ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Trieste

INFN/AE-93/15 bis

16 luglio 1993

A. Fridman

PRODUCTION AND DECAY OF THE BEAUTY BARYON

Servizio Documentazione
dei Laboratori Nazionali di Frascati

Production and Decay of the Beauty Baryon

A. Fridman+

Sezione di Trieste, INFN - Area di Ricerca, Trieste, Italy

Contribution to the Frascati Workshop
Heavy Quarks at Fixed Target
Frascati May 31st - June 2nd, 1993

+ LPNHE, Université de Paris VI et VII

Production and Decay of Beauty-Baryon

A. Fridman+
Sezione di Trieste, INFN - Area di Ricerca, Trieste

ABSTRACT

We estimate the beauty-baryon production in pN interactions at c.m. energies relevant to the LHC and SSC projects. The possibilities of searching for the CP violation effects in the beauty baryon are discussed. Measurements of special decay channels are suggested in order to estimate $|V_{ub}/V_{cb}|$ with good precision.

1 - Introduction

Recently, the reasons for studying the beauty baryon produced in pN interactions have been presented[1,2]. Here we will summarize some of these aspects. We will discuss the interest in searching for CP violation in beauty-baryon decay as well as the measurements of some CKM matrix elements. A list of beauty baryons (N_b) with their charge and quark content is given in Table 1. We use the following notation[1]. The baryon with isospin $I = 1$ will be denoted by Σ, whereas Ξ will be used for baryons having $I = 1/2$. For $I = 0$, we use Λ unless each quark forming a baryon has $I = 0$. In this case the notation will be Ω. The subscripts of Σ, Ξ, Λ, and Ω indicate the number and the type of the heavy quarks ($Q \equiv b, c$) contained in the considered baryon (the light quarks are represented by $q \equiv u, d, s$). The masses given in the table are those used in the PYTHIA Monte Carlo program[3].

We estimate the $N_b = bq_1q_2$ production cross-section, $\sigma(bq_1q_2)$, from the ratio $R = \sigma(bq_1q_2)/\sigma(b\bar{b})$ calculated with PYTHIA at the c.m. energies of $\sqrt{s} =$ 0.12, 0.19, 16 and 40 TeV, corresponding to the LHC and SSC projects (beam fixed-target and collider experiments). Here $\sigma(b\bar{b})$ is the $pN \to b\bar{b}X$ cross-section (X meaning anything) at the corresponding c.m. energy. Using the $\sigma(b\bar{b})$ cross-sections[4] given in Table 2, we obtain the cross-sections indicated[5] by Table 3.

Estimates of $\sigma(bcq)$ are based on the fact that the momentum of the light quark will be negligible with respect to the momentum of the b or c quark. The kinematics as well as the QCD interactions in the final state will thus depend essentially on the bc system. Therefore a rough estimate of $\sigma(bcq)$ could be written as[2]

+ LPNHE, Université de Paris VI et VII

Table 1 - Various beauty baryons using the notation explained above. The charge and the quarks forming the baryons are also given. The mass values are those used in the PYTHIA Monte Carlo program.

	Quarks	Charge	Mass (GeV)
Λ_b	bud	0	5.62
	buu	+1	5.80
Σ_b	bdu	0	"
	bdd	−1	"
Ξ_b	bsu	0	5.84
	bsd	−1	"
Ξ_{bc}	bcu	+1	7.01
	bcd	0	"
Ξ_{2b}	bbu	0	10.42
	bbd	−1	"
Ω_b	bss	−1	6.12
Ω_{bc}	bcs	0	7.19
Ω_{b2c}	bcc	+1	8.31
Ω_{2b}	bbs	−1	10.60
Ω_{2bc}	bbc	0	11.71
Ω_{3b}	bbb	−1	15.11

$$\sigma(bcq) \simeq \sigma(\bar{B}_c)\ G \times \eta_q\,, \tag{1}$$

($\bar{B}_c \equiv b\bar{c}$) where $G = 1/2$ is a color factor comparing the bcq color singlet with the $b\bar{c}$ one and where $\sigma(\bar{B}_c)$ is the $pp \to B_c X$ cross-section[6,7]. The estimate of η_q is obtained from the probability of producing a given q quark using the following ratio[2]:

$$bu : bd : bs : bqq = 0.38 : 0.38 : 0.14 : 0.10\ . \tag{2}$$

The $\sigma(bcq)$ values are then obtained (Table 3), taking the $\sigma(\bar{B}_c)$ from Ref. 7. Table 3 indicates also the number of N_b events expected in one year (10^7 s) of running.

Table 2 - The cross-section values utilized to determine $\sigma(bq_1q_2)$ and $\sigma(bcq)$.

σ	Ref.	0.12 TeV	0.19 TeV	16 TeV	40 TeV
$\sigma(b\bar{b})$	4	$\sim 2\ \mu$b	$\sim 2.5\ \mu$b	$\sim 200\ \mu$b	$\sim 500\ \mu$b
$\sigma(\bar{B}_c)$	6	$\sim$1 nb		$\sim$180 nb	–
$\sigma(\bar{B}_c$ or $\bar{B}_c^*)$	7	$\sim$27 pb	$\sim$ 100 pb	$\sim$ 60 nb	$\sim$ 147 nb

Table 3 - Cross-section estimates of the $pN \to N_b X$ reactions for various c.m. energies corresponding to fixed-target and collider experiments. Estimates of the number of $N_b X$ events produced in one year (10^7 s) of running are also given. For the beam target experiments a Cu target was considered with a length of 5 mm along the beam direction and a beam of $10^8\ p/$s. A luminosity of $L = 10^{32}$ cm^{-2}s^{-1} was taken for the colliders.

N_b	0.12 TeV	0.19 TeV	16 TeV	40 TeV
Λ_b	$(1.7 \pm 0.3)\ 10^{-1}\mu$b $\sim 4.6\ 10^8$/year	$(1.78 \pm 0.01)\ 10^{-1}\mu$b $\sim 4.8\ 10^8$/year	$17.0 \pm 0.1\ \mu$b $\sim 2\ 10^{10}$/year	$43.4 \pm 0.4\ \mu$b $\sim 4\ 10^{10}$/year
Σ_b	$(1.84 \pm 0.02)\ 10^{-2}\mu$b $\sim 5\ 10^7$/year	$(2.75 \pm 0.05)\ 10^{-2}\mu$b $\sim 7.4\ 10^7$/year	$2.9 \pm 0.1\ \mu$b $\sim 3\ 10^9$/year	$7.3 \pm 0.2\ \mu$b $\sim 7\ 10^9$/year
Ξ_b	$(1.70 \pm 0.02)\ 10^{-2}\mu$b $\sim 4.6\ 10^7$/year	$(2.45 \pm 0.05)\ 10^{-2}\mu$b $\sim 6.6\ 10^7$/year	$2.4 \pm 0.1\ \mu$b $\sim 2\ 10^9$/year	$5.8 \pm 0.2\ \mu$b $6\ 10^9$/year
Ω_b	$(2.0 \pm 0.4)\ 10^{-4}\mu$b $\sim 5.4\ 10^5$/year	$(2.5 \pm 0.5)\ 10^{-4}\mu$b $\sim 6.8\ 10^6$/year	$(2.0 \pm 0.4)\ 10^{-2}\mu$b $\sim 2\ 10^7$/year	$(10 \pm 2)\ 10^{-2}\mu$b $\sim 10^8$/year
Ξ_{bc}	~ 6 pb $\sim 1.6\ 10^4$/year	~ 21 pb $\sim 5.7\ 10^4$/year	~ 13 nb $\sim 10^7$/year	~ 31 nb $3\ 10^7$/year
Ω_{bc}	~ 2 pb $\sim 5.4\ 10^3$/year	~ 8 pb $\sim 2.2\ 10^4$/year	~ 5 nb $\sim 5\ 10^6$/year	~ 12 nb $\sim 10^7$/year

For the collider we use a luminosity of $L = 10^{32}$ cm^{-2}s^{-1}, whereas for the beam-target interactions we consider a beam of 10^8 p/s and a Cu target having a length of 5 mm along the beam direction.

The present estimates indicate that both collider projects (LHC and SSC) lead to similar statistics. With the present fixed-target example the statistics are lower by a factor of ~ 100 with respect to the collider experiments where $L = 10^{32}$cm^{-2}s^{-1}. The choice of longer targets as well as larger luminosities could certainly be envisaged. Within the present estimates, the search for bcq baryons could be carried out with the collider experiments.

2 - Comments about the search for CP violation

Similarly to the search for CP violation in the $B^{\pm}$ decay, the study of beauty-baryon decays does not need tagging processes of the associated beauty hadron produced in the same event. However, the search for an asymmetry in the B^+/B^- decay or in one of the cases, $\Lambda_b/\bar{\Lambda}_b$, $\Sigma_b/\bar{\Sigma}_b$, $\Xi_b/\bar{\Xi}_b$, etc., would, in principle, depend on final-state interactions[8].

In the present discussion, let us consider a beauty baryon of spin 1/2 decaying into two hadrons having spin 0 and 1/2 (this situation is similar to $\Lambda \to p\pi$ and $\Xi \to \Lambda\pi$ studied about 30 years ago[9]). The weak decay in these cases will be described by S and P waves (corresponding to relative orbital momenta of $l = 0, 1$, respectively). The partial width Γ and the decay parameters α, β and γ of N_b ($\alpha^2 + \beta^2 + \gamma^2 = 1$) as well as those related to $\bar{N}_b$ (having a bar sign on the parameters) can be used to search for CP violation by testing the non-zero values of the following ratios[9,10]:

$$\Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}, \tag{3a}$$

$$A = \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} \simeq \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}, \tag{3b}$$

$$B = \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}} \simeq \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}. \tag{3c}$$

Note that for a given CP violation effect we expect[10] that $|B| \gg |A| \gg |\Delta|$, indicating that the measurements of β and $\bar{\beta}$ might be very useful. In fact, even with CP violation, $\Delta \neq 0$ can only occur when more than one isospin transition (between the initial and final state) is present (see for instance Ref. 1).

The relations between the various parameters are given in Table 4 for CP conservation or violation in the beauty-baryon decay[1]. For each case we consider

Table 4 - The Γ, α and β relations between the N_b and $\bar{N}_b$ decays for CP conservation or violation. In each case final-state interactions (FSI) were assumed or neglected.

CP conservation		CP violation	
FSI	No FSI	FSI	No FSI
$\Gamma = \bar{\Gamma}$	$\Gamma = \bar{\Gamma}$	$\Gamma \neq \bar{\Gamma}^*$	$\Gamma = \bar{\Gamma}$
$\alpha = -\bar{\alpha}$	$\alpha = -\bar{\alpha}$	$\alpha \neq -\bar{\alpha}$	$\alpha = -\bar{\alpha}$
$\beta = -\bar{\beta}$	$\beta, \bar{\beta} = 0$	$\beta \neq -\bar{\beta}$	$\beta = \bar{\beta}$

* With only one isospin transition, $\Gamma = \bar{\Gamma}$ (see text).

the presence of final-state interactions or decay processes where the final state could be neglected. Note that non-zero values of the β or $\bar{\beta}$ parameters are related to the violation of the time reversal (T) applied to the considered decay process, and hence to the CP violation (CPT rule). However, final-state interactions can also lead to $\beta, \bar{\beta} \neq 0$. Table 4 indicates the relations between β and $\bar{\beta}$ that could indicate the violation of time reversal.

To clarify the discussion, we consider the $pp \to \Lambda_b X$ reaction with the weak decays of $\Lambda_b \to \Lambda\pi^0$ and $\Lambda \to p\pi^-$. Let us now see how to measure the $\alpha \equiv \alpha(\Lambda_b)$ and $\beta \equiv \beta(\Lambda_b)$ parameters $[\bar{\alpha} \equiv \bar{\alpha}(\bar{\Lambda}_b)$ and $\bar{\beta} \equiv \bar{\beta}(\bar{\Lambda}_b)]$. To this end we consider the angular distributions of the proton in the Λ rest frame with respect to the coordinate system shown in Fig. 1 and given by (see Appendix B in Ref. 1):

$$I(\theta_3) \propto 1 + \alpha(\Lambda_b)\alpha(\Lambda)\cos\theta_3 \; , \tag{4}$$

$$I(\theta_2) \propto 1 - \frac{\pi}{4} P(\Lambda_b)\beta(\Lambda_b)\alpha(\Lambda)\cos\theta_2 \; , \tag{5}$$

$$I(\theta_1) \propto 1 - \frac{\pi}{4} P(\Lambda_b)\gamma(\Lambda_b)\alpha(\Lambda)\cos\theta_1 \; . \tag{6}$$

The Λ distribution with respect to the Λ_b polarization $[\vec{P}(\Lambda_b)$, modulus $P(\Lambda_b)]$ in the Λ_b rest frame is (see Fig. 1):

$$I(\Theta) \propto 1 + \alpha(\Lambda_b)P(\Lambda_b)\cos\Theta \; . \tag{7}$$

The $\alpha(\Lambda_b)$ decay parameter can be measured with the distribution given by formula (4). Thus a measurement of $P(\Lambda_b)$ would be possible with distribution (7) valid in the Λ_b rest frame. If $P(\Lambda_b) \neq 0$, one could determine $\beta(\Lambda_b)$ and $\gamma(\Lambda_b)$ [formulae (5) and (6)].

Finally, we summarize the suggestions for measurements related to beauty baryons as follows

- production rates and branching ratios of N_b or/and $\bar{N}_b$,
- existence of baryons having more than one heavy quark,
- measurement of $\alpha(N_b)$ and $\bar{\alpha}(\bar{N}_b)$ for given decay channels.
- measurement of the polarization $P(N_b)$ and $P(\bar{N}_b)$,
- search for CP violation in the N_b, $\bar{N}_b$ decay by comparing their partial decay widths as well as $\alpha(N_b)$ with $\bar{\alpha}(\bar{N}_b)$,
- search for T reversal violation for beauty baryons decaying into two particles having $J = 0$ and $1/2$ if $P(N_b), P(\bar{N}_b) \neq 0$.

3 - CKM matrix elements

The lifetime of beauty baryons is expected to be shorter than that of the B mesons, similarly to the case of charmed hadrons[2]. The Λ_c, Ξ_c^0 are shorter than D^0 (which have similar non-spectator contributions) and Ξ_c^+ shorter than $D^\pm$ (which have less substantial non-spectator contributions). The argument is that QCD color factors make the meson lifetimes longer, basically due to the stronger binding of the light quarks. This difference in QCD effects could facilitate the determination of the CKM matrix elements (V_{ij}) in the beauty-baryon decays. In fact, the QCD effects are expected to be similar for the decay of $N_b \to D^0 X', \bar{D}^0 X'$ (X' representing here either a nucleon, hyperon, charmed or beauty baryon). This is because the spectator graphs yield similar amplitudes. Note, however, that the non-spectator diagrams are different for $N_b \to D^0 X'$ and $N_b \to \bar{D}^0 X'$. This can be seen from Fig. 2, which shows the example of $\Lambda_b \to D^0 \Lambda, \bar{D}^0 \Lambda$ decay. Assuming that the spectator model (factorization process) is dominant in the decay process, the measurement of branching ratios (BR) with $X' \equiv \Lambda, p$ (see Fig. 2) leads to:

$$\frac{BR(\Lambda_b \to \bar{D}^0 \Lambda)}{BR(\Lambda_b \to D^0 \Lambda)} = \frac{|V_{ub}\ V_{cs}|^2}{|V_{cb}\ V_{us}|^2}\,, \tag{8}$$

$$\frac{BR(\Lambda_b \to \bar{D}^0 p)}{BR(\Lambda_b \to D^0 p)} = \frac{|V_{ub}\ V_{cd}|^2}{|V_{cb}\ V_{ud}|^2}\,. \tag{9}$$

The errors in the measured $|V_{cs}|, |V_{us}|, |V_{cd}|, |V_{ud}|$ values are small[2], and will introduce in formulae (8) and (9), only a small systematic error on the $|V_{ub}/V_{cb}|$ measurement, of the order of 10^{-2}.

The decay $B^\pm \to D^0 K^\pm, \bar{D}^0 K^\pm$ could also be used to estimate CKM matrix

Table 5 - Examples of N_b decays having final states that could be easily detected. The Λ decay is not shown as we always consider the $\Lambda \to \pi^- p$ process.

$b \to q$	Baryon decay	Final state
$b \to u$	$\Omega_b^- \to \pi^- \Xi^0, \ \Xi^0 \to \Lambda \pi^0$	$\pi^- \pi^0 \Lambda$
$b \to c$	$\Omega_b^- \to \pi^- \Omega_c^0, \ \Omega_c^0 \to \pi^+ \Omega^-, \ \Omega^- \to K^- \Lambda$	$\pi^- \pi^+ K^- \Lambda$
$b \to u$	$\Xi_b^0 \to \pi^- \Sigma^+, \ \Sigma^+ \to p \pi^0$	$\pi^- \pi^0 p$
$b \to c$	$\Xi_b^0 \to \pi^- \Xi_c^+, \ \Xi_c^+ \to \pi^+ \Xi^0, \ \Xi^0 \to \pi^0 \Lambda$	$\pi^- \pi^+ \pi^0 \Lambda$
$b \to u$	$\Xi_b^- \to \pi^- \Lambda,$	$\pi^- \Lambda$
$b \to c$	$\Xi_b^- \to \pi^- \Xi_c^0, \ \Xi_c^0 \to \pi^+ \Xi^-, \ \Xi^- \to \pi^- \Lambda$	$\pi^- \pi^- \pi^+ \Lambda$
$b \to u$	$\Lambda_b^0 \to \pi^- p,$	$\pi^- p$
$b \to c$	$\Lambda_b^0 \to \pi^- \Lambda_c^+, \ \Lambda_c^+ \to \pi^+ \Lambda$	$\pi^- \pi^+ \Lambda$

elements. Two spectator diagrams will, however, contribute to the $B^+ \to \bar{D}^0 K^+$ ($B^- \to D^0 K^-$) processes (Fig. 2). This will complicate the extraction of the CKM matrix elements relations. In addition, there will be stronger QCD effects, as already stated above.

We present in Table 5 some beauty-baryon decays that could be measured easily. Here the $b \to c$ and $b \to u$ transitions lead to different final states. The QCD effects could then be different in each diagram. Nevertheless, comparison of the following measured ratios,

$$\frac{BR(\Omega_b^- \to \pi^- \Xi^0)}{BR(\Omega_b^- \to \pi^- \Omega_c^0)} \simeq \frac{|V_{ub}|^2}{|V_{cb}|^2} \frac{\phi(u)}{\phi(c)}$$

$$\frac{BR(\Xi_b^0 \to \pi^- \Sigma^+)}{BR(\Xi_b^0 \to \pi^- \Sigma_c^+)} \simeq \frac{|V_{ub}|^2}{|V_{cb}|^2} \frac{\phi(u)}{\phi(c)}$$

$$\frac{BR(\Xi_b^0 \to \pi^- \Lambda)}{BR(\Xi_b^0 \to \pi^- \Xi_c^0)} \simeq \frac{|V_{ub}|^2}{|V_{cb}|^2} \frac{\phi(u)}{\phi(c)}$$

$$\frac{BR(\Lambda_b \to \pi^- p)}{BR(\Lambda_b \to \pi^- \Lambda_c)} \simeq \frac{|V_{ub}|^2}{|V_{cb}|^2} \frac{\phi(u)}{\phi(c)}$$

with formulae (8) and (9) will allow the comparison of QCD effects in beauty-baryon decays. Here $\phi(u)$ [$\phi(b)$] is the phase-space factor corresponding to the $b \to u$ [$b \to c$] transition for a specific final state.

References

1) A. Fridman and R. Kinnunen, Comments on Beauty Baryon Decays and CP-Violation Effects, preprint CERN-PPE/93-61 (1993).

2) A. Fridman and B. Margolis, Beauty Baryon Production and Decays, and CKM Matrix Elements, preprint CERN-TH.6878/93 (1993).

3) H.-U. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. 46 (1987) 43; T. Sjöstrand, preprint CERN-TH.6488/92 (1992).

4) K.J. Foley et al., Proc. Workshop on Experiments, Detectors, and Experimental Areas for the Supercollider, Berkeley, 7-17 July (1987).

5) A. Fridman and R. Kinnunen, Estimates of Beauty Cross-Sections in pN collisions, preprint HU-SEFT, R 1993-03 (1993)

6) M. Luisignoli, M. Masetti and S. Petrarca, Phys. Lett. B266 (1991) 142 .

7) Chao-Hsi Chang and Yu-Qi Chen, The Hadronic Production of the B_c Meson at Tevatron, LHC and SSC, AS-ITP-92-74 Preprint (1992).

8) I.I. Bigi and A.I. Sanda, Nucl. Phys. B281 (1987) 41.

9) See, for instance:
T.D. Lee and C.N. Yang, Phys. Rev. 108 (1957) 1645;
J.W. Cronin and O.E Overseth, Phys. Rev. 129 (1963) 1795;
G. Källen, Elementary Particle Physics, Addison-Wesley Company Inc., Reading, Massachusetts, 1964;
T.D. Lee, Prelude in Theoretical Physics, North-Holland Publishing Company, Amsterdam, 1966;
P. Eberhard, J. Button-Shafer and D.W. Merril, UCRL-11427 Berkeley
P.M. Dauber et al., Phys. Rev. 179 (1969) 1261.

10) J.F. Donoghue and Sandip Pakvasa, Phys. Rev. Lett. 55 (1985) 162;
J.F. Donoghue, Xiao-Gang He and Sandip Pakvasa, Phys. Rev. D34 (1986) 833.

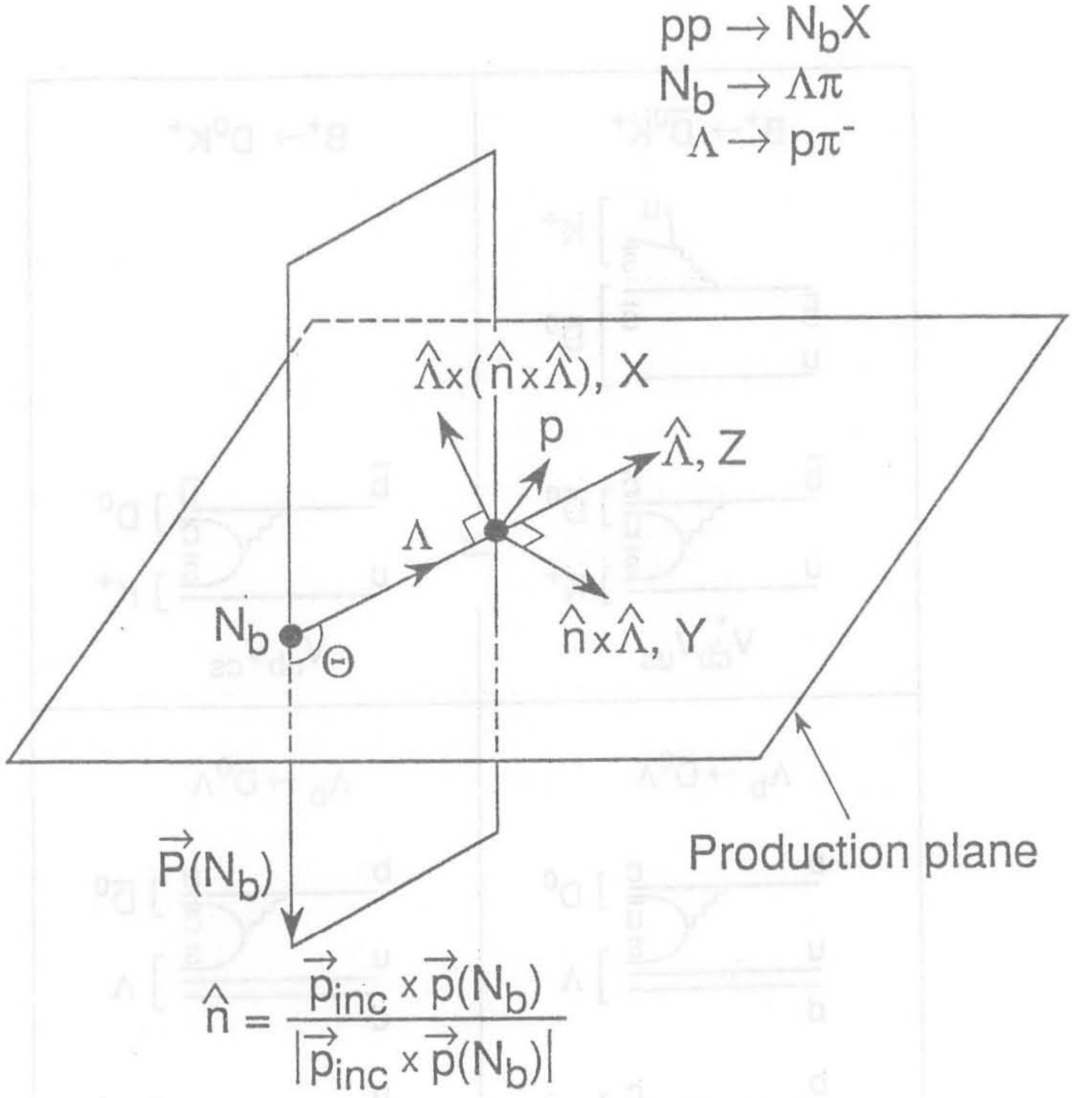

Fig. 1 - The production plane of the $pp \to N_b X$ reaction and the $\vec{P}(N_b)$ polarization normal to this plane. The X, Y, Z represent the coordinate system used in the Λ rest frame for defining the p angular (θ_{1-3}) distributions coming from the $\Lambda \to p\pi$ decay. Here Θ is the Λ emission angle with respect to the $P(N_b)$ direction in the N_b rest frame.

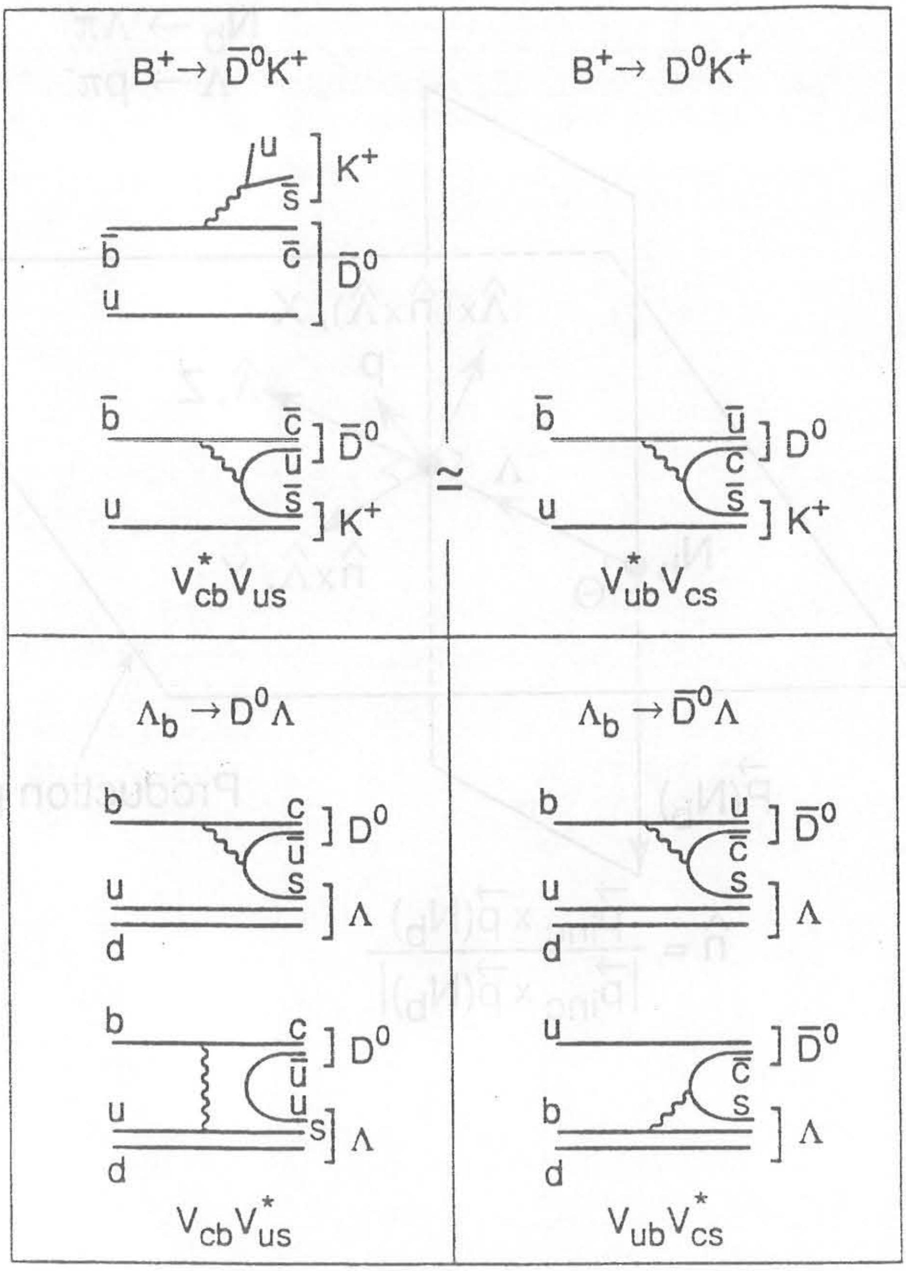

Fig. 2 - Diagrams for the $B^+ \to \bar{D}^0 K^+, D^0 K^+$ (top) and $\Lambda_b \to D^0\Lambda, \bar{D}^0\Lambda$ (bottom) decay channels (see Ref. 1). The CKM matrix elements entering in the diagrams are indicated. Note that the same kind of diagrams apply for the charge conjugated reactions but where $V_{ij} \leftrightarrow V^*_{ij}$.