

Triply Heavy Baryons

M.A. Gomshi Nobary

Department of Physics, Faculty of Science, Razi University, Kermanshah, Iran.

R. Sepahvand

Department of Physics, Faculty of Science, Lorestan University, Khoramabad, Iran.

The triply heavy baryons are very different in their mass. They are essentially Ω_{ccc} , Ω_{ccb} , Ω_{cbb} and Ω_{bbb} baryons which may be produced in a c or a b quark fragmentation. Here we briefly review the direct fragmentation production of these states and choose Ω_{ccc} and Ω_{bbb} baryons as prototype of them to consider their production at the hadron colliders with different \sqrt{s} . It becomes clear that their production cross sections fall within a rather diverse range according to \sqrt{s} , minimum transverse momentum and rapidity. We present and compare transverse momentum distributions of the differential cross sections, p_T^{min} distributions of total cross sections and the integrated total cross sections for all triply heavy baryons at CERN LHC and similar quantities for Ω_{ccc} and Ω_{bbb} at RHIC, Tevatron Run II and the CERN LHC. While some of them possess considerable event rates even at RHIC proton-proton collider, others need much more energetic hadron collider with appropriate kinematical cuts to be produced.

I. INTRODUCTION

Heavy hadrons have always been interesting. Recently significant progress have been made in understanding their production and decay and wherever light quarks are absent, they are nicely treated within the framework of effective field theory and perturbative QCD. Much insights have been revealed about states such as B_c , J/ψ and Υ in due course. Recently heavy baryons have also been focus of attention.

Heavy baryons are well distinguished according to the number of heavy quarks involved in their formation. Essentially they are Λ_Q 's, $\Xi_{QQ'}$'s and $\Omega_{QQ'Q''}$'s each group with special properties [1]. Although Λ_Q 's and $\Xi_{QQ'}$'s have been studied widely both in theory and in experiment, the triply heavy baryons, $\Omega_{QQ'Q''}$'s have received little attention. They are the heaviest composite states predicted by the constituent quark model, and are the last generation of the baryons within the standard model.

Since top quark does not materialize into hadrons [2], only c and b quarks take part in formation of these baryons. Therefore the possible triply heavy baryons would be Ω_{ccc} , Ω_{ccb} , Ω_{cbb} and Ω_{bbb} baryons in a c or a b quark fragmentation.

It is established that Heavy hadrons need to be produced at hadron colliders with sizable cross sections and that their cross sections is very small in e^+e^- colliders [3]. Therefore the fragmentation production of triply heavy baryons need to be studied in various existing and future $\bar{p}p$ and pp colliders.

In this work we review the fragmentation production of triply heavy baryons and have chosen mainly to emphasis on the production of the lightest (Ω_{ccc}) and the heaviest (Ω_{bbb}) as prototype them at RHIC, Tevatron Run II and the CERN LHC colliders.

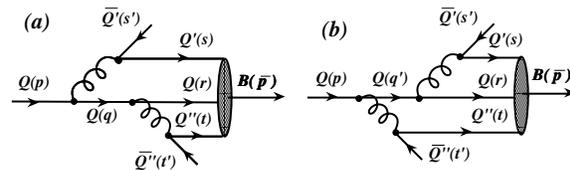


FIG. 1: The lowest order Feynman diagrams contributing to the fragmentation of a heavy quark (Q) into a triply heavy baryon (B). The four momenta are labelled.

II. FRAGMENTATION

To evaluate the cross section of triply heavy baryons in hadron colliders, we need their fragmentation functions. Here we have used the established fact that the fragmentation process in production of heavy hadrons could be understood in terms of perturbative QCD [4]. At sufficiently large transverse momenta, the dominant production mechanism is actually the fragmentation. Fig. 1 shows the fragmentation of a heavy quark Q into a triply heavy baryon $B(QQ'Q'')$ in lowest order perturbation theory.

The fragmentation of a quark into a baryon state is

described by fragmentation function $D(z, \mu)$, where z is the longitudinal momentum fraction of the baryon state and μ is the fragmentation scale. The fragmen-

tation function for the production of an S-wave triply heavy baryon B in the fragmentation of a quark Q may be put in the following form [5]

$$D_Q^B(z, \mu) = 32[\pi^2 \alpha_s(2m_{Q'}) \alpha_s(2m_{Q''}) M C_F f_B]^2 \int \frac{\frac{1}{2} \sum \bar{\Gamma} \Gamma \delta^3(\bar{\mathbf{p}} + \mathbf{s}' + \mathbf{t}' - \mathbf{p})}{p_o \bar{p}_o s'_o t'_o (\bar{p}_o + s'_o + t'_o - p_o)^2} d^3 \bar{p} d^3 s' d^3 t'. \quad (1)$$

To obtain the above form we have convoluted the hard scattering amplitude for Fig. 1 with an appropriate wave function for the baryon bound state with decay constant f_B . The α_s 's are appropriate strong coupling constant and C_F is the color factor. In our model we have considered emission of two gluons by the heavy quark Q , each producing a $\bar{Q}Q$ pair. The three heavy quarks thus obtained form the $\Omega_{QQ'Q''}$ bound state leaving the heavy anti-quarks to form the final state jet (See Fig. 1). To set up the kinematics, we have used the fragmentation parameter z defined as usual, i.e.

$$z = \frac{(E + p_{\parallel})_B}{(E + p_{\parallel})_Q}. \quad (2)$$

In an infinite momentum frame, which we have

adopted for our study here, this reduces to the following

$$z = \frac{E_B}{E_Q}. \quad (3)$$

In the above general form for the fragmentation function, three different cases are distinguished from which others could be obtained. They are $D_{c \rightarrow \Omega_{ccb}}(z, \mu)$, $D_{b \rightarrow \Omega_{ccb}}(z, \mu)$ and $D_{Q \rightarrow \Omega_{QQQ}}(z, \mu)$ fragmentation functions. Where Q may assume a c or a b quark. The fragmentation function for $b \rightarrow \Omega_{cbb}$ and $c \rightarrow \Omega_{cbb}$ are obtained with interchange of c and b quarks in the two earlier cases. The details of fragmentation functions for all triply heavy baryons have been described in [5]. For simplicity here we consider only the case for $D_{Q \rightarrow \Omega_{QQQ}}(z, \mu)$. It has the following form [6]

$$D_{Q \rightarrow \Omega_{QQQ}}(z, \mu_o) = \frac{\pi^4 \alpha_s^4 (2m_Q) f_B^2 C_F^2}{108 m^2 z^4 (1-z)^4 f^2(z) g^6(z)} [\xi^8 z^8 + 4\xi^6 z^6 (83 - 130z + 51z^2) + 6\xi^4 z^4 (1413 - 3084z + 3022z^2 - 2156z^3 + 821z^4) + 4\xi^2 z^2 (18711 - 51678z + 69417z^2 - 70308z^3 + 53529z^4 - 25950z^5 + 6343z^6) + 222345 - 740664z + 1179036z^2 - 1253448z^3 + 90126z^4 - 388872z^5 + 109916z^6 - 49912z^7 + 20649z^8], \quad (4)$$

where α_s is the strong interaction coupling constant evaluated at the pairs of vertices of each gluon in the Fig. 1, f_B is the baryon decay constant defined similar to meson decay constant f_M and C_F is the color factor of the baryon state formed in the fragmentation of the heavy quark. Moreover that here we have defined $\xi = \langle k_T^2 \rangle / m^2$ with k_T being the transverse momentum of the initial heavy quark and m is the heavy quark mass. The two functions $f(z)$ and $g(z)$ have the following form

$$f(z) = \frac{-\langle k_T^2 \rangle}{3m^2} + \frac{3}{z} + \frac{4}{3} \left[1 + \frac{\langle k_T^2 \rangle}{4m^2} \right] \frac{1}{1-z},$$

$$g(z) = -\frac{1}{3} + f(z). \quad (5)$$

The function $f(z)$ is the contribution of the energy denominator emerging from the phase space integration and the function $g(z)$ is due to the quark and gluon propagators.

The inputs for the fragmentation function (1) are the quark mass, baryon decay constant and the color factor. We have set $m = m_c = 1.25$ GeV and $m = m_b = 4.25$ GeV. For the decay constant and the color factor we have taken $f_B = 0.25$ GeV and $C_F = 7/6$ for both cases of the Ω_{ccc} and Ω_{bbb} states. We show the behavior of (4) for Ω_{ccc} and Ω_{bbb} fragmentation along with their evolution with different scales in Fig 2. We have also calculated the universal fragmentation probabilities and the average fragmentation parameter, $\langle z \rangle$. They appear in Table I.

TABLE I: The universal fragmentation probabilities (F.P.) and the average fragmentation parameter $\langle z \rangle$ at fragmentation scale for different Ω states in possible a c or a b quark fragmentation.

Process	F.P.	$\langle z \rangle (\mu_o)$
$c \rightarrow \Omega_{ccc}$	2.789×10^{-5}	0.521
$c \rightarrow \Omega_{ccb}$	2.475×10^{-6}	0.490
$b \rightarrow \Omega_{ccb}$	2.183×10^{-4}	0.634
$b \rightarrow \Omega_{bbb}$	6.459×10^{-7}	0.534
$b \rightarrow \Omega_{cbb}$	5.290×10^{-6}	0.562
$c \rightarrow \Omega_{cbb}$	1.086×10^{-7}	0.482

III. INCLUSIVE PRODUCTION

Here we have used the well known factorization scheme to evaluate the cross sections for triply heavy

$$\frac{d\sigma}{dp_T}(pp \rightarrow \Omega_{QQ'Q''}(p_T) + X) = \sum_{i,j} \int dx_1 dx_2 dz f_{i/p}(x_1, \mu) f_{j/p}(x_2, \mu) \times \left[\hat{\sigma}(ij \rightarrow Q(p_T/z) + X, \mu) D_{Q \rightarrow \Omega_{QQ'Q''}}(z, \mu) \right]. \quad (6)$$

TABLE II: The center of momentum energy (\sqrt{s}) and the acceptance cuts for the colliding facilities used in this work. The rapidity is defined as $y = \frac{1}{2} \log \left\{ \frac{E - p_L}{E + p_L} \right\}$.

	RHIC	Tevatron Run II	CERN LHC
\sqrt{s} [GeV]	200	1960	14000
p_T^{cut} [GeV]	2	6	10
$y \leq$	3	1	1

Where $f_{i,j}$ are parton distribution functions with momentum fractions of x_1 and x_2 , $\hat{\sigma}$ is the heavy quark production cross section and $D(z, \mu)$ represents the fragmentation of the produced heavy quark into a triply heavy baryon. We have employed the parameterization due to Martin-Roberts-Stirling (MRS) [7] for parton distribution functions and have included the heavy quark production cross section up to the order of α_s^3 [8]. We have employed this procedure in the case of RHIC, Tevatron Run II and CERN LHC colliders. The kinematical cuts appear in Table II.

baryons. Indeed the idea is to bring about the short distance high energy parton production and the long distance fragmentation process. All this is possible at a scale which is much higher than the scale at which the fragmentation functions are calculable. Therefore the fragmentation functions calculated at fragmentation scale are evolved up to a scale at which the convolution of parton distribution functions, bare cross section of the initiating heavy quark and the fragmentation function is possible. According to this scheme in a particular scale it is possible to write

IV. RESULTS AND DISCUSSION

In summary we have reviewed the fragmentation functions and production of triply heavy baryons with more emphasize on Ω_{ccc} and Ω_{bbb} states and have evaluated their production rates at different hadron colliders. To accomplish this the next leading order results for parton production cross sections are used. The fragmentation functions are calculated in leading order perturbation. They provide reliable fragmentation probabilities for the triply heavy baryons. In evolution of fragmentation functions through the Altarelli-Parisi equation we have included only the $P_{Q \rightarrow Q}$ splitting function.

The universal fragmentation probabilities and the average fragmentation parameters at μ_o are shown in table I. The probabilities at this table suggest that while some of these states would have considerable event rates at existing colliders, others are less probable.

Each collider with detection systems has restrictions about the measurements of the transverse momentum and the rapidity of the particles. The so called acceptance cuts for the colliders considered here appear in Table II.

The behavior of our fragmentation functions along with their evolutions at $\mu = \mu_R/2$ (μ_R), $2\mu_R$ (3μ and

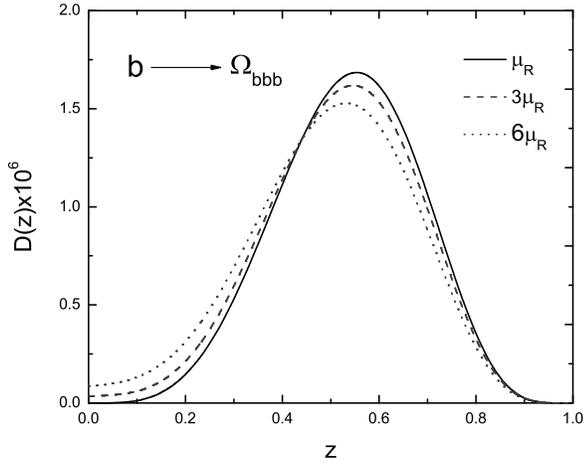
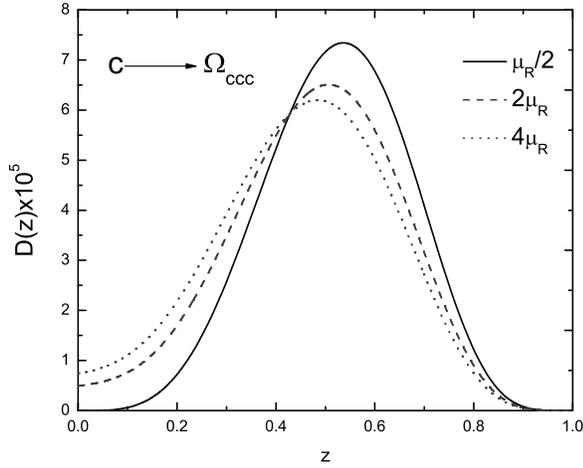


FIG. 2: The behavior of the fragmentation functions for Ω_{ccc} and Ω_{bbb} baryons, along with their evolutions at the scales specified.

$4\mu_R$ (6μ) using the Altarelli-Parisi evolution equation are shown in Fig. 2 for Ω_{ccc} and Ω_{bbb} baryons as examples of triply heavy baryons.

Next we consider the p_T distributions of the differential cross sections at the different hadron colliders for Ω_{ccc} and Ω_{bbb} . They appear in the Figures 3. Obviously the distributions are sensitive with respect to the scale μ . The choices of $\mu = 4\mu_R$ and $\mu = 6\mu_R$ respectively for Ω_{ccc} and Ω_{bbb} are at the regions of the scale with minimum sensitivity. Although the cross section for a given p_T differs up to three orders of magnitude from one collider to the other, they are still comparable. The difference is seen to grow with increasing p_T . It is more interesting in the case of

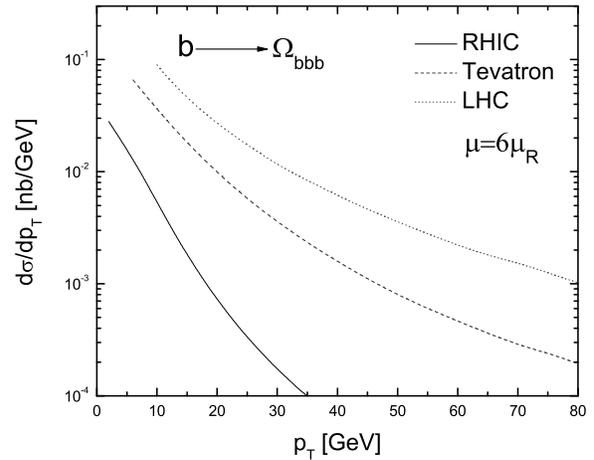
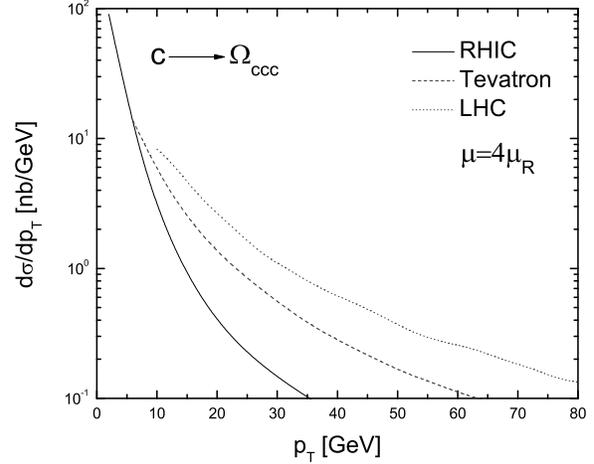


FIG. 3: The p_T distributions of the differential cross sections in nb for Ω_{ccc} and Ω_{bbb} production at RHIC, Tevatron Run II and the CERN LHC hadron colliders at the scale of $\mu = 4\mu_R$ and $\mu = 6\mu_R$ respectively.

Ω_{ccc} where the distributions seem to converge at sufficiently low p_T . Another important feature about these distributions is rather high cross section of Ω_{ccc} which is more striking in the case of RHIC where low p_T 's are available. Figures 4 show the total cross sections for production of Ω_{ccc} and Ω_{bbb} with transverse momentum above a minimum value p_T^{\min} . Note that in the Figures 3 only the range $p_T > p_T^{\min} = p_T^{\text{cut}}$ were considered. It seems that the general features mentioned in the above, holds in the case of p_T^{\min} distributions except for that the difference in the differential cross sections for a given p_T is not that much as in the case of p_T^{\min} distributions. It is also interesting to

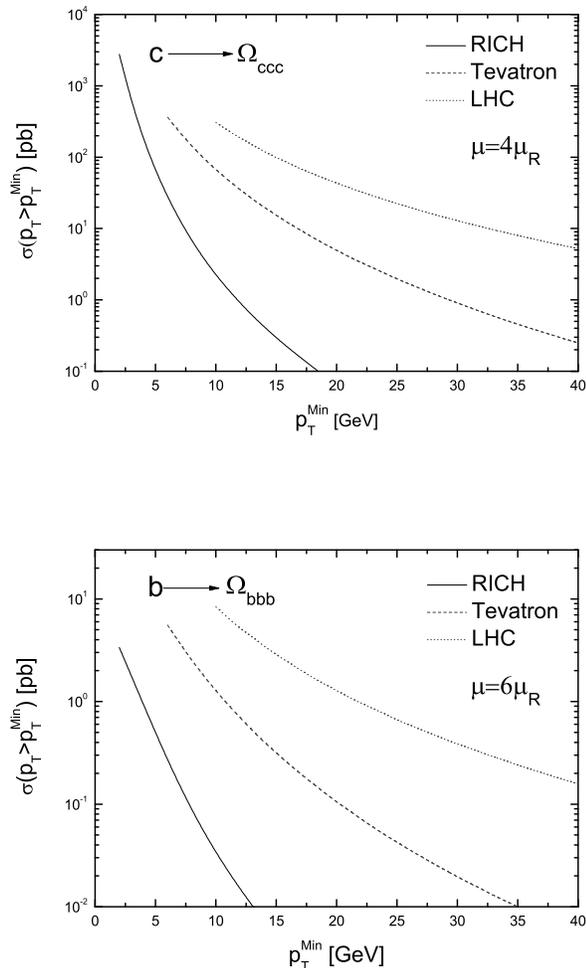


FIG. 4: The p_T^{\min} distribution of the total cross section in pb for Ω_{ccc} and Ω_{bbb} production at the RHIC, Tevatron Run II and the CERN LHC hadron colliders at the scale $\mu = 4\mu_R$ and $\mu = 6\mu_R$ respectively.

note that the fall off of the distributions decrease with increasing \sqrt{s} and also with increasing p_T^{\min} or p_T .

We have also calculated the total cross sections. They appear in Table III for the LHC and Table IV for RHIC, Tevatron Run II and LHC where they are compared with each other. A short look at table III reveals that although the total cross section for some of the triply heavy baryons are small indeed (order of pb) and their production needs energetic hadron colliders, some others such as $b \rightarrow \Omega_{ccb}$ and $c \rightarrow \Omega_{ccc}$ do possess larger cross sections of the order of nb and may easily be produced even at the Tevatron. An interesting point in table II is that although the total cross section for some of the particles such as $c \rightarrow \Omega_{ccb}$ and $c \rightarrow \Omega_{cbb}$ increase with increasing μ , but this is

not the case for the rest. Our investigation shows that this depends on the range of μ selected and also on the choice of p_T^{cut} [9]. Note that in Table IV the cross section for Ω_{bbb} increases with increasing \sqrt{s} . But this is not the case for Ω_{ccc} . Not only the order reverses in this case but the cross section at RHIC is nearly one order of magnitude higher.

A brief look at these tables reveal that the baryons with at least two c or at least two b quarks behave similarly apart from the magnitude of their cross sections. This is the main reason for our choice of Ω_{ccc} and Ω_{bbb} . Therefore we expect that the Ω_{ccb} state produced in c or b quark fragmentation to have similar distributions as Ω_{ccc} . Similarly the Ω_{cbb} state emerging from a c or a b quark will behave as Ω_{bbb} . It is also interesting to note that our chosen states Ω_{ccc} and Ω_{bbb} with fragmentation probabilities of about 2×10^{-5} and 6×10^{-7} are not the states with maximum and minimum fragmentation probabilities. In other words the lightest and heaviest in the case of triply heavy baryons does not mean the states with maximum and minimum fragmentation probabilities. Indeed the fragmentation probabilities for $b \rightarrow \Omega_{ccb}$ and $c \rightarrow \Omega_{cbb}$ possess the maximum and minimum fragmentation probabilities of 2×10^{-4} and 10^{-7} respectively.

We would like at the end discuss the uncertainties of our results. The choice of quark masses will not only alter the fragmentation probabilities, but also the value of μ and values of x at which the parton distribution functions are evaluated. This will of course be reflected on the total cross sections. We have chosen $m_c = 1.25$ GeV and $m_b = 4.25$ GeV which are the optimum values reported. However the slightly higher values of $m_c = 1.5$ GeV and $m_b = 4.7$ GeV are also used in the literature. Changes in quark mass will affect the fragmentation functions. In the scheme of our calculation, the fragmentation functions inversely depend on quark mass squared. Therefore increase in quark mass will decrease the probabilities. The other quantity which may depend on quark mass is the baryon decay constant. However the later is not much clear in the case of triply heavy baryons. Taking the explicit mass dependence of our fragmentation functions, we have obtained 18 percent decrease in the cross sections in average, when we use the above mentioned higher values.

There is no data on the baryon decay constant. Theoretically one may solve the Schrödinger like equation to obtain the wave function at the origin for these composite particles with heavy constituents and then relate the wave function at the origin to the baryon decay constant. We have avoided this procedure because of theoretical uncertainties instead have chosen $f_B = 0.25$ GeV on phenomenological grounds. The final quantity of interest is the color factor. We have calculated this quantity using the simple color line counting rule and have obtained $C_F = 7/6$ for our

TABLE III: Total cross section in pb for triply heavy baryons in possible c and b quark fragmentation at the CERN LHC collider. The various scales are specified.

	$\mu_R/2$	μ_R	$2\mu_R$	$3\mu_R$	$4\mu_R$	$6\mu_R$
$c \rightarrow \Omega_{ccc}$	301.88		306.99		307.59	
$c \rightarrow \Omega_{ccb}$	26.58		30.03		29.88	
$b \rightarrow \Omega_{ccb}$	2153.08		2155.31		1723.80	
$b \rightarrow \Omega_{bbb}$		6.34	6.38	5.77		8.40
$b \rightarrow \Omega_{cbb}$		50.30	34.77	47.78		52.34
$c \rightarrow \Omega_{cbb}$		1.14	1.38	1.47		1.49

TABLE IV: The total cross section in pb for Ω_{ccc} and Ω_{bbb} baryons at different hadron colliders. The acceptance cuts are introduced in Table II.

	RHIC	Tevatron Run II	CERN LHC
$c \rightarrow \Omega_{ccc} (4\mu_R)$	2758.26	382.938	307.598
$b \rightarrow \Omega_{bbb} (6\mu_R)$	3.3499	5.91677	8.40254

propose.

-
- [1] J.C. Anjos *et al*, Phys. Rev. D **56**, 394 (1997); A. Adamov and G.R. Goldstien, Phys. Rev. D **56**, 7381 (1997); ALEPH Collaboration, D. Buskulic *et al*, Phys. Lett. **B 374**, 319 (1996); Fermilab E704 Collaboration, A. Bravar *et al*, Phys. Rev. Lett. **78**, 4003 (1997); M.A. Doncheski *et al*, Phys. Rev. D **53**, 1247 (1996); V.V. Kiselev *et al*, Phys. Rev. D **60**, 014007-1 (1999)
- [2] F. Abe *et al*, Phys. Rev. Lett. **74**, 2626 (1995); S. Abachi *et al*, Phys. Rev. Lett. **74**, 2632 (1995)
- [3] S. P. Baranov, V.L. Slad, Phys. At. Nucl. **67**, 829 (2004)
- [4] E. Braaten *et al*, Phys. Rev. D **48**, 5049 (1993); E. Braaten *et al*, Phys. Rev. D **51**, 4819 (1995); M.A. Gomshi Nobary and T. O'sati, Mod. Phys. Lett. A **15**, 455 (2000)
- [5] M.A. Gomshi Nobary and R. Sepahvand, Phys. Rev. D **48**, 5049 (1993)
- [6] M.A. Gomshi Nobary and R. Sepahvand, Nucl. Phys. B **741** (2006) 34
- [7] A.D. Martin, R.G. Roberts and W.J. Stirling, Phys. Rev. D **50**, 6734 (1994)
- [8] P. Nason, S Dawson and R.K. Ellis, Nucl. Phys. B **303**, 607 (1988); W.Beenakker, H. Kuijff, W.L.Van Neerven and J. Smith, Phys. Rev. D **40**, 54 (1989); W.Beenakker, W.L.Van Neerven, R.Meng, G. Schuler and J. Smith, Nucl. Phys. B **351**, 507 (1991)
- [9] . Cheung and R.J. Oakes, Phys. Rev. D **53**, 1242 (1996)