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Impact of leptoquarks in semileptonic B decays

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based on arXiv:1609.04367[hep-ph]

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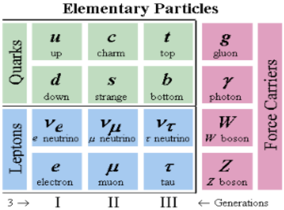
Outline

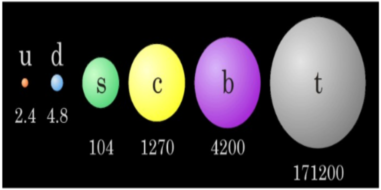
1. Introduction
2. Leptoquark Model
3. Constraint on LQ coupling
   - $B_s \to l^+ l^-$
   - $B \to X_s \nu \bar{\nu}$
   - $B_d \to X_s l^+ l^-$
4. Recent anomalies in rare B decays
   - $\bar{B} \to \bar{K}^{(*)} l^+ l^-$
   - $\bar{B} \to \bar{D}^{(*)} l \nu_l$
5. Conclusion

Motivation for studying flavour physics

- The standard model is very successful in explaining the observed data so far. Their study gives us fundamental informations.
- But there are also some open fundamental questions.



- Why are there 3 generations?
- Why there is a striking hierarchy in the quark masses?
- Why the Higgs mass is at the EW scale?



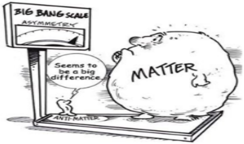
- Mass of neutrino.
- Dark matter and dark energy components.

- Big Bang Theory $\Rightarrow$ Equal amount of matter and antimatter ($\gamma\gamma \to P\bar{P}$)

- Wait .....

- See what's left (only matter !!)

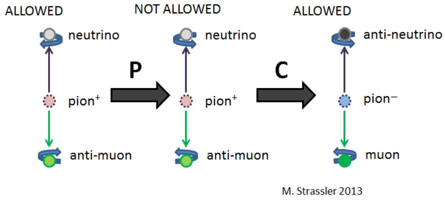
- **Why is there a large matter anti matter asymmetry in the universe?**



CP Violation

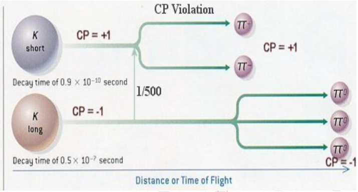
- CP violation represents matter-antimatter asymmetry of the Universe

- **Charge conjugation(C)** : transforms a particle into its antiparticle
- **Parity (P)**: creates the mirror image



- Where might we find it ?
  - **Quark sector :** Phase in CKM matrix
  - **Lepton sector :** CP violation in neutrino oscillations
  - Gauge sector, extra dimensions, **other new physics......**

- First observed in neutral kaon meson mixing but is very small in SM ($\sim \mathcal{O}(10^{-3})$)



Effective Hamiltonian

- The effective Hamiltonian describing $b \to s l^+ l^-$ process is

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu) O_i + \sum_{i=7,9,10}^{S,P} \left(C_i(\mu) O_i + C_i'(\mu) O_i' \right) \right],$$

$i = 1, 2$	Tree	$i = 9, 10$	Electroweak Penguin
$i = 3-6, 8$	Chromomagnetic Penguin	$i = S$	Scalar Penguin
$i = 7$	Electromagnetic Penguin	$i = P$	Pseudoscalar Penguin

- The effective Hamiltonian mediating the semileptonic decays $b \to c \bar{\tau} \nu_l$ is given by

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[\left(\delta_{l\tau} + C_{V_1}^l \right) \mathcal{O}_{V_1}^l + C_{V_2}^l \mathcal{O}_{V_2}^l + C_{S_1}^l \mathcal{O}_{S_1}^l + C_{S_2}^l \mathcal{O}_{S_2}^l \right],$$

- where the operators are

$$\mathcal{O}_{V_1}^l = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_{lL}), \qquad \mathcal{O}_{V_2}^l = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_{lL}),$$

$$\mathcal{O}_{S_1}^l = (\bar{c}_L b_R)(\bar{\tau}_R \nu_{lL}), \qquad \mathcal{O}_{S_2}^l = (\bar{c}_R b_L)(\bar{\tau}_R \nu_{lL}).$$

Lepton nonuniversality

- Recently LHCb and B factories have observed violation of lepton universality in $b \to s l^+ l^-$ and $b \to c l \nu_l$ processes.
- $\mathrm{Br}(B^+ \to K^+ ee)$ in agreement with SM.
- Can be explained if possible NP contributes to $b \to s\mu\mu$ not to $b \to see$.
- If same anomaly persists in R_{K^*}, it would be clear signature of NP.

Observables	Expt. value	SM prediction	Deviation
$R_K = \frac{Br(B^+ \to K^+ \mu^+ \mu^-)}{Br(B^+ \to K^+ e^+ e^-)}$	$0.745^{+0.090}_{-0.074} \pm 0.036$	1.0003 ± 0.0001	2.6σ
$R_D = \frac{Br(B \to D \tau \nu_l)}{Br(B \to D l \nu_l)}$	0.41 ± 0.05	0.286 ± 0.012	1.9σ
$R_{D^*} = \frac{Br(B \to D^* \tau \nu_l)}{Br(B \to D^* l \nu_l)}$	0.317 ± 0.017	0.252 ± 0.003	3.3σ

Leptoquark

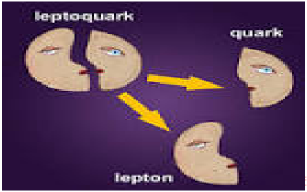
- Materialistic view of the standard model :

	quarks		leptons	
Q	-1/3	2/3	-1	0
3. family	b	t	τ	ν_τ
2. family	s	c	μ	ν_μ
1. family	d	u	e	ν_e

link?

- Several links between leptons and quarks:
  - electric charge are multiples of $1/3$
  - same number of generations
  - mixing between generations

- Color-triplet bosons with couplings to quarks and leptons simultaneously.



- Classified by :
  - Fermion number $F = 3B + L, F = 0, 2$
  - Spin $s = 0$ (scalar) or $s = 1$ (vector)
  - Charge $+\frac{1}{3}, +\frac{2}{3}, -\frac{4}{3}, -\frac{5}{3}$
- 14 chiral leptoquark species per generations:
  - 7 scalars (3 isospin singlets, 3 doublets and 1 triplets)
  - 7 vectors (3 isospin singlets, 3 doublets and 1 triplets)
- Intergenerational mixing is severely restricted by FCNC data
  $\Rightarrow$ LQ appear in 3 quark/lepton generations
- LQ-mediated π and K helicity-suppressed decays not observed
  $\Rightarrow$ chiral LQ couplings to fermions
- Appear in many unification theories beyond the SM:
  - $SU(5)$ GUT model
  - Super-string inspired model
  - Color $SU(4)$ Pati-Salam model
  - Composite model of quark and lepton
  - Technicolor model

- There are 6 relevant LQ invariant under the $SU(3) \times SU(2) \times U(1)$ gauge group.
- $(3, 1, 2/3)$ and $(3, 3, 2/3)$ vector LQ can mediate both $b \to c l \nu_l$ and $b \to s l^+ l^-$ processes.
- Conserve baryon number.
- avoid rapid proton decay.
- The interaction Lagrangian of $U_{1,3}$ LQ with the SM fermion bilinear is

$$\mathcal{L}^{LQ} = \left(h_{1L}^{ij} \bar{Q}_{iL} \gamma^{\mu} L_{jL} + h_{1R}^{ij} \bar{d}_{iR} \gamma^{\mu} l_{jR} \right) U_{1\mu} + h_{3L}^{ij} \bar{Q}_{iL} \boldsymbol{\sigma} \gamma^{\mu} L_{jL} \mathbf{U}_{3\mu},$$

Leptoquarks	Spin	$F = 3B + L$	$(SU(3)_C, SU(2)_L, U(1))$
S_1	0	-2	$(3^*, 1, 1/3)$
S_3	0	-2	$(3^*, 3, 1/3)$
R_2	0	0	$(3, 2, 7/6)$
U_1	1	0	$(3, 1, 2/3)$
U_3	1	0	$(3, 3, 2/3)$
V_2	1	-2	$(3^*, 2, 5/6)$

- Which contributes additional Wilson coefficients to $b \to c\tau\nu_l$ process as

$$C_{V_1}^{LQ} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3}\left[\frac{h_{1L}^{2l} h_{1L}^{k3\,*}}{M^2_{U_1^{2/3}}} - \frac{h_{3L}^{2l} h_{3L}^{k3\,*}}{M^2_{U_3^{2/3}}}\right],$$

$$C_{V_2}^{LQ} = 0, \qquad C_{S_1}^{LQ} = -\frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3} \frac{2h_{1L}^{2l} h_{1R}^{k3\,*}}{M^2_{U_1^{2/3}}}.$$

- This also give the following new parameters to $b \to s l^+ l^-$ process as

$$C_9^{LQ} = -C_{10}^{LQ} = \frac{\pi}{\sqrt{2}G_F V_{tb} V_{ts}^* \alpha} \sum_{m,n=1}^{3} V_{m3} V_{n2}^* \left[\frac{h_{1L}^{ni} h_{1L}^{mj\,*}}{M^2_{U_1^{2/3}}} + \frac{h_{3L}^{ni} h_{3L}^{mj\,*}}{M^2_{U_3^{-1/3}}}\right],$$

$$C_9^{\prime LQ} = C_{10}^{\prime LQ} = \frac{\pi}{\sqrt{2}G_F V_{tb} V_{ts}^* \alpha} \sum_{m,n=1}^{3} V_{m3} V_{n2}^* \frac{h_{1R}^{ni} h_{1R}^{mj\,*}}{M^2_{U_1^{2/3}}},$$

$$-C_P^{LQ} = C_S^{LQ} = \frac{\sqrt{2}\pi}{G_F V_{tb} V_{ts}^* \alpha} \sum_{m,n=1}^{3} V_{m3} V_{n2}^* \frac{h_{1L}^{ni} h_{1R}^{mj\,*}}{M^2_{U_1^{2/3}}},$$

$$C_P^{\prime LQ} = C_S^{\prime LQ} = \frac{\sqrt{2}\pi}{G_F V_{tb} V_{ts}^* \alpha} \sum_{m,n=1}^{3} V_{m3} V_{n2}^* \frac{h_{1R}^{ni} h_{1L}^{mj\,*}}{M^2_{U_1^{2/3}}}.$$

$B_s \to l^+ l^-$

- The branching ratio of $B_s \to l^+ l^-$ process in the SM is given by [?]

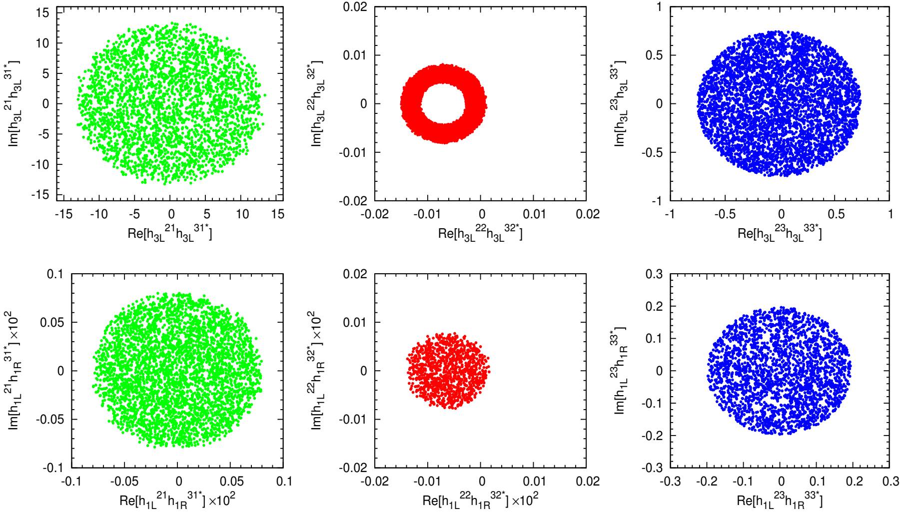
$$\mathrm{Br}(B_s \to l^+ l^-) = \frac{G_F^2}{16\pi^3} \tau_{B_s} \alpha^2 f_{B_s}^2 |C_{10}^{\mathrm{SM}}|^2 M_{B_s} m_l^2 |V_{tb} V_{ts}^*|^2 \sqrt{1 - \frac{4 m_l^2}{M_{B_s}^2}} \left(|P|^2 + |S|^2 \right)$$

where P and S are defined as

$$P \equiv \frac{C_{10}^{\mathrm{SM}} + C_{10}^{\mathrm{LQ}} - C_{10}^{\prime\mathrm{LQ}}}{C_{10}^{\mathrm{SM}}} + \frac{M_{B_s}^2}{2 m_l} \frac{m_b}{m_b + m_s} \left(\frac{C_P^{\mathrm{LQ}} - C_P^{\prime\mathrm{LQ}}}{C_{10}^{\mathrm{SM}}} \right),$$

$$S \equiv \sqrt{1 - \frac{4 m_l^2}{M_{B_s}^2}} \frac{M_{B_s}^2}{2 m_l} \frac{m_b}{m_b + m_s} \left(\frac{C_S^{\mathrm{LQ}} - C_S^{\prime\mathrm{LQ}}}{C_{10}^{\mathrm{SM}}} \right).$$

Leptoquark Couplings	**Real part**	**Imaginary Part**
$h^{21}_{1(3)L} h^{31*}_{1(3)L}$	$-13.0 \to 13.0$	$-13 \to 13$
$h^{22}_{1(3)L} h^{32*}_{1(3)L}$	$-0.016 \to 0.0$	$-0.008 \to 0.008$
$h^{23}_{1(3)L} h^{33*}_{1(3)L}$	$-0.8 \to 0.8$	$-0.8 \to 0.8$
$h^{21}_{1L} h^{31\,*}_{1R}$	$(-0.8 \to 0.8) \times 10^{-3}$	$(-0.8 \to 0.8) \times 10^{-3}$
$h^{22}_{1L} h^{32\,*}_{1R}$	$-0.016 \times 10^{-2} \to 0.0$	$(-0.8 \to 0.8) \times 10^{-4}$
$h^{23}_{1L} h^{33\,*}_{1R}$	$-0.2 \to 0.2$	$-0.2 \to 0.2$


Im[h3L^21 h3L^31*]
Re[h3L^21 h3L^31*]
Im[h3L^22 h3L^32*]
Re[h3L^22 h3L^32*]
Im[h3L^23 h3L^33*]
Re[h3L^23 h3L^33*]
Im[h1L^21 h1R^31*] ×10^2
Re[h1L^21 h1R^31*] ×10^2
Im[h1L^22 h1R^32*] ×10^2
Re[h1L^22 h1R^32*] ×10^2
Im[h1L^23 h1R^33*]
Re[h1L^23 h1R^33*]

$B \to X_s \nu \bar{\nu}$

- The effective Hamiltonian of $b \to s \nu_i \bar{\nu}_i$ process is given by

$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu \right) + h.c.,$$

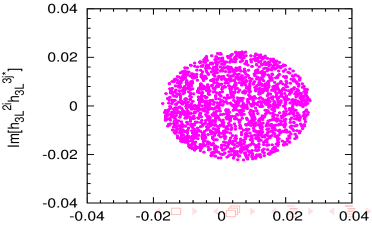
where the six-dimensional operators are

$$\mathcal{O}_L^\nu = \frac{\alpha}{4\pi} \left(\bar{s} \gamma_\mu L b \right) \left(\bar{\nu}_i \gamma^\mu \left(1 - \gamma_5\right) \nu_i \right), \quad \mathcal{O}_R^\nu = \frac{\alpha}{4\pi} \left(\bar{s} \gamma_\mu R b \right) \left(\bar{\nu}_i \gamma^\mu \left(1 - \gamma_5\right) \nu_i \right).$$

- U_3 leptoquark gives additional C_L^{LQ} coefficients as

$$C_L^{LQ} = \frac{2\pi}{\sqrt{2} G_F \alpha V_{tb} V_{ts}^*} \sum_{m,n=1}^{3} V_{m3} V_{n2}^* \frac{h_{3L}^{ni} h_{3L}^{mi^*}}{M_{U_3^{-1/3}}^2}.$$

$$-0.02 \le \mathrm{Re}[h_{3L}^{2i} h_{3L}^{3i^*}] \le 0.02,$$
$$-0.02 \le \mathrm{Im}[h_{3L}^{2i} h_{3L}^{3i^*}] \le 0.02.$$



$B_d \to X_s l^+ l^-$

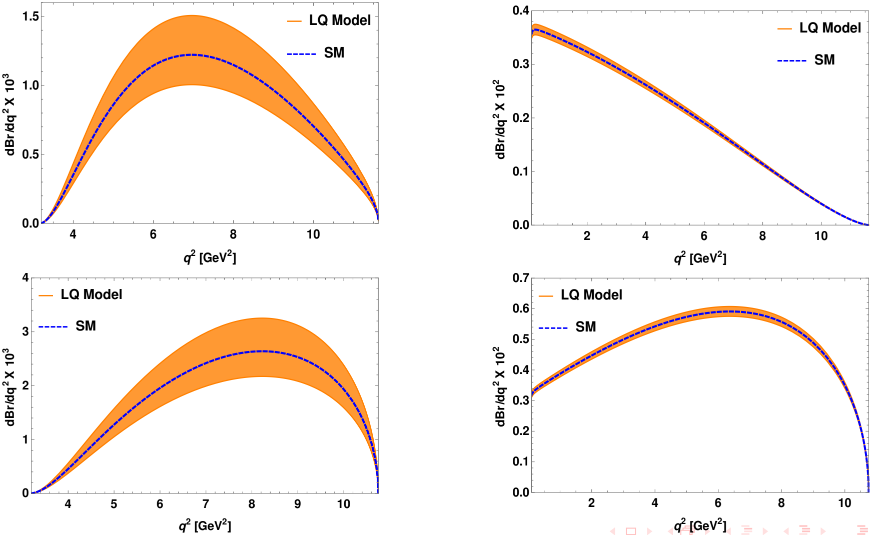
- Including the new physics contribution, the total branching ratio of $B_d \to X_s l^+ l^-$ process is given by

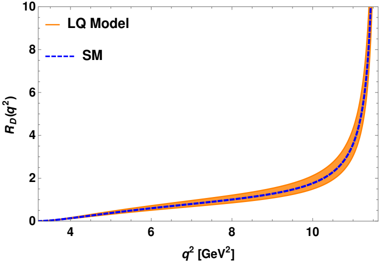
$$\left(\frac{d\mathrm{Br}}{ds_1}\right)_{\mathrm{Total}} = \left(\frac{d\mathrm{Br}}{ds_1}\right)_{\mathrm{SM}} + B_0\Big[\frac{16}{3}(1-s_1)^2(1+2s_1)[\mathrm{Re}(C_9^{eff}C_9^{LQ*}) + \mathrm{Re}(C_{10}C_{10}^{LQ*})] + 32(1-s_1)^2\ \mathrm{Re}(C_7 C_{10}^{LQ*}) + \frac{8}{3}(1-s_1)^2(1+2s_1)\left[|C_9^{LQ}|^2 + |C_{10}^{LQ}|^2 + |C_9^{\prime LQ}|^2 + |C_{10}^{\prime LQ}|^2\right]\Big]$$

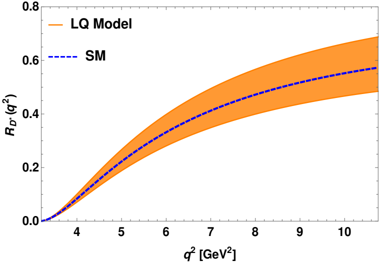
q^2 bin	Leptoquark Couplings	Real part	Imaginary Part
low q^2	$h_{1(3)L}^{21} h_{1(3)L}^{31*}$	$-0.01 \to 0.01$	$-0.01 \to 0.01$
	$h_{1(3)L}^{22} h_{1(3)L}^{32*}$	$-0.008 \to 0.008$	$-0.008 \to 0.008$
high q^2	$h_{1(3)L}^{21} h_{1(3)L}^{31*}$	$-0.022 \to 0.022$	$-0.022 \to 0.022$
	$h_{1(3)L}^{22} h_{1(3)L}^{32*}$	$-0.018 \to 0.018$	$-0.018 \to 0.018$
	$h_{1(3)L}^{23} h_{1(3)L}^{33*}$	$-3.8 \to 3.8$	$-3.8 \to 3.8$

$B \to D^{(*)} l \nu_l$

Results on $B \to D^{(*)} l \nu_l$ processes



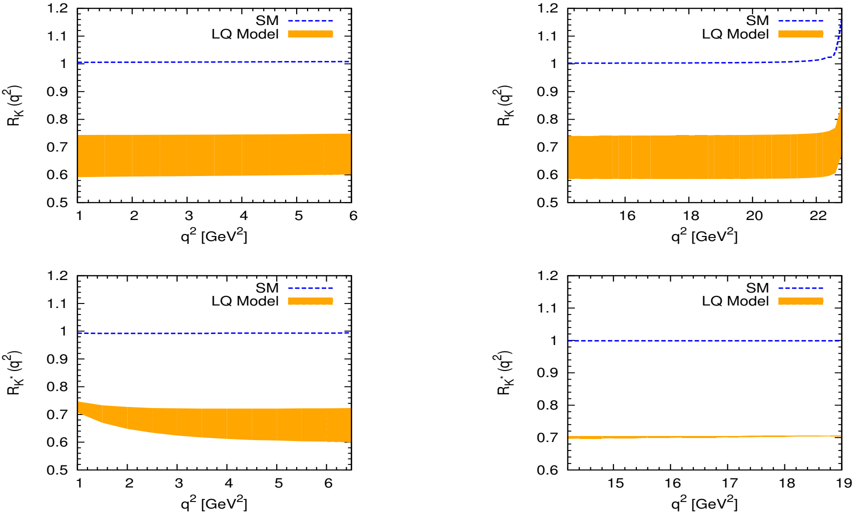




Observables	SM Predictions	Values in LQ Model	Experimental Limit
R_D	0.3	0.27 – 0.37	0.41 ± 0.05
R_{D^*}	0.26	0.23 – 0.31	0.317 ± 0.017
$R_K{}^{\mu e}_{q^2\in[1,6]}$	1.006	0.56 – 0.75	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_K{}^{\mu e}_{q^2\geq 14.18}$	1.004	0.586 – 0.742	$\cdots$
$R_{K^*}{}^{\mu e}_{q^2\in[1,6]}$	0.996	0.728 – 0.752	
$R_{K^*}{}^{\mu e}_{q^2\geq 14.18}$	0.999	0.816 – 0.819	$\cdots$

S. Sahoo, R. Mohanta and A. K. Giri [arXiv:1609.04367[hep-ph]].

Results on $B \to K^{(*)} ll$ processes



Conclusion

- **B decays:** a powerful tool for indirect searches of new physics
- Leptoquark exist in TeV scales and in extended SM (gives contribution to new physics) .
- We have studied the baryon number conserving vector leptoquark, invariant under the SM $SU(3) \times SU(2) \times U(1)$ gauge group.
- We constraint the LQ couplings using rare exclusive and inclusive $b \to s l^+ l^- (\nu \bar{\nu})$ decays.
- We calculate the branching ratios and asymmetries in $B \to K^{(*)} l^+ l^-$ and $B \to D^{(*)} l \nu_l$ processes in the LQ model which have significant deviation from the SM.
- We simultaneously explain the observed R_K, R_{D^*} anomalies in $U_{1,3}$ LQ.
- Hopefully future results from the Flavour Factories will settle the recent issues and/or provide the new direction to High Energy Physics.
- Stay tuned, more results to come from B-factories !!!

THANK YOU !!!