Heavy quarkonium production through the top quark rare decays via FCNC

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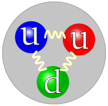
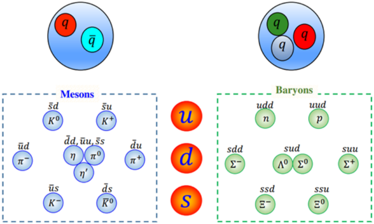
Quark model



- QCD quark confinement
- Quark has fractional charges

In 1964, Gell-Mann and Zweig proposed a way, quark model, to build the numerous hadrons out of three fundamental quarks.



M. Gell-Mann, Phys. Lett. 8, 214 (1964).

1995, CDF, top quark

Observation of Heavy quarkonium

- B_c meson is the only doubly flavoured meson.
- The results are available only at the hadron colliders (LHC, Tevatron).

J/Ψ, 德国汉堡, 1974

(1976 诺奖)

$\downarrow$

Υ, Fermilab, 1977

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B_c, CDF, 1998.

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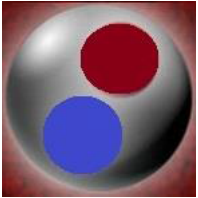

quantum number:

color: $3 \otimes \bar{3} = 1 \oplus 8$

color-singlet and color-octet

spin: $2 \otimes 2 = 1 \oplus 3$

${}^1S_0$ and ${}^3S_1$;

Platforms

There are already some analysis about the production of charmonium and B_c meson through different platforms:

'direct' production:

- ✓ $e^+ \; e^-$ colliders
- ✓ hadronic production
- ✓ gamma gamma production
- ✓ photoproduction
- ✓ heavy ion collisions

'indirect' production:

- ✓ top-quark decay
- ✓ Z^0 decay
- ✓ $W^\pm$ decay
- ✓ Higgs-boson decay

Sizable number of events can be produced at each platform.

BCVEGPY C.H. Chang et al, Comput. Phys. Commun, (2004, 2006).

flavour-changing neutral currents

top quark:

1 As the heaviest known fermion with a mass close to the EW symmetry breaking scale in SM;

2 Speculated to be a sensitive probe of new physics beyond SM.

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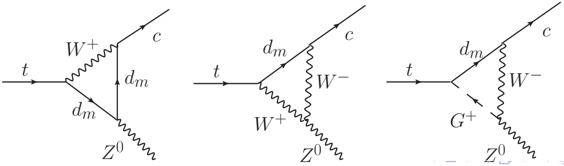
2 Speculated to be a sensitive probe of new physics beyond SM.

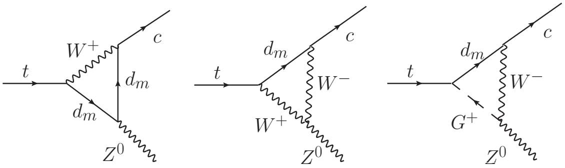
$t \to cZ^0$:

1 The Glashow–Iliopoulos–Maiani (GIM) mechanism through which FCNCs are suppressed in loop diagrams;

2 Cabibbo–Kobayashi–Maskawa (CKM) matrix;



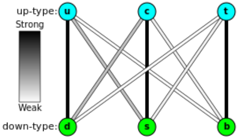
flavour-changing neutral currents



$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}$$

d quark loop can be negligible:

- small mass
- small CKM matrix element



flavour-changing neutral currents

top-quark rare decays via FCNC ($t \to cZ^0$):

in the SM and in the new models

two-Higgs-doublet models (2HDM),

the minimal supersymmetric model (MSSM),

the Topcolor-assisted Technicolor Model (TC2),

and etc.

flavour-changing neutral currents

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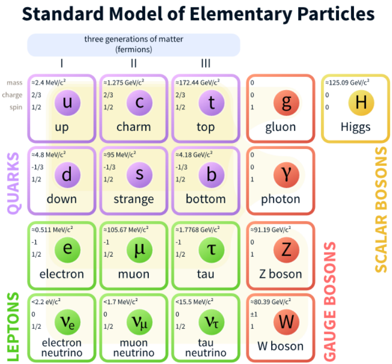
and etc.

These researchs confirmed that

- FCNC processes could be unambiguous small;
- The production of charmonium and $c\bar{b}$-quarkonium through the top-quark decays via the FCNC in the SM is requisite;
- Provide useful guidance for future new physics research from the heavy quarkonium involved processes.

Significances

- Quark model
- QCD: NRQCD, pQCD
- reveal the nature of strong and weak interactions



PDG, 2018

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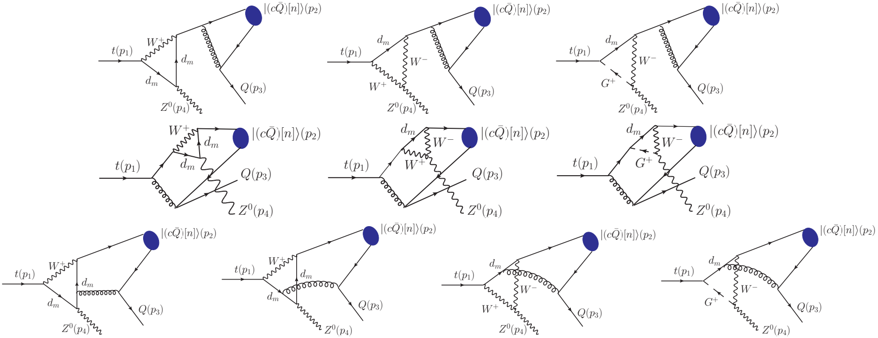
Feynman diagrams

$$t(p_1) \to |(c\bar{Q})[n]\rangle(p_2) + Q(p_3) + Z^0(p_4)$$



Q stands for c or b for the charmonium and the $(c\bar{b})$-quarkonium production.

NRQCD

The decay width of the process $t \to |(c\bar{Q})[n]\rangle + Q + Z^0$ can be written in the following factorized form

$$\Gamma = \sum_n \hat{\Gamma}(t \to |(c\bar{Q})[n]\rangle + Q + Z^0)\langle \mathcal{O}^H[n]\rangle, \quad (1)$$

short-distance coefficient long-distance matrix element

Non-perturbative matrix element $\langle \mathcal{O}^H(n)\rangle$:

1 from a perturbative $(c\bar{Q})$ pair into an observable hadronic state.

2 related to the Schrödinger wave function at the origin $|\Psi_S(0)|^2$ for S-wave state which can be derived from the potential model.

Decay width

$$\hat{\Gamma} = \int \frac{1}{2m_t} \overline{\sum} |\mathcal{M}|^2 d\Phi_3 \tag{2}$$

3-body phase space:

$$d\Phi_3 = (2\pi)^4 \delta^4 \left(p_1 - \sum_{f=2}^{4} p_f \right) \prod_{f=2}^{4} \frac{d^3\vec{p}_f}{(2\pi)^3 2p_f^0} \tag{3}$$

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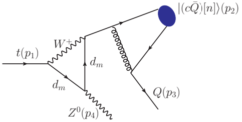
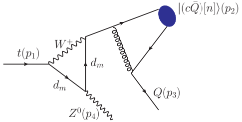


$\mathcal{M}$ is the hard amplitude,

$$i\mathcal{M}_{ss'}[n] = \mathcal{C}\ \bar{u}_{si}(p_3) \sum_{l=1}^{m} \mathcal{A}_l[n] u_{s'j}(p_1) \tag{4}$$

The color factor $\mathcal{C}$ for the color-singlet production equals to $\frac{4}{3\sqrt{3}}\delta_{ij}$.

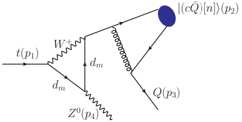


$$\mathcal{A}_1 = \int \frac{d^4q}{(2\pi)^4}(-ig_s)^2\gamma_\mu \frac{\Pi_{p_2}[n]}{(p_3+p_{22})^2}\gamma_\mu \frac{\not{p}_2+\not{p}_3+m_c}{(p_2+p_3)^2-m_c^2}(ie)^3\frac{\gamma_\nu P_L \mathrm{CKM}(2,d_m)}{\sqrt{2}\sin\theta_W}$$
$$\frac{\not{q}-\not{p}_4+m_{d_m}}{(q-p_4)^2-m_{d_m}^2}\left(\frac{\sin\theta_W\gamma_\eta P_R}{3\cos\theta_W}+\frac{\left(\frac{(\sin\theta_W)^2}{3}-\frac{1}{2}\right)\gamma_\eta P_L}{\cos\theta_W\sin\theta_W}\right)\not{\epsilon}(p_4)$$

The projector $\Pi_{p_2}[n]$ $(\nu(p_{22})\bar{\mu}(p_{21}))$ can be written as:

$$\Pi_{p_2}[n] \quad = \quad \frac{1}{2\sqrt{M}}\epsilon[n](\not{p}_2 + M).$$

where $\epsilon[^1S_0] = \gamma_5$ and $\epsilon[^3S_1] = \not{\epsilon}$ with ϵ^ρ is the polarization vector of $^3S_1$ state, and $M = m_c + m_Q$. (G. T. Bodwin and A. Petrelli, (2002))



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The specific momentum of these two constituent quarks:

$$p_{21}=\frac{m_c}{M}p_2+p, \quad p_{22}=\frac{m_Q}{M}p_2-p,$$

where p is the relative momentum between the two constituent quarks.

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Outline

- The decay width for the production of heavy quarkonium via FCNC.
- The kinematic distribution: invariant mass and angular differential decay width.
- The *theoretical uncertainties*: the quark mass, the renormalization scale and the wavefunction.
- The background for the $(c\bar{b})$-quarkonium production.
- New physics effects.

Program and Input parameters

Program package:

- FeynArts 3.9
- the modified FormCalc 7.3/LoopTools 2.1

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In numerical calculations, the input parameters are taken as follows:

$$m_Z = 91.1876\ \text{GeV},\ m_W = 80.385\ \text{GeV},\ m_t = 173.0\ \text{GeV},$$

$$m_c = 1.50\ \text{GeV},\ m_b = 4.90\ \text{GeV},\ m_s = 0.101\ \text{GeV},$$

$$|R_S(c\bar{c})(0)|^2 = 0.810\ \text{GeV}^3,\ |R_S(c\bar{b})(0)|^2 = 1.642\ \text{GeV}^3,$$

$$G_F = 1.1663787 \times 10^5, \quad \text{CKM}(2,3) = 0.041$$

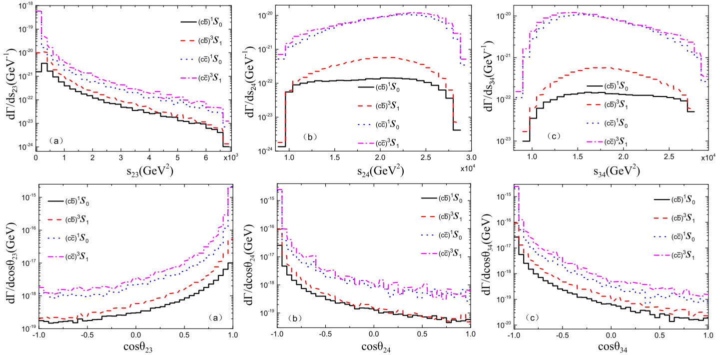
1.Decay widths

Total decay width for $t \to cZ^0$ is 9.59×10^{-13} GeV.

$t \to \|(c\bar{Q})[n]\rangle$	Γ (GeV)	R
$t \to \eta_c$	1.20×10^{-16}	1.25×10^{-4}
$t \to J/\psi$	1.37×10^{-16}	1.43×10^{-4}
$t \to B_c$	2.06×10^{-18}	2.15×10^{-6}
$t \to B_c^*$	6.27×10^{-18}	6.54×10^{-6}

- the ratio $R = \Gamma_{t\to|(c\bar{Q})[n]\rangle}/\Gamma_{t\to cZ^0}$.
- the decay width of the charmonium production is almost two orders of magnitude larger than that of the $(c\bar{b})$-quarkonium production.

2.differential decay widths



The largest contribution emerges when the heavy quarkonium moves along with the same direction of the outgoing quark but with the opposite direction of the outgoing Z^0 boson.

3.Uncertainties from the quark mass

Uncertainties from m_c by varying

$m_c \in [1.25, 1.75]$ GeV.

	$m_c = 1.25$ GeV	$m_c = 1.50$ GeV	$m_c = 1.75$ GeV
$\Gamma_{\|(c\bar{c})[^1S_0]\rangle}$	2.24×10^{-16}	1.20×10^{-16}	0.69×10^{-16}
$\Gamma_{\|(c\bar{c})[^3S_1]\rangle}$	2.40×10^{-16}	1.37×10^{-16}	0.86×10^{-16}
$\Gamma_{\|(c\bar{b})[^1S_0]\rangle}$	2.06×10^{-18}	2.06×10^{-18}	2.06×10^{-18}
$\Gamma_{\|(c\bar{b})[^3S_1]\rangle}$	6.53×10^{-18}	6.27×10^{-18}	6.06×10^{-18}

Uncertainties from m_b by varying

$m_b \in [4.50, 5.30]$ GeV.

	$m_b = 4.50$ GeV	$m_b = 4.90$ GeV	$m_b = 5.30$ GeV
$\Gamma_{\|(c\bar{c})[^1S_0]\rangle}$	0.82×10^{-16}	1.20×10^{-16}	1.70×10^{-16}
$\Gamma_{\|(c\bar{c})[^3S_1]\rangle}$	0.98×10^{-16}	1.37×10^{-16}	1.88×10^{-16}
$\Gamma_{\|(c\bar{b})[^1S_0]\rangle}$	1.89×10^{-18}	2.06×10^{-18}	2.23×10^{-18}
$\Gamma_{\|(c\bar{b})[^3S_1]\rangle}$	5.65×10^{-18}	6.27×10^{-18}	6.90×10^{-18}

Uncertainties from m_t by varying

$m_t \in [169, 177]$ GeV.

	$m_t = 169.0$ GeV	$m_t = 173.0$ GeV	$m_t = 177.0$ GeV
$\Gamma_{\|(c\bar{c})[^1S_0]\rangle}$	1.15×10^{-16}	1.20×10^{-16}	1.25×10^{-16}
$\Gamma_{\|(c\bar{c})[^3S_1]\rangle}$	1.32×10^{-16}	1.37×10^{-16}	1.45×10^{-16}
$\Gamma_{\|(c\bar{b})[^1S_0]\rangle}$	2.05×10^{-18}	2.06×10^{-18}	2.08×10^{-18}
$\Gamma_{\|(c\bar{b})[^3S_1]\rangle}$	5.71×10^{-18}	6.27×10^{-18}	6.88×10^{-18}

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$\Gamma_{\vert(c\bar{b})[^3S_1]\rangle}$	6.53×10^{-18}	6.27×10^{-18}	6.06×10^{-18}

Uncertainties from m_b by varying

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Uncertainties from m_t by varying

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$\Gamma_{\vert(c\bar{b})[^1S_0]\rangle}$	2.05×10^{-18}	2.06×10^{-18}	2.08×10^{-18}
$\Gamma_{\vert(c\bar{b})[^3S_1]\rangle}$	5.71×10^{-18}	6.27×10^{-18}	6.88×10^{-18}

$$\Gamma_{t\to\eta_c} = 1.20^{+1.04}_{-0.51} \times 10^{-16}\ \text{GeV},$$

$$\Gamma_{t\to J/\psi} = 1.37^{+1.03}_{-0.51} \times 10^{-16}\ \text{GeV},$$

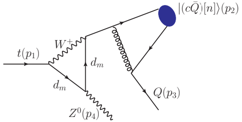
$$\Gamma_{t\to B_c} = 2.06^{+0.17}_{-0.17} \times 10^{-18}\ \text{GeV},$$

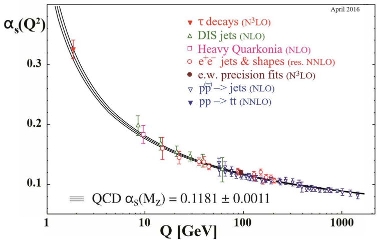
$$\Gamma_{t\to B_c^*} = 6.27^{+0.63}_{-0.62} \times 10^{-18}\ \text{GeV},$$

The mass uncertainties are large!

3.Uncertainties from the μ_R

PDG, 2018; (04 诺奖)





Decay width $\sim \alpha_s^2$

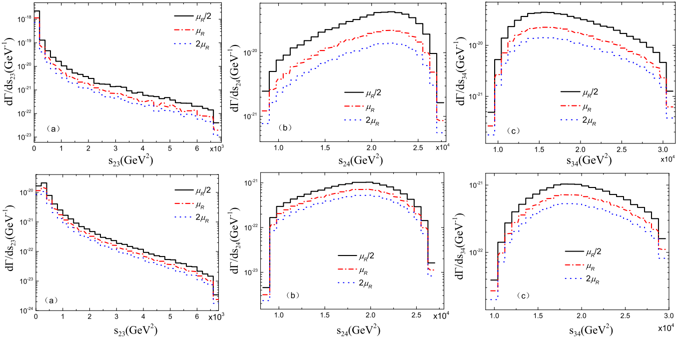
	μ_R	$\frac{1}{2}\mu_R$	$2\mu_R$
$\Gamma_{\lvert(c\bar{c})[^1S_0]\rangle}$	1.20×10^{-16}	2.34×10^{-16}	0.75×10^{-16}
$\Gamma_{\lvert(c\bar{c})[^3S_1]\rangle}$	1.37×10^{-16}	2.67×10^{-16}	0.86×10^{-16}
$\Gamma_{\lvert(c\bar{b})[^1S_0]\rangle}$	2.06×10^{-18}	2.97×10^{-18}	1.52×10^{-18}
$\Gamma_{\lvert(c\bar{b})[^3S_1]\rangle}$	6.27×10^{-18}	9.05×10^{-18}	4.63×10^{-18}

$\mu_R = 2m_c$ for charmonium

$\mu_R = 2m_b$ for $(c\bar{b})$-quarkonium.

large scale uncertainty!

3.Uncertainties from the μ_R



$t \to |(c\bar{c})[n]\rangle + c + Z^0$ (top three) and $t \to |(c\bar{b})[n]\rangle + b + Z^0$ (bottom three).

Higher-order perturbative calculation or proper scale-setting methods (PMC). (S. J. Brodsky and X. G. Wu, (2012))

3.Uncertainties from the wavefunction

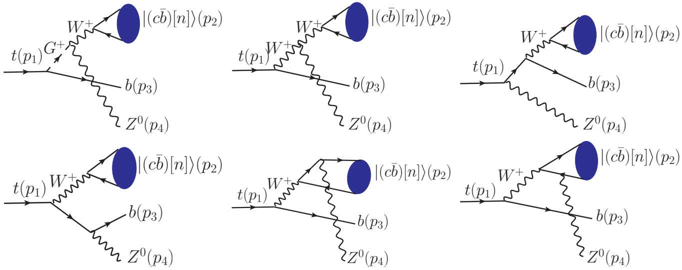
$|R_S(c\bar{Q})(0)|^2$ by some potential models:

$\|R_S(c\bar{Q})(0)\|^2$ (GeV^3)	$(c\bar{c})$	$(c\bar{b})$
QCD(Buchmüller-Type)	0.810	1.642
Power-law	0.999	1.710
Logarithmic	0.815	1.508
Cornell	1.454	3.184

E.J. Eichten and C. Quigg, Phys. Rev. D**52**, 1726 (1995)

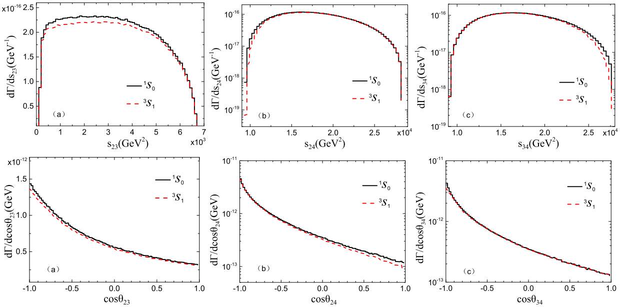
The wavefunction at the zero is an overall factor and its uncertainty can be conventionally discussed when we know its exact values.

4.Feynman diagrams without FCNC

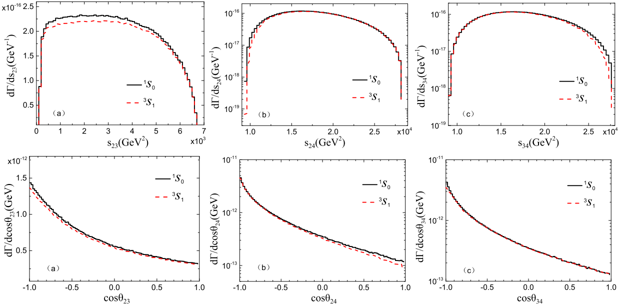


The Feynman diagrams for $t(p_1) \to |(c\bar{b})[n]\rangle(p_2) + b(p_3) + Z^0(p_4)$ without FCNC, which could be treated as the background for observing the FCNC effect.

4.Decay widths



4.Decay widths



- $\Gamma(t \to B_c) = 1.32 \times 10^{-12}$ GeV,
- $\Gamma(t \to B_c^*) = 1.26 \times 10^{-12}$ GeV.

$10^5 \sim 10^6$ times

When searching of new physics signals from the FCNC channels, those background should be taken into consideration.

5.New physics effect

Two ways:

- Tree level FCNC
- New particles in the loop

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The estimation of new physics effect with several new models by

$\Gamma = \Gamma_t \times BR(t \to cZ^0) \times R$:

new model	BR($t \to cZ^0$)	$\Gamma_{t\to(c\bar{c})+cZ^0}$	$\Gamma_{t\to(c\bar{b})+bZ^0}$
2HDM type III	10^{-3}	10^{-7}	10^{-9}
effective Lagrangian	10^{-4}	10^{-8}	10^{-10}
models with extra quarks	10^{-4}	10^{-8}	10^{-10}
TC2	10^{-5}	10^{-9}	10^{-11}
MSSM	10^{-6}	10^{-10}	10^{-12}

With such a branching ratio BR($t \to cZ^0$), the production of charmonium and $(c\bar{b})$-quarkonium through top quark rare decays may be accessible at LHC/HL-LHC.

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Summary and outlook

summary:

1 The decay width for the production of heavy quarkonium via FCNC are at the order of 10^{-16} (10^{-18}) for the production of charmonium (($c\bar{Q}$)-quarkonium).

2 The theoretical uncertainties have been analyzed (large).

3 The background for the ($c\bar{b}$)-quarkonium production can't be negligible.

4 The new physics effects have be estimated in some new models.

Summary and outlook

summary:

1 The decay width for the production of heavy quarkonium via FCNC are at the order of 10^{-16} (10^{-18}) for the production of charmonium ($(c\bar{Q})$-quarkonium).

2 The theoretical uncertainties have been analyzed (large).

3 The background for the $(c\bar{b})$-quarkonium production can't be negligible.

4 The new physics effects have be estimated in some new models.

outlook:

1 New physics effects analyzed in detail.

2 The production of the doubly heavy baryons.

3 The decay of the doubly heavy hadrons.

Thanks for your attention!