CP Symmetry and Time Reversal in $\Lambda_b \rightarrow \Lambda V(1^-)$

An Experimentalist-Theorist Collaboration

"Λ_b Decays into Λ-Vector", Physics Letters B614 (2005), 165-173;
"Testing Fundamental symmetries with Λ_b Decays", hep-ph/0602043;
"Analysis of $\Lambda_b \rightarrow \Lambda J\psi$", LHCb Physics 2005-067

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Summary

I)- Physical Motivations : $\Lambda_b \to \Lambda V(1^-)$

II)- Kinematics and Dynamics of Cascade Decays.

III)- Physical Results :
$\star$ Branching Ratios,
$\star$ Asymmetries,
$\star$ Polarizations,
$\star$ Time-Odd Observables.

IV)- Perspectives with LHCb Detector.

I- Physical Motivations

$\approx 10\%$ of produced $b\bar{b}$ pairs hadronize into Beauty Baryons :
$\mathcal{B}_b = \Lambda_b,\ \Sigma_b,\ \Xi_b, ...$
$\approx 90\%$ of $\mathcal{B}_b$ dominated by $\Lambda_b(\bar{\Lambda}_b)$.

$$\Downarrow$$

- Testing the validity of **CP** symmetry in Beauty Baryons like in ordinary Hyperons :

$$\Gamma(\mathcal{B}_b \to X) \neq \Gamma(\bar{\mathcal{B}}_b \to \bar{X}) \oplus \text{ Other Observables}$$

- Further Step :

$$\text{Hyperon } \mathcal{B}_s \longleftrightarrow \textit{Baryon } \mathcal{B}_b$$
$$\Downarrow$$
s-quark replaced by b-quark
$$\Downarrow$$
Significant Increase of the number of tests of both CP and TR Symmetries.

Main Properties of TR Operator

$$\vec{r} \to \vec{r},\ \vec{p} \to -\vec{p},\ \vec{\ell} = \vec{r} \times \vec{p} \to -\vec{\ell},\ \text{spin}\ \vec{s} \to -\vec{s}$$

AND

Initial State $\longleftrightarrow$ Final State

BUT

Impossibility to realize in Nature the Time-Reversed process of a physical one, like β Decay, $\Lambda \longrightarrow p\pi^-$

SO

$*$ Initial and Final States are NOT interchanged

$\Downarrow$

Time-Odd Operator $\neq$ Time-Reversal

$\Downarrow$

Triple Product Correlations (TPC)

$\star$ Pseudo-Scalar observables which change sign under TR :

$$\vec{v_i} = \vec{p_i}, \vec{s_i}\ ,\ C_{ijk} = \vec{v_i} \cdot (\vec{v_j} \times \vec{v_k}) \longrightarrow TR \rightarrow -C_{ijk}$$

like Transverse Polarization : $\vec{s_i} \cdot (\vec{p_j} \times \vec{p_k})$

IF : $< C_{ijk} > \neq 0 \quad \equiv$ distribution of C_{ijk} is not symmetric

$$\Downarrow$$

Sign of T-Odd effect

- T-Odd effect can be taken as a "Serious Candidate" for a TRV process if :

$\ast$ Final State Interactions (FSI) are negligible .

OR

$\ast$ FSI can be computed and subtracted from the data.

• Standard Channels which FSI are negligible or calculable :
(London et al, Aliev et al, Chen et al).

$$\Downarrow$$

$$\Lambda_b \to Baryon\ (Hyperon)\ell^+\ell^-, \quad Baryon\ (Hyperon)h^+h^-$$

$*$ 3 body final states; $\ell^\pm$ or $h^\pm$ not originating from an Intermediate Resonance.

• Our approach (Z.J.Ajaltouni, E.Conte, O.Leitner)

$*$ Emphasis on Physical Observables constructed from 2 Intermediate Resonances :

$$\Lambda_b \to \Lambda V(1^-), \quad \Lambda \to p\pi^-, \quad J/\psi \to \mu^+\mu^-, \quad \rho^0(\omega) \to \pi^+\pi^-$$

Weak Decay of the $\Lambda_b \Longrightarrow$ Two Polarized Intermediate Resonances.

$$\Downarrow$$

(1) Component(s) of the Vector-Polarization $\vec{\mathcal{P}}$ NOT invariant by TR

(2) Constructing many TPC, C_{ijk}

II- Kinematics and Dynamics of Cascade Decays

• Λ_b is Transversally Polarized because of a QCD mechanism at the partonic level.

• Laboratory Frame :
$\vec{p_1}$ = Incident Proton momentum

$$\Downarrow$$

$$\vec{e_1} = \vec{p_1}/p_1 \ , \ \vec{e_3} = \frac{\vec{p_1} \times \vec{p_b}}{|\vec{p_1} \times \vec{p_b}|} \ , \ \vec{e_2} = \vec{e_3} \times \vec{e_1}$$

with
$\mathcal{P}^{\Lambda_b} \ = < \vec{S_{\Lambda_b}} \cdot \vec{e_3} > = \ \rho_{++}^{\Lambda_b} - \rho_{--}^{\Lambda_b} \neq 0$

• Final Spin configurations in the Λ_b Transversity frame :

$$\Lambda_b(M_i) \Longrightarrow \Lambda(\lambda_1)V(\lambda_2)$$

$$(\lambda_1, \lambda_2) = (1/2, 0) \ , \ (1/2, 1) \ , \ (-1/2, -1) \ , \ (-1/2, 0)$$

$$M_i = \pm 1/2 \ \ , \ \ M_f = \lambda_1 - \lambda_2 \ = \ \pm 1/2.$$

Decay Amplitude expressed in the Jacob-Wick-Jackson (JWJ) formalism

- 1^{st} step : Λ_b Decay

$$A_0(M_i) = \langle 1/2, M_i | S^{(0)} | p, \theta, \phi; \lambda_1, \lambda_2 \rangle = \mathcal{M}_{\Lambda_b}(\lambda_1, \lambda_2) D^{1/2\star}_{M_i M_f}(\phi, \theta, 0) \tag{1}$$

$$D^j_{M_i M_f}(\phi, \theta, 0) = d^j_{M_i M_f}(\theta) \exp(-i M_i \phi)$$

- 2^{nd} step : Resonance Decays in their Helicity Frame
  $A_1(\lambda_1)$ and $A_2(\lambda_2)$

- 3^{rd} step : Total Decay Amplitude

$$\mathcal{A}_I = \sum_{\lambda_1, \lambda_2} A_0(M_i) A_1(\lambda_1) A_2(\lambda_2) \ . \tag{2}$$

$\Longrightarrow$ Decay Probability, $d\sigma$, with Λ_b PDM

$$d\sigma \propto \sum_{M_i, M_i'} \rho^{\Lambda_b}_{M_i M_i'} \mathcal{A}_I \mathcal{A}_I^* \tag{3}$$

• BUT , because of Parity Violation in Weak Hadronic Decays :
We introduce the

Helicity Asymmetry parameter, $\alpha_{AS}^{\Lambda_b}$

$$|\Lambda_b(+)|^2 = |\mathcal{A}_{(1/2,0)}(\Lambda_b \to \Lambda V)|^2 + |\mathcal{A}_{(-1/2,-1)}(\Lambda_b \to \Lambda V)|^2 \ , \tag{4}$$

$$|\Lambda_b(-)|^2 = |\mathcal{A}_{(-1/2,0)}(\Lambda_b \to \Lambda V)|^2 + |\mathcal{A}_{(1/2,1)}(\Lambda_b \to \Lambda V)|^2 \ , \tag{5}$$

$$\alpha_{AS}{}^{\Lambda_b} = \frac{|\Lambda_b(+)|^2 - |\Lambda_b(-)|^2}{|\Lambda_b(+)|^2 + |\Lambda_b(-)|^2} \ , \tag{6}$$

$$\Downarrow\Downarrow$$

Differential Cross-Section :

$$\frac{d\sigma}{d\Omega} \propto 1 + \alpha_{AS}\mathcal{P}^{\Lambda_b}\cos\theta + 2\alpha_{AS}\Re e(\rho_{+-}^{\Lambda_b}\exp i\phi)\sin\theta \ . \tag{7}$$

We notice :
⋆ Importance of the Polarization Density Matrix of the produced Λ_b.

$\star$ New insights in the estimation of the Hadronic Matrix Elements (O.Leitner).

$\star$ Factorization Procedure

$$\text{Hadronic Mat. El.} = \text{Current Products} \otimes \text{Form Factors.}$$

Form Factors

$\star$ Computed in the framework of Heavy Quark Effective Theory, HQET.
$\star$ Corrections of order $\mathcal{O}(1/m_b)$ are performed.

$$\Downarrow$$

Estimation of the Λ_b wave-function.

Current Products

$\star$ OPE formalism used to evaluate both the soft contributions and the hard ones.
$\Longrightarrow$ Both Tree and Penguin Diagrams are computed.

Details and Numerical Values can be found in our last publication, hep-ph/0602043.

III- Physical Results

1. Branching Ratios

$$\Gamma(\Lambda_b \to \Lambda V) = \frac{E_\Lambda + M_\Lambda}{M_{\Lambda_b}} \frac{P_V}{16\pi^2} \int_\Omega |A_0(M_i)|^2 d\Omega \tag{8}$$

• Number of Color, N_c^{eff} , free because of Factorization Hypothesis.

N_c^{eff}	2	2.5	3	3.5
$\Lambda_b \to \Lambda J/\psi$	8.95×10^{-4}	2.79×10^{-4}	0.62×10^{-4}	0.03×10^{-4}
$\Lambda_b \to \Lambda \rho^0$	1.62×10^{-7}	1.89×10^{-7}	2.2×10^{-7}	2.4×10^{-7}
$\Lambda_b \to \Lambda \omega$	22.3×10^{-7}	4.75×10^{-7}	0.2×10^{-7}	0.64×10^{-7}

Experimental Branching Ratios (PDG, 2004)

$\mathcal{BR}^{exp}(\Lambda_b \to \Lambda J/\psi) = (4.7 \pm 2.1 \pm 1.9) \times 10^{-4}$.

$$\Longrightarrow \quad 2.0 \;\leq\; N_c^{eff} \leq \; 3.0$$

2. Angular distribution parameters

$\Lambda_b \to \Lambda V(1^-)$

$$\alpha_{AS}^{\Lambda_b}(\Lambda\rho^0 - \omega) = 19.4\% \ , \ \alpha_{AS}^{\Lambda_b}(\Lambda J/\psi) = 49.0\%$$

$\Lambda \to p\pi$

$$W_1(\theta_1, \phi_1) \propto 1 + \mathcal{P}^{\Lambda}\alpha_{AS}^{\Lambda}\cos\theta_1 - \frac{\pi}{2}\mathcal{P}^{\Lambda_b}\alpha_{AS}^{\Lambda}\Re e\left[\rho_{ij}^{\Lambda}\exp\left(i\phi_1\right)\right]\sin\theta_1 \tag{9}$$

$$\begin{aligned} \mathcal{P}^{\Lambda} = -0.167 \ , \quad \rho_{+-}^{\Lambda} &= \quad 0.25 \ \ (J/\psi) \ , \\ \mathcal{P}^{\Lambda} = -0.21 \ , \quad \rho_{+-}^{\Lambda} &= \quad 0.31 \ \ (\rho^0(\omega)) \ . \end{aligned} \tag{10}$$

$V(1^-) \to \ell^+\ell^-$

$$\frac{dN}{d\cos\theta_2} \propto \ (3\rho_{00}^{V} - 1)\cos^2\theta_2 \ + \ (1 - \rho_{00}^{V})$$

$$\rho_{00}^{J/\psi} = 0.66$$

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

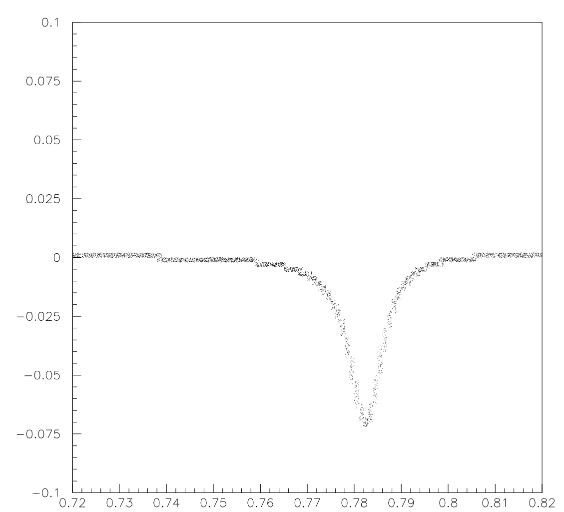
$\star$ Asmmetry parameter, $a_{CP}(s_\rho)$, between two conjugated channels :

$$a_{CP}(s_\rho) \ = \ \frac{\mathcal{BR}(\Lambda_b) - \mathcal{BR}(\bar{\Lambda}_b)}{\mathcal{BR}(\Lambda_b) + \mathcal{BR}(\bar{\Lambda}_b)} \ . \tag{11}$$

$s_\rho \ = \ \pi^+\pi^-$ Invariant Mass.

$*$ At the ω mass, Asymmetry $\approx$ 7.5% for $N_c^{eff} = 3.0$

$*$ Amplification of the Direct CP Violation between Λ_b and $\bar{\Lambda}_b$ because of strong phase δ_S passing through 90° at the ω mass.



4. Time-Odd Observables

- Laboratory Transversity Frame $\Longrightarrow$ Resonance Local Frame

$$\vec{e_1}\ ,\ \vec{e_2}\ ,\ \vec{e_3}\ \Longrightarrow\ \vec{e_X}\ ,\ \vec{e_Y}\ ,\ \vec{e_Z}$$

- Transverse Basis in Resonance rest-frame : (Jackson, 1965)

$$\vec{p} = \vec{p}_\Lambda \text{ or } \vec{p_V},\quad \vec{e}_L = \frac{\vec{p}}{p}\ ,\quad \vec{e}_T = \frac{\vec{e}_Z \times \vec{e}_L}{|\vec{e}_Z \times \vec{e}_L|}\ ,\quad \vec{e}_N = \vec{e}_T \times \vec{e}_L\ . \tag{12}$$

Resonance Vector-Polarization

$$\vec{\mathcal{P}}^{(i)} = {P_L}^{(i)}\vec{e}_L + {P_N}^{(i)}\vec{e}_N + {P_T}^{(i)}\vec{e}_T\ , \tag{13}$$

with

$$P_j^{(i)} = \vec{\mathcal{P}}^{(i)} \cdot \vec{e}_j \quad \text{with} \quad j = L, N, T$$

.

- Transformation under Parity and Time Reversal

Observable	Parity	TR
$\vec{s}$	Even	Odd
$\vec{\mathcal{P}}$	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

- If Normal Polarization $P_N \neq 0 \;\Rightarrow$ Sign of TR Violation.

Special Angles

$*\ \vec{n}_\Lambda$ and $\vec{n}_V$ unit vectors normal respectively to Λ and V decay planes.

$$\vec{n}_\Lambda = \frac{\vec{p}_p \times \vec{p}_\pi}{|\vec{p}_p \times \vec{p}_\pi|} \ , \quad \vec{n}_V = \frac{\vec{p}_{l+} \times \vec{p}_{l-}}{|\vec{p}_{l+} \times \vec{p}_{l-}|} \ , \quad \text{or} \quad \vec{n}_V = \frac{\vec{p}_{h+} \times \vec{p}_{h-}}{|\vec{p}_{h+} \times \vec{p}_{h-}|} \ . \tag{14}$$

$\Longrightarrow$ Vectors which are EVEN under TR.

BUT,

Cosine and Sine of their Azimuthal Angles :

$$\phi_{\vec{n}_\Lambda} \text{ and } \phi_{\vec{n}_V} \quad (\text{or} \quad \phi_{(n_i)})$$

$$\vec{u}_i = \frac{\vec{e}_Z \times \vec{n}_i}{|\vec{e}_Z \times \vec{n}_i|} \ , \quad \cos\phi_{(n_i)} = \vec{e}_Y \cdot \vec{u}_i \ , \quad \sin\phi_{(n_i)} = \vec{e}_Z \cdot (\vec{e}_Y \times \vec{u}_i) \ , \quad \vec{n}_i = \vec{n}_\Lambda \ , \ \vec{n}_V \ , \tag{15}$$

$$\Downarrow\Downarrow\Downarrow$$

$\cos\phi_{(n_i)}$, $\sin\phi_{(n_i)}$ are ODD by TR

• Those asymmetries depend on the azimuthal angle distributions of Λ in Λ_b rest-frame :

$$d\sigma/d\phi \;\propto\; 1+\frac{\pi}{2}\alpha_{AS}\Big(\Re e(\rho^{\Lambda_b}_{+-})\cos\phi-\Im m(\rho^{\Lambda_b}_{+-})\sin\phi\Big)\ , \tag{16}$$

⋆ Conservative values of non-diagonal elements of Λ_b PDM :
$\Re e(\rho^{\Lambda_b}_{+-})=-\Im m(\rho^{\Lambda_b}_{+-})=\sqrt{2}/2.$

$$\begin{aligned}\Lambda_b\to\Lambda J/\psi\ ; &\qquad AS(\cos\phi_{\vec{n}_\Lambda})=4.3\%\ ,\ \ \text{and}AS(\sin\phi_{\vec{n}_\Lambda})=-5.5\%\ ,\\ \Lambda_b\to\Lambda\rho^0(\omega)\ ; &\qquad AS(\cos\phi_{\vec{n}_\Lambda})=2.4\%\ ,\ \ \text{and}AS(\sin\phi_{\vec{n}_\Lambda})=-2.7\%\ .\end{aligned} \tag{17}$$

• NO Asymmetries in $\cos\phi_{\vec{n}_V}$ and $\sin\phi_{\vec{n}_V}$

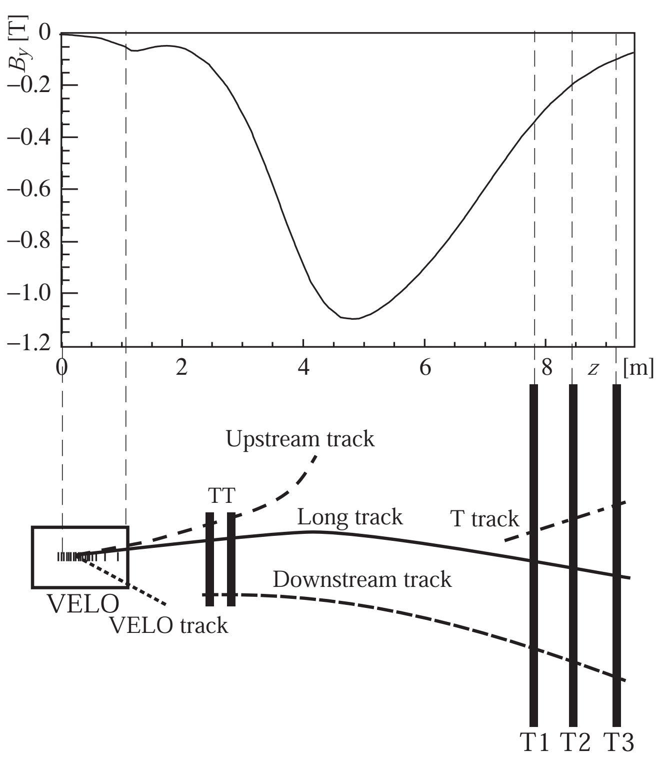
$\Longrightarrow$ Possible explanation (?)

⋆ T-Odd or TRV effects appear in processes where Parity is Violated like $\Lambda\to p\pi^-$
⋆ T-Odd effects absent in $V(1^-)\to\ell^+\ell^-\ ,\ h^+h^-$ where Parity is conserved.

IV- Perspectives with LHCb detector

- Dynamics models implemented in LHCb generator software(EvtGen) for $\Lambda_b \longrightarrow \Lambda J/\Psi$ and $\Lambda_b \longrightarrow \Lambda\rho^0(\omega)$

- A first analysis of $\Lambda_b \longrightarrow \Lambda J/\Psi$ is achieved with LHCb detector simulations. Study of channels with V $= \phi$, ρ^0 and $\omega(\pi^+\pi^-\pi^0)$ are in progress

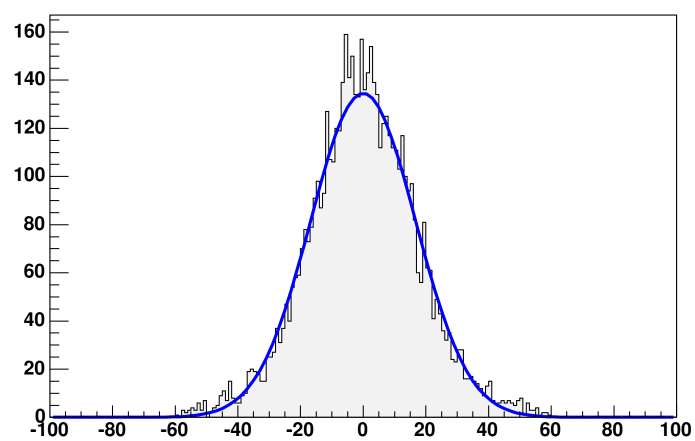


Λ life-time: $c\tau$=78.9 mm
(K_s^0 life-time : $c\tau$=26.8mm)

10% of Λ interact with the detector matter

Repartition of track combinations :
LL = 25%
DD = 53%
LU = 14%
LD = 5%

True Λ_b nominal mass - selected Λ_b mass
(sample of 280,000 evts)



- Global efficiency (including the 3 trigger levels) : 0.47%.
- B/S ratio for $b\bar{b}$ background : 0.30
- no prompt chamonium remains in the loose mass window
  other specific backgrounds negligible

about 19,000 reconstructed and selected Λ_b $(\Lambda\ J/\Psi)$ a year are expected !

Perspectives

- Some results ... :

$\star$ A complete calculation of the Hadronic Matrix Element : Tree $\oplus$ Penguin

$\star$ Implementation of these models in EvtGen code

- ... What remains to be done

$\star$ Computing analytically the vector-polarization of each resonance, Λ and $V(1^-)$.
$\Rightarrow$ allowing coherent tests to the Monte-Carlo results.

$\star$ Resolution of the T-odd observables given by LHCb detector

Time-Reversal, conservation or violation, is a Challenge for LHCb.

BACKUP SLIDES

Dynamics Model for Λ_b Decays

$\star$ New insights in the estimation of the Hadronic Matrix Elements (O.Leitner).

$\star$ Factorization Procedure

$$\text{Hadronic Mat. El.} = \text{Current Products} \otimes \text{Form Factors.}$$

Form Factors

$\star$ Computed in the framework of Heavy Quark Effective Theory, HQET.
$\star$ Corrections of order $\mathcal{O}(1/m_b)$ are performed.

$$\Downarrow$$

Estimation of the Λ_b wave-function.

Effective Field Theory (OPE)

$\star$ OPE formalism used to evaluate both the soft contributions and the hard ones.

$\Longrightarrow$

$$\mathcal{H}^{eff} = \frac{G_F}{\sqrt{2}} V_{qb} V_{qs}^{\star} \sum_{i=1}^{2} c_i(m_b) O_i(m_b) \ , \tag{18}$$

* $c_i(m_b) =$ Wilson Coefficients representing the Perturbative (hard) part.
* $O_i(m_b) =$ Operators representing the Non-Perturbative (soft) part.

$\star$ Both Tree and Penguin Diagrams are computed.

$$\mathcal{A}_{(\lambda_1,\lambda_2)}(\Lambda_b \to \Lambda V) = \frac{G_F}{\sqrt{2}} f_V E_V \langle \Lambda | \bar{s} \gamma_\mu (1-\gamma_5) b | \Lambda_b \rangle_{(\lambda_\Lambda, \lambda_V)} \tag{19}$$

$$\left\{ \mathcal{M}^T_{\Lambda_b}(\Lambda_b \to \Lambda V) - \mathcal{M}^P_{\Lambda_b}(\Lambda_b \to \Lambda V) \right\} , \tag{20}$$

with

$$\mathcal{M}^{T,P}_{\Lambda_b}(\Lambda_b \to \Lambda V) = V^{T,P}_{ckm} A^{T,P}_V(a_i) \ . \tag{21}$$

$a_i =$ Combinations of W.C. according to the nature of $v(1^-)$.

Current Matrix Element

⋆ Four amplitudes related respectively to the 4 Helicity Final States :

$$\mathcal{M}_{\Lambda_b}(\Lambda_b \to \Lambda V) = \begin{cases} -\dfrac{P_V}{E_V}\left(\dfrac{m_{\Lambda_b}+m_\Lambda}{E_\Lambda+m_\Lambda}F^-(q^2)+2F_2(q^2)\right); & (\lambda_\Lambda,\lambda_V)=(\frac{1}{2},0)\ , \\ \dfrac{1}{\sqrt{2}}\left(\dfrac{P_V}{E_\Lambda+m_\Lambda}F^-(q^2)+F^+(q^2)\right); & (\lambda_\Lambda,\lambda_V)=(-\frac{1}{2},-1)\ , \\ \dfrac{1}{\sqrt{2}}\left(\dfrac{P_V}{E_\Lambda+m_\Lambda}F^-(q^2)-F^+(q^2)\right); & (\lambda_\Lambda,\lambda_V)=(\frac{1}{2},1)\ , \\ \left(F^+(q^2)+\dfrac{P_V^2}{E_V(E_V+m_\Lambda)}F^-(q^2)\right); & (\lambda_\Lambda,\lambda_V)=(-\frac{1}{2},0)\ . \end{cases} \tag{22}$$

Details and Numerical Values can be found in our last publication, hep-ph/0602043.