

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

Z.J.AJALTOUNI

Laboratoire de Physique Corpusculaire/CNRS-IN2P3
Université Blaise Pascal-CLERMONT II

with the collaboration of

E.Conte, O.Leitner, E.DiSalvo, M.Jahjah, R.Lefèvre

LPSC, GRENOBLE, September 24-25 (2009)

I– Theoretical Introduction to **TIME-REVERSAL**.

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

III– SIMULATIONS and PERSPECTIVES with **LHCb**

IV– CONCLUSION

I- Time Reversal Symmetry : Theory and Problems

- 3 Discrete Transformations which are Approximate Symmetries :

★ **PARITY P** : $\vec{r}, \vec{p} \rightarrow -\vec{r}, -\vec{p}$, $\vec{\ell}, \vec{s}$ Unchanged

★ **CHARGE CONJUGATION C** : $Q \rightarrow -Q$, $\vec{r}, \vec{p}, \vec{\ell}, \vec{s}$ Unchanged

★ **TIME REVERSAL, T** : $\vec{r} \rightarrow \vec{r}$, $\vec{p}, \vec{\ell}, \vec{s} \rightarrow$ Opposite Sign

But,

P and C are **Hermitian-Unitary** Operators, while

T is an **ANTIUNITARY** Operator

⇓

NO Real Eigenvalues like P and C

⇓

≡ NO Intrinsic Quantum Numbers

How Testing Time-Reversal Symmetry ?

• Initial State $|i\rangle = |\vec{p}_i, \vec{s}_i\rangle \rightarrow |i^T\rangle = |-\vec{p}_i, -\vec{s}_i\rangle$

• Final State $|f\rangle = |\vec{p}_f, \vec{s}_f\rangle \rightarrow |f^T\rangle = |-\vec{p}_f, -\vec{s}_f\rangle$

★ If **TR** Exact Symmetry $\Rightarrow |\langle f|S|i\rangle| = |\langle i^T|S|f^T\rangle|$

★ 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 \implies T Violated

- (2) DIRECT WAY :

Looking for T-Odd Observables, like

$$C_{ijk} = \vec{v}_i \cdot (\vec{v}_j \times \vec{v}_k) \text{ with } \vec{v} = \vec{p} \text{ or } \vec{s}$$

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

Ex: POLARIZATION of Particles with Spin.

- Is this last Condition Sufficient ???

⇒ Existence of the Final State Interactions (FSI) which modify the Scattering Amplitude.

↓ ↓ ↓
Simulation of TRV effects !!??

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

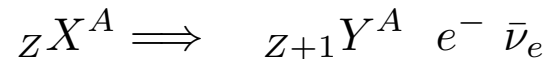
(1) Compute with high precision the FSI (including the non-perturbative contribution !?)

(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



- Looking for Correlations between Neutron Spin, s_n , and \vec{p}_e , \vec{p}_ν .
- ★ Electromagnetic FSI taken into account (Jackson-Treiman-Wyld, 1957).
- ★ Differential cross-section :

$$d\sigma \approx \vec{s}_n \cdot (A\vec{p}_e + B\vec{p}_\nu + D\vec{p}_e \times \vec{p}_\nu)$$

- (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))

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

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

3- Electric Dipole Moments (EDM)

- $d_e \neq 0$ or $d_n \neq 0 \implies$ 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 $\Lambda \rightarrow p\pi^-$ where Parity is Violated (R. Gatto, 1958).

If

\implies s-quark is replaced by b-quark

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

- (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" : $\Lambda_b \rightarrow \Lambda J/\psi$ (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,

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

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

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

- Performing $\Lambda_b \oplus \text{TRV}$ 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 $\Lambda_b \rightarrow \Lambda J/\psi$

1- DYNAMICS

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

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

- ★ c_i = Wilson Coefficients = Hard Perturbative Contributions
- ★ 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 :

\Downarrow

FOUR Helicity Amplitudes :

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

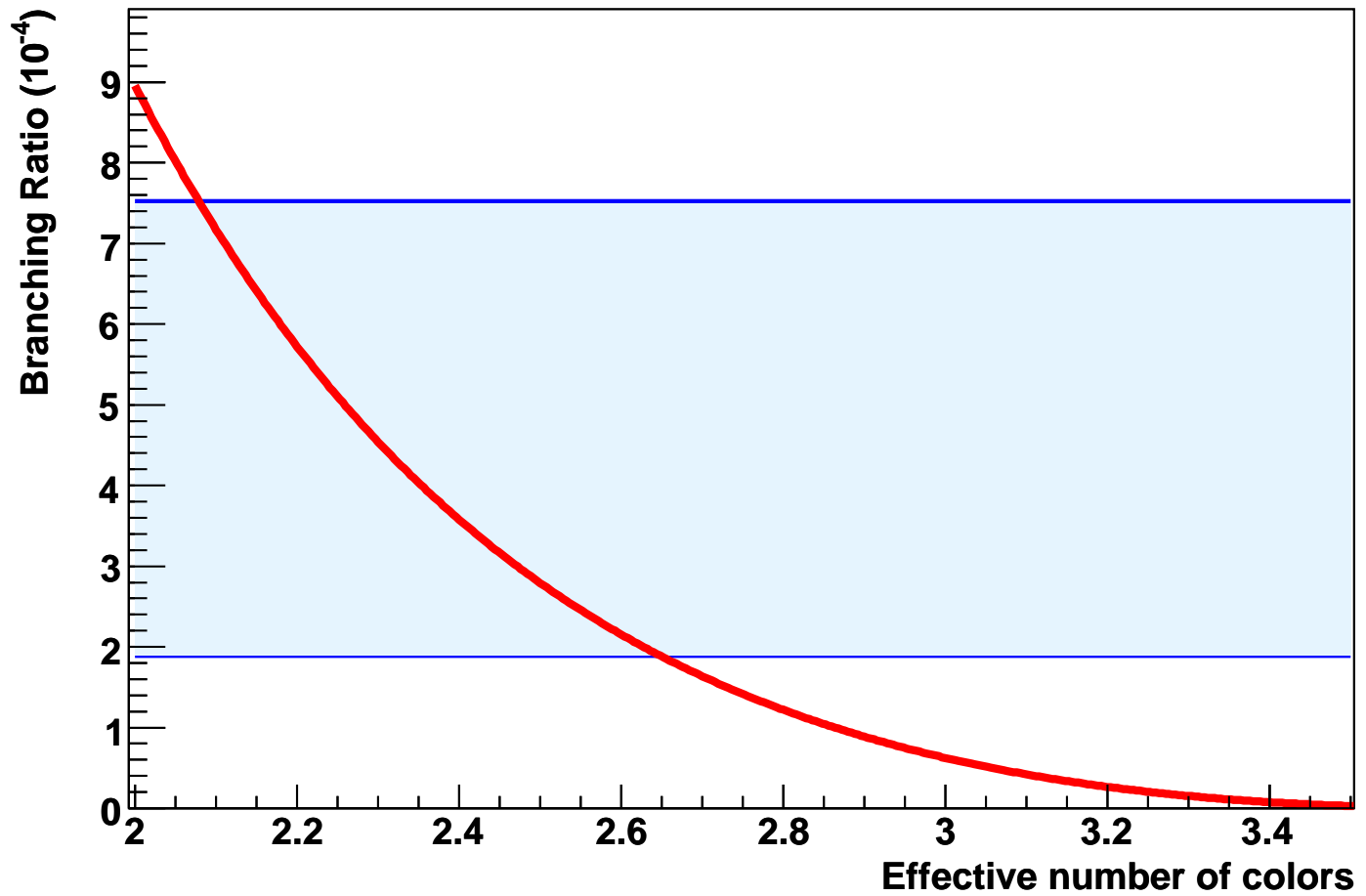
- **Analytical Expressions** of the corresponding four amplitudes given by :

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

★ 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 $\Lambda_b \rightarrow \Lambda J/\psi$

→ Quantization Axis being Normal to the Λ_b Decay Plane.

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

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

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

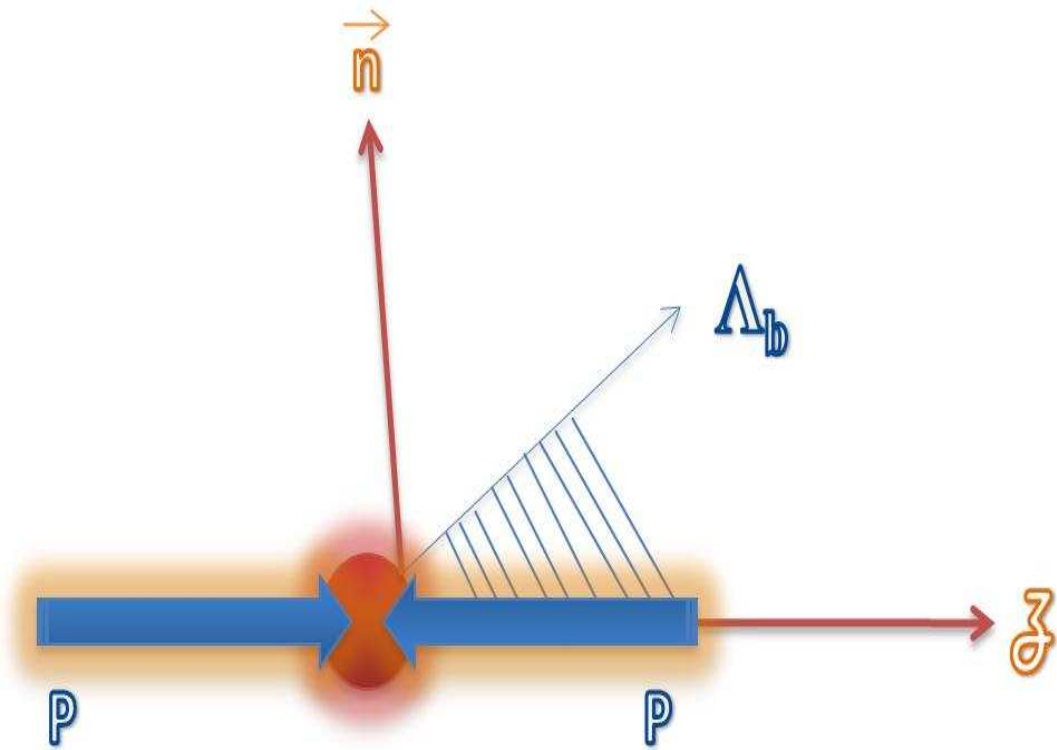


Figure 1: Λ_b in the Standard LHCb Frame

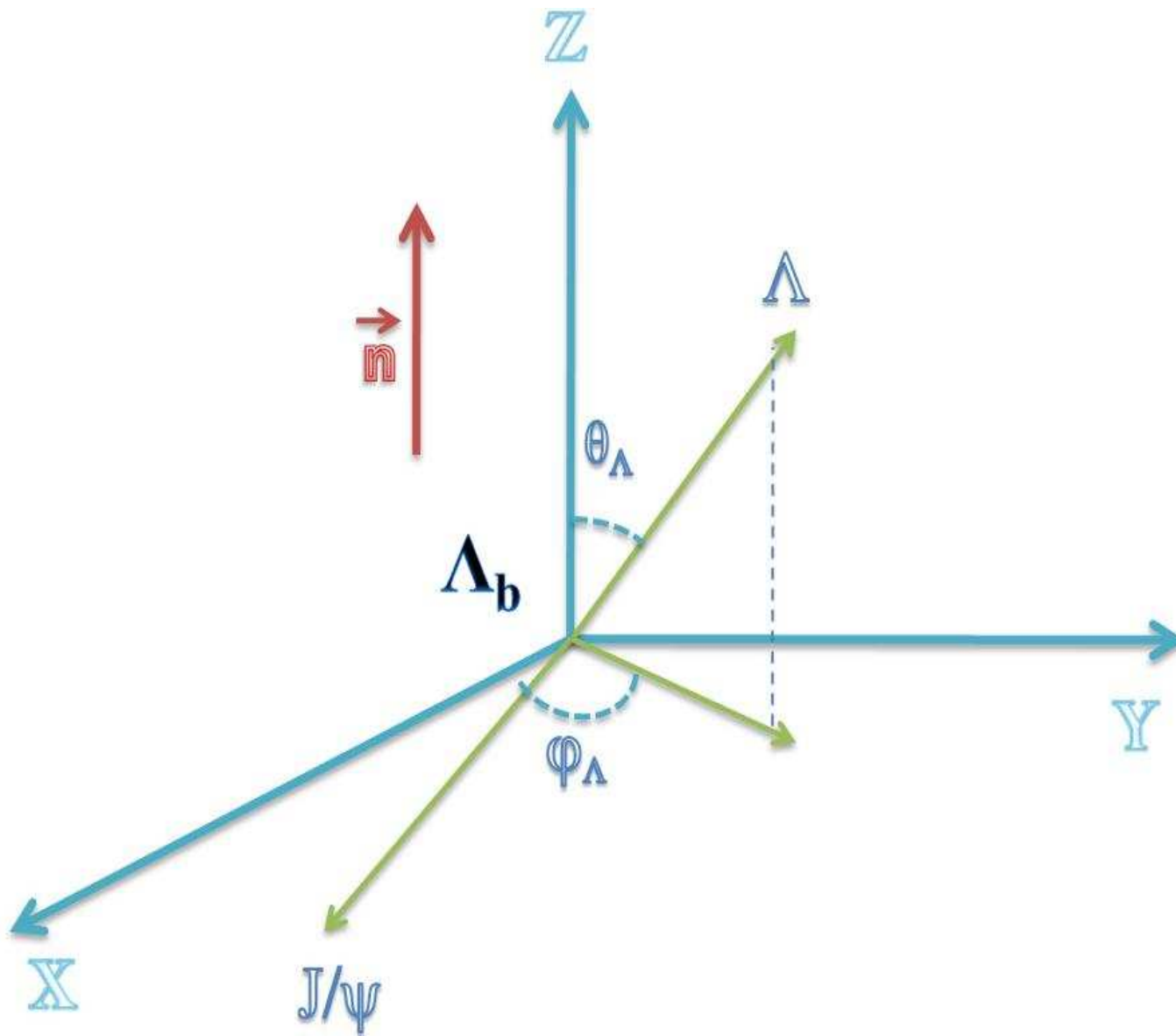
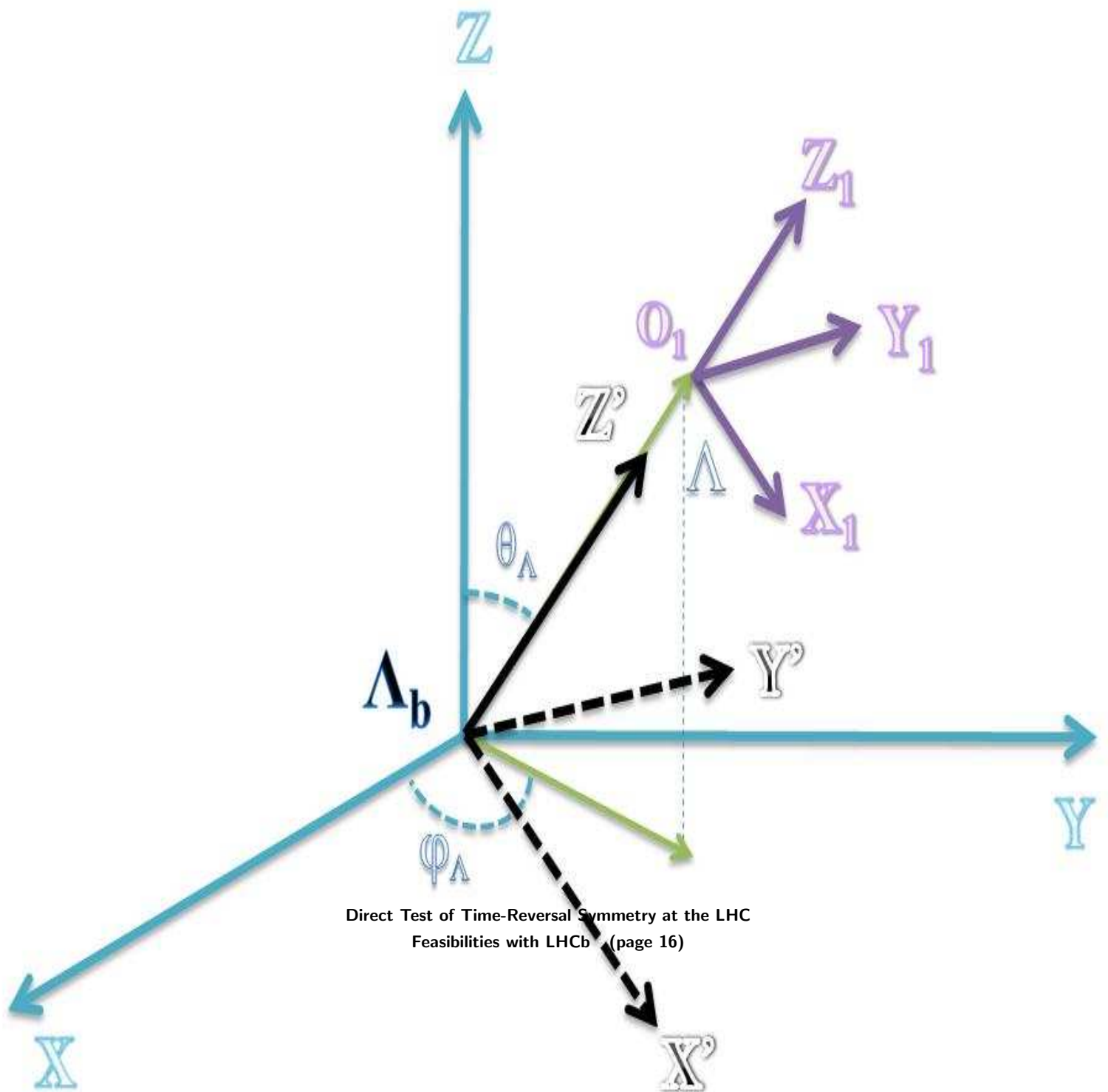


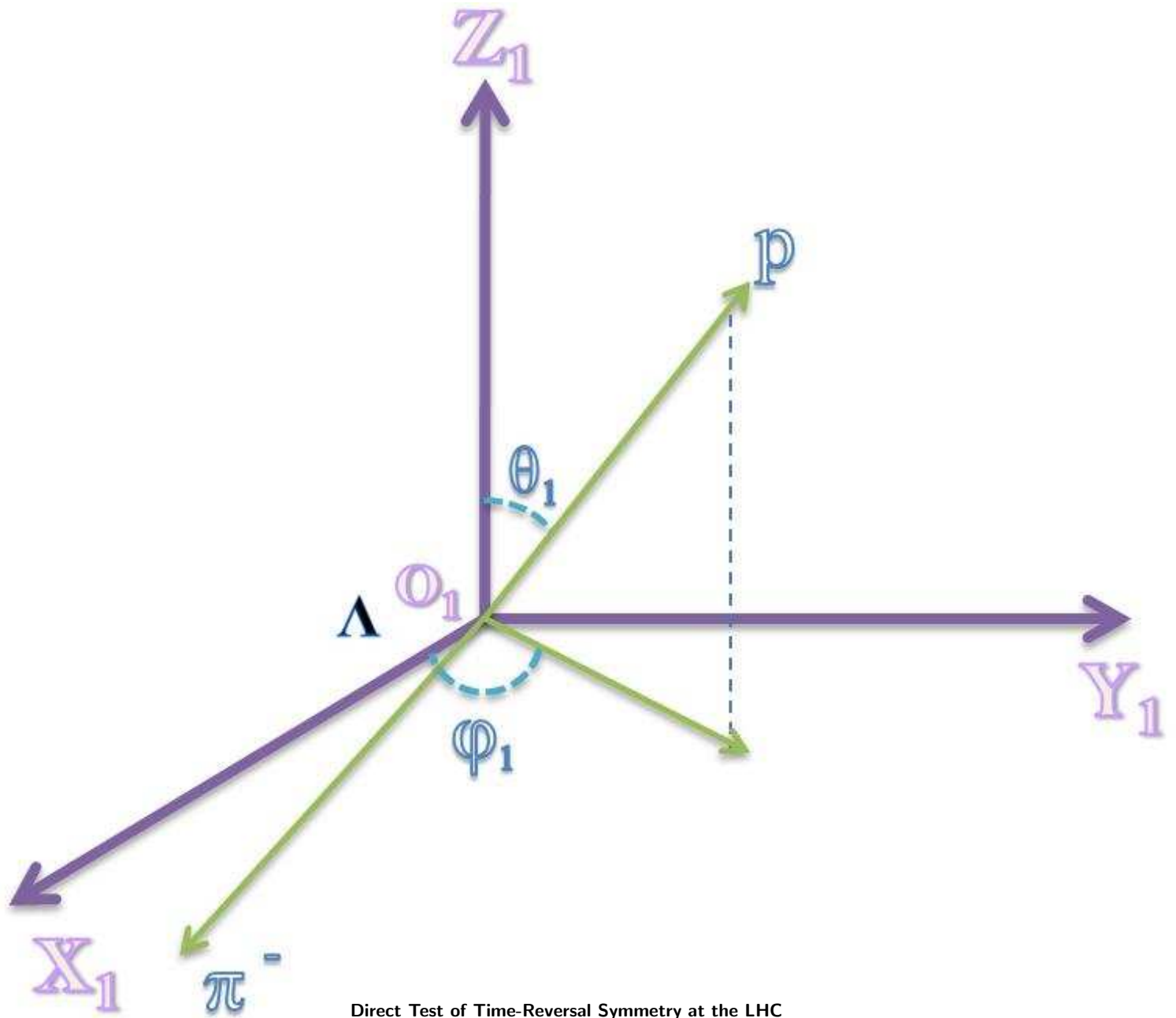
Figure 2: Λ_b Transversity Rest-Frame

Direct Test of Time-Reversal Symmetry at the LHC



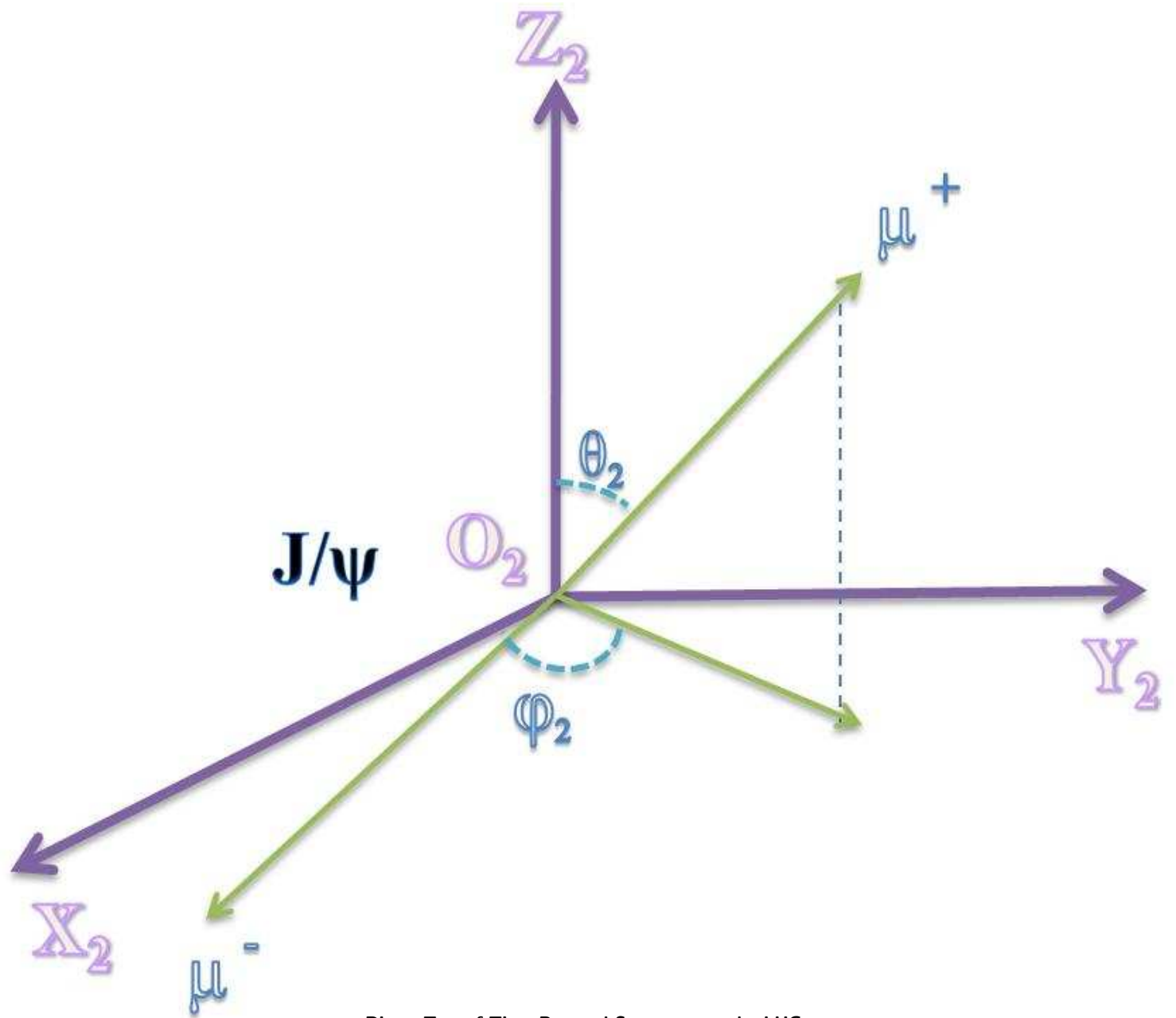
Direct Test of Time-Reversal Symmetry at the LHC
 Feasibilities with LHCb (page 16)

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



Direct Test of Time-Reversal Symmetry at the LHC
 Feasibilities with LHCb (page 17)

Figure 4: Λ Helicity Rest-Frame



Direct Test of Time-Reversal Symmetry at the LHC
Feasibilities with LHCb (page 18)

Figure 5: J/ψ Helicity Rest-Frame

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

$$\Lambda_b \implies \Lambda J/\psi \quad , \quad \Lambda \rightarrow p\pi^- \quad , \quad J/\psi \rightarrow \mu^+ \mu^-$$

can be determined, like :

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

Spin Density Matrices : ρ^Λ , ρ^V

Polarizations : \mathcal{P}^Λ , \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}^Λ	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

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

⇒ All the **Angular Distributions** in the different frames can be computed.

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

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

$$\Lambda \rightarrow p\pi^-$$

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

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

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

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

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

$$S = \mathcal{L}_{\text{year}}^{\text{int}} \times \sigma(pp \rightarrow b\bar{b}) \times 2 \mathcal{P}(b \rightarrow \Lambda_b^0) \times BR(\Lambda_b^0 \rightarrow \Lambda^0 J/\psi) \times BR(\Lambda^0 \rightarrow p\pi^-) \times BR(J/\psi \rightarrow \mu^+\mu^-) \quad (7)$$

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

\implies 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 : $1.7 \times 10^{-4} \leq A_{CP} \leq 2.8 \times 10^{-4}$
- 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 = 7.5×10^{-4}	$\sigma(A_{CP})$ for BR = 4.8×10^{-4}	$\sigma(A_{CP})$ for BR = 1.9×10^{-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 be reached (90% CL) for 10fb⁻¹ (5 data taking years).

III-2 T-Odd Observables and their Asymmetries

$$\vec{n}_{\Lambda^0} = \frac{\vec{p}_p \times \vec{p}_\pi}{|\vec{p}_p \times \vec{p}_\pi|} \quad \vec{n}_{J/\psi} = \frac{\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}}{|\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}|} \quad (8)$$

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

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

$\mathcal{P}^{\Lambda_b^0}$	$AS(\cos \phi_{(n_{\Lambda^0})})$	$AS(\sin \phi_{(n_{\Lambda^0})})$
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 = 7.5×10^{-4}	$\sigma(AS)$ for BR = 4.8×10^{-4}	$\sigma(AS)$ for BR = 1.9×10^{-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 evidence at 90% CL, $\Rightarrow \Lambda_b$ 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, $\Rightarrow \Lambda_b$ 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](https://arxiv.org/abs/hep-ph/0602043) and [Nucl.Phys.B.174\(2007\), 169-172](https://arxiv.org/abs/hep-ph/0602043))
- How Polarization could be related to **TRV** ??
- ★ Measurement of the Polarization according to a direction \vec{n} Invariant by TR.

$$P_n = \vec{\mathcal{P}} \cdot \vec{n} = \langle \vec{s} \rangle \cdot \vec{n} \rightarrow TR \rightarrow - \langle \vec{s} \rangle \cdot \vec{n} = -P_n$$

★ If **TR** is an EXACT SYMMETRY $\implies P_n = 0$

★ But, if $(P_n)_{measured} \neq 0 \implies$ **TR** Violated !!??

↓ ↓ ↓

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**.



SIGN of **TRV**iolation !?

*** 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 :
⇒ 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

⇓
Evidence for a new process beyond the SM
⇓
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

$\Lambda_b \rightarrow \Lambda + \text{meson} - \text{vecteur}$ ”

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.