Phenomenology of vector-like fermions and new scalars

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Talk Outline

- General aspects of vector-like fermions (VLFs)
- Indirect signatures of VLFs
    - in electroweak precision observables
    - find regions favored by hgg, $h\gamma\gamma$ at the LHC
- New scalars
    - Model independent, Effective model, Little Higgs model
- VLF LHC (Direct) signatures
    - $b'_{(-1/3)}$, $t'_{(2/3)}$, $\chi_{(5/3)}$
    - single and double resonant channels
    - find luminosity required for discovery

Motivation

Vector-like fermions and new scalars are present in many BSM scenarios

- Some examples are
    - Composite Higgs, Little Higgs, top see-saw, extra dimensions, supersymmetric models

Here we will focus on

- Model independent aspects of vector-like fermions & new scalars
- Little Higgs model (as an example)

Vectorlike ψ

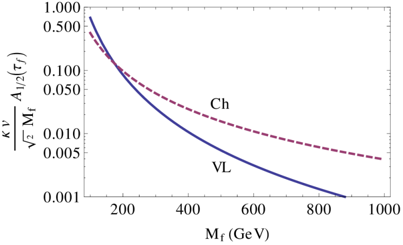
- Theory with Vectorlike fermions:
  - both χ and χ^c present
  - can write vectorlike mass term $\mathcal{L} \supset -M\,\chi\chi^c + h.c.$
    - contrast with SM (chiral theory):

$$q_L = (3,2)_{1/6} \qquad \text{No } (\bar{3},\bar{2})_{-1/6}$$
$$U_R = (3,1)_{+2/3} \qquad \text{No } (\bar{3},1)_{-2/3}$$
$$D_R = (3,1)_{-1/3} \qquad \text{No } (\bar{3},1)_{1/3}$$

- For a VL pair, define a Dirac state $\mathcal{X} \equiv \begin{pmatrix} \chi_\alpha \\ \chi^{c\,\dot{\alpha}} \end{pmatrix}$
  - in terms of which the mass term is: $\mathcal{L} \supset -M\,\bar{\mathcal{X}}\mathcal{X}$
  - Eg: SU(2) doublet $\mathcal{X} \equiv \begin{pmatrix} \mathcal{X}_1 \\ \mathcal{X}_2 \end{pmatrix}$

VL fermions Decoupling

- Independent source of mass M (not given by $m = \lambda v$)
  - Can make M arbitrarily large
    - without hitting Landau pole in Yukawa coupling (4th Gen)
  - M could be related to EW scale (or not)
    - Eg. of connection: ExtraDim Th $M = M_{KK} \sim TeV$, SUSY solutions to μ problem
  - Nice decoupling behavior : S, T, U, $h \to \gamma\gamma$, $gg \to h$, ...
    - For instance $h\gamma\gamma$, ggh couplings



Implications of VL Theory

Vectorlike fermions		Chiral (4-gen) fermions
M allowed by EW symmetry		m only after EWSB $= \lambda \langle H \rangle$
can be arbitrarily heavy		Landau pole in Yukawa coupling λ
CC + NC tree-level decays		only CC tree-level decays
loops decoupling		some loops nondecoupling

VECTOR-LIKE FERMIONS IN ELECTROWEAK PRECISION & HIGGS OBSERVABLES

[S.Ellis, R.Godbole, SG, J.Wells; 1404.4398 [hep-ph], JHEP 09 (2014) 130]

Simple VL extensions of SM

- $1\bar{1}$: $SU(2)$ singlet VL pair
- $2\bar{2}$: $SU(2)$ doublet VL pair
- $2\bar{2} + 1\bar{1}$: MVSM
- $2\bar{2} + 1\bar{1} + 1\bar{1}$: Vector-like extension of the SM (VSM)

$2\bar{2} + 1\bar{1} + 1\bar{1}$: VSM

- $VSM \equiv VLQ\ (\mathcal{X}_Q, \xi_U, \Upsilon_D) \oplus VLL\ (\mathcal{X}_L, \xi_N, \Upsilon_E)$
  - where $\mathcal{X} = (2, Y_\chi)$; $\Upsilon = (1, Y_\chi - 1/2)$; $\xi = (1, Y_\chi + 1/2)$

$$\mathcal{L}_{\rm Yuk} \supset -\lambda_\xi \bar{\mathcal{X}} \cdot H^* \xi - \lambda_\Upsilon \bar{\mathcal{X}} H \Upsilon + h.c.$$

$Y_\chi = \pm Y_{SM}$ assignments:

Y_χ	-1/2	-1/6	1/6	1/2
Q_1, Q_4	0	1/3	2/3	1
Q_2, Q_3	-1	-2/3	-1/3	0

$$\mathcal{L}_{\rm mass} \supset -\begin{pmatrix}\bar{\mathcal{X}}_1 & \bar{\xi}\end{pmatrix}\begin{pmatrix}M_\chi & \tilde{m}\\ \tilde{m} & M_\xi\end{pmatrix}\begin{pmatrix}\mathcal{X}_1\\ \xi\end{pmatrix} - \begin{pmatrix}\bar{\mathcal{X}}_2 & \bar{\Upsilon}\end{pmatrix}\begin{pmatrix}M_\chi & m\\ m & M_\Upsilon\end{pmatrix}\begin{pmatrix}\mathcal{X}_2\\ \Upsilon\end{pmatrix}$$

Diagonalize and obtain W^a_μ, B_μ and h couplings

We assume tiny VL-SM mixing Yukawa terms

Mixing with SM fields?

$$\mathcal{L}_{\rm Yuk} \supset -\lambda'_\xi \bar{Q} \cdot H^* \xi - \lambda'_\Upsilon \bar{Q} H \Upsilon - \lambda'_U \bar{\mathcal{X}} \cdot H^* U - \lambda'_D \bar{\mathcal{X}} H D + h.c.$$

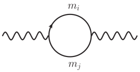
similarly for the VL-leptons

- EWSB $\langle H \rangle = v/\sqrt{2}$ will mix SM $\leftrightarrow$VL fermions
  - Here, take λ' small
    - such that flavor constraints are satisfied
    - $Zb\bar{b}$ coupling is not shifted too much
    - but big enough to have prompt decays
    - no significant effect in Higgs observables

For sizable mixing case, see: [Dawson, Furlan '12] [Aguilar-Saveedra '13] [Fajfer et al. '13] [Dermisek, Raval '13]

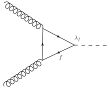
Observables

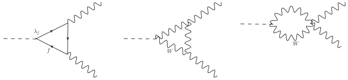
Precision electroweak observables (S, T, U)



Modifications to hgg, $h\gamma\gamma$ couplings:

$\sigma(gg \to h)$ $\Gamma(h \to \gamma\gamma)$



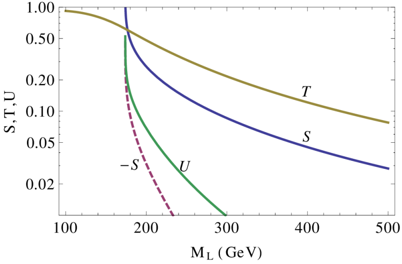


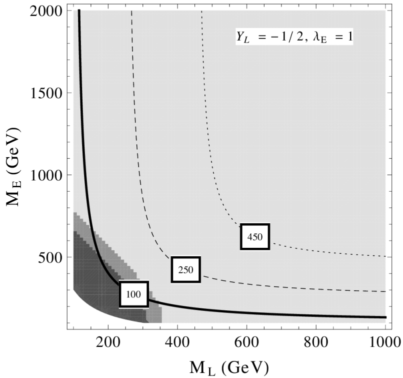
We compute ratios $\frac{\Gamma_{h\to gg}}{SM}$, $\frac{\Gamma_{h\to\gamma\gamma}}{SM}$ using leading-order expressions

QCD corrections to ratios small: [Furlan '11] [Gori, Low '13]

$$\mu^{VBF}_{\gamma\gamma} \approx \frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} \; ; \quad \mu^{ggh}_{ZZ} \approx \frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} \; ; \quad \mu^{ggh}_{\gamma\gamma} \approx \frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} \frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} \; ; \quad \frac{\mu^{ggh}_{\gamma\gamma}}{\mu^{ggh}_{ZZ}} \approx \frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} \approx \mu^{VBF}_{\gamma\gamma}$$

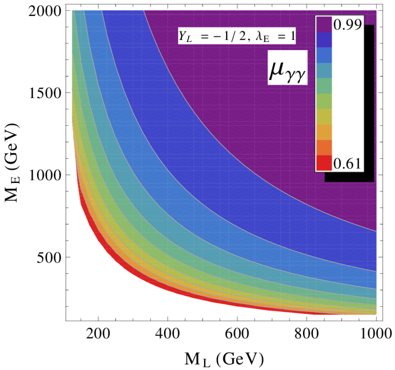
$2\bar{2} + 1\bar{1}$: MVLE



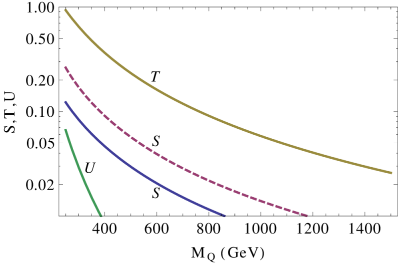


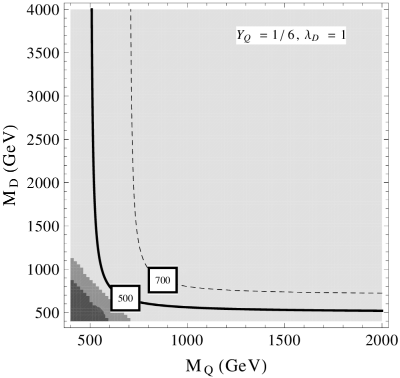
$\lambda_E = 1,\ M_E = M_L,\ Y_L = (-1/2, 1/2)$ (solid,dashed)

$2\bar{2} + 1\bar{1}$: MVLE



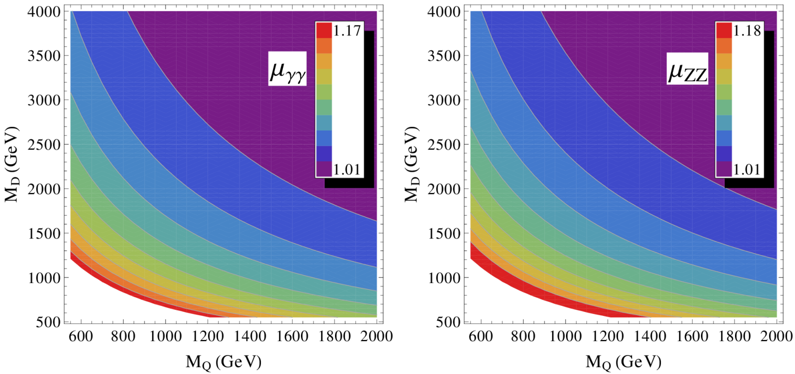
$2\bar{2} + 1\bar{1}$: MVQD



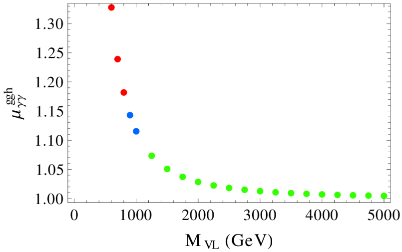


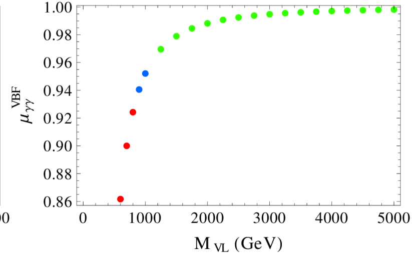
$\lambda_D = 1,\ M_D = M_Q,\ Y_Q = (1/6, -1/6)$ (solid, dashed)

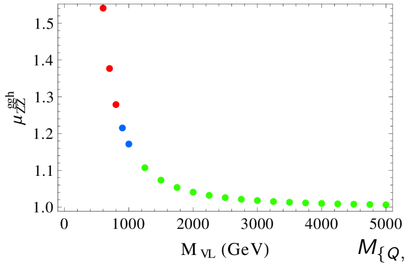
$2\bar{2} + 1\bar{1}$: MVQD



$2\bar{2} + 1\bar{1} + 1\bar{1}$: VSM



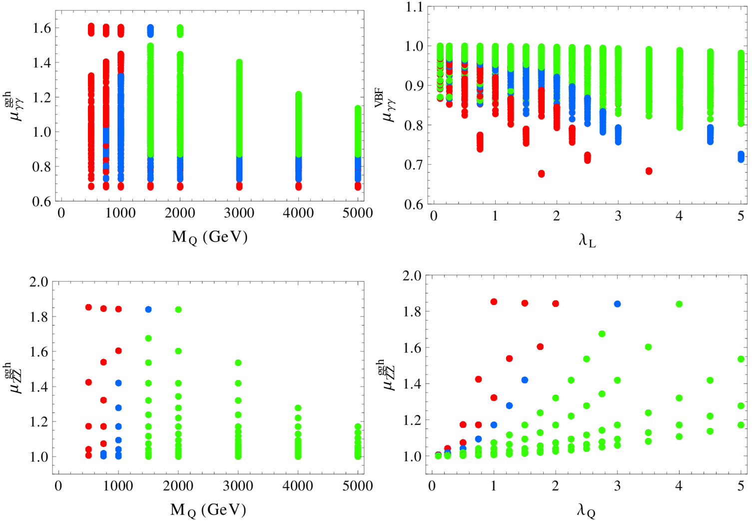




Category	M_q(Gev)	M_ℓ (GeV)	Color
Light	≤ 700	≤ 450	Red
Medium	(700, 1000)	(450, 750)	Blue
Heavy	> 1000	> 750	Green

$$M_{\{Q,U,D,L,E,N\}} = M_{VL},\ Y_Q = 1/6\ ,\ Y_L = -1/2$$

$2\bar{2} + 1\bar{1} + 1\bar{1}$: VSM



$M_Q = M_U = M_D, \quad M_L = M_E = M_N, \quad \lambda_U = \lambda_D \equiv \lambda_Q, \quad \lambda_E = \lambda_N \equiv \lambda_L, \quad Y_Q = 1/6, \quad Y_L = -1/2$

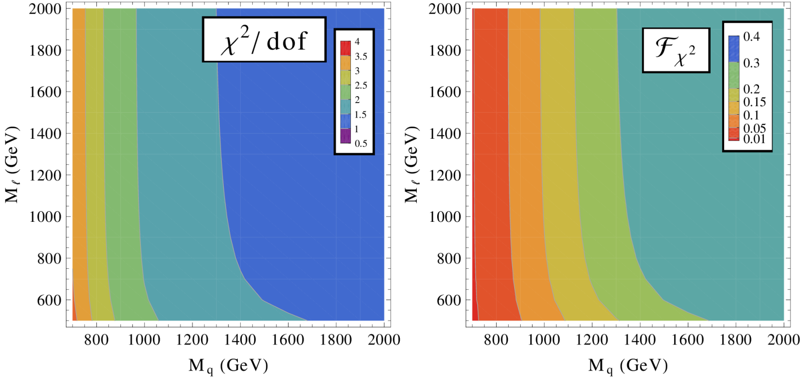
χ^2 fit to the LHC Data

[ATLAS arXiv:1307.1427] [CMS-PAS-HIG-13-005, 2013]

Coupling	ATLAS	CMS
κ_g	1.04 ± 0.14	0.83 ± 0.11
κ_γ	1.2 ± 0.15	0.97 ± 0.18

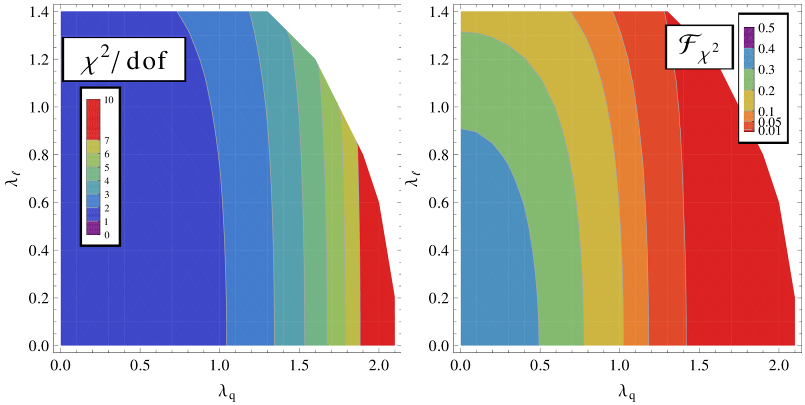
$$\chi^2 = \sum_{i=1}^{4} \left(\kappa_i^{\rm Exp} - \kappa_i^{\rm Th}\right)^2 / \left(\sigma_i^{\rm Exp}\right)^2$$

$2\bar{2} + 1\bar{1} + 1\bar{1}$: VSM χ^2 fit



$$Y_Q = 1/6,\ Y_L = -1/2, \lambda_q = 1, \lambda_\ell = 1$$

$2\bar{2} + 1\bar{1} + 1\bar{1}$: VSM χ^2 fit

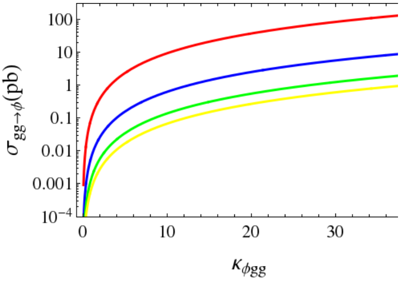


$Y_Q = 1/6, Y_L = -1/2, M_q = 1000\ GeV, M_\ell = 500\ GeV$

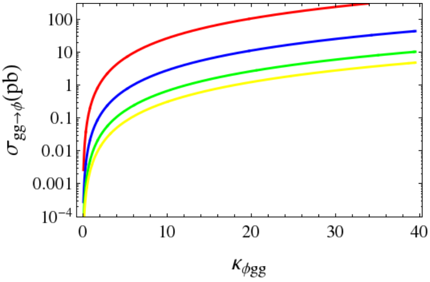
ASPECTS OF NEW SCALARS (IN 2HDM)

[In progress: SG, T. Mukherjee, S. Sadhukhan] $\oplus$ [arXiv:1504.01074]

$\sigma(gg \to \phi)$ at 8, 14 TeV LHC



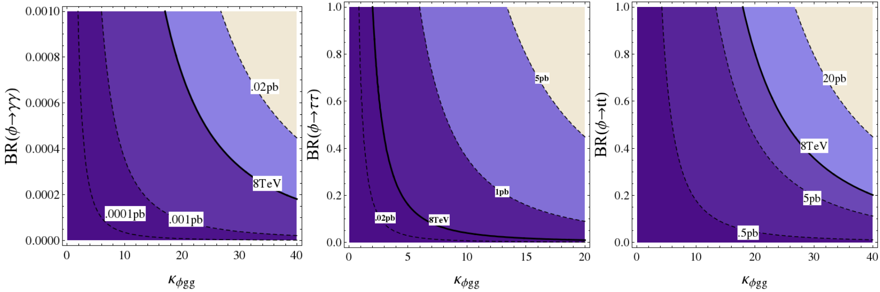
8 TeV



14 TeV

m_ϕ =200 GeV (red), 500 GeV (blue), 800 GeV (green), 1000 GeV (yellow)

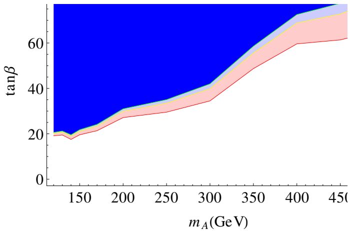
14 TeV LHC $\sigma * BR$



for $M_\phi = 500$ GeV (Thick black line: 8 TeV exclusion)

Effective Model: 2HDM-II + VLF

- $SU(2)$ doublet ψ + singlet ξ
  - Eg: $\mathcal{L} \supset y_1 \bar{\psi}_L \Phi_1^c \xi_R + \tilde{y}_1 \bar{\psi}_R \Phi_2 \xi_L + h.c.$



Exclusion from $A \to \tau\tau$

for $y_1 = \tilde{y}_1 = 1$;

$M_\psi = M_\xi = 700, 1000$ GeV

- VLF opens up more 2HDM-II parameter space

Little Higgs Model

[In progress: SG, T. Mukherjee, S. Sadhukhan]

Implement collective symmetry breaking

- Higgs is a pseudo Goldstone boson
- no Λ^2 divergent contribution at 1-loop
  - Gauge sector & Yukawa couplings specially constructed

A case study: Low, Skiba, Smith, 2002 : $SU(6)/Sp(6)$

- Coset: $35 - 21 = 14$ $\rightarrow$PNGB (Higgs included)
- Gauge sector: $SU(2)_1 \otimes SU(2)_2 \rightarrow SU(2)$
- Vector-like fermions
  - SU(2) doublet: $Q' = \begin{pmatrix} t' \\ b' \end{pmatrix}$; SU(2) singlets: ψ'_t, ψ'_b
- Higgs sector is a 2HDM

$$V \supset m_1^2 \left|\phi_1\right|^2 + m_2^2 \left|\phi_2\right|^2 + \left(b^2 \phi_1^T \cdot \phi_2 + h.c.\right) + \lambda'_5 \left|\phi_1^T \cdot \phi_2\right|^2$$

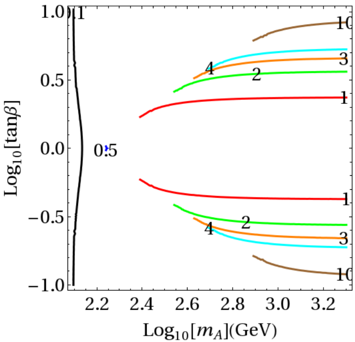
$SU(6)/Sp(6)$ Little Higgs with 2HDM structure

Scalars are: h, H, A, $H^{\pm}$; We focus on neutral scalars

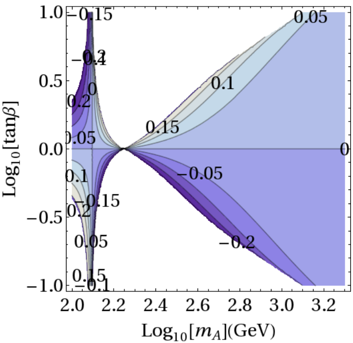
- Seek hWW, hZZ SM like
  - Alignment limit: $\cos(\beta - \alpha) \approx \frac{\pi}{2}$; [Gunion, Haber, 2002]
    - HWW, HZZ $\approx$ zero!
- Also seek htt SM like
- AWW, AZZ are zero at tree-level : $\mathcal{CP}$ inv

$$\langle \phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}; \quad \langle \phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_2 \\ 0 \end{pmatrix}; \quad \tan\beta = \frac{v_1}{v_2}$$

Constrain m_h =125 GeV

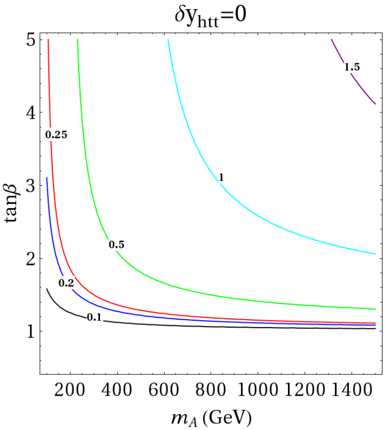


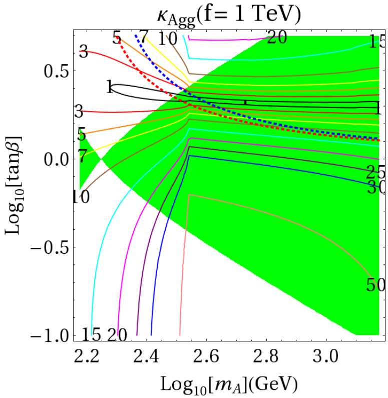
λ_5'



$\cos(\beta - \alpha)$

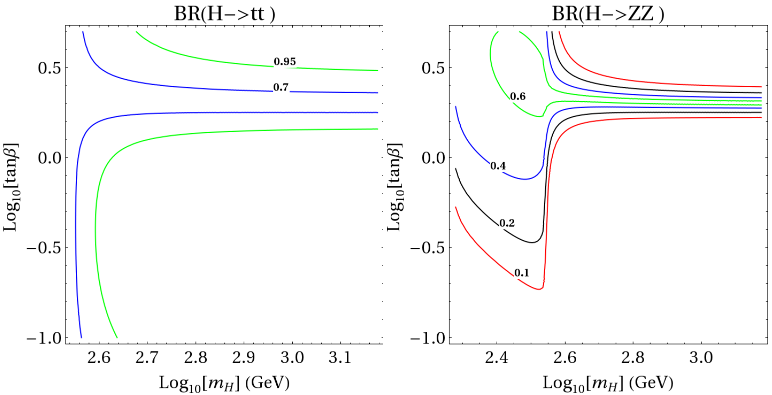
(preliminary plots)





y_2 (Yukawa) κ_{Agg}

(preliminary plots)



Relax alignment limit to $\cos(\beta - \alpha) = 0.1$

(preliminary plots)

DIRECT PRODUCTION OF t', b', $\chi_{5/3}$ VECTORLIKE FERMIONS AT THE LHC

Model independent analysis.

Benchmark points from *Warped extra dimensions*

[SG, T.Mandal, S.Mitra, R.Tibrewala, arXiv:1107.4306, PRD84 (2011) 055001]
[SG, T.Mandal, S.Mitra, G.Moreau : arXiv:1306.2656, JHEP 1408 (2014) 079]

See Also: [SG, Moreau, Singh, '10]
[Dennis et al, '07] [Carena et al, '07] [Contino, Servant, '08]
[Atre et al, '08, '09, '11] [Han et al. '10] [Aguilar-Saavedra, '09] [Mrazek, Wulzer, '09]
[SG, Moreau, Singh, '10][Bini et al. '12][Buchkremer et al. '13]

Decay Modes of t', b', χ

EWSB induced mixing $\implies$ Tree-level NC Couplings

- as usual will have $t'_L b_L W^\pm$ and $b'_L t_L W^\pm$ CC couplings
- also, from Yukawa coupling $\langle \Sigma \rangle = v \implies t \leftrightarrow t'$, $b \leftrightarrow b'$ mixing

$$\mathcal{L} \supset \begin{pmatrix} b & b' \end{pmatrix} \gamma^\mu \begin{pmatrix} g_Z & 0 \\ 0 & g'_Z \end{pmatrix} \begin{pmatrix} b \\ b' \end{pmatrix}_{L,R} Z_\mu + \begin{pmatrix} b_L & b'_L \end{pmatrix} \begin{pmatrix} m_b & 0 \\ \tilde{m}_b & M_{b'} \end{pmatrix} \begin{pmatrix} b_R \\ b'_R \end{pmatrix} + h.c.$$

- Diagonalize to go to mass basis
  - $v \to v(1 + h/v)$ leads to $b'bh$ coupling
  - $g_Z \neq g'_Z$ leads to $b'bZ$ coupling
  - Similarly $t'tZ$, $t'th$ couplings also, in addition to $t'bW$

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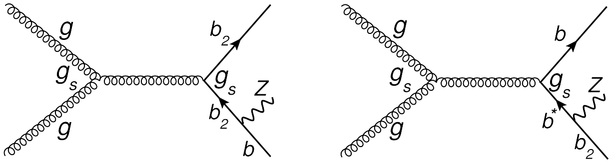
- Diagonalize to go to mass basis
  - $v \to v(1 + h/v)$ leads to $b'bh$ coupling
  - $g_Z \neq g'_Z$ leads to $b'bZ$ coupling
  - Similarly $t'tZ$, $t'th$ couplings also, in addition to $t'bW$
- VL Tree-level Decays
  - $b' \to tW$, $b' \to bZ$, $b' \to bh$
  - $t' \to bW$, $t' \to tZ$, $t' \to th$
  - $\chi \to tW$

b' Phenomenology at the LHC

[SG, T.Mandal, S.Mitra, R.Tibrewala, arXiv:1107.4306, PRD84 (2011) 055001]
[SG, T.Mandal, S.Mitra, G.Moreau : arXiv:1306.2656, JHEP 1408 (2014) 079]

See Also: [Contino, Servant '08][Mrazek, Wulzer '10]

b' Single & Double Resonant channels

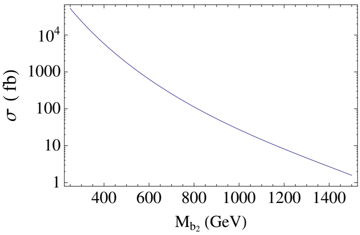


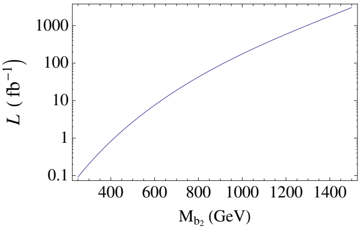
... followed by $b_2 \to bZ$

- Both b_2 on-shell : **Double Resonant (DR) channel**
- Only one b_2 on-shell : **Single Resonant (SR) channel**
  - $|M(bZ) - M_{b_2}| \geq \alpha_{cut} M_{b_2}; \quad \alpha_{cut} = 0.05$

b' Double Resonant

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



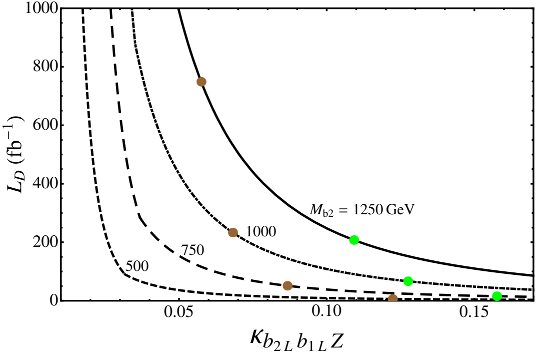


Cuts:

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 Resonant - I

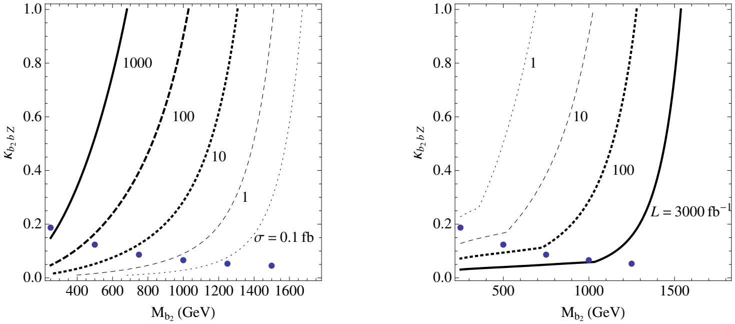
Single Resonant : $bg \to b'bZ \to bZbZ \to bbJJ\ell\ell$
Model Independent LHC-14 reach



Brown dots : DT Model   Green dots : TT Model

b' Single Production - II

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



Cuts:

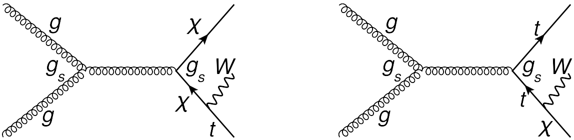
Rapidity: $-2.5 < y_{b,j,Z} < 2.5$,
Transverse momentum: $p_{T\,b,j,Z} > 0.1 M_{b_2}$,
Invariant mass cuts:
$M_Z - 10$ GeV $< M_{jj} < M_Z + 10$ GeV,
$0.95 M_{b_2} < M_{(bZ)\ OR\ (bjj)} < 1.05 M_{b_2}$.

χ Phenomenology at the LHC

[SG, T.Mandal, S.Mitra, G.Moreau : arXiv:1306.2656, JHEP 1408 (2014) 079]

[Contino, Servant '08][Mrazek, Wulzer '10][Cacciapaglia et al. '12]

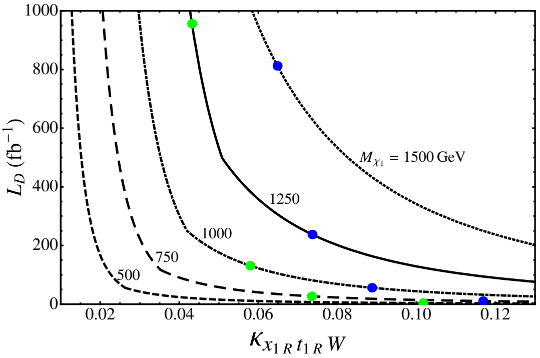
χ Double and Single Resonant channels



$$pp \to \chi tW \to tWtW \to tWt\ell\nu$$

X	M_χ (GeV)	σ_{tot} (fb)	σ_{SR} (fb)	cuts	S (fb)	BG (fb)	$\mathcal{L}$ (fb^{-1})
X_1	500	2406	261.5	Basic	977.5	3.257	-
				Disc.	146.1	0.115	0.826
X_2	750	235.5	29.31	Basic	99.99	3.257	-
				Disc.	42.74	0.115	2.824
X_3	1000	39.19	5.198	Basic	17.92	3.257	-
				Disc.	11.36	0.115	10.63
X_4	1250	8.576	1.231	Basic	4.305	3.257	-
				Disc.	3.226	0.115	37.42
X_5	1500	2.188	0.364	Basic	1.235	3.257	-
				Disc.	1.010	0.115	119.5
X_6	1750	0.613	0.121	Basic	0.393	3.257	-
				Disc.	0.339	0.115	355.8

χ Single Resonant Channel



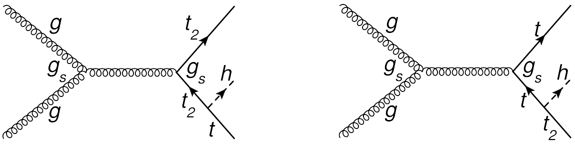
Blue Dots - ST Model Green Dots - TT Model

t' Phenomenology at the LHC

[SG, T. Mandal, S. Mitra, G. Moreau : arXiv:1306.2656, JHEP 1408 (2014) 079]

See also: [Harigaya et al., '12] [Giridhar, Mukhopadhyaya, 2012] [Azatov et al., '12] [Berger, Hubisz, Perelstein, '12] [Cacciapaglia et al., '10, '12] [Aguilar-Saavedra et al. '05]

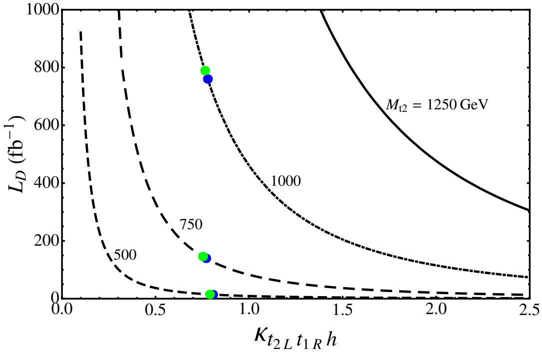
t' Double and Single Resonant channels



$$pp \rightarrow t_2 th \rightarrow thth \rightarrow tbbtbb \rightarrow 6\ b\ 4\ j \qquad \text{(4 b-tags)}$$

T	M_{t_2} (GeV)	σ_{tot} (fb)	σ_{SR} (fb)	cuts	S (fb)	BG (fb)	$\mathcal{L}$ (fb^{-1})
T_1	500	1207	223.0	Basic	237.4	102.7	-
				Disc.	52.38	0.389	6.379
T_2	750	115.2	18.30	Basic	22.67	102.7	-
				Disc.	13.25	0.389	25.22
T_3	1000	18.38	2.715	Basic	3.088	102.7	-
				Disc.	2.421	0.389	138.0
T_4	1250	3.821	0.590	Basic	0.477	102.7	-
				Disc.	0.415	0.389	1889.2

t' Single Resonant channel



Blue Dots - ST Model Green Dots - TT Model

Conclusions

- Many BSM extensions include vector-like fermions and new scalars
- Indirect probes
  - hgg, $h\gamma\gamma$ couplings may show deviations in the future
    - if no deviation, constraint on parameter space
- Analyzed model-independent, effective model, little Higgs model
- Direct LHC signatures
  - Identified promising Double Resonant and Single Resonant channels
    - Single Resonant channels can probe EW couplings
  - 8 TeV LHC limits on vector-like quarks around 750 GeV

BACKUP SLIDES

BACKUP SLIDES

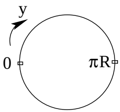
Warped Model

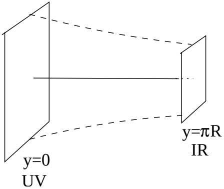
SM in background 5D warped AdS space [Randall, Sundrum '99]

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

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:

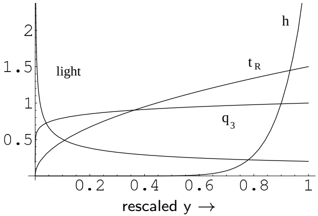
- IR localized Higgs : $M_{EW} \sim ke^{-k\pi R}$: Choose $k\pi R \sim 34$
  - Gauge-theory dual is a composite Higgs model

Explaining SM mass hierarchy

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

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

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



FCNC largely under control, but still strong constraints

AdS/CFT Correspondence

AdS/CFT Correspondence [Maldacena, 1997]

- A classical supergravity theory in $AdS_5 \times S_5$ at weak coupling is **dual** to a 4D large-N CFT at strong coupling
- The CFT is at the boundary of AdS [Witten 1998; Gubser, Klebanov, Polyakov 1998]

$$Z_{CFT}[\phi_0] = e^{-\Gamma_{AdS}[\phi_0]}$$

$\mathcal{L} \supset \int d^4x\, \mathcal{O}_{CFT}(x)\, \phi_0(x)$ Eg: $\langle \mathcal{O}(x_1)\, \mathcal{O}(x_2) \rangle = \frac{\delta^2 Z_{CFT}[\phi_0]}{\delta\phi_0(x_1)\delta(x_2)}$ with Z_{CFT} given by the RHS	$\Gamma_{AdS}[\phi]$ supergravity eff. action $\phi(y,x)$ is a solution of the EOM ($\delta\Gamma = 0$) for given bndry value $\phi_0(x) = \phi(y = y_0, x)$

4D Duals of Warped Models

[Arkani-Hamed, Porrati, Randall, 2000; Rattazzi, Zaffaroni, 2001]

- Dual of Randall-Sundrum model **RS1 (SM on IR Brane)**
  - Planck brane $\Longrightarrow$ UV Cutoff; Dynamical gravity in the 4D CFT
  - TeV (IR) brane $\Longrightarrow$ IR Cutoff; Conformal invariance broken below a TeV
    - All SM fields are composites of the CFT
- Dual of Warped Models with **Bulk SM**
  - UV localized fields are elementary
  - IR localized fields (Higgs) are composite
    - 4D dual is Composite Higgs model [Georgi, Kaplan 1984]
    - Shares many features with Walking Extended Technicolor
  - Partial Compositeness
    - AdS dual is weakly coupled and hence calculable!
  - KK states are dual to composite resonances

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: $A|_{y=0} = 0\,;\;\; \partial_y A\,|_{y=\pi R} = 0$
    - $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$
  - By VEV of IR localized Higgs — Higgs $\Sigma = (2,2)_0$
    - $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

Warped Fermions

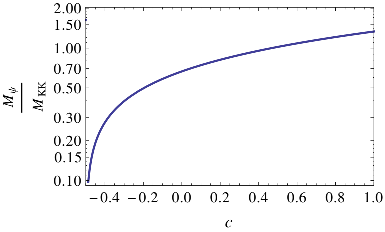
- SM fermions : $(+,+)$ BC $\to$ zero-mode
- "Exotic" fermions : $(-,+)$ BC $\to$ No zero-mode
  - 1^{st} KK vectorlike fermion

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

  c : Fermion bulk mass parameter

  [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 : '13]

Fermion rep : $Zb\bar{b}$ not protected (DT model)

[Agashe, Delgado, May, Sundrum '03]

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

Fermion rep : $Zb\bar{b}$ protected (ST & TT models)

- $Q_L = (2,2)_{2/3} = \begin{pmatrix} t_L & \chi \\ b_L & T \end{pmatrix}$ [Agashe, Contino, DaRold, Pomarol '06]
  - $Zb_L\overline{b_L}$ protected by custodial $SU(2)_{L+R} \otimes P_{LR}$ invariance
    $Wt_L b_L$, $Zt_L t_L$ not protected, so shifts

Fermion rep : $Zb\bar{b}$ protected (ST & TT models)

- $Q_L = (2,2)_{2/3} = \begin{pmatrix} t_L & \chi \\ b_L & T \end{pmatrix}$ [Agashe, Contino, DaRold, Pomarol '06]
  - $Zb_L\overline{b_L}$ protected by custodial $SU(2)_{L+R} \otimes P_{LR}$ invariance
    $Wt_L b_L$, $Zt_L t_L$ not protected, so shifts

Two t_R possibilities:

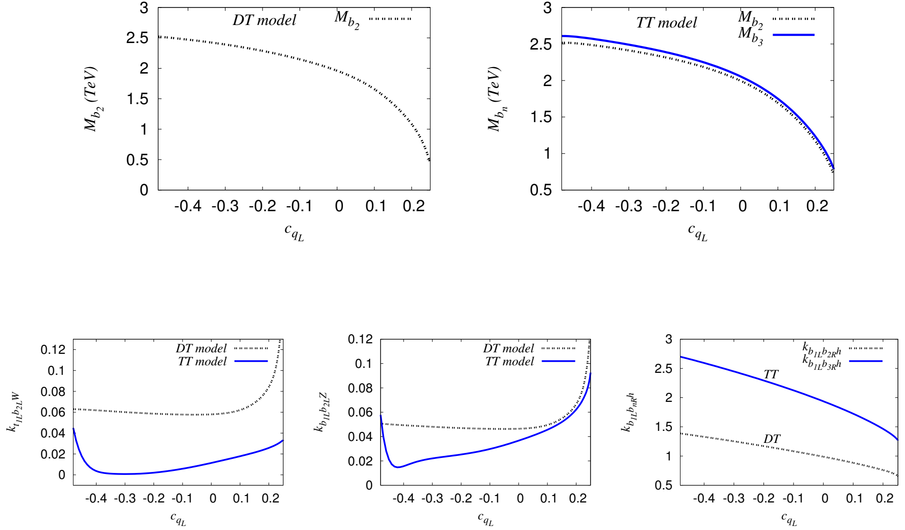
1. Singlet t_R (ST Model) : $(1,1)_{2/3} = t_R$ New ψ_{VL} : χ, T
2. Triplet t_R (TT Model) :
   $$(1,3)_{2/3} \oplus (3,1)_{2/3} = \psi'_{t_R} \oplus \psi''_{t_R} = \begin{pmatrix} \frac{t_R}{\sqrt{2}} & \chi' \\ b' & -\frac{t_R}{\sqrt{2}} \end{pmatrix} \oplus \begin{pmatrix} \frac{t''}{\sqrt{2}} & \chi'' \\ b'' & -\frac{t''}{\sqrt{2}} \end{pmatrix}$$
   New ψ_{VL} : χ, T, χ', b', χ'', t'', b''

Yukawa Couplings

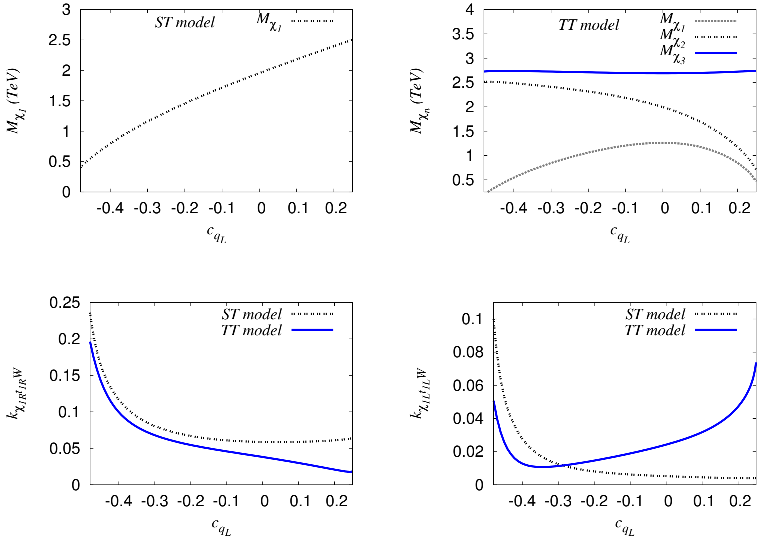
Yukawa Couplings

- No $Zb\bar{b}$ protection
  $$\mathcal{L}_{\mathrm{Yuk}} \supset \lambda_t \; \bar{Q}_L \Sigma \psi_{t_R} + \lambda_b \; \bar{Q}_L \Sigma \psi_{b_R} + h.c.$$
- With $Zb\bar{b}$ protection
  - ST Model $\quad \mathcal{L}_{\mathrm{Yuk}} \supset \lambda_t \; \mathrm{Tr}[\bar{Q}_L \Sigma] \; t_R + h.c.$
  - TT Model $\quad \mathcal{L}_{\mathrm{Yuk}} \supset \lambda_t \mathrm{Tr}\left[\bar{Q}_L \Sigma \psi'_{t_R}\right] + \lambda'_t \mathrm{Tr}\left[\bar{Q}_L \Sigma \psi''_{t_R}\right] + h.c.$

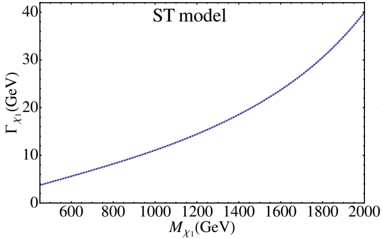
Warped model b' parameters

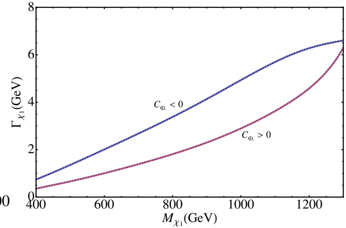


Warped model χ parameters



Warped model Γ_χ

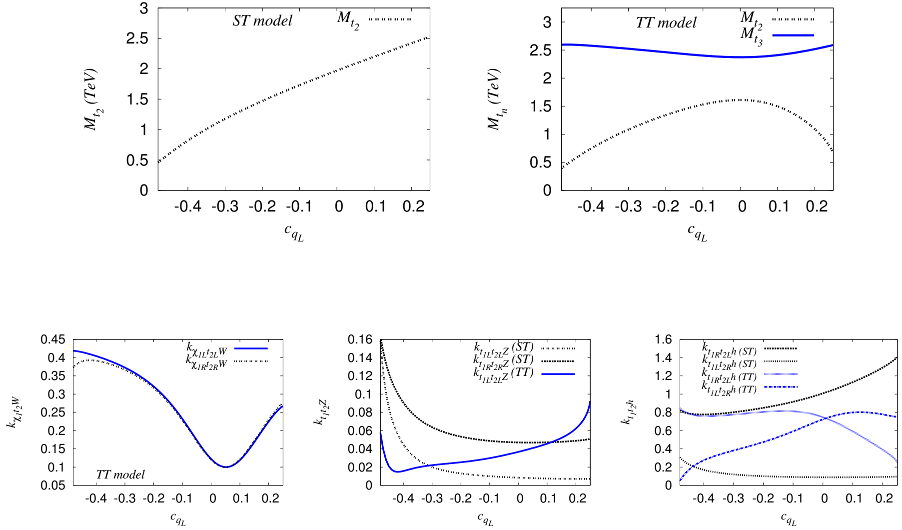




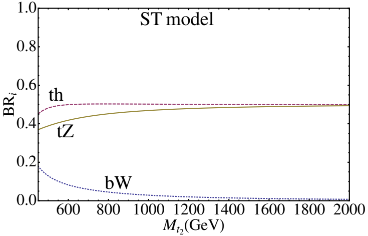
ST Model

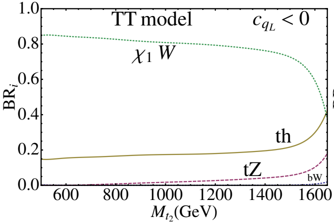
TT Model

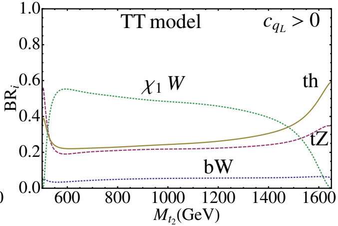
Warped model t' parameters



Warped model t' BR







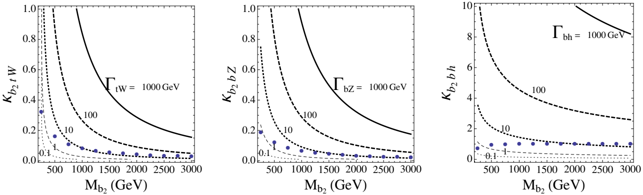
b' Pair Production Details

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

M_{b_2} (GeV)	Signal σ_s (in fb) $bZbZ$		Background σ_b (in fb) $bZbZ$		$(bjjbZ)_{\rm tot}$		$\mathcal{L}$ (fb^{-1})
	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' Signature (Model Independent)

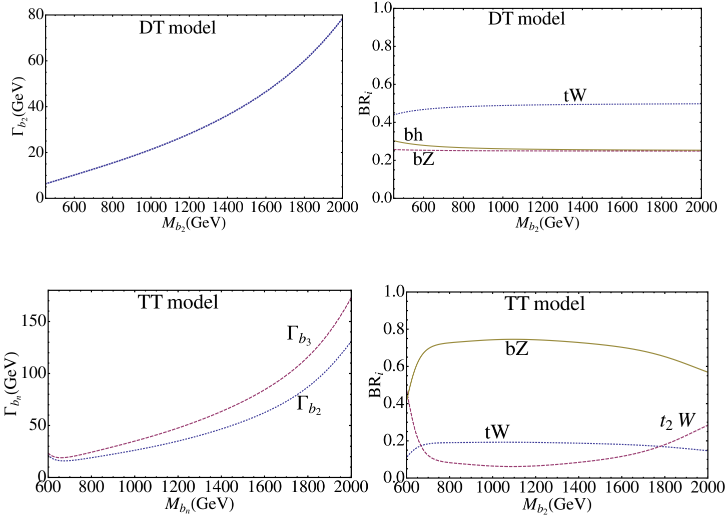


Benchmark Points (Model I):

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

Warped model b' : Γ and BR



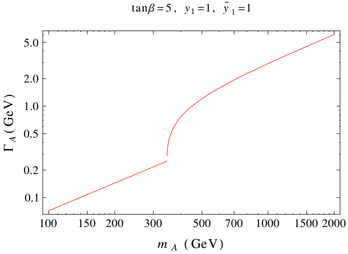
b' Single Resonant II Details

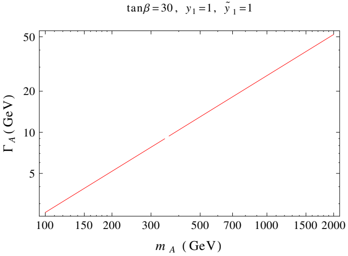
$$pp \to b'Z \to bZZ \to bjj\ell^+\ell^-$$

$M_{b'}$ (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

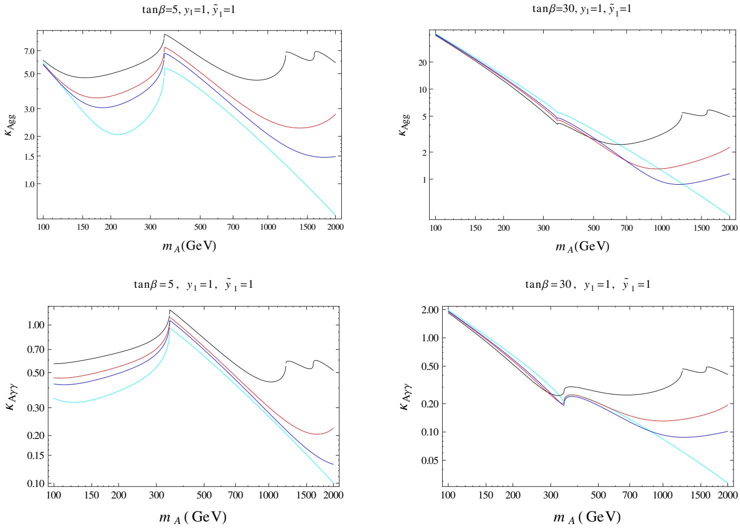
$M_{b'}$ (GeV)	QCD background (in fb)		
	$bjjZ$	$bjbZ$	$bbbZ$
250	546.36	634.32	17.19
500	10.14	7.76	0.35
750	0.52	0.66	0.03
1000	0.02	0.06	0.002

Model: 2HDM-II + VLF





Model: 2HDM-II + VLF



$M_{\psi,\xi}$ = 700, 1200, 1700 GeV (& 2HDM-II)