$K^+ \to \pi^+ \nu\bar{\nu}$ and FCNC from non-universal Z' bosons

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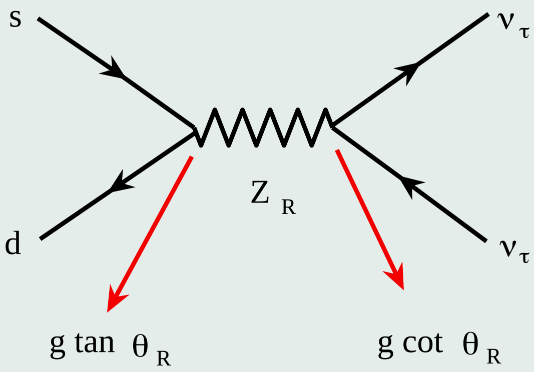
Motivation

- E787 and E949 at BNL see 3 events
- corresponds to $B(K^+ \to \pi^+ \nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$
- SM predicts $B(K^+ \to \pi^+ \nu\bar{\nu}) = (7.2 \pm 2.1) \times 10^{-11}$
- consistent within errors but room for new physics
  - Many examples in the literature
  - Here: non-universal Z'

Non-universal Z'

- Z' that couples strongly to 3'd generation but very weakly to other two.
- introduced to accommodate A^b_{FB}
- Masses and couplings constrained from LEP, LEP-II
- would affect $K^+ \to \pi^+ \nu\bar{\nu}$ via the ν_τ: net effect of electroweak strength suppressed by $M_Z^2/M_{Z'}^2$.



Models

The first two generations are chosen to have the same transformation properties as in the standard model with $U(1)_Y$ replaced by $U(1)_{B-L}$,

$$\begin{aligned} &Q_L = (3,2,1)(1/3), \quad U_R = (3,1,1)(4/3), \\ &D_R = (3,1,1)(-2/3), \\ &L_L = (1,2,1)(-1), \quad E_R = (1,1,1)(-2). \end{aligned}$$

The numbers in the first parenthesis are the $SU(3)$, $SU(2)_L$ and $SU(2)_R$ group representations respectively, and the number in the second parenthesis is the $U(1)$ charge.

The third generation is chosen to transform differently,

$$\begin{aligned} &Q_L(3) = (3,2,1)(1/3), \quad Q_R(3) = (3,1,2)(1/3), \\ &L_L(3) = (1,2,1)(-1), \quad L_R = (1,1,2)(-1). \end{aligned}$$

Correct symmetry breaking and mass generation are induced with three Higgs representations.

Main Features

- relative strength $g_R/g_L \sim \cot\theta_R$
- R-H gauge bosons can be triplet or singlet.
- The $W_L - W_R$ mixing is severely constrained by $b \to s\gamma$.
- The $Z - Z'$ mixing ξ_Z is also constrained from Z pole measurements at LEP.
- If the couplings to τ, ν_τ are large, $g_{R\tau}$ at LEP implies: (He, G.V PRD 66, 013004 (2002))

$$\cot\theta_R \xi_Z \leq 10^{-3}$$

- choose $\xi_Z = 0$
- $e^+e^- \longrightarrow b\bar{b}$ at LEP-II allows $M_{Z'}$ as low as: (He, G.V PRD 68, 033011 (2003))

$$\cot\theta_R \tan\theta_W \left(\frac{M_W}{M_{Z'}}\right) \leq 1.$$

FCNC: two sources

- Tree-level

$$\begin{aligned}\mathcal{L}_Z &\approx \frac{g}{2}\tan\theta_W \cot\theta_R(\sin\xi_Z Z_\mu + \cos\xi_Z Z'_\mu)\\ &\cdot \left(\bar{d}_{Ri}\gamma^\mu V^{d*}_{Rbi}V^d_{Rbj}d_{Rj} - \bar{u}_{Ri}\gamma^\mu V^{u*}_{Rti}V^u_{Rtj}u_{Rj}\right.\\ &+ \left.\bar{\tau}_R\gamma^\mu\tau_R - \bar{\nu}_{R\tau}\gamma^\mu\nu_{R\tau}\right)\end{aligned}$$

  – Z mediated $\sim \cot\theta_R \xi_Z / M_Z^2$
  – Z' mediated $\sim \cot^2\theta_R / M_{Z'}^2$ dominates

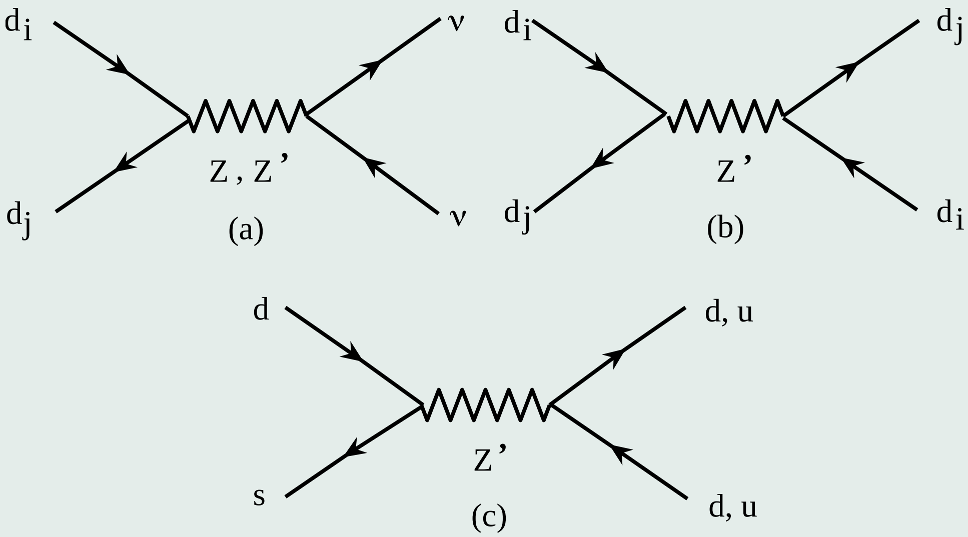
- One-loop

  – effective Z' penguin operator:

$$\mathcal{L}_{eff} = \frac{g^3}{16\pi^2}\tan\theta_W \cot\theta_R V^\star_{ti}V_{tj} I(\lambda_t, \lambda_H)\bar{d}_i\gamma_\mu P_L d_j \; Z'^\mu$$

  – $I(\lambda_t, \lambda_H)$ is the loop function
  – corrections to tree-level (will ignore)

Tree level diagrams responsible for (a) $K \longrightarrow \pi\nu\bar{\nu}$ and $b \longrightarrow (s \text{ or } d)\nu\bar{\nu}$; (b) $K - \bar{K}$ and $B - \bar{B}$ mixing; and (c) CP violation in $K \longrightarrow \pi\pi$.



Constraints

Process	Constraint	From
I. $(\Delta M)_K$	$\mathrm{Re}\,(V^{d\star}_{Rbs} V^d_{Rbd})^2 < 2.4 \times 10^{-8}$	$(SM)_{sd}$
II. $(\Delta M)_{B_d}$	$\|V^{d\star}_{Rbb} V^d_{Rbd}\| < 1.8 \times 10^{-4}$	σ_{th}
III. $(\Delta M)_{B_s}$	$\|V^{d\star}_{Rbb} V^d_{Rbs}\| < 2 \times 10^{-3} \sqrt{\delta_{B_s}}$	δ_{B_s}
IV. ϵ	$\mathrm{Re}\,(V^{d\star}_{Rbs} V^d_{Rbd})\,\mathrm{Im}\,(V^{d\star}_{Rbs} V^d_{Rbd})$ $< 2 \times 10^{-11}$	σ_{th}
V. ϵ'	$(\|V^d_{Rbd}\|^2 + \|V^u_{Rtu}\|^2)\,\mathrm{Im}\,(V^{d\star}_{Rbs} V^d_{Rbd})$ $\leq 1.3 \times 10^{-5}$	$(\epsilon')_6$
VI. $K^+ \to \pi^+ \nu \bar{\nu}$	$\|V^{d\star}_{Rbs} V^d_{Rbd}\| < 1.0 \times 10^{-5}$	$(E949)_{cv}$

δ_{B_s} characterizes the deviation from the standard model prediction

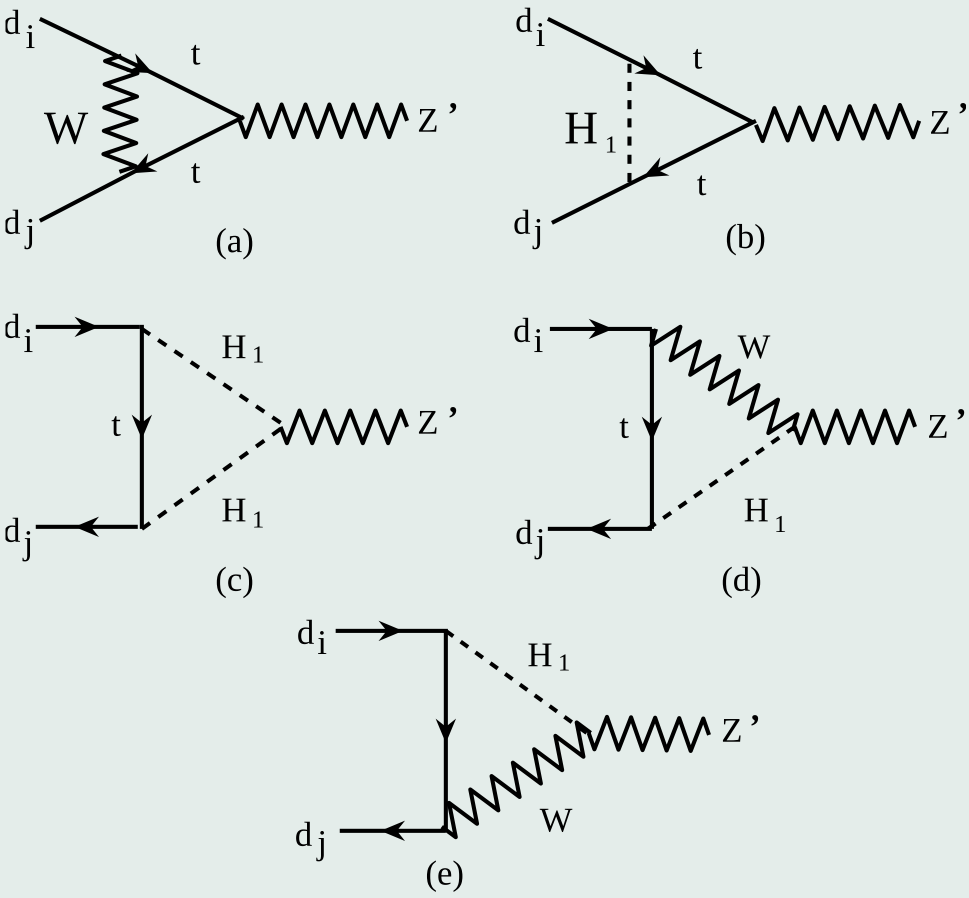
$$\delta_{B_s} \equiv \left(\frac{(\Delta M)_{B_s} - 17.2\ \mathrm{ps}^{-1}}{17.2\ \mathrm{ps}^{-1}} \right).$$

Predictions

At present, the models can reproduce the central value of E787 and E949 for the rate for $K^+ \longrightarrow \pi^+ \nu\bar{\nu}$ with the tree-level FCNC. However this can easily change if B_s mixing is measured and does not deviate much from the standard model.

Process	Upper bound with Z'	From	SM
$B(K^+ \longrightarrow \pi^+ \nu\bar{\nu})$	1.5×10^{-10} (E949)	-	7.2×10^{-11}
$B(K_L \longrightarrow \pi^0 \nu\bar{\nu})$	1.4×10^{-10}	VI	2.4×10^{-11}
$B(B \longrightarrow X_d \nu\bar{\nu})$	2.5×10^{-6}	II	1.6×10^{-6}
$B(B \longrightarrow X_s \nu\bar{\nu})$	$4 \times 10^{-5}(1 + 2\,\delta_{B_s})$	III	4×10^{-5}
$B(B_d \longrightarrow \tau^+\tau^-)$	1.8×10^{-7}	II	3.3×10^{-8}
$B(B_s \longrightarrow \tau^+\tau^-)$	$1.1 \times 10^{-6}(1 + 15\,\delta_{B_s})$	III	1.1×10^{-6}

One-loop Feynman diagrams generating the Z' penguin operator of the form $\bar{d}_i \gamma_\mu P_L d_j Z'^\mu$ in unitary gauge.



First Diagram

- divergent - dimensional regularization

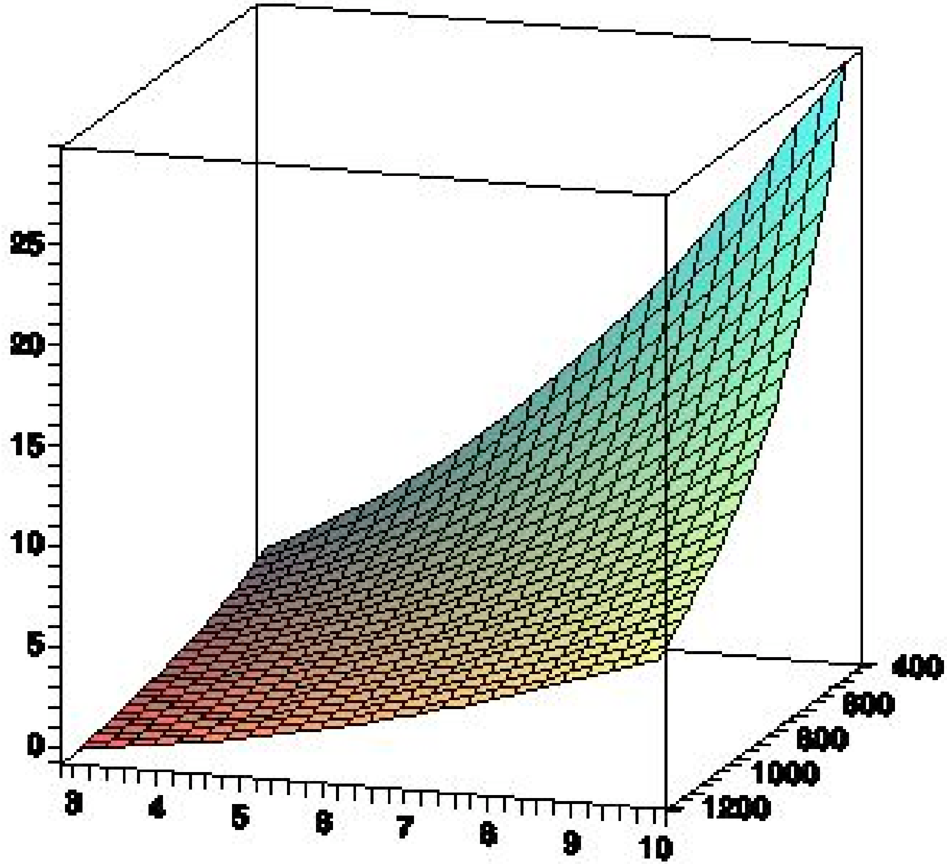
$$I(\lambda_t, \lambda_H)_a = \frac{\lambda_t}{8}\left[\frac{\lambda_t^2 - 2\lambda_t + 4}{(1-\lambda_t)^2}\log\lambda_t - \frac{3}{\lambda_t - 1} + \frac{1}{2} - \frac{1}{\hat{\epsilon}}\right].$$

- add other diagrams:

$$\begin{aligned}
&I(\lambda_t, \lambda_H) \longrightarrow \\
&\frac{\lambda_t}{8}\left[\frac{-2\cot^2\theta_R\lambda_t}{(\lambda_t-\lambda_H)^2}\left(\lambda_H \log\left(\frac{\lambda_t}{\lambda_H}\right) + \lambda_H - \lambda_t\right)\right. \\
+ \quad &\frac{\lambda_H^2(\lambda_t^2 - 2\lambda_t + 4) + 3\lambda_t^2(2\lambda_t - 2\lambda_H - 1)}{(\lambda_t - 1)^2(\lambda_t - \lambda_H)^2}\log\lambda_t \\
- \quad &\frac{\lambda_H(\lambda_H^2 + 6\lambda_t - 7\lambda_H)}{(\lambda_H - 1)(\lambda_t - \lambda_H)^2}\log\lambda_H \\
+ \quad &\left.\frac{2\lambda_t^2 - 3\lambda_H\lambda_t - 5\lambda_t + 6\lambda_H}{(\lambda_t - 1)(\lambda_t - \lambda_H)}\right].
\end{aligned}$$

  – finite answer within simple model: M_H, θ_R

  – model dependent on scalar parameters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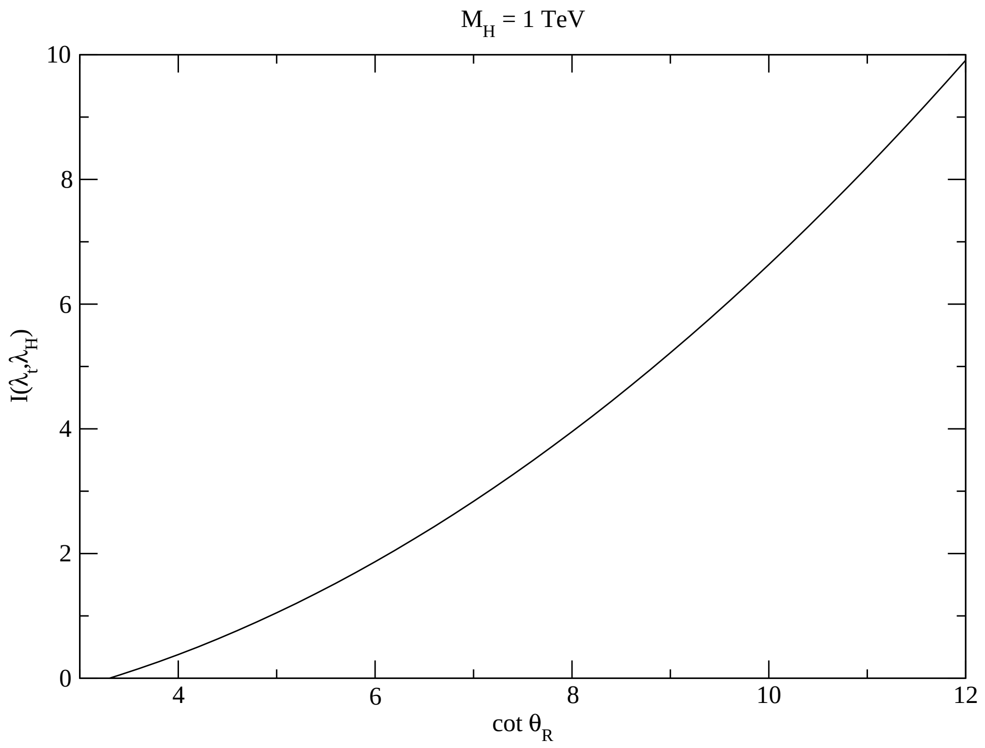
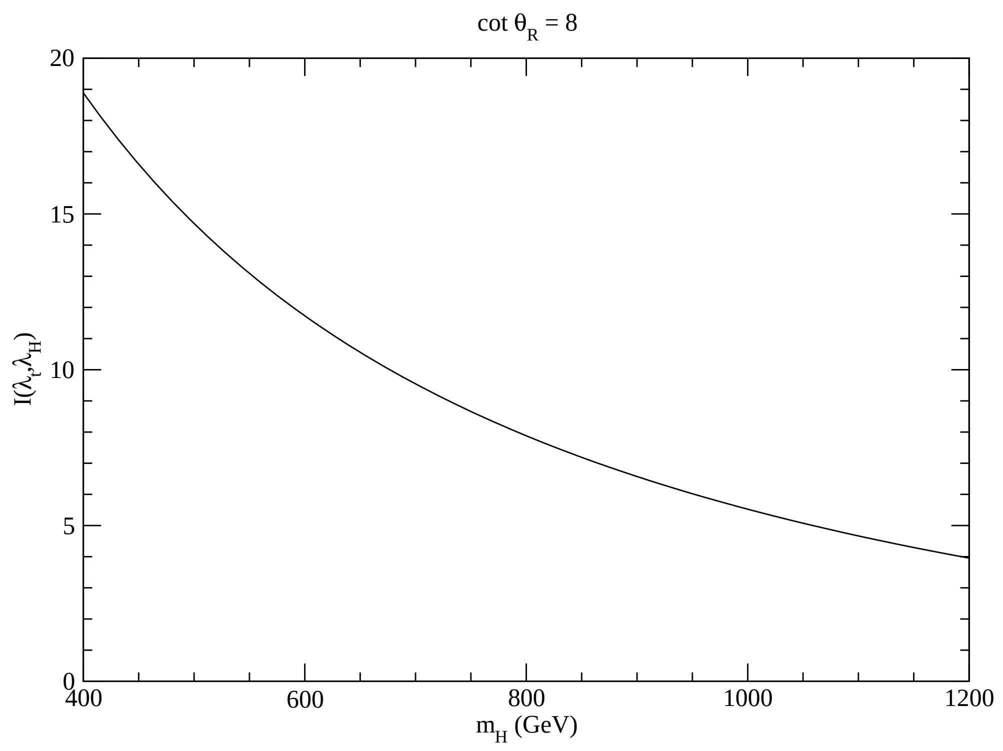


$$I(\lambda_t, \lambda_H) \leq 5.54 \rightarrow \cot\theta_R \leq 9$$



$$I(\lambda_t, \lambda_H) \leq 5.54 \longrightarrow M_H > 950 \text{ GeV}$$

Constraints and Predictions at one-loop

- $\Gamma(K^+ \to \pi^+ \nu\bar{\nu})_{NEW} \sim \frac{1}{3}\cot^4\theta_R \left(\frac{M_W}{M_{Z'}}\right)^4 I(\lambda_t, \lambda_H)\Gamma_{SM}$
- It is possible to accommodate E787 and E949.
- To reproduce the central value one needs $\Gamma_{NEW} \sim \Gamma_{SM}$, implying $I(\lambda_t, \lambda_H) \sim 5.6$, or

$$\cot\theta_R \sim 9 \quad \text{for} \quad M_H = 1 \text{ TeV}$$
$$M_H \sim 950 \text{ GeV} \quad \text{for} \quad \cot\theta_R = 8.$$

- Our simple model had "minimal flavor violation", so the ratio Γ_{NEW}/Γ_{SM} is the same for $K_L \to \pi^0\nu\bar{\nu}$ as well as the $B \to X\nu\bar{\nu}$ modes.
- The enhancement is larger in

$$\frac{\Gamma(B \to \tau^+\tau^-)_{NEW}}{\Gamma(B \to \tau^+\tau^-)_{SM}} \sim 6\frac{\Gamma(K^+ \to \pi^+\nu\bar{\nu})_{NEW}}{\Gamma(K^+ \to \pi^+\nu\bar{\nu})_{SM}}$$

  – no 1/3 for ν_τ
  – SM loop factor smaller

Conclusions

- Non-universal Z' bosons induce FCNC in general and can thus affect $K^+ \to \pi^+\nu\bar{\nu}$.
- At tree level the FCNC depend on new mixing parameters. At present there are constraints on these parameters that allow us to accommodate the E787-949 result for $K^+ \to \pi^+\nu\bar{\nu}$, but this may no longer be true when mixing in the B_s system is observed.
- At one-loop level there is a new penguin operator that depends on details of the scalar sector of the models. In simple models it is possible to accommodate the central value of E787-949, but it would not be possible to accommodate a much larger rate.
- If we fit the model to the central value of E787-949, we predict an enhancement in the rate of $B \to \tau^+\tau^-$ of about a factor of 7 with respect to the SM.