Direct Test of Time-Reversal Symmetry at the LHC Feasibilities with LHCb

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$I-$ Theoretical Introduction to TIME-REVERSAL.

$II-$ PHENOMENOLOGY of TRV, $\Lambda_b \to \Lambda V(1^-)$

$III-$ SIMULATIONS and PERSPECTIVES with LHCb

$IV-$ CONCLUSION

I- Time Reversal Symmetry : Theory and Problems

- 3 Discrete Transformations which are Approximate Symmetries :

⋆ PARITY P : $\vec{r}, \vec{p} \longrightarrow -\vec{r}, -\vec{p} \quad , \quad \vec{\ell}\ , \ \vec{s}$ Unchanged

⋆ CHARGE CONJUGATION C : $Q \longrightarrow -Q \quad , \quad \vec{r}, \vec{p}, \vec{\ell}, \vec{s}$ Unchanged

⋆ TIME REVERSAL, T : $\vec{r} \longrightarrow \vec{r} \quad , \quad \vec{p}, \vec{\ell}, \vec{s} \longrightarrow$ Opposite Sign

But,

P and C are Hermitian-Unitary Operators, while

T is an ANTIUNITARY Operator

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NO Real Eigenvalues like P and C

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$\equiv$ NO Intrinsic Quantum Numbers

How Testing Time-Reversal Symmetry ?

- Initial State $|i> = \ |\vec{p}_i, \vec{s}_i > \rightarrow \ |i^T> = \ |-\vec{p}_i, -\vec{s}_i >$
- Fitial State $|f> = \ |\vec{p}_f, \vec{s}_f > \rightarrow \ |f^T> = \ |-\vec{p}_f, \vec{s}_f >$

⋆ If TR Exact Symmetry $\Rightarrow |<f|S|i>| \ = \ |<i^T|S|f^T>|$

⋆ If Equality above Not Verified $\Rightarrow$ Sign of TR VIOLATION !?

But, Main Problem :

⋆ Difficulties to realize experimentally the Reversed Time of any elementary process !?

So,
How to put into evidence any Violation of Time-Reversal Symmetry (TRV) ???

•• (1) INDIRECT (TRADITIONAL) WAY :
CPT Exact Symmetry because of LORENTZ Invariance of QFT.

If CP Violated $\Longrightarrow$ T Violated

•• (2) DIRECT WAY :

Looking for T-Odd Observables, like

$$C_{ijk} = \vec{v_i} \cdot (\vec{v_j} \times \vec{v_k}) \ \text{with} \ \vec{v} = \vec{p} \ or \ \vec{s}$$

$$C_{ijk} \rightarrow \text{TR} \rightarrow -C_{ijk}$$

Ex: POLARIZATION of Particles with Spin.

••• Is this last Condition Sufficient ???

$\Longrightarrow$ Existence of the Final State Interactions (FSI) which modify the Scattering Amplitude.

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Simulation of TRV effects !!??

• In order to test TR Symmetry without Reversing Initial and Final states, we must

(1) Compute with high precision the FSI (including the non-perturbative contribution !?)

(2) or, the FSI could be **neglected** (Wolfenstein, IJMPE, Vol.8 (1999), 501-511)

Moral of the Story : NO Special Rule for the estimation of the FSI

II- PHENOMENOLOGY of TRV

1- Historically β Decay

$$_{Z}X^{A} \Longrightarrow \quad _{Z+1}Y^{A} \;\; e^{-} \;\; \bar{\nu}_e$$

• Looking for Correlations between Neutron Spin, s_n, and $\vec{p_e}$, $\vec{p_\nu}$.

⋆ Electromagnetic FSI taken into account (Jackson-Treiman-Wyld, 1957).

⋆ Differential cross-section :

$$d\sigma \quad \approx \vec{s}_n \cdot (A\vec{p_e} + B\vec{p_\nu} + D\vec{p_e} \times \vec{p_\nu})$$

(i) A and B violates Parity .
(ii) D, related to Neutron Transverse Polarization, violates TR.

⋆ Experimental Results (KEK, 2007) : $D \sim 0$ with a high confidence level.

2- $K^0 - \bar{K}^0$ Oscillations (CP-LEAR, KTEV (1999))

$$P(K^0 \to \bar{K}^0) \quad \neq \quad P(\bar{K}^0 \to K^0)$$

• First Observation of **Direct** **TRV** in Particle Physics

3- Electric Dipole Moments (EDM)

- $d_e \neq 0$ or $d_n \neq 0 \Longrightarrow$ Sign of TRV
- ILL (Grenoble) best placed to provide the most recent results.....

Why Λ_b Decay ?

• Search for TRV in Hyperon Weak Decays like $\Lambda \to p\pi^-$ where Parity is Violated (R. Gatto, 1958).

If

$\Longrightarrow$ s-quark is replaced by b-quark

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

(1) Important Increase of the Phase Space : $m_{\Lambda_b}/m_{\Lambda} \approx 5$

(2) Both CP and TR could be Tested.

(3) Possible Tests of some specific models beyond the SM :

SuperSymmetry, FCNC, LR Symmetric Models, ...

• "Best 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 :

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

• Performing $\Lambda_b \oplus \mathrm{TRV}$ Physics in two Steps :

(1) Constructing T-Odd Observables from the Kinematics of the Final Particles : p, π^-, μ^+, μ^- (O.Leitner, E.Conte, Z.J.A.)

(2) Looking for Polarization-Vectors of the Intermediate Resonances which Transverse Components are T-Odd observables (E.DiSalvo, M.Jahjah, R.Lefèvre, Z.J.A.)

Kinematics and Dynamics of $\Lambda_b \to \Lambda J/\psi$

1- DYNAMICS

• Hadronic Matrix Element (**HME**) computed by the techniques of the Operator Product Expansion, OPE.

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{qb} V_{qs}{}^{\star} \sum_{i=1}^{10} c_i(m_b) O_i(m_b)$$

$\star$ c_i = Wilson Coefficients = Hard Perturbative Contributions

$\star$ O_i = Soft Non-Perturbative Contributions.

• Factorization Hypothesis $\Rightarrow$ HME = Sum of Products of Currents

$$\mathcal{A}_{(\lambda_1,\lambda_2)} = \frac{G_F}{\sqrt{2}} f_{J/\psi} E_{J/\psi} \times \langle \Lambda^0 | \bar{s}\gamma_\mu (1-\gamma_5) b | \Lambda_b^0 \rangle$$

$$\times \left\{ V_{cb}V_{cs}^* \left[C_1 + \frac{C_2}{N_c^{eff}} \right] - V_{tb}V_{ts}^* \left[C_3 + C_5 + C_7 + C_9 + \frac{C_4 + C_6 + C_8 + C_{10}}{N_c^{eff}} \right] \right\}$$

• Form-Factors estimated in the framework of the HQET by performing perturbative calculations of order $O(1/m_b)$.

• Conservation of the Angular Momentum :

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FOUR Helicity Amplitudes :

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

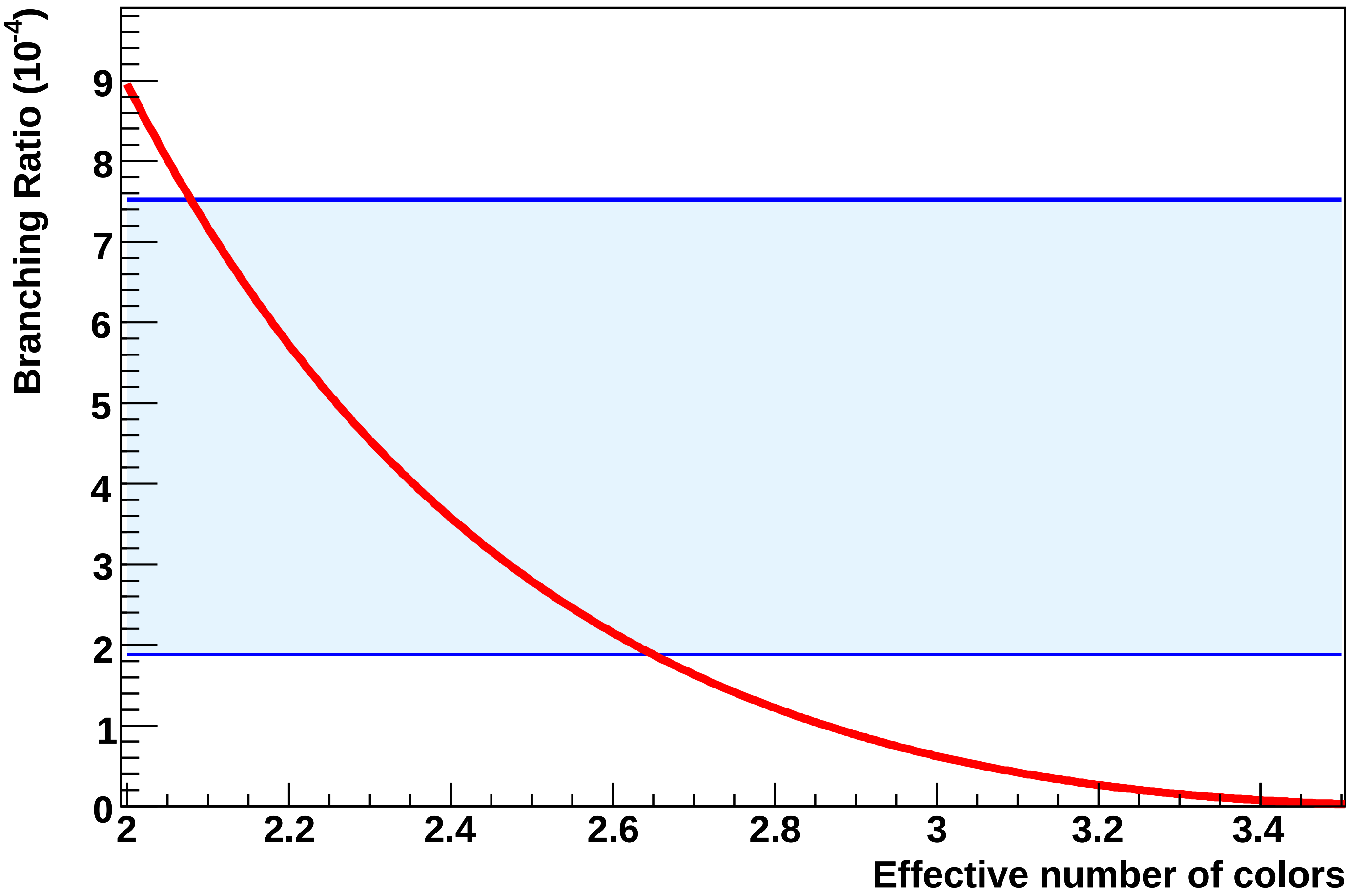
• Analytical Expressions of the corresponding four amplitudes given by :

$$\langle \Lambda^0 | \bar{s}\gamma_\mu (1-\gamma_5) b | \Lambda_b^0 \rangle = \begin{cases} -\frac{P_{J/\psi}}{E_{J/\psi}} \left(\frac{m_{\Lambda_b^0} + m_{\Lambda^0}}{E_{\Lambda^0} + m_{\Lambda^0}} \zeta^- + \zeta^+ - \zeta^- \right); & (\lambda_{\Lambda^0}, \lambda_{J/\psi}) = (\\ \frac{1}{\sqrt{2}} \left(\frac{P_{J/\psi}}{E_{\Lambda^0} + m_{\Lambda^0}} \zeta^- + \zeta^+ \right); & (\lambda_{\Lambda^0}, \lambda_{J/\psi}) = (\\ \frac{1}{\sqrt{2}} \left(\frac{P_{J/\psi}}{E_{\Lambda^0} + m_{\Lambda^0}} \zeta^- - \zeta^+ \right); & (\lambda_{\Lambda^0}, \lambda_{J/\psi}) = (\\ \left(\zeta^+ + \frac{P_{J/\psi}^2}{E_{J/\psi}(E_{J/\psi} + m_{\Lambda^0})} \zeta^- \right); & (\lambda_{\Lambda^0}, \lambda_{J/\psi}) = (\end{cases} \quad (1)$$

⋆ ζ^+ and ζ^- are the corresponding Form-Factors.

• N_C can vary in the range $[2, 3]$ in order to take account of the Non-Perturbative effects.

- Red Curve $\equiv$ Our Model



At 90% CL $\Rightarrow$ $2.1 \leq N_C^{eff} \leq 2.7$

2- KINEMATICS

• Use of the Helicity Formalism of Jacob-Wick-Jackson.

⋆ **TRANSVERSE Frame** for the Decay $\Lambda_b \to \Lambda J/\psi$

$\longrightarrow$ Quantization Axis being Normal to the Λ_b Decay Plane.

$$\overrightarrow{OX} \parallel \vec{p}_{proton}, \qquad \overrightarrow{OZ} = \frac{\vec{p}_{proton} \times \vec{p}_{\Lambda_b^0}}{|\vec{p}_{proton} \times \vec{p}_{\Lambda_b^0}|}, \qquad \overrightarrow{OY} = \overrightarrow{OZ} \times \overrightarrow{OX} \quad (2)$$

⋆ **HELICITY Frame** for each Resonance Decay.

$\longrightarrow$ Quantization Axis being parallel to the Resonance momentum, $\vec{p_{\Lambda}}$, $\vec{p_{J/\psi}}$, in the Λ_b rest-frame.

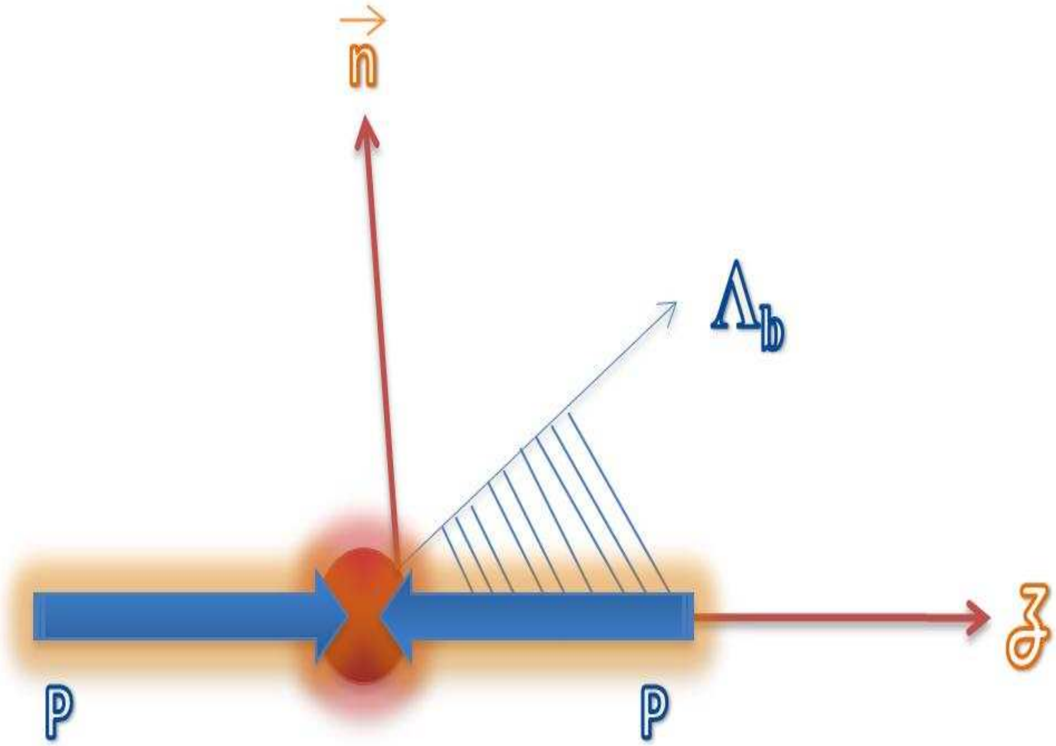


Figure 1: Λ_b in the Standard LHCb Frame

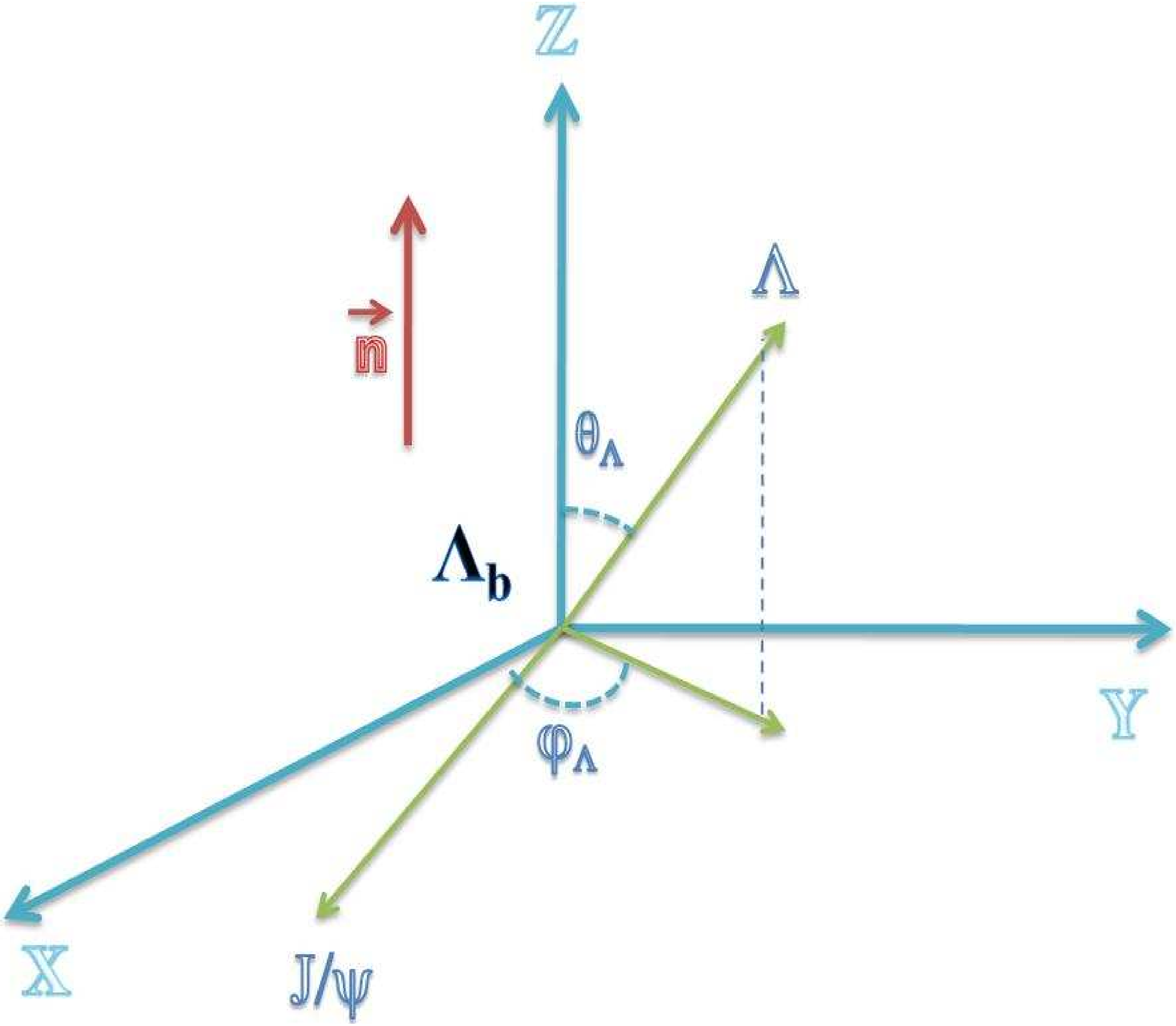


Figure 2: Λ_b Transversity Rest-Frame

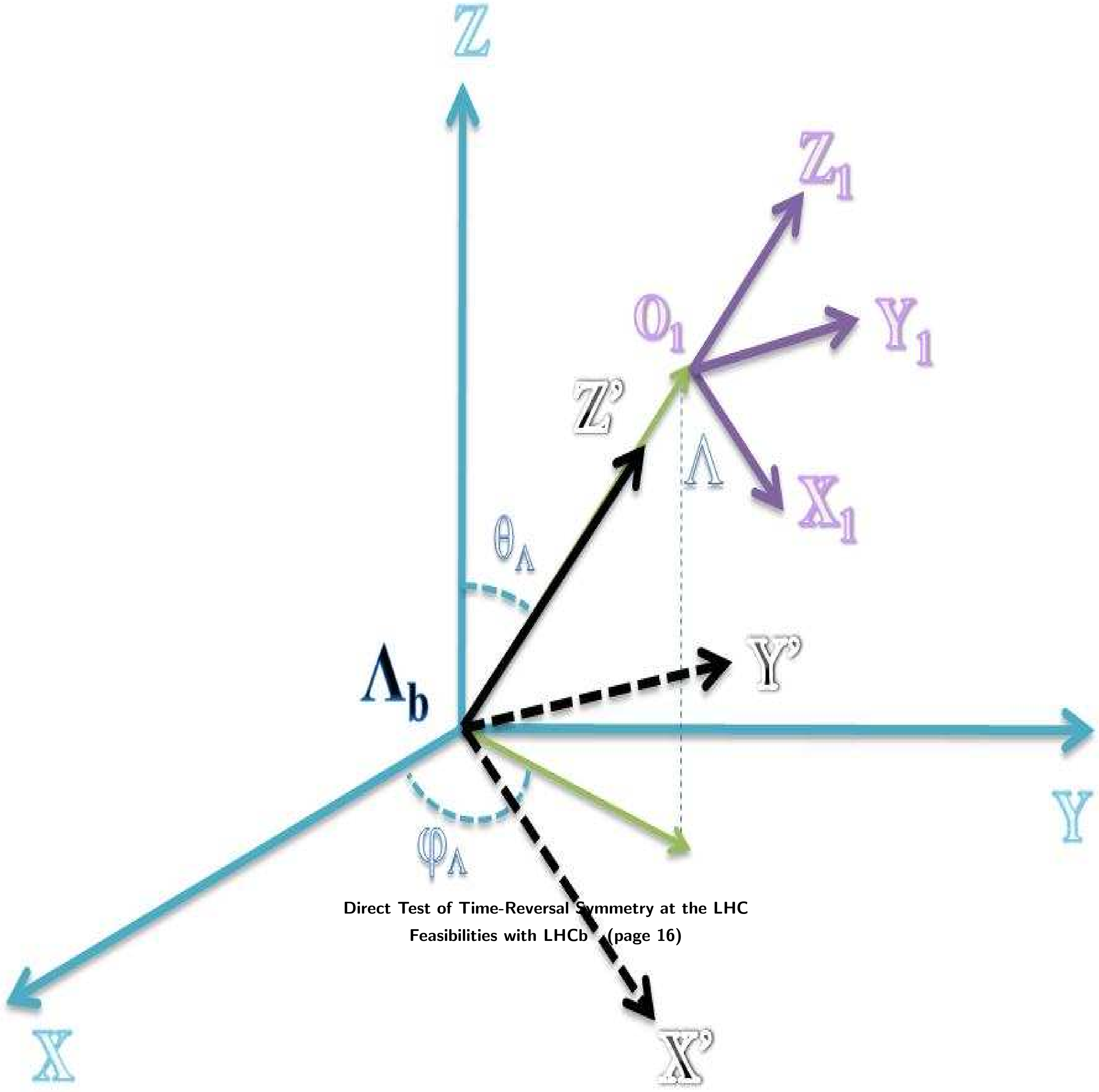


Figure 3: From Λ_b rest-frame to Λ Helicity rest-frame

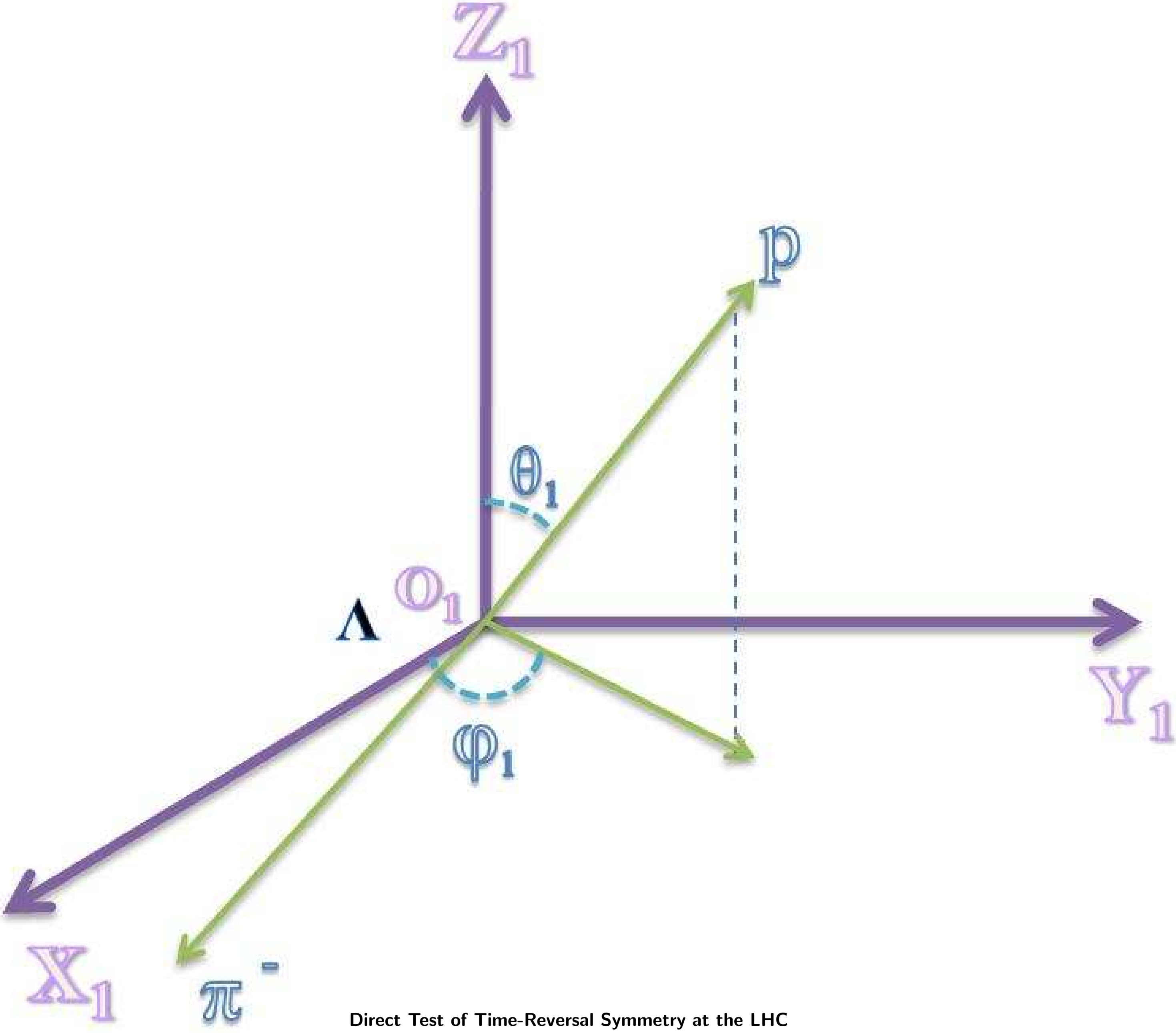


Figure 4: Λ Helicity Rest-Frame

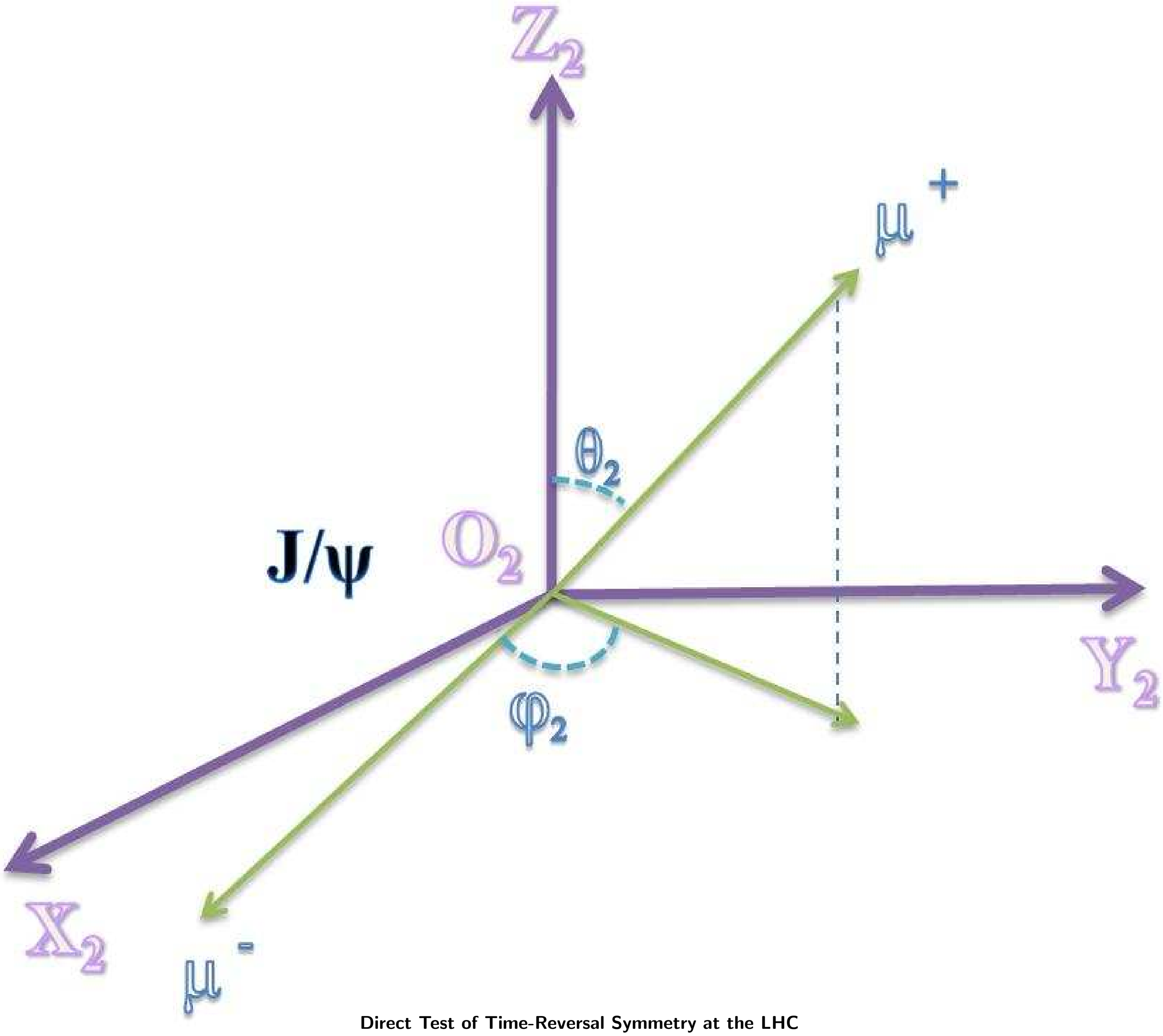


Figure 5: J/ψ Helicity Rest-Frame

• According to our Phenomenological Model, all the parameters entering into the 3 Decays :

$$\Lambda_b \Longrightarrow \Lambda J/\psi \;\;,\;\; \Lambda \to p\pi^- \;,\; J/\psi \to \mu^+\mu^-$$

can be determined, like :

Asymmetry Parameter, $\alpha_{AS}^{\Lambda_b}$

Spin Density Matrices : ρ^{Λ} , ρ^{V}

Polarizations : $\mathcal{P}^{\Lambda}$, $\mathcal{P}^{V}$

- Main Results :

Decay mode	$\alpha_{AS}^{\Lambda_b}$
$\Lambda J/\psi$	49.0%
$\Lambda\rho^0$	19.4%

Table 1: Asymmetry Parameter of the Λ_b

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

Table 2: Long. Polarizations and SDM main elements

$\star$ ρ_{00}^V = Probability of the Vector-Meson to be **Longitudinally** Polarized

$\Longrightarrow$ All the Angular Distributions in the different frames can be computed.

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

$$\frac{d\sigma}{d\Omega} \propto 1 + \alpha_{AS}^{\Lambda_b} \mathcal{P}^{\Lambda_b} \cos\theta + 2\alpha_{AS}^{\Lambda_b} \Re e(\rho_{+-}^{\Lambda_b} \exp i\phi) \sin\theta \ . \tag{3}$$

$\Lambda \to p\pi^-$

$$\frac{d\sigma}{d\Omega_1} \propto \left\{ 1 + \alpha_{AS}^{\Lambda} \mathcal{P}^{\Lambda} \cos\theta_1 - \frac{\pi}{2} \mathcal{P}^{\Lambda_b} \alpha_{AS}^{\Lambda} \Re e \left[\rho_{+-}^{\Lambda} \exp(i\phi_1) \right] \sin\theta_1 \right\} , \tag{4}$$

$J/\psi \to \mu^+\mu^- \ , \ \rho^0 \to \pi^+\pi^-$

$$\frac{d\sigma}{d\cos\theta_2} \propto \left(1 - 3\rho_{00}^V\right) \cos^2\theta_2 + (1 + \rho_{00}^V) \ , \tag{5}$$

$$\frac{d\sigma}{d\cos\theta_2} \propto \left(3\rho_{00}^V - 1\right) \cos^2\theta_2 + (1 - \rho_{00}^V) \ , \tag{6}$$

III- SIMULATIONS and PERSPECTIVES with LHCb

- Calculations implemented in the Generator Code of LHCb, EvtGen
- Full Simulations of the LHCb Detector.
- Main Systematic Effects : Λ , $\bar{\Lambda}$ Absorption by the detector material

$\Longrightarrow$ $\approx 10\%$ of the events are lost.

$$S = \mathcal{L}^{\rm int}_{\rm year} \times \sigma(pp \to b\bar{b}) \times 2\,\mathcal{P}(b \to \Lambda_b^0) \times BR(\Lambda_b^0 \to \Lambda^0 J/\psi) \times BR(\Lambda^0 \to p\pi^-) \times BR(J \tag{7}$$

with $BR(\Lambda^0 \to p\pi^-) = 63.9\%$, $BR(J/\psi \to \mu^+\mu^-) = 6.76\%$, $\mathcal{L}^{\rm int}_{\rm year} \; = \; 2 \; {\rm fb}^{-1}$

$\Longrightarrow$ Expected Signal (including errors on the branching ratio measurements) :

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

⋆ Eric Conte's PhD Thesis, Université Blaise Pascal-Clermont II, Novembre 2007.

⋆ E.Conte, Z.J.A., "**Beauty Baryons at LHCb**", Public Note, LHCb-2008-005 (May 18, 2009)

III-1 CP Asymmetry

- Standard Model predictions : $1.7 \times 10^{-4} \leq \mathrm{AS_{CP}} \leq 2.8 \times 10^{-4}$

- Limits on CP-Asymmetry Beyond the Standard Model could be set, provided total error is estimated.

$\int \mathcal{L}dt$ (fb^{-1})	$\sigma(A_{CP})$ for BR $= 7.5 \times 10^{-4}$	$\sigma(A_{CP})$ for BR $= 4.8 \times 10^{-4}$	$\sigma(A_{CP})$ for BR $= 1.9 \times 10^{-4}$
2	0.84%	0.95%	1.36%
4	0.74%	0.81%	1.06%
6	0.70%	0.75%	0.94%
8	0.69%	0.72%	0.87%
10	0.67%	0.70%	0.83%

Table 3: Total Error on the CP Asymmetry

- CP Asymmetry of 2.8% (90% CL) can be put into evidence after one year of data taking.

- Limit of 1.6% can been reached (90% CL) for $10\mathrm{fb}^{-1}$ (5 data taking years).

III-2 T-Odd Observables and their Asymmetries

$$\overrightarrow{n}_{\Lambda^0} = \frac{\overrightarrow{p}_p \times \overrightarrow{p}_\pi}{|\overrightarrow{p}_p \times \overrightarrow{p}_\pi|} \qquad \overrightarrow{n}_{J/\psi} = \frac{\overrightarrow{p}_{\mu^+} \times \overrightarrow{p}_{\mu^-}}{|\overrightarrow{p}_{\mu^+} \times \overrightarrow{p}_{\mu^-}|} \tag{8}$$

- T-Odd Observables : Cosine and Sine of $\phi_{\overrightarrow{n}_{\Lambda^0}}$

$$\cos\phi_{(n_{\Lambda^0})} = \frac{\overrightarrow{e}_Y \cdot (\overrightarrow{e}_Z \times \overrightarrow{n}_{\Lambda^0})}{|\overrightarrow{e}_Z \times \overrightarrow{n}_{\Lambda^0}|}, \qquad \sin\phi_{(n_{\Lambda^0})} = \frac{\overrightarrow{e}_Z \cdot (\overrightarrow{e}_X \times \overrightarrow{n}_{\Lambda^0})}{|\overrightarrow{e}_X \times \overrightarrow{n}_{\Lambda^0}|} \tag{9}$$

$\mathcal{P}^{\Lambda_b^0}$	$AS(\cos\phi_{(n_{\Lambda^0})})$	$AS(\sin\phi_{(n_{\Lambda^0})})$
100%	5.2%	−5.0%
75%	3.3%	−3.6%
50%	2.2%	−2.9%
25%	0.6%	−1.8%
0%	0%	0%

Table 4: Asymmetry Variations of the **C-S Observables**

Potentialities of LHCb to put into evidence TRV

$\int \mathcal{L}dt$ (fb^{-1})	$\sigma(AS)$ for BR $= 7.5 \times 10^{-4}$	$\sigma(AS)$ for BR $= 4.8 \times 10^{-4}$	$\sigma(AS)$ for BR $= 1.9 \times 10^{-4}$
2	0.56%	0.72%	1.21%
4	0.40%	0.51%	0.85%
6	0.32%	0.41%	0.70%
8	0.28%	0.36%	0.60%
10	0.25%	0.32%	0.54%

Table 5: Statistical Error on the Asymmetry of the **C-S observables**

•• Consequences :

(1) For 1 year of data taking, an Asymmetry of 2.4% can be put into eveidence at 90% CL, $\Rightarrow$ Λ_b Polarization, $\mathcal{P}^{\Lambda_b} \geq 50\%$

(2) With an Integrated Luminosity of $10 fb^{-1}$, an Asymmetry $\geq 1\%$ could be detected at 90% CL, $\Rightarrow$ Λ_b Polarization, $\mathcal{P}^{\Lambda_b} \geq 20\%$

III-3 Polarizations of the Resonances Λ and J/ψ

- New Method to put into evidence TRV

- Intermediate Resonances, Λ and J/ψ , are still POLARIZED even if Λ_b is not polarized, $\mathcal{P}^{\Lambda_b} = 0$
(O.L, Z.J.A., hep-ph/0602043 and Nucl.Phys.B.174(2007), 169-172)

- How Polarization could be related to TRV ??

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

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

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

⋆ But, if $(P_n)_{measured} \neq 0 \Rightarrow$ TR Violated !!??

$$\Downarrow \ \Downarrow \ \Downarrow$$

VIOLATION of TR, if and only if

FSI are NEGLIGIBLE

• 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**).

• In some Specific Frames related to the Resonances :

(1) Transverse Component, P_T, is T-Odd

(2) Correlations P_{TN} and P_{NT} between Vector-Polarizations of the Resonances Λ and J/ψ are T-Odd.

$\Downarrow \Downarrow \Downarrow$

SIGN of TRViolation !?

$\star\star\star$ Only DATA could help to answer this fundamental question....

IV- CONCLUSION

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

- Putting into evidence T-Odd Observables like the C-S Parameters is possible, provided Λ_b is Polarized; but need to handle the Systematic Effects.

- (Very) Promising Method :

$\Longrightarrow$ Measuring **Transverse Polarization** of the Resonances Λ , J/ψ and their Correlations independently of any value of the Λ_b polarization.

- If TRViolation process **not predicted** by the Standard Model

$\Downarrow$

Evidence for a new process beyond the SM

$\Downarrow$

New Physics ?

If Saint-Augustin was hearing us, He would say :

... Finally, what is Time (Reversal) ??

"If nobody asks me, I know the answer.
But,
if somebody does ask me and I must explain it, thus I would be unable to do it"

Publications

"Analysis of the channel $\Lambda_b^0 \rightarrow \Lambda^0 J/\psi$ "
note LHCb 2005-067 (2005).

"Angular Analysis of Λ_b decays into $\Lambda V(1^-)$ "
hep-ph/0409262, PCCF RI 0409.

"Testing Fundamental Symmetries with $\Lambda_b \rightarrow \Lambda - Vector$ Decays"
hep-ph/0602043, PCCF RI0601.

" Λ_b Decays into $\Lambda - Vector$ **"**
Phys.Lett.**B614** (2005), 165-175; hep-ph/0412116.

Eric Conte,
"Recherche de la violation des symétries CP et T dans les réactions $\Lambda_b \rightarrow \Lambda + \mathrm{meson} - \mathrm{vecteur}$ **"**
Thèse de Doctorat d'Université, Université Blaise Pascal; DU1785, EDSF546, PCCF T0710 (Novembre 2007).

"Testing CP and Time Reversal Symmetries with $\Lambda_b \rightarrow \Lambda V(1^-)$ **Decays"**
Nucl.Phys.**B (Proc.Suppl.)174** (2007), 169-172; hep-ph/0610189.

E.DiSalvo, Z.J.Ajaltouni
"Model independent tests for Time Reversal and CP violations and for CPT theorem in $\Lambda_b, \bar{\Lambda}_b$ **two body decays"**
Modern Physics Letters A, Vol. 24 (2009), 109-121.