



# Heavy quarkonium production from top quark decay at the LHC

Li Gang

安徽大学

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◆ Heavy quarkonium physics

◆ Heavy quarkonium production from top quark decay at the LHC

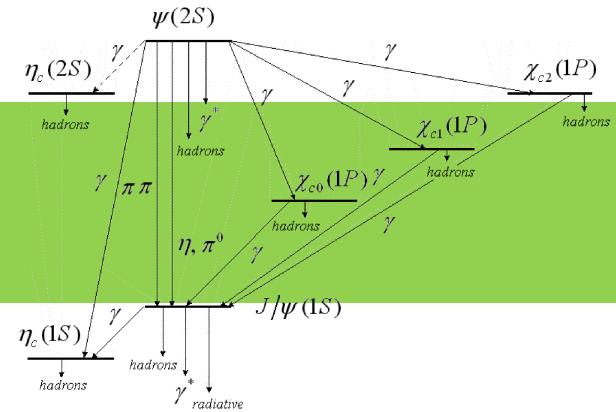
◆ Conclusion & Discussion

# Contents

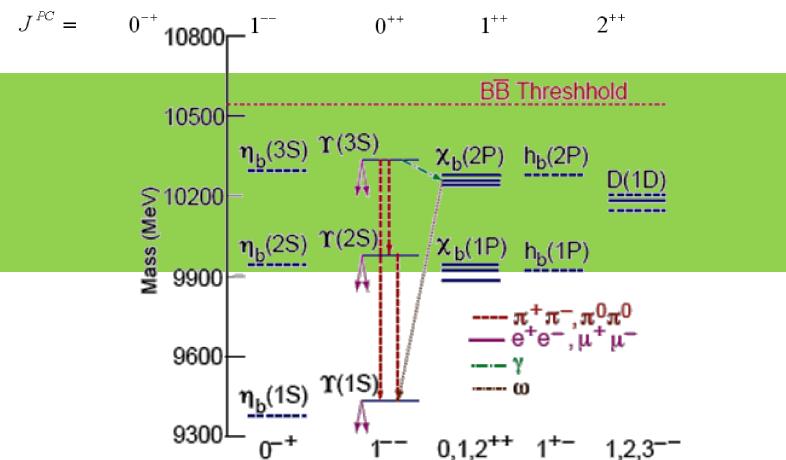
- ◆ Heavy quarkonium physics
- ◆ Heavy quarkonium production from top quark decay at the LHC
- ◆ Conclusion & Discussion

# Heavy quarkonium physics

Discovery . 1974 -----  
J/ $\psi$ -----



1977-----  
 $\Upsilon$ -----



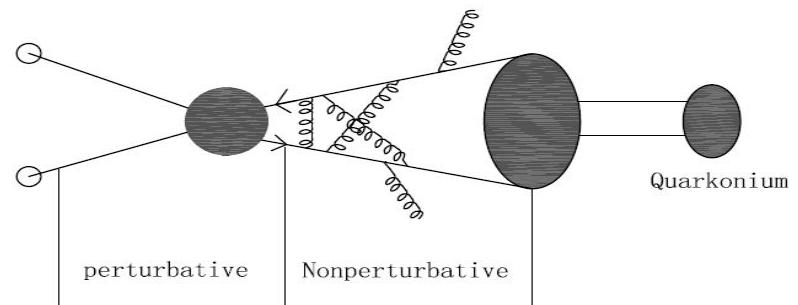
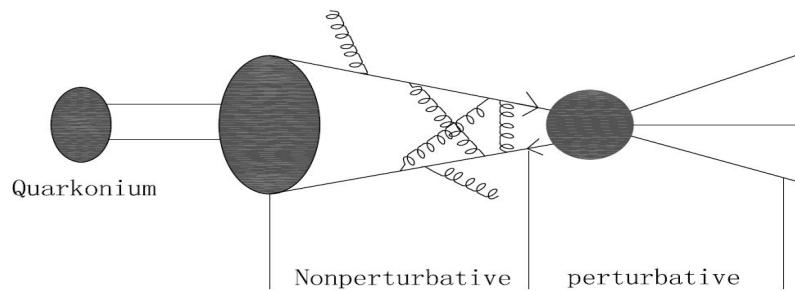
- A non-relativistic QCD bound state
- Consisted by heavy quark-antiquark pair (  $c\bar{c}$  or  $b\bar{b}$  )



for the mass of top is too heavy

# Heavy quarkonium physics

- Heavy quarkonium production and decay can be factorized into two parts: short distance and long distance parts.



- It provides important tests of our understanding of various aspects of Quantum Chromodynamics (QCD).

# Heavy quarkonium physics

## ● Heavy quarkonium production

Short distance process+ long distance process

### ◆ Approximation idea:

□ Short distance process: the production of the on-shell heavy quark pair

- FFNS ----- Fixed-Flavour-Number Scheme
- ZM-VFNS ----- Zero-Mass Variable-Flavour-Number Scheme
- GM-VFNS ----- General-Mass Variable-Flavour-Number Scheme
- FONLL ----- Fixed-Order plus Next-to-Leading Logarithms

## ● Heavy quarkonium production

Short distance process+ long distance process

### ◆ Approximation idea:

□ Long distance process: heavy quark pair evolve into the physical quarkonium state

Different approaches differ essentially in the treatment of the hadronisation

➤ CEM---- Colour-Evaporation Model

$$\sigma_Q^{(N)LO} = F_Q \int_{2m_Q}^{2m_H} \frac{d\sigma_{Q\bar{Q}}^{(N)LO}}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$$

It reasonably account for existing J/Ψ hadroproduction data of the late 90's

.....

polarisation observables  
some transverse momentum spectra

.....

Phys. Lett. B67 (1977) 217

Phys. Lett. B69 (1977) 105

# Heavy quarkonium physics

## ● Heavy quarkonium production

Short distance process+ long distance process

### ◆ Approximation idea:

□ Long distance process: heavy quark pair evolve into the physical quarkonium state

Different approaches differ essentially in the treatment of the hadronisation

#### ➤ CSM---- Colour-Singlet Model

$$d\sigma[Q + X] = \sum_{i,j} \int dx_i dx_j f_i(x_i, \mu_F) f_j(x_j, \mu_F) d\hat{\sigma}_{i+j \rightarrow (Q\bar{Q})+X}(\mu_R, \mu_F) |\psi(0)|^2$$

Made many phenomenological successes until 1994

.....

the  $Q\bar{Q}$  pair share the same quantum numbers with the quarkonium state

$J/\psi$ ,  $\psi'$  production at the Tevatron  
NLO P-wave (D-wave) decays into light hadrons

.....

# Heavy quarkonium physics

## ● Heavy quarkonium production

Short distance process+ long distance process

## ◆ Approximation idea:

□ Long distance process: heavy quark pair evolve into the physical quarkonium state

➤ NRQCD ---- Non-Relativistic QCD

$$d\sigma[Q + X] = \sum_{i,j,n} \int dx_i dx_j f_i(x_i, \mu_F) f_j(x_j, \mu_F) d\hat{\sigma}_{i+j \rightarrow (Q\bar{Q})_n + X}(\mu_R, \mu_F, \mu_\Lambda) \langle O_Q^n \rangle.$$

Different approaches differ essentially in the treatment of the hadronisation

NRQCD@LO

Self consistent  
explain  $J/\psi$ ,  $\psi'$  production at the Tevatron  
Phys. Rev. Lett. **74**, 3327(1995).

.....  
 $e^+e^- \rightarrow J/\psi \eta_c, J/\psi J/\psi, J/\psi \psi'$  factory  
Polarization production at Tevatron

The only effective field theory  
allowing for consistent QCD-  
based calculations beyond the  
born approximation

NRQCD --From 1994

BBL, 9407339

# Heavy quarkonium physics

## ◆ 1997- NRQCD@NLO

A P, 9707223-----

$e^+e^- \rightarrow J/\psi\eta_c, J/\psi J/\psi, J/\psi\chi_{cJ}$  at B factory

$J/\psi$  production at HERA

NLO NRQCD LDMEs (Hamburg ,IHEP and PKU ), 1201.1872, 1205.6682, 1201.2675.

.....

Polarization puzzle, Made great progress,  
Production

but still under doubt

.....  
 $\eta_c$ .....

.....

high  $P_T$ , low  $P_T$  region

$\Upsilon(1S, 2S, 3S)$  at LHC

$J/\Psi + W$  at LHC

- .....
- A. Andronica, 1506.03981; N. Brambilla, 1010.5827

# Heavy quarkonium physics

## ◆ Heavy quarkonium production

### Recent progress

#### ➤ Relativistic correction

- Zhi-Guo He, Bernd A. Kniehl, 1507.03883
  - A. P. Martynenko, 1207.3245
- .....

#### ➤ NRQCD@NNLO

- $\gamma\gamma^* \rightarrow \eta_c$  Feng Feng, Yu Jia, Wen-Long Sang, 1505.02665

#### ➤ Low $P_T$

##### CGC+NRQCD

- Zhong-Bo Kang, Yan-Qing Ma, Raju Venugopalan, 1309.7337
  - Yan-Qing Ma, Raju Venugopalan, 1408.4075
- .....

#### ➤ High $P_T$

##### collinear factorization, SCET

- Zhong-Bo Kang, Yan-Qing Ma, Jian-Wei Qiu, George Sterman, 1411.2456, 1401.0923
- .....

## ◆ Heavy quarkonium production from at LHC

**high  $P_T$  , low  $P_T$  region?**

### ➤ Heavy quarkonium direct prompt production

- A. Andronica, 1506.03981

.....

### ➤ Heavy quarkonium indirect prompt production via heavier charmonia radiative decay

- LHCb collaboration, 1307.4285
- A. Andronica, 1506.03981

.....

### ➤ Heavy quarkonium non-prompt production from the decay of b-hadrons

- ALICE Collaboration, JHEP 11 (2012) 065.

.....

# Heavy quarkonium physics

## ◆ Heavy quarkonium production from SM Heavy particle decay at LHC

- Heavy quarkonium production from z decay
  - Cong-feng Qiao, Feng Yuan, and Kuang-Ta Chao, 9609284

- .....
- Heavy quarkonium production from Higgs decay
  - Georey Bodwin, 1306.5770
  - Geoffrey T. Bodwin, 1407.6695
  - Cong-Feng Qiao, 9805431

- .....
- Heavy quarkonium production from W decay
  - Qi-Li Liao, Xing-Gang Wu, 1111.4609
  - Qi-Li Liao, Xing-Gang Wu, 1204.2594

- .....
- Heavy quarkonium production from top decay

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◆ Heavy quarkonium physics

◆ Heavy quarkonium production from top quark decay at the LHC

◆ Conclusion & Discussion

# Heavy quarkonium production from top quark decay at the LHC

## ➤ Heavy quarkonium production from top decay

Qi-Li Liao, Xing-Gang Wu, 1304.1303

Feng Yuan, Cong-Feng Qiao, Kuang-Ta Chao, 9709400

Cong-Feng Qiao, Chong Sheng Li, Kuang-Ta Chao, 9603275

TABLE I: The decay widths of the processes  $t \rightarrow \bar{B}_c^* + W^+ + c$ ,  $t \rightarrow \bar{B}_c + W^+ + c$ ,  $t \rightarrow \Upsilon + W^+ + b$  and  $t \rightarrow \eta_b + W^+ + b$  at the tree level and with the NLO QCD corrections are presented in two renormalization scale  $\mu$  limits, those are  $2m_c$  and  $m_t$  for the first two processes and  $2m_b$  and  $m_t$  for the other two.

	$t \rightarrow \bar{B}_c^* + W^+ + c$	$t \rightarrow \bar{B}_c + W^+ + c$	$t \rightarrow \Upsilon + W^+ + b$	$t \rightarrow \eta_b + W^+ + b$				
$\mu$	$2m_c$	$m_t$	$2m_c$	$m_t$	$2m_b$	$m_t$	$2m_b$	$m_t$
$\Gamma_{LO}$	0.793MeV	0.151MeV	0.572MeV	0.109MeV	26.8keV	9.54keV	27.1keV	9.67keV
$\Gamma_{NLO}$	0.619MeV	0.307MeV	0.514MeV	0.227MeV	52.3keV	28.2keV	34.3keV	24.5keV

The  $J/\psi$  production from top decay is dominated by color octet channels

$$\alpha_s = 0.253, m_c = 1.5 GeV$$

$$m_b = 4.9 GeV \quad m_t = 176 GeV$$

$$B(t \rightarrow W^+ b J/\psi) \approx 1.46 \times 10^{-4}.$$

$$|\mathcal{M}_8(J/\psi)|^2 = 0.68 \times 10^{-3} \text{ GeV}^2$$

Peng Sun, Li-Ping Sun, Cong-Feng Qiao,  
1003.5360

Cong-feng Qiao, Kuang-Ta Chao, 9606462

# Heavy quarkonium production from top quark decay at the LHC

## NNLO theoretical top quark cross section at the LHC

$\sqrt{S} = 14 \text{ TeV}$

$$\sigma(pp \rightarrow t\bar{t}) = 874^{+14}_{-33} \text{ pb} \quad m_t = 173 \text{ GeV} \quad \text{CTEQ6.6 PDF set}$$

U. Langenfeld, S. Moch, P. Uwer, 0907.2527

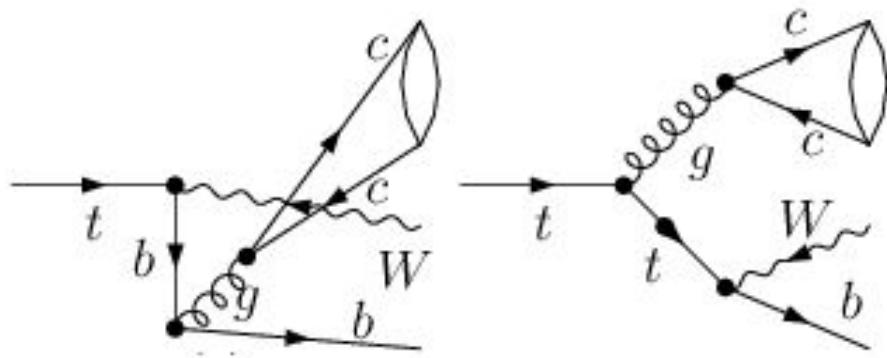
MRST 2006 NNLO		
Mass (GeV)	$\sigma(\text{NLO} \pm \text{scale} \pm \text{PDF}) \text{ (pb)}$	$\sigma(\text{NNLO approx} \pm \text{kinematics} \pm \text{scale} \pm \text{PDF}) \text{ (pb)}$
165	$1089^{+135}_{-129} {}^{+12}_{-14}$	$1173 \pm 5 {}^{+95}_{-62} {}^{+13}_{-15}$
166	$1059^{+132}_{-125} {}^{+12}_{-13}$	$1141 \pm 5 {}^{+93}_{-60} {}^{+13}_{-14}$
167	$1030^{+128}_{-122} {}^{+12}_{-13}$	$1109 \pm 5 {}^{+90}_{-58} {}^{+13}_{-14}$
168	$1003^{+124}_{-119} {}^{+12}_{-13}$	$1080 \pm 5 {}^{+87}_{-57} {}^{+13}_{-14}$
169	$976^{+120}_{-116} {}^{+12}_{-12}$	$1050 \pm 5 {}^{+85}_{-55} {}^{+13}_{-13}$
170	$950^{+117}_{-113} {}^{+12}_{-12}$	$1022 \pm 5 {}^{+83}_{-53} {}^{+13}_{-13}$
171	$924^{+114}_{-110} {}^{+12}_{-12}$	$994 \pm 5 {}^{+81}_{-52} {}^{+13}_{-13}$
172	$900^{+110}_{-107} {}^{+11}_{-12}$	$968 \pm 4 {}^{+79}_{-50} {}^{+12}_{-13}$
173	$876^{+108}_{-104} {}^{+11}_{-11}$	$943 \pm 4 {}^{+77}_{-49} {}^{+12}_{-12}$
174	$853^{+105}_{-101} {}^{+11}_{-11}$	$918 \pm 4 {}^{+75}_{-48} {}^{+12}_{-12}$
175	$831^{+102}_{-98} {}^{+11}_{-11}$	$894 \pm 4 {}^{+73}_{-46} {}^{+12}_{-12}$
176	$809^{+99}_{-96} {}^{+10}_{-10}$	$871 \pm 4 {}^{+71}_{-45} {}^{+11}_{-11}$

MRST 2006 NNLO

# Heavy quarkonium production from top quark decay at the LHC

Song Mao, Li Gang\*, “ $J/\psi$  associated production with  $W^+ b$  from top quark decay in next-to-leading order QCD”, **Phys. Rev.** D91, 116004 (2015)

## ● LO

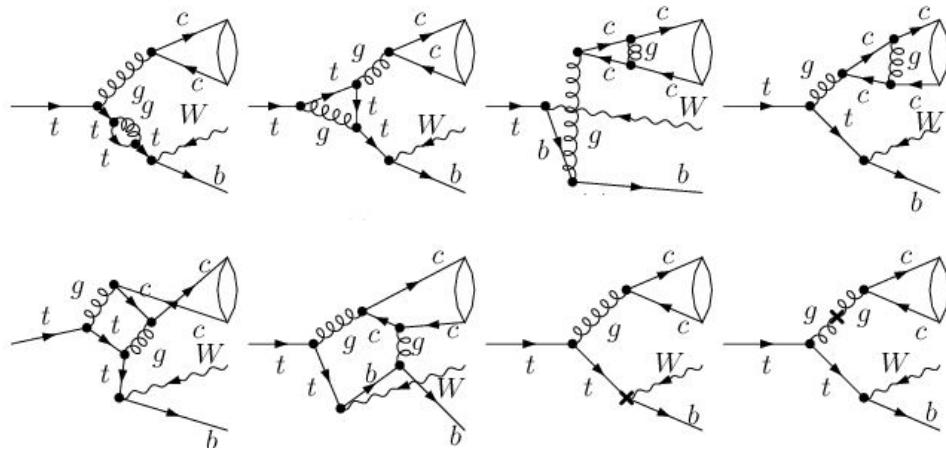


${}^3S_1^{(8)}$

- t'Hooft-Feynman gauge
- The analytic differential cross section for  $t \rightarrow J/\psi + W^+ + b$  is same as 9606462

# Heavy quarkonium production from top quark decay at the LHC

- NLO
- virtual corrections and renormalization



$3 S_1^{(8)}$

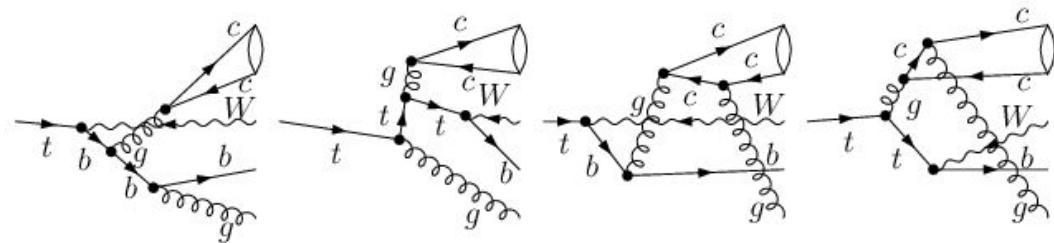
UV, Soft, Coulomb singularity

- DR scheme to regularize the UV and IR Divergences
- $\overline{\text{MS}}$  and OS schemes to renormalize the strong coupling constant and the quark wave functions

# Heavy quarkonium production from top quark decay at the LHC

- NLO

- real gluon emission



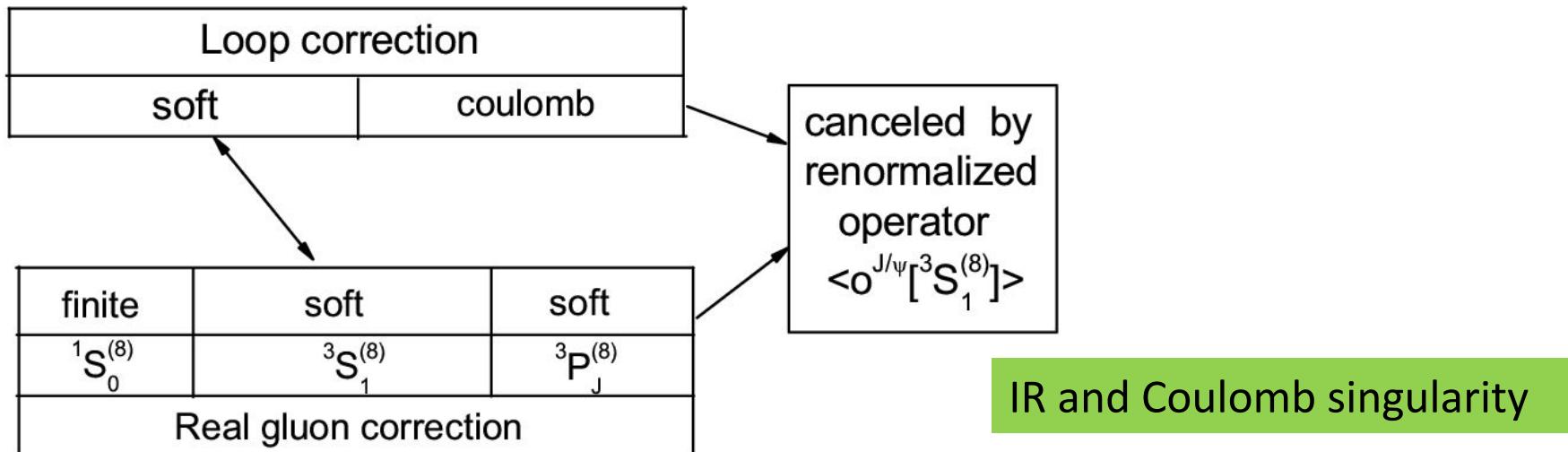
$^1S_0^{(8)}, ^3S_1^{(8)}, ^3P_J^{(8)}$

Soft singularity

- $^1S_0^{(8)}$  Fock state is free of divergence
- $^3S_1^{(8)}, ^3P_J^{(8)}$  Fock states has soft singularities, but has no collinear IR singularity
- The method of dealing with soft IR singularity: PSS method

# Heavy quarkonium production from top quark decay at the LHC

- NLO
- IR and Coulomb singularity structures



- Finite NLO QCD corrected total decay width

$$\Gamma_{NLO} = \Gamma_{LO}(^3S_1^{(8)}) + \Delta\Gamma_{virtual}(^3S_1^{(8)}) + \Delta\Gamma_{Real}(^1S_0^{(8)}, ^3S_1^{(8)}, ^3P_J^{(8)})$$

# Heavy quarkonium production from top quark decay at the LHC

## ● Input parameters:

$$\alpha_s(M_Z) = 0.118$$

LO

$$\alpha_s(M_Z) = 0.130$$

NLO

$$m_c = m_{J/\psi}/2 = 1.5 \text{ GeV}, \quad m_W = 80.398 \text{ GeV}, \quad m_b = 4.75 \text{ GeV}$$

$$m_t = 173 \text{ GeV}, \quad \alpha = 1/137.036 \quad \mu_r = m_t \quad \mu_\Lambda = m_c$$

$$\langle \mathcal{O}^{J/\psi}[{}^3S_1^{(8)}] \rangle = 1.68 \times 10^{-3} \text{ GeV}^3 \quad \langle \mathcal{O}^{J/\psi}[{}^3P_0^{(8)}] \rangle = -9.08 \times 10^{-3} \text{ GeV}^3$$

$$\langle \mathcal{O}^{J/\psi}[{}^1S_0^{(8)}] \rangle = 3.04 \times 10^{-2} \text{ GeV}^3$$

## ● Numerical results

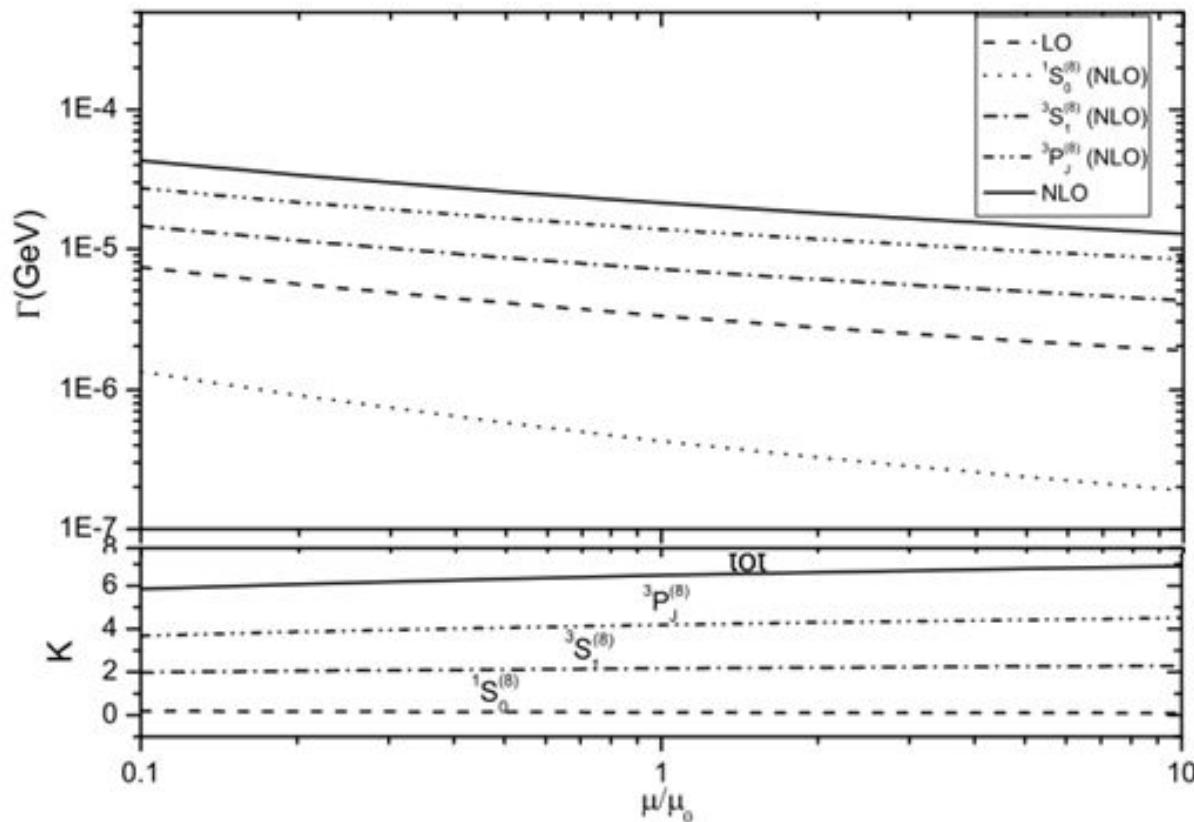
$$\Gamma_{LO}(t \rightarrow J/\psi + W^+ + b + X) = 3.3 \times 10^{-6} \text{ GeV}$$

$$\Gamma_{NLO}(t \rightarrow J/\psi + W^+ + b + X) = 21.11 \times 10^{-6} \text{ GeV}$$

# Heavy quarkonium production from top quark decay at the LHC

## ● Numerical results

### ➤ Uncertainty analysis



■  $\mu$  dependence ,  $\mu = \mu_r$  ,  $\mu_0 = m_t$

# Heavy quarkonium production from top quark decay at the LHC

## ● Numerical results

### ➤ Uncertainty analysis

## ■ LDME Uncertainty

	Set 1 ( $GeV^3$ )	Set 2 ( $GeV^3$ )	Set 3 ( $GeV^3$ )
$\langle \mathcal{O}^{J/\psi}[{}^1S_0^{(8)}] \rangle$	$3.04 \times 10^{-2}$	$8.9 \times 10^{-2}$	$2.86 \times 10^{-3}$
$\langle \mathcal{O}^{J/\psi}[{}^3S_1^{(8)}] \rangle$	$1.68 \times 10^{-3}$	$3 \times 10^{-3}$	$2.73 \times 10^{-3}$
$\langle \mathcal{O}^{J/\psi}[{}^3P_0^{(8)}] \rangle$	$-9.08 \times 10^{-3}$	$5.6 \times 10^{-3}$	$1.82 \times 10^{-3}$

	Set 1 ( $GeV$ )	Set 2 ( $GeV$ )	Set 3 ( $GeV$ )
LO	$3.30 \times 10^{-6}$	$5.89 \times 10^{-6}$	$5.36 \times 10^{-6}$
NLO	$21.11 \times 10^{-6}$	$11.41 \times 10^{-6}$	$14.26 \times 10^{-6}$

# Heavy quarkonium production from top quark decay at the LHC

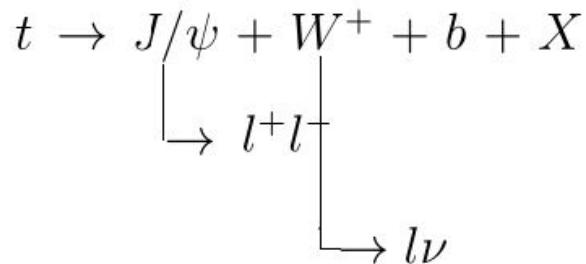
## ● Numerical results

### ➤ NLO BR

$$\Gamma_{t \rightarrow bW^+ + X}^{\text{Born}} = \frac{g^2}{64\pi m_W^2 m_t} \lambda^{\frac{1}{2}}(1, \frac{m_b^2}{m_t^2}, \frac{m_W^2}{m_t^2}) [m_W^2(m_t^2 + m_b^2) + (m_t^2 - m_b^2)^2 - 2m_W^4]$$

$$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$$

$$B(t \rightarrow J/\psi + W^+ + b + X) = 8.69 \times 10^{-6} \quad \text{Set 1 CO LDME}$$



About 600 J/ψ events

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- ◆ Heavy quarkonium physics
- ◆ Heavy quarkonium production from top quark decay at the LHC
- ◆ Conclusion & Discussion

# Conclusion & Discussion

- the decay width for process  $t \rightarrow J/\psi + W^+ + b + X$  at the LO is significantly enhanced by the NLO QCD corrections.
- The source of large correction from NLO?  
Renormalon?

Xing-Gang Wu, Yang Ma, Sheng-Quan  
Wang, Hai-Bing Fu, Hong-Hao Ma,  
Stanley J. Brodsky, Matin Mojaza,  
1405.3196

Uncanceled large logarithms as well as the factorial growth of the “renormalon” terms in higher orders will provide sizable contributions to the theoretical predictions and largely dilute the perturbative nature of the expansion series. As an example, the large next-to-leading order (NLO) contributions observed in the literature for the heavy quarkonium productions/decays are mainly caused by such renormalon terms. It is sometimes argued that the correct renormalization scale for the fixed-order prediction can be decided by comparing with the experimental data; however, this procedure is process-dependent, and it greatly depresses the predictive power of pQCD.

## Conclusion & Discussion

- This process is an interesting platform for studying COM for the  $J/\psi$  production from top decay is dominated by color octet channels
  
- This process and other heavy quarkonium production from top quark decay may provide interesting signature that can be studied at the LHC

*Thank you!*