TEV SCALE MODELS OF NEW PHYSICS AT THE LHC

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[S.Chakdar,T. Li, S. Nandi and S. K. Rai, Phys.Lett.B 718,121(2012); S. Chakdar, T. Li, S. Nandi and S. K. Rai, Phys. Rev. D 87, 096002(2013); S. Chakdar, K. Ghosh, S. Nandi, S.K. Rai, Phys. Rev D 88, (2013); S. Chakdar, K. Ghosh, S. Nandi, Phys. Lett. B 732(2014)]
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Introduction

- In this talk, I present two well motivated models of new physics to solve some of the drawbacks of the SM
- Predictions of the models can be tested at the LHC
- MODEL 1: TOP $SU(5)$ MODEL $\Rightarrow$ new vector bosons
- MODEL 2: LEFT-RIGHT SYMMETRIC MIRROR MODEL $\Rightarrow$ new fermions
- MODEL 3: PARALLEL UNIVERSE, DARK MATTER AND INVISIBLE HIGGS DECAYS $\Rightarrow$ new Higgs-like boson

MODEL 1 :Top $SU(5)$ model

(S.Chakdar,T. Li, SN, S. K. Rai, Phys.Lett.B 718,121(2012); S. Chakdar, T. Li, SN, S. K. Rai, Phys. Rev. D 87, 096002(2013)).

MOTIVATION

- Remedy the non-unification of gauge couplings in SM.
- Has lepto-quark and di-quark gauge bosons at the TeV scale.
- Has baryon and lepton number violating interactions at the LHC.
- Potential for generating baryon asymmetry of the universe.

MODEL 1 :Top $SU(5)$ model

- Our gauge symmetry is non-supersymmetric $SU(5) \times SM'$ where $SM' = SU(3)'_C \times SU(2)'_L \times U(1)'_Y$.
- First two families of the SM fermions are charged under SM' and singlet under the $SU(5)$.
- The third family is charged under $SU(5)$ and singlet under SM'
- The symmetry is broken to SM at TeV scale.
- Have lepto-quark and di-quark gage bosons, X and Y at the TeV scale coupling only to 3rd family.

TOP $SU(5)$ MODEL

- The lepto-quark and di-quark gauge bosons, X and Y: $Q_X = +4/3$, $Q_Y = +1/3$ decays as
- $X \Rightarrow \bar{b}\tau^+, tt$; $Y \Rightarrow \bar{b}\nu_\tau, tb, \bar{t}\tau^+$.
- The decays of X and Y violate both baryon number and lepton number.
- X can be observed as a resonance in $\bar{b}\tau^+$ and tt mode
- Y can be observed as a resonance in $\bar{t}\tau^+$ and tb mode.

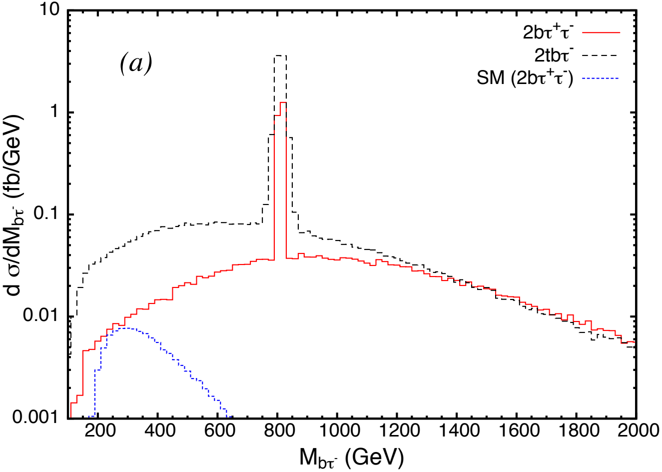
TOP $SU(5)$ MODEL

- Lepto-quark gauge bosons X and Y can be pair produced at the LHC via QCD strong interaction.

- $pp \to X\bar{X} \Rightarrow (\bar{b}\tau^+)(b\tau^-); (tt)(\bar{t}\bar{t}); (\bar{b}\tau^+)(\bar{t}\bar{t})$.

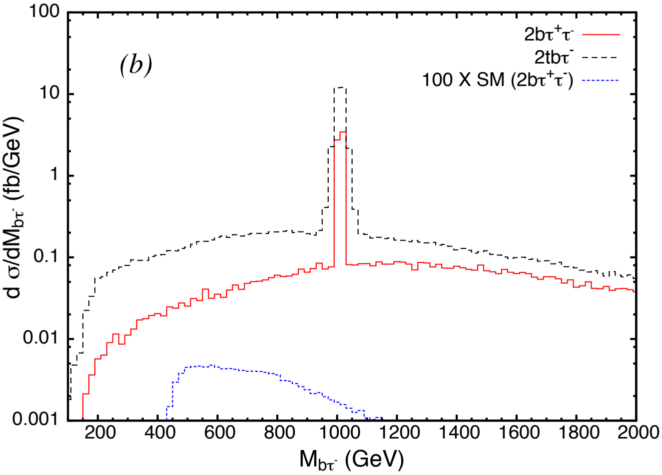
- Similarly for $Y\bar{Y}$ production
- From $X\bar{X}$ productions $\Rightarrow$ Resonance peaks in $(b\tau)$ and (tt).
- For $Y\bar{Y}$ productions, $\Rightarrow$ Resonance peaks in $(\bar{t}\tau^+) and (tb)$.
- Dominant SM background for $(\bar{b}\tau^+)(b\tau^-)$ final state $pp \Rightarrow 2b2\tau, 4b, 2j2b, 4j, t\bar{t}$
- Similarly for the other final states.

$\bar{X}$ resonance in the $b\tau^-$ mode at 8 LHC



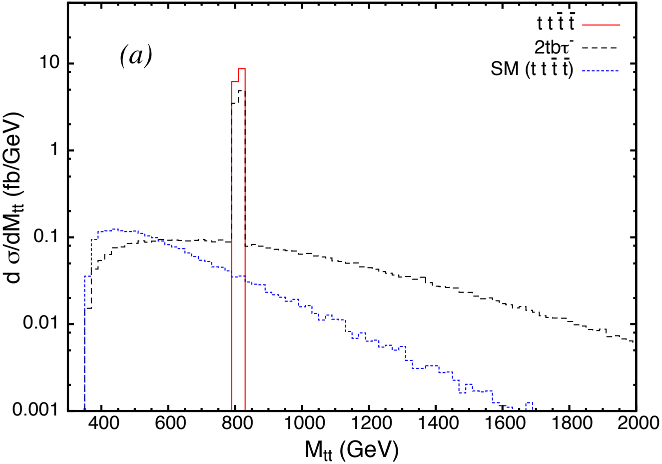
- Invariant mass distribution for the $b\tau^-$ channel for 8 TeV LHC

X resonance in the $b\tau^-$ mode at 14 LHC



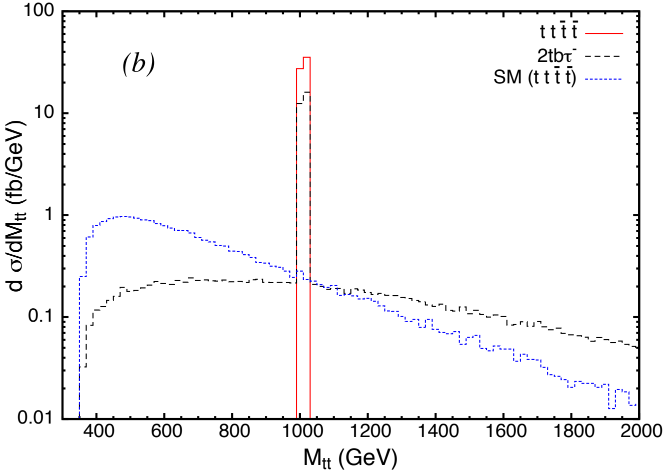
- Invariant mass distribution for the $b\tau^-$ channel for 14 TeV LHC

X resonance in the tt mode at 8 TeV LHC



Invariant mass distribution for the tt channel for $M_X = 800$ GeV at 8 TeV

X resonance in the tt mode at 14 TeV LHC



Invariant mass distribution for the tt channel for $M_X = 1000$ GeV at 14 TeV

TOP $SU(5)$ MODEL

LHC SEARCH SO FAR

- CMS COLLABORATION: Search for $b\tau$ resonance: 7 TeV LHC , $4.8fb^{-1}$ (PRL) $\Rightarrow M_X > 760$ GeV (95%CL); 8 TeV LHC , $19.7fb^{-1} \Rightarrow M_{scalar} > 740$ GeV.

- ATLAS COLLABORATION: Search for $b\tau$ resonance: 7 TeV LHC , $4.7fb^{-1} \Rightarrow M_{scalar} > 534$ GeV (95% CL).

- **NOTE** : Observation of Resonances at both $X \to b\tau$ and tt are needed to establish bayon and lepton number violation.

  LHC REACH at 5σ

- 8 TeV LHC, $30fb^{-1} \Rightarrow M \simeq 800$ GeV.
- 14 TeV LHC, $100fb^{-1} \Rightarrow M \simeq 1.5$ TeV.

LHC sensitivity to the X and Y gauge bosons

For the sensitivity analysis we define

$$\sigma_s \geq \frac{N}{L}\left[N + 2\sqrt{L\sigma_b}\right], \tag{0.1}$$

	$\sqrt{s}$= 8 TeV		$\sqrt{s}$= 14 TeV	
Final States	$L(fb^{-1})$	$M_Y(GeV)$	$L(fb^{-1})$	$M_Y(GeV)$
b b MET	10	737	30	1325
	20	772	100	1440
	30	793	300	1545
$bt\tau^- ME_T$	20	770	200	1650
$+b\bar{t}\tau^+ ME_T$	30	795	300	1690

MODEL 2 :LEFT-RIGHT (L-R) SYMMETRIC MIRROR MODEL

(S. Chakdar, K. Ghosh, SN, S.K. Rai, Phys. Rev D 88, 2013)

MOTIVATION

- Explain parity violation at low energy.
- Solve strong CP problem.
- Generate tiny neutrino masses
- Can have mirror fermions at the TeV scale and be explored at the LHC.

USUAL L-R SYMMETRIC MODEL
Gauge Symmetry : $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.
FERMIONS: For every left handed doublet, there is a right handed doublet

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \Rightarrow \begin{pmatrix} \nu \\ e \end{pmatrix}_R$$
$$\begin{pmatrix} u \\ d \end{pmatrix}_L \Rightarrow \begin{pmatrix} u \\ d \end{pmatrix}_R \tag{0.2}$$

HIGGSES: Under $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
$(2,1,1) + (1,2,1) + (1,2,2)$

MODEL 2 :LEFT-RIGHT SYMMETRIC MIRROR MODEL

Gauge Symmetry: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{Y'} \times Z_2$

FERMIONS: Ordinary sector: blue, mirror sector : red with hat.

$$l_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \sim (1,2,1,-1) \quad , \quad e_R \sim (1,1,1,-2) \quad , \quad \nu_R \sim (1,1,1,0);$$

$$\hat{l}_R = \begin{pmatrix} \hat{\nu} \\ \hat{e} \end{pmatrix}_R \sim (1,1,2,-1) \quad , \quad \hat{e}_L \sim (1,1,1,-2) \quad , \quad \hat{\nu}_L \sim (1,1,1,0);$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \sim (3,2,1,\frac{1}{3}) \quad , \quad u_R \sim (3,1,1,\frac{4}{3}) \quad , \quad d_R \sim (3,1,1,-\frac{2}{3});$$

$$\hat{Q}_R = \begin{pmatrix} \hat{u} \\ \hat{d} \end{pmatrix}_R \sim (3,1,2,\frac{1}{3}) \quad , \quad \hat{u}_L \sim (3,1,1,\frac{4}{3}) \quad , \quad \hat{d}_L \sim (1,1,1,-\frac{2}{3});$$

$Q = T_{3L} + T_{3R} + Y'/2.$

- Z_2: SM and RH singlet ν's : even
- Mirror fermions and LH singlet ν's : odd

MODEL 2 :LEFT-RIGHT SYMMETRIC MIRROR MODEL

- **HIGGSES: Under** $SU(2)_L \times SU(2)_R \times U(1)_{Y'}$
- $(2,1,1) + (1,2,1) + (2,2,1) \Rightarrow Z_2$ even
- Additional Higgs: $\chi(1,1,0) \Rightarrow Z_2$ odd $\rightarrow$ needed for the mixing between the ordinay fermions and mirror fermions.
- **SYMMETRY BREAKING**:
- $SU(2)_L \times SU(2)_R \times U(1)_{Y'} \times Z_2 \rightarrow$ $SU(2)_L \times SU(2)_R \times U(1)_{Y'} \rightarrow SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$
- Z_2 is broken spontaneously by $< V_\chi > \simeq 10^7$ GeV, and also softly.
- χ mixes ordinary fermions with mirror fermions.
- $L_{mix} = h_u \bar{u}_R \hat{u}_L \chi + h_d \bar{d}_R \hat{d}_L \chi + h_e \bar{e}_R \hat{e}_L \chi + h.c.$

MODEL 2 :LEFT-RIGHT SYMMETRIC MIRROR MODEL

NEUTRINO MASSES

- Four ν's per family (one light, 3 very heavy)

- Dirac masses : $m = f_\nu V/\sqrt{2}, m' = f_\nu \hat{V}/\sqrt{2}$, $M_{\nu\hat{\nu}} = \bar{\nu_R}\hat{\nu}_L$

- Majorana masses, M : $\nu_R \nu_R, \hat{\nu}_L \hat{\nu}_L$

- Assuming $M_{\nu\hat{\nu}} \simeq M \simeq \hat{V} \Rightarrow ((m_\nu)_{light} \simeq m^2/M$;
- all other ν's are heavy

- To get $(m_\nu)_{light} \simeq 10^{-2}$ eV $\Rightarrow M \simeq \hat{V} \simeq 10^7$ GeV [with $f_\nu \simeq 10^{-4}$]

MODEL 2 :LEFT-RIGHT SYMMETRIC MIRROR MODEL

MIRROR PARTICLE MASSES

- Only first mirror family is light
- $\frac{m_{\hat{u}}}{m_u} \simeq \frac{m_{\hat{d}}}{m_d} \simeq \frac{m_{\hat{e}}}{m_e} \simeq \frac{v'}{v}$
- With $\hat{V} \simeq 10^7$ GeV
  $\Rightarrow m_{\hat{u}}, m_{\hat{d}} \Rightarrow$ few hundred GeV - TeV range

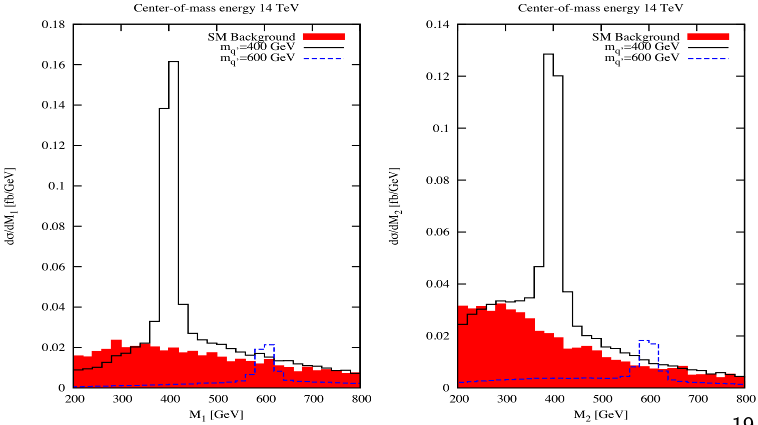
DOMINANT DECAY MODES

$\hat{u} \Rightarrow uz, dW$
$\hat{d} \Rightarrow dz, uW$

MODEL 2 :LEFT-RIGHT SYMMETRIC MIRROR MODEL

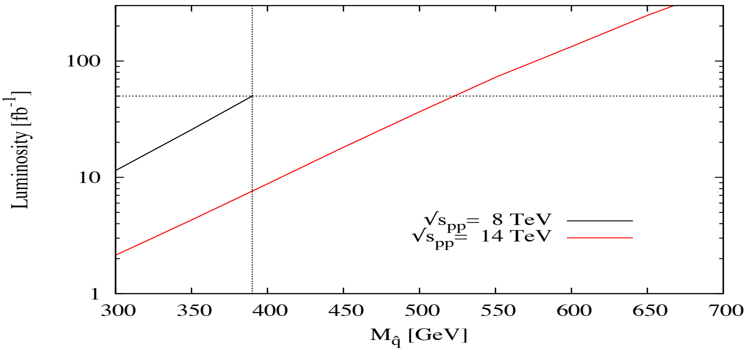
- $pp \Rightarrow \hat{q}\bar{\hat{q}} \Rightarrow (qZ)(\bar{q}Z)$: 2 jets + 2 Z final states
- $pp \Rightarrow \hat{q}\bar{\hat{q}} \Rightarrow (qZ)(\bar{q}'W)$: 2 jets $+Z+W$ final states
- Resonance in (q Z), (q W) modes

2 jets+Z-boson+W boson signature after $\Delta\phi$ cut



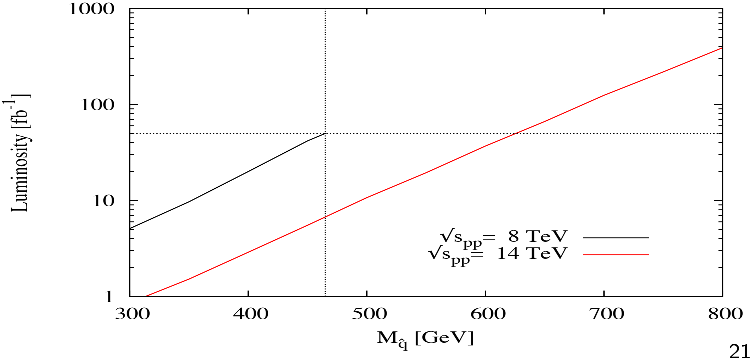
MODEL 2 :LEFT-RIGHT SYMMETRIC MIRROR MODEL

Reach at the LHC in ZZ channel in 99% CL



MODEL 2 :LEFT-RIGHT SYMMETRIC MIRROR MODEL

Reach at the LHC in ZW channel in 99% CL



CONCLUSIONS

- Presented two well motivated TeV scale models of new physics.

  MODEL 1: TOP $SU(5)$ MODEL
- Has di-quark and lepto-quark gauge bosons, violating both baryon and lepton number.
- Resonances in $(b\tau), (tt)$ and (tb) channels.
- Reach: 14 TeV LHC, $100fb^{-1} \simeq 1.5$ TeV. (Current LHC limit $\Rightarrow M > 760$ GeV (CMS Collaboration).

  MODEL 2: LEFT-RIGHT SYMMETRIC MIRROR MODEL
- Has mirror fermions (1st family at TeV scale)
- Resonances at (u Z), (d Z), (u W), (d W) channels.
- Reach at 14 TeV LHC, $100fb^{-1}$ luminosity, $\Rightarrow \simeq 800$ GeV.
- Current LHC limit : Analysis in progress by ATLAS Collaboration.