Production of triply heavy baryons at LHC

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ITP, CAS , Oct. 2011

Ω_{QQQ}

- bound state of three heavy quarks predicted by QCD
- difficult to produce in experiments, only available at LHC
- perturbative QCD calculation is quite nontrivial
  hadronic production
  lead order: α_s^6 (more than 4000 Feynman diagrams)
- numerical calculations finished, a number of events at LHC
  10^4-10^5 for 10 fb^{-1} integrated luminosity
  promising to discovery it at LHC!

JHEP , Volume 2011, Number 8, 144
Yu-Qi Chen & Su-Zhi Wu

Why do we study Ω_{QQQ} ?

- enrich content of heavy hadron physics
- understanding three-body static potential and confinement
- in both large N_c and heavy limit, mean field approximation, wavefunction can be gained by solving an ordinary differential equation (E. Witten)
- weak decay features of the ground state are very interesting
  identical Fermion in the initial state , large recoil effects , spectator mechanism doesn't work

What is Ω_{QQQ} ?

- Nonrelativistic bound state of three heavy quarks

Three distinct energy scales:

$$m \quad >> \quad mv \quad >> \quad mv^2$$

mass   3-mom   energy

Size: $1/(mv)$

What is Ω_{QQQ} ?

- Nonrelativistic bound state of three heavy quarks

Three energy distinct energy scales:

$m \gg mv \gg mv^2$

mass 3-mom energy

Size: $1/(mv)$

- color-singlet state

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

- flavor and spin

flavor ccc ccb bbb

Ω_{ccc} , Ω_{bbb} 3/2 spin symmetric

Ω_{ccb} , Ω_{bbc} 3/2 spin symmetric

1/2

Production mechanism

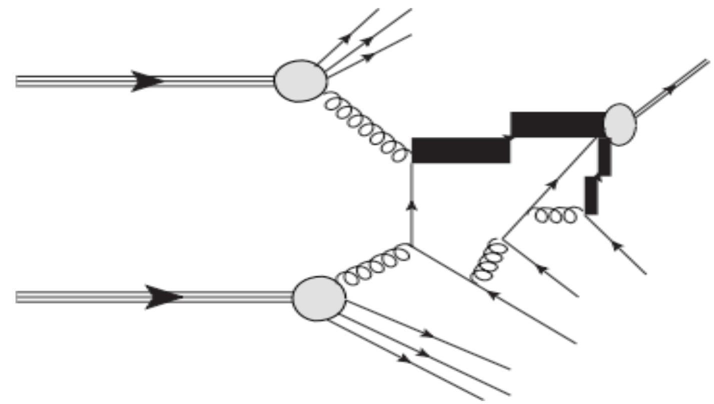
Difficult to produce

At high energy colliders, triply heavy quark antiquark can be produced first at distance scale 1/m or shorter, followed by the formation of the triply heavy baryons via combining three heavy quarks (antiquarks) at distance scale 1/(mv).

In hadronic collision,

g – g fusion subprocess,

$$gg \to \underbrace{Q_1Q_2Q_3}_{\Omega_{Q_1Q_2Q_3}}\overline{Q}_1\overline{Q}_2\overline{Q}_3$$



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

In e+e- collision,

$$e^+e^- \to \gamma^*(Z^{0*}) \to Q_1Q_2Q_3\underbrace{\overline{Q}_1\overline{Q}_2\overline{Q}_3}_{\Omega_{Q_1Q_2Q_3}}$$

NRQCD effective theory is valid not only for $Q\overline{Q}$ system, but also for the QQQ triply heavy baryon system. The cross section can be factored into the product of the short-distance coefficient and long-distance matrix element

The calculation of the short-distance coefficient is very complicated because of a large number of Feynman diagrams

Previous approximation calculation work on the production

S. P. Baranov etal , (2004). $e^{+}e^{-} \to \Omega_{Q_1Q_2Q_3}\,\overline{Q}_1\overline{Q}_2\overline{Q}_3$

The cross section turns out to be very small

In calculation, they neglected the mass terms in the numerator of the quark propagator. The approximation significantly simplifies the calculations. However, it will lead to quite large errors (the same order contributions).

Hadronic production (fragmentation approximation)
Model calculation not from QCD

Saleev (1999)

calculated the fragmentation function in the diquark model by treating two of the three heavy quarks as a point-like diquark.

It is inappropriate

1. two heavy quarks can be treated as a point-like diquark particle only when the momenta of the gluons

$$q \ll mv$$

But in the process $q \sim m$, the above condition does not satisfied

2. the produced two free heavy quarks are enforced moving in the same direction. It is not true

Gomshi Nobary *etal*

Perturbative QCD

1. Feynman gauge
2. only 2 of the seven diagrams are contained

Even with correct fragmentation function, the fragmentation approxiamtion is inappropriate, it requires Pt>> M,
the production rate dominated by the region PT ~ M

Our work: calculating contributions from all diagrams
in order of α_s^6

For gg subprocess, over 4000 diagrams

Conventional method

- Helicity amplitude method   not effecient   too many diagrams
- MHV method   not available $m_Q \neq 0$
- recursive relation   not available   some diagrams contain double pole

Direct amplitude method (Barger, Stange , & Phillips, 1991)

- Given the momenta and quantum numbers in the initial states and final states,
- Calculating amplitude of diagrams directly by multiplying matrixes (or tensors)

It is good for process with small number diagrams
Not efficient for the gluon fusion subprocess with more than 4000 diagrams

Chang & Chen (1993) applied it to calculate production of B_c

Solving the problem by incorporating

- automatic creating diagrams,
- mapping each diagram by a set of integer number,
- the direct amplitude method

refer to it as automatic direct amplitude method

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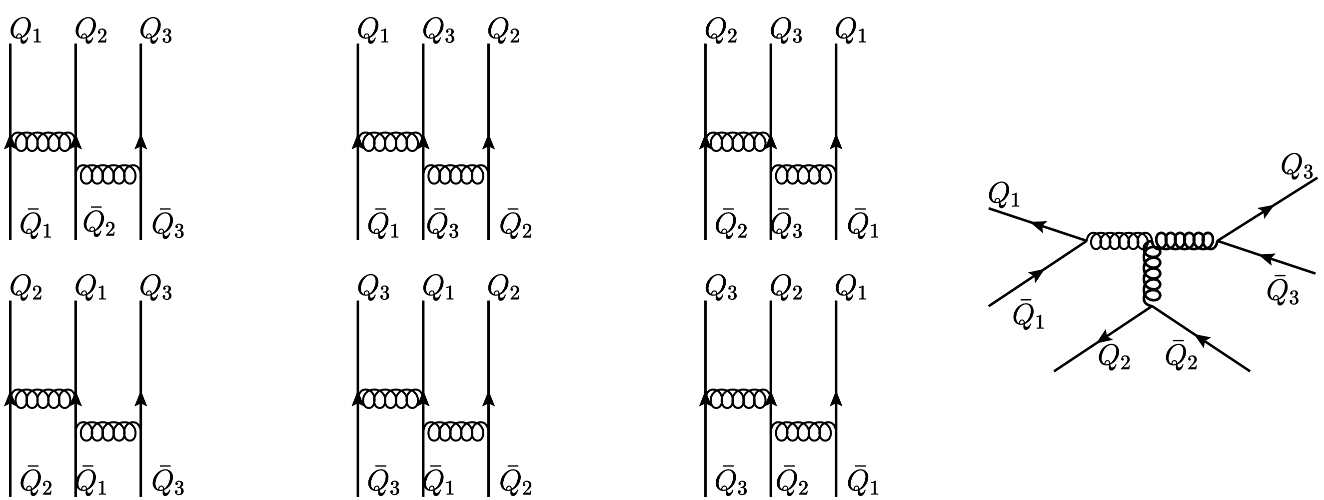
Generating Feynman diagram for $gg \to Q_1Q_2Q_3\overline{Q}_1\overline{Q}_2\overline{Q}_3$

Removing external two gluon lines, all diagrams reduce to 7 basic diagrams



For 2 identical quarks, 7×2!=14 basic diagrams

For 3 identical quarks, 7×3!=42 basic diagrams

It implies that all diagrams can be recovered by inserting two gluon lines one by one in all possible way in these basic diagrams.

2 classes : class 1 without 4-gluon vertex , class 2 with one 4-gluon vertex

Class 1:
Generated by inserting the external gluon lines in between the gluon or quark lines of the basic diagrams one by one.

basic diagrams	3 internal + 6 external lines.
1st gluon insertion	9 possible insertions
Basic diagrams + 1 gluon insertion	4 internal + 7 external lines
2nd gluon insertion	11 possible

Class 1: $7\times 9 \times 11=693$ diagrams

Class 2:

2 ways , (1) one gluon inserting into the 7th basic diagram ,
the other one inserting into other positions 19
(2) two gluon inserting into the gluon internal 15

Class 2: 34

Total numbers (class1+class 2) $693 + 34 =727$ diagrams

For the baryon with 2 identcal quarks $727 \times 2! = 1432$ diagrams
For the baryon with 3 identcal quarks $727 \times 3! = 4362$ diagrams

Coding the programs

Given the quantum numbers and momenta of the initial and final States, Feynman diagram is just the product of the matrices to a numerical number against Fermion lines.

(1)assigned to an integer number to propagators or vertexes
(2)Maping each diagram to a set of ordered number
(3)Automatic calculation by Incorporating with the Direct Amplitude Method

The color factor is complicated, but straightforward
12 independent color factors

To ensure the correctness of the code, we examine all possible gauge invariance by substituting the polarization vector into the momentum of the gluon.

Comparison with MadGraph 5 (2011 June)

Our method	Madgraph 5
$gg \to Q_1 Q_2 Q_3 \overline{Q}_1 \overline{Q}_2 \overline{Q}_3$	$gg \to q_1 q_2 \overline{q}_1 \overline{q}_2 l \bar{l}$
massive	massless
10^6 events	10^4 events
1 hour	2.5 hour
CPU 2.7 GHZ Single core	CPU 2.5 GHZ 128 Core

Numerical predictions

Parameter used in the calculations

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 ccc

$|\Psi(0,0)|^2$=0.00746 GeV^6 for bcc

Factorization Energy scale

$$Q = \mu_R, \frac{\mu_R}{2}, \quad \mu_R{}^2 = m^2 + P_T^2$$

Hadronic production cross section at LHC with $\sqrt{s}$ = 7.0 TeV. Some typical PT cuts are adopted. As for the pseudo-rapidity cut, we take $|\eta| < 2.5$ for CMS and ATLAS, and $1.9 < \eta < 4.$ for LHCb

-	-	LHC (CMS, ATLAS)		LHCb	
-	ηcut PT cut	$\lvert\eta\rvert < 2.5$		$1.9 < \eta < 4.9$	
Q	-	μR	μR /2	μR	μR /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

Hadronic production cross section at LHC with $\sqrt{s}$ = 14.0 TeV with typical P_T pseudo-rapidity cut, we take $|\eta| < 2.5$ for CMS and ATLAS, and $1.9 < \eta < 4.$ for LHCb

-	-	LHC (CMS, ATLAS)		LHCb	
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Q	-	μR	μR /2	μR	μR /2
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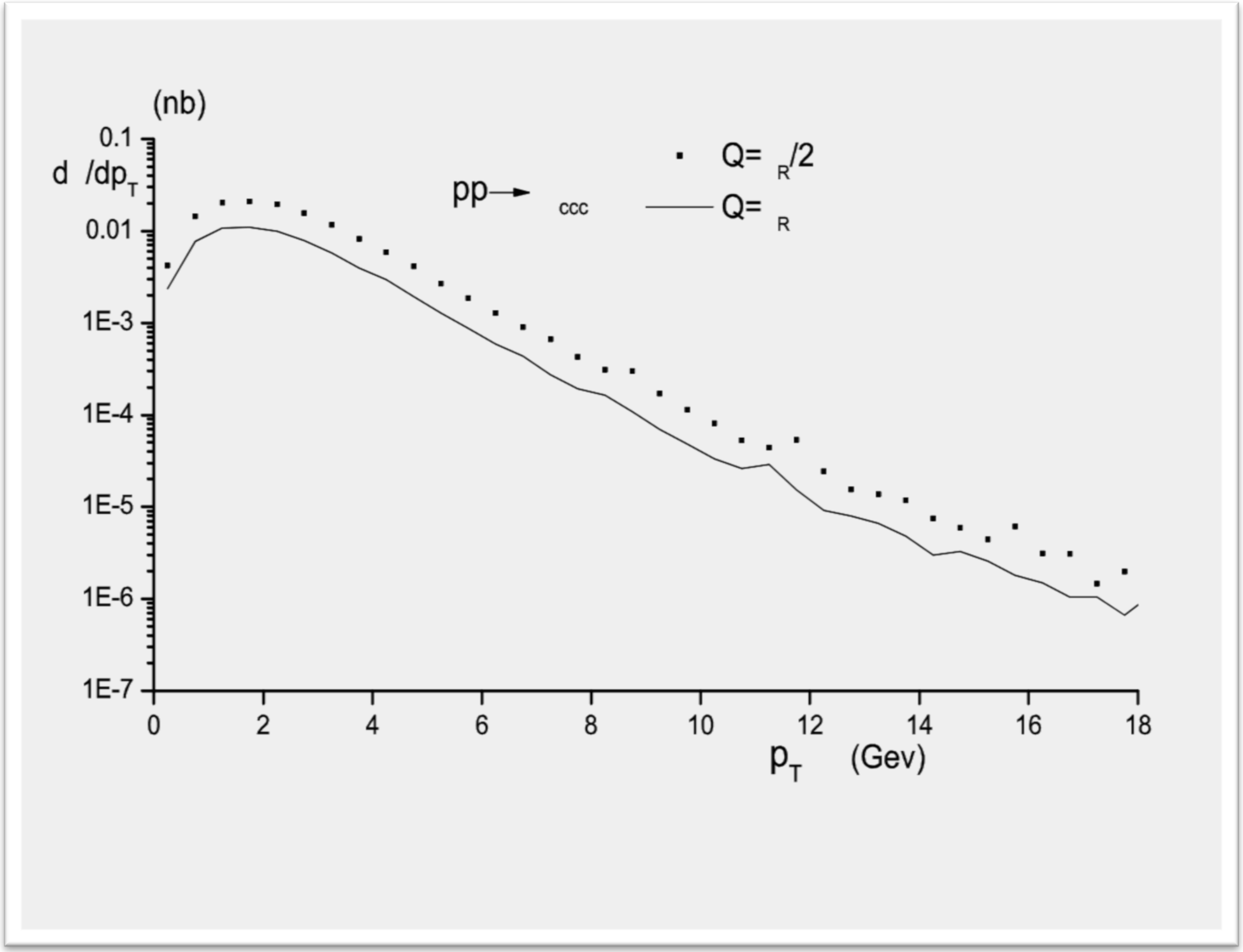
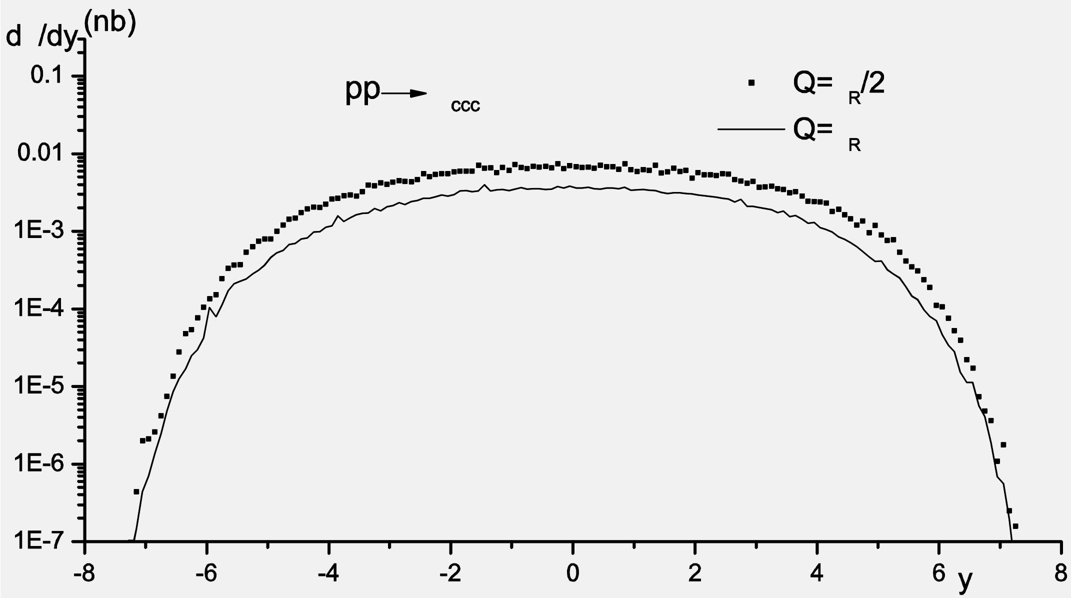
The events with a luminosity of $L \sim 2 \times 10^{32} cm^{-2} s^{-1}$ and $PT > 5$ GeV in unit ($year^{-1}$).

√s(TeV)	baryon	CMS, ATLAS		LHCb	
	-	Q = μR	Q = μR/2	Q = μR	Q = μR /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

The events number with a luminosity of L ~ 1 × $10^{34}cm^{-2}s^{-1}$ and PT > 10 GeV for ALTAS and CMS and PT > 10 GeV for LHCb in unit ($year^{-1}$).

$\sqrt{s}$(TeV)	baryon	CMS, ATLAS		LHCb	
	-	$Q = \mu_R$	$Q = \mu_R/2$	$Q = \mu_R$	$Q = \mu_R/2$
14	Ω_{ccc}	$1.8\cdot10^5$	$4.2\cdot10^5$	$1.2\cdot10^6$	$2.8\cdot10^6$
	Ω^*_{ccb}	$7.0\cdot10^4$	$1.5\cdot10^5$	$1.6\cdot10^5$	$3.3\cdot10^5$
	Ω_{ccb}	$3.3\cdot10^4$	$7.1\cdot10^4$	$5.7\cdot10^4$	$1.3\cdot10^5$

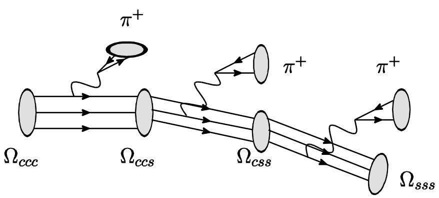

(nb)
d /dp_T
0.1
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
pp ccc
Q= R/2
Q= R
0
2
4
6
8
10
12
14
16
18
p_T (Gev)



d /dy (nb)
0.1
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
pp ccc
Q= R/2
Q= R
-8
-6
-4
-2
0
2
4
6
8
y

Signatures

.Nonleptonic decays

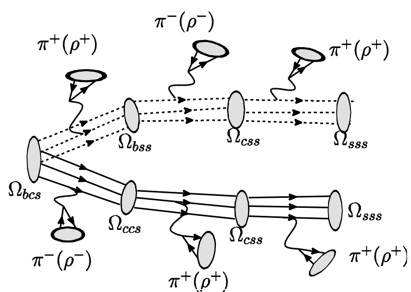


$$
\begin{array}{rl}
\Omega_{ccc} & \\
\downarrow & \\
\Omega_{ccs} & +\ \pi^+\ (\rho^+) \\
\downarrow & \\
\Omega_{css} & +\ \pi^+\ (\rho^+) \\
\downarrow & \\
\Omega_{sss} & +\ \pi^+\ (\rho^+) \\
\hline
\Omega_{ccc} \to \Omega_{sss} & +3\ \pi^+(\rho^+)
\end{array}
$$

Signatures

- $\Omega^*_{ccb} \to \Omega_{ccb}\gamma$

- 1. $\Omega_{ccb} \to \Omega_{ccc} + \pi^-$
- 2. $\Omega_{ccb} \to \Omega_{bcs} + \pi^+$



$$
\begin{array}{ccccc}
 & & \Omega_{ccb} & & \\
 & \swarrow & & \searrow & \\
\Omega_{bcs} + \pi^+ & & & & \Omega_{ccc} + \pi^- \\
\swarrow \quad \searrow & & & & \downarrow \\
\Omega_{bss} + \pi^+ & & \Omega_{ccs} + \pi^- & & \Omega_{ccs} + \pi^+ \\
\downarrow & & \downarrow & & \downarrow \\
\Omega_{css} + \pi^- & & \Omega_{css} + \pi^+ & & \Omega_{css} + \pi^+ \\
\downarrow & & \downarrow & & \downarrow \\
\Omega_{sss} + \pi^+ & & \Omega_{sss} + \pi^+ & & \Omega_{sss} + \pi^+
\end{array}
$$

$$\Omega_{bcc} \to \Omega_{sss} + 3\pi^+ + \pi^-$$

Signatures

.Semileptonic decays

$$
\begin{array}{l}
\Omega_{ccc} \\
\downarrow \\
\Omega_{ccs} + l^{+} + \nu_l \\
\downarrow \\
\Omega_{css} + l^{+} + \nu_l \\
\downarrow \\
\Omega_{sss} + l^{+} + \nu_l \\
\hline
\Omega_{ccc} \to \Omega_{sss} + 3\,l^{+} + 3\,\nu_l,
\end{array}
$$

$$
\begin{array}{cccc}
 & & \Omega_{bcc} & \\
 & \swarrow & & \searrow \\
 & \Omega_{bcs} + l^{+}\nu_l & & \Omega_{ccc} + l^{-}\bar{\nu}_l \\
\swarrow & \searrow & & \downarrow \\
\Omega_{bss} + l^{+}\nu_l & \Omega_{ccs} & + l^{-}\bar{\nu}_l & \Omega_{ccs} + l^{+}\nu_l \\
\downarrow & \downarrow & & \downarrow \\
\Omega_{css} + l^{-}\bar{\nu}_l & \Omega_{css} & + l^{+}\nu_l & \Omega_{css} + l^{+}\nu_l \\
\downarrow & \downarrow & & \downarrow \\
\Omega_{sss} + l^{+}\nu_l & \Omega_{sss} & + l^{+}\nu_l & \Omega_{sss} + l^{+}\nu_l \\
\hline
\multicolumn{4}{l}{\Omega_{bcc} \to \Omega_{sss} + 3l^{+} + l^{-} + 3\nu_l + \bar{\nu}_l}
\end{array}
$$

Conclusion and Summary

- We calculate contributions from all diagrams in order of α_s^6
  For gg subprocess, over 4000 diagrams

- We propose an automatic direct amplitude method Solving the problem
  The method incorporates automatic creatinging diagrams with the direct amplitude method. It turns out to be very efficient in calculating amplitude of complicated process at tree level.

A number of events of triply heavy baryons can be produced at LHC. 10^4-10^5 for 10 fb^{-1} integrated luminosity

it is quite promising to discover those triply heavy baryons in LHC experiments both for large number events and for their unique signatures in detectors.