Resonance Polarization and Tests of Fundamental Symmetries

From PHENOMENOLOGY to EXPERIMENT

Z.J.AJALTOUNI
Laboratoire de Physique Corpusculaire/CNRS-IN2P3
Université Blaise Pascal-CLERMONT II

with the collaboration of

M.JAHJAH, R.LEFEVRE **and** E.DISALVO

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$I-$ Basic Formalism and Analytical Calculations.

$II-$ Specific Calculations in the case of $\Lambda_b \to \Lambda J/\psi$

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I- Basic Formalism and Analytical Calculations

1) Why SPIN is so Important in Scattering and Resonance Decays

• Quantum Parameter $\Rightarrow$ Discrete Values are measured.

• $If \ <\vec{S}> \neq 0$ $\Rightarrow$ Polarized Resonances $\rightarrow$ Constraints on the Angular Distributions of their decay products.

• Polarized Resonances $\Rightarrow$ Test of Symmetries and Conservation Laws, like Parity Violation in β decay of polarized nucleus, Co^{60}.

• Polarization and Time-Reversal, TR :

$\star$ Measurement of the Polarization according to a direction $\vec{n}$ Invariant by TR.

$$P_n = \vec{\mathcal{P}} \cdot \vec{n} = <\vec{S}> \cdot \vec{n} \rightarrow \ TR \ \rightarrow - <\vec{S}> \cdot \vec{n} = -P_n$$

$\star$ If TR is an EXACT SYMMETRY $\Longrightarrow$ $P_n = 0$

⋆ But,

If $(P_n)_{measured} \neq 0$

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Sign of TR Violation ??

NOT necessarily, because ....

Initial and Final States are NOT Exchanged

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Time-Odd Observable : Naive TR

2) Spin Density Matrix

⋆ Incoherent Production of Resonances, especially in hadron-hadron collisions.

$\Longrightarrow$ Initial State $\neq$ Pure State, but a Mixing of several pure states.

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Best Formalism describing Mixing :

Density Matrix(Dirac, Von-Neumann, Landau).

$$\rho = \rho^\dagger \quad \text{and} \quad Tr(\rho) = 1$$

Diagonal Element : $\rho_{ii} =$ Probability of occurrence of state $|i> \rightarrow \rho_{ii} \geq 0$

$Tr(\rho) = \Sigma_i \rho_{ii} = 1 \Rightarrow$ Positive Semi-Definite Matrix

$\Longrightarrow$ Important Constraints on ρ and on the Vector-Polarization, $\vec{\mathcal{P}}$.

3) Resonance Decay

$$\text{Resonance } R_0(J) \rightarrow R_1(S_1)\ R_2(S_2)$$

- $\rho^i =$ Spin Density-Matrix (SDM) of the initial resonance R_0.
- Scattering Matrix describing the Decay : $S = 1 + iT$,
- SDM of the composite final state :

$$\rho^f = T^\dagger \rho^i T \quad , \quad Tr(\rho^f) = d\sigma/d\Omega = W(\theta, \phi)$$

$\Longrightarrow$ Polarization of a produced Resonance $R_i (i = 1, 2)$

$$\overrightarrow{\mathcal{P}^{R_i}} = Tr(\rho^f \vec{S}_i)/Tr(\rho^f)$$

after summing over the degrees of freedom of the other resonance R_j.

Which Frames must be used ?

• R_0 rest-frame $=$ Transversity Frame built from the Laboratory one , with

$$\vec{e_Z} \; || \; \vec{n} \; , \; \vec{n} \; = \; \text{Normal to the } R_0 \text{ Production Plane.}$$

⋆ Specific **Helicity Frames** deduced from the original R_0 rest-frame : (J.D.Jackson (1965), Martin-Spearman (1970))

For each R_i Resonance :

$$\vec{e}_L = \frac{\vec{p}}{p} \; , \quad \vec{e}_T = \frac{\vec{e}_Z \times \vec{e}_L}{|\vec{e}_Z \times \vec{e}_L|} \; , \quad \vec{e}_N = \vec{e}_L \times \vec{e}_T \; , \tag{1}$$

• $\vec{\mathcal{P}} \; = \; R_i$ Vector-Polarization expressed by :

$$\vec{\mathcal{P}} = P_L \vec{e}_L + P_N \vec{e}_N + P_T \vec{e}_T$$

with

⋆ $P_L =$ Longitudinal Component.

⋆ $P_N =$ Normal Component.

⋆ $P_T =$ Transverse Component.

4) Analytical Calculations

$$\vec{\mathcal{P}}\, W(\theta,\phi) = N\, \Sigma_\lambda \Big(\langle \theta,\phi,\lambda|\rho_i^f \vec{S}|\theta,\phi,\lambda\rangle\Big)$$

- $S = 1/2$ like Λ

$$P_x^\Lambda\, W(\theta,\phi) \;\propto\; 2\Re e(\langle \theta,\phi,1/2|\rho^\Lambda|\theta,\phi,-1/2\rangle)$$
$$P_y^\Lambda\, W(\theta,\phi) \;\propto\; -2\Im m(\langle \theta,\phi,1/2|\rho^\Lambda|\theta,\phi,-1/2\rangle)$$
$$P_z^\Lambda\, W(\theta,\phi) \;\propto\; \bar{\omega}(+1/2) - \bar{\omega}(-1/2)$$

($\bar{\omega}(\pm)$ = Weight of the helicity state $\lambda = \pm$)

- $S = 1$ like J/ψ

$$P_x^V\; W(\theta,\phi) \;\propto\; \sqrt{2}\Re e\Big((\langle 0|\rho^V|-1\rangle) + (\langle 1|\rho^V|0\rangle)\Big)$$
$$P_y^V\; W(\theta,\phi) \;\propto\; \sqrt{2}\Im m\Big((\langle 0|\rho^V|-1\rangle) + (\langle 1|\rho^V|0\rangle)\Big)$$
$$P_z^V\; W(\theta,\phi) \;\propto\; (\langle 1|\rho^V|1\rangle) - (\langle -1|\rho^V|-1\rangle)$$

5) Transformation of $\vec{\mathcal{P}}$ under Parity and TR

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**

II- Specific Calculations in the case of $\Lambda_b \rightarrow \Lambda J/\psi$

1) WHY Λ_b Physics

• Historical Reason :
Search for TRV in Hyperon Weak Decays like, $\Lambda \rightarrow p\pi^-$,
after discovery of **Parity Violation**. (R. Gatto, 1958).

• Extension to Λ_b : **b-quark replacing the s-quark**

$$\Lambda \equiv (uds) \Longleftrightarrow \Lambda_b \equiv (udb)$$

$$\Downarrow \;\; \Downarrow$$

$$m_{\Lambda_b}/m_{\Lambda} \;\approx\; 5$$

$$\Downarrow \;\; \Downarrow$$

(1) Important Increase of the Phase Space.

(2) Much more channels to test TR Invariance .

(3) Possible Tests of CP Symmetry between Λ_b and its anti-particle.

• "Known Channel" : $\Lambda_b \to \Lambda J/\psi$ (LEP, CDF) where both $\Lambda(1/2^+)$ and $J/\psi(1^-)$ are POLARIZED because of Λ_b Weak Decay.

- What is expected at **LHCb** ?

⋆ Branching Ratio,

$$BR(\Lambda_b \to \Lambda J/\psi) = (4.7 \pm 2.1_{(stat)} \pm 1.9_{(sys)}) \times 10^{-4}$$

⋆ With a mean luminosity $\mathcal{L} \simeq 10^{32} cm^{-2} s^{-1}$ for 1 year data taking ($\approx 10^7$ sec), we expect :

$$10^{12}\ (b\bar{b})\ \text{pairs}$$
$$\Downarrow$$
$$\approx\ 9.2\%\ \text{of b} - \text{quark hadronize into}\ \Lambda_b$$
$$\Downarrow$$
$$\approx\ 2 \times 10^6\ \ \Lambda_b(\bar{\Lambda}_b)$$
$$\Downarrow$$

$$S = \mathcal{L}^{\rm int}_{\rm year} \times \sigma(pp \to b\bar{b}) \times 2\ \mathcal{P}(b \to \Lambda_b^0) \times BR(\Lambda_b^0 \to \Lambda^0 J/\psi) \times BR(\Lambda^0 \to p\pi^-)$$
$$\times BR(J/\psi \to \mu^+\mu^-)$$

with

$$BR(\Lambda^0 \to p\pi^-) = 63.9\% \ , \ BR(J/\psi \to \mu^+\mu^-) = 6.76\%$$

$$\mathcal{L}^{\rm int}_{\rm year} \ = \ 2 \ {\rm fb}^{-1}$$

• Number of Expected Signal Events, including errors on the measured branching ratio :

$$S \ = \ (3.4 \pm 2.2) \times 10^6$$

2) Model Independent Calculations

• Complete Calculations of the Cascade Decay Amplitudes.

• **Correlations** among decay products arise automatically.

• Spin Density Matrices of both Λ and J/ψ can be inferred

• Intensive use of the Helicity Formalism of Jacob-Wick and Jackson.

• Helicity of a particle of spin $\vec{s}$ and momentum $\vec{p}$ defined by :

$$\lambda = \vec{s} \cdot \vec{p}/|\vec{p}| \quad .$$

Why Helicity is so Useful ?

because of :
(i) Rotation Invariance
(ii) Lorentz Invariance
(iii) Contribution of *Orbital Angular Momentum* is eliminated.

$$\Downarrow \quad \Downarrow \quad \Downarrow$$

FOUR Helicity Amplitudes :

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

- **General Decay Amplitude** :

$$\mathcal{A}_I^g(M_i, \lambda_1, \lambda_2) = \sum_{\lambda_1, \lambda_2} A_0(M_i) A_1(\lambda_1) A_2(\lambda_2)$$

with

$$A_1(\lambda_1) = \langle \lambda_1, m_1 | S^{(1)} | p_1, \theta_1, \phi_1; \lambda_3, \lambda_4 \rangle = \mathcal{A}_{(\lambda_3, \lambda_4)}(\Lambda \to p\pi^-) D^{1/2\star}_{\lambda_1 m_1}(\phi_1, \theta_1, 0)$$

and

$$A_2(\lambda_2) = \langle \lambda_2, m_2 | S^{(2)} | p_2, \theta_2, \phi_2; \lambda_5, \lambda_6 \rangle = \mathcal{A}_{(\lambda_5, \lambda_6)}(V \to l^+ l^-) D^{1\star}_{\lambda_2 m_2}(\phi_2, \theta_2, 0)$$

$\Longrightarrow$ **Decay Probability** :

$$d\sigma \propto \sum_{M_i, M_i'} \rho^{\Lambda_b}_{M_i M_i'} \mathcal{A}^g_I(M_i, \lambda_1, \lambda_2) \mathcal{A}^{g*}_I(M_i, \lambda_1, \lambda_2)$$

So,

$$d\sigma \propto$$

$$\sum_{\lambda_1, \lambda_2, \lambda_1', \lambda_2'} D_{\lambda_1 - \lambda_2, \lambda_1' - \lambda_2'}(\theta, \phi) \mathcal{A}_{(\lambda_1, \lambda_2)}(\Lambda_b \to \Lambda V) \mathcal{A}^*_{(\lambda_1', \lambda_2')}(\Lambda_b \to \Lambda V)$$

$$\times \; F^{\Lambda}_{\lambda_1 \lambda_1'}(\theta_1, \phi_1) G^{V}_{\lambda_2 \lambda_2'}(\theta_2, \phi_2)$$

where

$$D_{\lambda_1 - \lambda_2, \lambda_1' - \lambda_2'}(\theta, \phi) =$$

$$\sum_{M_i M_i'} \rho^{\Lambda_b}_{M_i M_i'} d^{1/2}_{M_i, \lambda_1 - \lambda_2}(\theta) d^{1/2}_{M_i', \lambda_1' - \lambda_2'}(\theta) \exp i(M_i' - M_i)\phi$$

$$F^{\Lambda}_{\lambda_1 \lambda'_1}(\theta_1, \phi_1) =$$

$$\Big(|\mathcal{A}_{(1/2,0)}(\Lambda \to p\pi^-)|^2 d^{1/2}_{\lambda_1 1/2}(\theta_1) d^{1/2}_{\lambda'_1 1/2}(\theta_1) +$$

$$|\mathcal{A}_{(-1/2,0)}(\Lambda \to p\pi^-)|^2 d^{1/2}_{\lambda_1 -1/2}(\theta_1) d^{1/2}_{\lambda'_1 -1/2}(\theta_1) \Big) \exp i(\lambda'_1 - \lambda_1)\phi_1$$

and

$$G^{V}_{\lambda_2 \lambda'_2}(\theta_2, \phi_2) =$$

$$\sum_{\lambda_5,\lambda_6} |\mathcal{A}_{(\lambda_5,\lambda_6)}(V \to l^+ l^-)|^2 d^1_{\lambda_2 m_2}(\theta_2) d^1_{\lambda'_2 m_2}(\theta_2) \exp i(\lambda'_2 - \lambda_2)\phi_2$$

3) Spin Density Matrices and Angular Distributions

$\Lambda \to p\pi^-$ Decay

$$W_1(\theta_1, \phi_1) \propto$$

$$\frac{1}{2}\left\{(\rho^{\Lambda}_{++} + \rho^{\Lambda}_{--}) + (\rho^{\Lambda}_{++} - \rho^{\Lambda}_{--})\alpha^{\Lambda}_{AS}\cos\theta_1 - \frac{\pi}{2}\mathcal{P}^{\Lambda_b}\alpha^{\Lambda}_{AS}\Re e\left[\rho^{\Lambda}_{ij}\exp(i\phi_1)\right]\sin\theta_1\right\}$$

with

$$\rho^{\Lambda}_{ii} = \int_{\theta_2,\phi_2} G^{V}_{00}(\theta_2,\phi_2)\ |\mathcal{A}_{(\pm 1/2,0)}(\Lambda_b \to \Lambda V)|^2 +$$

$$\int_{\theta_2,\phi_2} G^{V}_{\pm1\pm1}(\theta_2,\phi_2)|\mathcal{A}_{(\pm 1/2,\pm 1)}(\Lambda_b \to \Lambda V)|^2$$

and

$$\rho^{\Lambda}_{ij} =$$

$$\int_{\theta_2,\phi_2} G^{V}_{00}(\theta_2,\phi_2)\mathcal{A}_{(-1/2,0)}(\Lambda_b \to \Lambda V)\mathcal{A}^{*}_{(1/2,0)}(\Lambda_b \to \Lambda V)$$

$V \to \ell^+\ell^-$ **Decay**

$$W_2(\theta_2, \phi_2) \propto$$

$$(\rho^V_{ii} + \rho^V_{jj})(G^V_{00}(\theta_2, \phi_2) + G^V_{\pm 1 \pm 1}(\theta_2, \phi_2)) - \frac{\pi}{4}\mathcal{P}^{\Lambda_b}\Re e\left[\rho^V_{ij}\exp(i\phi_2)\right]\sin 2\theta_2$$

with

$$\rho^V_{ii} = \int_{\theta_1,\phi_1} F^{\Lambda}_{\lambda_1\lambda_1'}(\theta_1,\phi_1)\Big[\delta_{\lambda_2\lambda_2'}|\mathcal{A}_{(\pm 1/2,0)}(\Lambda_b \to \Lambda V)|^2 +$$

$$\delta_{\lambda_2 \pm \lambda_2'}|\mathcal{A}_{(\pm 1/2,\pm 1)}(\Lambda_b \to \Lambda V)|^2\Big]$$

and

$$\rho^V_{ij} =$$

$$\int_{\theta_1,\phi_1} F^{\Lambda}_{\lambda_1\lambda_1'}(\theta_1,\phi_1)\Big[\Big\{\mathcal{A}_{(1/2,0)}(\Lambda_b \to \Lambda V)\mathcal{A}^*_{(1/2,1)}(\Lambda_b \to \Lambda V) + h.c.\Big\}$$

$$-\Big\{\mathcal{A}_{(-1/2,0)}(\Lambda_b \to \Lambda V)\mathcal{A}^*_{(-1/2,-1)}(\Lambda_b \to \Lambda V) + h.c.\Big\}\Big]\mathcal{M}_{V\to l^+l^-}$$

- Owing to Parity Conservation in $V \to l^+l^-$, we introduce

$$\mathcal{M}_{V\to l^+l^-} = |\mathcal{A}_{(1/2,-1/2)}(V \to l^+l^-)|^2 - 2|\mathcal{A}_{(+1/2,+1/2)}(V \to l^+l^-)|^2$$

III- Experimental Perspectives and Simulations

• Main elements of both SDM, (ρ^{Λ}) and $(\rho^{J/\psi})$ can be **extracted** from the "Experimental Angular Distributions".

$$\Downarrow\Downarrow\Downarrow$$

Extraction of Components of $\overrightarrow{\mathcal{P}^{R_i}}$

1) $\vec{\mathcal{P}}^{\Lambda_b}$ from $\Lambda_b \longrightarrow \Lambda V(1^-)$

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

⋆ Basic Relation between ρ^{Λ_b} and $\overrightarrow{\mathcal{P}^{\Lambda_b}}$:

$$\text{Spin } 1/2 \ \Rightarrow \ \rho = \frac{1}{2}(1 + \vec{\mathcal{P}} \cdot \vec{\sigma})$$

(1) Fitting the $\cos\theta$ Distribution $\Rightarrow \mathcal{P}_z^{\Lambda_b}$
with

$$\mathcal{P}_z^{\Lambda_b} = \rho_{++} - \rho_{--} = 2\rho_{++} - 1$$

(2) Fitting the ϕ_Λ Distribution $\Rightarrow \Re(\rho_{+-})$ and $\Im(\rho_{+-})$
with

$$\mathcal{P}_x^{\Lambda_b} = 2\Re(\rho_{+-}) \ \text{ and } \ \mathcal{P}_y^{\Lambda_b} = 2\Im(\rho_{+-})$$

• Some Remarks :

⋆ The Asymmetry Parameter, $\alpha_{AS}^{\Lambda_b}$, is computed from a specific phenomenological model developed by O.Leitner and Z.J.A. (hep-ph/060243, and Nucl.Phys.B, Proc.Suppl. **174** (2007), 169-172). Its numerical value is $\alpha_{AS}^{\Lambda_b} = 0.49$.

⋆ The beauty baryon, Λ_b , is expected to be essentially Transversally Polarized; but some Λ_b could come from W and Z decays and have *longitudinal polarization.*

2) $\vec{\mathcal{P}}^{\Lambda}$ from $\Lambda \to p\pi^-$

• Same procedure than the previous one with an advantage :
the Asymmetry Parameter of he Hyperon Λ is known with great precision, $\alpha_{AS} = 0.642$.

⋆ General Expression of the Proton Angular distribution in Λ Helicity r-f :

$$\frac{d\sigma}{d\Omega_1} \propto \left\{ 1 + \alpha_{AS}^{\Lambda} \mathcal{P}^{\Lambda} \cos\theta_1 + 2\alpha_{AS}^{\Lambda} \Re e \left[\rho_{+-}^{\Lambda} \exp\left(i\phi_1\right) \right] \sin\theta_1 \right\}$$

with

⋆ $\mathcal{P}^{\Lambda} =$ Polarization according to the Helicity Axis

⋆ $\rho_{+-}^{\Lambda} \propto \mathcal{P}^{\Lambda_b}\ \Lambda_b(1/2,0)\ \Lambda_b(-1/2,0)^*$
(Hadronic Matrix Element corresponding to (λ_1, λ_2) helicity state).

$\Longrightarrow$ Proton Azimuthal Distribution depending directly on Λ_b Polarization !!

⋆ Polar Angle Distribution provides $\mathcal{P}^{\Lambda} = 2\rho_{++}^{\Lambda} - 1$

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Again, the Three Components of $\overrightarrow{\mathcal{P}^{\Lambda}}$ could be **determined**

3) Matrix Elements from $J/\psi \to \mu^+\mu^-$

- Spin of $J/\psi = 1 \;\to\; 8$ elements to be determined ??

But...

- Experimentally, access to **ONE Diagonal** matrix element, $\rho_{00} =$ Longitudinal Probability

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

- "Practical hypothesis" done in our calculations :

$$V(++) = V(--) \;\text{ and }\; |V(+-)| \text{ much bigger than } |V(++)|$$

because of :

(1) Parity Conservation in E.M. decay , and

(2) Chirality $\approx$ Helicity Conservation for ultra-relativistic spin $1/2$ particles.

• **In our model**, we get :

Decay mode	$\mathcal{P}^{\Lambda}$	ρ^{Λ}_{+-}	ρ^{V}_{00}
$\Lambda J/\psi$	-0.17	0.25	0.66
$\Lambda\rho^{0}$	-0.21	0.31	0.79

Table 1: Longitudinal Polarizations and SDM main elements

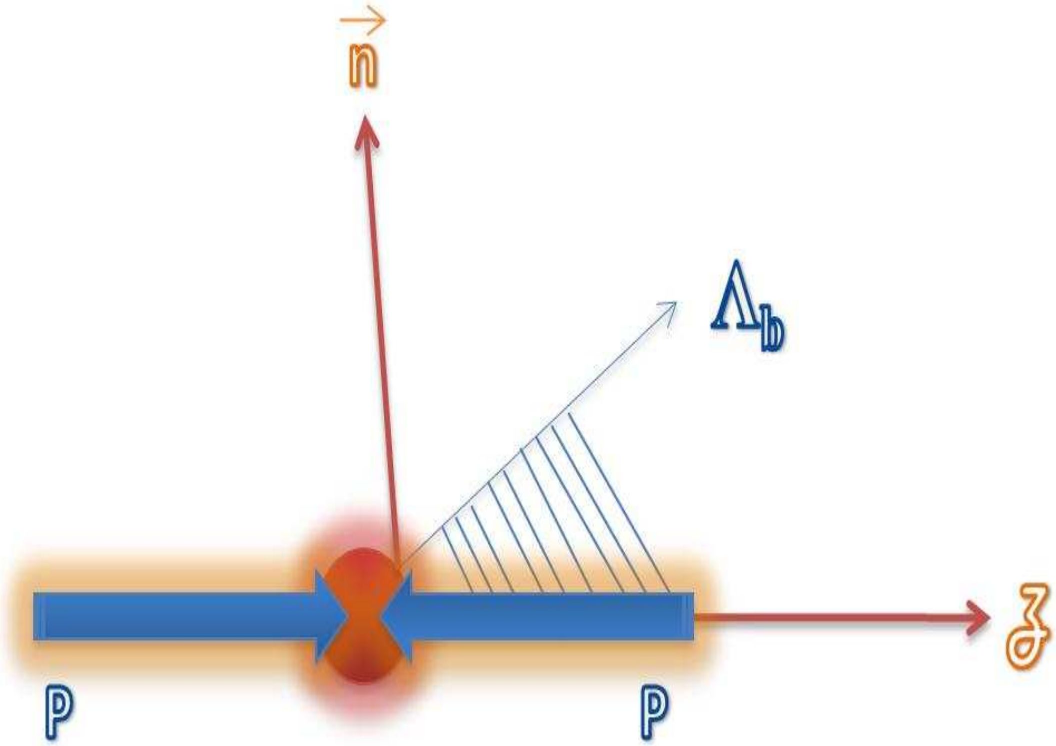

Figure 1: Λ_b in the Standard LHCb Frame

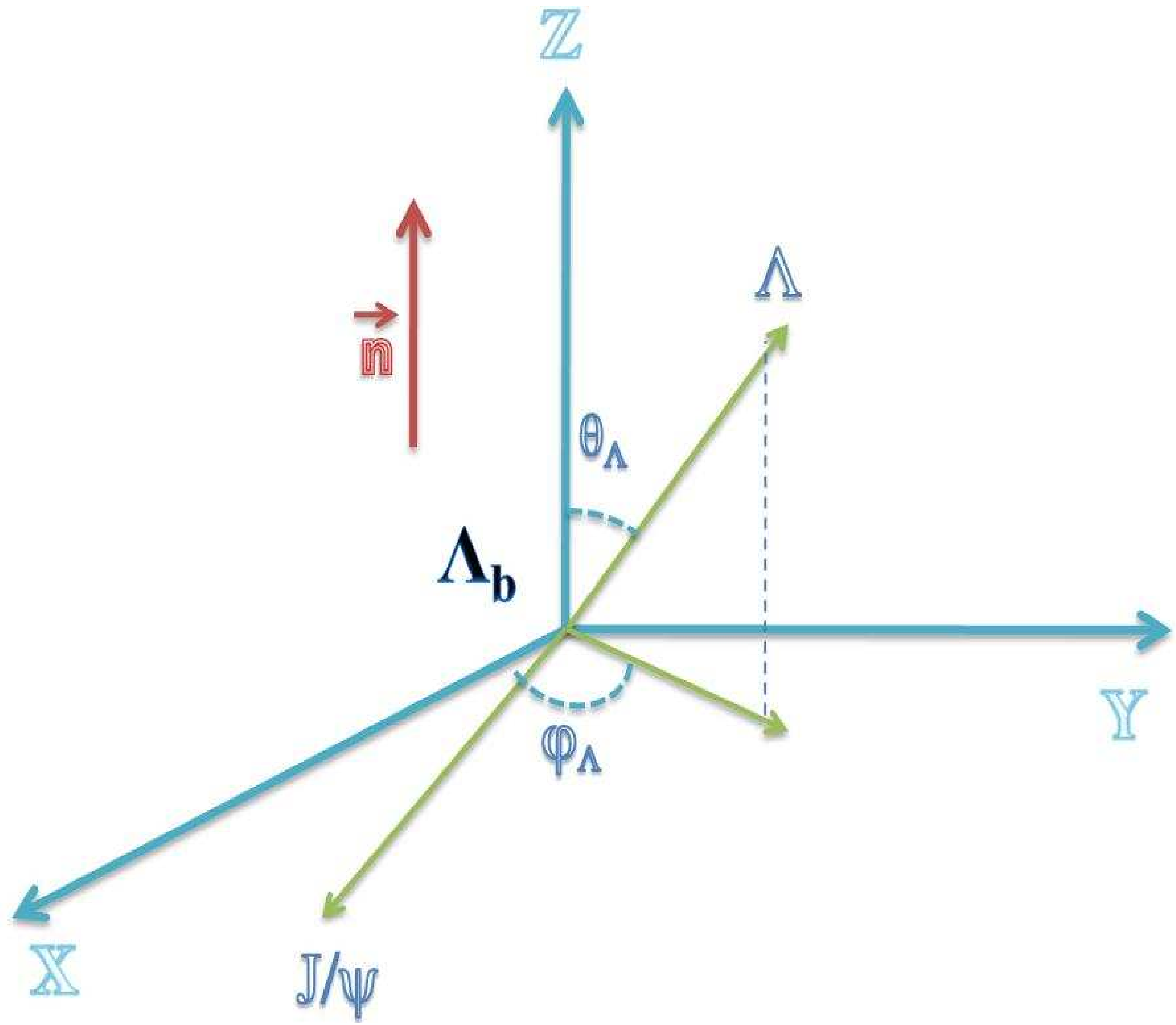

Figure 2: Λ_b Transversity Rest-Frame

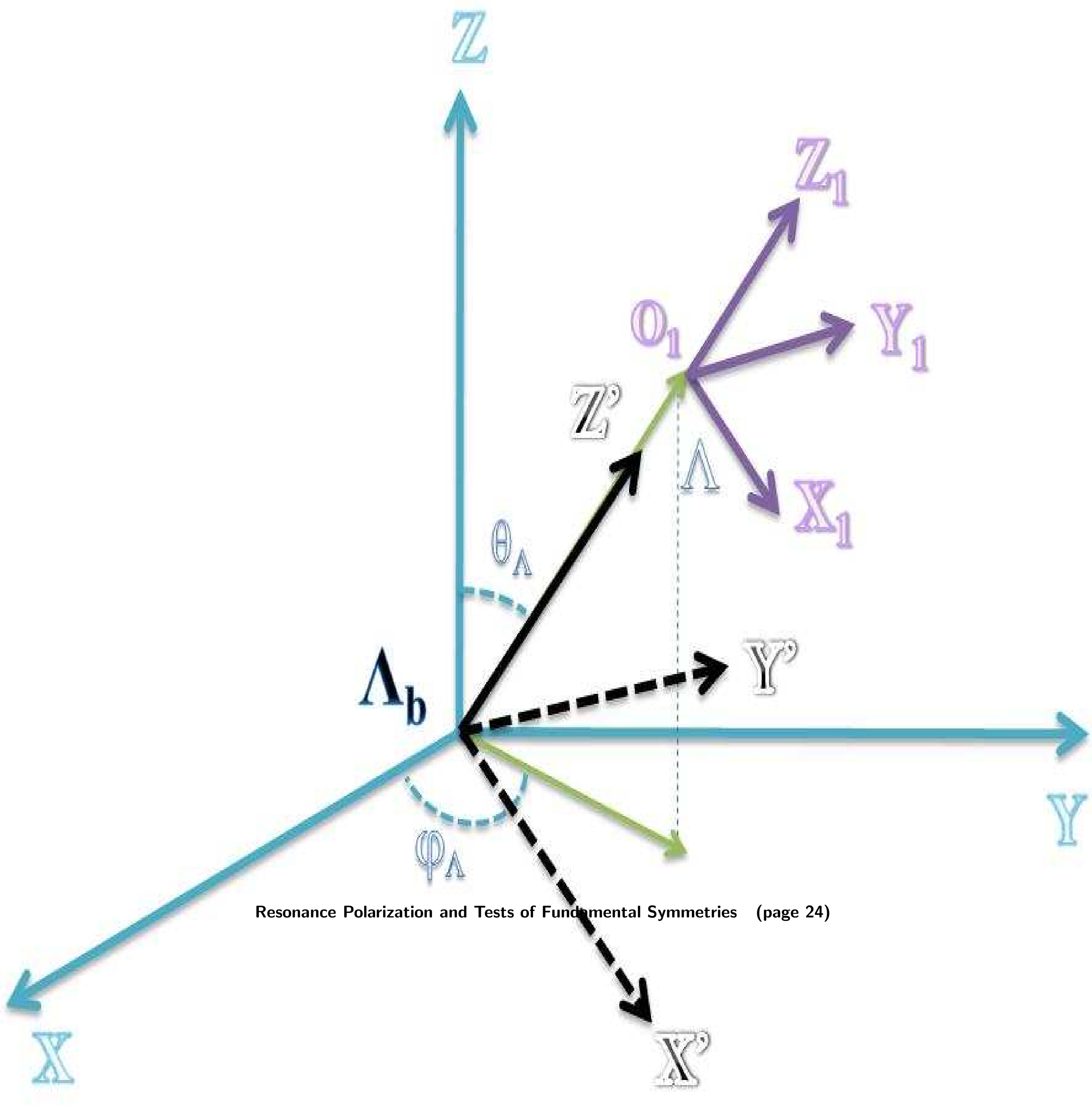

Figure 3: From Λ_b rest-frame to Λ Helicity rest-frame

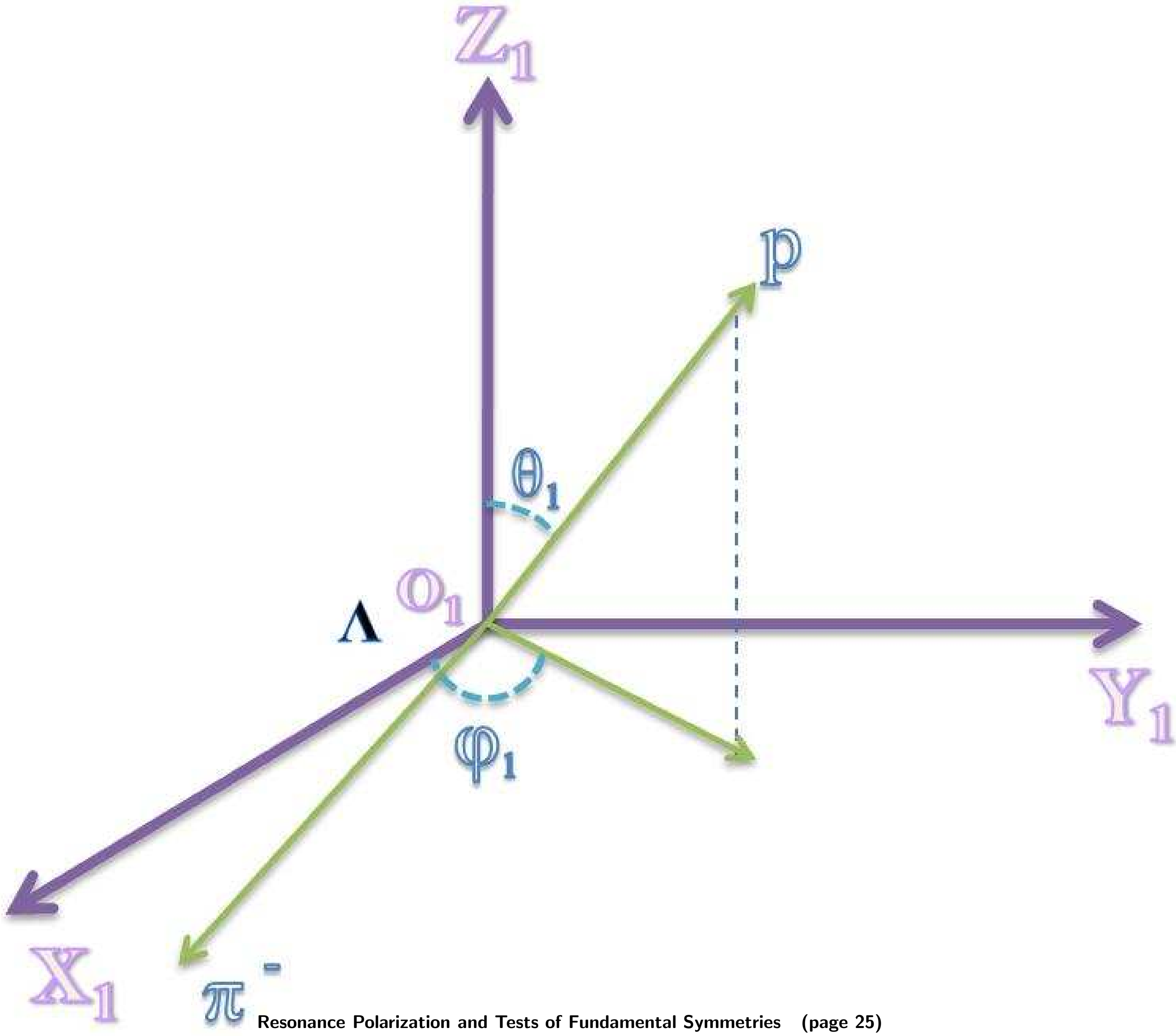

Figure 4: Λ Helicity Rest-Frame

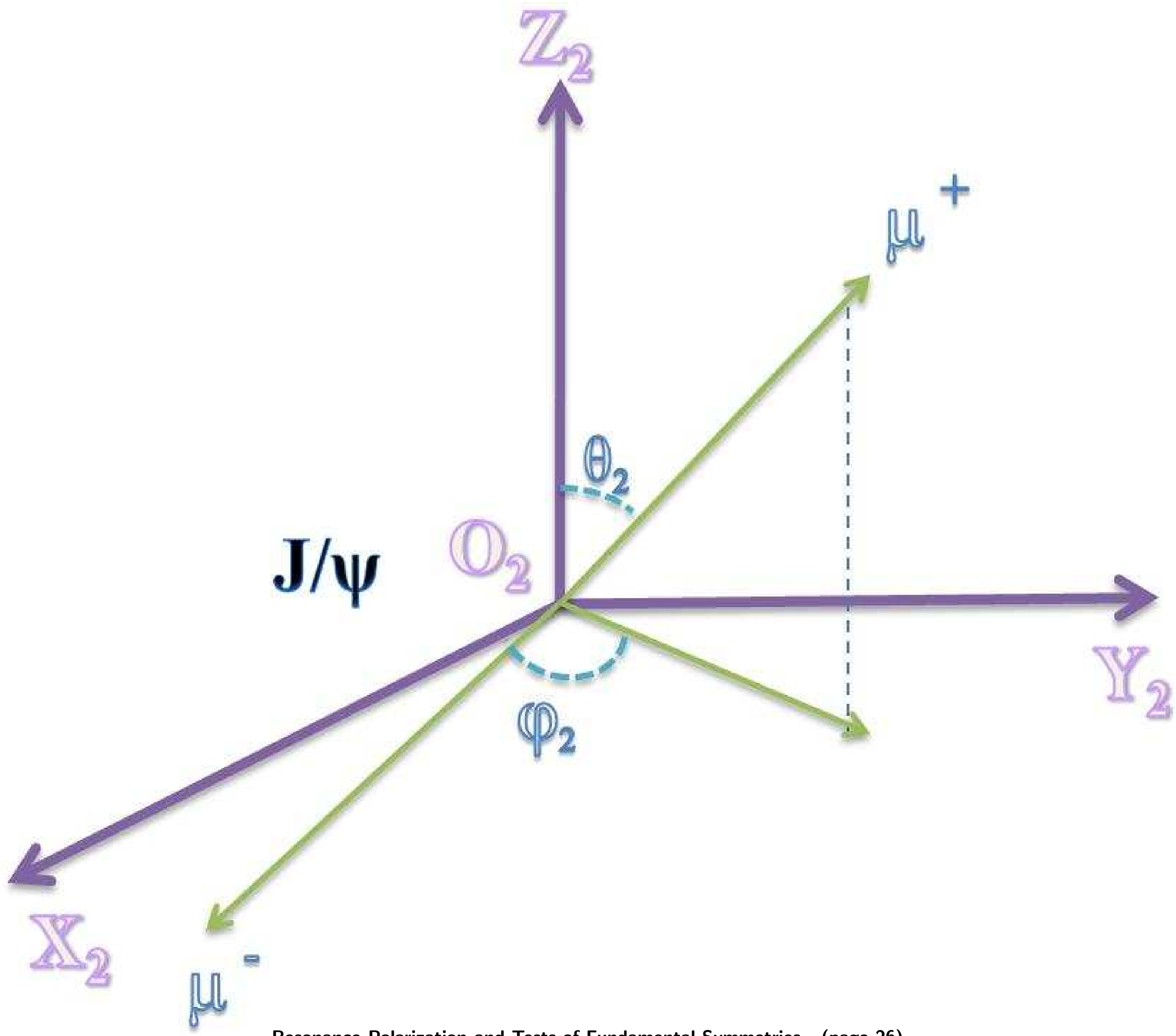

Figure 5: J/ψ Helicity Rest-Frame

IV- CONCLUSION

• Performing a Model-Independent method to measure Vector-Polarization Components and their Correlations (E.DiSalvo, Z.J.A., **Mod.Phys.Let.A 24, p.109-121** and paper in preparation).

• Possibility to measure the Λ_b Polarization, which is a challenge for QCD, similarly to the Hyperon Polarizations in Hadron-Hadron Collisions.

• Realistic Method :

$\Longrightarrow$ Measuring **Normal or Transverse** Polarization of the Resonances Λ , J/ψ and their Correlations.

• Comparing Decays of both Λ_b and $\bar{\Lambda}_b$ in order to test **CP** and ebventually .... **CPT (!?)**.

Les Théories passent, les Expériences se déroulent, mais ...
les Lois de Conservation restent ...
(unknown author)

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Thèse de Doctorat d'Université, Université Blaise Pascal; DU1785, EDSF546, PCCF T0710 (Novembre 2007).

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$\star$ Z.J.Ajaltouni, E.DiSalvo, M.Jahjah,
Paper in preparation.