Signatures of Vector-like Fermions at the LHC

Shrihari Gopalakrishna

Institute of Mathematical Sciences (IMSc)
Chennai, India

—

With: T.Mandal, S.Mitra, G.Moreau, R.Tibrewala

BSM Institute
CERN
28 June 2012

Talk Outline

- Vector-like fermions in Warped models
  - b', t' (T), $\chi_{5/3}$
- Single production couplings
  - Mixing with SM states
- LHC Signatures
  - Promising channels
  - Luminosity required for discovery

Vector-like ψ

Vector-like fermions, compared to chiral (4-gen) fermions

- Separate mass (M) independent of $\langle H \rangle$
  - Can be arbitrarily heavy w/o Landau pole in Yukawa coupling
  - Tree-level decays
    - $b' \to tW$, $b' \to bZ$, $b' \to bh$
    - $T \to bW$, $T \to tZ$, $T \to th$
    - $\chi \to tW$

[ATLAS $\mathrm{arXiv{:}1112.5755}$ Vqq channel $M_Q \gtrsim 900$ GeV]

Warped Model

SM in background 5D warped AdS space [Randall, Sundrum '99]

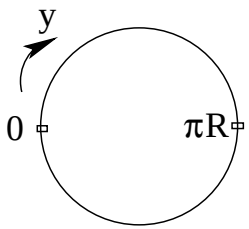
$$ds^2 = e^{-2k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2$$

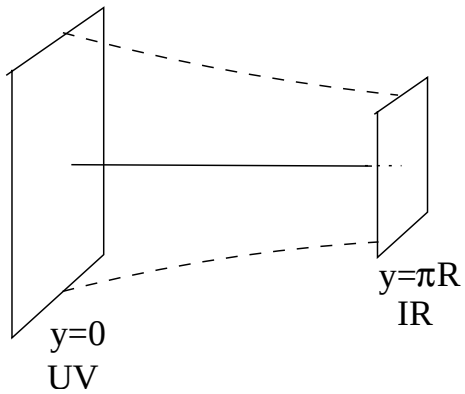
Z_2 orbifold fixed points:

- Planck (UV) Brane
- TeV (IR) Brane

R : radius of Ex. Dim.

k : AdS curvature scale ($k \lesssim M_{pl}$)





Hierarchy prob soln:

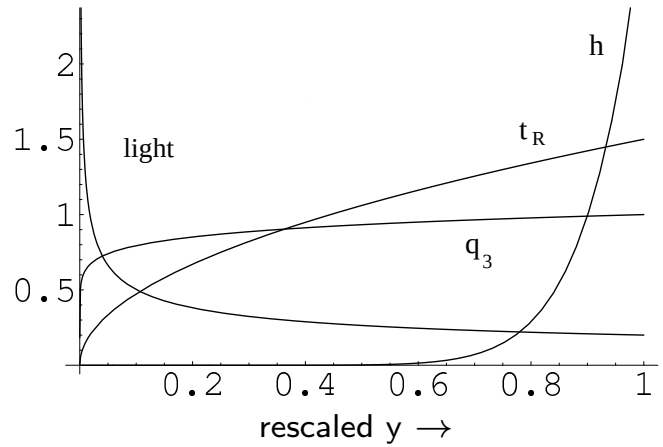
- IR localized Higgs : $M_{EW} \sim k e^{-k\pi R}$: Choose $k\pi R \sim 34$
  - Gauge-theory dual is a composite Higgs model

Explaining SM mass hierarchy

Bulk Fermions explain SM mass hierarchy [Gherghetta, Pomarol 00][Grossman, Neubert '00]

$$\mathcal{L}^{(5)}_{Yuk} \supset \sqrt{|g|}\left\{c_L k\,\bar{\psi}_L\psi_L + c_R k\,\bar{\psi}_R\psi_R + \left(\lambda_5\,\bar{\psi}_R\psi_L H + h.c.\right)\right\}$$

$$\Psi_L(x,y) = \frac{e^{(2-c)ky}}{\sqrt{2\pi R N_0}}\Psi^{(0)}_L(x) + \ldots$$



FCNC largely under control, but still strong constraints

Warped Bulk Gauge Group

[Agashe, Delgado, May, Sundrum '03]

Bulk gauge group : $SU(3)_{QCD} \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_X$

- Gauge Symmetry breaking:
  - By Boundary Condition (BC): $A_{-+}(x,y)$ BC: $A|_{y=0} = 0\,;\ \partial_y A\,|_{y=\pi R} = 0$
    - $SU(2)_R \times U(1)_X \to U(1)_Y$
  - By VEV of IR localized Higgs Higgs $\Sigma = (2,2)$
    - $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

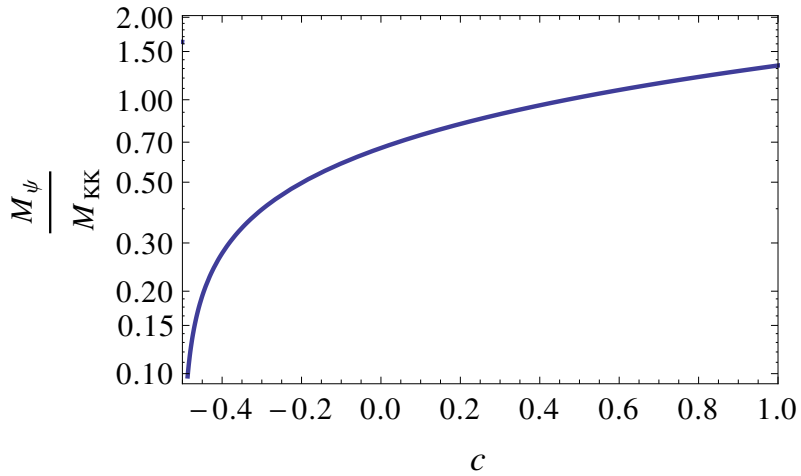
Warped Fermions

- SM fermions : $(+,+)$ BC $\rightarrow$ zero-mode
- "Exotic" fermions : $(-,+)$ BC $\rightarrow$ No zero-mode
  - 1^{st} KK vector-like fermion

- Typical c_{t_R}, c_{t_L} : $(-,+)$ top-partners "light"

  [Choi, Kim, 2002] [Agashe, Delgado, May, Sundrum, 03]
  [Agashe, Perez, Soni, 04] [Agashe, Servant 04]

  - Look for it at the LHC



[Dennis et al, '07] [Carena et al, '07] [Contino, Servant, '08]
[Atre et al, '09, '11] [Aguilar-Saavedra, '09] [Mrazek, Wulzer, '09]
[SG, Moreau, Singh, '10] [SG, Mandal, Mitra, Tibrewala, '11] [SG, Mandal, Mitra, Moreau : Work In Progress]

Fermion reps (Model I)

[Agashe, Delgado, May, Sundrum '03]

- Complete $SU(2)_R$ multiplet
  - $Q_L \equiv (\mathbf{2}, \mathbf{1})_{1/6} = (t_L, b_L)$
  - $Q_{t_R} \equiv (\mathbf{1}, \mathbf{2})_{1/6} = (t_R, b')$
  - $Q_{b_R} \equiv (\mathbf{1}, \mathbf{2})_{1/6} = (T, b_R)$
- "Project-out" b', T zero-modes by $(-,+)$ B.C.
- $b \leftrightarrow b'$ mixing
  - $Zb\bar{b}$ coupling shifted
    - So severe constraints (LEP)

Fermion reps (Model II)

Impose custodial $SU(2)_{L+R} \otimes P_{LR}$ invariance [Agashe, Contino, DaRold, Pomarol '06]

- $Zb_L\overline{b_L}$ coupling protected

Fermions:

- $Q_L = (2,2) = \begin{pmatrix} t_L & \chi \\ b_L & T \end{pmatrix}$

$t_R : (1,1)$ OR

$t_R : (1,3) \oplus (3,1) = \begin{pmatrix} \chi' \\ t_R \\ b' \end{pmatrix} \oplus \begin{pmatrix} \chi'' \\ t'' \\ b'' \end{pmatrix}$

New vector-like fermions $\chi,\ T,\ \chi',\ b',\ \chi'',\ t'',\ b''$

- No zero-mode. $(-,+)$ BC $\implies M_{\psi'} < M_{A'}$
- Promising LHC signatures

Single Production Couplings (Eg: Model II, T)

- Focus on Single production
  - reveals EWSB mechanism
- t_R singlet :

$$\mathcal{L}_{\rm Yuk} \supset \lambda_t \ {\rm Tr}\left[\bar{Q}_L \Sigma\right] t_R + h.c.$$

  - $\langle \Sigma \rangle = v \implies t \leftrightarrow T$ mixing
    - $\mathcal{L}_{\rm mass} \supset \begin{pmatrix} t_L & T_L \end{pmatrix} \begin{pmatrix} m_t & 0 \\ \tilde{m} & M_T \end{pmatrix} \begin{pmatrix} t_R \\ T_R \end{pmatrix} + h.c.$
    - leads to $T_L b_L W^{\pm}$, TtZ, Tth couplings

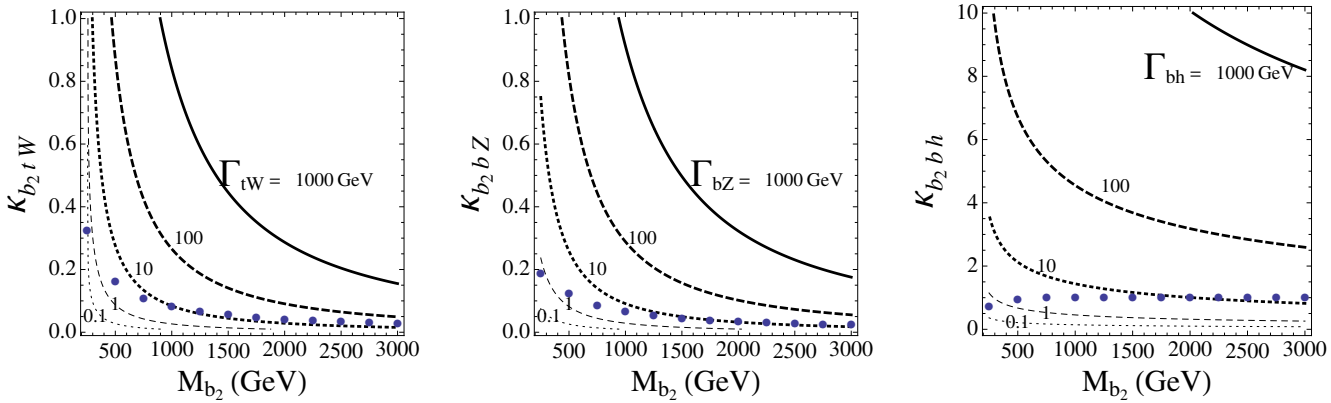
Parameters and Mixing angles (Eg: Model II, T)

c_{tR}	c_{tL}	$\tilde{m}$ (GeV)	M_T (GeV)	$\sin\theta_R$	$\sin\theta_L$
-0.50	0.256	348.2	2516.247	-0.138	-0.00932
0.00	0.012	246.2	1988.015	-0.124	-0.01063
0.15	-0.197	206.0	1469.807	-0.141	-0.01630
0.21	-0.341	187.5	1031.906	-0.184	-0.03009
0.23	-0.404	180.9	793.166	-0.232	-0.04905
0.24	-0.438	177.6	632.386	-0.289	-0.07537
0.25	-0.476	174.6	428.905	-0.426	-0.15640

b' Phenomenology at the 14TeV LHC

[SG, T.Mandal, S.Mitra, R.Tibrewala, arXiv:1107.4306]

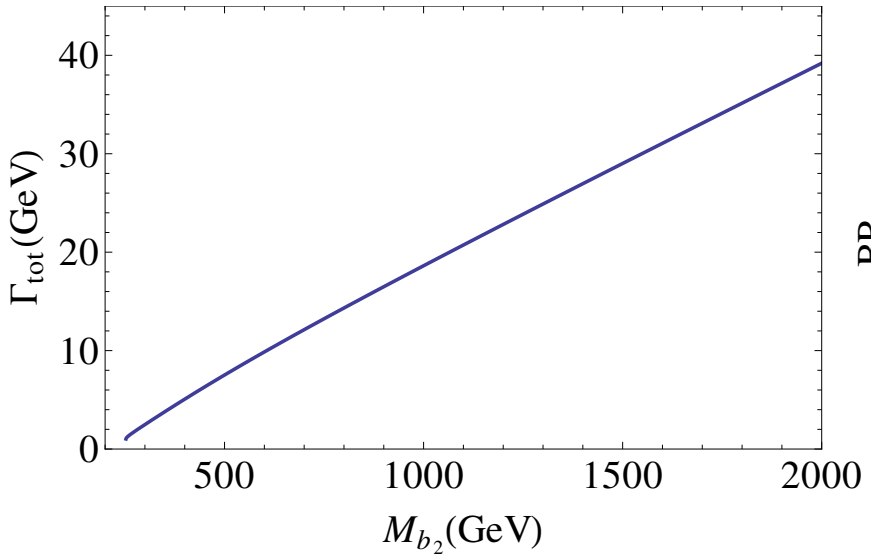
b' Signature (Model Independent)

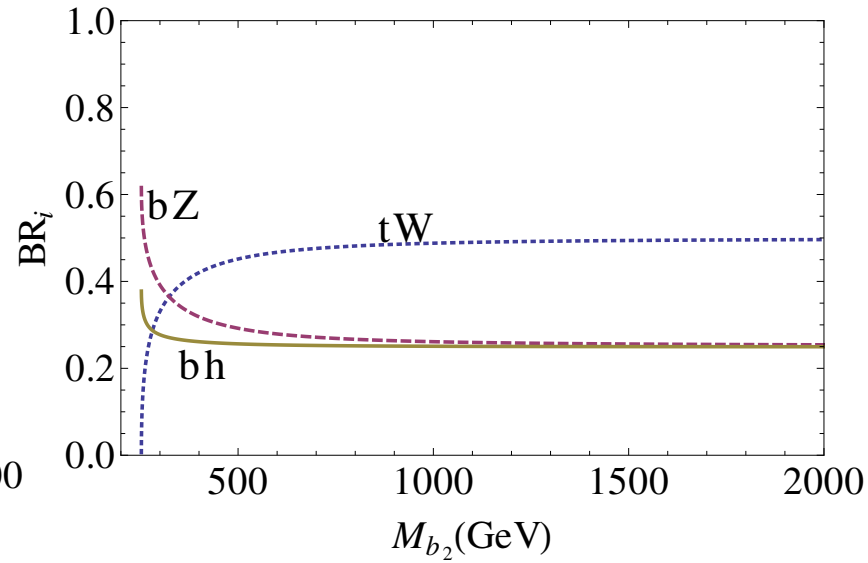


Benchmark Points (Model I):

M_{b_2} (GeV)	250	500	750	1000	1250	1500
$\kappa^L_{b_2 bZ}$	0.185	0.121	0.084	0.064	0.051	0.043
$\kappa_{b_2 tW}$	0.322	0.161	0.107	0.080	0.064	0.054
$\kappa_{hb_L b_{2R}}$	0.714	0.937	0.972	0.985	0.990	0.993
M_{b_2} (GeV)	1750	2000	2250	2500	2750	3000
$\kappa^L_{b_2 bZ}$	0.037	0.032	0.029	0.026	0.024	0.022
$\kappa_{b_2 tW}$	0.046	0.040	0.036	0.032	0.029	0.027
$\kappa_{hb_L b_{2R}}$	0.995	0.996	0.997	0.998	0.998	0.998

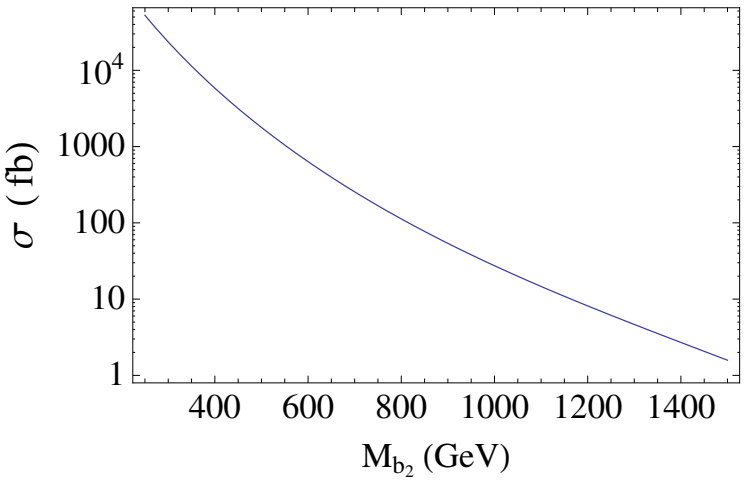
b' Decay (Model I)

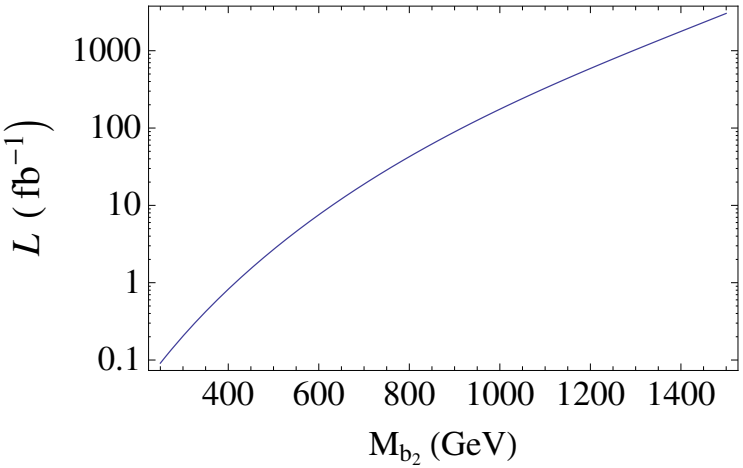




b' Pair Production

Pair Production : $pp \to b'\bar{b}' \to bZ\bar{b}Z \to bjj\bar{b}\ell\ell$



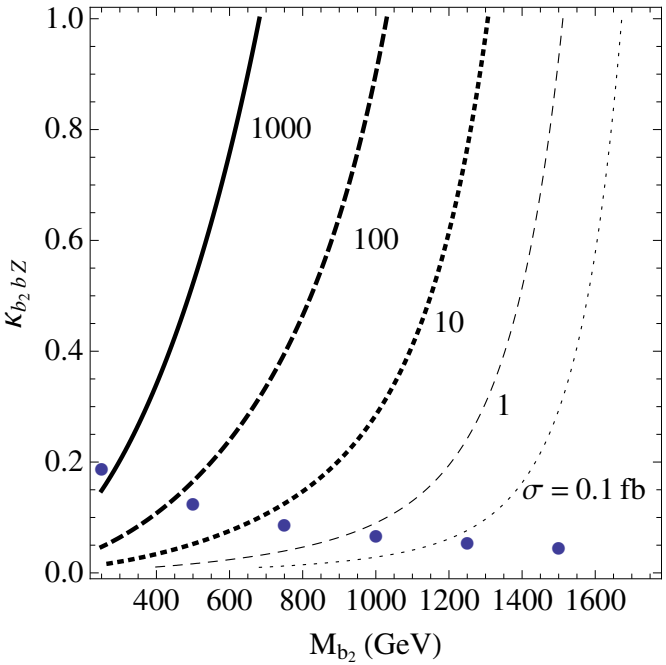


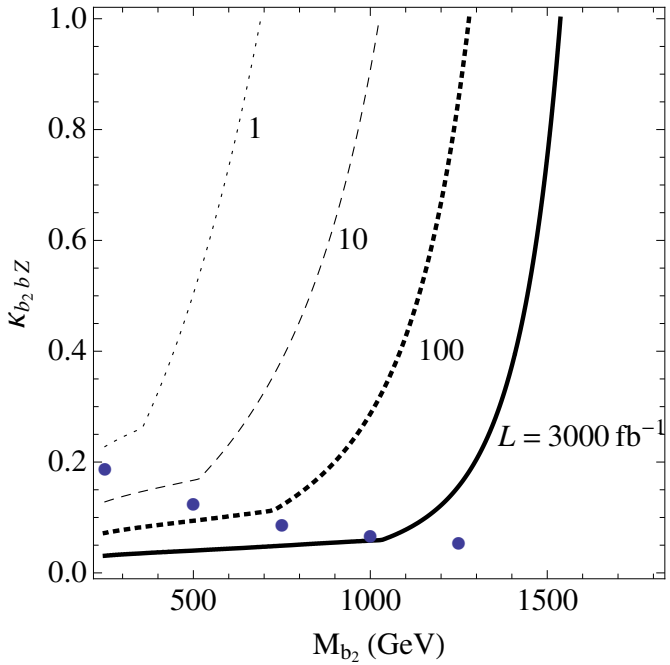
Cuts:

Rapidity: $-2.5 < y_{b,j,Z} < 2.5$,
Transverse momentum: $p_{T\,b,j,Z} > 25$ GeV,
Invariant mass cuts:
$M_Z - 10\ \mathrm{GeV} < M_{jj} < M_Z + 10\ \mathrm{GeV}$,
$0.95 M_{b_2} < M_{(bZ)} < 1.05 M_{b_2}$.

b' Single Production

Single Production : $bg \to b'Z \to bZZ \to bjj\ell\ell$





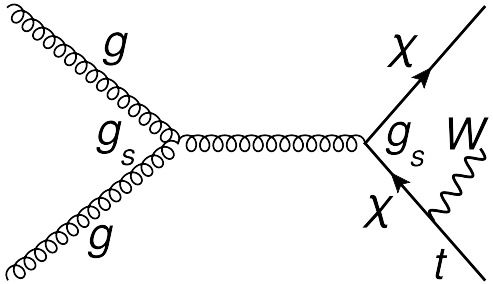
Cuts:

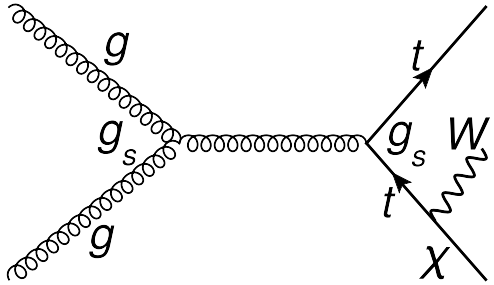
Rapidity: $-2.5 < y_{b,j,Z} < 2.5$,
Transverse momentum: $p_{T\,b,j,Z} > 0.1 M_{b_2}$,
Invariant mass cuts:
$M_Z - 10\ \mathrm{GeV} < M_{jj} < M_Z + 10\ \mathrm{GeV}$,
$0.95 M_{b_2} < M_{(bZ)\ OR\ (bjj)} < 1.05 M_{b_2}$.

χ Phenomenology at the 14TeV LHC

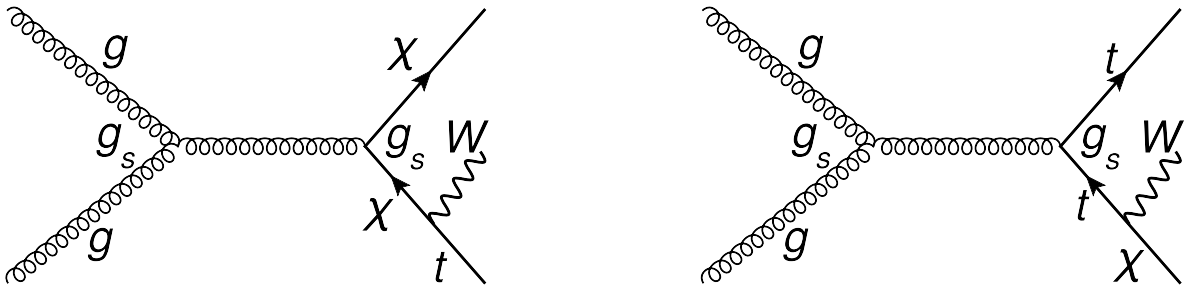
[SG, Mandal, Mitra, Moreau : Work In Progress]

χ Production (Model II, t_R singlet)





χ Production (Model II, t_R singlet)



$$pp \to \chi \bar{t} W^- \to t W^+ \bar{t} W^- \to b W^+ W^+ \bar{b} W^- W^- \to b\bar{b} + 6\, j + 1\, l + \not{E}_T .$$

M_χ (GeV)	cuts	S (fb)	m_h=120 (GeV)		m_h=180 (GeV)	
			BG (fb)	$\mathcal{L}$ (fb^{-1})	BG (fb)	$\mathcal{L}$ (fb^{-1})
750	Basic	187.9	3.257	-	49.96	-
	Disc.	79.69	0.115	1.515	0.473	1.515
1000	Basic	31.36	3.257	-	49.96	-
	Disc.	19.58	0.115	6.164	0.473	6.164
1250	Basic	6.836	3.257	-	49.96	-
	Disc.	4.988	0.115	24.20	0.473	24.20
1500	Basic	1.730	3.257	-	49.96	-
	Disc.	1.387	0.115	87.05	0.473	87.05
1750	Basic	0.476	3.257	-	49.96	-
	Disc.	0.403	0.115	299.5	0.473	878.5

Basic Cuts:

1. $|y(l)| \leq 2.5$
2. $p_T(l) \geq 10$ GeV

Disc. Cuts:

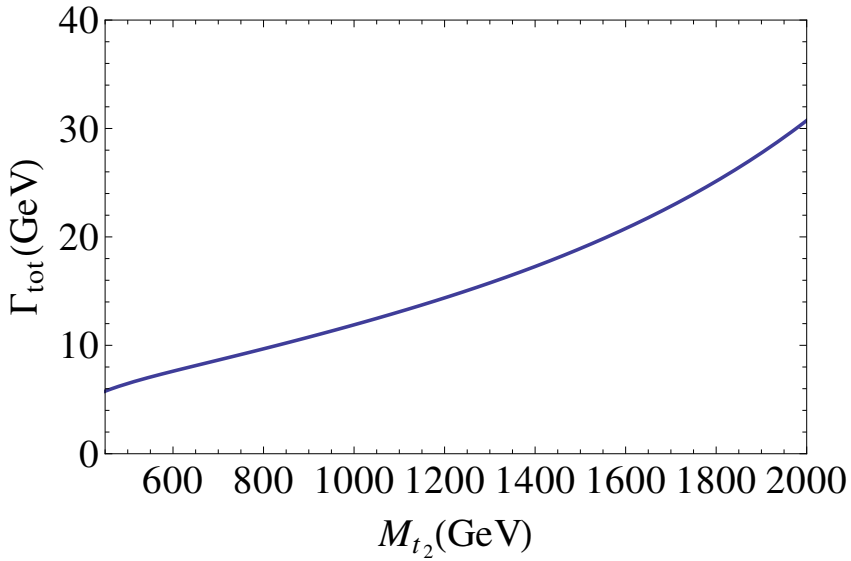
1. $|y(l)| \leq 2.5$
2. $p_T(l) \geq 125$ GeV
3. $p_T(W) \geq 250$ GeV

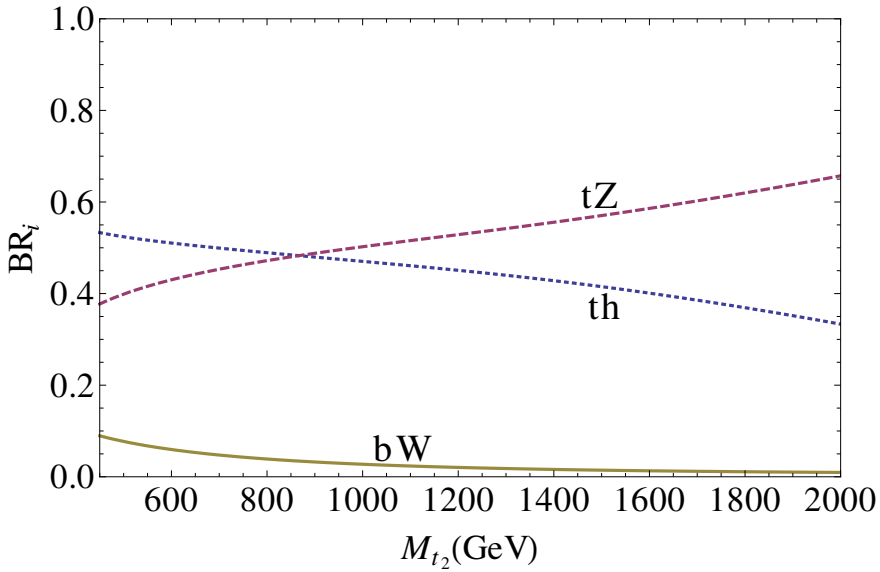
T Phenomenology at the 14TeV LHC

[SG, Mandal, Mitra, Moreau : Work In Progress]

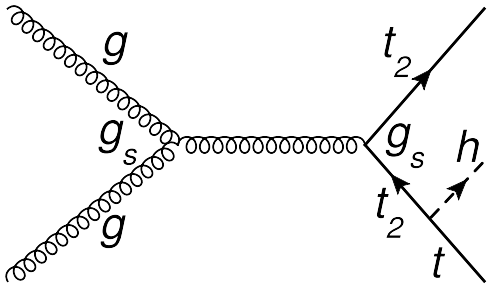
See also: [Harigaya et al., '12] [Giridhar, Mukhopadhyaya, 2012] [Azatov et al., '12]
[Berger, Hubisz, Perelstein, '12] [Cacciapaglia et al., '10, '12]
[CMS-EXO-11-005 $T \to tZ$, $Z \to \ell\ell$: $M_{t_2} \gtrsim 470\,\text{GeV}$ (BR=1)]

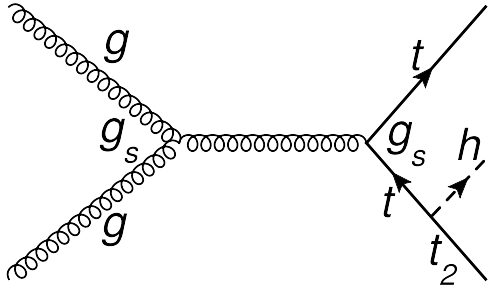
T Decay (Model II, t_R singlet)



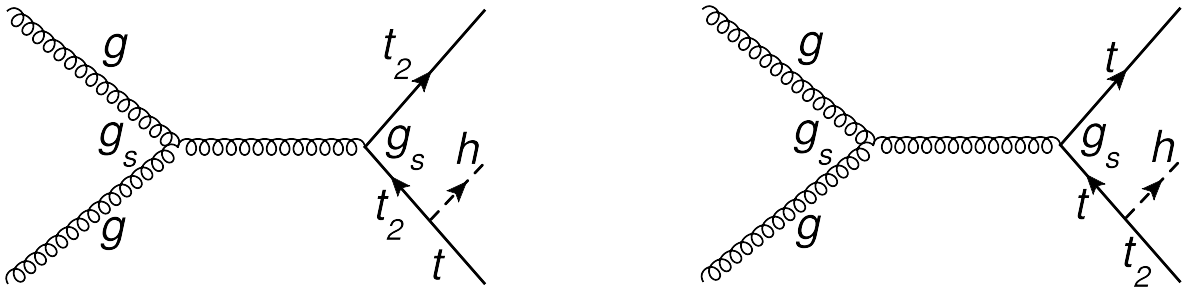


T Production (Model II, t_R singlet)





T Production (Model II, t_R singlet)



$$pp \to t_2\bar{t}h \to (th)\bar{t}h \to bW^+h\bar{b}W^-h \to 6\ b + 4\ j. \quad (1)$$

M_{t_2} (GeV)	cuts	S (fb)	BG (fb)	$\mathcal{L}$ (fb^{-1})
500	Basic	524.4	121.3	-
	Disc.	118.6	0.438	2.817
750	Basic	49.26	121.3	-
	Disc.	28.59	0.438	11.69
1000	Basic	6.511	121.3	-
	Disc.	5.089	0.438	65.66
1250	Basic	0.965	121.3	-
	Disc.	0.833	0.438	526.8

Basic Cuts:

1. $|y(J)| \leq 2.5$
2. $\Delta R(JJ) \geq 0.4$
3. $p_T(J) \geq 25$ GeV

Disc. Cuts:

1. $|y(J)| \leq 2.5$
2. $\Delta R(JJ) \geq 0.4$
3. $p_T^{1st}(J), p_T^{2nd}(J) \geq 175$ GeV and $p_T^{3rd}(J), p_T^{4th}(J) \geq 25$ GeV
4. $|M(J_i, J_j) - m_h| \leq 10$ GeV and $|M(J_k, J_l) - m_h| \leq 10$ GeV

Conclusions

- Vector-like fermions
  - have neutral current (and charged current) decays
  - could be much lighter than V_μ^{KK} in warped models
- Single production will probe EW couplings
  - look for channels sensitive to it
- 14 TeV LHC reach about 1.5 TeV
  - in the channels we analyzed

BACKUP SLIDES

b' Pair Production Details

$pp \to b'\bar{b}' \to bZ\bar{b}Z \to bjj\bar{b}\ell\ell$

M_{b_2} (GeV)	Signal σ_s (in fb)		Background σ_b (in fb)				$\mathcal{L}$ (fb^{-1})
	$bZbZ$		$bZbZ$		$(bjjbZ)_{\rm tot}$		
	y, p_T cuts	All cuts	y, p_T cuts	All cuts	y, p_T cuts	All cuts	
250	25253	25082	21.804	0.3797	16938	29.52	0.021
500	171.34	148.69	21.804	0.047	16938	3.74	3.514
750	14.508	12.221	21.804	0.0097	16938	0.997	42.752
1000	2.314	1.9214	21.804	0.0027	16938	0.259	271.92
1250	0.484	0.399	21.804	0.0011	16938	0.048	1310

M_{b_2} (GeV)	QCD background (in fb)					
	$bjjbZ$		$bbjbZ$		$bbbbZ$	
	y, p_T cuts	All cuts	y, p_T cuts	All cuts	y, p_T cuts	All cuts
250	16790	27.304	255.41	2.7	81.01	1.92
500	16790	3.513	255.41	0.256	81.01	0.194
750	16790	0.958	255.41	0.031	81.01	0.057
1000	16790	0.2514	255.41	0.0052	81.01	0.008

b' Single Production Details

$$pp \to b'Z \to bZZ \to bjj\ell^+\ell^-$$

$M_{b'}$ (GeV)	signal σ_s (in fb)		background σ_b (in fb)				$\mathcal{L}_{\mathrm{SemiLep}}$ (fb^{-1})
	$bjjZ$		$(bjjZ)_{EW}$		$(bjjZ)_{\mathrm{QCD}}$		
	Primary cuts	all cuts	Primary cuts	all cuts	Primary cuts	all cuts	
250	1017.66	995.86	77.03	10.33	7853.02	867.82	0.66
500	16.84	15.50	8.81	0.68	419.75	14.11	45.94
750	1.26	1.14	1.85	0.10	56.26	0.86	551.26
1000	0.14	0.12	0.47	0.01	12.38	0.05	3399.67

$M_{b'}$ (GeV)	QCD background (in fb)		
	$bjjZ$	$bjbZ$	$bbbZ$
250	546.36	634.32	17.19
500	10.14	7.76	0.35
750	0.52	0.66	0.03
1000	0.02	0.06	0.002