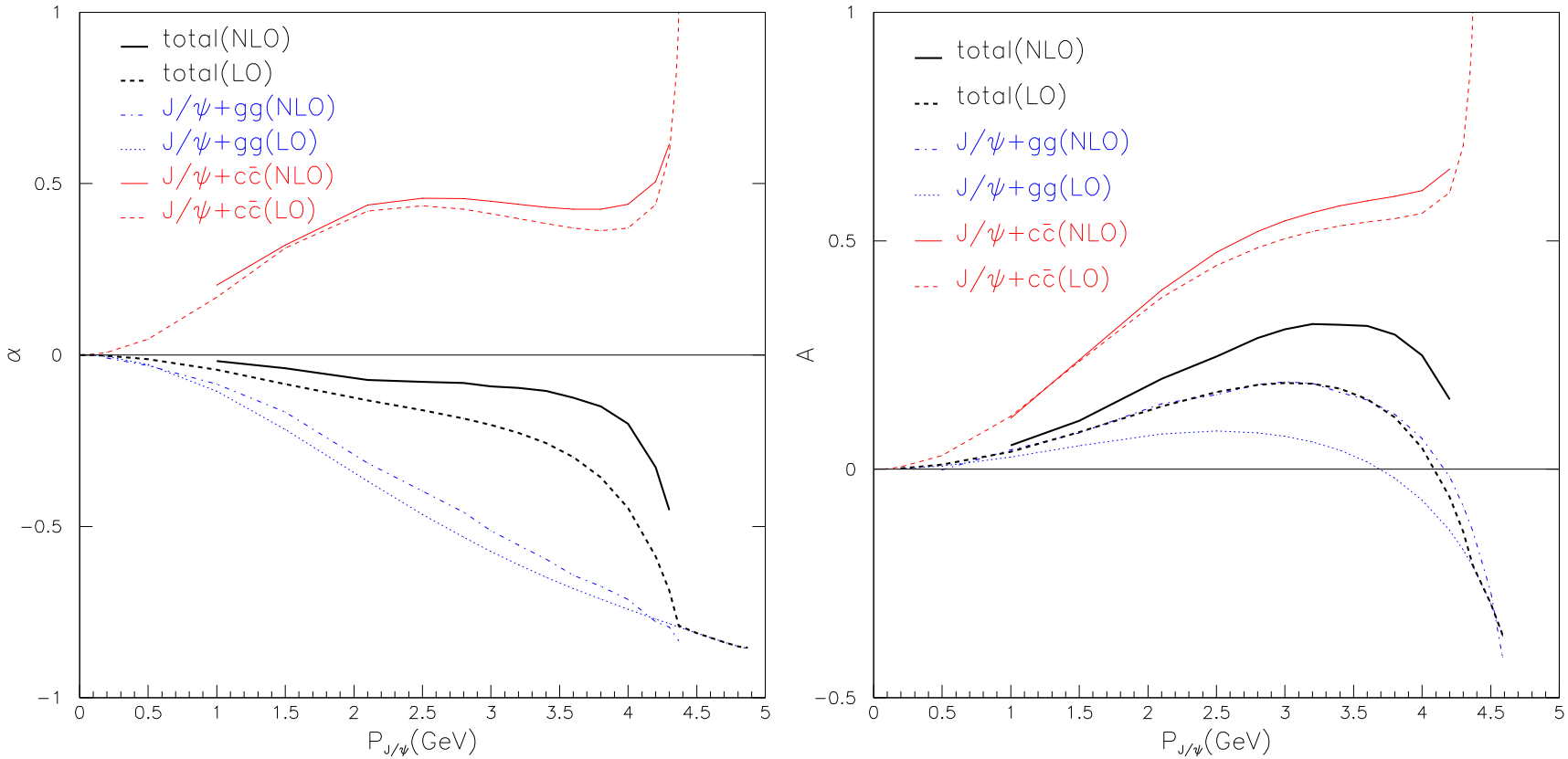


Momentum distribution of inclusive J/ψ production with $\mu = \mu^*$ and $m_c = 1.4$ GeV is taken for the $J/\psi cc$ channel. The contribution from the feed-down of ψ' has been added to all curves by multiplying a factor of 1.29.



Momentum and angular distributions of inclusive J/ψ production.

The contribution from the feed-down of ψ' has been added to all curves by multiplying a factor of 1.29.



Polarization parameter α and angular distribution parameter A of J/ψ as functions of p.

Constraint for color-octect matrix element of $c\bar{c}(^1S_0^8, 3P_J^8)$

$$\sigma[e^+e^- \to J/\psi + X_{\text{non}-c\bar{c}}] = (0.43 \pm 0.09 \pm 0.09)\ \text{pb}$$

$$\sigma[e^+e^- \to J/\psi + X_{\text{non}-c\bar{c}}]^{color-singleTh} > (0.43)\ \text{pb}$$

$$\sigma[e^+e^- \to J/\psi + X_{\text{non}-c\bar{c}}]^{color-octetTh} > (0.6)\ \text{pb}$$

From the contribution of $e^+e^- \to J/\psi(^1S_0^8, 3P_J^8) + g$ at NLO

PRD81, (2010) Y. J. Zhang, Y. Q. Ma, K. Wang and K. T. Chao

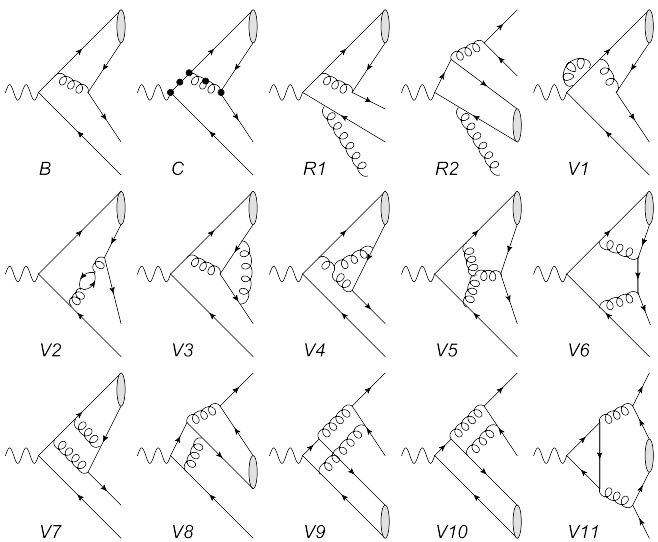
- Experimental and Leading-order Theoretical Results.[Acciarri:1998]

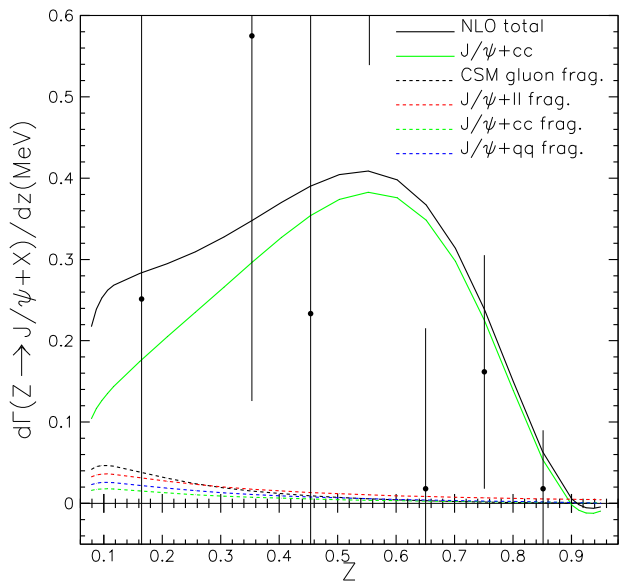
$$Br(Z \to J/\psi_{prompt} + X) = (2.1^{+1.4}_{-1.2}) \times 10^{-4}$$

Dominant process: $Z \to J/\psi + c\bar{c} + X$, and the total decay width is presented as

$$\Gamma^{NLO}(\mu) = \Gamma^{LO}(\mu)[1 + \frac{\alpha_s(\mu)}{\pi}(A + \beta_0 ln\frac{\mu}{2m_Q} + Bn_f)]. \quad (1)$$

$$Br^{total} = (7.3 \sim 10) \times 10^{-5}$$





The result is presented in: PRD82, (2010), Li and J. X. Wang,
The Experimental Data points from PRD 59, 054016 1999.

The situation for J/ψ production in Υ decay

LO NRQCD Predictions:

$Br(\Upsilon \to J/\psi(^3S_1^8) + gg) = 6.2 \times 10^{-4}$,M. Napsuciale, Phys. Rev. D **57**, 5711 (1998)

$Br(\Upsilon \to J/\psi + c\bar{c}g) = 5.9 \times 10^{-4}$,S. Y. Li, Q. B. Xie and Q. Wang, Phys. Lett. B **482**, 65 (2000)

$Br(\Upsilon \to J/\psi + gg) = order\ at \times 10^{-4}$,????

Experimental Data for $Br(\Upsilon \to J/\psi + X)$:

$\mathrm{CLEO}(11 \pm 4 \pm 2) \times 10^{-4} Phys.\ Lett.\ B\ \mathbf{224},\ 445$
$\mathrm{ARGUS} < 6.8 \times 10^{-4} Z.\ Phys.\ C\mathbf{55}, 25(1992)$
$\mathrm{CLEO}(6.4 \pm 0.4 \pm 0.6) \times 10^{-4} Phys.\ Rev.\ D\mathbf{70}, 072001(2004)$

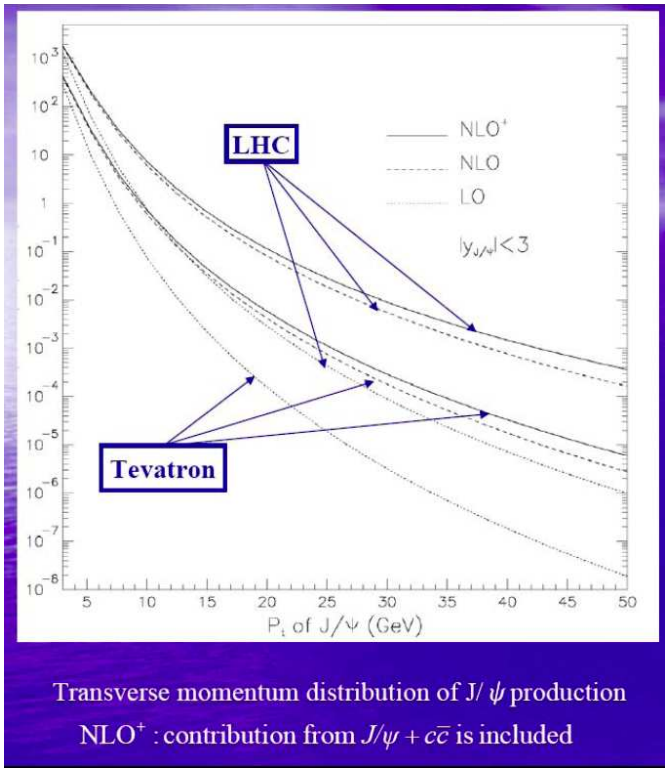
The situation is quite strange ????

The correct leading order prediction is
$\mathcal{B}_{\mathrm{Direct}}(\Upsilon \to J/\psi + c\bar{c}g) = 3.9 \times 10^{-5}$.
Z. G. He and J. X. Wang, Phys.Rev.D81:054030,2010.

Part of NLO prediction from $\Upsilon \to J/\psi + gg$ is
$\mathcal{B}_{\mathrm{Direct}}(\Upsilon \to J/\psi + gg) = 3.1 \times 10^{-5}$.
Z. G. He and J. X. Wang, arXiv:1009.1563[hep-ph]].

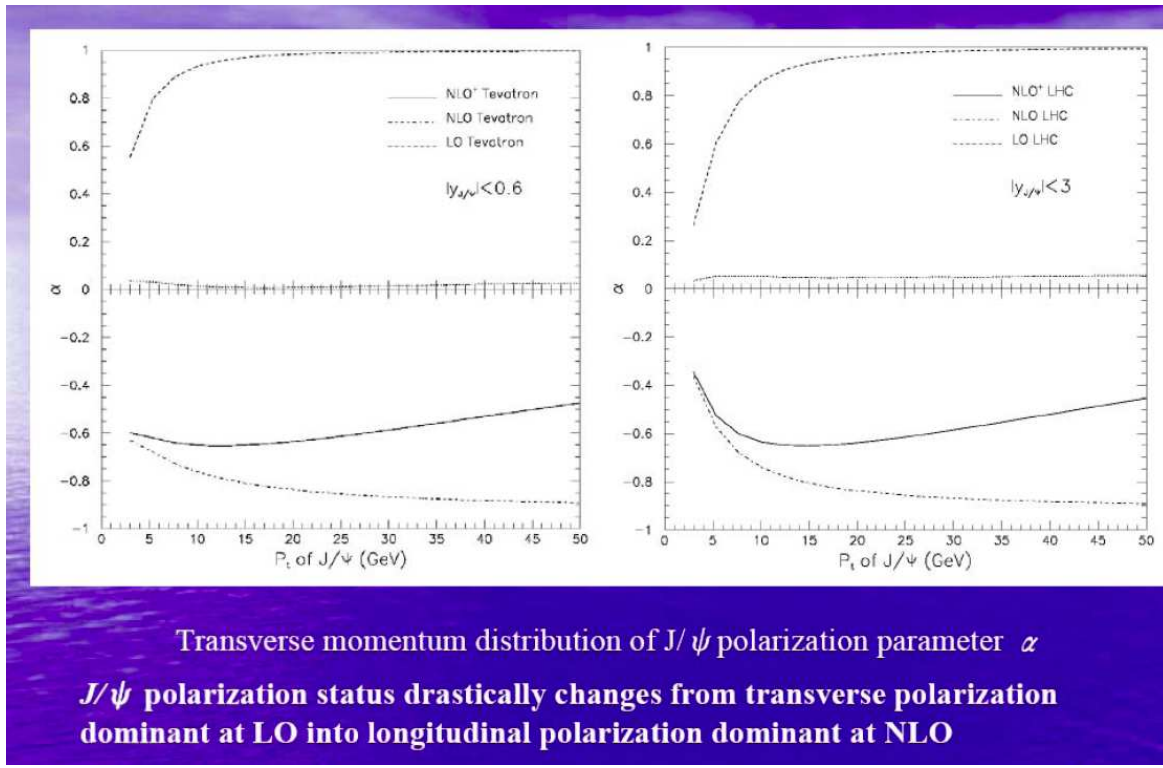
The full QCD correction for the inclusive J/ψ production in Υ decay would be a very interesting and challenge work for explaining the experimental data.

QCD Correction to color-singlet J/ψ production



Transverse momentum distribution of J/ψ production

NLO$^+$: contribution from $J/\psi + c\bar{c}$ is included



Transverse momentum distribution of J/ψ polarization parameter α

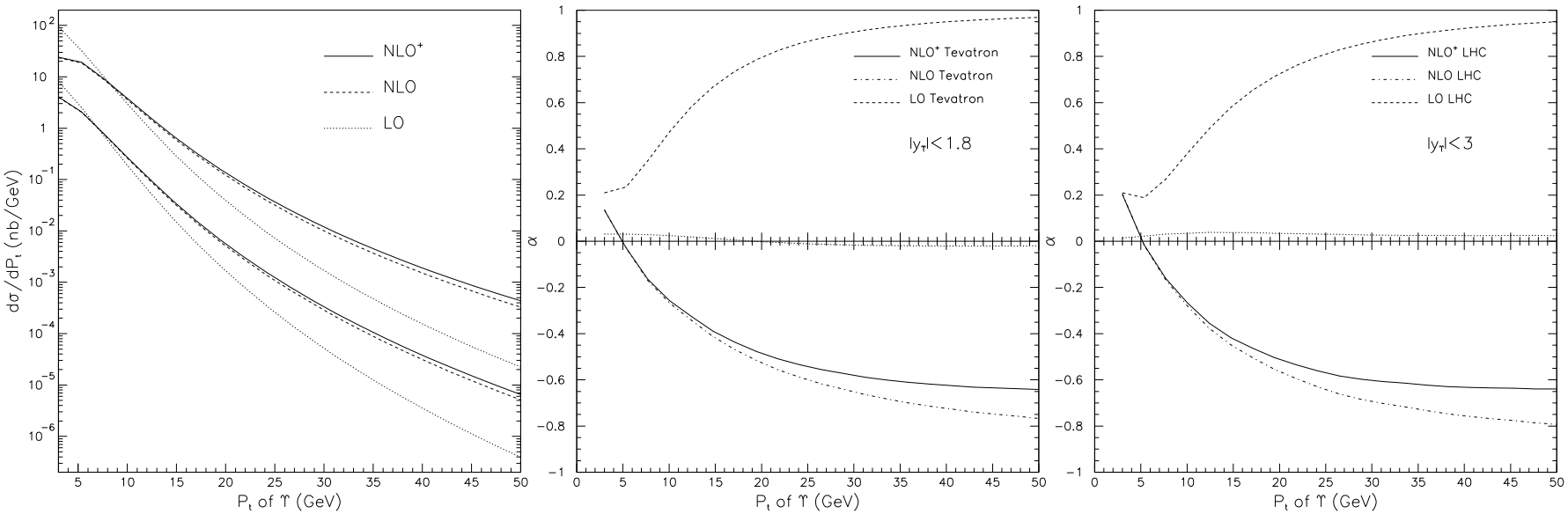
J/ψ polarization status drastically changes from transverse polarization dominant at LO into longitudinal polarization dominant at NLO

P_t distribution of J/ψ production at QCD NLO was calculated in
PRL98,252002 (2007), J. Campbell, F. Maltoni F. Tramontano

Some technique problems must be solved to calculate J/ψ polarization

P_t distribution of J/ψ polarization at QCD NLO was calculated in
PRL100,232001 (2008), B. Gong and J. X. Wang

QCD Correction to color-singlet Υ production



Υ polarization drastically changes from transverse polarization dominant at LO into longitudinal polarization dominant at NLO

P_t distribution of Υ polarization at QCD NLO was calculated with detail in PRD78 074011 (2008), B. Gong and J. X. Wang

Partly NNLO calculation for Υ production calculated by PRL101, 152001(2008), P. Artoisenet, John M. Campbell, J.P. Lansberg, F. Maltoni, F. Tramontano

NLO QCD corrections to J/ψ production via S-wave color octet states

3 tree processes at LO

At NLO

$$g(p_1) + g(p_2) \to J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right](p_3) + g(p_4), \quad (267, 413)$$

$$g(p_1) + q(p_2) \to J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right](p_3) + q(p_4), \quad (49, 111)$$

$$q(p_1) + \bar{q}(p_2) \to J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right](p_3) + g(p_4). \quad (49, 111)$$

Real Correction (8 processes at NLO)

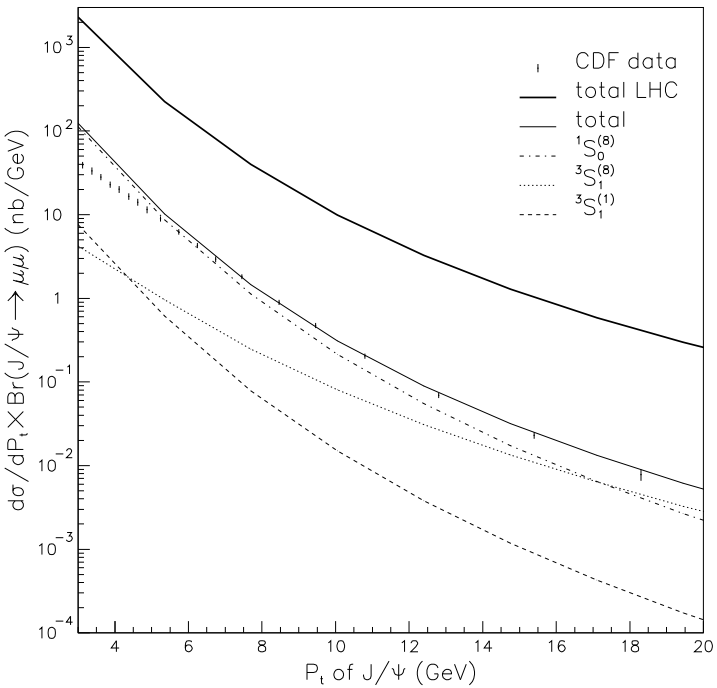
$$gg \to J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]gg, \quad gg \to J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]q\bar{q},$$

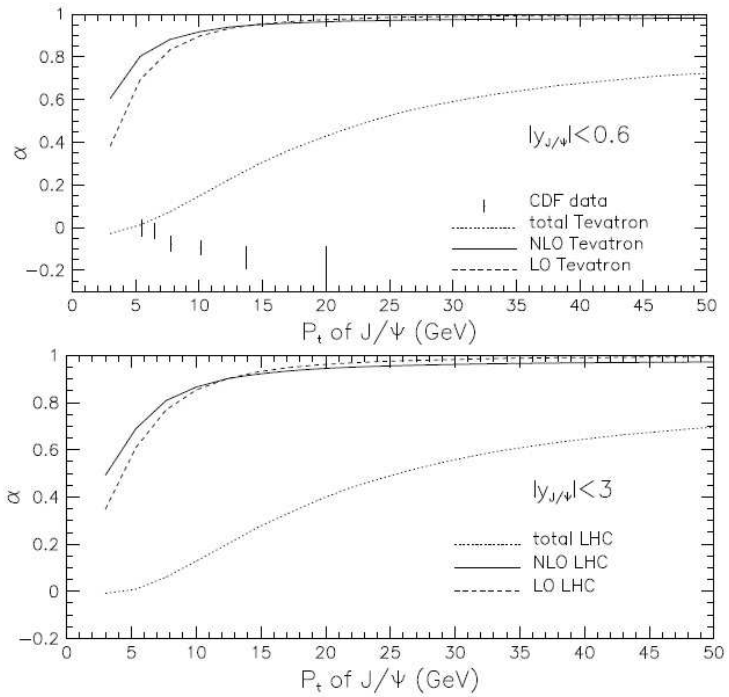
$$gq \to J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]gq, \quad q\bar{q} \to J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]gg,$$

$$q\bar{q} \to J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]q\bar{q}, \quad q\bar{q} \to J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]q'\bar{q}',$$

$$qq \to J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]qq, \quad qq' \to J/\psi\left[{}^1S_0^{(8)}, {}^3S_1^{(8)}\right]qq',$$

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

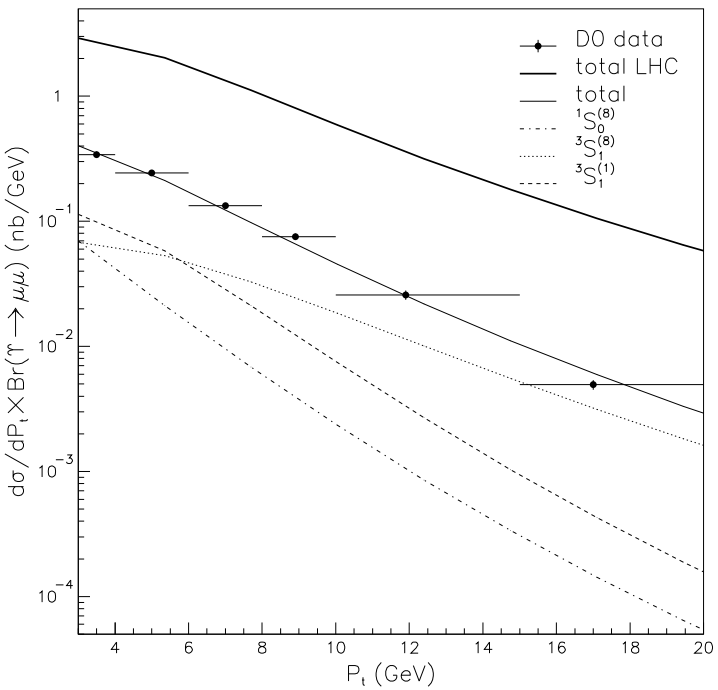


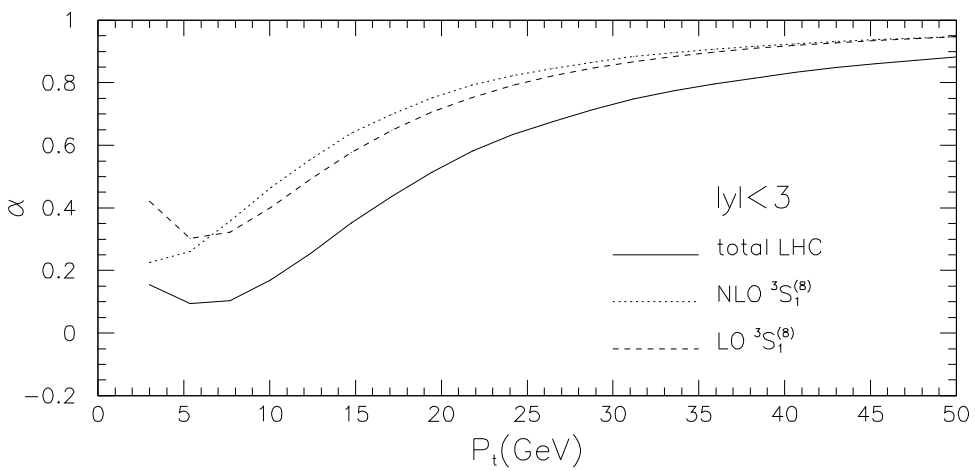


To fit the Tevatron P_t distribution give more $\langle \mathcal{O}_8^{\psi}({}^1S_0)\rangle = 0.075\ \mathrm{GeV}^3$ and less $\langle \mathcal{O}_8^{\psi}({}^3S_1)\rangle = 0.0021\ \mathrm{GeV}^3$ than they are at LO fitting The experimental data with $p_t < 6$ GeV have to abandon
PLB673:197,2009, Erratum-ibid.693:612,2010 , B. Gong X. Q. Li and J. X. Wang

Correction to color-octet $J/\psi({}^1S_0^8,\ {}^3S_1^8, {}^3P_J^8)$ production was done recently and gave almost the same prediction for p_t distribution as before without calculation of polarization, by
arXiv:1009.3655, Yan-Qing Ma, Kai Wang, Kuang-Ta Chao
arXiv:1009.5662, Mathias Butenschoen, Bernd A. Kniehl

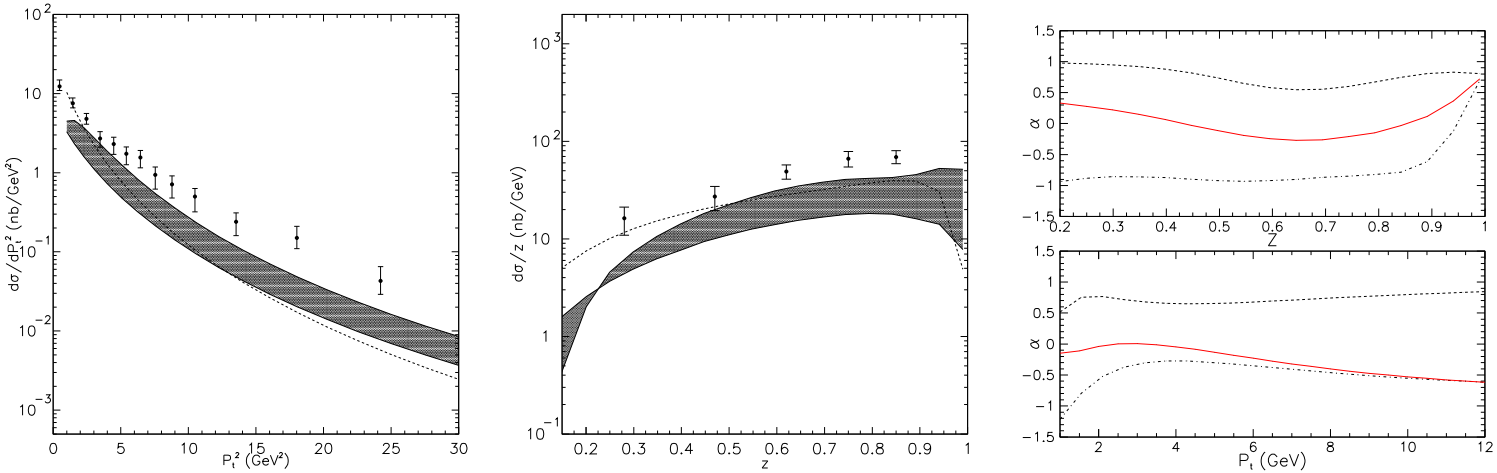
QCD Correction to color-octet $\Upsilon(^1S_0^8,\ ^3S_1^8)$ production





arXiv:1009.3839, B. Gong, J. X. Wang and H. F. Zhang

QCD Correction to J/ψ production at HERA.



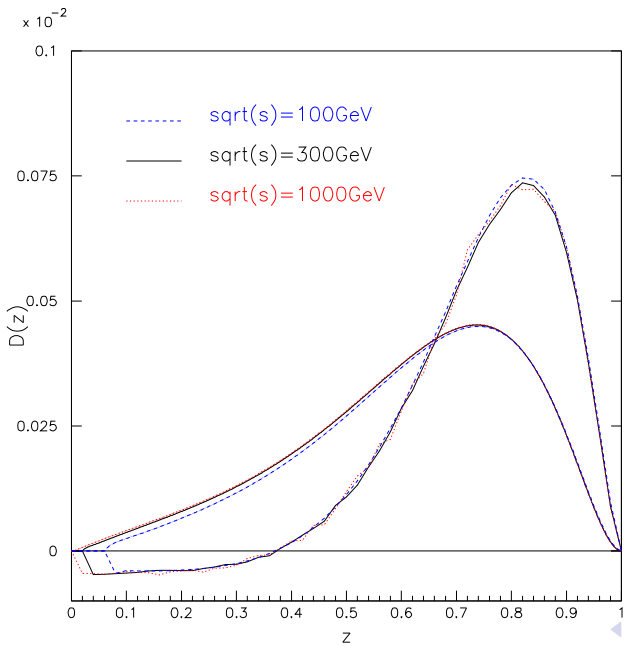
P_t distribution of production and different scheme of polarization for J/ψ (color-singlet)
at QCD NLO was calculated in
PRL102, 142001 (2009), P. Artoisenet, John M. Campbell, F. Maltoni, F. Tramontano,
C. H. Chang, R. Li, J. X. Wang, PRD80,034020 (2009).
P_t distribution of production J/ψ (color-octet) at QCD NLO was calculated in
M. Butenschoen and B. A. Kniehl, PRL104, 072001 (2009)
It include p-wave state and some progress in technique must be archived.

Other New Progress

χ_{cJ} production at hadron colliders with QCD radiative corrections
Y. Q. Ma, K. Wang and K. T. Chao, arXiv:1002.3987 [hep-ph].
It include p-wave state and some progress in technique must be archived.

A new factorization scheme for J/ψ hadronproduction proposed by
J. W. Qiu, et al, Qiu's talk

Fragmentation function of $c \longrightarrow J/\psi$ at QCD NLO was calculated by
B. Gong and J. X. Wang, in prepare



Summary

- For B-factories: NRQCD at NLO of α_s and v can well described J/ψ production data. strong constraint to **the values of color-octect matrix element of** $c\bar{c}(^1S_0^8, 3P_J^8)$ **to almost zero**. The dominant part $c\bar{c}(^3S_1^8)$ for hadronproduction is still there.
- For J/ψ production in Υ decay, the LO prediction is one order in magnitude smaller than experimental measurement.
- The NLO results for J/ψ production in z^0 decay is just half of experimental measurement.
- $c \to J/\psi$ fragmentation function is obtained at NLO level for the first time.
- The polarization problem for J/psi hadroproduction is still there even at QCD NLO
- New Progress, ...

Thank you!

- K. Abe et al. (Belle), Phys. Rev. Lett. **89**, 142001 (2002), hep-ex/0205104.
- P. Pakhlov (Belle) (2004), hep-ex/0412041.
- B. Aubert et al. (BABAR), Phys. Rev. **D72**, 031101 (2005), hep-ex/0506062.
- G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. **D51**, 1125 (1995).
- E. Braaten and J. Lee, Phys. Rev. **D67**, 054007 (2003), hep-ph/0211085.
- K.-Y. Liu, Z.-G. He, and K.-T. Chao, Phys. Lett. **B557**, 45 (2003), hep-ph/0211181.
- K. Hagiwara, E. Kou, and C.-F. Qiao, Phys. Lett. **B570**, 39 (2003), hep-ph/0305102.

- Y.-J. Zhang, Y.-j. Gao, and K.-T. Chao, Phys. Rev. Lett. **96**, 092001 (2006).
- B. Gong and J.-X. Wang, Phys. Rev. **D77**, 054028(2008).
- G. T. Bodwin, J. Lee and E. Braaten, Phys. Rev. Lett. **90**, 162001(2003a); Phys. Rev. Lett. **95**, 239901(E) (2005).
- K. Abe et al. (Belle), Phys. Rev. **D70**, 071102 (2004).
- B. Gong and J.-X. Wang, Phys. Rev. Lett. **100**, 181803 (2008b), 0801.0648.
- K. Abe et al. (BELLE), Phys. Rev. Lett. **88**, 052001 (2002a), hep-ex/0110012.
- B. Aubert et al. (BABAR), Phys. Rev. Lett. **87**, 162002 (2001), hep-ex/0106044.
- R. A. Briere et al. (CLEO), Phys. Rev. **D70**, 072001 (2004).

- P. Pakhlov et al. (Belle Collaboration), Phys. Rev. **D79**, 071101 (2009).
- Y.-Q. Ma, Y.-J. Zhang, and K.-T. Chao, Phys. Rev. Lett. **102**, 162002 (2009), 0812.5106.
- Y.-J. Zhang and K.-T. Chao, Phys. Rev. Lett. **98**, 092003 (2007).
- S. J. Brodsky, G. P. Lepage, and P. B. Mackenzie, Phys. Rev. D **28**, 228 (1983).
- Z. G. He, Y. Fan and K. T. Chao, Phys. Rev. D **81**, 054036 (2010) [arXiv:0910.3636 [hep-ph]].
- Y. Jia, arXiv:0912.5498 [hep-ph].
- Y. J. Zhang, Y. Q. Ma, K. Wang and K. T. Chao, Phys. Rev. D **81**, 034015 (2010) [arXiv:0911.2166 [hep-ph]].