Some Issues in Charmonium Exclusive Production and Decays

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I. Polarized J/ Ψ Pair Production at the LHC

- Color-singlet model made a successful description of heavy quarkonium production and decays

  [Wise, 1980; Chang, 1980; Berger & Jones, 1981; ...]

- However, its leading order result is challenged by some experimental data

- In phenomenology, non-relativistic QCD based Color-octet mechanism improves the theoretical results greatly in several cases

- Recently, the NLO QCD calculations in CSM significantly enhance the color-singlet yield in lots of charmonium production processes, and hence diminish the estimated color-octet contributions

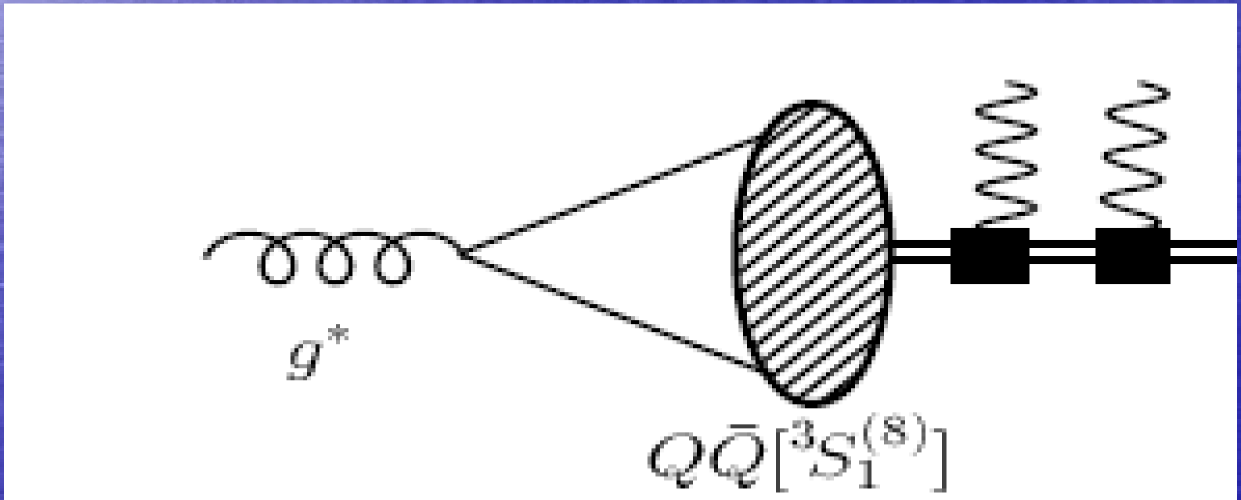
  [Chao et al., 2006, 2007, 2010; Wang et al., 2007 2008, 2010; Artoisenet, et al., 2007; ...]

- In some cases, the higher order calculations in CSM can even explain the data

- The application of COM to charmonium physics keeps on being a debatable issue

- In all, to what degree the color-octet mechanism plays the role in quarkonium production is still an unsettled, urgent and interesting question

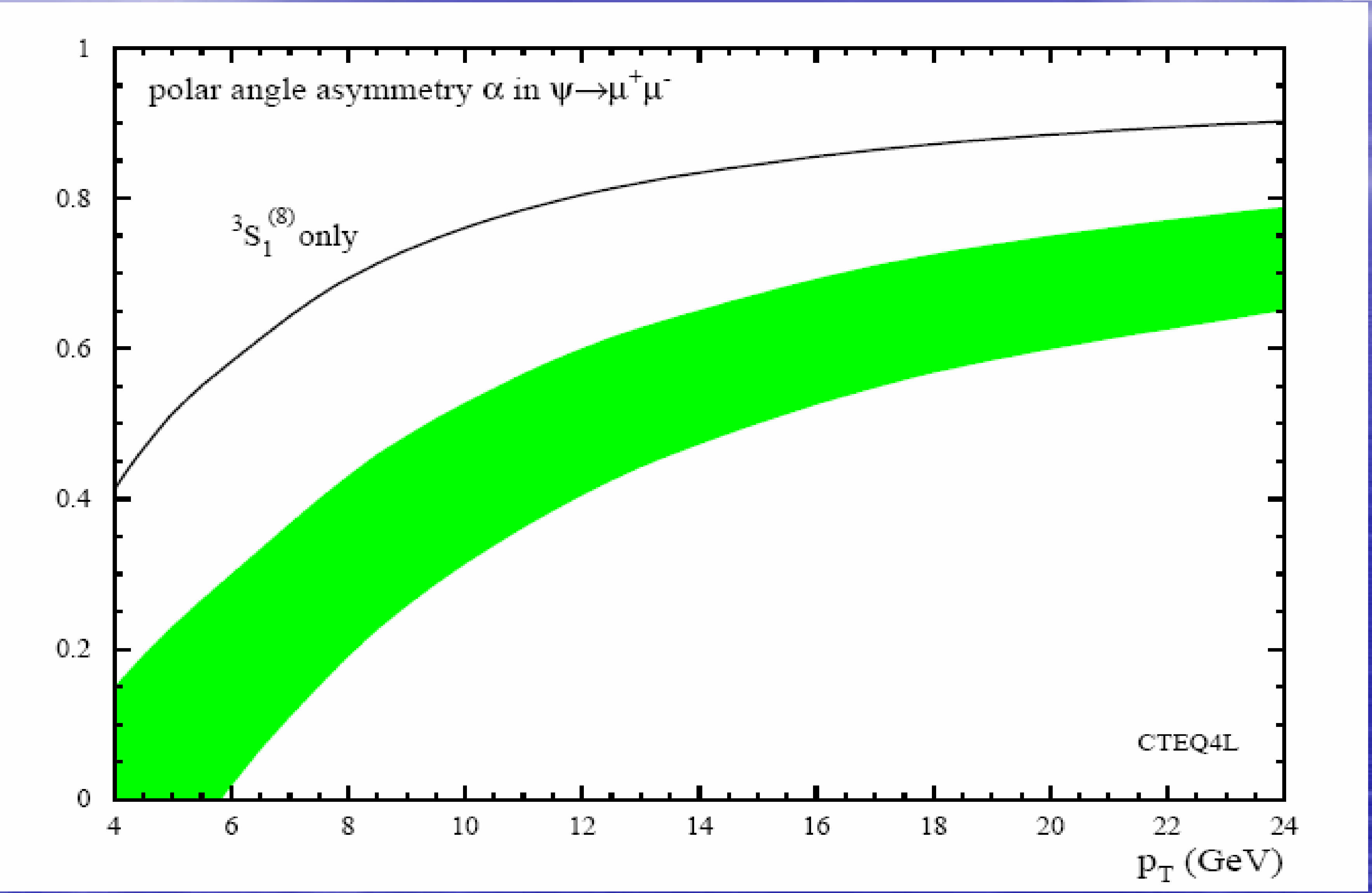
- The J/Ψ from color-octet state $^3S_1$ at the leading order of strong coupling constant, are mostly transversely polarized



- Higher order corrections to color-octet state $^3S_1^8$ production and the effect of color-octet states $^1S_0^8$ and $^3P_J^8$ may yield some longitudinally polarized charmonium

[Beneke and Rothstein 1996; Braaten, Kniehl and lee, 2000]

- Predicting the J/Ψ polarization in inclusive production is impaired in certain degree by the large higher order corrections


polar angle asymmetry α in ψ→μ⁺μ⁻
³S₁⁽⁸⁾ only
CTEQ4L
1
0.8
0.6
0.4
0.2
0
4
6
8
10
12
14
16
18
20
22
24
p_T (GeV)

- In exclusive process the higher order contributions are relatively suppressed

- Therefore, to measure the J/Ψ pair production at the LHC is possibly a feasible way to detect the charmonium production mechanism

As the LHC with

- The luminosity : 10^{32} — 10^{32} cm^{-2}/s
- Center mass of energy: 7 — 10 — 14 TeV
- The pseudorapidity : η < 2.2

- The polarized J/Ψ pair hadroproduction is estimated

[Barger et al. 1996; CFQ 2002; Li, Zhang and Chao 2009; Sun, Sun and QCF 2010]

- Both the color-singlet and color-octet effects are considered, at the leading order of strong coupling constant

Fock State Configuration of the J/Ψ pair

$$|J/\psi\rangle = O(1)|c\bar{c}[^3S_1^{(1)}]\rangle + O(v)|c\bar{c}[^3P_J^{(8)}]g\rangle + O(v^2)|c\bar{c}[^3S_1^{(1,8)}]gg\rangle + O(v^2)|c\bar{c}[^1S_0^{(8)}]g\rangle + \ldots$$

$$|J/\psi\rangle|J/\psi\rangle = |c\bar{c}[^3S_1^{(1)}]\rangle|c\bar{c}[^3S_1^{(1)}]\rangle + \underbrace{|c\bar{c}[^3S_1^{(1)}]\rangle|c\bar{c}[^3S_1^{(8)}]gg\rangle}_{Part_1}$$

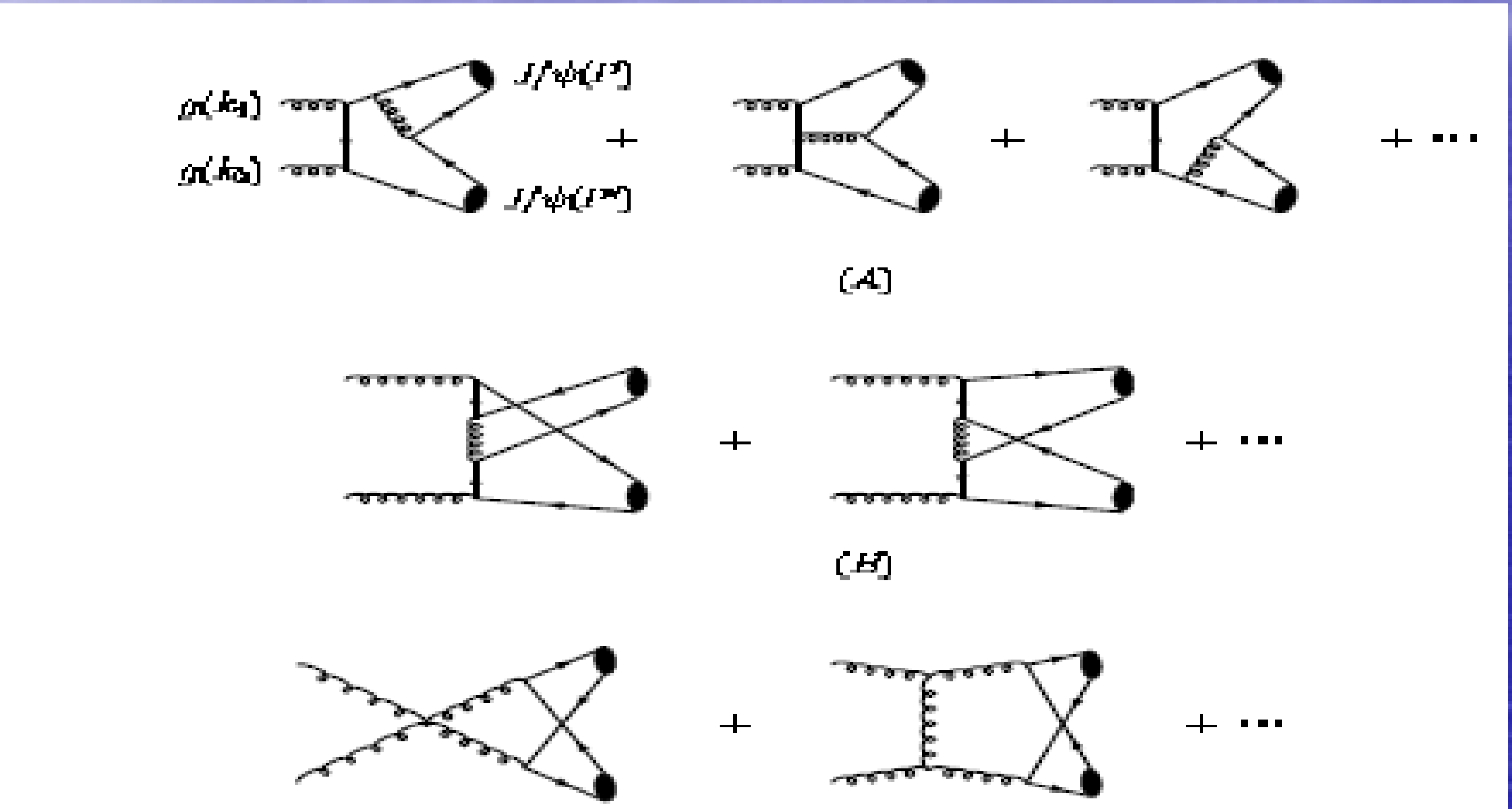
$$+ \underbrace{|c\bar{c}[^3S_1^{(1)}]\rangle(|c\bar{c}[^3P_J^{(8)}]g\rangle + |c\bar{c}[^1S_0^{(8)}]g\rangle)}_{Part_2} + \underbrace{|c\bar{c}[^3S_1^{(8)}]gg\rangle|c\bar{c}[^3S_1^{(8)}]gg\rangle}_{Part_3}$$

$$+ \underbrace{|c\bar{c}[^3S_1^{(8)}]gg\rangle(|c\bar{c}[^3P_J^{(8)}]g\rangle + |c\bar{c}[^1S_0^{(8)}]g\rangle)}_{Part_4}$$

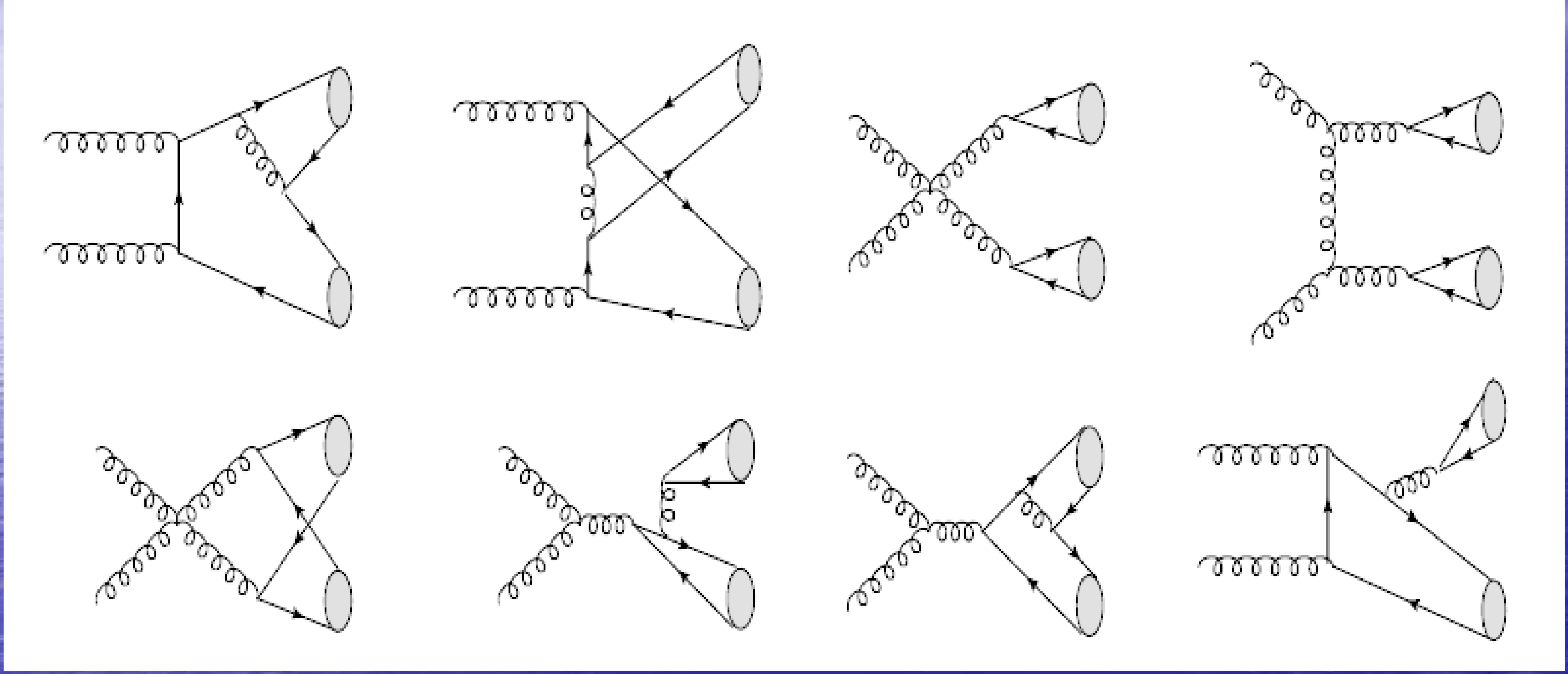
$$+ \underbrace{(|c\bar{c}[^3P_J^{(8)}]g\rangle + |c\bar{c}[^1S_0^{(8)}]g\rangle)(|c\bar{c}[^3P_J^{(8)}]g\rangle + |c\bar{c}[^1S_0^{(8)}]g\rangle)}_{Part_5}$$

The typical Feynman diagrams

in color singlet case



In color octet case



With Input parameters

$$m_c = 1.5 \text{ GeV}$$

$$|R(0)|^2_{cs} = 0.8 \text{ GeV}^3$$

$$< O_8^{J/\psi}(^3S_1) >= 0.012 \text{ GeV}^3$$

$$B(J/\psi \to \mu^+\mu^-) = 0.0597$$

$$\eta(J/\psi) < 2.2$$

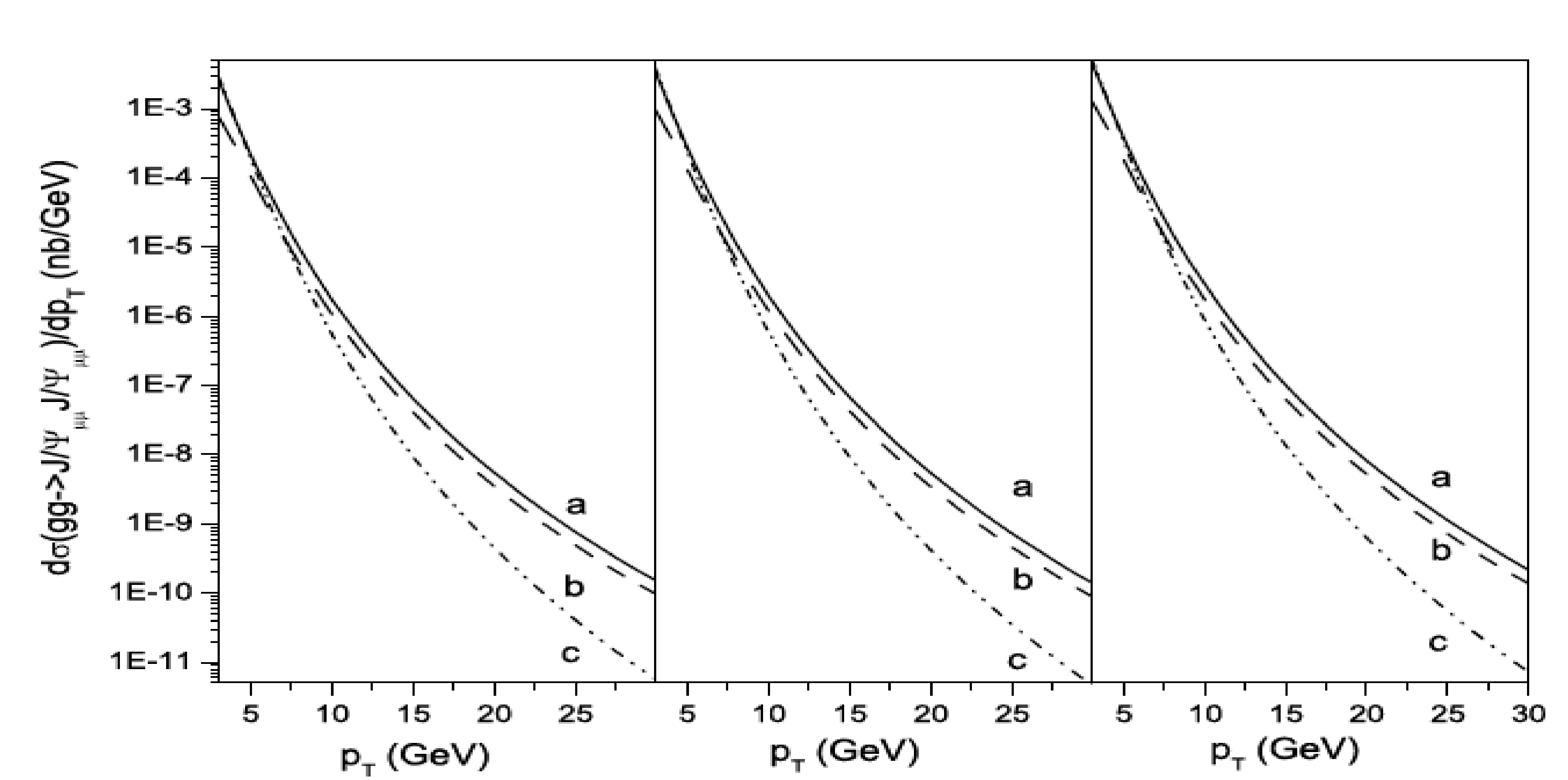
The integrated cross sections of J/Ψ pair production in color-singlet model

	7TeV					10TeV					14TeV				
$\sigma \setminus p_{Tcut}$	3 GeV	4 GeV	5 GeV	6 GeV	7 GeV	3 GeV	4 GeV	5 GeV	6 GeV	7 GeV	3 GeV	4 GeV	5 GeV	6 GeV	7 GeV
$\perp\perp$	2.07pb	0.61pb	0.20pb	0.070pb	0.027pb	2.84pb	0.85pb	0.29pb	0.10pb	0.039pb	3.81pb	1.16pb	0.38pb	0.14pb	0.055pb
$\parallel\parallel$	0.79pb	0.29pb	0.11pb	0.040pb	0.016pb	1.09pb	0.41pb	0.15pb	0.040pb	0.023pb	1.45pb	0.55pb	0.20pb	0.079pb	0.033pb
$\parallel\perp$	2.16pb	0.55pb	0.14pb	0.040pb	0.012pb	2.96pb	0.76pb	0.20pb	0.056pb	0.018pb	3.96pb	1.04pb	0.27pb	0.079pb	0.024pb
tot_{gg}	4.96pb	1.43pb	0.44pb	0.15pb	0.055pb	6.81pb	2.00pb	0.62pb	0.21pb	0.079pb	9.12pb	2.72pb	0.85pb	0.29pb	0.11pb
$tot_{q\bar{q}}$	0.040pb	0.013pb	4.27fb	1.57fb	0.64fb	0.047pb	0.015pb	5.12fb	1.90fb	0.77fb	0.056pb	0.017pb	6.12fb	2.28fb	0.93fb

The integrated cross sections of J/Ψ pair production in color-octet model

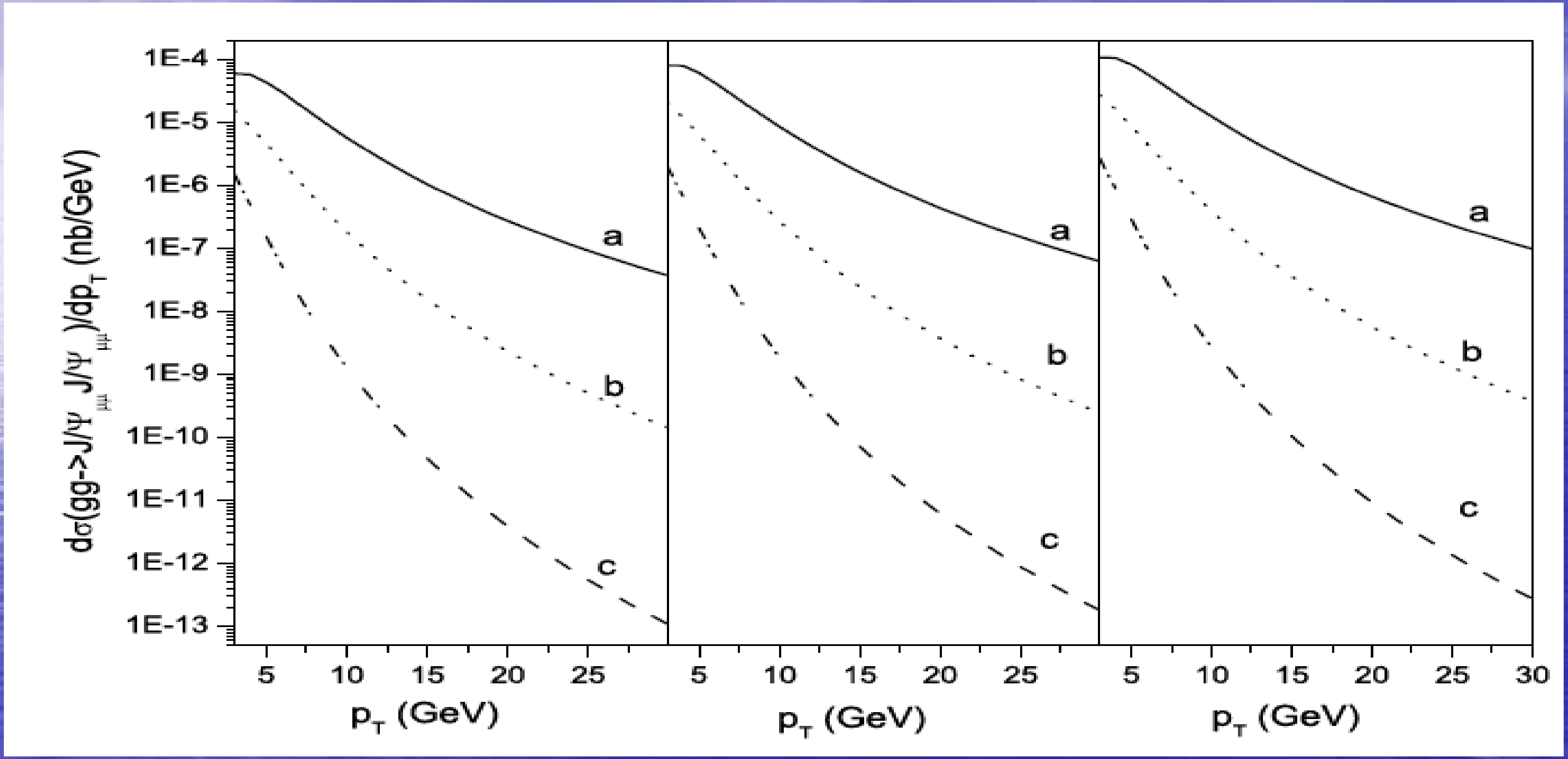
	7TeV					10TeV					14TeV				
$\sigma \backslash p_{Tcut}$	3 GeV	4 GeV	5 GeV	6 GeV	7 GeV	3 GeV	4 GeV	5 GeV	6 GeV	7 GeV	3 GeV	4 GeV	5 GeV	6 GeV	7 GeV
$\perp\perp_{88}$	0.22pb	0.16pb	0.11pb	0.075pb	0.051pb	0.31pb	0.23pb	0.16pb	0.11pb	0.076pb	0.43pb	0.32pb	0.23pb	0.16pb	0.11pb
$\|\|\|\|_{88}$	1.33fb	0.43fb	0.14fb	0.051fb	0.020fb	1.84fb	0.60fb	0.20fb	0.073fb	0.029fb	2.46fb	0.81fb	0.28fb	0.10fb	0.040fb
$\|\|\perp_{88}$	0.025pb	0.013pb	6.95fb	3.62fb	1.93fb	0.035pb	0.019pb	9.95fb	5.25fb	2.84fb	0.047pb	0.026pb	0.014pb	7.36fb	4.02fb
tot_{88}	0.25pb	0.18pb	0.12pb	0.080pb	0.053pb	0.35pb	0.25pb	0.17pb	0.12pb	0.079pb	0.48pb	0.35pb	0.24pb	0.16pb	0.11pb
tot_{18}	0.15pb	0.047pb	0.015pb	5.14fb	1.95b	0.21pb	0.065pb	0.021pb	7.37fb	2.83fb	0.29pb	0.089pb	0.029pb	0.010pb	3.97fb

The differential cross-section of J/Ψ pair production versus p_T at the LHC in CSM



a , b , c represent ⊥⊥ , || || , || ⊥, respectively

The differential cross-section of J/Ψ pair production versus p_T at the LHC in COM



a , b , c represent ⊥⊥ , || || , || ⊥, respectively

The results show:

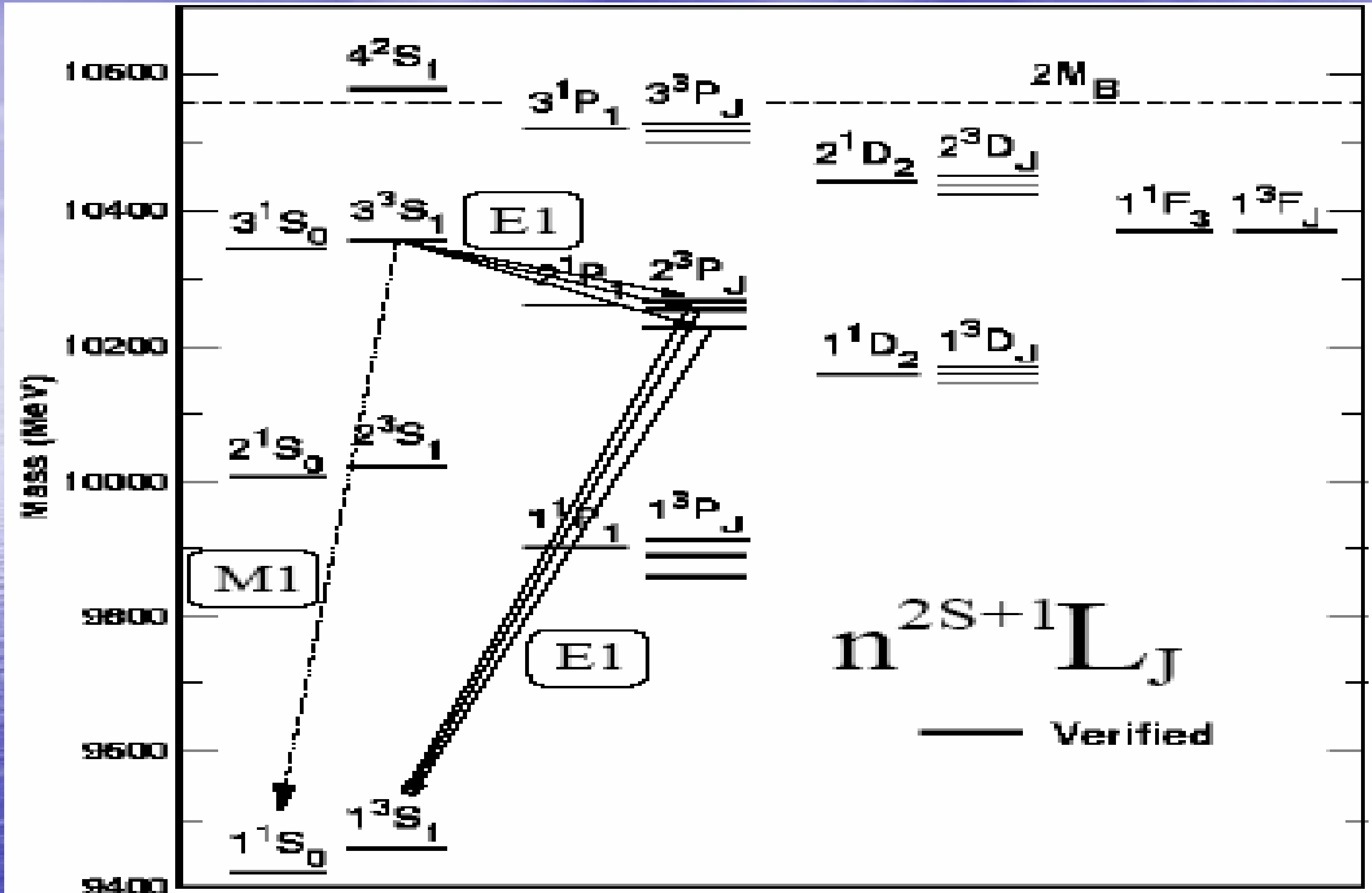
- For the case of colliding energy up to 10 TeV and luminosity 1fb^-1 , the data with at least one J/Ψ in a pair being longitudinally polarized are about fifty percent of the total yield with the lower transverse momentum bound of 5 GeV
- In the pair production, both color-singlet and -octet schemes exhibit that the J/Ψ should be dominated by the transversely polarized yield in large transverse momentum region

II. η_b Exclusive Decays to J/ Ψ Pair

- The lowest energy state in Υ family, the η_b , is very elusive

- About thirty year after it spin triplet partner being found, recently it was observed for the first time by Babar through Υ (3s) --> η_b γ

[Aubert, et al., Babar Collaboration, 2008]



10600
10400
10200
10000
9800
9600
9400
Mass (MeV)
4²S₁
3¹P₁
3³P_J
2M_B
2¹D₂
2³D_J
3¹S₀
3³S₁
E1
1¹F₃
1³F_J
2¹P₁
2³P_J
1¹D₂
1³D_J
2¹S₀
2³S₁
1¹P₁
1³P_J
M1
E1
n^{2S+1}L_J
Verified
1¹S₀
1³S₁

The experimental search for η_b

- The existence of the η_b is a solid prediction of the quark model

- In recent years, the search for η_b has been conducted at CLEO, LEP, and CDF, B-factories, using both inclusive and exclusive methods

Search η_b at CDF [Tseng, CDF, 2002]

- $\eta_b \rightarrow J/\psi\ J/\psi$
- A small cluster of 7 events can be seen, where 1.8 events are expected from background
- If this cluster is due to η_b decay, then the product of its production cross-section and decay branching fractions are near the lower limit of expectation from Braaten et al.

- According Braaten, Fleming and Leibocich (hep-ph/0008091)，though helicity suppressed,

$$Br[\eta_b \to J/\psi + J/\psi] = 7\times 10^{-3} \sim 7\times 10^{-5}$$

- Which seems to be overestimated, since

$$Br[\eta_b \to C + C + \overline{C} + \overline{C}] \sim 10^{-5}$$

[Maltoni and Polosa,hep-ph/0405082]

- A recent analysis shows:

[Y.Jia, hep-ph/0611130]

$$Br[\eta_b \to \phi + \phi] \approx (0.9 - 1.4) \times 10^{-9}$$

$$Br[\eta_b \to J/\psi + J/\psi] = 2.4^{+4.2}_{-1.9} \times 10^{-8}$$

- If so, such a rare decay mode perhaps will not be observed in the foreseeable future in experiment

- More recently, the $\eta_b \rightarrow J/\psi\ J/\psi$ process was calculated at the next-to-leading order accuracy and find the NLO correction many enhance the branching fraction to the same level of relativistic correction
- However, there exists a disagreement in this result

[Braguta & Kartvelishvili, arXiv:0907.2772]

- The radiative correction to $\eta_b \rightarrow J/\psi\ J/\psi$ process is recalculated by a third party. Preliminary result shows there is no agreement with either initial calculation or with the criticism

- Nevertheless, numerical results are all in a similar order

[Sun, Hao, QCF, 2010]

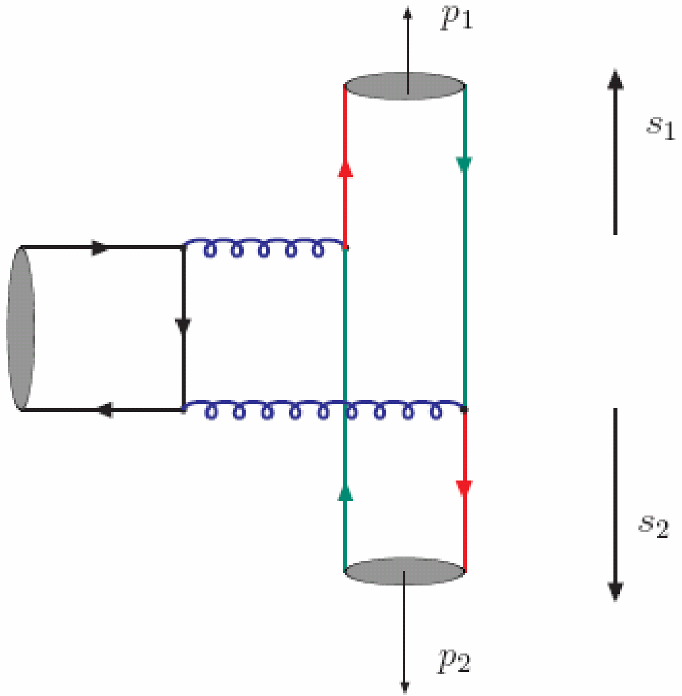
III. η_c Exclusive Decays to Vector Meson Pair

- Theoretically, the description of $\eta_c \rightarrow VV$ process is a long-standing unsolved problem

- Perturbatively, this process is helicity suppressed

- HSR prediction: $\lambda_1 + \lambda_2 = 0$;
- Parity conservation $\Rightarrow \mathcal{M} \sim \mathcal{A}\epsilon_{\mu\nu\rho\sigma}\varepsilon_1^{\mu}\varepsilon_2^{\nu}p_1^{\rho}p_2^{\sigma}$

$\varepsilon_L = ap_1 + bp_2$ $\Rightarrow$ No longitudinal polarization!



$P \rightarrow VV$ decay:

$L = 1,\ S = 1$

$\Downarrow$

$\lambda_1 + \lambda_2 = \pm 2$

$\Downarrow$

$\eta_c \rightarrow VV$ decays should be suppressed!

Experiment measurement on $\eta_c \to VV$ processes

- BES Collaboration, Phys.Rev.D72:072005,2005.

Final state	Branching ratio(Br)	Br/κ_{12}^3
$\rho^0\rho^0$	4.15×10^{-3}	6.6×10^{-3}
$K^{*0}\overline{K}^{*0}$	5.2×10^{-3}	5.0×10^{-3}
$\phi\phi$	2.5×10^{-3}	6.0×10^{-3}
$\omega\omega$	$<4\times10^{-3}$	$<6.4\times10^{-3}$
$\omega\phi$	$<7.1\times10^{-3}$	$<6.8\times10^{-3}$

- There were lots of theoretical investigations on this issue in the literature, e.g.

- η_c-glueball mixing
  Anselmino et al., PRD42(1990)3218,PRD50(1994)595.
- three-particle wave functions for light vectors
  Chernyak et al., NPB348(1991)327.
- Bethe-Salpeter wave functions
  Jia and Chao, HEP&NP.23(1995)765.
- $\eta_c - \eta' - \eta$ mixing
  Feldmann and Kroll, PRD62(2000)074006.
- $^3P_0$ quark-creation mechanism
  B.S.Zou et al., PRD71(2005)114002.
- intermediate meson exchange model
  Q.Zhao, PLB636(2006)197.

- In light-cone distribution formalism we calculate this process, up to the next-to-leading order in twist expansion, and find

Final state	Br[ex]	Br[AS]	Br[GP]
$\rho\rho$	$(2.0 \pm 0.7) \times 10^{-2}$	2.0×10^{-4}	2.8×10^{-4}
$K^*\bar{K}^*$	$(9.2 \pm 3.4) \times 10^{-3}$	7.2×10^{-4}	9.0×10^{-4}
$\omega\omega$	$< 3.1 \times 10^{-3}$	9.1×10^{-5}	1.3×10^{-4}
$\phi\phi$	$(2.7 \pm 0.9) \times 10^{-3}$	6.6×10^{-4}	8.1×10^{-4}

- It in disagreement with the experiment measurements

[Sun, Hao, QCF, 2010]

IV. Brief Summary

- The early running of the LHC will supply numerous event numbers of J/Ψ pair production

- At the LHC, we expect the experiment measurement on double J/Ψ production may tell us more about the charmonium production mechanism

- The η_b → J/ψ J/ψ process may still have problem in the NLO QCD calculation

- In the framework of quark model and perturbative QCD calculation, the η_c →V V puzzle still exists

Thank you for your attention