U(1) family dependent models at the TeV scale

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- Many extensions of the SM contain extra gauged $[U(1)]$ groups which are used to alleviate SM unanswered questions
- One of these is the generation of hierarchical masses and mixings
- Plethora of models constructed in the context of supersymmetric GUT theories which break the extra gauge sector near $M_{\text{GUT}} \rightarrow$ boring phenomenology...
- Can we realize a model instead at the TeV scale?
  - A single gauged $U(1)$ coupled to all SM fermions cannot describe all the mass hierarchies and produce Z' below 1 TeV
  - Two $U(1)'$s could produce the mass and mixing hierarchies but the lightest $Z' \sim 12$ TeV
  - Two $U(1)'$s coupled to different fermions can reach a $Z' \sim 1$ TeV [in progress]
  - To probe the rich associated phenomenology at TeV scale we consider a toy model with one approxiamte global $U(1)$ [massive pseudo-Goldstone boson of ~ 1 TeV]

Outline

- LEP & Tevatron bounds on $U(1)'$
- Basic features of TeV scalars [Flavons] associated to the breaking of this particular extra gauge symmetries
- Why Flavons at the TeV scale?
- Model building for such scenarios
- Conclusion

LEP & Tevatron bounds on $U(1)'$

- Bounds from LEP can be used by identifying the contact interactions between SM fields and an extra Abelian gauge boson.

Eichten, Lane & Peskin, Phys. Rev. Lett. **50** (1983)
LEP & ALEPH Report, arXiv:hep-ex/0312023

- These are basically the contributions to the amplitude of the process

$$\overline{e}e \to \overline{f}f$$

from the s channel, mediated by a Z' boson. The effective amplitude for these processes can be expressed as

$$\frac{\pm 4\pi}{(1+\delta_{ef})\left(\Lambda^{f\pm}_{AB}\right)^2}\left(\overline{e}\gamma_\mu \mathsf{P}_A e\right)\left(\overline{f}\gamma^\mu \mathsf{P}_B f\right),$$

$\mathsf{P}_{A,B} = \frac{1\pm\gamma_5}{2} \quad \delta_{ee} = 1,\ \delta_{ef} = 0,\ f \neq e.$

LEP & Tevatron bounds on $U(1)'$

[PDG, Dobrescu & Chen]

- For a theory with SM fermions charged under an extra $U(1)'$ the neutral current interaction, mediated by Z' can be written as

$$\mathcal{L} = \sum_f q^f \overline{f} \gamma^\mu Z'_\mu f,$$

hence the effective amplitude for the interactions mediated by Z' is,

$$\frac{g_F^2 \overline{e} \gamma^\mu \left(q_L^e \mathsf{P}_L + q_R^e \mathsf{P}_R\right) e \overline{f} \gamma_\mu \left(q_L^f \mathsf{P}_L + q_R^f \mathsf{P}_R\right) f}{s - m_{Z'}^2},$$

- A bound on $m_{Z'}^2 / g_F^2$ can thus be easily obtained:

$$m_{Z'}^2 \geq \frac{g_F^2}{4\pi} |q_A^e q_B^f| \left(1 + \delta_{ef}\right) \left(\boldsymbol{\Lambda}_{AB}^{f\pm}\right)^2 .$$

LEP & Tevatron bounds on $U(1)'$

$e^+e^- \to \ell^+\ell^-$			
M	ϵ (TeV^{-2})	Λ^- TeV	Λ^+ TeV
LL	$-0.0044^{+0.0035}_{-0.0035}$	9.8	13.3
RR	$-0.0049^{+0.0039}_{-0.0039}$	9.3	12.7
VV	$-0.0016^{+0.0013}_{-0.0014}$	16.0	21.7
AA	$-0.0013^{+0.0017}_{-0.0017}$	15.1	17.2
LR	$-0.0036^{+0.0052}_{-0.0054}$	8.6	10.2
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V0	$-0.0023^{+0.0018}_{-0.0018}$	13.5	18.4
A0	$-0.0018^{+0.0026}_{-0.0026}$	12.4	14.3

$e^+e^- \to e^+e^-$			
M	ϵ (TeV^{-2})	Λ^- TeV	Λ^+ TeV
LL	$0.0049^{+0.0084}_{-0.0084}$	9.0	7.1
RR	$0.0056^{+0.0082}_{-0.0092}$	8.9	7.0
VV	$0.0004^{+0.0022}_{-0.0016}$	18.0	15.9
AA	$0.0009^{+0.0041}_{-0.0039}$	11.5	11.3
LR	$0.0008^{+0.0064}_{-0.0052}$	10.0	9.1
RL	$0.0008^{+0.0064}_{-0.0052}$	10.0	9.1
V0	$0.0028^{+0.0038}_{-0.0045}$	12.5	10.2
A0	$-0.0008^{+0.0028}_{-0.0030}$	14.0	13.0

Table: Fitted values of ϵ and the derived 95% CL lower limits on Λ. The contact interaction are derived from fits to lepton-pair CsS and asymmetries and from fits to hadronic CsS. For l^+l^- ($\ell \neq e$) the couplings to $\mu^+\mu^-$ and $\tau^+\tau^-$ are a assumed to be universal.

- For $q \sim 1$

$$\frac{m_{Z'}}{g_F} \gtrsim 6 \text{ TeV}$$

- For $q < 1$ and different couplings of fermions to leptons this bound could be lowered

Basic features of TeV Flavons

- To generate the effective hierarchical Yukawa couplings introduce scalars coupling in powers to the SM fermions

  Froggatt & Nielsen, Nucl. Phys. B **147** (1979) 277

$$-\mathcal{L} =$$

$$\overline{L}_i e_{Rj} H (c^{\overline{L}e}_{\varphi^e_n})_{ij} \left[\frac{v_{\varphi^e_n} + \varphi^e_n}{\Lambda_{\varphi^e_n}}\right]^{p^e_{ij}} + \overline{Q}_i d_{Rj} H (c^{\overline{Q}d}_{\varphi^d_m})_{ij} \left[\frac{v_{\varphi^d_m} + \varphi^d_m}{\Lambda_{\varphi^d_m}}\right]^{p^d_{ij}}$$

$$+\overline{Q}_i u_{Rj} H (c^{\overline{Q}u}_{\varphi^u_r})_{ij} \left[\frac{v_{\varphi^u_r} + \varphi^u_r}{\Lambda_{\varphi^u_r}}\right]^{p^u_{ij}},$$

- A straightforward realization of this is to generate the powers p^f_{ij} using a $U(1)$ gauged symmetry. Then there will be at least two scalars involved in the breaking for such $U(1)$, one charged such that it can produce different powers p^f_{ij} for different fermions and one neutral acquiring a vev setting the scale Λ_φ.

Basic features of TeV Flavons

- We want to set $\Lambda_\varphi \sim 1$ TeV and need

$$\frac{v_\varphi}{\Lambda_\varphi} \sim 0.1 \sim \lambda_C$$

- Thus v_φ few hundred GeV $\rightarrow$ accessible at the LHC
- Strongest requirements: $SU(2)_L$ singlet scalars with $Y = 0$ or doublets with $Y = \pm\frac{1}{2}$ because we know these choices keep EW symmetry breaking conditions unaffected at tree level.

Why Flavons at the TeV scale?

- The transformation of electro-weak eigenstates into mass eigenstates accounts for the flavour violating parameters

$$Q \to U_L^Q Q, \quad q_R \to U_R^q q_R \quad \Rightarrow \quad Y^q = U_L^{Q\dagger} Y^q_{\text{diag}} U_R^q,$$

- For simplicity consider just one flavon which can only couple to SM fermions with positive powers then

$$-\mathcal{L}_\varphi^{\text{eff}} \;= m_i^f \,\overline{f_L}_i f_{Ri} \left(1 + \tfrac{H}{v}\right) + \kappa_{ij}^f \,\overline{f_L}_i f_{Rj} \left(\frac{\varphi}{v_\varphi}\right) + \text{H.c.},$$

where the flavour violating parameters are given by

$$\begin{aligned}\kappa_{ij}^f \;&=\; m_j^f \sum_k q_{Lk}^f \left(U_L^f\right)_{ik} \left(U_L^f\right)^*_{jk} + m_i^f \sum_k q_{Rk}^f \left(U_R^f\right)_{ik} \left(U_R^f\right)^*_{jk} \\ &=\; \kappa_{Lij}^f + \kappa_{Rij}^f .\end{aligned}$$

Why Flavons at the TeV scale?

- As a guideline take U_L^f to be CKM like

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(\rho + i\eta) & -A\lambda^2(1+\lambda^2(\rho+i\eta)) & 1-\frac{A^2\lambda^4}{2} \end{pmatrix}$$

- In general we can parameterize the mixing angles [unless there are very specific relations given by the family symmetries] by identifying their magnitude to that one of the corresponding angle in $V_{\rm CKM}$

$$\begin{aligned} \mathsf{s}^f_{12} &= B^f_{12}\lambda + C^f_{12}\lambda^2 + D^f_{12}\lambda^3 \\ \mathsf{s}^f_{13} &= D^f_{13}\lambda^3 + E^f_{13}\lambda^4 + F^f_{13}\lambda^5 \\ \mathsf{s}^f_{23} &= C^f_{23}\lambda^2 + D^f_{23}\lambda^3 + E^f_{23}\lambda^4, \end{aligned}$$

Why Flavons at the TeV scale?

Then the sctructure of flavour violation is as follows

$$k^u = \begin{pmatrix} \begin{matrix} m_u p^u_{11} + \\ \lambda^2 m_c (p^u_{11} - 2p^u_{12} + p^u_{22}) \\ \lambda^6 m_t O(1) \end{matrix} & \begin{matrix} -\lambda m_c (1 + B^d_{12})(p^u_{12} - p^u_{22}) \\ +\lambda^5 m_t O(1) \end{matrix} & -\lambda^3 m_t \mathrm{e}^{-i\phi_u} D^u_{13} p^u_{13} \\ \dots & \begin{matrix} m_c p^u_{22} \\ +\lambda^4 m_t (A + C^d_{23})^2 (p^u_{22} - 2p^u_{23}) \end{matrix} & -\lambda^2 m_t p^u_{23} (A + C^d_{23}) \\ \dots & \dots & k^u_{33} \end{pmatrix}$$

$$k^d_{33} = m_b (p^d_{33} + O(\lambda^2)),$$

$$k^u_{33} = m_t (p^u_{33} + O(\lambda^2)), \qquad k^u_{33} = \begin{matrix} -\lambda^2 m_t 2 p^u_{23} \left(A + C^d_{23}\right)^2 \\ -\lambda^4 m_c p^u_{22} \left(A + C^d_{23}\right)^2 \end{matrix}$$

$$q^t_R + q^t_L \neq 0, \qquad q^t_R + q^t_L = 0$$

WHY FLAVONS AT THE TEV SCALE?

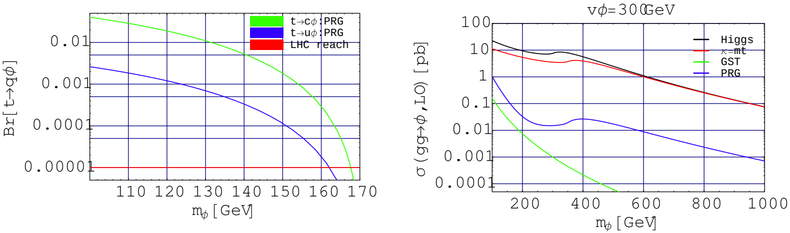
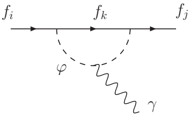


FIGURE: On the left, the decay branching fraction of the process $t \to q\varphi$ is shown as a function of m_φ. On the right, the production cross section of the flavon via the gluon fusion mechanism is evaluated at the LHC for $\kappa^u_{33} \approx m_t, m_t V^2_{ud}, m_t V^4_{ud}$.

Model building for such scenarios

- Strong constraints from flavour violation



- Gauged models $\rightarrow$ severely constrained by anomaly cancellation:
[Without SUSY] The SM fermions can only contain additional $U(1)$ gauged anomaly free symmetries whose charges are proportional to

$$\alpha Y + \beta(B - L)$$

but do require some extra fermions. If $\alpha = 0$ we require three $Y = 0$ fermions that can be identified with the neutrinos.

Model building for such scenarios

- Non-supersymmetric example with a $U(1)_1 \times Z_2$ symmetry

$$Y^u = \begin{bmatrix} \lambda^8 & \lambda^6 & \lambda^6 \\ \lambda^6 & \lambda^4 & \lambda^2 \\ \lambda^4 & \lambda^2 & 0 \end{bmatrix}, \; Y^d = \begin{bmatrix} 0 & \lambda^7 & \lambda^7 \\ 0 & \lambda^5 & \lambda^5 \\ 0 & \lambda^3 & \lambda^3 \end{bmatrix}, \; Y^e = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \lambda^4 & \lambda^3 \\ 0 & \lambda^3 & \lambda^2 \end{bmatrix}$$

- Requires an additional $U(1) = U(1)_2$

$$Y^d = \begin{bmatrix} \lambda'^7 & 0 & 0 \\ \lambda'^7 & 0 & 0 \\ \lambda'^7 & 0 & 0 \end{bmatrix}, \quad Y^e = \begin{bmatrix} \lambda'^7 & 0 & \lambda'^5 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

- We could check which of the $U(1)'s$ has a lighter extra Z' boson. With $U(1)_2$ the bound on $m_{Z'}/g_F$ is increased:

$$\frac{m_{Z'}}{g_F} \geq \sqrt{4\pi |q_A^e q_B^f| \left(1 + \delta_{ef}\right)} \left(\Lambda_{AB}^{f\pm}\right) \gtrsim 6 \text{ TeV} \rightarrow \; 24\text{TeV}$$

- With $U(1)_1$, there is no direct coupling to e but a conservative bound on $\mu^+\mu^- \rightarrow \mu^+\mu^-$ kicks in and thus we have $m_{Z_1}/g_{F_1} \sim 12$ TeV

Model building for such scenarios

- The increase in the limits with non-family dependent $U(1)'s$ [e.g. $U(1)_{B-L} \sim 1$ TeVs] is because in order to achieve high powers for Yukawa couplings we need large charges

$$C[Y_{11}^u] = q_{1R}^u + q_{1R}^u = 8, \quad q_1^u \sim 4,$$

while the charges associated to $U(1)_{B-L}$ are fractional and smaller than 1.

- Assuming no gauge mixing among $U(1)_1$, $U(1)_2$ and $U(1)_Y$, $[D_\mu \Phi]$ is just as in the SM and

$$\begin{aligned} D_\mu \varphi_2 &= \frac{1}{\sqrt{2}} \left(\partial_\mu - \frac{i}{2} g_{F_2} \mathcal{Q}_{F2} Z'_\mu \right) \varphi_2 \\ D_\mu \varphi_1 &= \frac{1}{\sqrt{2}} \left(\partial_\mu - \frac{i}{2} g_{F_1} \mathcal{Q}_{F1} \tilde{Z}_\mu \right) \varphi_1, \end{aligned}$$

the masses at tree level are given by

$$m_Z^2 = \frac{1}{4} \frac{g^2}{\cos^2\theta_w} v^2, \quad m_{Z'}^2 = \frac{1}{4} g_{F_2}^2 \mathcal{Q}_{F}{}_2^2 v_2^2, \quad m_{\tilde{Z}}^2 = \frac{1}{4} g_{F_1}^2 \mathcal{Q}_{F}{}_1^2 v_1^2.$$

Model building for such scenarios

- Since $v_2 = \frac{2}{Q_F}\frac{m_Z}{g_Z} \gtrsim 24$ TeV, flavour violation is quite suppressed
- The process $\varphi\overline{\varphi} \to Z' \to \overline{f} f$ could be used to test these kind of symmetries
- Scalar masses

$$m_H^2 = 2\lambda v^2 \left(1 - \frac{\lambda_2'^2}{\lambda\lambda_{\varphi_2}}\right), \quad m_{\varphi_2}^2 = 2\lambda_{\varphi_2} v_{\varphi_2}^2 \left(1 + \frac{\lambda_2'^2}{\lambda^2}\frac{v^2}{v_{\varphi_2}^2}\right),$$

$$m_{\varphi_1}^2 = 2\lambda_{\varphi_1} v_{\varphi_1}^2 \left(1 + \frac{\lambda_{12}'^2}{\lambda_{\varphi_1}\lambda_{\varphi_2}}\frac{v_{\varphi_2}^2}{v_{\varphi_1}^2}\right).$$

It is clear that with small λ_{φ_i} couplings $m_{\varphi_i} \leq 1$ TeV, but v_{φ_i} can never get lower than 1 TeV.

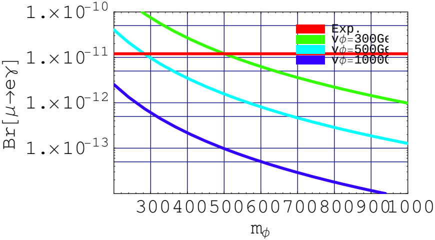
Model building for such scenarios

- Consider global $U(1)$'s
- They could be just approximate global symmetries showing at low energies.
- Broken with an explicit mass term [which of course would need an explanation] $\longrightarrow$ pseudo GB could be heavy

$$\begin{aligned} V(\Phi, \phi) &= -\mu^2 |\Phi|^2 + \lambda |\Phi|^4 - \mu_\varphi^2 |\varphi|^2 + \lambda_\varphi |\varphi|^4 + 2\lambda' |\Phi|^2 |\varphi|^2 \\ &- \frac{M^2}{2}(\varphi^2 + \varphi^{*2}), \end{aligned}$$

Model building for such scenarios

- These kind of models could be easily confirmed or ruled-out



Conclusions

- Need to explain the hierarchy of Fermion Masses and since they are often associated to extra gauge-symmetries, the connection to $U(1)'s$ at low energy is straightforward
- Gauged family dependent $U(1)$ could be tested through the decays $\varphi\overline{\varphi} \to Z' \to \overline{f} f$
- "Global" family dependent $U(1)$ can be tested through flavour violating processes
- SUSY + $U(1)$ severely constrained