

**EFFECT OF  $Z'$ - MEDIATED FLAVOUR-CHANGING  
NEUTRAL CURRENTS ON  $B_q^0 - \overline{B}_q^0$  MIXING AND B  
MESON DECAYS**

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## What is a $Z'$ Boson?

- The  $Z'$  is a neutral, colorless, self-adjoint, and spin-1 gauge boson.
- The 2<sup>nd</sup> Z Boson – Prof. R. N. Mohapatra
- Theoretically it is predicted that  $Z'$  bosons exist in extensions of the Standard Model (SM).
- They exist in Grand Unified Theories (GUTs), left-right symmetric models, Little Higgs models, superstring theories and theories with large extra dimensions.
- But experimentally this gauge boson is not discovered so far. It is expected to be discovered at the LHC.

## 2. The Standard Model

- Physicists are trying to unify the four fundamental forces of the nature with a view to develop a fundamental theory. Till today physicists have been able to unify three fundamental forces and have constructed the *Standard Model* of elementary particles.
- The Standard Model expresses our present understanding of the known fundamental fermions (quarks and leptons) and the forces between them: Electromagnetic force, Weak force and Strong force.
- This model is also known as Quark-Lepton Model. This model assumes three generations of quarks and three generations of leptons.
- Quarks have the unusual characteristic of having a *fractional electric charge*.
- Quarks also carry another type of charge called *colour charge*.  
Red (R), Blue (B) & Green (G).

- The forces are mediated by fundamental gauge bosons: the photon, the  $W^\pm$  and  $Z$ , and the gluons.
- The symmetry of the model is expressed mathematically as  $SU(3)_C \times SU(2)_L \times U(1)_Y$  or  $G_{321}$ .
- The main predictions of the Standard Model: Existence of  $W^+, W^-$  and  $Z$  bosons, Existence of t-quark, Existence of Higgs boson.
- The Large Hadron Collider project at CERN and its experiments (ATLAS and CMS) will search for the Higgs boson.

# Drawbacks of the Standard Model

- The Standard Model does not incorporate **gravity**. Without gravity the SM is incomplete. This is why “**String Theory**” comes into picture. The SM may be called as a theory of “**Three-Fourth of Everything**”.
- There is no explanation for the replication of the generations in the fermion sector. **Why three generations??**
- It can't explain about the existence of **dark matter** and **dark energy**.
- Left-handed fermions are doublets whereas right-handed fermions are singlets by convention.
- The SM cannot explain the **baryon asymmetry** in the Universe.
- It doesn't explain the existence of **massive neutrino** which is found from neutrino-oscillation experiments.

## Extensions of the Standard Model

- The number of neutral gauge bosons ‘ $n$ ’ of a GUT is given by the rank of the theory i.e.  $n = \text{rank [G]}$ .
- The group  $G_{321}$  is a group of rank 4 and it has four neutral gauge bosons: the photon, the Z boson, and two of the gluons.
- If the rank of G is greater than four, the gauge theory based on it will have additional neutral gauge bosons, which are generically known as  $Z'$  bosons e.g.  $\text{rank [SO(10)]} = 5$  and  $\text{rank of } E_6 \text{ is } 6$ .
- GUTs with gauge groups larger than SO(10) predict more than one extra neutral gauge bosons and many new fermions. These new (exotic) fermions can mix with the SM fermions. Such mixing induces flavour-changing neutral currents (FCNCs).
- Mixing between ordinary (doublet) and exotic singlet left-handed quarks induces FCNC, mediated by the SM Z boson.
- The mixing of the right-handed ordinary and exotic quarks, all  $SU(2)_L$  singlets, induces FCNC, mediated by  $Z'$  boson.

### 3. $Z'$ -mediated flavour-changing neutral currents and their contributions to $B_q^0 - \bar{B}_q^0$ mixing.

[S. Sahoo and L. Maharana, *Physical Review D* **69**, 115012 (2004)]

- We search for new-physics contributions to  $B_q^0 - \bar{B}_q^0$  mixing ( $q = d, s$ ) at least comparable to that of SM.
- The mass matrix element in the SM can be expressed as:

$$M_{12}^{SM}(B_q) = \frac{G_F^2 M_{B_q} \eta_{B_q} M_W^2}{12\pi^2} f_{B_q}^2 B_{B_q} x_t f_2(x_t) (V_{tq} V_{tb}^*)^2 \quad (1)$$

where  $M_{12}$  is the mass matrix element

$G_F$  is the Fermi coupling constant

$M_W$  is the mass of W boson

$V_{tq}, V_{tb}$  are the CKM matrix elements

- The mass difference  $\Delta M$  is related to  $M_{12}$  by

$$\Delta M_{B_q} = 2 |M_{12}^{(B_q)}|, \quad (2)$$

where  $x_t = m_t^2 / M_W^2$ , and

$$f_2(x) = \left[ \frac{1}{4} + \frac{9}{4} \frac{1}{(1-x)} - \frac{3}{2} \frac{1}{(1-x)^2} - \frac{3}{2} \frac{x^2 \ln x}{(1-x)^3} \right] \quad (3)$$

- The recent experimental values are

$$\Delta M_{B_d} = (0.507 \pm 0.004) \times 10^{12} \text{ s}^{-1} \quad \text{and} \quad 17.0 \times 10^{12} < \Delta M_{B_s} < 21.0 \times 10^{12} \text{ s}^{-1} \quad (4)$$

- The Z-mediated flavour-changing couplings  $U_{qb}$  can

contribute to  $B_q^0 - \overline{B_q^0}$  mixing :

$$M_{12}^Z(B_q) = \frac{\sqrt{2} G_F M_{B_q} \eta_{B_q}}{12} f_{B_q}^2 B_{B_q} (U_{qb}^*)^2 \quad (5)$$

- Similarly, the contribution of  $Z'$ -mediated FCNCs to  $B_q^0-\bar{B}_q^0$  mixing is,

$$M_{12}^Z(B_q) = \frac{\sqrt{2}G_F M_{B_q} \eta_{B_q}}{12} \frac{M_Z^2}{M_{Z'}^2} f_{B_q}^2 B_{B_q} (U_{qb}^*)^2 \quad (6)$$

- These contributions can be compared with those of the SM as:

$$\frac{\Delta M_q^{Z'}}{\Delta M_q^W} = \frac{\sqrt{2}\pi^2}{G_F M_W^2} \frac{1}{x_t f_2(x_t)} \frac{M_Z^2}{M_{Z'}^2} \frac{|U_{qb}^{Z'}|^2}{|V_{tq} V_{tb}|^2} = 80 \frac{M_Z^2}{M_{Z'}^2} \frac{|U_{qb}^{Z'}|^2}{|V_{tq}|^2} \quad (7)$$

and

$$\frac{\Delta M_q^Z}{\Delta M_q^W} = 80 \frac{|U_{qb}^Z|^2}{|V_{tq}|^2} \quad (8)$$

We have taken  $|V_{tb}|=1$ ,  $m_t = 170$  GeV, and  $M_Z=91.1882$  GeV.

- First consider  $B_S^0 - \overline{B_S^0}$  mixing. We assume that  $U_{sb}^{Z'} = 0.1$ ,  $M_{Z'} = 500$  GeV,  $|V_{ts}| = |V_{cb}| = 0.04$ . We get

$$\frac{\Delta M_S^{Z'}}{\Delta M_S^W} = 16.63. \quad (9)$$

Thus,  $B_S^0 - \overline{B_S^0}$  mixing can be dominated by the exchange of a  $Z'$ .

- We have 
$$\frac{\Delta M_S^Z}{\Delta M_S^W} = 80 \frac{|U_{sb}^{Z'}|^2}{|V_{ts}|^2} \leq 0.02888 \quad (10)$$
- Hence, the contribution of Z-mediated FCNCs to  $B_S^0 - \overline{B_S^0}$  mixing is negligible compared to that of the SM.
- Now consider the  $B_d^0 - \overline{B_d^0}$  mixing. This mixing can also be dominated by  $Z'$ -mediated FCNCs because there are no constraints on  $U_{db}^{Z'}$  from  $B$  decays.

- Although a sizeable contribution from Z-mediated FCNCs to  $B_d^0 - \overline{B}_d^0$  mixing is still possible, we have seen that both  $B_d^0 - \overline{B}_d^0$  and  $B_s^0 - \overline{B}_s^0$  mixing can be dominated by  $Z'$ -mediated FCNCs.
- The study of  $Z'$ -mediated FCNC effects is very interesting due to the fact that they would be a hint of new physics because of their large suppression in the SM.

## 4. The Effect of $Z'$ Boson on $B$ Meson Decays

- We have studied the effect of a  $Z'$ -mediated FCNC on the  $B \rightarrow \pi K$  decay process.
- The effective Hamiltonian for the decay process can be written as:

$$H_{eff}^{SM} = \frac{G_F}{\sqrt{2}} \sum_{q=u,c} \lambda_q \left[ C_1 Q_1^q + C_2 Q_2^q + \sum_{i=3}^{10} C_i Q_i + C_g Q_g \right] + h.c. \quad (11)$$

where  $\lambda_q = V_{qb}^* V_{qs}$ ,  $C_i$ 's are Wilson coefficients and  $Q_i$ 's are local operators containing quark and gluon fields.

- New physics comes into play in  $B$  decays in two different ways :
  - (a) through a new contribution to the Wilson coefficients or
  - (b) through a new structure in the effective Hamiltonian,which are both absent in the SM.

- The  $Z'$  boson contributes to the QCD penguin operators  $Q_{3(5)}$  as well as EW penguin operators  $Q_{7(9)}$ .
- The resulting  $Z'$  contributions to the Wilson coefficients corresponding to QCD penguin operators at the weak scale  $\Delta_{3(5)} \approx 0$ .
- But flavor-changing couplings of the  $Z'$  with the left-handed fermions will contribute to the  $Q_9$  and  $Q_7$  operators for left (right)-handed couplings at the flavor-conserving vertex i.e. and operators receive new contributions from  $Z'$  boson. Similarly, right-handed flavor-changing couplings also yield new contributions.
- Hence, we can say Wilson coefficients of the corresponding operators are modified due to  $Z'$  effect and hence Hamiltonian changes.
- As a result, we find the branching ratio is enhanced from its SM value and gives the possibility of new physics (NP).

- The SM predictions for the branching ratios of the four decay modes of  $B \rightarrow \pi K$  are given as :

$$B(B^- \rightarrow \pi^- \bar{K}^0) = 31.06 \times 10^{-6} \quad (12)$$

$$B(B^- \rightarrow \pi^0 K^-) = 17.31 \times 10^{-6} \quad (13)$$

$$B(\bar{B}^0 \rightarrow \pi^+ K^-) = 25.87 \times 10^{-6} \quad (14)$$

$$B(\bar{B}^0 \rightarrow \pi^0 \bar{K}^0) = 11.41 \times 10^{-6} \quad (15)$$

- Using mass,  $M_{Z'} = 500 \text{ GeV}$ , our calculation gives :

$$B(B^- \rightarrow \pi^- \bar{K}^0) |_{\text{SM}+Z'} = 58.12 \times 10^{-5} \quad (16)$$

$$B(B^- \rightarrow \pi^0 K^-) |_{\text{SM}+Z'} = 32.39 \times 10^{-5} \quad (17)$$

$$B(\bar{B}^0 \rightarrow \pi^+ K^-) |_{\text{SM}+Z'} = 48.41 \times 10^{-5} \quad (18)$$

$$B(\bar{B}^0 \rightarrow \pi^0 \bar{K}^0) |_{\text{SM}+Z'} = 21.35 \times 10^{-5} \quad (19)$$

**S. Sahoo** and L. Maharana, IJPAP, **46**, 306-311 (2008).

- The recent experimental results for the four branching ratios of decay are given in units of  $10^{-6}$  as:

Mode	BABAR	BELLE	Average
$B(B^- \rightarrow \pi^- \bar{K}^0)$	$23.9 \pm 1.1 \pm 1.0$	$22.9^{+0.8}_{-0.7} \pm 1.3$	$23.40 \pm 1.06$
$B(B^- \rightarrow \pi^0 K^-)$	$13.3 \pm 0.56 \pm 0.6$	$12.4 \pm 0.5^{+0.7}_{-0.6}$	$12.83 \pm 0.59$
$B(\bar{B}^0 \rightarrow \pi^+ K^-)$	$19.7 \pm 0.6 \pm 0.6$	$20.0 \pm 0.4^{+0.9}_{-0.8}$	$19.83 \pm 0.63$
$B(\bar{B}^0 \rightarrow \pi^0 \bar{K}^0)$	$10.5 \pm 0.7 \pm 0.5$	$9.2^{+0.7+0.6}_{-0.6-0.7}$	$9.89 \pm 0.63$

- We hope the effect of  $Z'$  boson in the  $B \rightarrow \pi K$  decay process may provide a solution for  $B \rightarrow \pi K$  puzzles.
- We have also studied the effect of both  $Z$  and  $Z'$ -mediated FCNC on the  $B_d \rightarrow \ell^+ \ell^-$  ( $\ell = \mu, \tau$ ) rare decay.

- In the SM:  $B(B_d \rightarrow \mu^+ \mu^-) = (1.5 \pm 1.4) \times 10^{-10}$  (20)

$$B(B_d \rightarrow \tau^+ \tau^-) = (3.1 \pm 2.9) \times 10^{-8} \quad (21)$$

- The recent upper bound:

From CDF:  $B(B_d \rightarrow \mu^+ \mu^-) < 3.0 \times 10^{-8}$  (95 % C. L.) (22)

From BABAR:  $B(B_d \rightarrow \tau^+ \tau^-) < 4.1 \times 10^{-3}$  (95 % C. L.) (23)

- Our results :

$$B(B_d \rightarrow \mu^+ \mu^-) |_{Z, Z'} = 1.56 \times 10^{-8} \quad (24)$$

$$B(B_d \rightarrow \tau^+ \tau^-) |_{Z, Z'} = 3.16 \times 10^{-6} \quad (25)$$

**S. Sahoo** and L. Maharana, MPLA, **22**, 1591-1599 (2007).

- Recently we have also studied the effect of  $Z'$ -mediated FCNC on the  $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$  ( $\ell = \mu, \tau$ ) decay.

- In the SM:  $B(\Lambda_b \rightarrow \Lambda \mu^+ \mu^-) = 4.55 \times 10^{-6}$

$$B(\Lambda_b \rightarrow \Lambda \tau^+ \tau^-) = 0.17 \times 10^{-6}$$

- Our results :

- Using the mass of  $Z'$ -boson = 130 GeV, we get

$$B(\Lambda_b \rightarrow \Lambda \mu^+ \mu^-)_{Z+Z'} = (4652 \pm 0.01) \times 10^{-6}$$

$$B(\Lambda_b \rightarrow \Lambda \tau^+ \tau^-)_{Z+Z'} = (2.03 \pm 0.12) \times 10^{-6}$$

- Using the mass of  $Z'$ -boson = 1000 GeV, we get

$$B(\Lambda_b \rightarrow \Lambda \mu^+ \mu^-)_{Z+Z'} = (21.23 \pm 0.11) \times 10^{-6}$$

$$B(\Lambda_b \rightarrow \Lambda \tau^+ \tau^-)_{Z+Z'} = (0.93 \pm 0.02) \times 10^{-6}$$

**S. Sahoo, C. K. Das and L. Maharana, *Int. J. Mod. Phys. A* **24**, 6223 (2009).**

## 8. Conclusions

- The  $Z'$  is a neutral, colorless, self-adjoint, and spin-1 gauge boson.
- We have found that both  $B_d^0 - \overline{B_d^0}$  and  $B_s^0 - \overline{B_s^0}$  mixing can be dominated by  $Z'$ -mediated FCNCs, although a sizeable contribution from  $Z$ -mediated FCNCs to  $B_d^0 - \overline{B_d^0}$  mixing is still possible.  
Depending on the precise value of the  $M_{Z'}$ ,  $Z'$ -mediated FCNCs give sizeable contributions to both  $B_d^0 - \overline{B_d^0}$  and  $B_s^0 - \overline{B_s^0}$  mixing.
- The branching ratios of  $B_d \rightarrow \ell^+ \ell^-$ ,  $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$  and  $B \rightarrow \pi K$  decay processes are reasonably enhanced from its SM value due to the effect of both  $Z$  and  $Z'$ -mediated FCNCs, and gives the possibility of new physics beyond the standard model.
- The physics beyond the Standard Model will show up after the discovery of the  $Z'$  boson.
- It is hoped that the  $Z'$  boson would be studied at the LHC.

# References

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**We have no doubt that an exciting future is ahead of us!**

***THANK YOU***