Charmonium(J/Ψ) Production at B-factories and Hadron Colliders

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Contents

- A Brief Introduction
- J/Ψ Production at the B-factories
- J/Ψ Hadroproduction
- Revisiting the J/Ψ Hadroproduction Issue
- Summary and Conclusions

Introduction

-----Why Quarkonium Physics still interesting?

- Due to the approximately non-relativistic nature, the description of heavy quark and antiquark system stands as one of the simplest applications of Quantum Chromodynamics(QCD). Quarkonium production and decays have long been taken as an ideal means to investigate the nature of QCD

- The heavy, but not very heavy, quark mass enables one to get knowledge of both perturbative and nonperturbative QCD via investigating quarkonium production and decays

- The rich spectrum of its radial and orbital excitations provides a suitable play ground for testing QCD based models

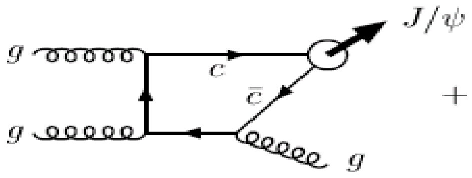
- The clean signals of quarkonium leptonic decays enable quarkonium to be used for calibration purposes in experiment, and therefore, quarkonia play an unique role in investigating other phenomena as well, e.g. in detecting the parton distribution, the QGP signal, and even new physics
- ……

J/Ψ hadroProduction

- The Tevatron run I data on charmonium(J/Ψ , Ψ') overshot the color-singlet calculation by more than an order of magnitude in large transverse momentum region(5 GeV < Pt < 20 GeV)

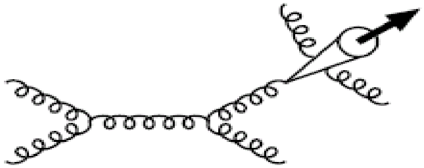
[Chang, Nucl.Phy. 1980; Baier and Rueckl, Phys.Lett.1981,Phys.Rev.D 1983; Braaten et al., Phys. Lett. B 1994; Cacciari and Greco, Phys. Rev.Lett 1994; …..]

(a) leading-order colour-singlet: $g + g \to c\bar{c}[{}^3S_1^{(1)}] + g$



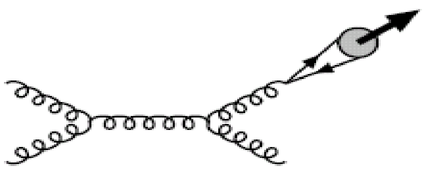
$+ \ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$

(b) colour-singlet fragmentation: $g + g \to [c\bar{c}[{}^3S_1^{(1)}] + gg] + g$



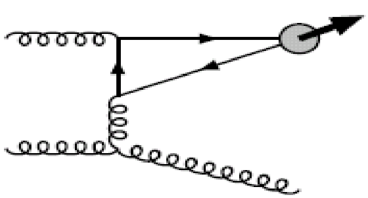
$+ \ldots \qquad \sim \alpha_s^5 \frac{1}{p_t^4}$

(c) colour-octet fragmentation: $g + g \to c\bar{c}[{}^3S_1^{(8)}] + g$



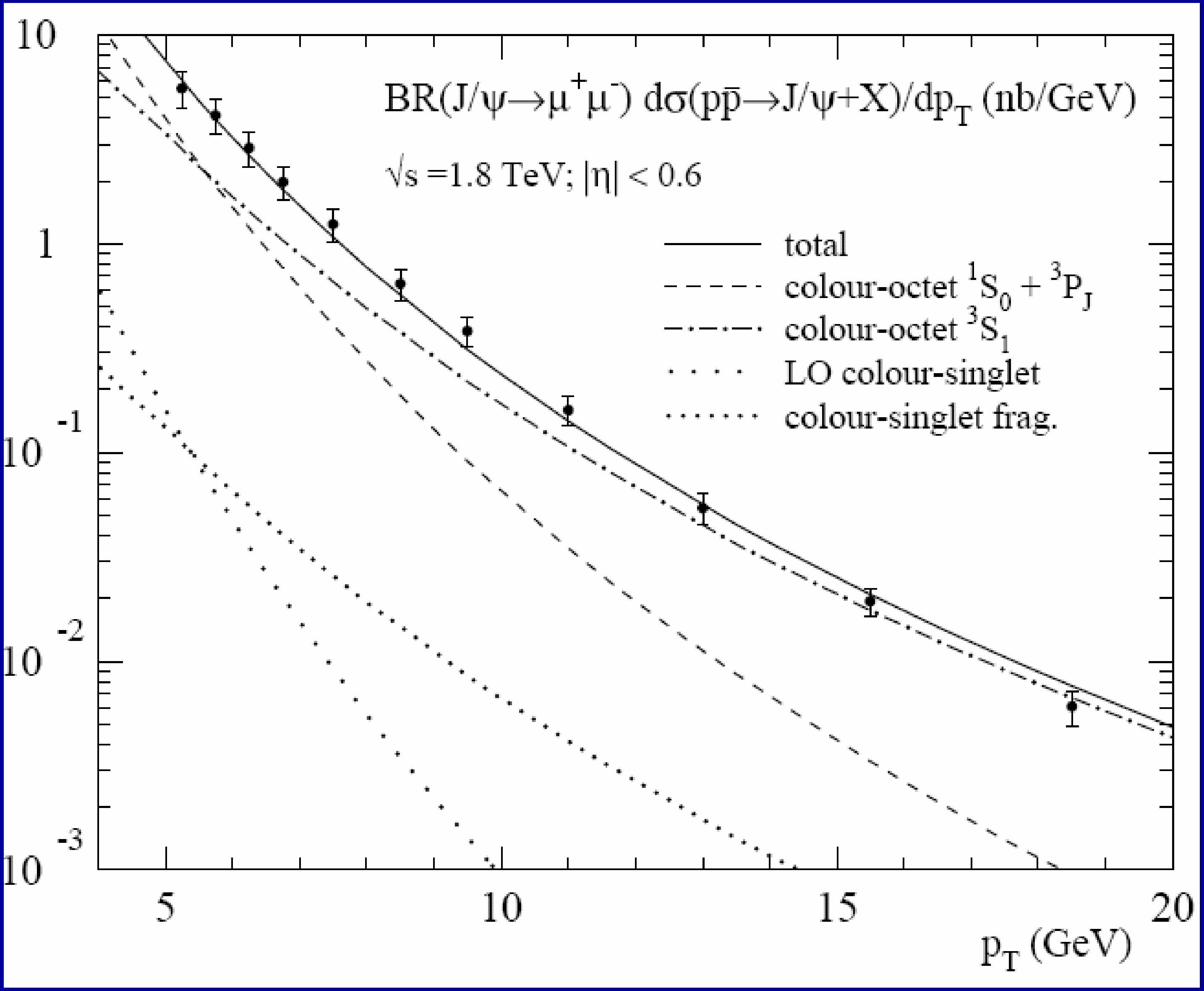
$+ \ldots \qquad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$

(d) colour-octet t-channel gluon exchange: $g + g \to c\bar{c}[{}^1S_0^{(8)}, {}^3P_J^{(8)}] + g$



$+ \ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4$

Kramer, Prog. Part. Nucl. Phys. 2001


BR(J/ψ→μ+μ-) dσ(pp̄→J/ψ+X)/dpT (nb/GeV)
√s =1.8 TeV; |η| < 0.6
total
colour-octet 1S0 + 3PJ
colour-octet 3S1
LO colour-singlet
colour-singlet frag.
pT (GeV)

- A QCD effective theory, the Non-relativistic QCD (NRQCD) factorization formalism appeared in 1995 [Bodwin, Braaten, Lepage, Phys.Rev.D 1995, Erratum 1997]

- With the color-octet mechanism, NRQCD can fit the Tevatron data reasonable well. That is by fitting the color-octet fragmentation process $g^* \to {}^3S_1^{[8]}$ to the data

  [Braaten and Flemming, Phys. Rev. Lett. 1995]

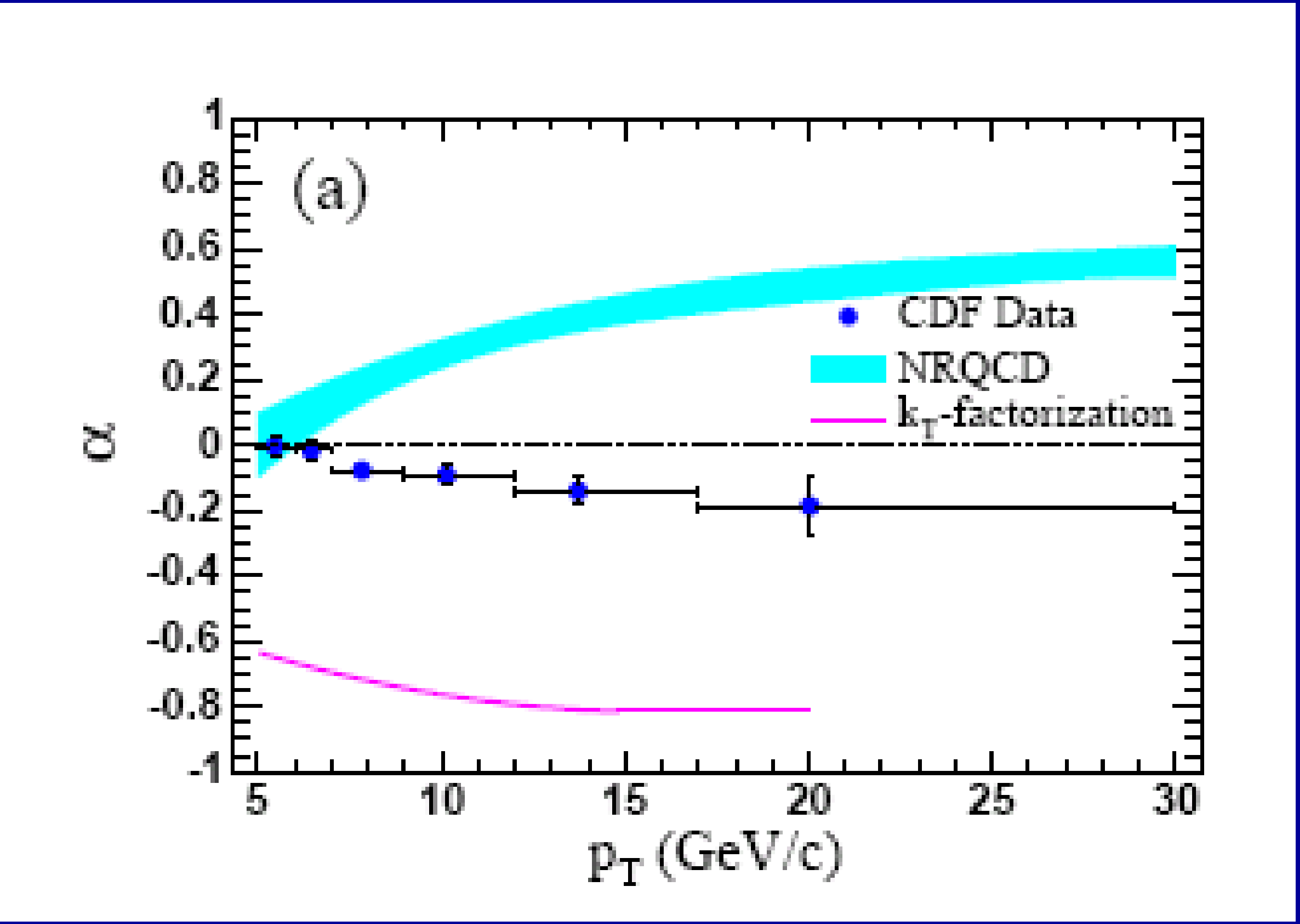
- If this is true, the large transverse momentum J/Ψ should be mostly transversely polarized, theoretically.

- However, it seems not to be the case

Tevatron II data and Theoretical Expectation

[Braaten, Kniehl and Lee, Phys. Rev.D 2000]

[CDF, Phys. Rev. Lett. 2007]



- **Recently, NLO theoretical calculation for the leading order color-singlet process was done. People find there is a huge correction for *J/Ψ* production cross-section in large transverse momentum**

[Campbell, Maltoni and Tramontano, Phys.Rev.Lett, 2007]

- **But this is not a solution to the polarization problem measured by CDF!**

J/Ψ Production at the B-factories

- J/Ψ production in e^+e^- annihilation has been paid special attention, since J/Ψ possesses the same quantum number as the virtual photon, which renders the experiment detection with a high precision

- With including the color-octet mechanism, the dominant inclusive production processes are:

[Yuan, Chao, C.F.Q, Phys. Rev.D 1997; Boyd, Leibovich and Rothstein, Phys. Rev. D 1999; ……]

In Color-Singlet

$$e^+e^- \to J/\Psi\ g\ g,\ e^+e^- \to J/\Psi\ c\ \bar{c}$$

$$e^+e^- \to J/\Psi\ g\ g\ q\ \bar{q},\ e^+e^- \to \chi_{cJ}\ g\ q\ \bar{q}$$

$$\text{followed by } \chi_{cJ} \to J/\Psi + \gamma$$

In Color-Octet:

$$e^+e^- \to J/\Psi\, g\, g \quad \text{and} \quad e^+e^- \to J/\Psi\, q\, \bar{q}$$

- Belle and Babar recently measured the inclusive process $e^+e^- \to J/\Psi\, c\, \bar{c}$ and they found that experimental result of the cross section is about 10 times larger than the LO theoretical predictions from the NRQCD analysis [BELLE, Phys. Rev. Lett. 89, 2002, Babar, Phys. Rev. D72, 2005]

They also found that:

$$\sigma(e^+e^- \to \mathrm{J}/\Psi\ \mathrm{c}\ \bar{\mathrm{c}}) / \sigma(e^+e^- \to \mathrm{J}/\Psi + \mathrm{X})$$

ratio is about 0.6 or even more, which is far from expected

[Cho and Leibovich, Phys. Rev. D,1996; Baek, Ko, Lee and Song, Phys. Lett. B,1996; Yuan, Chao and C.F.Q, Phys. Rev. D,1997]

- Very recently, NLO QCD and relativistic corrections to process

$$e^{+}e^{-} \rightarrow J/\Psi\ c\ \bar{c}$$

are done. It is found that these corrections, although very big, but still not enough to explain the data

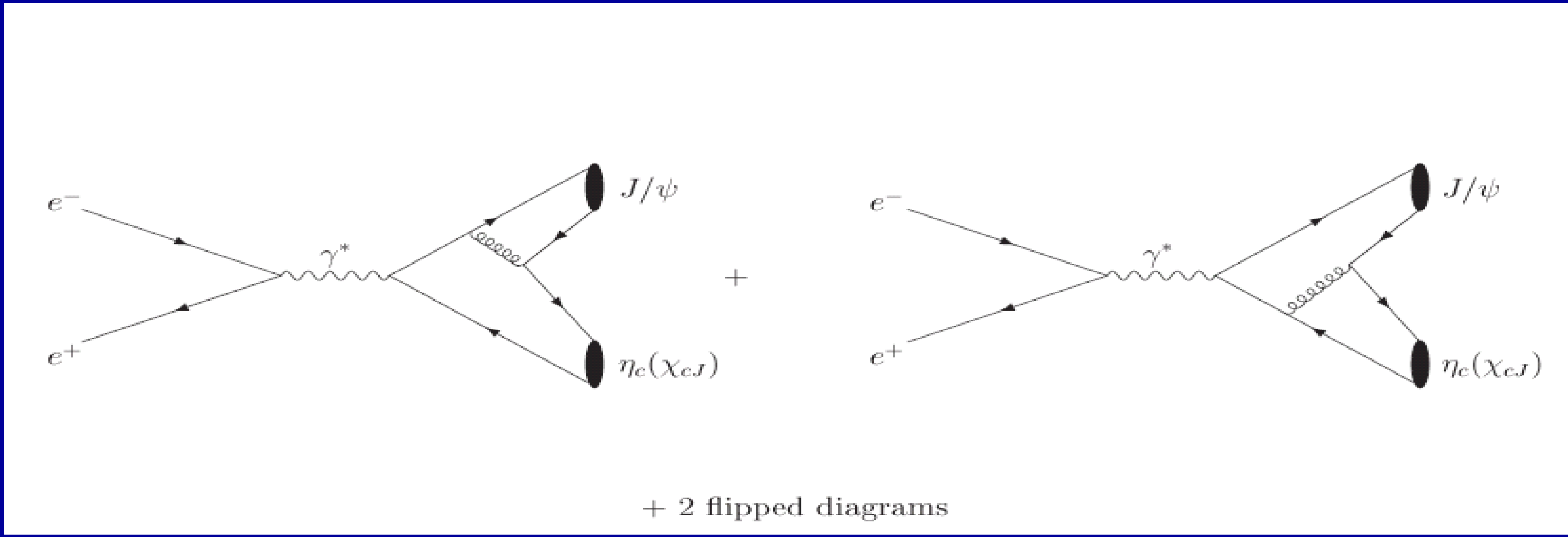
[Zhang and Chao, Phys. Rev. Lett.98, 2007; He, Fan and Chao, Phys. Rev.D75, 2007]

The double charmonium exclusive production rates are also measured at the B-factories

[Belle, Phys. Rev.Lett. 89, 2002; 70, 2004; Babar, Phys.Rev.Lett.94, 2005]

- The Experiment measurement is about one order of magnitude larger than the leading order theoretical calculation

[Braaten and Lee, Phys. Rev.D67 2003; Liu, He and Chao, Phys. Lett. B557, 2003; Hagiwara, Kou and C.F.Q., Phys.Lett. B570, 2003]



A lot of researches have been performed on this exclusive process from different aspects

[Bodwin, Lee and Braaten, Phys. Rev.Lett.90,2003; Brodsky Goldbaber and Lee, Phys.Rev.Lett.91,2003; Ma and Si, Phys.Rev.D70, 2004; Bondar and Cherniyak, Phys.Lett.B612,2005;…..]

- The NLO QCD and relativistic corrections are found can almost explain the data

[Zhang, Gao and Chao, Phys.Rev.Lett.96, 2006]

- However, there are still open questions on this issue

[Nayak, Qiu and Sterman, Phys. Lett.B613, 2005, Phys.Rev.D72, 2005]

Revisiting J/Ψ Surplus HadroProduction

- Recently, Charmonium surplus production at the Fermilab Tevatron is revisited.

[Hagiwara, Qi, Wang and C.F.Q.; arXiv:0705.0803

- The analysis includes two main ingredients:

1) The leading Charm-sea contributions are fully considered

[C.F.Q.,J.Phys.G29,2003]

2) From the knowledge obtained in the study of Charmonium production at the B-factories, we try to include the higher order contributions by employing a self-consistent K-factor.

- The processes

$$c + \bar{c} \rightarrow J/\Psi + g,\ c(\bar{c}) + g \rightarrow J/\Psi + c(\bar{c}) + g,$$

$$c(\bar{c}) + (\bar{q}) \rightarrow J/\Psi + c(\bar{c}) + q(\bar{q})$$

are found to be dominant in color-singlet processes

- The B-factory inclusive J/Ψ surplus problem can be phenomenologically solved by introducing a large K-factor, 4 to 8, to process

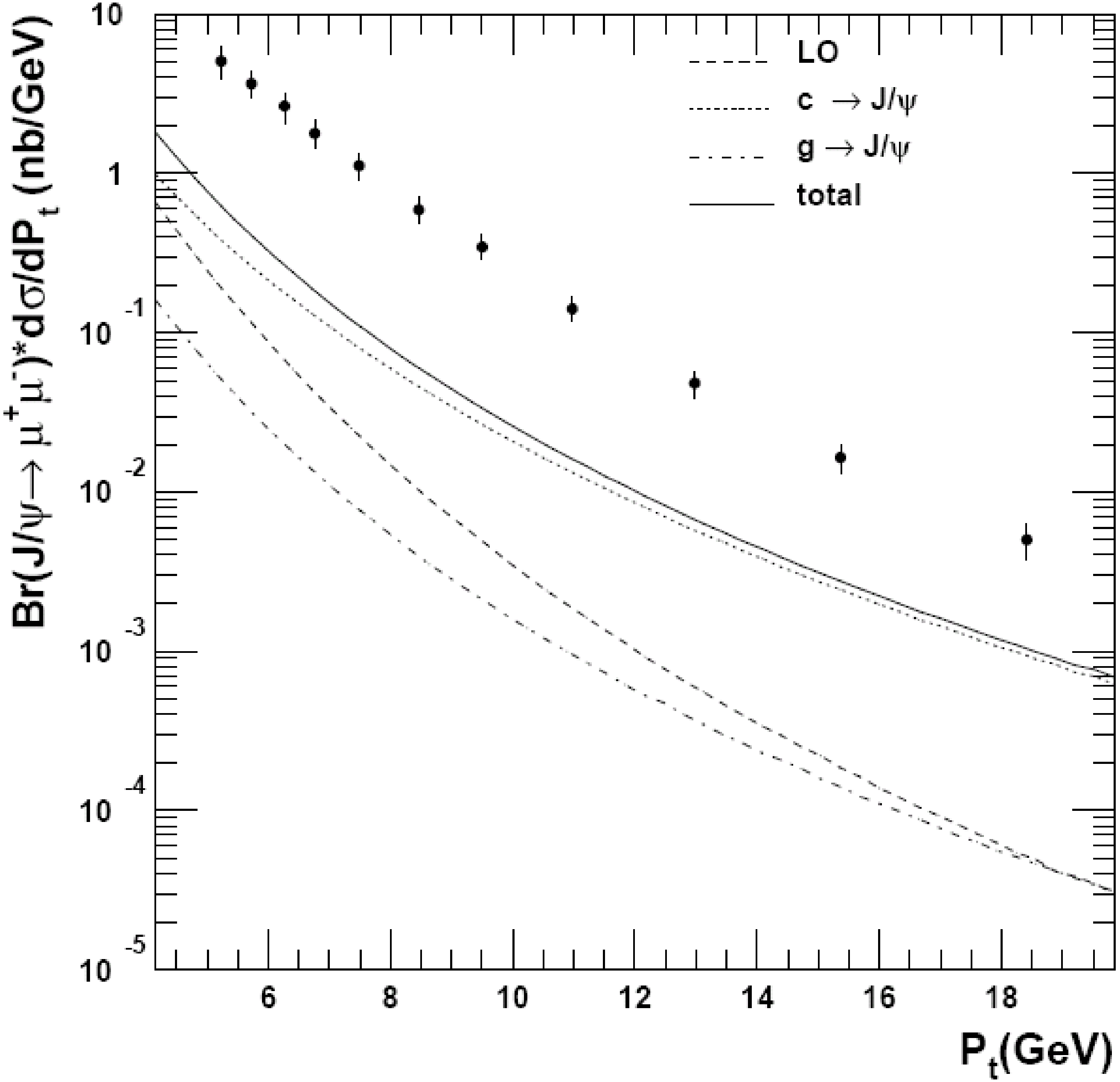
$$e^+e^- \to J/\Psi\ c\ \bar{c}$$

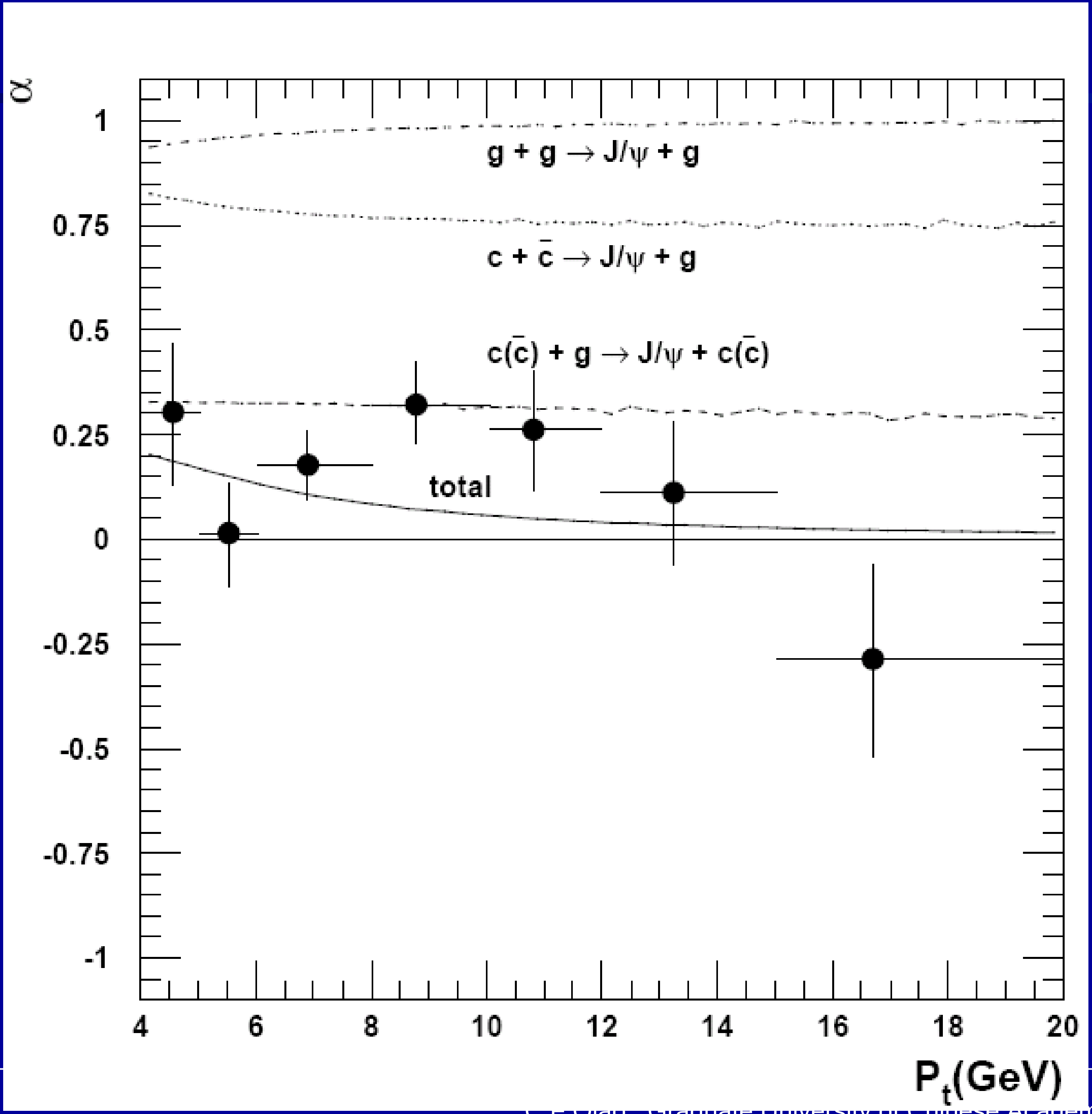
[Hagiwara, Kou, Lin, Zhu and C.F.Q., Phys. Rev.D70,2004]

- which means that the c-quark fragmentation function $D[c(\bar{c}) \to J/\Psi + c(\bar{c})]$ may have a similar K-factor

- Considering of the charm-sea contributions and applying the rescaled charm quark fragmentation function to the J/Ψ production at the Fermilab Tevatron, we find that the experimental data can be almost reached, depending on the magnitude of the K-factor

- The J/Ψ should have no special polarization in our scheme, which has no severe conflict to the data


LO
c → J/ψ
g → J/ψ
total
Br(J/ψ→ μ+μ-)*dσ/dPt (nb/GeV)
Pt(GeV)
10
1
10-1
10-2
10-3
10-4
10-5
6
8
10
12
14
16
18


α
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
g + g → J/ψ + g
c + c̄ → J/ψ + g
c(c̄) + g → J/ψ + c(c̄)
total
4
6
8
10
12
14
16
18
20
P_t(GeV)

Summary and Conclusions

- There are still many open questions regarding to the qaurkonium production mechanism

- Phenomenological study shows that the color-octet contribution to charmonium production may not be that important as previously expected.

- To calculate the NLO QCD correction to process

$$e^+e^- \to \mathrm{J}/\Psi\ \mathrm{g}\ \mathrm{g}$$

is one of the urgent issues in quarkonium physics today.

- LHC may tell more about the nature of quakonium production and decays.

Thank you for your attention