T-ODD AND T-EVEN OBSERVABLES IN HADRON WEAK DECAYS

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SUMMARY

1. T-ODD AND T-EVEN ASYMMETRIES

2. REAL T-R ODD AND FAKE T-ODD OBSERVABLES

3. SPIN – ORBIT INTERACTION

4. APPLICATION TO $B^{\pm} \rightarrow K^{\pm}\, p\, \bar{p}$ DECAY

5. APPLICATIONS TO BARYON DECAYS

6. HIGHLIGHTS

1. T-ODD AND T-EVEN ASYMMETRIES

ASYMMETRIES → INTERFERENCE TERMS

$$\text{Asymm} = \frac{N(C > 0) - N(C < 0)}{N(C > 0) + N(C < 0)}$$

"C" : CORRELATION AMONG MOMENTA

AND/OR SPINS INVOLVED IN A PROCESS

T-EVEN CORRELATIONS:

$C_a = \mathbf{p} \bullet \mathbf{s}$ (LONGITUDINAL POLARIZATION $\rightarrow$
$\rightarrow$ PARITY VIOLATION)

$C_b = (\mathbf{p}_1 \times \mathbf{p}_2) \times \mathbf{p}_1 \bullet \mathbf{s}$ (TRANSVERSE POLARIZATION)

$C_c = \mathbf{p}_1 \bullet \mathbf{p}_2$

T-ODD CORRELATIONS:

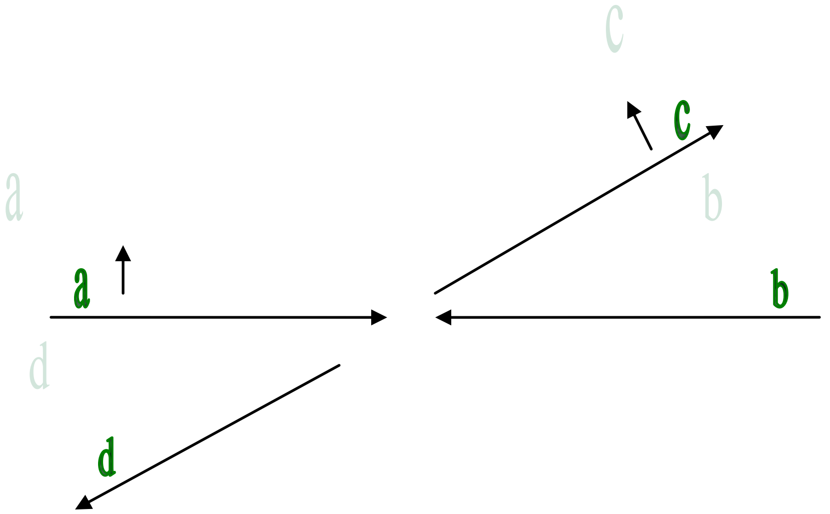
$C_1 = \mathbf{p}_1 \times \mathbf{p}_2 \bullet \mathbf{s}$ (NORMAL POLARIZATION),

$C_2 = \mathbf{s}_1 \times \mathbf{s}_2 \bullet \mathbf{p}$, $C_3 = \mathbf{p}_1 \times \mathbf{p}_2 \bullet \mathbf{p}_3$

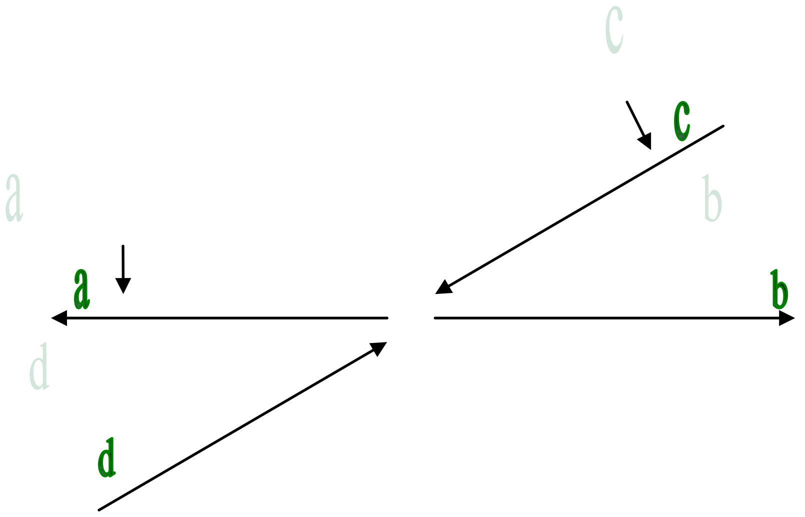
AMBIGUITY BETWEEN REAL TRV

AND FAKE T-ODD OBSERVABLES

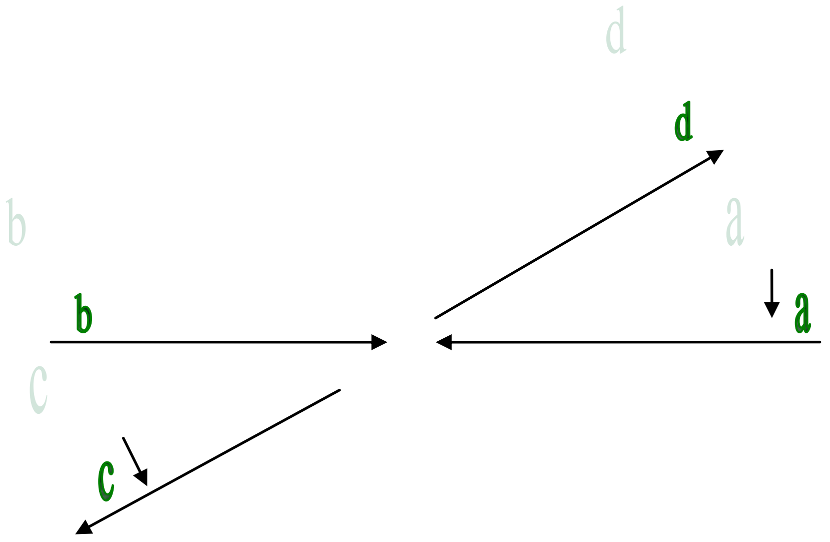
2. REAL T-R ODD AND FAKE T-ODD OBSERVABLES



SCATTERING PROCESS



REAL TIME REVERSAL



FAKE T-ODD PROCESS

DIRECT TIME REVERSAL VIOLATION :

$K° \leftrightarrow \overline{K°}$

CPLEAR Coll. : Phys. Lett. B **444** (1998) 43

$K° \rightarrow \pi^- \, e^+ \, \nu_e$, $\overline{K°} \rightarrow \pi^+ \, e^- \, \overline{\nu}_e$

$K° \leftrightarrow \overline{K°}$ OSCILLATIONS ➔

➔ "WRONG SIGN" LEPTONS (W S L)

W S L COUNTING ➔

$\Gamma (K° \rightarrow \overline{K°}) \neq \Gamma (\overline{K°} \rightarrow K°)$ ➔ TRV

TIME REVERSAL VIOLATION CONSISTENT

WITH CPT SYMMETRY

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nTRV Coll. : Phys. Rev. C **85** (2012) 045501

FREE NEUTRON DECAY : SUBTRACTION OF

FAKE T-ODD TERM, PRODUCED BY e-p

L-s QED INTERACTIONS

HOW TO SEPARATE REAL T-R ODD TERMS

FROM FAKE T-ODD ONES

IN HADRONIC DECAYS:

DECAY $J \rightarrow a \quad b$

+ OBSERVABLE "O_{od}"

CP-CONJUGATED PROCESS: $\bar{J} \rightarrow \bar{a} \quad \bar{b}$,

+ OBSERVABLE "$\bar{O}_{od}$"

CPT SYMMETRY ➔

$\Delta O_{od} = O_{od} \pm \bar{O}_{od}$ PURELY TRV , SIGN

DEPENDING ON P TRANSFORMATION

OF THE CORRELATION

SEPARATION USEFUL ALSO

FOR T-EVEN OBSERVABLES:

GIVEN TWO OBSERVABLES "O_{ev}" AND "$\bar{O}_{ev}$",

$$\Delta O_{ev} = O_{ev} \pm \bar{O}_{ev}$$

IS A T-EVEN, TRV TERM → INTERFERENCE

BETWEEN FAKE AND REAL TRV

ΔO_{ev} AS CONVENIENT AS ΔO_{od}:

- COMPLEMENTARY INFORMATION
- IMMEDIATE HINT TO NP

3. SPIN – ORBIT INTERACTION

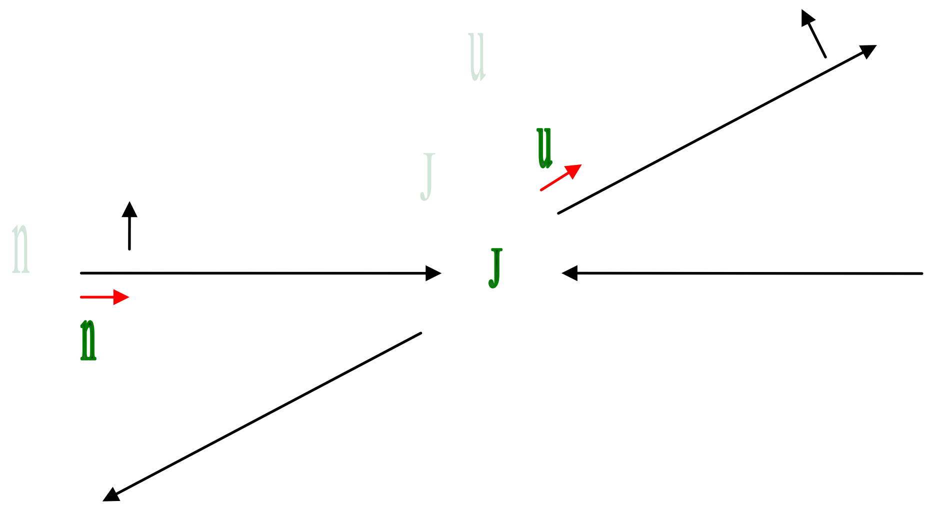
A TERM OF THE TYPE **L.s** : FAKE T-ODD,

COMMON TO QED AND QCD

DECAY J → a b

IDEAL SCATTERING EXPERIMENT:

a b → J → a b



INITIAL WAVEFUNCTION → $4\,\delta\,(1 - \mathbf{u}\cdot\mathbf{n})$

SCATTERING OPERATOR: $S = \alpha + \beta\, \mathbf{L}\cdot\mathbf{s}$

$S\,[4\,\delta\,(1 - \mathbf{u}\cdot\mathbf{n})] \rightarrow \mathbf{L}\cdot\mathbf{s}\,(\mathbf{p}\cdot\mathbf{n}) = i\, \mathbf{n}\times\mathbf{u}\cdot\mathbf{s}$

SPIN – ORBIT COUPLING: $\mathbf{L \cdot s \; (p \cdot n) = i \; n \times u \cdot s}$

- NORMAL POLARIZATION (T-ODD)

- SAME EFFECTS AS TRV

- PHASE – SHIFT BY $\pi/2$ W.R.T.

  SPIN-INDEPENDENT AMPLITUDES

PARITY VIOLATION ←→ LONGIT. POLAR.

L-s COUPLING TIME REV. VIOL.	←→	NORMAL POLAR.

ALTERNATIVE DERIVATION OF

PHASE SHIFT $\pi/2$:

A. Datta & D. London: IJMPA **19** (2004) 2505

(CP CONSIDERATIONS)

4. APPLICATION TO $B^{\pm} \rightarrow K^{\pm}\, p\, \bar{p}$ DECAY

DATA: LHCb Coll. , hep/ex 1304.3035 (2013)

* GLUEBALL STATE IN $p\bar{p}$?

* POSSIBLE DISCREPANCY WITH SM:

EXP: A_{CP} = (-16 ± 7) % - PDG 2012

SM: A_{CP} = $(6 \pm 1 \pm 3 \pm 1)$ % - PRL 98 (2007) 011801

CORREL. C_{od}, C_{ev} ➔ ASYMM. A_{od} , A_{ev}

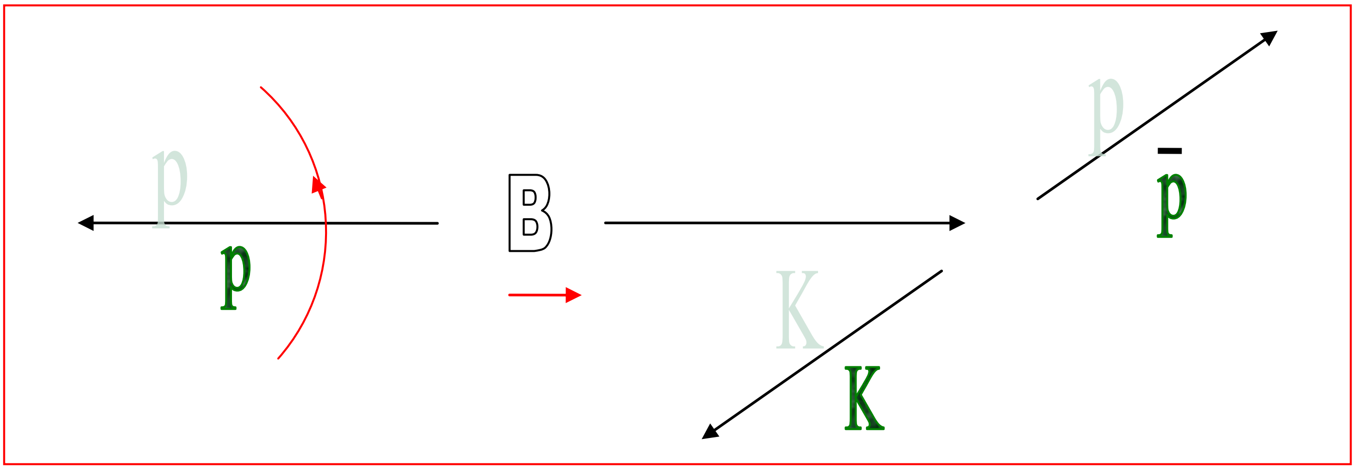
$$C_{od} = \mathbf{p}_B \bullet \mathbf{p}_p \times \mathbf{p}_K \quad ➔ \quad A_{od}: \text{ T-ODD AS.}$$

$$C_{ev} = \mathbf{p}_p \bullet \mathbf{p}_K \quad ➔ \quad A_{ev}: \text{ T-EVEN AS.}$$

SYSTEM $p\ (\bar{p}\ K)$

CORRELATION $C_{od} = \mathbf{p}_B \bullet \mathbf{p}_p \times \mathbf{p}_K$

=> T-ODD ASYMMETRY A_{od}



SPIN OF B ZERO & p IN HELICITY STATE

=> π ROTATING AROUND $\mathbf{p}_p$: $C_{od} \rightarrow -C_{od}$

=> $A_{od} = 0$: USEFUL AS A CHECK

T-EVEN ASYMMETRY:

ASSOCIATED TO THE CORRELATION

$$C_{ev} = \mathbf{p}_p \bullet \mathbf{p}_K$$

SYSTEM $(p\ \Sigma)$, with $\Sigma = (\bar{p}\ K)$

G. C. Wick, Ann. Phys. **18**, 65 (1962)

$$A_{ev} = \frac{N(C_{ev} > 0) - N(C_{ev} < 0)}{N(C_{ev} > 0) + N(C_{ev} < 0)}$$

BUT $J_B = 0$, $J_S = 1/2, 3/2, 5/2, \ldots$

A_{ev} GENERALLY NONZERO :

MORE AMPLITUDES INTERFERE :

$$A_{ev} \cong \Sigma_{J,J'} \mathrm{Re}\,(H_J\ H_{J'}^*)$$

$2\,\Delta A_{ev} = A_{ev} - \bar{A}_{ev}$, T-EVEN, BUT TIME REV. ODD

STANDARD MODEL PREDICT.: $\Delta A_{ev} \cong 3.5\,\%$

(RESULT OF CALCULATIONS SIMILAR

TO G. Q. Geng et al. : PRL **98**, 011801 (2007))

CALCULATION OF ΔA_{ev} FROM LHCb DATA:

IN PROGRESS

5. APPLICATIONS TO BARYON DECAYS

$$B_0 \rightarrow B \;\; P\,(V)$$

B_0, B : BARYONS

$P\,(V)$: PSEUDOSCALAR (VECTOR) MESONS

EXAMPLES:

$\Lambda_b \rightarrow \Lambda \;\; P\,(V)$; $\quad \Lambda_b \rightarrow \Lambda_c \;\; \pi$;

$\Lambda_c \rightarrow \Lambda \;\; \pi$; $\quad \Xi \rightarrow \Lambda \;\; \pi$;

$\Sigma_b \rightarrow \Sigma_c \;\; P(V)$; $\quad \Omega_b \rightarrow \Omega_c \;\; P(V)$

SECONDARY DECAY:

$$\Lambda \rightarrow p \;\; \pi$$

E. D. S. & Z. J. Ajaltouni: MPLA **28**, 1350048 (2013)

EXPERIMENTAL DATA OF BARYON DECAYS:

CDF Coll.: PRL **104**, 102002 (2010); **98**, 122001 (2007)

D0 Coll.: PRL **99**, 142001 (2007); PRD **84**, 031102 (2011)

INTEREST IN BARYON DECAYS:

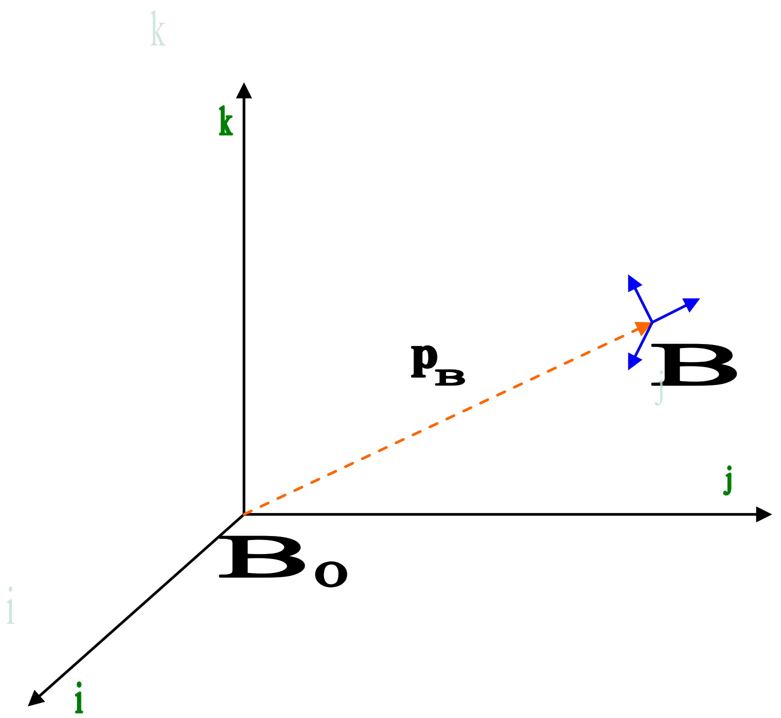
SPIN ENHANCES ASYMMETRIES

W. Bensalem et al.: PRD **64,** 116003 (2001);

PRD **66**, 094004 (2002)

DECAY $B_0 \rightarrow B \;\; P\,(V)$

HELICITY FRAME (BLUE) :



UNIT VECTORS IN HELICITY FRAME :

$\mathbf{e}_L = \mathbf{p}_B / |\mathbf{p}_B|$, $\mathbf{e}_T = \mathbf{e}_L \times \mathbf{k} \, / \, |\mathbf{e}_L \times \mathbf{k}|$,

$\mathbf{e}_N = \mathbf{e}_T \times \mathbf{e}_L$

DEF. VECTOR $\mathbf{A} = (A_N, A_T, A_L)$

A_N, A_T, A_L : ASYMMETRIES CONNECTED TO

CORRELATIONS p_N, p_T, p_L :

$p_N = \mathbf{p}_s \bullet \mathbf{e}_N$, $p_T = \mathbf{p}_s \bullet \mathbf{e}_T$, $p_L = \mathbf{p}_s \bullet \mathbf{e}_L$

$\mathbf{p}_s$ = MOMENTUM OF A SECONDARY

DECAY PRODUCT

$$A_N = \frac{N(p_N > 0) - N(p_N < 0)}{N(p_N > 0) + N(p_N < 0)}, \quad \text{etc.}$$

E.D.S. & Z.J. Ajaltouni : MPLA **28**, 1350048 (2013) :

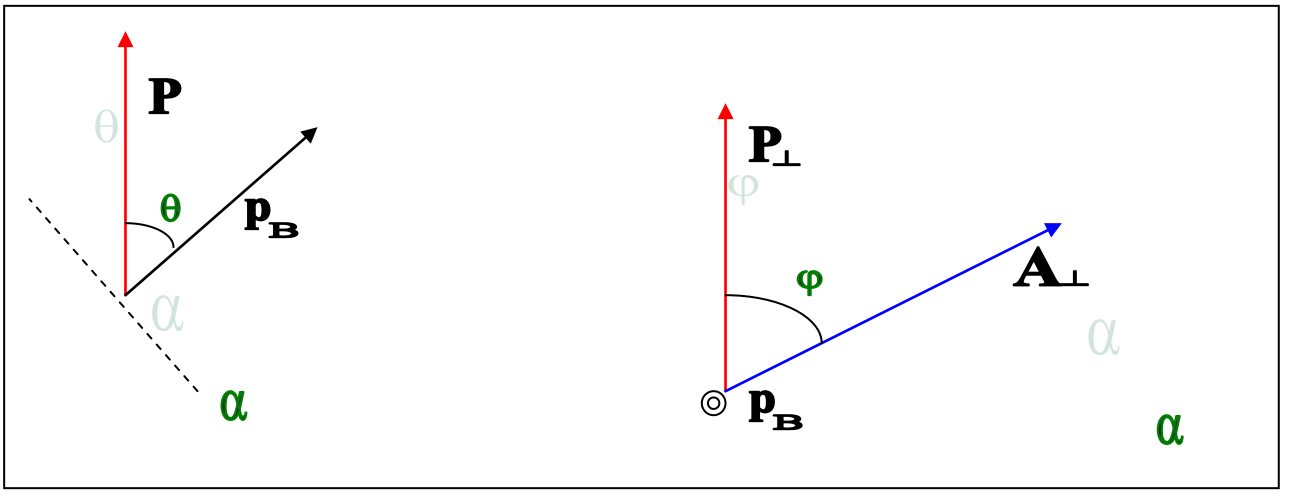
$$A_{\perp i} = C \; R_{\perp ij}(\varphi) \; P_{\perp j}$$

$\mathbf{P}_\perp$ = PERP. POLARIZ. OF B_0 (HEL. FRAME)

$\mathbf{A}_\perp$ = PERP. ASYMM. OF B (HEL. FRAME)

$\mathbf{R}_\perp$ = ROTATION MATRIX AROUND $\mathbf{p}_B$

φ = ANGLE BETWEEN $\mathbf{A}_\perp$ AND $\mathbf{P}_\perp$



PHYSICAL RESULT: $-\varphi$ EQUALS THE RELATIVE PHASE OF THE HELICITY DECAY AMPLITUDES

$\mathcal{A}_{1/2,0}$ AND $\mathcal{A}_{-1/2,0}$

♣ SIMILAR TO THE ROTATION OF THE POLARIZATION PLANE OF LIGHT

♣ A_N : T-ODD; A_T, A_L : T-EVEN

♣ φ, $\sin\varphi$, $\tan\varphi$: T-ODD; $\cos\varphi$: T-EVEN

♣ NO SIMPLE RELATION BETWEEN

P AND INTERM. BARYON POLAR. **P**’

ROTATION ANGLE = - (RELATIVE PHASE)

PHYSICAL INTERPRETATION:

TWO HELICITY STATES: $h = \pm 1/2$

FRAME ROTATION BY ANGLE φ AROUND $\mathbf{p}_B$ =>

- HEL. ST. $h = +\frac{1}{2}$: PHASE CHANGE BY $-\varphi/2$
- HEL. ST. $h = -\frac{1}{2}$: PHASE CHANGE BY $+\varphi/2$

=> RELATIVE PHASE CHANGE :

$$\Delta\varphi = -\varphi/2 - \varphi/2 = -\varphi$$

DETECTABLE BY MEANS OF INTERFERENCE

TERMS : Re $(\mathcal{A}_{1/2,0}\, \mathcal{A}^*_{-1/2,0})$, Im $(\mathcal{A}_{1/2,0}\, \mathcal{A}^*_{-1/2,0})$

ORDERS OF MAGNITUDE OF φ

FOR BARYON DECAYS IN SM

A RESULT: $\mathbf{A}_B \leq \tan\varphi$

$\mathbf{A}_B$ = T-ODD ASYMMETRY CONNECTED TO

CORRELATION $\mathbf{C}_B = \mathbf{s}_0 \times \mathbf{s} \bullet \mathbf{p}_B$

Decay	$\mathbf{A}_B$
$\Lambda_b \rightarrow \Lambda \ P$	$\cong 2\%$ *
$\Lambda_b \rightarrow \Lambda \ \rho^\circ/\omega$	$\cong 6\%$ *
$\Xi^\circ \rightarrow \Lambda \ \pi^\circ$	$\cong 15\%$
$\Lambda_b \rightarrow \Lambda_c \ \pi^-$	$\cong 1\%$ *
$\Sigma_b \rightarrow \Sigma_c \ P(V)$	$\cong 1.7\%$ *

* GREATLY INCREASED BY NEW PHYSICS

EXTENSION TO THREE-BODY DECAYS:

$B_0 \rightarrow B\ a\ b$

e. g. ,

$\Lambda_b \rightarrow \Lambda\ l+\ l-$; $\Lambda_b \rightarrow \Lambda\ \pi\ \pi$

A_N, A_T, A_L : ASYMMETRIES CONNECTED TO

CORRELATIONS p_N, p_T, p_L :

$p_N = \mathbf{p}_a \bullet \mathbf{e}_N$, $p_T = \mathbf{p}_a \bullet \mathbf{e}_T$, $p_L = \mathbf{p}_a \bullet \mathbf{e}_L$

$\mathbf{p}_a$ = MOMENTUM OF PARTICLE a

$$A_N = \frac{N(\, p_N > 0\,) - N(\, p_N < 0\,)}{N(\, p_N > 0\,) + N(\, p_N < 0\,)}, \quad \text{etc.}$$

6. HIGHLIGHTS

T-ODD & T-EVEN OBSERVABLES (L-s FAKE T.O.)

APPLICATIONS TO THREE-BODY DECAYS:

♣ (PSEUDO)-SCALAR RESONANCES:

T-ODD : MIXED PRODUCT => $A_{od} = 0$: A CHECK

T-EVEN : FB ASYMM. => $A_{ev} - \bar{A}_{ev}$ SENSIT. TO NP

♣ BARYON RESONANCES:

T-ODD: A_N, P_N, P'_N, φ, $\sin\varphi$, $\tan\varphi$

T–EVEN: A_L, A_T, P_T, P'_T, P_L, P'_L, $\cos\varphi$

COMPLEMENTARY INFORMATION

$\boxed{\text{T-EVEN OBSERVABLES AS USEFUL AS T-ODD ONES}}$