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Decays and Production of Beauty Baryons in pp Interactions

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Abstract

We present some physics interests for the study of beauty baryons produced in pp interactions at a center-of-mass energy corresponding to the Large Hadron Collider (LHC) project, $\sqrt{s} \simeq 14$ TeV. The comparison of beauty-baryon (N_b) production with their charge conjugate particles ($\bar{N}_b$) is discussed as well as the measurement of their polarization. The search for CP violation in the $N_b, \bar{N}_b$ decays is considered. A possibility for estimating the $|V_{cb}|$ CKM matrix element is also presented. In order to evaluate the N_b production rates and their detection efficiencies, we utilize a pp luminosity of $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and the example of the Compact Muon Solenoid (CMS) detector.

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1 - Introduction

During the last years there has been much interest in the possibilities of studying beauty-hadron decays. Essentially, two methods for producing beauty hadrons have been considered: the e^+e^- B -factories at a c.m. energy around $\sqrt{s} \simeq 10$ GeV and pp collisions at large c.m. energies. For the latter case we will consider here the pp interactions at an energy of $\sqrt{s} \simeq 14$ TeV corresponding to that expected in the Large Hadron Collider (LHC) project.

Let us remember that it will be easy to detect and identify the outgoing particles in a B -factory experiment but the cross-section of the $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ reaction is expected to be much smaller than the $pp \rightarrow B\bar{B}X$ one¹⁻⁴ (X meaning anything). The advantages and inconveniences of both cases have been discussed in detail^{1,2}. In fact the study of beauty hadrons with a B -factory and pp collisions are complementary as these approaches will allow one to investigate different physics domains. For instance, the pp interactions at $\sqrt{s} \simeq 14$ TeV will be particularly suitable to search for CP violation in the B_s^0 ($\bar{B}_s^0$) decay and for studying the properties of the beauty baryons as the production rate of these particles is rather negligible in a B -factory. In the following we will discuss the decay of beauty baryons and their production features in pp interactions at $\sqrt{s} \simeq 14$ TeV.

Table 1 presents various beauty baryons that could be produced in pp interactions, the charge conjugate (c.c.) ones being not omitted. Excited states are also not shown. Therefore, all the baryons have spin $S = 1/2$, apart from the bbb state which has $S = 3/2$. The masses of these particles are those used in the PYTHIA Monte Carlo program⁵ except for the measured Λ_b mass⁶. We use the following notation: the baryon with isospin $I = 1$ will be denoted by Σ , whereas Ξ will be taken 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 baryon considered. (the light quarks will be denoted by $q \equiv u, d, s$). Note that the Λ_b resonance has been observed⁶ although with rather small statistics. For the present discussion we consider only baryons containing at most one heavy quark ($N_b \equiv bq_1q_2$ and $N_c \equiv cq_1q_2$ or their c.c. ones).

In Section 2 we discuss the interests of studying the production and decay of beauty baryons appearing in pp interactions. We consider the measurement possibilities of the polarization of the produced beauty baryons. The search for CP violation in their decays is also discussed in Section 2. Then, the production rates and the detection efficiencies of various decay channels are considered (Section 3) using the example of the Compact Muon Solenoid (CMS) detector⁷. In Section 4 we consider the beauty-baryon decay with a J/ψ and a Λ appearing in the final

Table 1 - Various beauty baryons (N_b) 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 apart the mass of the Λ_b which has been measured⁶.

	Quarks	Charge	Mass (GeV)
Λ_b	bud	0	5.64
Σ_b	buu	+1	5.80
	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}	$bb s$	-1	10.60
Ω_{2bc}	$bb c$	0	11.71
Ω_{3b}	bbb	-1	15.11

state. Some estimates about the N_b decay into two particles having spin 1/2 and 0 are given in Section 5. In that cases the polarization of the $\Lambda_b, \bar{\Lambda}_b$ could be attempted as well as estimates of the $|V_{cb}|$ CKM matrix element. Finally, some conclusions about the interests of analyzing the beauty baryons, production and decay, are presented in Section 6.

Let us recall that in pp interactions the difficulty of studying beauty hadrons is related to the triggering process for $pp \rightarrow b\bar{b}X$ events. In contrast to B -factories and fixed-target experiments, B -physics studies in pp colliders at large luminosities are based on lepton triggers. Usually one considers cases where leptons due to beauty-hadron decays appear in the final state. Here we will only consider muon trigger. The two basic triggers we are considering are⁷:

- 1) inclusive single muon trigger that requires at least one muon with $p_T > 9$ GeV/c in the rapidity range $|\eta| < 2.4$.
- 2) inclusive two-muon trigger that requires at least two muons in the rapidity range $|\eta| < 2.4$ and with $p_T > 4.5$ GeV/c

The first trigger, whose threshold must lie in the 7 – 10 GeV/c range in order to cope with an acceptable level-1 trigger rate (≤ 50 kHz), is well suited for the study of rare decays (i.e. $B \rightarrow \pi^+\pi^-$) and $B_s^0 - \bar{B}_s^0$ mixing. In our simulation we assume a conservative threshold at $p_T > 9$ GeV/c.

The second trigger, whose threshold can be lower because of a smaller rate, is limited by the range of muons in the material that must be traversed to reach the first muon chamber. Therefore, the p_T -threshold will depend on the rapidity (p_T -threshold: 2.6 - 4.5 GeV/c). This trigger is well suited to accept events containing a J/Ψ in the final state.

2 - Physics interests

2.1 - Beauty-baryon production and decay

Let us mention some of the interests in measuring the production of beauty baryons in pp interactions. One could compare the production of beauty baryons (N_b) with their charged conjugate ($\bar{N}_b$) particles. In pN interactions the production should not be equal (in contrast to the $\bar{p}p$ interactions), mainly because of the valence quarks of the beam particles. The comparison between the N_b and $\bar{N}_b$ (as well as the B and $\bar{B}$) production could certainly give some information about the production mechanism at large c.m. energy.

Another aspect related to the production process would consist in observing the polarization of the beauty baryon produced. Let us remember that in the $pN \rightarrow N_b(\bar{N}_b)X$ interactions, the polarization of N_b (or $\bar{N}_b$) in its rest frame can only be along $\hat{n}$, the normal to the production plane (see Fig. 1). This plane is defined here by the momenta of the incident proton ($\vec{p}_{inc}$) and the outgoing N_b or $\bar{N}_b$ ($\vec{p}_{out}$) produced in the laboratory (or in the c.m.) system, i.e. $\hat{n} = \vec{p}_{inc} \times \vec{p}_{out} / |\vec{p}_{inc} \times \vec{p}_{out}|$. The polarization of the hyperons Λ, Σ, Ξ (denoted here by Y) has been measured in several p -target experiments⁸⁻¹⁰ ($pN \rightarrow YX, \bar{Y}X$) with p incident momentum around 400 – 800 GeV/c. The polarization of Λ has been observed in the $pN \rightarrow \Lambda X$ production, in contrast with that of the $\bar{\Lambda}$ which vanishes in the same type of interaction⁹. For Ξ^- and Ξ^+ the situation is different as both have nearly the same polarization^{8,10} in the pN production with an incident momentum around 800 GeV/c. The polarization measurement of beauty baryons could certainly be useful for a better understanding of the production mechanism.

By considering the decay of the beauty hadron into two particles as:

$$\begin{aligned} N_b &\rightarrow Y + M \\ &\rightarrow N_c + M \end{aligned}$$

(and their charge conjugate reactions) one could, in principle, compare the polarization of N_b [$\vec{P}(N_b)$, modulus $P(N_b)$] with that of $\bar{N}_b$ [$\vec{P}(\bar{N}_b)$, modulus $P(\bar{N}_b)$]. Here we consider the mesons M having a spin $S = 0, 1$. Note that the $S = 1$ case applies essentially to the $Y + J/\psi$ or $N_c + J/\psi$ final states. In order to clarify the present discussion, let us consider the $\Lambda_b \rightarrow \Lambda M$ example with $\Lambda \rightarrow p\pi^-$. Some angular distributions of the p in the Λ rest frame as well as the Λ_b angular distribution in the pp rest frame with respect to $\vec{P}(\Lambda_b)$ (the later one being expressed in the Λ_b rest frame) could be measured.

a) The spin 0 value of the outgoing meson

For a meson M with $S = 0$ one has the angular distributions used in the past for studying the $\Xi \rightarrow \Lambda\pi$ and $\Lambda \rightarrow p\pi$ decays¹¹. By using the coordinate system shown in Fig. 1, one has^{11,12}

$$I_0(\theta_3) \propto 1 + \alpha(\Lambda_b)\alpha(\Lambda) \cos \theta_3 , \quad (1)$$

$$I_0(\theta_2) \propto 1 - \frac{\pi}{4} P(\Lambda_b)\beta(\Lambda_b)\alpha(\Lambda) \cos \theta_2 , \quad (2)$$

$$I_0(\theta_1) \propto 1 - \frac{\pi}{4} P(\Lambda_b)\gamma(\Lambda_b)\alpha(\Lambda) \cos \theta_1 , \quad (3)$$

$$I_0(\Theta) \propto 1 + \alpha(\Lambda_b)P(\Lambda_b) \cos \Theta , \quad (4)$$

where the index appearing in I_0 (I_1) will represent the spin $S = 0$ (1) value of the outgoing M meson. For $S = 0$, the $\alpha(\Lambda_b)$, $\beta(\Lambda_b)$ and $\gamma(\Lambda_b)$ are the $\Lambda_b \rightarrow \Lambda M$ decay parameters ($\alpha^2 + \beta^2 + \gamma^2 = 1$) while $\alpha(\Lambda) = 0.64$ (Ref. 13) is one of the $\Lambda \rightarrow p\pi^-$ decay parameters. Once $\alpha(\Lambda_b)$ is measured from the $I_0(\theta_3)$ distribution, the Λ angular distribution in the pp rest frame [formula (4)] can be used in order to obtain the $P(\Lambda_b)$ value. If $P(\Lambda_b) \neq 0$, we could (in principle) determine $\beta(\Lambda_b)$ and $\gamma(\Lambda_b)$ by measuring the $I_0(\theta_2)$ and $I_0(\theta_1)$ distributions. By applying the same method to $\bar{\Lambda}_b$ one could obtain $\bar{\alpha}(\bar{\Lambda}_b)$, $P(\bar{\Lambda}_b)$, and the other decay parameters if $P(\bar{\Lambda}_b) \neq 0$.

b) The spin 1 value of the outgoing meson

With mesons having $S = 1$, one could, for instance, utilize the following angular distributions^{14,15}

$$I_1(\theta_3) \propto 1 \pm \alpha''(\Lambda_b)\alpha(\Lambda) \cos \theta_3 , \quad (5)$$

$$I_1(\Theta) \propto 1 \pm \alpha'(\Lambda_b) P(\Lambda_b) \cos \Theta . \quad (6)$$

As $\alpha'' \neq \alpha'$, one cannot obtain the polarization $P(\Lambda_b)$ from the measurement of the angular distributions described by (5) and (6). However, a comparison between $\alpha'(\Lambda_b)P(\Lambda_b)$ and $\bar{\alpha}'(\bar{\Lambda}_b)P(\bar{\Lambda}_b)$ could give some information about the polarization (size and direction) by assuming that $\alpha'(\Lambda_b) + \bar{\alpha}'(\bar{\Lambda}_b) \simeq 0$ (no CP violation, see next section).

2.2 - Search for CP violation in beauty-baryon decays

The search for CP violation in beauty-baryon decays does not need any tagging process of the associated beauty hadron produced in the same event. The measurement of an asymmetry parameter due to CP violation in the decay could also depend on the final-state interactions (FSI). As above, we will consider the beauty baryons of spin 1/2 decaying into two hadrons where the meson has a spin $S = 0, 1$.

a) The spin 0 value of the outgoing meson

The weak decays will be described here by S and P waves (corresponding to relative orbital momenta of $l = 0, 1$, respectively, between the two outgoing particles). The partial width Γ and the decay parameters¹¹, α, β of N_b (γ is not used here since $\alpha^2 + \beta^2 + \gamma^2 = 1$) 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^{11,16}

$$\Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} , \quad (7)$$

$$A = \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} \simeq \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} , \quad (8)$$

$$B = \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}} \simeq \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}} . \quad (9)$$

Here we use the simplified notations, $\Gamma \equiv \Gamma(\Lambda_b)$, $\alpha \equiv \alpha(\Lambda_b)$ and $\beta \equiv \beta(\Lambda_b)$ (and the bar sign for the $\bar{\Lambda}_b$ parameter).

Table 2 - 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).

Note that for a given CP violation effect we expect¹⁶ that $|B| \gg |A| \gg |\Delta|$, indicating that the measurements of β and $\bar{\beta}$ might be 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) leads to final states with a non-unique isospin value. The non-zero values of the β or $\bar{\beta}$ parameters are related to the violation of the time reversal (T) applied to the decay process¹¹ considered, and hence to the CP violation (CPT rule). However, final-state interactions can also lead to $\beta, \bar{\beta} \neq 0$ (Ref. 16). Table 2 indicates the relation between β and $\bar{\beta}$ which could indicate the violation of time reversal^{12,16}. The table also give the relations between other decay parameters. Let us repeat that β ($\bar{\beta}$) can only be measured if $P(\Lambda_b) \neq 0$ ($P(\bar{\Lambda}_b) \neq 0$).

b) The spin 1 value of the outgoing meson

These cases will be somewhat more complicated. First, one has to notice that here also the contribution of only one isospin transition between the initial and final state (or several transitions with the same final isospin value) leads to the equality of the partial widths of the N_b and $\bar{N}_b$ decays considered ($\Gamma = \bar{\Gamma}$) yielding $\Delta = 0$. The decay channels that we will consider (Section 4) will all have $\Delta = 0$. In principle, the comparison of α' with $\bar{\alpha}'$ or α'' with $\bar{\alpha}''$ through the parameters

$$A' = \frac{\alpha' + \bar{\alpha}'}{\alpha' - \bar{\alpha}'} \quad \text{or} \quad A'' = \frac{\alpha'' + \bar{\alpha}''}{\alpha'' - \bar{\alpha}''} \quad (10)$$

could be used to search for CP violation. However, as already mentioned above, the coefficient $\alpha'(\Lambda_b)$ can only be measured with distribution (6) if the polarization $P(\Lambda_b)$ is known.

Table 3 - The $R(N_b) = \sigma(N_b)/\sigma(b\bar{b})$ and $R(\bar{N}_b) = \sigma(\bar{N}_b)/\sigma(b\bar{b})$ ratios at $\sqrt{s} = 0.11, 14$ TeV as obtained from PYTHIA. The first (second) line corresponds to the $R(N_b)$ [$R(\bar{N}_b)$] rate.

$\sqrt{s}$ (TeV)	$R(\Lambda_b)$ $R(\bar{\Lambda}_b)$	$R(\Sigma_b)$ $R(\bar{\Sigma}_b)$	$R(\Xi_b)$ $R(\bar{\Xi}_b)$	$R(\Omega_b)$ $R(\bar{\Omega}_b)$
0.11	$(6.1 \pm 0.1) 10^{-2}$ $(4.4 \pm 0.1) 10^{-2}$	$(9.2 \pm 0.4) 10^{-3}$ $(6.4 \pm 0.1) 10^{-3}$	$(8.8 \pm 0.4) 10^{-3}$ $(5.6 \pm 0.1) 10^{-3}$	$\sim 6 10^{-5}$ $\sim 10^{-4}$
16	$(8.00 \pm 0.03) 10^{-2}$ $(7.72 \pm 0.03) 10^{-2}$	$(1.32 \pm 0.01) 10^{-2}$ $(1.25 \pm 0.01) 10^{-2}$	$(1.10 \pm 0.01) 10^{-2}$ $(1.06 \pm 0.01) 10^{-2}$	$(1.1 \pm 0.1) 10^{-4}$ $(1.1 \pm 0.1) 10^{-4}$

3 - Beauty-baryon production rates

3.1 - Cross-sections and efficiencies

We estimate the N_b and $\bar{N}_b$ production cross-section [$\sigma(N_b)$ and $\sigma(\bar{N}_b)$, respectively] from the ratios $R(N_b) = \sigma(N_b)/\sigma(b\bar{b})$ and $R(\bar{N}_b) = \sigma(\bar{N}_b)/\sigma(b\bar{b})$ calculated with the PYTHIA Monte Carlo program. Here $\sigma(b\bar{b})$ represents the $pp \rightarrow b\bar{b}X$ cross-section at the c.m. energy considered. For comparison we present these ratios in Table 3 at $\sqrt{s} = 0.11$ and 14 TeV corresponding to the LHC project (beam fixed-target and collider experiments). We see from this table that $R(N_b)$ and $R(\bar{N}_b)$ are not too dependent on the c.m. energy. At $\sqrt{s} = 14$ TeV, the cross-section of the N_b and $\bar{N}_b$ production are obtained from the estimates given in Table 3 and using $\sigma(b\bar{b}) \simeq 300 \mu\text{b}$ (Ref. 3).

We thus obtain the following cross-sections:

$$\begin{aligned}
\sigma(\Lambda_b) &\simeq 24.0 \mu\text{b} , & \sigma(\bar{\Lambda}_b) &\simeq 23.2 \mu\text{b} \\
\sigma(\Sigma_b) &\simeq 4.0 \mu\text{b} , & \sigma(\bar{\Sigma}_b) &\simeq 3.8 \mu\text{b} \\
\sigma(\Xi_b) &\simeq 3.3 \mu\text{b} , & \sigma(\bar{\Xi}_b) &\simeq 3.2 \mu\text{b} \\
\sigma(\Omega_b) &\sim 0.03 \mu\text{b} , & \sigma(\bar{\Omega}_b) &\sim 0.03 \mu\text{b} .
\end{aligned}$$

Let us now explain the manner used to evaluate the production and decay rates of the various N_b that could be studied in the pp interactions. To this end we estimate the number of events (N_{sig}) obtained in one year of running (10^7 s) for the various decay channels. For the two-muon and single-muon triggers, these estimates are given by

$$N_{sig} = \mathcal{L}_{int} \times \sigma(N_b) \times BR(tot) \times \epsilon_{tr} \times \epsilon_{cut} \quad (11a)$$

$$N_{sig} = \mathcal{L}_{int} \times \sigma(N_b) \times BR(b \rightarrow \mu) \times BR(tot) \times \epsilon_{tr} \times \epsilon_{cut} , \quad (11b)$$

respectively. Here ϵ_{cut} represents the total efficiency depending on the various cuts for the channels considered and on the detector (see below) whereas $\mathcal{L}_{int}$ is the luminosity ($\mathcal{L}$) integrated over one year of running. For the one-muon trigger [equation (11.b)], $BR(b \rightarrow \mu)$ represents the semileptonic branching ratio of the associated beauty hadron produced in the same event. Note that $\overline{N}_{sig} \simeq N_{sig}$ will represent the number of triggered and reconstructed events obtained for the $\overline{N}_b$ hadrons.

The triggering efficiency ϵ_{tr} is based on the detector simulation done for the different trigger modes used for the CMS detector⁷. In the case of a dimuon trigger the following η -dependent p_T thresholds are considered:

$$\begin{aligned} 0.0 < |\eta| \leq 1.5 & \text{ and } p_T > 4.5 \text{ GeV}/c \\ 1.5 < |\eta| \leq 2.0 & \text{ and } p_T > 3.6 \text{ GeV}/c \\ 2.0 < |\eta| \leq 2.5 & \text{ and } p_T > 2.6 \text{ GeV}/c \end{aligned}$$

where η and p_T denote their pseudorapidity and transverse momentum (with respect to the beam direction), respectively. These cuts were defined by studying the triggering method for the the $B_d^0, \overline{B}_d^0 \rightarrow J/\psi K_s^0$ with the CMS detector⁷.

For the single-muon trigger, the cuts

$$|\eta| \leq 2.4 \text{ and } p_T > 9 \text{ GeV}/c$$

are applied to the muon candidate. The large p_T threshold is introduced here in order to decrease the important background (Section 5).

3.2 - The luminosity

During the last years one admitted that a luminosity of 10^{31} – $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ would be convenient for the study of beauty physics in pp collisions for a c.m. energy in the 14-40 TeV region^{2,7}. For the LHC project, $\mathcal{L} = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ ($10^{32} \text{ cm}^{-2}\text{s}^{-1}$) would correspond to an average of 1.1 (0.11) interactions per bunch-crossing using a non-diffractive cross-section of $\sigma'(pp) \simeq 60 \text{ mb}$ (Ref. 17). Assuming that the probability of m interactions per bunch-crossing follows a Poisson distribution, one obtains that the average number of interactions for minimum-bias events ($\overline{m}_{min}$) and for events with a specific trigger signature ($\overline{m}_{str}$) are given

by:

$$\begin{aligned}\mathcal{L} = 10^{32} \text{ cm}^{-2}\text{s}^{-1} : & \quad \overline{m}_{min} \simeq 1.06, \quad \overline{m}_{str} \simeq 1.11 \\ \mathcal{L} = 10^{33} \text{ cm}^{-2}\text{s}^{-1} : & \quad \overline{m}_{min} \simeq 1.65, \quad \overline{m}_{str} \simeq 2.11.\end{aligned}$$

In the identification of beauty baryons (specially the neutral ones), cuts on their flight lengths as well as those on the hyperons present in the final states (in space or/and in the transverse plane) would require the knowledge of the interaction vertex from which the N_b (or $\overline{N}_b$) is produced as well as the N_b decay vertex. Therefore, $\overline{m}_{str} > 2$ could complicate the identification of the interaction vertex.

One has also to note that the averaged charged multiplicity of the outgoing tracks ($\langle n \rangle$) will be large with $\overline{m}_{str} > 1$. This may also complicate the beauty baryon reconstruction. For the following kinematical cuts on the charged outgoing particles, the $\langle n \rangle$ values obtained with the Monte Carlo calculations (based on one pp interaction per bunch-crossing) are:

$$\begin{aligned}|\eta| < 2.4, \quad \langle n \rangle &\simeq 52 \\ |\eta| < 2.4, p_T > 0.5 \text{ GeV}/c, \quad \langle n \rangle &\simeq 19 \\ |\eta| < 2.4, p_T > 0.7 \text{ GeV}/c, \quad \langle n \rangle &\simeq 11.\end{aligned}$$

The latter case corresponding to the kinematical cuts that will be applied for the hadrons produced (see below) and lead to a small $\langle n \rangle$ value. The outgoing tracks coming from the pp interaction point and having rather small $|\eta|$ values will be used for the reconstruction of the interaction vertex. Different kinematical cuts for these outgoing particles could be considered to improve the accuracy on the measured interaction-vertex position. This could occur for events having a small number of charged outgoing particles.

4 - The decays with J/ψ and Λ in the final state

4.1 - The detection efficiencies

In the following we first consider beauty baryon decaying into two particles, one of them being a $J/\psi \rightarrow \mu^+\mu^-$, while a Λ is also required to be among the decay products. Table 4 presents some N_b decay channels (the $\overline{N}_b$ cases are not shown) having only charged particles among the outgoing particles. The branching ratios (BR) of N_b given in this table are roughly estimated by considering that the decay processes are essentially due to spectator diagrams. We then assume that relations between N_b branching ratios are given by CKM matrix elements taking into account the color suppression factors and using the basic value of $BR(\Lambda_b \rightarrow J/\psi \Lambda) \simeq 2 \times 10^{-2}$ (see Ref. 18). Phase space and QCD effects were not taken into account.

Table 4 - The branching ratios (BR) for various cascades of the N_b decays are given in the table¹² as well as the final states. The $BR(J/\Psi \rightarrow \mu^+\mu^-) = 0.06$, and $BR(\Lambda \rightarrow p\pi^-) = 0.64$ are not indicated. The total branching ratio is represented by $BR(tot)$.

Channel	BR	$BR(tot)$	Final state
$\Lambda_b \rightarrow \Lambda J/\Psi$	$\sim 2 \cdot 10^{-2}$	$\sim 7.7 \cdot 10^{-4}$	$p\pi^-\mu^+\mu^-$
$\Xi_b^0 \rightarrow \Lambda J/\Psi$	$\sim 10^{-3}$	$\sim 3.8 \cdot 10^{-5}$	$p\pi^-\mu^+\mu^-$
$\Xi_b^- \rightarrow \Xi^- J/\Psi$	$\sim 2 \cdot 10^{-2}$	$\sim 7.7 \cdot 10^{-4}$	$p\pi^-\pi^-\mu^+\mu^-$
$\Xi^- \rightarrow \Lambda\pi^-$	~ 1		
$\Omega_b^- \rightarrow \Omega^- J/\Psi$	$\sim 2 \cdot 10^{-2}$	$\sim 5.2 \cdot 10^{-4}$	$pK^-\pi^-\mu^+\mu^-$
$\Omega^- \rightarrow \Lambda K^-$	0.68		
$\Omega_b^- \rightarrow \Xi^- J/\Psi$	$\sim 2 \cdot 10^{-2}$	$\sim 7.7 \cdot 10^{-4}$	$p\pi^-\pi^-\mu^+\mu^-$
$\Xi^- \rightarrow \Lambda\pi^-$	~ 1		

For the decay channels given in Table 4 the total detection efficiency will be given by $\epsilon_{tot} = \epsilon_{tr} \times \epsilon_{cut}$. By using the two-muon trigger one obtains a trigger efficiency $\epsilon_{tr} = 0.030$ for all the decay channels indicated in Table 4. The efficiency ϵ_{cut} is based on Monte Carlo calculations in order to identify the N_b baryons and to decrease the background (Section 4.2). Based on our investigation, the following cuts and conditions are proposed:

- (1) the kinematical cuts on the produced hadrons are $|\eta| < 2.4$ and $p_T > 0.7$ GeV/c (defined with respect to the beam direction),
- (2) the reconstruction efficiency for each charged track is estimated to be 0.9 per track,
- (3) the obligation that the calculated $\mu^+\mu^-$ effective mass should be compatible with the J/ψ mass within $\pm 2.5 \times \sigma(J/\psi)$ where $\sigma(J/\psi) = 16$ MeV is the experimental width of the expected J/ψ mass distribution,
- (4) the condition that the calculated mass of the Λ should be within $\pm 2.5\sigma(\Lambda)$ where $\sigma(\Lambda) = 5$ MeV is the width of the measured Λ mass distribution,
- (5) the $|p_+^2 - p_-^2|/p^2 > 0.35$ and $p_t < 0.11$ GeV/c conditions where $p_{\pm}$ denotes the momenta of the charged particles coming from the Λ candidate and where p_t are their transverse momenta with respect to the Λ direction,
- (6) the reconstruction efficiency (~ 0.25) of the $\Lambda \rightarrow p\pi^-$ due to pattern recognition including that the distance between the Λ decay vertex and the pp interaction point should be between 2 and 40 cm (because of the track reconstruction in the central part of the detector),

Table 5 - The N_b cross-section, as well as the ϵ_{cut} efficiencies for various N_b decay channels. For all these cases, one has $\epsilon_{tr} = 0.030$. With these efficiencies and a luminosity of $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, one obtains the number of events (N_{sig}) in one year of running (note that the $\bar{N}_b$ events are not included here). Estimates of the ratios N_{sig}/N_{back} are also given, N_{back} representing the number of background events.

Channel	$\sigma(N_b)$ (μb)	ϵ_{cut}	N_{sig}	N_{sig}/N_{back}
$\Lambda_b \rightarrow \Lambda J/\Psi$	24	0.038	$\sim 2.1 \cdot 10^5$	~ 20
$\Xi_b^0 \rightarrow \Lambda J/\Psi$	1.7	0.038	$\sim 6.8 \cdot 10^2$	$\sim 7 \cdot 10^{-2}$
$\Xi_b^- \rightarrow \Xi^- J/\Psi$	1.7	0.021	$\sim 8 \cdot 10^3$	~ 2
$\Omega_b^- \rightarrow \Omega^- J/\Psi$	0.030	0.020	~ 100	$\sim 2 \cdot 10^{-2}$
$\Omega_b^- \rightarrow \Xi^- J/\Psi$	0.030	0.020	$\sim 1.4 \cdot 10^2$	$\sim 2 \cdot 10^{-2}$

- (7) the angle between the J/ψ and the hyperon has to be smaller than 40 degrees in the laboratory system,
- (8) the calculated N_b mass that should be compatible with the predicted N_b mass within $\pm 2.5 \times \sigma(N_b)$, $\sigma(N_b) = 15 \text{ MeV}$ being the expected width of the measured N_b mass distribution,
- (9) the distance in the transverse plane between the primary and the N_b decay vertices should be greater than $500 \mu\text{m}$, corresponding to 3 times the error of the reconstructed vertices (yielding an additional efficiency of ~ 0.8).

With the above selections (point 1 to 9) we obtain the efficiency ϵ_{cut} given in Table 5. Taking also into account the trigger efficiency $\epsilon_{tr} = 0.030$ we indicate the number of events (N_{sig}) expected in one year of running (see Table 5). For the estimates of the production and background (next section) rates, we consider only N_b baryons as the N_b and $\bar{N}_b$ are expected to be produced in nearly equal amounts (and will have, therefore, almost the same signal-to-background ratio).

We also have to emphasize that for the Λ (or $\bar{\Lambda}$) identification, our cuts (points 1 to 5) do not lead to ambiguity between the $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ despite the fact that there is no particle identification in the detector taken as an example. This can be seen from the study of $\Lambda \rightarrow p\pi^-$ generated events where the misidentification of the decay particles ($p\pi^- \rightarrow \pi^+\bar{p}$) was applied. As seen in Fig. 2, the misidentification of the decay particles gave a reconstructed effective mass very different from that of the Λ , taking into account the angular and momentum resolution of the charged particles⁷ as well as the various kinematical cuts. Therefore, the production and decay of the $N_b \rightarrow \Lambda X$ and $\bar{N}_b \rightarrow \bar{\Lambda} X$ processes could be

compared and studied in pp interactions at $\sqrt{s} = 14$ TeV.

4.2 - The background events

We estimate the background events (which will be denoted by N_{back} for one year of running) by considering reactions where a (right or wrong) $J/\psi \rightarrow \mu^+ \mu^-$ appears in the final state. This could occur by the following processes:

- (1) the J/ψ appearing in the final state from the direct or indirect decay of the B mesons, namely

$$\begin{aligned} B &\rightarrow J/\psi X \\ &\rightarrow \psi' X, \quad \psi' \rightarrow J/\psi X \\ &\rightarrow \chi_c X, \quad \chi_c \rightarrow J/\psi \gamma \end{aligned}$$

with a total branching ratio value (direct or indirect J/ψ production) of 1.1×10^{-2} (Ref. 6);

- (2) a μ^- and a μ^+ coming from a beauty or/and the charm quark decay, having an effective mass compatible with the J/ψ and appearing from the

$$\begin{aligned} b\bar{b} \text{ production}, \quad & b \rightarrow \mu^-, \quad \bar{b} \rightarrow \mu^+, \\ b\bar{b} \text{ production}, \quad & b \rightarrow c\mu^-, \quad c \rightarrow \mu^+ \quad (+ \text{ c.c.}), \\ b\bar{b} \text{ production}, \quad & c \rightarrow \mu^+, \quad \bar{c} \rightarrow \mu^-, \\ c\bar{c} \text{ production}, \quad & c \rightarrow \mu^+, \quad \bar{c} \rightarrow \mu^-; \end{aligned}$$

(the $\mu^+ \mu^-$ effective mass is shown in Fig.3 for the first three cases);

- (3) the $\pi^\pm \rightarrow \mu^\pm \nu$ and $K^\mp \rightarrow \mu^\mp \nu$ decays leading to a $\mu^+ \mu^-$ effective mass equal to the expected J/ψ value.

For our estimates we use a cross-section ratio of $\sigma(c\bar{c})/\sigma(b\bar{b}) \simeq 4$. The direct $pp \rightarrow J/\psi X$ interaction, or $pp \rightarrow \chi_c X$ with $\chi_c \rightarrow J/\psi \gamma$, were not taken into account as the $J/\psi \rightarrow \mu^+ \mu^-$ decay will occur near the interaction region. The flight length cut on the outgoing N_b (or $\bar{N}_b$) will eliminate these processes (point 9 in Section 4.1).

Based on our Monte Carlo calculations and applying the cuts and conditions described in Section 4.1, we find that the background due to points 2 and 3 is negligible with respect to the $B \rightarrow J/\psi X$ process (point 1). The N_{sig}/N_{back} obtained with the present approximations are given in Table 5. We note the large signal expected for the $\Lambda_b \rightarrow \Lambda J/\psi$ channel (see also Fig. 4). Within our present estimates the $\Xi_b^- \rightarrow \Xi^- J/\psi$ could also be studied although N_{sig}/N_{back} is much smaller than in the former case. Further investigations have to be done in order to

see if the signal over background could be increased for the $\Xi^- \rightarrow \Xi^- J/\psi$ channel as well as for some of the Ξ_b^0 and Ω_b^- decay channels (Table 5).

4.3 Measurements of the decay parameters

For the measurements of the decay parameters we will consider only the beauty-baryon decays produced with acceptable statistics and N_{sig}/N_{back} ratios (Table 5), namely:

$$\begin{aligned}\Lambda_b &\rightarrow \Lambda J/\psi, & \Lambda &\rightarrow p\pi^- \\ \Xi_b^- &\rightarrow \Xi^- J/\psi, & \Xi^- &\rightarrow \Lambda\pi^-\end{aligned}$$

where the corresponding hyperon decays are indicated (while $J/\psi \rightarrow \mu^+\mu^-$). As discussed in Section 2.1, the decay parameter $\alpha''(N_b)$ could be obtained by studying the angular distribution of the baryon (or meson) coming from the (first) parent hyperon in its rest frame, formula (5) written here as

$$I_1(\theta_3) \propto 1 \pm \alpha''(N_b)\alpha(Y) \cos \theta_3 .$$

The minimum value $\alpha''(N_b)_{min}$ of $|\alpha''(N_b)|$ that could be measured with N events and n_s standard deviations is given by (see the Appendix)

$$\alpha''_{min} = \frac{1}{\alpha} \left(\frac{3n_s^2}{N + n_s^2} \right)^{1/2} . \quad (12)$$

Taking roughly into account our background estimate with $k = N_{back}/N_{sig}$ (Table 5), the right hand-side of equation (12) has to be multiplied by $1+k$ (Appendix). With this approach we indicate in Table 6 the minimum values that could be measured with the number of standard deviations n_s indicated in the table and one year of running with a luminosity of $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. We also give in the table the minimum value of $|\alpha'(N_b)P(N_b)|$ appearing in the angular distribution given by formula (6) namely,

$$I_1(\Theta) \propto 1 \pm \alpha'(N_b) P(N_b) \cos \Theta . \quad (6)$$

In the same manner as above the minimum value that could be measured with given N and n_s is obtained from

$$[\alpha'(N_b)P(N_b)]_{min} = \left[\frac{3n_s^2}{N + n_s^2} \right]^{1/2} . \quad (13)$$

Table 6 - The minimum of the absolute values of $\alpha''(N_b)$ and $[\alpha'(N_b)P(N_b)]$ that could be measured with n_s standard deviations and one year of running with a luminosity of $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. For the second channel we take $n_s = 3$ because of its small statistics (see Table 5).

Channel	n_s	$\alpha''(N_b)$	$\alpha'(N_b)P(N_b)$
$\Lambda_b \rightarrow \Lambda J/\Psi$	5	0.031	0.020
$\Xi_b^- \rightarrow \Xi^- J/\Psi$	3	0.14	0.09

The results are presented in Table 6 for the two channels considered taking again into account the expected backgrounds.

Because of the large statistics expected for the $\Lambda_b \rightarrow \Lambda J/\psi$ (and $\bar{\Lambda}_b \rightarrow \bar{\Lambda} J/\psi$) channel, we estimate for this case the lower limit of the measurement of the CP asymmetry parameter

$$A'' = \frac{\alpha''(\Lambda_b) + \bar{\alpha}''(\bar{\Lambda}_b)}{\alpha''(\Lambda_b) - \bar{\alpha}''(\bar{\Lambda}_b)}. \quad (14)$$

Practically, one measures the $\alpha''\alpha \equiv \alpha''(\Lambda_b)\alpha(\Lambda)$ and the $\bar{\alpha}''\bar{\alpha} \equiv \bar{\alpha}''(\bar{\Lambda}_b)\bar{\alpha}(\bar{\Lambda})$ quantities that can be compared by using the ratio

$$A_m = \frac{\alpha''\alpha - \bar{\alpha}''\bar{\alpha}}{\alpha''\alpha + \bar{\alpha}''\bar{\alpha}} \simeq \frac{\alpha'' + \bar{\alpha}''}{\alpha'' - \bar{\alpha}''} + \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}. \quad (15)$$

Assuming that there is no CP violation in the Λ decay ($\alpha + \bar{\alpha} = 0$) one obtains $A_m = A''$. The calculated error on A'' depends on the value of $|\alpha''|$ (see Appendix) and will then lead to^{15,19}:

$$(\alpha'' A'')_{min} \simeq \frac{n_s}{\alpha} \left(\frac{3}{2N} \right)^{1/2}. \quad (16)$$

With one year of running and $n_s = 5$, one obtains $(\alpha'' A'')_{min} \simeq 2.2 \cdot 10^{-2}$.

5 - The N_b decays into two particles with spin 1/2 and 0

Let us now evaluate the number of N_b events decaying into two particles with a spin configuration of $1/2 \rightarrow 1/2 + 0$. In principle, the $\alpha(N_b)$ decay parameter could be measured [formula (1)] as well as the polarization $P(N_b)$ [formula (4)] from the N_b events produced with the decay channels $N_b \rightarrow YM$. Table 7 presents some decay channels having only charged particles in the final state. Rough estimates of branching ratios of these processes are also given. In addition to these channels

Table 7 - The branching ratios (BR) for various final states due to N_b decaying into two particles having spin 1/2 and spin 0. The $BR(J/\Psi \rightarrow \mu^+\mu^-)=0.06$, $BR(\Lambda \rightarrow p\pi^-) = 0.64$ and $BR(K_s^0 \rightarrow \pi^+\pi^-) = 0.69$ are not indicated. The total branching ratio is represented by $BR(tot)$.

Channel	BR	$BR(tot)$	Final state
$\Lambda_b \rightarrow \Lambda D^0$ $D^0 \rightarrow K^-\pi^+$	$\sim 10^{-3}$ $\sim 3.7 \cdot 10^{-2}$	$\sim 2.4 \cdot 10^{-5}$	$pK^-\pi^+\pi^-$
$\Lambda_b \rightarrow \Lambda \bar{D}^0$ $\bar{D}^0 \rightarrow K^+\pi^-$	$\sim 2 \cdot 10^{-4}$ $\sim 3.7 \cdot 10^{-2}$	$\sim 4.7 \cdot 10^{-6}$	$pK^+\pi^-\pi^-$
$\Lambda_b \rightarrow \Lambda_c^+\pi^-$ $\Lambda_c^+ \rightarrow pK^+\pi^-$ $\Lambda_c^+ \rightarrow pK^0$	$\sim 2 \cdot 10^{-1}$ $\sim 3.2 \cdot 10^{-2}$ $\sim 1.6 \cdot 10^{-2}$	$\sim 6.4 \cdot 10^{-3}$ $\sim 10^{-3}$	$pK^+\pi^+\pi^-$ $p\pi^+\pi^+\pi^-$
$\Xi_b^0 \rightarrow \Lambda D^0$ $D^0 \rightarrow K^-\pi^+$	$\sim 2 \cdot 10^{-2}$ $\sim 3.7 \cdot 10^{-2}$	$\sim 4.7 \cdot 10^{-4}$	$pK^-\pi^+\pi^-$
$\Xi_b^- \rightarrow \Xi^- D^0$ $\Xi^- \rightarrow \Lambda\pi^-$ $D^0 \rightarrow K^-\pi^+$	$\sim 10^{-3}$ ~ 1 $\sim 3.7 \cdot 10^{-2}$	$\sim 2.4 \cdot 10^{-5}$	$pK^-\pi^+\pi^-\pi^-$
$\Xi_b^- \rightarrow \Xi_c^0\pi^-$ $\Xi_c^0 \rightarrow \Xi^-\pi^+$ $\Xi^- \rightarrow \Lambda\pi^-$	$\sim 2 \cdot 10^{-1}$ $\sim 5.8 \cdot 10^{-3}$ ~ 1	$\sim 7.4 \cdot 10^{-4}$	$p\pi^+\pi^-\pi^-\pi^-$

we also consider the $\Lambda_b \rightarrow \Lambda_c^+ M$ with $\Lambda_c \rightarrow pK^+\pi^-, pK^0$. The detection of all the reactions is based on the semileptonic leptonic decay (with $l = \mu$) of the associated beauty hadron produced in the event. In this one-muon trigger (Section 3.1), the transverse momentum and the pseudorapidity of the muon candidate are $p_T(\mu) > 9 \text{ GeV}/c$, $|\eta| < 2.4$, respectively. For all the channels indicated in Table 7, we obtain a trigger efficiency of $\epsilon_{tr} = 0.010$ (Ref. 7). The detection efficiencies ϵ_{cut} for the various channels are given in Table 8. They are estimated with the cuts and conditions defined by points 1, 2, 4 – 6 and 8 described in Section 4.1. However, in point 1 we take $p_T > 1.5 \text{ GeV}/c$ for the charged hadrons. With these efficiencies the number of events obtained in one year of running is estimated as well as the signal-over-background ratio. One sees from Table 8 that the observation of $\Lambda_b \rightarrow \Lambda D^0$ and $\Xi_b^0 \rightarrow \Lambda D^0$ could be attempted in one year of running with the luminosity considered. In contrast, more important statistics for the $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$

Table 8 - Same as Table 5 but this time for N_b decaying into two particles having spins 1/2 and 0. For the one-muon trigger one has here $\epsilon_{tr} = 0.010$ for all cases.

Channel	$\sigma(N_b)$ (μb)	ϵ_{cut}	N_{sig}	N_{sig}/N_{back}
$\Lambda_b \rightarrow \Lambda D^0$	24	0.13	~ 120	~ 2
$\Lambda_b \rightarrow \Lambda \bar{D}^0$	24	0.13	~ 30	~ 2
$\Lambda_b \rightarrow \Lambda_c^+ \pi^-$	24			
$\Lambda_c^+ \rightarrow p K^+ \pi^-$		0.05	~ 9500	~ 4
$\Lambda_c^+ \rightarrow p K^0$		0.02	~ 570	~ 2
$\Xi_b^0 \rightarrow \Lambda D^0$	1.7	0.09	~ 120	~ 2
$\Xi_b^- \rightarrow \Xi^- D^0$	1.7	0.06	~ 10	--

are expected with the $\Lambda_c^+ \rightarrow p K^+ \pi^-$, $p K^0$. By analyzing these data with the distributions given by formulae (1) and (4), one could measure the following quantities:

$$\alpha(\Lambda_b \rightarrow \Lambda_c^+ \pi^-) P(\Lambda_b) \quad \text{and} \quad (17a)$$

$$\alpha(\Lambda_b \rightarrow \Lambda_c^+ \pi^-) \alpha(\Lambda_c^+ \rightarrow p K^0) \quad (17b)$$

as well as the values obtained from the charged conjugate channels. Taking into account the background, we estimate the minimum values that could be observed with n_s standard deviations after one year of running with the luminosity of $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ (Table 9).

For the specific $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$, one can expect the possibility of measuring the polarization of Λ_b . Indeed, theoretical models²⁰⁻²³ predict the values of the decay parameters $\alpha(\Lambda_b \rightarrow \Lambda_c^+ \pi^-) \simeq \pm 1$ and $\alpha(\Lambda_c^+ \rightarrow \Lambda \pi^+) \simeq \pm 1$ using only spectator diagrams (factorizable contributions) as shown in Fig. 5. The $\alpha(\Lambda_c^+ \rightarrow \Lambda \pi^+)$ parameter has been measured yielding -0.96 ± 0.42 (Ref. 24) and $-1_{-0.0}^{+0.4} \pm 0.1$ (Ref. 25), in agreement with the theoretical predictions. Assuming that the same type of mechanism will contribute to the Λ_b ($\bar{\Lambda}_b$) decay (see Fig. 5), one can expect that the $|\alpha(\Lambda_b \rightarrow \Lambda_c^+ \pi^-)|$ could also be close to one. Then the minimum value of the measurement of the Λ_b (or $\bar{\Lambda}_b$) polarization after one year of running and with $n_s = 5$ will be $\simeq 0.11$.

Table 9 - The minimum of the absolute values that can be measured from the $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ decay in one year of running are estimated. We consider n_s standard deviations and a luminosity of $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. For the second channel we take $n_s = 3$ because of its small statistics.

Channel	n_s	$\alpha(\Lambda_b) \alpha(\Lambda_c \rightarrow pK^0)$	$\alpha(\Lambda_b) P(\Lambda_b)$
$\Lambda_b \rightarrow \Lambda_c^+ \pi^-$	5	--	0.11
$\Lambda_c \rightarrow pK^+ \pi^-$			
$\Lambda_b \rightarrow \Lambda_c^+ \pi^-$	3	0.28	--
$\Lambda_c \rightarrow pK^0$			

The predominance of the diagrams shown in Fig. 5 for the $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ and $\Lambda_c^+ \rightarrow \Lambda \pi^+$ may also give some information on the ratio of the CKM matrix elements $|V_{cb}/V_{cs}|$. Assuming that the QCD effects are similar in both diagrams, the relations between the following branching ratios could be expressed by

$$\frac{BR(\Lambda_b \rightarrow \Lambda_c^+ \pi^-)}{BR(\Lambda_c^+ \rightarrow \Lambda \pi^+)} \simeq \frac{|V_{cb}|^2}{|V_{cs}|^2} \frac{\phi(b)}{\phi(c)}.$$

Here $\phi(b)$ [$\phi(c)$] is the phase-space factor corresponding to the $b \rightarrow c$ ($c \rightarrow s$) transition for the final state considered. In this approach the systematic error on the measurement of $|V_{cb}|$ due to the actual knowledge of $|V_{cs}|$ will be of the order of 1.6×10^{-2} .

6 - Suggestions and summary

In the present discussion we consider only beauty baryons having a b quark and two of the light quarks $q = u, d, s$. As a first step we suggest the measurement of the production rates of beauty-baryon in pp interactions as well as their decay branching ratios. The comparison between the production of beauty baryon (N_b) and their charge conjugate ones ($\bar{N}_b$) could be tested as their production rates are not necessarily equal in pp interactions. For the decay channels considered here, the differences between the $N_b \rightarrow f$ and $\bar{N}_b \rightarrow \bar{f}$ rates cannot be due to CP violation effects as one would always have

$$\Delta = \frac{\Gamma(N_b \rightarrow f) - \Gamma(\bar{N}_b \rightarrow \bar{f})}{\Gamma(N_b \rightarrow f) + \Gamma(\bar{N}_b \rightarrow \bar{f})} = 0$$

(with or without CP violation effects) in the framework of the standard model. Therefore, the N_b and $\bar{N}_b$ comparison through the considered decay channels could

lead to a better understanding of the production mechanism at large c.m. energies. Another aspect related to production process would be to compare the polarization $\vec{P}(N_b)$ and $\vec{P}(\bar{N}_b)$ of the produced N_b and $\bar{N}_b$, respectively.

We consider the measurement of decay parameters of the $N_b, \bar{N}_b$ decaying into two particles within the spin configuration

$$1/2 \rightarrow 1/2 + 1 \quad \text{or} \quad 1/2 \rightarrow 1/2 + 0 .$$

The comparison of the decay parameters between two charge conjugate decay channels leads to the search for CP violation in the beauty baryon decay. We discuss the (different) decay parameters that could be used in both cases. If the polarizations are known (and if $\vec{P}(N_b), \vec{P}(\bar{N}_b) \neq 0$) additional decay parameters could be envisaged.

For having an order of magnitude of the N_b production rate, we consider the Compact Muon Solenoid (CMS) detector and a pp luminosity of $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ at a c.m. energy of 14 TeV (the Large Hadron Collider project). The N_b ($\bar{N}_b$) decays having a J/ψ and a Λ ($\bar{\Lambda}$) among the outgoing particles could be detected easily despite the absence of particle identification in the CMS detector. In this case ($1/2 \rightarrow 1/2 + 1$), the polarizations $\vec{P}(N_b)$ and $\vec{P}(\bar{N}_b)$ will not be measured directly but compared (direction and size) assuming that any CP violation effect on the decay parameter α' (Section 2.1 b) will have a smaller influence than the measurement errors on the decay parameter. With our rough estimates of the N_b cross-sections and branching ratios, as well as the detection efficiencies of the CMS detector, one can expect to study the decay channels

$$\begin{aligned} \Lambda_b &\rightarrow \Lambda J/\psi , \quad \sim 2 \times 10^5 \text{ events/year} \\ \Xi_b^- &\rightarrow \Xi^- J/\psi , \quad \sim 8 \times 10^3 \text{ events/year} . \end{aligned}$$

With these estimations only the $\Lambda_b \rightarrow \Lambda J/\psi$ could be envisaged to search for CP violation effects.

The study of N_b decaying according to the $1/2 \rightarrow 1/2 + 0$ spin properties will be difficult because of the triggering (semileptonic decay of the associated beauty hadron). However, the decays of the

$$\begin{aligned} \Lambda_b &\rightarrow \Lambda_c^+ \pi^- , \quad \Lambda_c^+ \rightarrow p K^+ \pi^- ; \quad \sim 9500 \text{ events/year} \\ \Lambda_b &\rightarrow \Lambda_c^+ \pi^- , \quad \Lambda_c^+ \rightarrow p K^0 \quad ; \quad \sim 570 \text{ events/year} \end{aligned}$$

could be investigated. By assuming the validity of theoretical models predicting that the decay parameter $|\alpha(\Lambda_b \rightarrow \Lambda_c^+ \pi^-)| \simeq 1$ (similar to the prediction and

measurement of $|\alpha(\Lambda_c^+ \rightarrow \Lambda \pi^+)| \simeq 1$, the polarizations $\vec{P}(\Lambda_b)$ and $\vec{P}(\bar{\Lambda}_b)$ could be measured. With these assumptions we estimate that the minimum of the polarization modulus that could be measured with 5 standard deviations in one year of running would be ~ 0.11 . Assuming the predominance of the factorizable contribution for the $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ and $\Lambda_c^+ \rightarrow \Lambda \pi^+$ decays, one could also have an estimate of the $|V_{cb}|$ CKM matrix element.

To summarize, we present various interests for studying beauty baryons, production and decay, in pp interactions at c.m energies around 14 TeV. The production rates presented have to be considered as an order of magnitude because of our rough estimates of cross-sections and branching ratios. Moreover, the detector used for our estimates is not planned to investigate beauty-hadron physics as a first priority. Nevertheless, various aspects related to beauty baryons could be studied with the detector considered. One has also to note that the utilization of a vertex-detector device, particle identification and the development of further trigger methods could be very useful for improving the beauty-hadron program with the detector type that we considered.

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Appendix

a - The background influence on the decay parameter measurements

We discuss the measurement of a parameter (called here x) appearing in an angular distribution of the type $I(\theta) \propto 1 + x \cos(\theta)$. If we define this distribution as a probability density of the $\cos \theta$ variable, $f(\cos \theta)$, one would have

$$f(\cos \theta) = \frac{1}{2} (1 + x \cos \theta) \quad (a.1)$$

This leads to the following expressions used to calculate the number of events (N) required to observe an x value with n_{sd} standard deviations, or the minimum value of x that could be measured with given N and n_{sd} values, namely:

$$N = n_{sd}^2 \left[\frac{3}{x^2} - 1 \right] \quad (a.2)$$

$$x_{min} = \left[\frac{3n_{sd}^2}{N + n_{sd}^2} \right]^{1/2} \quad (a.3)$$

Assuming that the background of a $k = N_{back}/N_{sig}$ importance contribute to a constant $\cos \theta$ distribution, the density probability becomes

$$f(\cos \theta) = \frac{1}{2} \left(1 + \frac{x}{1+k} \cos \theta \right) . \quad (a.4)$$

This distribution transforms formulae (a.2) and (a.3) to the expressions:

$$N = n_{sd}^2 \left[\frac{3(1+k)^2}{x^2} - 1 \right] \quad (a.6)$$

$$x_{min} = \left[\frac{3n_{sd}^2}{N + n_{sd}^2} \right]^{1/2} (1+k) \quad (a.3)$$

b - Measurement of the asymmetry parameter

Let us estimate the error in the measurement of the asymmetry parameter A'' depending on the decay parameters α'' of the various beauty-baryon channels. For

simplicity let us take the example of $\Lambda_b \rightarrow \Lambda J/\Psi$ where $\Lambda \rightarrow p\pi^-$ and

$$\alpha'' \equiv \alpha''(\Lambda_b) ; \quad \alpha \equiv \alpha(\Lambda)$$

($\bar{\alpha}''$ and $\bar{\alpha}$ will denote the decay of the conjugated particles). The angular distribution of the meson in the Λ rest frame [formula (10)]:

$$I(\theta_3) \propto 1 - \alpha''\alpha \cos \theta_3 \quad (10)$$

allows the measurement of $x = \alpha''\alpha$ whereas $\bar{x} = \bar{\alpha}''\bar{\alpha}$ will be obtained from the $\bar{\Lambda}_b$ cascade decay. The difference between these measured quantities, i.e.

$$A_m = \frac{\alpha''\alpha - \bar{\alpha}''\bar{\alpha}}{\alpha''\alpha + \bar{\alpha}''\bar{\alpha}} \simeq \frac{\alpha'' + \bar{\alpha}''}{\alpha'' - \bar{\alpha}''} + \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} , \quad (15)$$

could be used to search for CP violation in the Λ_b decay. By neglecting CP violation in the Λ decay, we would have $A_m = A''$. The error on the A'' measurement will then be given by

$$\Delta A'' = \frac{2}{(x + \bar{x})^2} \sqrt{x^2 (\Delta \bar{x})^2 + \bar{x}^2 (\Delta x)^2} . \quad (b.1)$$

From the measurement of the angular distributions $I_3(\theta)$ coming from the Λ_b decay [formula (4)], the error on $x = \alpha\alpha''$ is then given by

$$(\Delta x)^2 = \frac{3}{N} \left(1 - \frac{x^2}{3}\right) \simeq \frac{3}{N} , \quad (b.2)$$

where N is the number of events used for the measurement of the angular distribution. In the expression used to determine $\Delta A''$ we use the approximations $\Delta x \simeq \Delta \bar{x}$ and $x \simeq \bar{x}$. This leads to

$$(\Delta A'')^2 \simeq \frac{3}{2N} \frac{1}{(\alpha''\alpha)^2} \quad (b.3)$$

and to the minimum value that can be measured

$$(\alpha'' A'')_{min} = \frac{n_s}{\alpha} \left(\frac{3}{2N} \right)^{1/2} \quad (b.4)$$

with N being the number of events and n_s the number of standard deviations.

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

Fig. 2 - The misidentification of the Λ decay particles ($p\pi^- \rightarrow \bar{p}\pi^+$) leads to the effective mass [$M(\bar{p}\pi^+)$] distribution shown in this figure. Our kinematical cuts were applied to the events generated by PYTHIA and having a Λ in the final state.

Fig. 3 - The effective $\mu^+\mu^-$ mass [$M(\mu^+\mu^-)$] distribution for muons coming from the $b\bar{b}$, bc and $c\bar{c}$ decays produced in the $pp \rightarrow b\bar{b}X$ reaction. No kinematical cuts were applied to the μ . Note that in case (2), the charged conjugated processes have also to be taken into account for the background estimate.

Fig. 4 - The effective $\Lambda J/\psi$ mass distribution for generated events where a $\Lambda_b \rightarrow \Lambda J/\psi$ candidate appears in the final state after our cuts and selection procedures (see text).

Fig. 5 - Spectator diagrams responsible for the $\Lambda_c^+ \rightarrow \Lambda \pi^-$ and $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ decays.