Quark Lepton Unification in Higher Dimensions

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- To unify quarks and leptons at TeV scale.
- Have lepto-quark gauge bosons belonging to a non-adjoint representation of the SM gauge symmetry.
- To explore the phenomenological implications of such as unification at the LHC.
- Possible new dark matter candidate

Outline of Talk

- Introduction
- Model and the Formalism
- Phenomenological Implications
- Conclusions and Outlook

Introduction

Why extra dimensions?

- In 4D, quarks and leptons can be unified in Grand Unified Theories or Pati-Salam model
- In GUTs (e.g. $SU(5)$, $SO(10)$) the gauge bosons connecting such unification cause proton decay
  - Scale of unification $\sim 10^{16}$ GeV
- Pati-Salam model (lepton number as 4th color)
  - $K_L \to \mu e$ gives $M_{LQ} > 2300$ TeV
  - No implications for LHC.
- Such a high scale can be avoided by going to the extra dimensions. We are interested in a model with M_{LQ} $\sim$TeV with implications for physics to be explored at the LHC.

Model & Formalism

- Our model is in 5D, the gauge symmetry is $SU(4)_c \times SU(2)_L \times U(1)_R$.
- $SU(4)_c$ unifies quarks and leptons à la Pati-Salam (lepton number is 4th color).
- The extra dim. y is compactified on an $S^1/Z_2 \times Z_2'$ orbifold.
- $SU(4)_c$ is broken to $SU(3)_c \times U(1)_{B-L}$ via this compactification at a scale $\sim$TeV

Model & Formalism

- After compactification, space is: $M^4 \times S^1/Z_2 \times Z_2'$.
- The coordinates are x^μ $(\mu = 0, 1, 2, 3)$ and $y = x^5$.
- Radius of compactification is R
- The radius for the 5th dimension is R. The orbifold $S^1/(Z_2 \times Z_2')$ is obtained by S^1 moduloing the equivalent class

$$P : y \sim -y, \qquad P' : y' \sim -y',$$

  where $y' \equiv y - \pi R/2$.
- There are two fixed points, $y = 0$ and $y = \pi R/2$.

- Gauge bosons belong to the adjoint representations of $SU(4)_c \times SU(2)_L \times U(1)_{I_{3R}}$.
- In 5 dimensions they are $A4^A_M$, $A2^A_M$, and A^R_M, respectively, and $M = \mu, 5$. The corresponding four-dimensional gauge fields A^A_μ and real scalar fields A^A_5.
- Fermions and Higgs representation in 5 dimensions

$$FL = (\mathbf{4}, \mathbf{2}, \mathbf{0}), \quad FU = (\mathbf{4}, \mathbf{1}, \frac{\mathbf{1}}{\mathbf{2}}), \qquad FD = (\mathbf{4}, \mathbf{1}, -\frac{\mathbf{1}}{\mathbf{2}}),$$
$$FL' = (\mathbf{4}, \mathbf{2}, \mathbf{0}), \quad FU' = (\mathbf{4}, \mathbf{1}, \frac{\mathbf{1}}{\mathbf{2}}), \qquad FD' = (\mathbf{4}, \mathbf{1}, -\frac{\mathbf{1}}{\mathbf{2}}),$$
$$H = (\mathbf{1}, \mathbf{1}, -\frac{\mathbf{1}}{\mathbf{2}}).$$

Model & Formalism

- In the usual left and right handed notation, the particle contents in FL, FL', FU, FU', FD, FD' are

$$
\begin{aligned}
FL_L &= (q_L, l'_L), & FL_R &= (q_R, l'_R), \\
FL'_L &= (q'_L, l_L), & FL'_R &= (q'_R, l_R), \\
FU_R &= (U_R, N'_R), & FU_L &= (U_L, N'_L), \\
FU'_R &= (U'_R, N_R), & FU'_L &= (U'_L, N_L), \\
FD_R &= (D_R, E'_R), & FD_L &= (D_L, E'_L), \\
FD'_R &= (D'_R, E_R), & FD'_L &= (D'_L, E_L).
\end{aligned}
$$

- Note: fermion content in each family has been quadrupled
- q_L, l_L, u_R, d_R, e_R and N_R represent the usual fermions in a family
- The primes represent the additional fermions with same corresponding quantum numbers

Model & Formalism

- Fermion representations

$$
\begin{aligned}
FL_L &= (q_L, l'_L), & FL_R &= (q_R, l'_R), \\
FL'_L &= (q'_L, l_L), & FL'_R &= (q'_R, l_R), \\
FU_R &= (U_R, N'_R), & FU_L &= (U_L, N'_L), \\
FU'_R &= (U'_R, N_R), & FU'_L &= (U'_L, N_L), \\
FD_R &= (D_R, E'_R), & FD_L &= (D_L, E'_L), \\
FD'_R &= (D'_R, E_R), & FD'_L &= (D'_L, E_L).
\end{aligned}
$$

- Note that the lepto-quark gauge bosons connect ordinary quarks to the exotic (primed) leptons, and ordinary leptons to exotic (primed) quarks.
- This will avoid the high experimental bound on the masses of these leptoquarks, and will allow us a low compactification scale for the $SU(4)_c \rightarrow SU(3)_c \times U(1)_{B-L}$ breaking.

Model & Formalism

Orbifold transformations and $SU(4)_c \to SU(3)_c \times U(1)$ breaking

- Under the Z_2 and Z_2' parity operators P and P', the vector fields transform as

$$A_\mu(x^\mu, y) \to A_\mu(x^\mu, -y) = P A_\mu(x^\mu, y) P^{-1}$$
$$A_\mu(x^\mu, y') \to A_\mu(x^\mu, -y') = P' A_\mu(x^\mu, y') P'^{-1}$$
$$A_5(x^\mu, y) \to A_5(x^\mu, -y) = -P A_5(x^\mu, y) P^{-1}$$
$$A_5(x^\mu, y') \to A_5(x^\mu, -y') = -P' A_5(x^\mu, y') P^{-1}$$

where A_5 is the 5th component of the vector field.

Model & Formalism

- Under the P' parity, the gauge generators T^{α} ($\alpha = 1, 2, \ldots, 15$) for $SU(4)_c$ are separated into two sets:
  - T^{a} are the generators for the $SU(3)_c \times U(1)_{B-L}$ gauge group.
  - $T^{\hat{a}}$ are the generators for the broken gauge group.

$$P' T^{a} P'^{-1} = T^{a}, \qquad P' T^{\hat{a}} P'^{-1} = -T^{\hat{a}}.$$

The zero modes of the $SU(4)_c/(SU(3)_c \times U(1)_{B-L})$ gauge bosons,(as well A_5 scalars) are projected out; thus, the five-dimensional $SU(4)_c$ gauge symmetry is broken down to the four-dimensional $SU(3)_c \times U(1)_{B-L}$ gauge symmetry.

Transformation of the fermion fields

$$
\begin{aligned}
Z_2: &\qquad FL_L(x^\mu, y) \to FL_L(x^\mu, -y) = PFL_L(x^\mu, y), \\
Z_2': &\qquad FL_L(x^\mu, y') \to FL_L(x^\mu, -y') = P'FL_L(x^\mu, y'), \\
Z_2: &\qquad FL_R(x^\mu, y) \to FL_R(x^\mu, -y) = -PFL_R(x^\mu, y), \\
Z_2': &\qquad FL_R(x^\mu, y') \to FL_R(x^\mu, -y') = -P'FL_R(x^\mu, y').
\end{aligned}
$$

This projects out zero modes of all the primed fermions, as well as zero modes of all the SM fermions with wrong chirality.

Model & Formalism

Denoting the generic fields ϕ with parities $(P,\ P')$=$(\pm,\pm)$ by $\phi_{\pm\pm}$, we obtain the KK mode expansions

$$\phi_{++}(x^\mu,y)=\sum_{n=0}^{\infty}\frac{1}{\sqrt{2^{\delta_{n,0}}\pi R}}\phi_{++}^{(2n)}(x^\mu)\cos\frac{2ny}{R},$$

$$\phi_{+-}(x^\mu,y)=\sum_{n=0}^{\infty}\frac{1}{\sqrt{\pi R}}\phi_{+-}^{(2n+1)}(x^\mu)\cos\frac{(2n+1)y}{R},$$

$$\phi_{-+}(x^\mu,y)=\sum_{n=0}^{\infty}\frac{1}{\sqrt{\pi R}}\phi_{-+}^{(2n+1)}(x^\mu)\sin\frac{(2n+1)y}{R},$$

$$\phi_{--}(x^\mu,y)=\sum_{n=0}^{\infty}\frac{1}{\sqrt{\pi R}}\phi_{--}^{(2n+2)}(x^\mu)\sin\frac{(2n+2)y}{R},$$

where n is a non-negative integer.

Gauge fields and fermion mass spectrum

(P, P')	Field	Mass
$(+,+)$	$A4^a_\mu$, $A2^A_\mu$, A^R_μ, q_L, U_R, D_R, l_L,N_R, E_R, H	$\frac{2n}{R}$
$(+,-)$	$A4^{\hat{a}}_\mu$, q'_L, U'_R, D'_R, l'_L, N'_R, E'_R	$\frac{2n+1}{R}$
$(-,+)$	$A4^{\hat{a}}_5$, q'_R, U'_L, D'_L, l'_R, N'_L, E'_L	$\frac{2n+1}{R}$
$(-,-)$	$A4^a_5$, $A2^A_5$, A^R_5, q_R, U_L, D_L, L_R, N_L, E_L,	$\frac{2n+2}{R}$

Table : Parity assignments and masses ($n \geq 0$) for the bulk fields.

One loop correction and mass Spectrum of fermions

- First KK excitations of the the particles belonging to $(++)$ and $(--)$ have masses $2/R$,
- Those belonging to $(+-)$ and $(-+)$ have masses $1/R$ also.
- Thus at the tree level, all of the $(+-)$ and $(-+)$ are degenerate.
- However, radiative corrections will split these masses. The candidate for the dark matter, the decay pattern of these particles, and the associated collider phenomenology will depend crucially on these radiative splittings.

Mass spectrum after radiative correction:

- Parameters : Compactification scale $1/R$, cut off Λ.

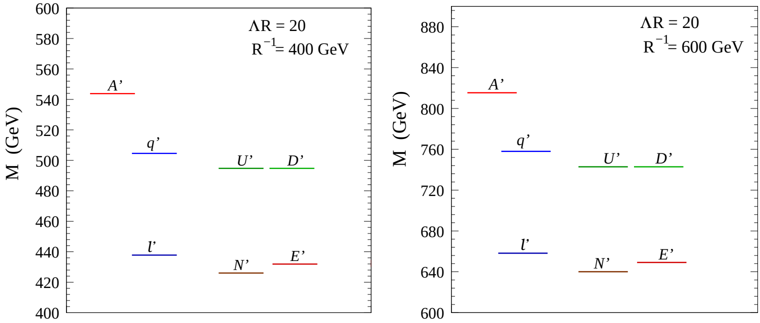

Figure : *The particle mass spectrum as a function of the compactification scale R^{-1} after including the mass splittings.*

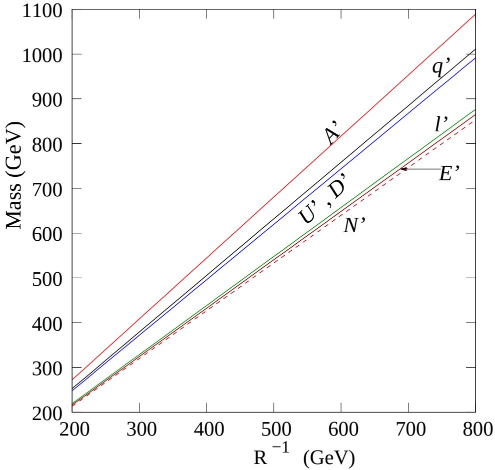

Figure : *The particle mass spectrum as a function of the compactification scale R^{-1} after including the mass splittings.*

- Production cross sections

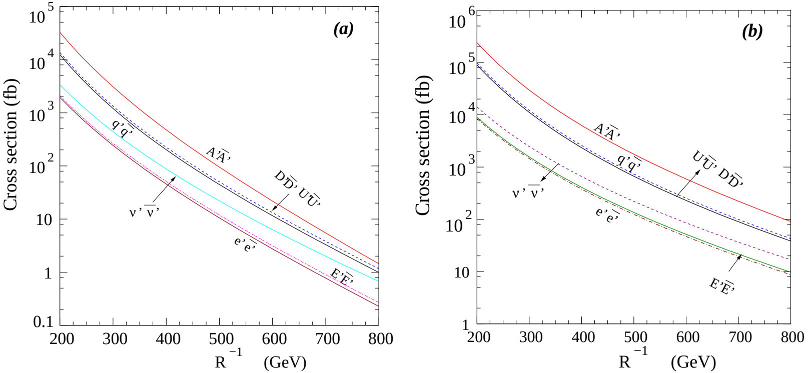

Figure : *Illustrating the pair production cross sections for the first KK excitations as functions of the compactification scale R^{-1} at LHC for the center-of-mass energies of (a) $\sqrt{s} = 7$ TeV and (b) $\sqrt{s} = 14$ TeV.*

Phenomenological Implications

Decay Modes	$R^{-1} = 400$ GeV	$R^{-1} = 600$ GeV	i
BR($A' \to \bar{e}^i {D'}^i_R$)	2.03%	1.99%	1, 2, 3
BR($A' \to \nu^i_L {u'}^i_L$)	1.34%	1.31%	1, 2, 3
BR($A' \to \bar{e}^i {d'}^i_L$)	1.34%	1.31%	1, 2, 3
BR($A' \to d^i \bar{E}'^i_R$)	8.81%	8.64%	1, 2, 3
BR($A' \to d^i \bar{e}'^i_L$)	8.06%	7.91%	1, 2, 3
BR($A' \to u^i {\nu'}^i_L$)	8.06%	7.91%	1, 2
BR($A' \to u^i {N'}^i_R$)	9.57%	9.38%	1, 2
BR($A' \to t {N'}^3_R$)	–	1.94%	
BR(${q'}^1_L \to \nu^i_L d^i \bar{E}'^i_R$)	10.8%	10.8%	1, 2, 3
BR(${q'}^1_L \to \nu^i_L d^i \bar{e}'^i_L$)	7.7%	7.7%	1, 2, 3
BR(${q'}^1_L \to \nu^i_L u^i {\nu'}^i_L$)	7.7%	7.7%	1, 2
BR(${q'}^1_L \to \nu^i_L u^i {N'}^i_R$)	14.6%	14.6%	1, 2

Table : *(Continued on next slide.)*

Decay Modes	$R^{-1} = 400$ GeV	$R^{-1} = 600$ GeV	i
BR($D'^1_R \to ed^i\bar{E}'^i_R$)	10.9%	10.9%	$1,2,3$
BR($D'^1_R \to ed^i\bar{e}'^i_L$)	7.3%	7.3%	$1,2,3$
BR($D'^1_R \to eu^i\nu'^i_L$)	7.3%	7.3%	$1,2,3$
BR($D'^1_R \to eu^iN'^i_R$)	15.6%	15.6%	$1,2$
BR($\nu'^1_L \to u\bar{u}^iN'^i_R$)	50%	49%	$1,2$
BR($e'^1_L \to \bar{u}dN'^1_R$)	49.5%	48.6%	
BR($e'^1_L \to \bar{c}dN'^2_R$)	47.1%	47.6%	
BR($E'^1_R \to \bar{u}dN'^1_R$)	55.0%	52.3%	
BR($E'^1_R \to \bar{c}dN'^2_R$)	45.0%	47.7%	

Table : *The dominant decay modes and the respective branching ratios for the first KK excitation of the new exotic particles for two values of the compactification scale.*

LHC signals

	$R^{-1} = 400$ GeV	$R^{-1} = 600$ GeV
Signal	$\sigma \times BR$ (fb)	$\sigma \times BR$ (fb)
2 hard jets and $\not{E}_T$	8330	787
4 hard jets and $\not{E}_T$	611	53.6
1 lepton, 3 hard jets and $\not{E}_T$	1890	102
2 leptons, 2 hard jets and $\not{E}_T$	5020	393
2 leptons, 4 hard jets and $\not{E}_T$	30.0	2.75
4 leptons, 2 hard jets and $\not{E}_T$	30.0	2.75
Monojet ($p_T^j > 20$ GeV) and $\not{E}_T$	2000	215

Table : *Illustrating the $\sigma \times BR$ for the various final states obtained for the signal from the production and decay of the exotics at LHC with center-of-mass energy $\sqrt{s} = 14$ TeV. The leptons considered in the final states are either e or μ.*

- Dijet plus missing energy
  - Pair production of $A'A'$, and the subsequent decay of each $A' \to u' N'_R \Longrightarrow$ Two hard jets plus missing energy.
  - $\sigma \times \mathrm{BR} \sim$ 8 pb at 14 TeV for $R^{-1} = 400$ GeV.
  - $\sigma \times \mathrm{BR} \sim$ 0.8 pb at 14 TeV for $R^{-1} = 600$ GeV.
  - SM background can be reduced to ~ 0.2 pb with suitable cuts.
- Dijet plus dilepton plus missing energy
  - Pair production of D'^1_R, and the subsequent decay of each $D'^1_R \to e u^i N'^i_R \Longrightarrow$ Two hard leptons and two hard jets plus missing energy.
  - $\sigma \times \mathrm{BR} \sim$ 5 pb at 14 TeV for $R^{-1} = 400$ GeV.
  - $\sigma \times \mathrm{BR} \sim$ 0.4 pb at 14 TeV for $R^{-1} = 600$ GeV.
  - Dominant SM background comes from $t\bar{t}Z$, and can be suppressed using b-jet veto.

LHC signals

- Monojet plus missing energy
  - This can happen from the subprocess $uu \to N\prime N'$ via the t-channel A' exchange, and radiating of one gluon from the A' or one of the initial u quark.
  - $\sigma \times \mathrm{BR} \sim$ 2 pb with a p_T cut on the gluon of 20 GeV.
  - $\sigma \times \mathrm{BR} \sim$ 0.2 pb with a p_T cut on the gluon of 20 GeV.
  - Dominant SM background is Z + jet, and can be eliminated by high missing E_T cut.

- Four charged leptons plus missing energy
  - $\sigma \times \mathrm{BR} \sim$ 30 fb at 14 TeV for $R^{-1} = 400$ GeV.
  - $\sigma \times \mathrm{BR} \sim$ 2 fb at 14 TeV for $R^{-1} = 400$ GeV.
  - SM background is negligible.

A long lived colored charged particle

- Our model has an exotic particle, U' which can be very long-lived.
- Mass of $U' = 550(740)$ GeV for $R^{-1} = 400(600)$ GeV.
- It decays to 5 body final states through the decay chain $U'_R \to A'^* N^*_R \to (uN')(eW^*) \to uN'eu\bar{d}$.
- Assuming that the light neutrino masses are generated by the TeV scale, N_R, the mixing angle for the $N_R eW$ coupling is $\sim 10^{-6}$. With the 5 body decay, U' becomes long-lived with width $\sim 10^{-27}$ GeV.
- This colored particle will quickly hadronize and will escape the detector.

Conclusions

- Presented a TeV scale model for quark lepton unification in 5 dimensions.
- Has lepto-quark gauge bosons, A', as well as exotic quarks and lepton at the TeV scale.
- These can be produced at the LHC giving rise to distinctive hard multi-jet, multi-jet and multi-lepton, as well as monojet final states with missing energy.
- Has a exotic long-lived colored triplet which will hadronize and escape the detector.
- The model has an exotic neutral lepton, N', which is the lightest exotic particle (LXP) at the TeV scale, and is a possible candidate for dark matter.