Production of triply heavy baryons and six free heavy quarks at LHC

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October 25, 2012

OUTLINE

. Triply heavy baryons production

.Overview of the triply heavy baryons.

.The production of the triply heavy baryons.

. Six free heavy quarks production

1.1 Overview of the triply heavy baryons

.The color configuration: $\frac{1}{\sqrt{6}}\varepsilon^{ijk}Q_{1i}Q_{2j}Q_{3k}$

.Three energy scales: $m >> |mv| >> mv^2$

.Size: $1/|mv|$

.Spin structure: Ω_{ccc}:$\frac{3}{2}$, Ω^*_{ccb}:$\frac{3}{2}$, Ω_{ccb}: $\frac{1}{2}$

.The nonrelativistic triply heavy baryon in the ground state is:

$$|\Omega_{Q_1Q_2Q_3}, S, S_Z, \vec{P}=0\rangle = \int \frac{d^3\overrightarrow{V}_1}{(2\pi)^3}\frac{d^3\overrightarrow{V}_2}{(2\pi)^3}\sum_{\xi_i,\eta_i}\frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}\langle S, S_Z|\eta_1,\eta_2,\eta_3\rangle$$

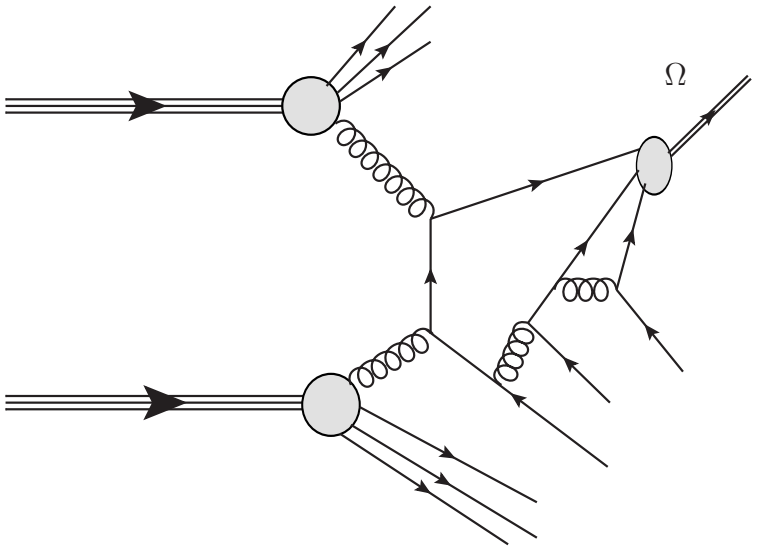
$$\frac{\sqrt{2M}}{\sqrt{2E_1 2E_2 2E_3}}\frac{1}{\sqrt{d!}}\psi(\overrightarrow{V}_1,\overrightarrow{V}_2)\times|Q_1,\xi_1,\eta_1,\vec{p}_1=\overrightarrow{V}_1\rangle$$

$$\times|Q_2,\xi_2,\eta_2,\vec{p}_2=\overrightarrow{V}_2\rangle\times|Q_3,\xi_3,\eta_3,\vec{p}_3=-\overrightarrow{V}_1-\overrightarrow{V}_2\rangle\ .$$

1.2 The process of $pp \to \Omega_{Q_1Q_2Q_3}\bar{Q}_1\bar{Q}_2\bar{Q}_3 + X$

The production mechanism:

$g - g$ fusion,
$q\bar{q}$ annihilation (u, d, s).



. Energy scales: $m >> mv$

. *the short-distance coefficient*

. *the long-distance matrix element*

.For g-g fusion process:

All diagrams shrink to seven basic diagrams:

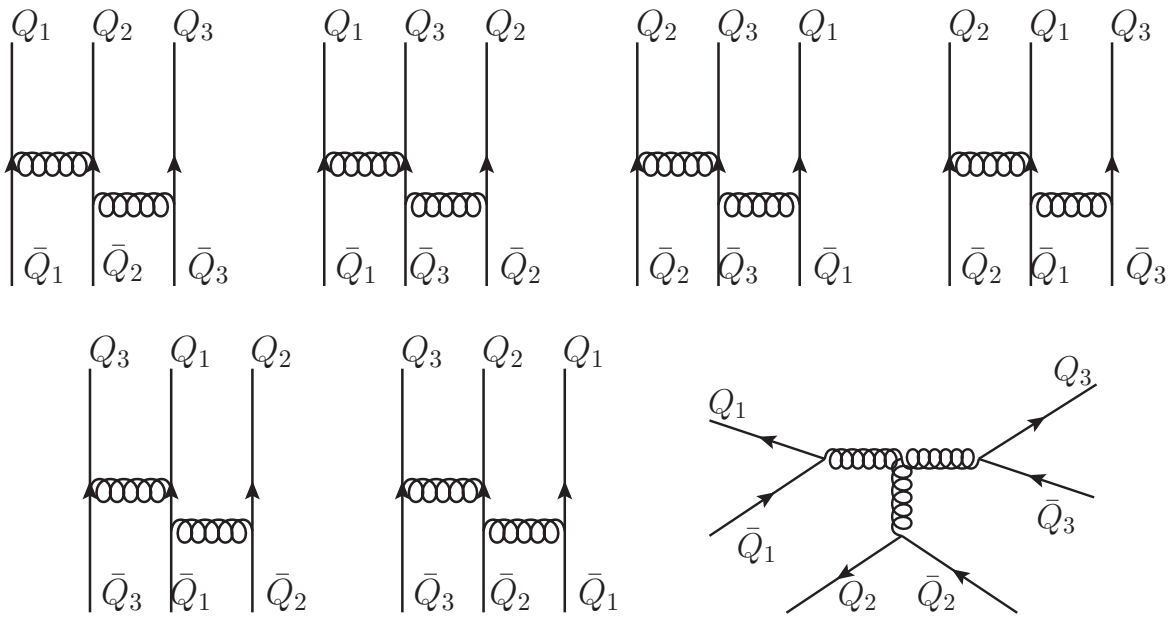


Figure: The seven inequivalent topological constructions of three heavy quark pairs assuming three heavy quarks with different heavy flavors.

.Feynman diagram generation

Feynman diagrams containing a quartic-gluon vertex:

$2\times6+22=34$

Feynman diagrams without quartic-gluon vertex:

$(6+3)\times11\times7=693$

The number of the Feynman diagrams:

$34+693=727$

Distinct amplitudes:

$727+2\times34=795$

. For process $gg \to ccb\bar{c}\bar{c}\bar{b}$.

two permutations:
$(c_1\bar{c}_1c_2\bar{c}_2b\bar{b})$,
$(c_1\bar{c}_2c_2\bar{c}_1b\bar{b})$,
Feynman diagrams: $727\times2!=1454$
Distinct amplitudes: $795\times2!=1590$

. For process $gg \to ccc\bar{c}\bar{c}\bar{c}$:

.six permutations:
$(c_1\bar{c}_1c_2\bar{c}_2c_3\bar{c}_3)$, $(c_1\bar{c}_1c_2\bar{c}_3c_3\bar{c}_2)$,
$(c_1\bar{c}_2c_2\bar{c}_3c_3\bar{c}_1)$, $(c_1\bar{c}_2c_2\bar{c}_1c_3\bar{c}_3)$,
$(c_1\bar{c}_3c_2\bar{c}_1c_3\bar{c}_2)$, $(c_1\bar{c}_3c_2\bar{c}_2c_3\bar{c}_1)$.
Feynman diagrams: $727\times3!=4362$
Distinct amplitudes: $795\times3!=4770$

.Simplification

Color factor antisymmetry.

Spin wave function symmetry.

Non-relativistic approximation.

. Generating basic Feynman diagrams automatically

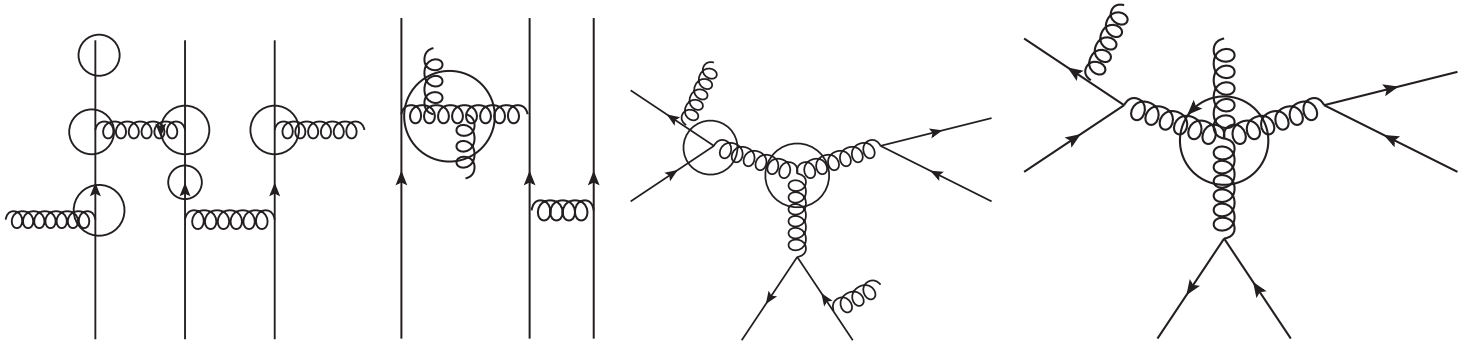
three integers:

i denoting the position of the first gluon

j denoting the position of the second gluon

k denoting the topological construction of three heavy quark pairs

.Amplitudes of the Feynman diagrams:



gauge invariance: ward identity (12 independent color factors)

Twelve independent color factors.

$$C_1 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a\lambda^b)_{\xi_1\chi_2}\delta_{\xi_2\chi_1}\delta_{\xi_3\chi_3}\ , C_2 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^b\lambda^a)_{\xi_1\chi_2}\delta_{\xi_2\chi_1}\delta_{\xi_3\chi_3},$$

$$C_3 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a\lambda^b)_{\xi_1\chi_1}\delta_{\xi_2\chi_2}\delta_{\xi_3\chi_3}\ , C_4 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^b\lambda^a)_{\xi_1\chi_1}\delta_{\xi_2\chi_2}\delta_{\xi_3\chi_3},$$

$$C_5 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a\lambda^b)_{\xi_1\chi_3}\delta_{\xi_2\chi_1}\delta_{\xi_3\chi_2}\ , C_6 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^b\lambda^a)_{\xi_1\chi_3}\delta_{\xi_2\chi_1}\delta_{\xi_3\chi_2},$$

$$C_7 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_1}(\lambda^b)_{\xi_2\chi_2}\delta_{\xi_3\chi_3}\ , C_8 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_2}(\lambda^b)_{\xi_2\chi_1}\delta_{\xi_3\chi_3},$$

$$C_9 = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_2}(\lambda^b)_{\xi_2\chi_3}\delta_{\xi_3\chi_1}\ , C_{10} = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_3}(\lambda^b)_{\xi_2\chi_2}\delta_{\xi_3\chi_1},$$

$$C_{11} = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_3}(\lambda^b)_{\xi_2\chi_1}\delta_{\xi_3\chi_2}\ , C_{12} = \frac{\varepsilon^{\xi_1\xi_2\xi_3}}{\sqrt{6}}(\lambda^a)_{\xi_1\chi_1}(\lambda^b)_{\xi_2\chi_3}\delta_{\xi_3\chi_2}.$$

. In leading order (expansion in v), the differential cross section of $g-g$ fusion is:

$$
\begin{aligned}
d\hat{\sigma} &= \sum_{S_Z} \frac{(2\pi)^4}{2\hat{s}} \delta^4(k_1+k_2-P-q_1-q_2-q_3) \\
&\times \frac{d^3P}{(2\pi)^3 2E} \frac{d^3q_1}{(2\pi)^3 2E_1} \frac{d^3q_2}{(2\pi)^3 2E_2} \frac{d^3q_3}{(2\pi)^3 2E_3} \\
&\frac{1}{64} \sum |\mathcal{A}|^2 \frac{M}{4m_1m_2m_3} |\frac{\Psi(0,0)}{\sqrt{d!}}|^2. \qquad (2)
\end{aligned}
$$

The differential cross section of $pp \to \Omega^S_{Q_1Q_2Q_3} \bar{Q}_1 \bar{Q}_2 \bar{Q}_3 + X$ is:

$$
\frac{d\sigma}{dP_T} = \frac{1}{d!} \int dx_1 dx_2 f_{g_1}(x_1,Q) f_{g_2}(x_2,Q) \frac{d\hat{\sigma}}{dP_T} \qquad (3)
$$

1.3 Numerical results and conclusions for the triply heavy baryons production

. The parameters:

mass:

m_c=1.5 GeV, m_b=4.9 GeV, and M=m_1+m_2+m_3,

wave function at the origin:

$|\Psi(0,0)|^2$=0.00610 GeV^6 for Ω_{ccc},

$|\Psi(0,0)|^2$=0.00746 GeV^6 for Ω^*_{ccb} and Ω_{ccb}.

energy scales:

Q=$\mu_R/2$, μ_R, where μ_R^2=P_T^2+M^2.

Table: Hadronic Production Cross sections (in unit nb) of the triply heavy baryons at LHC with $\sqrt{s} = 7.0$ TeV. Some typical P_T cuts are adopted. As for the pseudo-rapidity cut, we take $|\eta| < 2.5$ for CMS and ATLAS, and $1.9 < \eta < 4.9$ for LHCb.

-	-	LHC (CMS, ATLAS)		LHCb	
-	η_{cut} / P_{Tcut}	$\lvert\eta\rvert < 2.5$		$1.9 < \eta < 4.9$	
Q	-	μ_R	$\mu_R/2$	μ_R	$\mu_R/2$
Ω_{ccc}	0GeV	0.0604(6)	0.132(1)	0.0329(3)	0.0724(7)
-	5GeV	0.00599(8)	0.0140(3)	0.00163(3)	0.00391(6)
-	10GeV	2.6(1)E-4	6.3(2)E-4	4.8(1)E-5	1.21(2)E-4
Ω^*_{ccb}	0GeV	0.00151(1)	0.00351(2)	7.24(6)E-4	0.00172(2)
-	5GeV	6.49(5)E-4	0.00152(1)	1.89(1)E-4	4.54(4)E-4
-	10GeV	9.62(7)E-5	2.26(2)E-4	1.95(2)E-5	4.67(5)E-5
Ω_{ccb}	0GeV	4.89(3)E-4	0.00114(1)	2.15(1)E-4	5.09(4)E-4
-	5GeV	2.43(2)E-4	5.67(4)E-4	6.86(5)E-5	1.65(1)E-4
-	10GeV	4.49(4)E-5	1.05(1)E-4	0.894(9)E-5	2.13(2)E-5

Table: Hadronic Production Cross sections (in unit nb) of the triply heavy baryons at LHC with $\sqrt{s} = 14.0$ TeV. There typical P_T cuts are adopted. For the pseudo-rapidity cut, we take $|\eta| < 2.5$ for CMS and ATLAS, and $1.9 < \eta < 4.9$ for LHCb.

-	-	LHC (CMS, ATLAS)		LHCb	
-	η_{cut} / P_{Tcut}	$\lvert\eta\rvert < 2.5$		$1.9 < \eta < 4.9$	
Q	-	μ_R	$\mu_R/2$	μ_R	$\mu_R/2$
Ω_{ccc}	0GeV	0.113(1)	0.216(3)	0.0684(6)	0.135(2)
-	5GeV	0.0123(2)	0.0258(5)	0.00412(8)	0.00906(9)
-	10GeV	0.000625(9)	0.00136(2)	0.000145(5)	0.000349(6)
Ω^*_{ccb}	0GeV	0.00320(2)	0.00677(5)	0.00175(2)	0.00378(3)
-	5GeV	0.00143(1)	0.00307(3)	0.000521(4)	0.00114(1)
-	10GeV	2.34(2)E-4	5.03(5)E-4	0.625(7)E-4	1.38(2)E-4
Ω_{ccb}	0GeV	0.00105(1)	0.00222(2)	0.000527(3)	0.00115(1)
-	5GeV	0.000544(5)	0.00117(1)	0.000190(1)	0.000419(3)
-	10GeV	0.000109(1)	0.000236(2)	0.289(4)E-4	0.639(8)E-4

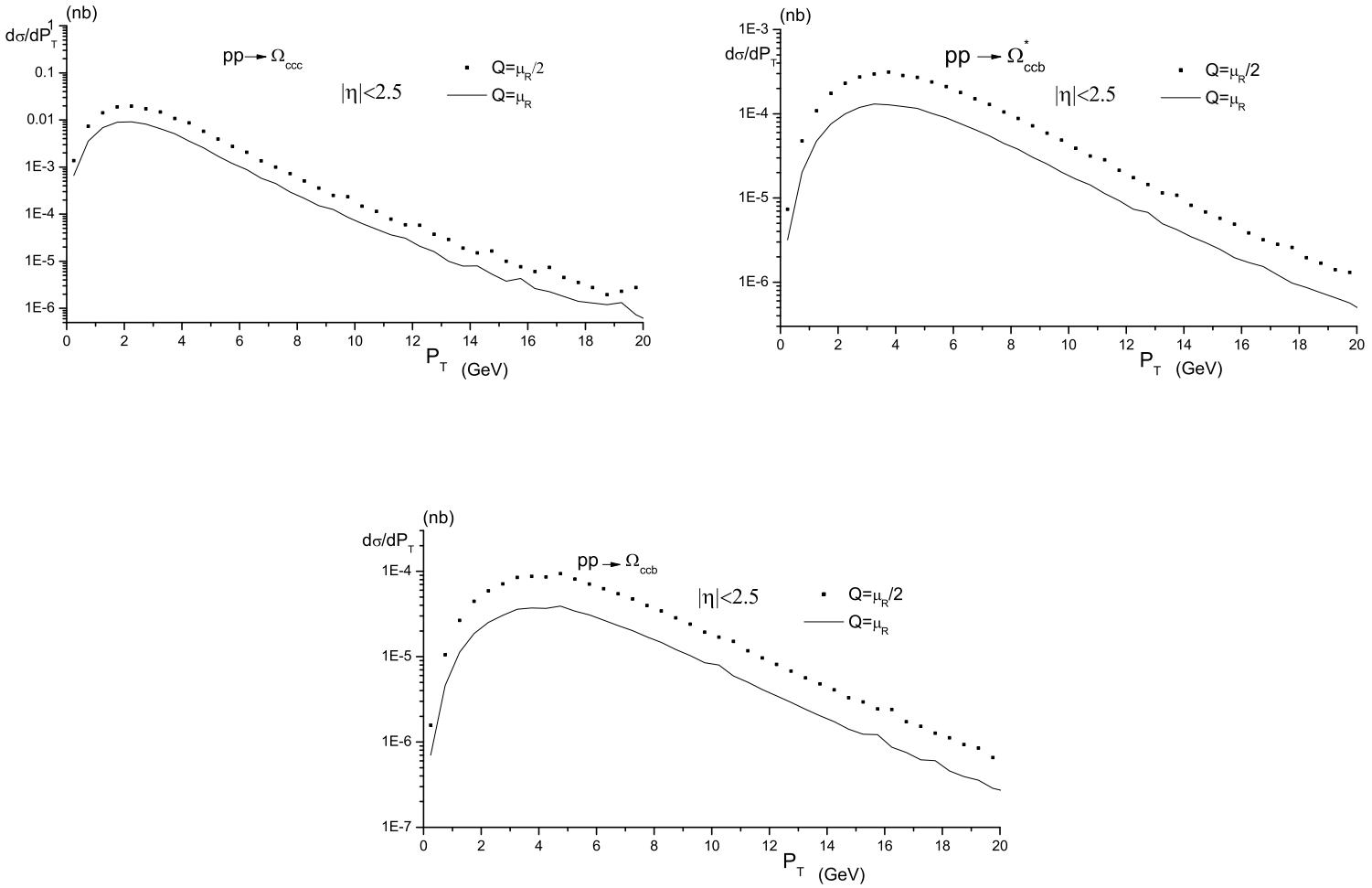


Figure: The P_T-distributions of the production cross sections of the baryons with three heavy quarks in CMS and ATLAS at $\sqrt{s}$=7 TeV.

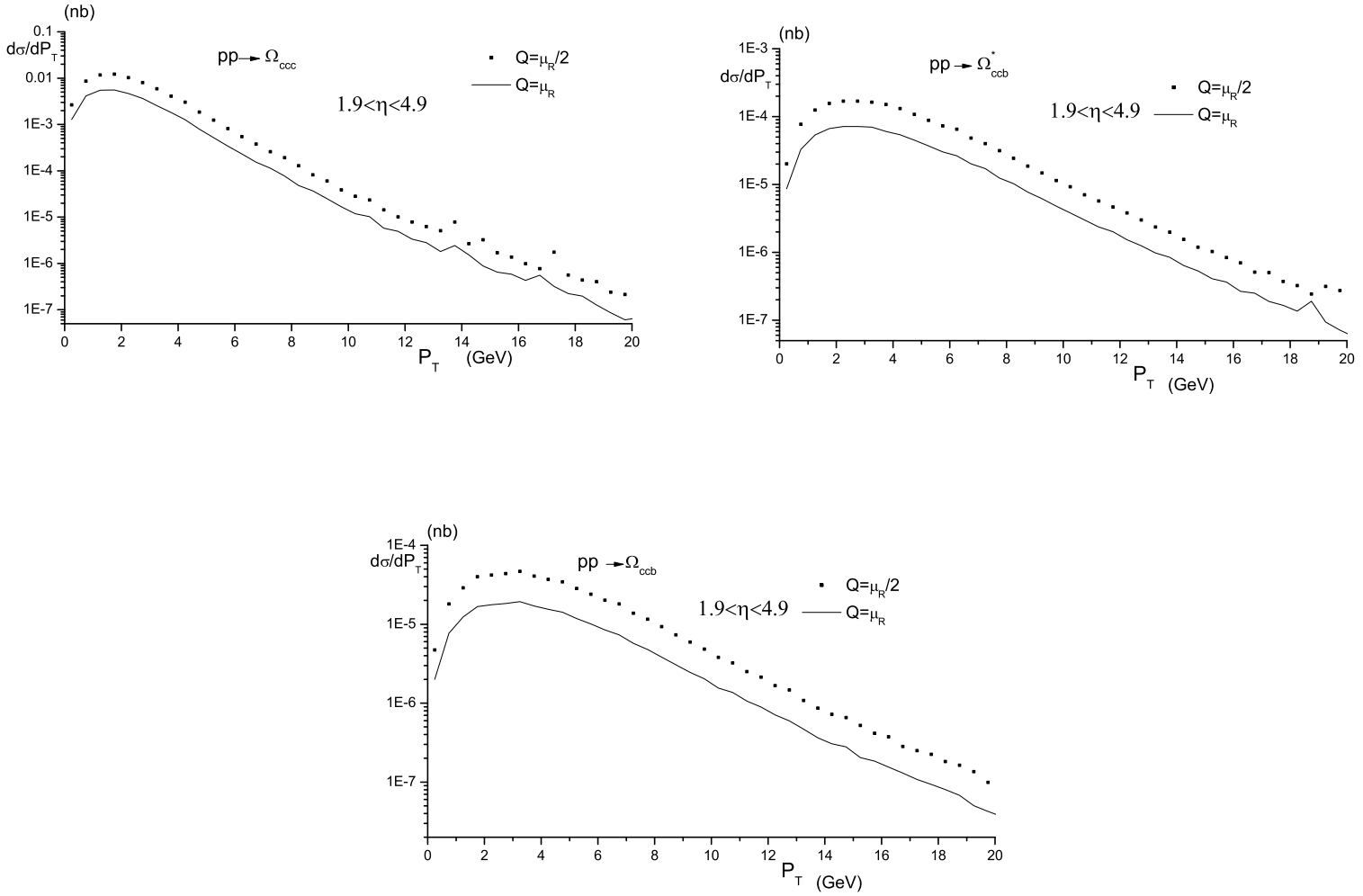


Figure: The P_T-distributions of the production cross sections of the baryons with three heavy quarks in LHCb at $\sqrt{s}$=7 TeV.

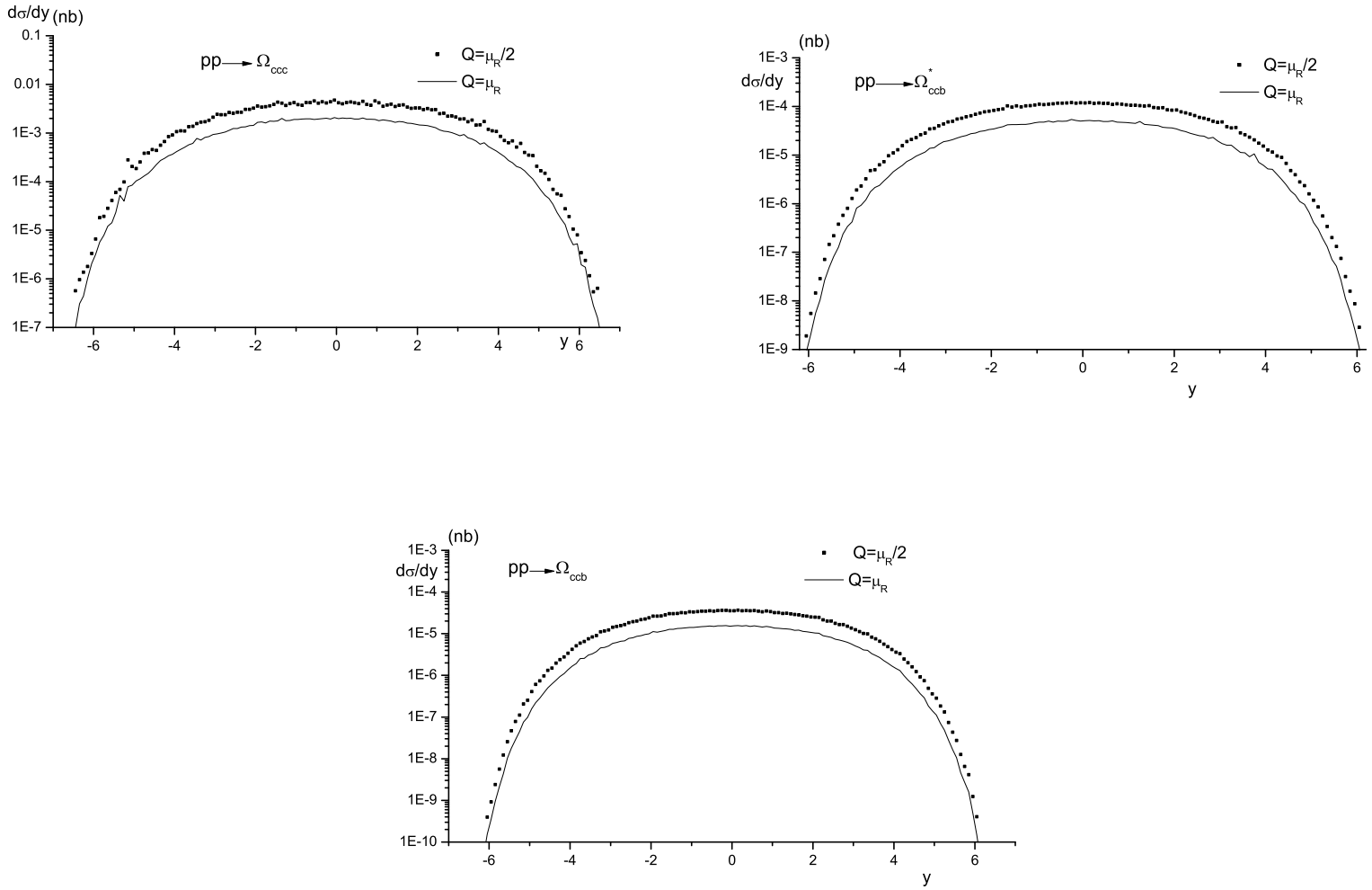


Figure: The y-distributions of the production cross sections of the baryons with three heavy quarks at LHC, with $\sqrt{s}$=7 TeV.

Table: The events with a luminosity of $L \sim 2 \times 10^{32} cm^{-2} s^{-1}$ and $P_T > 5$ GeV in unit (year^{-1}).

$\sqrt{s}$(TeV)	baryon	CMS, ATLAS		LHCb	
	-	$Q = \mu_R$	$Q = \mu_R/2$	$Q = \mu_R$	$Q = \mu_R/2$
7	Ω_{ccc}	$3.6 \cdot 10^4$	$8.4 \cdot 10^4$	$9.8 \cdot 10^3$	$2.3 \cdot 10^4$
	Ω^*_{ccb}	$3.9 \cdot 10^3$	$9.1 \cdot 10^3$	$1.1 \cdot 10^3$	$2.7 \cdot 10^3$
	Ω_{ccb}	$1.5 \cdot 10^3$	$3.4 \cdot 10^3$	412	990

Table: The events with a luminosity of $L \sim 1 \times 10^{34} cm^{-2} s^{-1}$, and with $P_T > 5$ GeV in LHCb and $P_T > 10$ GeV in in ATLAS and CMS. (year^{-1})

$\sqrt{s}$(TeV)	baryon	CMS, ATLAS		LHCb	
	-	$Q = \mu_R$	$Q = \mu_R/2$	$Q = \mu_R$	$Q = \mu_R/2$
14	Ω_{ccc}	$1.8 \cdot 10^5$	$4.2 \cdot 10^5$	$1.2 \cdot 10^6$	$2.8 \cdot 10^6$
	Ω^*_{ccb}	$7.0 \cdot 10^4$	$1.5 \cdot 10^5$	$1.6 \cdot 10^5$	$3.3 \cdot 10^5$
	Ω_{ccb}	$3.3 \cdot 10^4$	$7.1 \cdot 10^4$	$5.7 \cdot 10^4$	$1.3 \cdot 10^5$

2.1 Production of six free heavy quarks

.Feynman diagrams

727: three pairs quarks with different flavors:

$$gg \to c\bar{c}b\bar{b}t\bar{t}$$

1454: two of the final three quarks with the same flavor,

eg. $gg \to c\bar{c}c\bar{c}b\bar{b}$

4362: three quarks with the same flavor,

eg. $gg \to c\bar{c}c\bar{c}c\bar{c}$

.there are 72 independent color factors

.a more integer, 'L', is asked to produce and describe the Feynman diagrams

.the integral dimensions of phase space are much more

running time:

$pp \to c\bar{c}c\bar{c}c\bar{c} + X$: event: 12800, time: 4 s , computer: 128-core

(Madgraph: $pp \to l^+l^-jjjj$, 10000, MG4: 7:16 h, MG5: 2:45 h)
(In MG: $p, j = g/u/\bar{u}/d/\bar{d}/s/\bar{s}/c/\bar{c}$)

Table: Hadronic Production Cross sections (in unit nb) of three pairs of free quarks at LHC with $\sqrt{s} = 7.0$ TeV. Some typical P_T cuts are adopted. As for the pseudo-rapidity cut, we take $|\eta| < 2.5$

final states \ P_{Tcut}	0 GeV	5 GeV	10 GeV
$c\bar{c}c\bar{c}b\bar{b}$	15.9(1)	1.23(2)	0.121(3)
$c\bar{c}b\bar{b}b\bar{b}$	2.56(3)	0.488(9)	0.066(1)
$c\bar{c}c\bar{c}c\bar{c}$	40.4(4)	1.02(3)	0.071(2)
$b\bar{b}b\bar{b}b\bar{b}$	0.154(1)	0.0622(7)	0.0122(2)

Table: Hadronic Production Cross sections (in unit nb) of three pairs of free quarks at LHC with $\sqrt{s} = 14.0$ TeV. Some typical P_T cuts are adopted. As for the pseudo-rapidity cut, we take $|\eta| < 2.5$

final states \ P_{Tcut}	0 GeV	5 GeV	10 GeV
$c\bar{c}c\bar{c}b\bar{b}$	32.0(2)	3.27(7)	0.41(2)
$c\bar{c}b\bar{b}b\bar{b}$	5.87(8)	1.33(4)	0.228(6)
$c\bar{c}c\bar{c}c\bar{c}$	69.28)	2.60(8)	0.225(8)
$b\bar{b}b\bar{b}b\bar{b}$	0.401(3)	0.183(3)	0.0417(7)

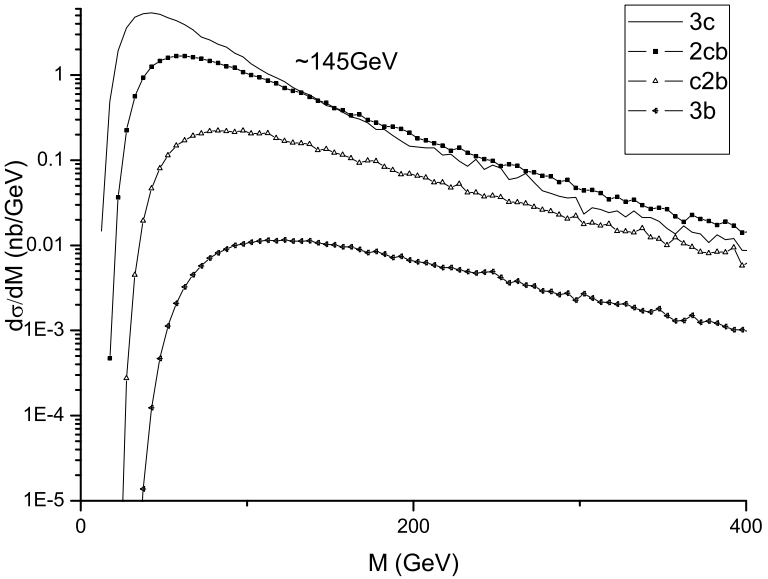


Figure: The differential cross sections, with M being the invariant mass of the final states and $\sqrt{s}$=14 TeV.

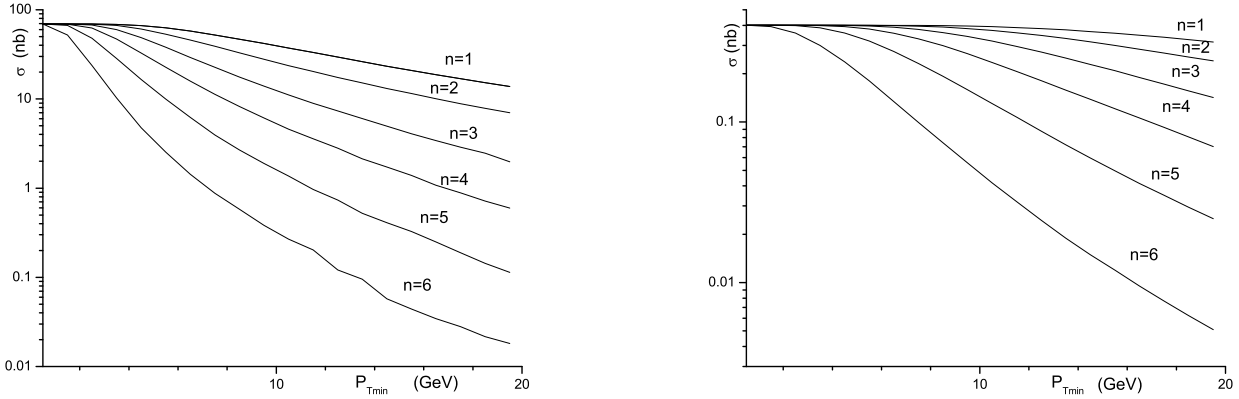


Figure: 1:$gg \to c\bar{c}c\bar{c}c\bar{c}$ and 2:$gg \to b\bar{b}b\bar{b}b\bar{b}$, with n being the number of final particles who has $P_T > P_{Tmin}$, and with $\sqrt{s}$=14 TeV.

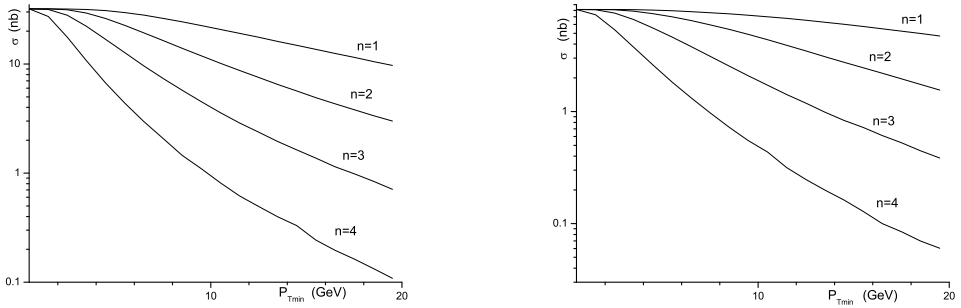


Figure: $gg \to c\bar{c}c\bar{c}b\bar{b}$,with n being the number of four $c(\bar{c})$ quarks who has $P_T > P_{Tmin}$ and no cut for two b quarks in first fig and both b quarks $P_T > 10$ GeV in the second fig, and with $\sqrt{s}$=14 TeV.

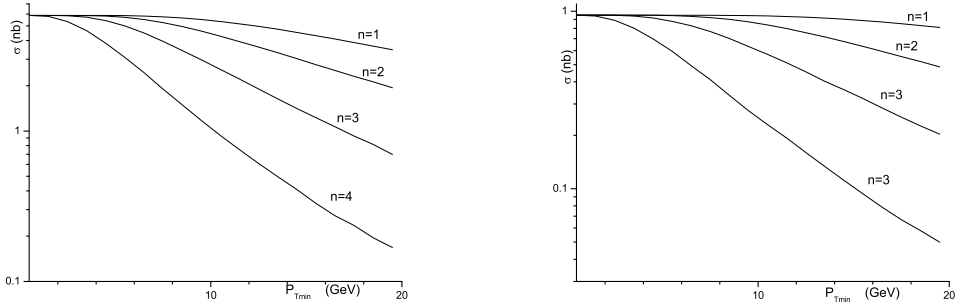


Figure: $gg \to c\bar{c}b\bar{b}b\bar{b}$,with n being the number of four $b(\bar{b})$ quarks who has $P_T > P_{Tmin}$ and no cut for two c quarks in first fig and both c quarks $P_T > 10$ GeV in the second fig, and with $\sqrt{s}$=14 TeV.

Thanks!