Flavor changing neutral currents and a Z´

- We consider a Z´ that prefers the third generation as an example of new physics affecting primarily the top quark
- Constraints on mass and coupling strength of a non-universal Z´
- Constraints on FCNC and their implications
- Ansatz to understand the smallness of FCNC in terms of the CKM matrix

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based on work with Xiao-Gang He and Sudhir Gupta

Generic Z´ bosons

- A Z´ is associated with an additional U(1)′ and it is present in many extensions of the SM such as
  - grand unified theories
  - left-right models
  - many more: composite Higgs, extra dimensions...
- A Z´ is one of the easiest and cleanest signals experimentally, so it is usually one of the first new physics searches in new experiments
- Many Z´ models have been studied:
  - \`Canonical′ models- electroweak strength, universal
  - leptophobic, fermiophobic, etc
  - non-universal that prefers third family (this talk)

Bounds on `canonical´ Z´ bosons

1216 Paul Langacker: The physics of heavy Z' gauge bosons

TABLE IV. 95% C.L. lower limits on various extra Z' gauge boson masses (GeV) and 90% C.L. ranges for the mixing $\sin\theta$ from precision electroweak data (columns 2–4), Tevatron searches (assuming decays into SM particles only), and LEP 2. The Tevatron numbers in parentheses are preliminary CDF results from March, 2008 based on 2.5 fb^{-1} (CDF note CDF/PUB/EXOTIC/PUBLIC/9160). From Erler and Langacker, 1999; Alcaraz *et al.*, 2006; Yao *et al.*, 2006; Aaltonen *et al.*, 2007.

	ρ_0 free	$\rho_0=1$	$\sin\theta(\rho_0=1)$	Tevatron	LEP 2
χ	551	545	(−0.0020)–(+0.0015)	822 (864)	673
ψ	151	146	(−0.0013)–(+0.0024)	822 (853)	481
η	379	365	(−0.0062)–(+0.0011)	891 (933)	434
LR	570	564	(−0.0009)–(+0.0017)	630	804
Sequential	822	809	(−0.0041)–(+0.0003)	923 (966)	1787

P. Langacker, Rev.Mod.Phys. 81 (2009) 1199-1228

- many models studied so far
- masses ruled out below ~ 1 TeV
- LHC will increase limits to about 3 TeV
- Z- Z´ mixing tightly constrained

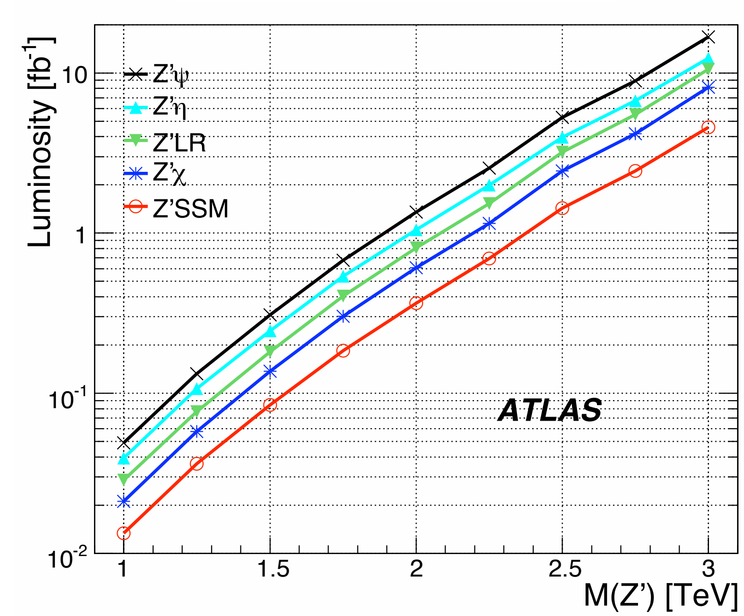

Figure 3: Integrated luminosity needed for a 5σ discovery potential as a function of $m(Z')$ in di-electron channel, for various models [5].

Bounds on `canonical´ Z´ bosons

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For non-universal models preferring the third generation

P. Langacker, Rev.Mod.Phys. 81 (2009) 1199-1228

- mo[illegible]els studied so far
- ~~masses ruled out below ~ 1 TeV~~
- 0.5 TeV is possible
- LHC will increase limits to about 3 TeV maybe ...
- Z- Z´ mixing tightly constrained
- this is still true

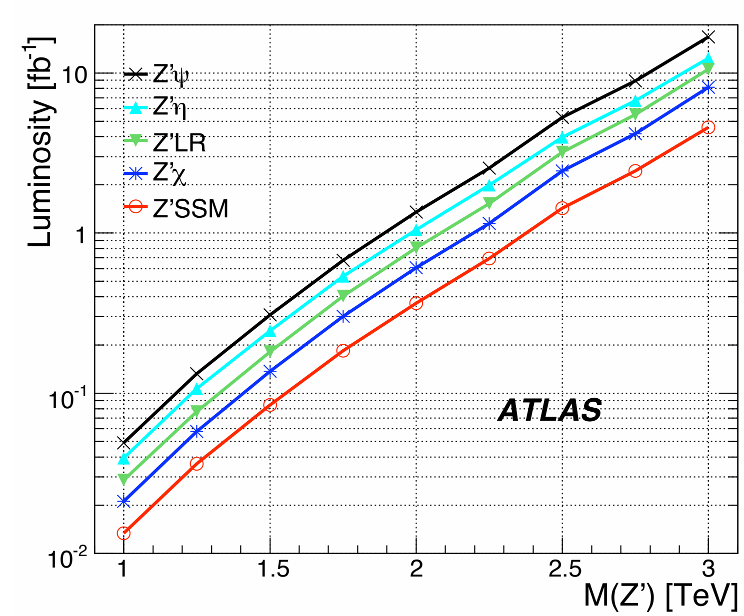


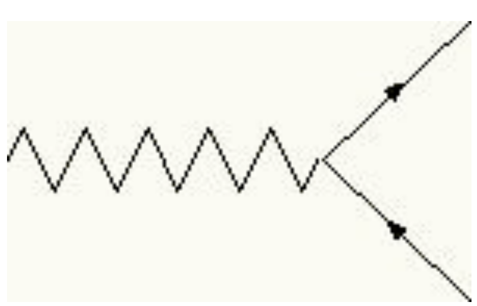
Figure 3: Integrated luminosity needed for a 5σ discovery potential as a function of $m(Z')$ in di-electron channel, for various models [5].

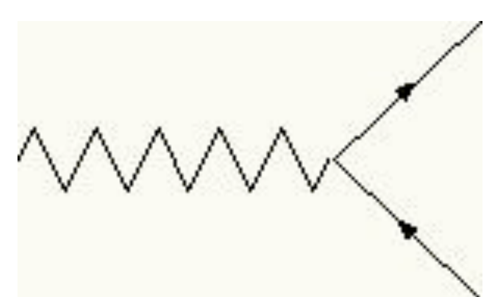
Non-universal Z´ bosons

- We construct models based on SU(3)xSU(2)$_L$xSU(2)$_R$xU(1)$_{B-L}$

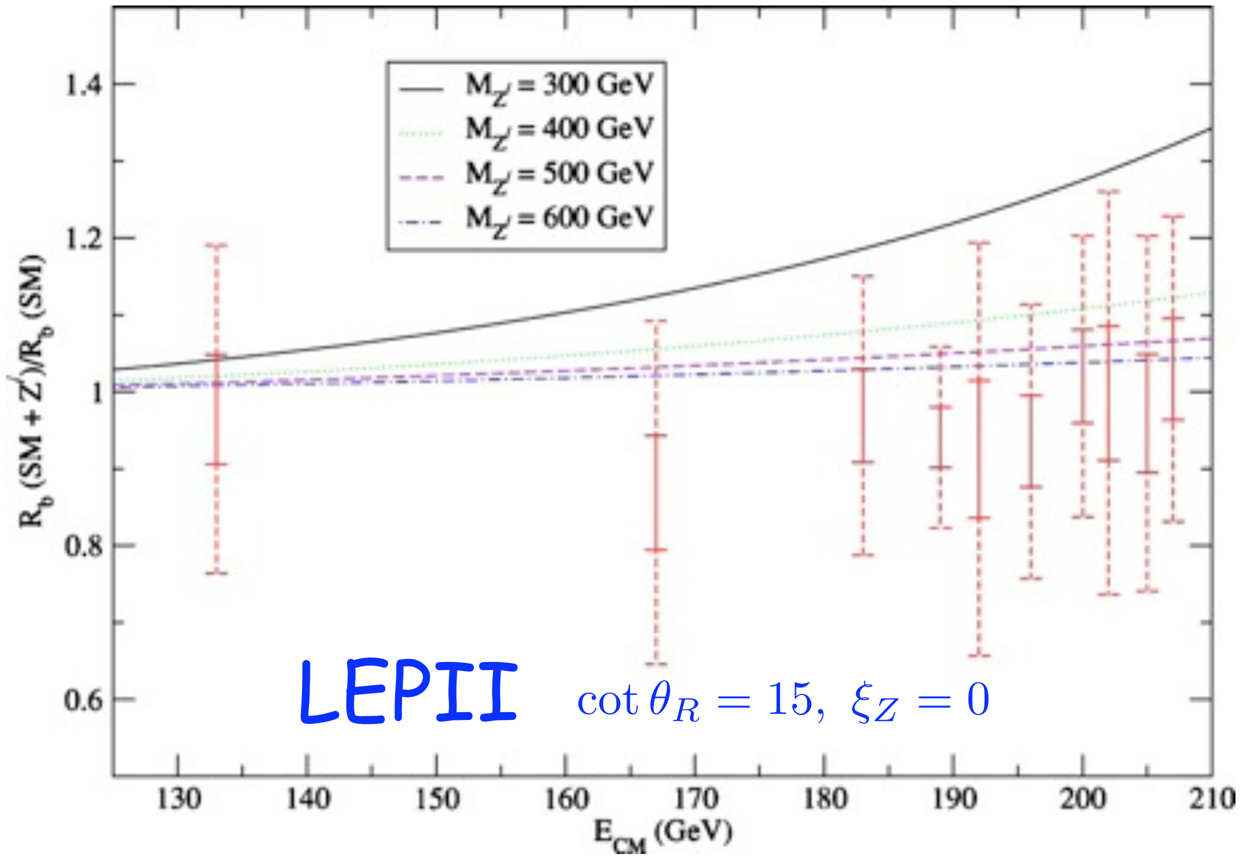
$$Z_R = \cos\theta_R W_{3R} - \sin\theta_R B$$

- Single out the third generation with QN assignments that keep the model anomaly free (may require extra heavy fermions, in particular if we want to exclude the tau from enhanced couplings)
- We need the W-W´ and Z-Z´ mixing to be zero (or very small at tree level) to satisfy $b \to s\ \gamma$ and $Z \to \tau^+\tau^-$ constraints
- generically this produces a pattern of couplings:

Z'  f_3, f_3: $\sim g\cot\theta_R$

Z'  $f_{1,2}$, $f_{1,2}$: $\sim g\tan\theta_R$

Constraints on mass and strength



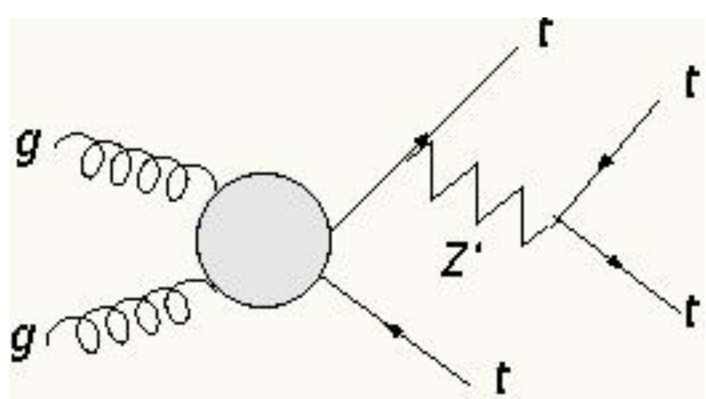
- From LEP and LEPII using R_b, A^b_{FB}, and $\sigma(e^+e^- \to \tau^+\tau^-)$:

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

- For $\cot\theta_R \sim 10 \implies M_{Z'} > 450\ \mathrm{GeV}$
- Perturbative unitarity

$$\cot\theta_R \leq 20$$

LHC



- LHC might reach ~1.5 TeV but due to large QCD background in $t\bar{t}$ or $b\bar{b}$ channels, would need channels with 4 tops (or bottom) and ~300 fb^{-1} to get there

Flavor Changing Neutral Currents

- We start with couplings of the Z´to quarks in the weak basis:

$$\mathcal{L}_{Z'} = -\frac{g}{2\cos\theta_W}(\bar{U}_L\delta^U_L\gamma_\mu U_L + \bar{U}_R\delta^U_R\gamma_\mu U_R + \bar{D}_L\delta^D_L\gamma_\mu D_L + \bar{D}_R\delta^D_R\gamma_\mu D_R)Z'^\mu$$

- which are diagonal but non-universal. For our models with enhanced couplings to the third generation

$$\delta_R^{U,D} = \kappa_R^{t,b}\ Z_\kappa \qquad Z_\kappa = \begin{pmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & 1 \end{pmatrix},\ r << 1$$

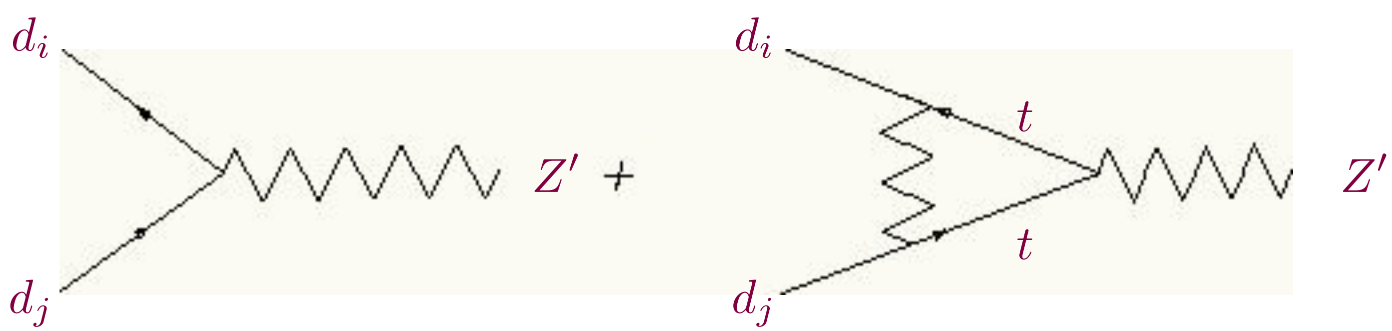
- Because these matrices are not proportional to the unit matrix, the rotation to the quark mass eigenstate basis (with the matrices $V^{U,D}{}_{L,R}$) introduces FCNC:

$$\mathcal{L}_{FCNC} = \frac{g}{2\cos\theta_W}\ \left(\bar{U}_i\gamma^\mu\left(\kappa^t_L a^u_{ij}P_L + \kappa^t_R b^u_{ij}P_R\right)U_j\ +\ \bar{D}_i\gamma^\mu\left(\kappa^b_L a^d_{ij}P_L + \kappa^b_R b^d_{ij}P_R\right)D_j\right)Z'^\mu$$

$$a^d_{ij} = V_L^{D\dagger}Z_\kappa V_L^D\ ,\quad a^u_{ij} = V_L^{U\dagger}Z_\kappa V_L^U\ ,\quad b^d_{ij} = V_R^{D\dagger}Z_\kappa V_R^D\ ,\quad b^u_{ij} = V_R^{U\dagger}Z_\kappa V_R^U\,,$$

Z´ couplings and FCNC operators

Couplings enhanced by $\cot\theta_R$ $\qquad \frac{g}{2\cos\theta_W}\bar{q}_i\gamma^\mu\left(a_{ij}P_L + b_{ij}P_R\right)q_j Z'_\mu$

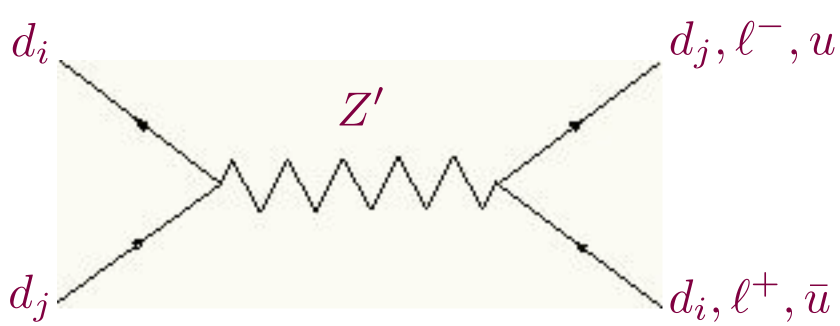


$$b_{ij} = \sin\theta_W \cot\theta_R \cos\xi_Z V^{D\star}_{Rbi}V^{D}_{Rbj} \qquad a_{ij} = \frac{\alpha}{2\pi\sin\theta_W}I(\lambda_t,\lambda_H)\cot\theta_R V^{\star}_{ti}V_{tj}$$

$\xi_Z = 0$ $\qquad$ (no mixing)

$$5.5 \leq I(\lambda_t,\lambda_H)\left|\frac{V^{\star}_{tb}V_{ts}}{0.04}\right| \leq 6.5 \qquad (\Delta M_{B_s})$$

$\Delta F = 1, 2$ operators



$$\Delta F = 2, 1 \quad \propto \quad \begin{cases} -\frac{g^2\tan^2\theta_W\cot^2\theta_R}{4M^2_{Z'}}\left(V^{D\star}_{Rbi}V^{D}_{Rbj}\right)^2 \bar{d}_i\gamma_\mu P_R d_j\ \bar{d}_i\gamma^\mu P_R d_j, \\ \frac{g^2\tan^2\theta_W\cot^2\theta_R}{4M^2_{Z'}}V^{D\star}_{Rbi}V^{D}_{Rbj}\bar{d}_i\gamma_\mu P_R d_j\ \left(V^{U\star}_{Rtu}V^{U}_{Rtu}\bar{u}\gamma^\mu P_R u - V^{D\star}_{Rbd}V^{D}_{Rbd}\bar{d}\gamma^\mu P_R d\right), \end{cases}$$

FCNC in up-quark sector: $\quad b_{u_i u_j} = \sin\theta_W\cot\theta_R\cos\xi_Z V^{U\star}_{Rti}V^{U}_{Rtj}$

Some constraints and predictions

Table 1: Summary of constraints for the right-handed mixing angles.

Process	Constraint (down-quark sector)	
$(\Delta M)_K$	$\mathrm{Re}\left(V^{D\star}_{Rbs}V^{D}_{Rbd}\right)^2 < 2.4\times 10^{-8}$	I
$(\Delta M)_{B_d}$	$\left\lvert V^{D\star}_{Rbb}V^{D}_{Rbd}\right\rvert < 1.8\times 10^{-4}$	II
$(\Delta M)_{B_s}$	$\left\lvert V^{D\star}_{Rbb}V^{D}_{Rbs}\right\rvert < 3.5\times 10^{-3}$	II_s
ϵ	$\mathrm{Re}\left(V^{D\star}_{Rbs}V^{D}_{Rbd}\right)\mathrm{Im}\left(V^{D\star}_{Rbs}V^{D}_{Rbd}\right) < 2\times 10^{-11}$	III
ϵ'	$\left(\left\lvert V^{D}_{Rbd}\right\rvert^2 + \left\lvert V^{u}_{Rtu}\right\rvert^2\right)\mathrm{Im}\left(V^{D\star}_{Rbs}V^{D}_{Rbd}\right) \le 1.3\times 10^{-5}$	IV
$B(K^+\to\pi^+\nu\bar\nu)$	$\left\lvert V^{D\star}_{Rbs}V^{D}_{Rbd}\right\rvert < 1.0\times 10^{-5}$	V
	Constraint (up-quark sector)	
x (D-mixing)	$\left\lvert V^{U\star}_{Rtc}V^{U}_{Rtu}\right\rvert < 2.0\times 10^{-4}$	I_u

` how much room is there' between the SM and experiment for meson mixing and rare decays?

Table 1: Summary of Predictions.

Process	Prediction	From	SM[&]
$B(K_L\to\pi^0\nu\bar\nu)$	$< 1.4\times 10^{-10}$	V	$(2.43^{+0.40}_{-0.37}\pm 0.06)\times 10^{-11}$
$B(B\to X_d\nu\bar\nu)$	$< 2.5\times 10^{-6}$	II	1.6×10^{-6}
$B(B\to X_s\nu\bar\nu)$	$< 3.7\times 10^{-4}$	II_s	4×10^{-5}
$B(B\to X_s\tau^+\tau^-)$	$< 4.4\times 10^{-5}$	II_s	3.2×10^{-7} (short dis.)
$B(B_d\to\tau^+\tau^-)$	$< 1.8\times 10^{-7}$	II	3.3×10^{-8}
$B(B_s\to\tau^+\tau^-)$	$< 6.3\times 10^{-5}$	II_s	1.1×10^{-6}
$B(D^0\to X_u\nu\bar\nu)$	$< 3\times 10^{-10}$	I_u	$5.0\times 10^{-16*}$ (s.d.) 10^{-13*} (l.d.)
$B(D^0\to\mu^+\mu^-)$	$< 4\times 10^{-15}$	I_u	$3\times 10^{-13*}$
$B(t\to c\tau^+\tau^-)$	$< 4\times 10^{-4}$	I_u	
$B(t\to cb\bar b)$	$< 1\times 10^{-3}$	I_u	

→ up to 2 orders of magnitude enhancement

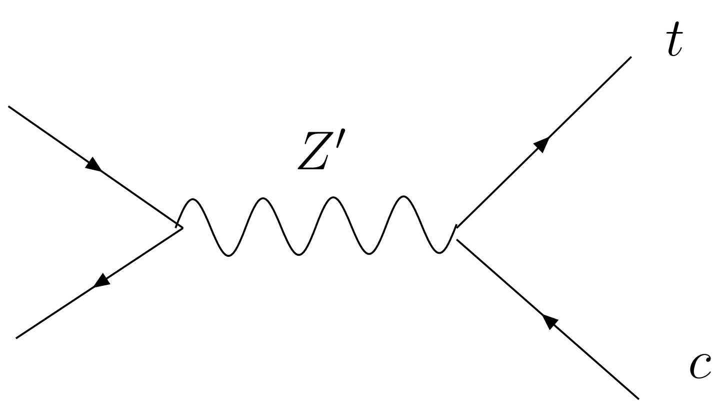
→ up to 3 orders of magnitude enhancement but still too small

→ observable at LHC?

[&] G. Buchalla, A J. Buras, M E. Lautenbacher Rev.Mod.Phys. 68 (1996) 1125-1144

[*] G. Burdman, E Golowich, J L. Hewett, S. Pakvasa. Phys.Rev. D66 (2002) 014009

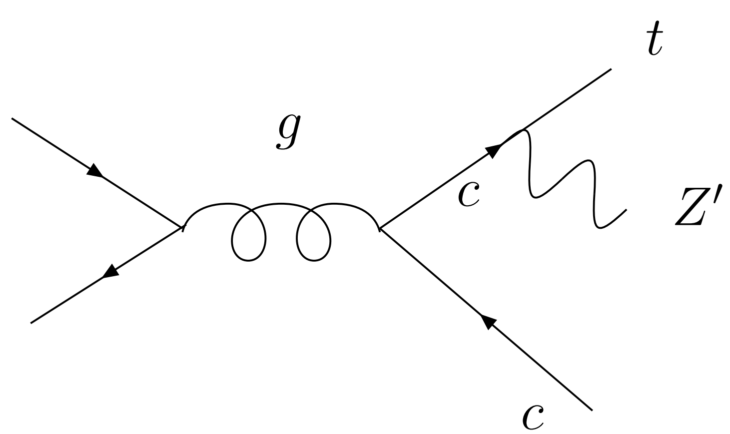
Flavor changing Z´ couplings at LHC



- Single top production: is the lowest order process

A.Arhrib, K.Cheung, C.-W.Chiang and T.-C.Yuan,

- overwhelmed by background (single top in SM)



- Z´ produced in association with single top: non leading but can stand out above background. Integrated luminosities of a few hundred fb^{-1} at 14~TeV are needed

Approximate Constraints

- We can summarize the constraints (approximately) as: $\kappa \sim \sin\theta_W \cot\theta_R \cos\xi_Z$

$$\left(\frac{M_Z}{M_{Z'}}\kappa_b\right) b^d_{ij} \lesssim \begin{pmatrix} - & 10^{-4} & 10^{-4} \\ 10^{-4} & - & 10^{-3} \\ 10^{-4} & 10^{-3} & - \end{pmatrix}$$

$$\left(\frac{M_Z}{M_{Z'}}\kappa_t\right) b^u_{ij} \lesssim \begin{pmatrix} - & 10^{-4} & ? \\ 10^{-4} & - & ? \\ ? & ? & - \end{pmatrix}.$$

  - for an overall strength $\left(\frac{M_Z}{M_{Z'}}\kappa\right) \sim 1$
  - the constraints get weaker with weaker overall strength
  - numerically similar for left-handed couplings (the a_{ij})

Mass matrices

- The quark mass matrices are diagonalized in general by a bi-unitary transformation with the quark mixing matrices

$$M_{D,U} = V_L^{D,U}\,\hat{M}_{D,U} V_R^{D,U\dagger}$$

- These matrices are related to the CKM matrix: $V_{CKM} = V_L^{U\dagger} V_L^D$
  - but it is not possible to extract them from experiment
- in certain models the left and right rotation matrices are related and one can then predict the Z´ FCNC couplings:
  - Hermitian mass matrix: $M = V_L \hat{M} V_L^\dagger \quad \Longrightarrow \quad V_R = V_L$ (up to phases)
    - LR models
  - Symmetric mass matrix: $M = V_L \hat{M} V_L^T \quad \Longrightarrow \quad V_R = V_L^\star$
    - SO(10)
- In these cases a simple ansatz can fix all the matrices

Georgi-Jarlskog example

- One example that works for us is the Georgi-Jarlskog ansatz where a down-quark mass matrix of the form

$$M_D \sim \begin{pmatrix} 0 & B & 0 \\ B & A & 0 \\ 0 & 0 & C \end{pmatrix}$$

- is diagonalized by a matrix like

$$V_L^D \sim \begin{pmatrix} 1 & \lambda & 0 \\ -\lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- which would leave us with

$$b^D = V_R^{D\dagger} Z_\kappa V_R^D = \begin{pmatrix} r\ (1+\lambda^2) & 0 & 0 \\ 0 & r\ (1+\lambda^2) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- or no FCNC in down quark sector

the up-quark sector

- Requiring that $V_L^{U\dagger} V_L^D = V_{CKM}$
- One finds FCNC for the up quark sector:

$$V_L^U \sim \begin{pmatrix} 1 & -b\lambda^2 & -A\lambda^3(\rho - i\eta) \\ b\lambda^2 & 1 & -A\lambda^2 \\ A\lambda^3(\rho + i\eta) & A\lambda^2 & 1 \end{pmatrix} \quad \sim 10^{-4}$$

$$\Longrightarrow \quad b^u_{ij} \sim \begin{pmatrix} r & \mathcal{O}(\lambda^5) & (1-r)A\lambda^3(\rho - i\eta) \\ \mathcal{O}(\lambda^5) & r & (1-r)A\lambda^2 \\ (1-r)A\lambda^3(\rho + i\eta) & (1-r)A\lambda^2 & 1 \end{pmatrix}$$

- predicting the largest FCNC in the up-quark sector in the t to c transition with strength comparable to V_{ts}
- c to u is at the upper level allowed by D mixing

Other very simple scenarios

- An obvious possibility is that one of the rotation matrices is the unit matrix, for a hermitian M then:

$$(a) V_L^D = I \implies V_L^{U\dagger} = V_{CKM} \quad \text{so} \quad a^u_{ij}(b^u_{ij}) = V_{CKM} Z_\kappa V^\dagger_{CKM}, \;\; a^d_{ij}(b^d_{ij}) = Z_\kappa$$

$$(b) V_L^U = I \implies V_L^{D} = V_{CKM} \quad \text{so} \quad a^d_{ij}(b^d_{ij}) = V^\dagger_{CKM} Z_\kappa V_{CKM}, \;\; a^u_{ij}(b^u_{ij}) = Z_\kappa$$

- similar expressions for symmetric case with $b^{d,u}_{ij} \to a^{d,u\star}_{ij}$
- Since:

$$V^\dagger_{CKM} Z_\kappa V_{CKM} = \begin{pmatrix} r & \mathcal{O}(\lambda^5) & A(1-r)\lambda^3(1-\rho+i\eta) \\ \mathcal{O}(\lambda^5) & r & -A(1-r)\lambda^2 \\ A(1-r)\lambda^3(1-\rho-i\eta) & -A(1-r)\lambda^2 & 1 \end{pmatrix}$$

$$V_{CKM} Z_\kappa V^\dagger_{CKM} = \begin{pmatrix} r & \mathcal{O}(\lambda^5) & A(1-r)\lambda^3(\rho-i\eta) \\ \mathcal{O}(\lambda^5) & r & A(1-r)\lambda^2 \\ A(1-r)\lambda^3(\rho+i\eta) & A(1-r)\lambda^2 & 1 \end{pmatrix}.$$

$$\left(\frac{M_Z}{M_{Z'}}\kappa_b\right) b^d_{ij} \lesssim \begin{pmatrix} - & 10^{-4} & 10^{-4} \\ 10^{-4} & - & 10^{-3} \\ 10^{-4} & 10^{-3} & - \end{pmatrix}$$

$$\left(\frac{M_Z}{M_{Z'}}\kappa_t\right) b^u_{ij} \lesssim \begin{pmatrix} - & 10^{-4} & ? \\ 10^{-4} & - & ? \\ ? & ? & - \end{pmatrix}.$$

- In general (a) is compatible, (b) is not with FCNC phenomenology

Conclusions

- We constructed explicit anomaly-free toy models for non-universal Z´ bosons that prefer the third generation as examples of new physics for top.
- We have revisited the phenomenology of Z´ bosons for this case
  - We constrain the mass and interaction strength, mostly from the non-observation of Z´ at LEP
- We consider in detail the FCNC associated with a non-universal Z´ including operators at tree-level and those enhanced at one-loop.
  - we obtain constraints on the mass mixing matrices from meson mixing and rare decays
  - we find large enhancements over SM are still possible in other rare decays
- We construct an ansatz to show how the smallness of FCNC can occur from the same physics behind the CKM matrix due to the simple form of the additional flavor structure present in the models.