1. PHYSICAL MOTIVATIONS

Modern Particle Physics is well described by gauge field theories which are built on fundamental principles, the most important ones being Lorentz Invariance, Unitarity and Hermiticity. An immediate consequence of these principles is the famous CPT theorem which stipulates that any physical system and its CPT-conjugate have identical physical laws. On another side, CPT theorem supposes that, if CP symmetry is violated, Time Reversal (TR) is no longer a good symmetry and this mathematical feature represents only an indirect violation of TR symmetry. However some experiments performed recently at CERN and Fermilab have shown a clear signal of direct TR violation in the $K^0\bar{K}^0$ system. Our aim is to demonstrate that search for direct TR violation can be performed at the LHC energies by studying the cascade decays of $\Lambda_b \to AV (1-)$ decays because of $\Lambda_b$ weak decays, the intermediate resonances are polarized and some components of their vector-polarization $\vec{P}$ are not invariant by TR; (ii) it is expected that $\Lambda_b$ produced in p-p collisions is transversely polarized like ordinary hyperons in hadron collisions and, this physical property will be exploited in order to find many interesting TPC parameters which are T-odd, see Ref. [2].

2. DYNAMICS OF $\Lambda_b$ DECAYS

At LHC energies, 10% of the produced $b\bar{b}$ pairs hadronize into beauty baryons $B_0 = \Lambda_b, \Sigma_b, \Xi_b, ...$ and approximately 90% of $B_0$ are dominated by $\Lambda_b$. Recently many authors have pointed out the possibility of both testing TR invariance and searching for New Physics in $\Lambda_b$ three-body decays like $\Lambda_b \to Baryon \ell^+\ell^-$, $Baryon h^+h^-$, where $\ell^\pm$ and $h^\pm$ could originate from continuum and/or resonances like $J/\psi$. The model developed in references [12] is based on the same final states but, emphasis is put on measuring physical observables built from the two intermediate resonances, $\Lambda$ and $J/\psi$ or $\rho^0 - \omega$ which come from $\Lambda_b$ decays. Our method offers some advantages: (i) because of $\Lambda_b$ weak decays, the intermediate resonances are polarized and some components of their vector-polarization $\vec{P}$ are not invariant by TR; (ii) it is expected that $\Lambda_b$ produced in p-p collisions is transversely polarized like ordinary hyperons in hadron collisions and, this physical property will be exploited in order to find many interesting TPC parameters which are T-odd, see Ref. [2].

2.1. Cascade decays

The initial laboratory frame to which $\Lambda_b$ polarization is referred is defined like: $\vec{e}_1 = p_1^f/p_1, e_3^f = \vec{p}_\Lambda^f \times \vec{p}_b^f$, $\vec{e}_2 = e_3^f \times e_1^f$ where $p_1$ and $p_b$ are respectively the incident proton momentum and the produced $\Lambda_b$ one. $\Lambda_b$ being transversely polarized, its polarization value is given by $P_{\Lambda_b} = \langle S_{\Lambda_b}^\perp \cdot e_3^f \rangle$. Let $M_i$ be the $\Lambda_b$ spin projection along $e_3^f$ axis and, $\lambda_1$ and $\lambda_2$ are respectively the helicity values of $\Lambda$ and $V$. Conservation of total angular momentum leads to four possible values for the pair $(\lambda_1, \lambda_2) = (1/2, 0), (1/2, 1), (-1/2, -1), (-1/2, 0)$.
are evaluated from the effective hamiltonian, expansion with
\[ H_{\text{ME}} = \text{current products} \]
from which the decay probability can be deduced, \[ d\sigma \propto \sum_{M_i,M'_i} \rho_{M_i,M'_i}^{\Lambda_b} A_t A'_t \].

2.2. Hadronic matrix element (HME)

Full computation of the HME has been performed by using the Operator Product Expansion (OPE) formalism supplemented by hypothesis derived from the Heavy Quark Effective Theory (HQET). In the framework of the factorization hypothesis, the HME can be written as: \[ \mathcal{A}(\Lambda_b \rightarrow A\nu) = \frac{G_F}{\sqrt{2}} f_V E_V \langle A|s\Gamma_{\mu\nu}|b\rangle \]

\[ \left\{ M_{\Lambda_b}^{T,P}(\Lambda_b \rightarrow A\nu) - M_{\Lambda_b}^{T,P}(\Lambda_b \rightarrow \Lambda\nu) \right\} , \]

with \( \Gamma_{\mu\nu} = \gamma_\mu(1 - \gamma_5) \), \( M_{\Lambda_b}^{T,P}(\Lambda_b \rightarrow A\nu) = V_{ckm}^{##} A_{V}^{T,P}(c_i) \), where \( f_V \) is the vector-meson decay constant, \( A_{V}^{T,P}(c_i) \) are tree (T) and penguin (P) amplitudes made of combinations of Wilson coefficients according to the nature of \( V(1^-) \), \( V_{ckm} \) are the Cabbibo-Kobayashi-Maskawa matrix elements and, finally the \( \rho^0 - \omega \) mixing is taken into account for the case \( V \rightarrow \pi^+\pi^- \).

3. MAIN PHYSICAL RESULTS

Several results which can be tested experimentally have been obtained. The most important ones are:

3.1. Branching ratios

In the framework of the factorization hypothesis, the color number is an effective parameter which is let free. The different branching ratios are proportional to the following width given by:

\[ \Gamma(\Lambda_b \rightarrow A\nu) = \frac{E_{\Lambda_{b}} + M_{\Lambda_{b}}}{M_{\Lambda_{b}}} \frac{P_{V}}{16\pi^2} \int_{\Omega} |A_{0}(M_{b})|^2 d\Omega , \]

while the only experimental branching ratios (Ref. \cite{3}) is \( BR^{\exp}(\Lambda_b \rightarrow A\nu) = (4.7 \pm 2.1 \pm 1.9) \times 10^{-4} \) which permits to state that \( 2.0 \leq N_{c}^{\text{eff}} \leq 3.0 \). Numerical results are shown in Table 1.

3.2. Polarizations and asymmetries

Values of the resonance polarizations as well as their density matrix are essential ingredients for Monte-Carlo simulations, particularly for angular distributions. They can be computed from our model as well as other parameters like \( \Lambda \) helicity asymmetries. In Table 2 are listed the numerical results: It is worth noticing that (i) all these "geometrical" parameters do not depend on \( N_{c}^{\text{eff}} \).

Table 1: Branching ratio, \( BR \), for \( \Lambda_b \rightarrow A\nu, \Lambda_b \rightarrow \Lambda\rho^0 \) and \( \Lambda_b \rightarrow \Lambda\omega \).

| \( N_{c}^{\text{eff}} \) | 2       | 2.5     | 3       | 3.5     |
|-----------------|---------|---------|---------|---------|
| \( \Lambda \nu \) | 8.95 × 10^{-4} | 2.79 × 10^{-4} | 6.20 × 10^{-4} | 0.03 × 10^{-4} |
| \( \Lambda\rho^0 \) | 1.62 × 10^{-7} | 1.89 × 10^{-7} | 2.2 × 10^{-7} | 2.4 × 10^{-7} |
| \( \Lambda\omega \) | 22.3 × 10^{-7} | 4.75 × 10^{-7} | 0.2 × 10^{-7} | 0.64 × 10^{-7} |
Table 2
Polarizations and asymmetries in case of $\Lambda_b \rightarrow \Lambda V$ with $V$ is $\rho^0(\omega)$ or $J/\Psi$.

| Parameter | $\Lambda \rho^0 - \omega$ | $\Lambda J/\Psi$ |
|-----------|--------------------------|-----------------|
| $\alpha_{\Lambda_b}^{\Lambda_N}$ | 0.194 | 0.490 |
| $\rho^\Lambda$ | -0.21 | -0.17 |
| $\rho^0_{+-}$ | 0.31 | 0.25 |
| $\rho^0_{00}$ | 0.79 | 0.66 |

but they are related directly to the weak decay process and, (ii) longitudinal polarizations of the vector mesons are dominant.

3.3. Effects of $\rho^0 - \omega$ Mixing

Figure 1. Branching ratio asymmetry, $a_{CP}(\omega)$, as a function of the $\pi^+\pi^-$ invariant mass in case of $\Lambda_b \rightarrow \Lambda \rho^0(\omega) \rightarrow \Lambda \pi^+\pi^-$ and for $N_{eff}^{c} = 3$.

The asymmetry parameter between two conjugate channels defined by:

$$a_{CP}(s_p) = \frac{BR(\Lambda_b) - BR(\bar{\Lambda}_b)}{BR(\Lambda_b) + BR(\bar{\Lambda}_b)}$$

where $s_p$ is $\pi^+\pi^-$ invariant mass, varies with $N_{eff}^{c}$ and it is usually too small, $a_{CP} \lesssim 10^{-3}$. However in the case of $\rho^0 - \omega \rightarrow \pi^+\pi^-$, this asymmetry is amplified in the vicinity of the $\omega$ mass $[4]$, as it is shown on Fig. 1, and it reaches 7.5% at the $\omega$ pole for $N_{eff}^{c} = 3.0$. This process is a new way to detect Direct CP Violation, as it has been already shown in beauty meson $B$ decays.

4. TIME ODD OBSERVABLES

The initial laboratory frame is transposed to the $\Lambda_b$ rest-frame as $(\vec{e}_X, \vec{e}_Y, \vec{e}_Z)$ with $\vec{e}_Z$ parallel to $\vec{p}$. For each resonance with momentum $\vec{p}$, a new frame is defined (Jackson [5]) as follows:

$$\vec{e}_L = \frac{\vec{p} \times \vec{p}}{|\vec{p} \times \vec{p}|}, \quad \vec{e}_T = \frac{\vec{e}_Z \times \vec{e}_L}{|\vec{e}_Z \times \vec{e}_L|}, \quad \vec{e}_N = \vec{e}_T \times \vec{e}_L.$$  

4.1. Vector-polarization

Each vector-polarization $\vec{P}^{(i)}$ can be expanded on the new basis and its components are studied under Parity and Time-Reversal operations.

$$\vec{P}^{(i)} = P_L^{(i)} \vec{e}_L + P_N^{(i)} \vec{e}_N + P_T^{(i)} \vec{e}_T,$$

with $P_j^{(i)} = \vec{P}^{(i)} \cdot \vec{e}_j$ and $j = L, N, T$. It could be noticed that if the normal component $P_N$ is non equal to zero, it would be a clear signal of TR Violation. See Table 3 for TR and parity operations on vector polarization.

4.2. Special angles

$\vec{n}_\Lambda$ and $\vec{n}_V$ are defined respectively as the unit normal vetors to $\Lambda$ and $V$ decay planes.

$$\vec{n}_\Lambda = \frac{\vec{p}_\Lambda \times \vec{p}_\pi}{|\vec{p}_\Lambda \times \vec{p}_\pi|}, \quad \vec{n}_V = \frac{\vec{p}_V \times \vec{p}_{\bar{\pi}}}{|\vec{p}_V \times \vec{p}_{\bar{\pi}}|}.$$

Table 3
Vector-polarization under Parity and TR operations.

| Observable | Parity | TR |
|------------|--------|----|
| $\vec{s}$  | Even   | Odd|
| $\vec{P}$  | Even   | Odd|
| $\vec{e}_Z$| Even   | Even|
| $\vec{e}_L$| Odd    | Odd|
| $\vec{e}_T$| Odd    | Odd|
| $\vec{e}_N$| Even   | Even|
| $P_L$      | Odd    | Even|
| $P_T$      | Odd    | Even|
| $P_N$      | Even   | ODD|
Those vectors are even under TR; but, if we compute the cosine and the sine of their azimuthal angles, \( \phi_{(n_1)} = \phi_{\vec{n}_A}, \phi_{\vec{n}_V} \), as it was suggested by Seghal and Wolfenstein for the decay \( K_L^0 \to \pi^+ \pi^- e^+ e^- \), \( \vec{u}_i = \frac{\vec{e}_Z \times \vec{m}}{|\vec{e}_Z \times \vec{m}|} \), \( \cos \phi_{(n_i)} = \vec{e}_Y \cdot \vec{u}_i \), \( \sin \phi_{(n_i)} = \vec{e}_Z \cdot (\vec{e}_Y \times \vec{u}_i) \), we notice that \( \cos \phi_{(n_i)} \) and \( \sin \phi_{(n_i)} \) are odd under TR; and these asymmetries depend essentially on the azimuthal angle distributions of the \( \Lambda_b \) resonance in the \( \Lambda_b \) rest-frame, which analytical expression is given by:

\[
\frac{d\sigma}{d\phi} \propto 1 + \frac{\pi}{2} \alpha_{AS} \left( \Re(\rho_{\Lambda^0_b}) \cos \phi - \Im(\rho_{\Lambda^0_b}) \sin \phi \right).
\]

By choosing conservative values for the nondiagonal elements of the \( \Lambda_b \) polarization density matrix: \( \Re(\rho_{\Lambda^0_b}) = -\Im(\rho_{\Lambda^0_b}) = \sqrt{2}/2 \), the following asymmetries are obtained:

- For \( \Lambda_b \to \Lambda J/\psi \), one obtains:
  
  \( \alpha_{AS}(\cos \phi_{\vec{n}_A}) = 4.3\% \),
  
  \( \alpha_{AS}(\sin \phi_{\vec{n}_A}) = -5.5\% \).

- For \( \Lambda_b \to \Lambda \rho^0(\omega) \), one obtains:
  
  \( \alpha_{AS}(\cos \phi_{\vec{n}_A}) = 2.4\% \),
  
  \( \alpha_{AS}(\sin \phi_{\vec{n}_A}) = -2.7\% \).

But, no asymmetries in \( \cos \phi_{\vec{n}_V} \) and \( \sin \phi_{\vec{n}_V} \) of the resonances \( V(1^-) \) are seen. A realistic explanation for these different asymmetries is suggested: (i) T-Odd or TRV effects appear in processes where already Parity is violated like \( \Lambda \to p \pi^- \), (ii) while for processes as \( V(1^-) \to \ell^+ \ell^-, h^+ h^- \) where Parity is conserved, T-Odd effects are absent.

5. CONCLUSION

Complete calculations of the processes \( \Lambda_b \to \Lambda V(1^-) \) have been performed. On the kinematics side, they are based on the helicity formalism and the use of resonance polarization density matrices. On the dynamics side, sophisticated methods using the OPE formalism and HQET have been developed in the framework of the factorization hypothesis. Our model is entirely built in the framework of the Standard Model. No ingredients coming from “Beyond Standard Model” are introduced. The only unknown parameters are the elements of the polarization density matrix of the produced \( \Lambda_b \) in p-p collisions. By adopting conservative values for these matrix elements and an entirely polarized \( \Lambda_b \), asymmetries related to Time-Reversal Invariance are observed. So, crucial questions may arise: (i) Is there any dynamics behind Time-Reversal Violation? (ii) Is this dynamics related to the CKM mechanism? Whatever are the answers, it is plausible to assert that Time-Reversal Violation or T-odd processes are real challenges for the next LHC experiments.

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