Search for Direct Time-Reversal Violation

An Experimentalist-Theorist Collaboration

Z.J.AJALTOUNI
LPCCF - UBP/CNRS-IN2P3

Elvio Di Salvo
INFN-GENOVA

Heavy Baryon LHCb Workshop

$I-$ Introduction

$II-$ T-odd Observables and Asymmetries

$III-$ Kinematics and Dynamics

$IV-$ Observable Measurements

I- Introduction

- **CPT** (theorem) $\equiv$ Exact Symmetry, but CP violated $\Rightarrow$ Indirect Violation of T

- Why Direct Search for Time-Reversal Violation (TRV) ??

TR symmetry can be tested **independently** of CP
$\Longrightarrow$ CP conjugated channel not required

Example : Electric Dipole Moment of an elementary particle : electron, neutron ...

$$\vec{D}_e \quad = \quad d_e \; \vec{s} \qquad d_e \neq 0 \Longrightarrow \; \mathrm{TRV}$$

- Historically, TR tested in Hyperon weak decays just after **Parity** Violation (R. Gatto, 1958) like :

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

Also in Weak β-Decay of the Neutron (Jackson et al, 1958)

$\Longrightarrow$ Essential to produce a **Polarized** particle (Resonance) in order to test TRV.

- Our Method : *Phenomenological and Intuitive approach*.

II- T-Odd Observables and Polarization

- Action of TR :

$$\vec{p} \to -\vec{p}\ (1), \quad \vec{s} \to -\vec{s}\ (2), \quad \text{and} \quad |i> \leftrightarrow |f> \quad (3)$$

But :

- Last condition not (easy) realized in Nature $\Longrightarrow$ TR limited to transformations(1) and (2)

$$\Downarrow$$

Naive Time-Reversal operation.

$$\Downarrow$$

T-odd Observable $\equiv$ Physical quantity changing sign by TR transformation

$$O \Longrightarrow \quad -O$$

• If TR is a **Good Symmetry** $\Longrightarrow O = 0, \quad \text{or} \quad < O >= 0$.

⋆ **But :**
Every T-odd Observable $\neq \ 0$ is not a sign of TRV, because of **Final State Interaction** (FSI).

$$A + B \rightarrow \ C + D \ \Longrightarrow \ TR \ \Longrightarrow \ C' + D' \rightarrow A' + B' \quad X' = X(-\vec{p}, -\vec{s})$$

Normally, Strong Interactions between C and D $\neq$ between $A^{(')}$ and $B^{(')}$

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FSI are **Unavoidable** Systematic Effects in Direct TRV searches

• Example : Transverse Polarization of Hyperons produced in p-p or p-nucleus collisions

$$\vec{t} = \frac{\vec{p_i} \times \vec{p}_h}{|\vec{p_i} \times \vec{p}_h|}, \quad P_t = \vec{t} \cdot \vec{s} \rightarrow \vec{t} \cdot (-\vec{s}) = -P_t$$

Usually, $P_t \neq 0$ and no sign of TRV.

Wolfenstein "Theorem" (1990-2000) :
If the FSI are negligible in a given process or if they can be subtracted from the scattering amplitude, any T-odd Observable is a *Sign of TRV*.

III- Kinematics and Dynamics

- General expression of a T-odd Observable :

$$C \;=\; \vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3), \quad \vec{v}_i = \vec{s}_i \text{ or } \vec{p}_i$$

- Searching for T-odd Observables in Heavy Baryon Decays :

$$\mathcal{B}_b \Longrightarrow R_1(\to a_1 + b_1) \;+\; R_2(\to a_2 + b_2)\;,\; R_1 = (1/2)^+ \; R_2 = 0^-, 1^-$$

"Best Example" , $\Lambda_b \Longrightarrow \; \Lambda(\to p\pi^-) \; J/\psi(\to \mu^+\mu^-)$

- Kinematics based on the **Helicity Formalism** of Jacob-Wick-Jackson.

1-Frames

Transversity Frame constructed from the standard laboratory frame :

$$\mathbf{e}_x = \hat{\mathbf{p}}_{proton}, \; \mathbf{e}_z = \frac{\mathbf{e}_x \times \mathbf{p}_b}{|\mathbf{e}_x \times \mathbf{p}_b|}, \; \mathbf{e}_y = \mathbf{e}_z \times \mathbf{e}_x.$$

Then boosted to the $\mathcal{B}_b$ rest-frame along $\mathbf{p}_b$, the quantization axis being taken parallel to $\mathbf{e}_z$. Then R_i *helicity frame* is defined as :

$$\mathbf{e}_L = \hat{\mathbf{p}}_R,\ \mathbf{e}_T = \frac{\mathbf{e}_z \times \mathbf{e}_L}{|\mathbf{e}_z \times \mathbf{e}_L|},\ \mathbf{e}_N = \mathbf{e}_T \times \mathbf{e}_L,$$

$\Rightarrow$ Analysis of the Angular Distributions of particles $a_i(b_i)$

2-Transformation under TR

$\mathbf{e}_x$ and $\mathbf{e}_y$ Change Sign under TR.

$\mathbf{e}_z$ Unchanged.

In each R_i rest frame, $\mathbf{e}_L$ and $\mathbf{e}_T$ are **T-odd**, whereas $\mathbf{e}_N$ is **T-even**.

3-Decay Amplitude

$$A_0(M_i) = \langle 1/2, M_i|\mathcal{S}^{(0)}|p,\theta,\phi;\lambda_1,\lambda_2\rangle = \mathcal{A}_{(\lambda_1,\lambda_2)}(\Lambda_b \to R_1 R_2) D^{1/2\star}_{M_i M_f}(\phi,\theta,0)\ , \quad (1)$$

$$D^j_{M_i M_f}(\phi,\theta,0) = d^j_{M_i M_f}(\theta)\exp(-iM_i\phi)\ , \quad (2)$$

⋆ Weighting by the PDM of Initial Resonance Λ_b and Summation over all the states (intermediate and helicity final) :

$$\frac{d\Gamma}{d\Omega} = N^J \sum_{M_i, M_i'} \sum_{\lambda_1, \lambda_2} \rho^{\Lambda_b}_{M_i M_i'} |\mathcal{A}_{(\lambda_1,\lambda_2)}(\Lambda_b \to R_1 R_2|^2 d^{1/2}_{M_i \lambda} d^{1/2}_{M_i' \lambda} \exp i(M_i' - M_i)\phi \ . \quad (3)$$

⋆ $A_{(\lambda_1,\lambda_2)} \neq A_{(-\lambda_1,-\lambda_2)}$ because of Parity violation.

⋆ Dynamics Model and 3 real parameters to fully determine $W(\theta,\phi) = \frac{d\Gamma}{d\Omega}$: $\mathcal{P}^b$, and complex ρ_{+-}

4-Asymmetry and Polarization(s)

• *Helicity Asymmetry Parameter*, α_{As}, computed according to :

$$\alpha_{As} = \frac{|\mathcal{B}_b(+)|^2 - |\mathcal{B}_b(-)|^2}{|\mathcal{B}_b(+)|^2 + |\mathcal{B}_b(-)|^2}, \quad (4)$$

with

$$|\mathcal{B}_b(\pm)|^2 = |A^J_{\pm 1/2,0}|^2 + |A^J_{\mp 1/2,\mp 1}|^2. \quad (5)$$

• Polarization-vector of each Resonance R_i : Standard Relations (JWJ)

$$\vec{\mathcal{P}}_i = \frac{Tr({\rho_i}^f \vec{S})}{W(\theta,\phi)}, \quad {\rho_i}^f \text{being final PDM of } R_i$$

- Transformation of $\vec{\mathcal{P}}_i$ under TR :

$$\mathcal{P}_N \;=\; \vec{\mathcal{P}}_{(i)} \cdot \vec{e}_N \Longrightarrow (-\vec{\mathcal{P}}_{(i)}) \cdot \vec{e}_N \;=\; -\mathcal{P}_N$$

$\Rightarrow$ The Normal Component $\mathcal{P}_N$ is **T-Odd**. So,
If $\mathcal{P}_N \neq 0 \;\Rightarrow$ *Sign of TRV*.

IV- Observable Measurements

- Weak Decaying Resonance $\quad X \rightarrow (1/2)^+ + 0^-(1^-)$

$X = \Lambda_b$ or Λ , α^X its asymmetry parameter

$$\frac{dN}{d\Omega} \;\propto\; 1 + \alpha^X \mathbf{P}^X \cdot \hat{\mathbf{p}}, \tag{6}$$

$\Rightarrow$ Polar and Azimuthal angle distributions :

$$f(\cos\theta) \;=\; \frac{1}{2}(1 + \alpha^X P_z^X \cos\theta) \tag{7}$$

and

$$g(\phi) \;=\; \frac{1}{2\pi}\big(1 + \frac{\pi}{4}\alpha^X (P_x^X \cos\phi \;+\; P_y^X \sin\phi)\big) \tag{8}$$

• Inferring P_x^X, P_y^X and P_z^X for the primary resonance, $\mathcal{B}_b$,

• Secondary (Baryon) decay $R_1 \to a_1 + b_1$, P_x^X identified with the Normal Component $P_N^{R_1}$, a **T-odd observable**.

• Resonance R_2 Decay which conserves Parity, like $J/\psi \to \mu^- \mu^+$

$$\frac{dN}{d\cos\theta} \propto (1 - 3\rho_{00}) \cos^2\theta + (1 + \rho_{00}) \propto 1 + \gamma \cos^2\theta, \tag{9}$$

ρ_{00} is the probability for J/ψ to be longitudinally polarized, and

$\gamma = \frac{1-3\rho_{00}}{1+\rho_{00}}$.

⋆ Azimuthal Distribution of μ^- in J/ψ rest-frame is **Uniform**

How handling FSI (?)

• How to disentangle **FSI** from experimental results :

New Calculation Techniques in QCD, QCDF(Factorization).

• Old argument of Bjorken (1990) : *FSI are very weak* if Transition between

Heavy Quarks, like :

$$Q \Longrightarrow Q' \ + \ X..... \ \text{like}\ \Lambda_b \rightarrow \ J/\psi + \Lambda$$

• Independently of *any argument or model*, we notice that FSI coming from Strong Interactions are **CP Invariant**

$\Longrightarrow$ Comparing $\mathcal{B}_b$ and $\bar{\mathcal{B}}_b$ decays. (Valencia, London).

• Increasing the Number of TR tests as follows :

$$P_\alpha^{(1)} P_\beta^{(2)} \quad \alpha, \beta = \mathrm{L},\ \mathrm{T},\ \mathrm{N}$$

• Time-Reversal Asymmetry parameter defined by :

$$\mathcal{A}_T \ = \ \frac{O - \bar{O}}{O + \bar{O}} \ \text{ with } \ \bar{O} = CP|O>$$

Usually, we have **Interference** of two different amplitudes like *Spin-Orbit* term and another one.

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$$\mathcal{A}_T \ = \ 2A_1A_2 \, \cos\delta_s \, \sin\phi_W$$

Even for small FSI, $\equiv \delta_s \rightarrow 0$, TR Asymmetry will be amplified.

Looking for New Physics (?)

• Defining new T-odd observables and Comparing them to their CP Conjugate ones.

• Eventual TRV effects independently of CPT theorem (?)

Thank you for your attention

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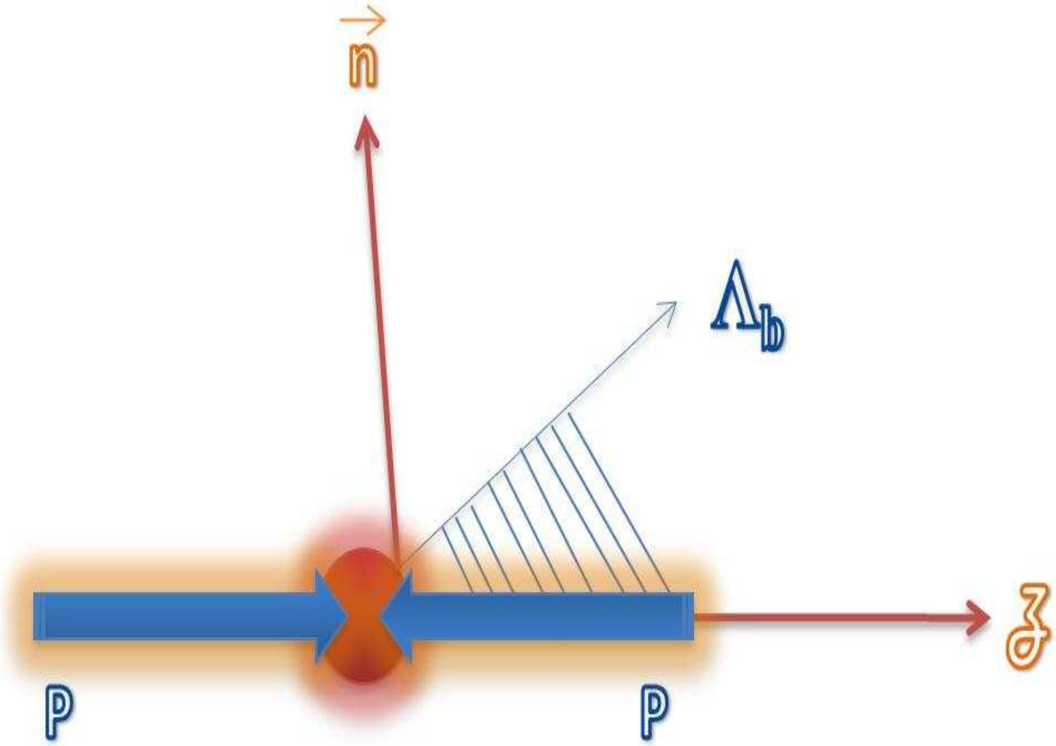

Figure 1: Λ_b in the Standard LHCb Frame

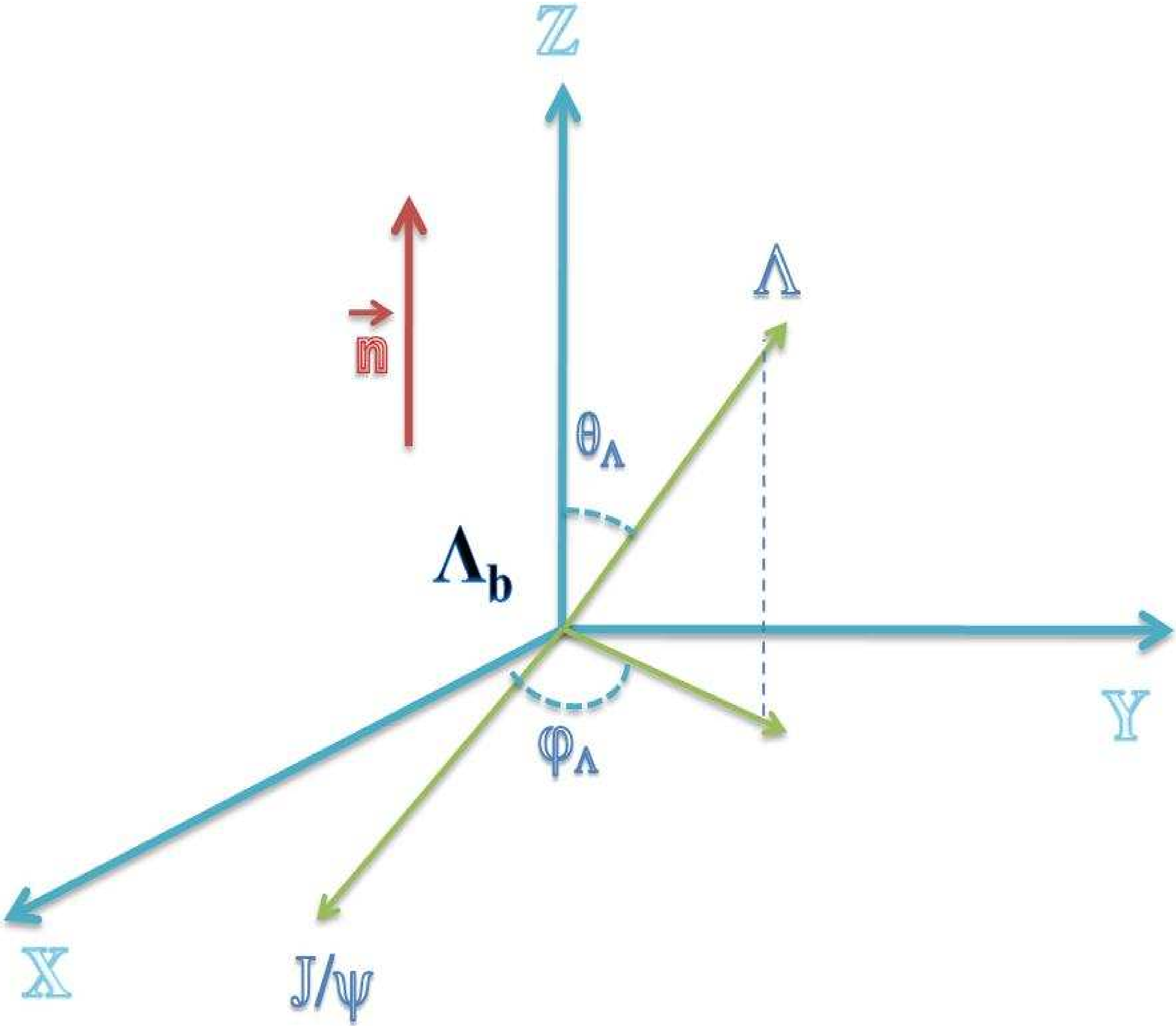

Figure 2: Λ_b Transversity Rest-Frame

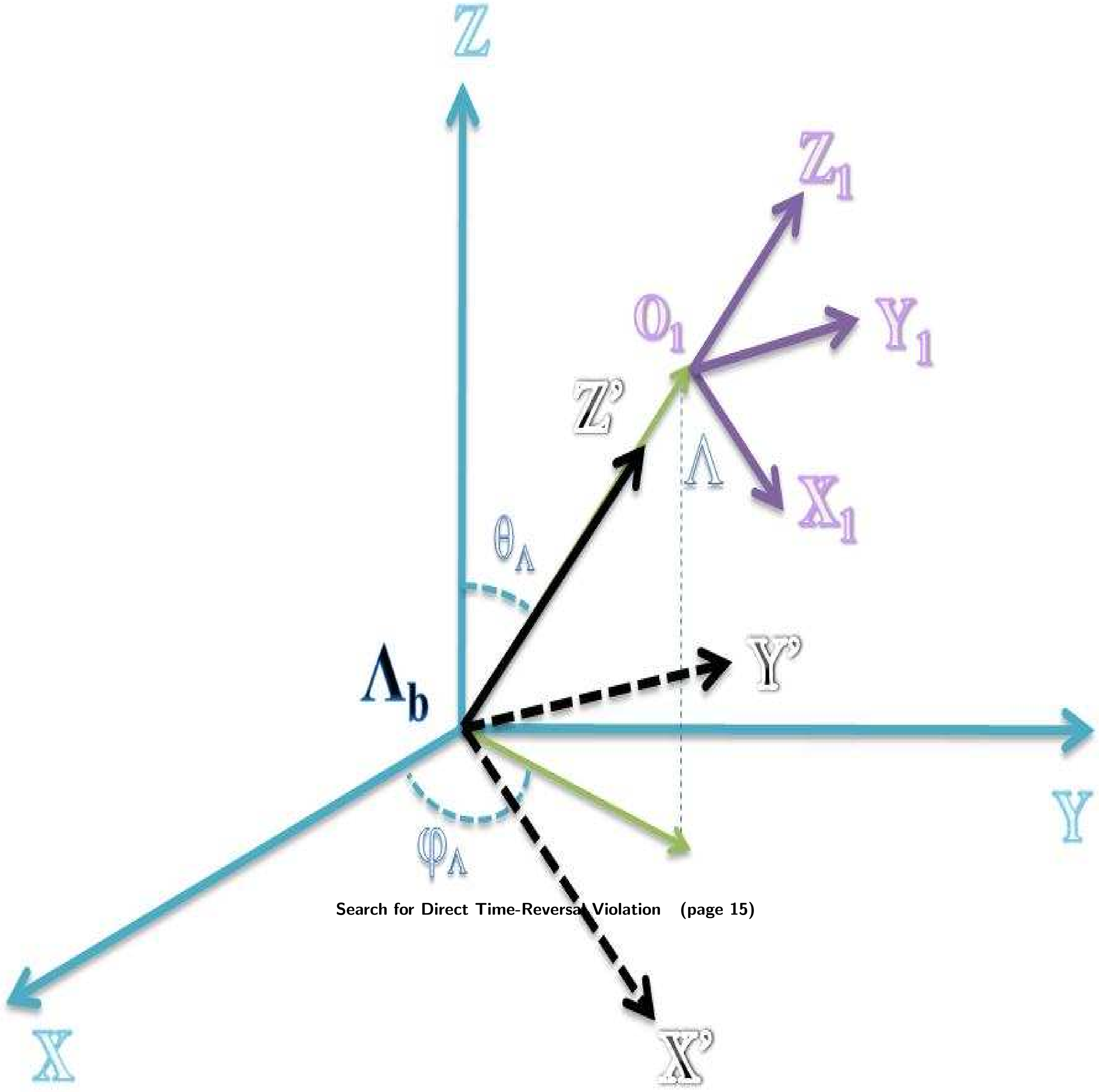

Figure 3: From Λ_b rest-frame to Λ^0 Helicity rest-frame

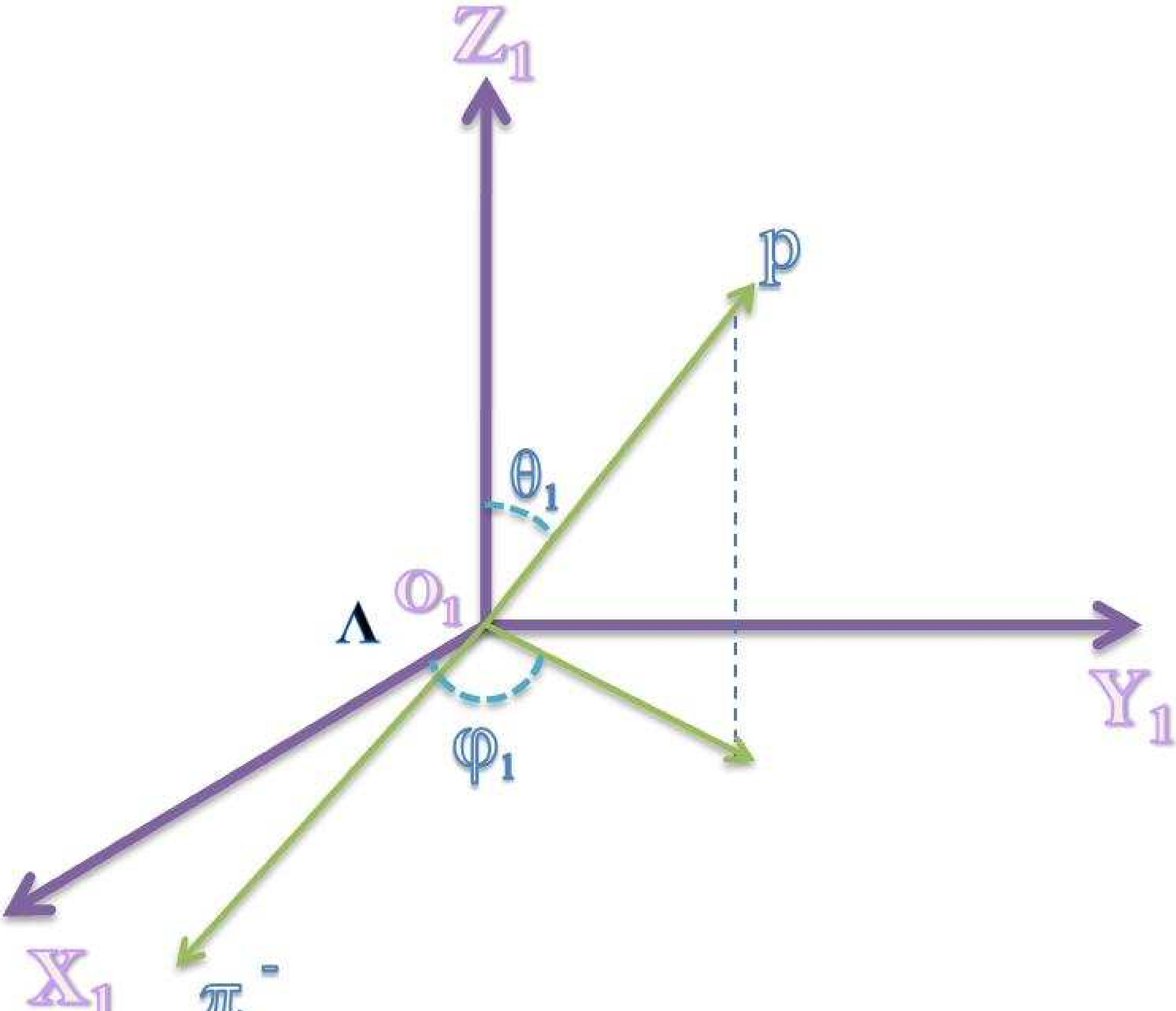

Figure 4: Λ^0 Helicity Rest-Frame

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