Current Status of Vector-like Fermions

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Talk Outline

- General aspects of vector-like fermions (VLFs)
- BSM scalars and VLFs
  - Model independent, 2HDM, Little Higgs, Singlet model
- Indirect signatures of VLFs
  - in EW precision obs.; hgg, $h\gamma\gamma$ shifts at the LHC
- VLF LHC (Direct) signatures
  - $b'_{(-1/3)}$, $t'_{(2/3)}$, $\chi_{(5/3)}$
  - Recent LHC limits
- VLF Dark Matter

Motivation

Vector-like fermions are present in many BSM scenarios

- extra dimensions, composite Higgs, little Higgs, top see-saw, ...

Here we will consider

- some example effective models of vector-like fermions (VLF)

Vectorlike ψ

- Theory with fermions vectorlike under $SU(3)$, $SU(2)$, $U(1)$:
  - χ (rep) and χ^c (conjugate rep) both present
  - can write vectorlike mass term $\mathcal{L} \supset -M\, \chi\chi^c + h.c.$

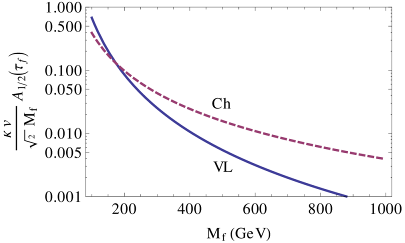
[contrast with SM (chiral theory): Higgs VEV needed to get fermion masses]

- M could be related to EW scale (or not)
  - Eg. of connection to EW scale:
    extraDim $M = M_{KK} \sim TeV$, composite Higgs $M = M_{comp} \sim TeV$

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

- Nice decoupling behavior : $S, T, U, h \to \gamma\gamma, gg \to h, \ldots$
    - For instance $h\gamma\gamma$, ggh couplings



$2\bar{2} + 1\bar{1} + 1\bar{1}$: VL extn. of SM (VSM)

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

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

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

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

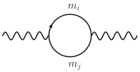
$$\mathcal{L}_{\rm mass} \supset -\begin{pmatrix}\bar{\mathcal{X}}_1 & \bar{\xi}\end{pmatrix}\begin{pmatrix}M_\chi & \tilde{m} \\ \tilde{m} & M_\xi\end{pmatrix}\begin{pmatrix}\mathcal{X}_1 \\ \xi\end{pmatrix} - \begin{pmatrix}\bar{\mathcal{X}}_2 & \bar{\Upsilon}\end{pmatrix}\begin{pmatrix}M_\chi & m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

Diagonalize and obtain W_μ^a, B_μ and h couplings

We assume tiny VL-SM mixing Yukawa terms

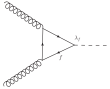
Observables

Precision electroweak observables (S, T, U)

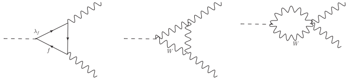


Modifications to hgg, $h\gamma\gamma$ couplings:

$\sigma(gg \to h)$



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

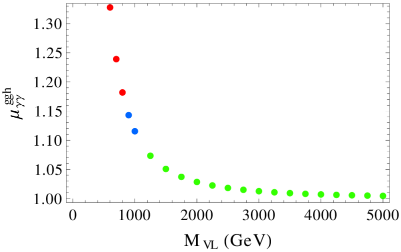


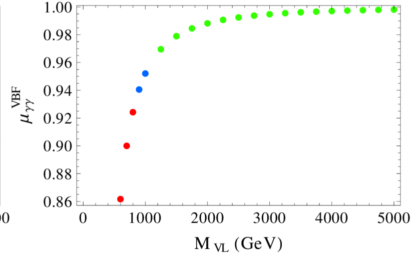
We compute ratios $\frac{\Gamma_{h\to gg}}{SM}$, $\frac{\Gamma_{h\to\gamma\gamma}}{SM}$ using leading-order expressions

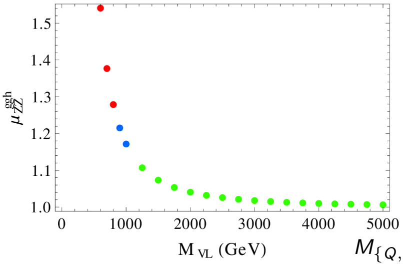
QCD corrections to ratios small: [Furlan '11] [Gori, Low '13]

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

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



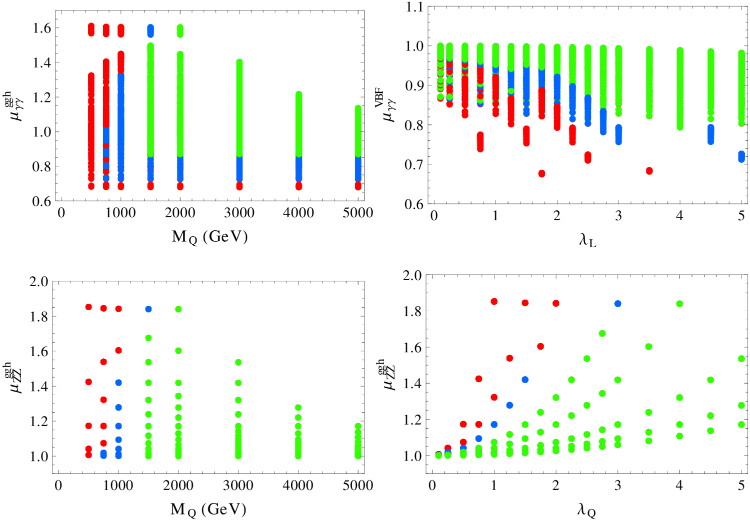




Category	M_q(Gev)	M_ℓ (GeV)	Color
Light	≤ 700	≤ 450	Red
Medium	$(700, 1000)$	$(450, 750)$	Blue
Heavy	> 1000	> 750	Green

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

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



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

Effective Model: 2HDM-II + VLQ

[SG, T. Mukherjee, S. Sadhukhan: PRD 93, 055004 (2016)]

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

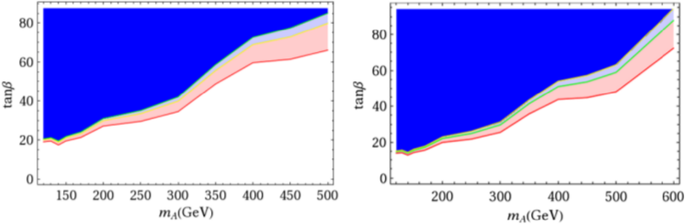


FIG. 26. For the $MVQU_{12}$ model, regions of the m_A- $\tan\beta$ parameter space excluded at the 95% C.L. from $\phi \to \tau^+\tau^-$ decay when only A is present (left), and when A and H are degenerate and both present (right), with $y_1 = \tilde{y}_1 = 1$, $M_\psi = M_\chi =$ 800 GeV (dark blue region), 1000 GeV (light blue and dark blue regions). All shaded regions are excluded in the 2HDM-II.

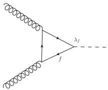
Singlet scalar and VLFs

[SG, T. Mukherjee: In progress]

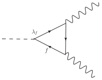
Add $SU(2)$ singlets: Φ (scalar), ψ (VLL), U (VLQ)

$$\mathcal{L}_{mass} \supset -M_h^2 H^\dagger H - M_\phi^2 \Phi^\dagger \Phi - M_\psi \bar{\psi}\psi - M_U \bar{U} U$$

$$\mathcal{L}_{int} \supset -\kappa \Phi^\dagger \Phi H^\dagger H - \frac{\mu}{\sqrt{2}} \hat{\phi} H^\dagger H - \frac{y_\psi}{\sqrt{2}} \hat{\phi} \bar{\psi}\psi - \frac{y_U}{\sqrt{2}} \hat{\phi} \bar{U} U$$



- ϕgg coupling due to VLQ
  - $gg \to \phi$ at the LHC (singlet production)



- $\phi\gamma\gamma$ coupling due to VLQ
  - $\phi \to \gamma\gamma$ signal at the LHC (singlet detection)
- If $Q_\psi = 0$, ψ can be dark matter
  - Relic density set by $\psi\psi \to \phi \to \gamma\gamma$, gg (self annihilation)
  - Direct detection $\psi N \to \psi N$:
    t-channel ϕ exchange (due to ϕgg coupling)

$gg \to \phi \to \gamma\gamma$ due to VLF

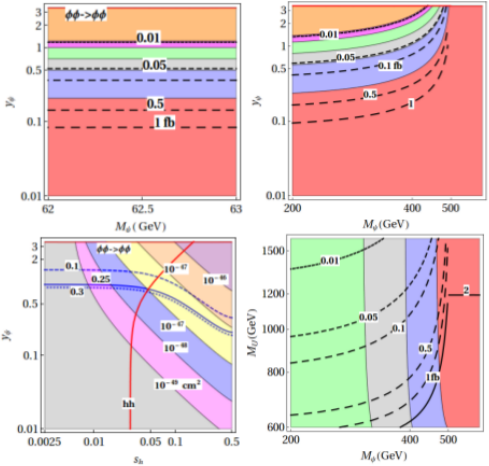


Figure 5: In the $SVU\psi$ model for $Y_\psi = 0$, $Y_U = 2/3$, the contours of $\sigma_\phi * BR_{\gamma\gamma}$ (in fb), and regions of $\kappa_\Gamma^2 < 0.1$ (red), $0.1 < \kappa_\Gamma^2 < 0.5$ (blue), $0.5 < \kappa_\Gamma^2 < 1$ (gray), $1 < \kappa_\Gamma^2 < 2$ (green), $2 < \kappa_\Gamma^2 < 3$ (pink), $\kappa_\Gamma^2 > 3$ (orange); parameters not along the axes are fixed at $s_h = 0.01$, $M_\psi = 475$ GeV, $M_U = 1200$ GeV, $M_\phi = 1000$ GeV $y_\psi = 1$, $y_U = 5$. Unitarity constraint on y_ψ for $y_U = 5$ is shown

VLF dark matter

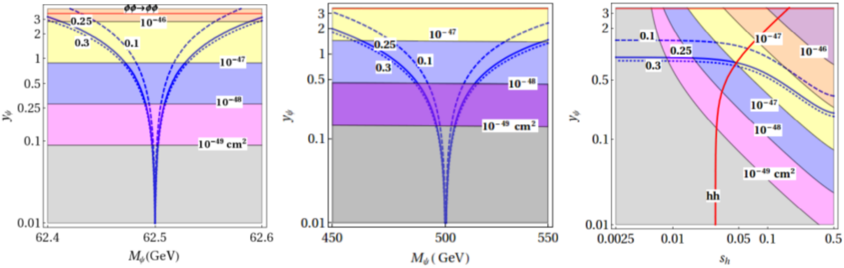


Figure 9: In the $SVU\psi$ model for $Y_\psi = 0$, $Y_U = 2/3$, $M_\phi = 1000$ GeV contours of $\Omega_{dm} = 0.1,\ 0.25,\ 0.3$, with the colored bands showing σ_{DD} as marked, for $y_U = 5$, $M_U = 1200$ GeV, and with the parameters not varied along the axes fixed at $s_h = 0.01$ and $M_\psi = 475$ GeV. The red horizontal line shows the unitarity constraint for $y_U = 5$, and the thick red line shows the 8 TeV LHC hh channel constraint.

Little Higgs Model

[SG, T. Mukherjee, S. Sadhukhan: PRD 94, 015034 (2016)]

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 (LSS) Model, 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: $\psi'_t,\ \psi'_b$
- In LSS model, Higgs sector is a 2HDM

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

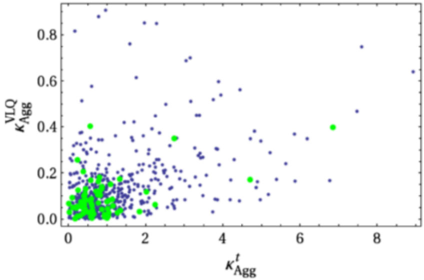
$SU(6)/Sp(6)$ Little Higgs with 2HDM structure

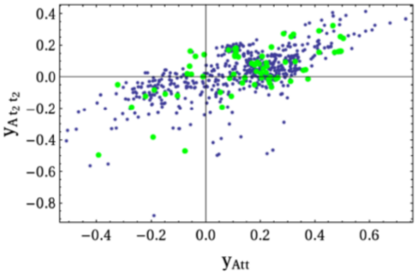
Scalars are: h, H, A, $H^{\pm}$; We focus on neutral scalars

- 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

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

Effects from VLF on A, H





The Minimal Composite Higgs Model (MCHM)

[Agashe, Contino, Pomarol, 2004] [Agashe, Contino, da Rold, Pomarol, 2006]
[Contino, Nomura, Pomarol 2003] [Agashe, Delgado, May, Sundrum 2003]
[Contino, TASI Lectures 2009]

- Start with $\mathcal{G} = SO(5) \otimes U(1)_X$ global symmetry $(10 + 1$ gens$)$
- $\langle \Sigma \rangle \neq 0$ such that $\mathcal{G}$ broken to $\mathcal{H} = SO(4) \otimes U(1)_X$ $(6 + 1$ gens$)$
- So **4 (massless) Goldstone Bosons** (GB): π^a $(a = 1, ..., 4)$ in $\mathcal{G}/\mathcal{H}$
  - $\pi^a = \{\phi^{1,2,3}, H\}$ Note: physical Higgs also a GB!
- Gauging $SU(2)_L \otimes U(1)_Y$ subgroup & writing Yukawa terms
  - Explicitly breaks $SO(5) \otimes U(1)_X$
    $\Longrightarrow$ **Higgs gets a mass (at one loop) : pseudo-GB (PGB)**

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

For custodial symmetry, at least have [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

Embedding in $SO(5)$ (showing $SO(4) \sim SU(2)_L \otimes SU(2)_R$) :

- $\underline{4}$ of $SO(5) = (2,1) \oplus (1,2)$ **(MCHM4)**

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)

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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) :

$$(1,3)_{2/3} \oplus (3,1)_{2/3} = \psi'_{t_R} \oplus \psi''_{t_R} = \begin{pmatrix} \frac{t_R}{\sqrt{2}} & \chi' \\ b' & -\frac{t_R}{\sqrt{2}} \end{pmatrix} \oplus \begin{pmatrix} \frac{t''}{\sqrt{2}} & \chi'' \\ b'' & -\frac{t''}{\sqrt{2}} \end{pmatrix}$$

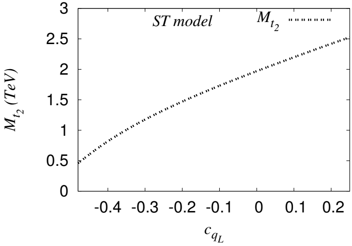
New ψ_{VL} : χ, T, χ', b', χ'', t'', b''

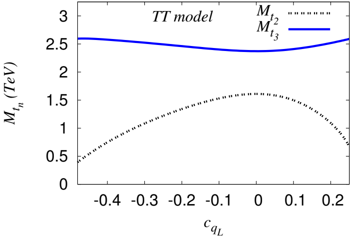
Embedding in $SO(5)$ (showing $SO(4) \sim SU(2)_L \otimes SU(2)_R$):

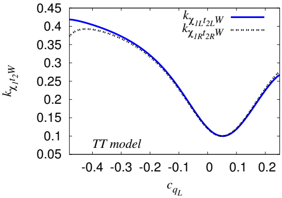
- $\underline{5}$ of $SO(5) = (2,2) \oplus (1,1)$ (**MCHM5**)
- $\underline{10}$ of $SO(5) = (2,2) \oplus (1,3) \oplus (3,1)$ (**MCHM10**)

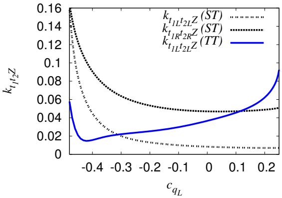
Warped model t' parameters

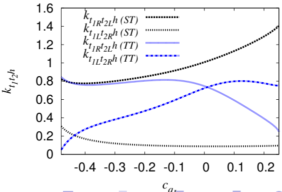
[SG, T. Mandal, S. Mitra, G. Moreau : arXiv:1306.2656, JHEP 1408 (2014) 079]



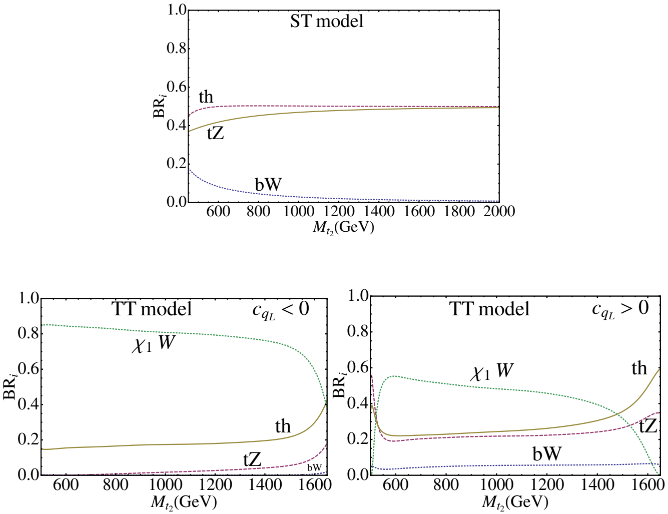




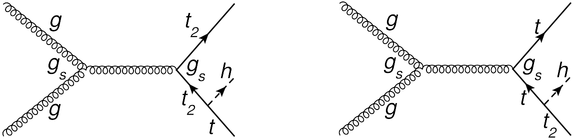




Warped model t' BR



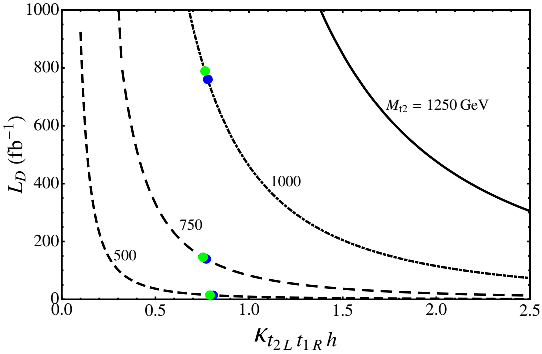
t' Double and Single Resonant channels



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

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

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 $t'bW$

Decay Modes of t', b', χ

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

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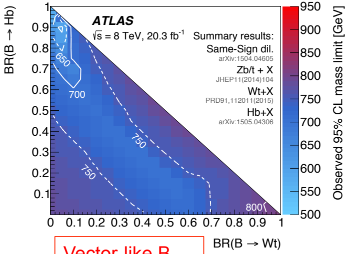
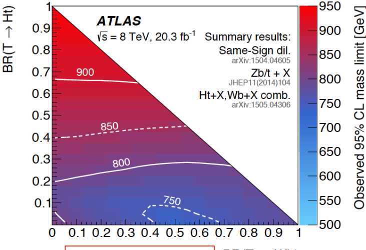
  - $g_Z \neq g'_Z$ leads to $b'bZ$ coupling
  - Similarly $t'tZ$, $t'th$ couplings also, in addition to $t'bW$
- VL Tree-level Decays
  - $b' \to tW$, $b' \to bZ$, $b' \to bh$
  - $t' \to bW$, $t' \to tZ$, $t' \to th$, $[t' \to \chi W]$
  - $\chi \to tW$

Previous limits at 8 TeV from ATLAS

- pair-production in Run I:
  - same-sign dileptons: JHEP10(2015) 150, (1504.04605)
    - m(B, singlet) > 620 GeV
    - m(T, singlet) > 590 GeV
    - $m(T_{5/3})$ > 750 GeV
  - Zb/t + X: JHEP11(2014)104, (1409.5500)
    - m(B in (B,Y) doublet) > 755 GeV
  - Wt + X: PRD91, 112011 (2015)
    - $m(T_{5/3})$ > 840 GeV
  - Q → Hb, Ht,Wb + X: JHEP08(2015) 105, (15050.04306)
    - m(T in (T,B) doublet) > 855 GeV
    - m(Y in (B,Y) doublet) > 770 GeV
    - m(B, singlet) > 735 GeV
- single production
  - T/Y – Wb (1602.05606)
    - m(T/Y) > 950 GeV (for coupling =1)
- single production via heavy gluon
  - G* → Bb → Hbb → 4b (1602.06034)
    - m(B) vs m(G*)



Vector-like B



Vector-like T

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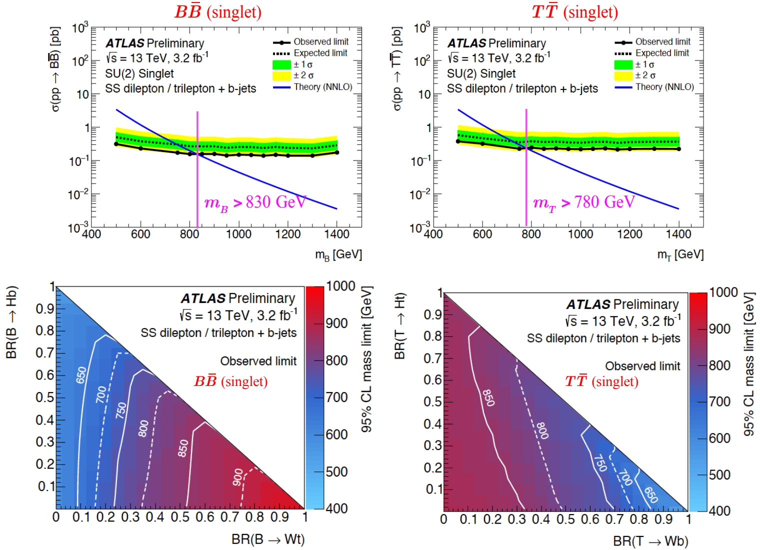
Limits for B and T VLQ's

ATLAS-CONF-2016-032



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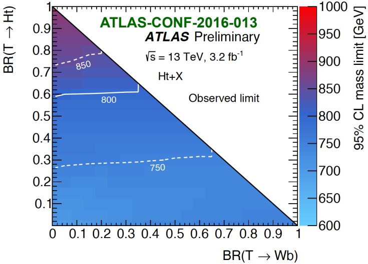
VLQ, 4-tops, in lepton + jets: limits



$m_T > 900$ GeV (if $BR(T \to Ht) = 1$)

> 750 GeV (T singlet)

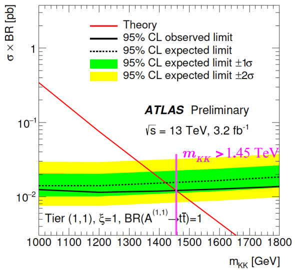
> 800 GeV (T in doublet)

$\sigma(pp \to 4t) < 190$ fb (SM kinematics)

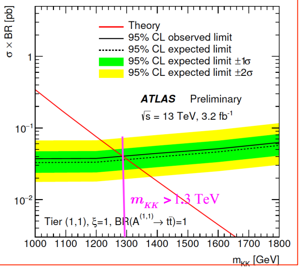
< 140 fb (contact interaction)

$|C_{4t}|/\Lambda^2 < 4.8$ TeV^{-2}

small- and large-R jets: **ATLAS-CONF-2016-013**



High jet multiplicity: **ATLAS-CONF-2016-020**



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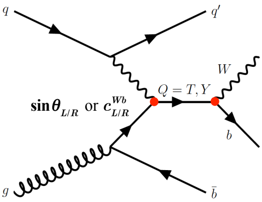
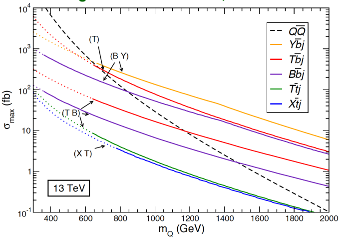
Single Production T,Y → Wb

ATLAS-CONF-2016-072

- Single production is sensitive to high mass, if coupling is sufficiently large

Aguilar-Saavedra et al., 1306.0572





- Coupling QWb

Aguilar-Saavedra et al., 1306.0572

  - mixing term

$$\begin{pmatrix} t \\ T \end{pmatrix}_{L/R} = \begin{pmatrix} \cos\theta_{L/R} & -\sin\theta_{L/R} e^{i\phi} \\ \sin\theta_{L/R} e^{-i\phi} & \cos\theta_{L/R} \end{pmatrix} \begin{pmatrix} t^0 \\ T^0 \end{pmatrix}_{L/R}$$

$$\tan\theta^q_R = \frac{m_q}{m_Q}\tan\theta^q_L \quad \text{(singlets, triplets)}$$

$$\tan\theta^q_L = \frac{m_q}{m_Q}\tan\theta^q_R \quad \text{(doublets)}$$

    - similarly for b-B mixing

  - or, more generally, phenomenological Lagrangian, in effective model with coupling $c^{Wb}_{L/R} = \sqrt{2}\sin\theta_{L/R}$ $\sigma(Q\bar{b}) \sim (c_L^2 + c_R^2)$

O. Matsedonskyi et al., 1409.0100

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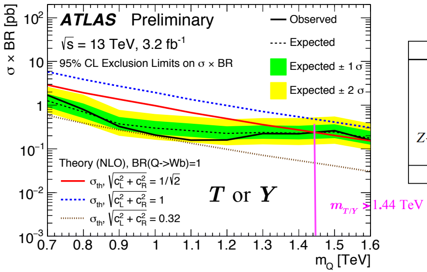
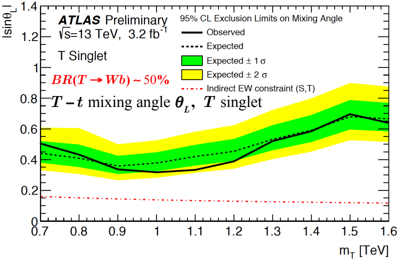
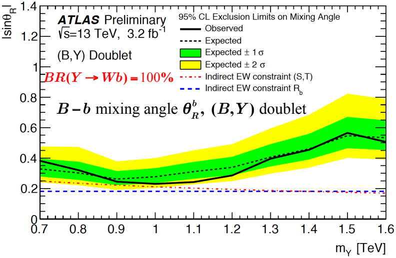
Limit on T, Y from single production



ATLAS-CONF-2016-072

	SR	$t\bar{t}$ CR	W+jets CR
$t\bar{t}$	13.7 ± 3.6	154.0 ± 13.1	200.9 ± 36.9
single top	9.6 ± 1.4	27.9 ± 3.8	41.7 ± 6.0
W+jets	10.4 ± 1.9	21.2 ± 3.0	1086.1 ± 54.1
Multijet	0.1 ± 0.1	5.3 ± 5.9	26.5 ± 15.9
Z+jets, diboson	0.6 ± 0.2	3.1 ± 0.6	71.6 ± 5.7
Total	34.3 ± 3.6	211.5 ± 14.9	1426.9 ± 51.0
Data	37	199	1427





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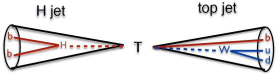
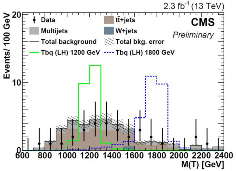
$T_{2/3} \rightarrow tH$: all hadronic

B2G-16-005

- Reconstruct M(T) by identifying boosted Higgs & top jets
- Require high jet activity: $H_T > 1100$ GeV



H jet	top jet
M_P 105 – 135 GeV	M_{SD} 110 – 210 GeV
$\tau_2/\tau_1 < 0.6$	$\tau_3/\tau_2 < 0.54$
2 b tagged subjets	1 b tagged subjet



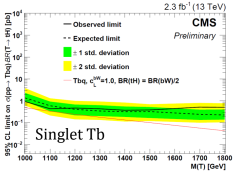
"ABCD method" for multijet background: three new regions from inverting tags

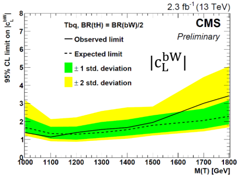
$$N_A/N_B = N_C/N_D$$

Other backgrounds ($t\bar{t}$, W+jets) modeled using simulation with correction to H_T distribution

A H tag: 0-1 b's, 0 top tags	**B** H tag: 0-1 b's, 1 top tag
C H tag: 2 b's, 0 top tags	**D** **Signal Region**

Limits on T singlet/doublet cross section with 25%/50% BR to tH, and couplings c(bW) and c(tZ)



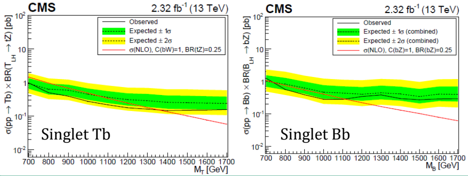


$T_{2/3} \rightarrow tZ$: dilepton

B2G-16-001

NEW

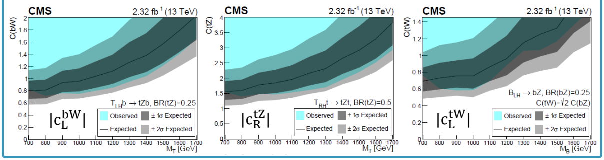
Limits on T singlet or doublet cross section, with BR(tZ) = 25% or 50%

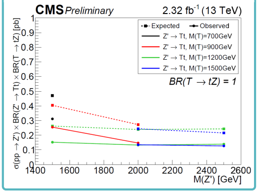


For unit b-associated couplings:

- Exclude T singlet below 1350 GeV
- Exclude B singlet below 1120 GeV
- First Z' → VLQ result from CMS
  - Exotic production mode: Z' → tT → ttZ
  - Probing M(Z') 1.5 – 2.5 TeV

Coupling limits for c(bW), c(tZ), and c(tW) based on T/B singlet or doublet models





Julie Hogan

Conclusions

- Many BSM extensions include vector-like fermions
- Indirect probes
  - hgg, $h\gamma\gamma$ couplings may show deviations in the future
    - if no deviation, constraint on parameter space
- Direct LHC signatures
  - LHC probing interesting region - discovery of VLF soon?

BACKUP SLIDES

BACKUP SLIDES

Mixing with SM fields?

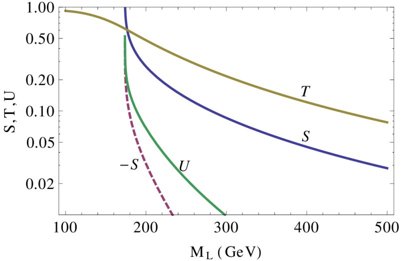
$$\mathcal{L}_{\text{Yuk}} \supset -\lambda'_{\xi}\bar{Q}\cdot H^*\xi - \lambda'_{\Upsilon}\bar{Q}H\Upsilon - \lambda'_{U}\bar{\mathcal{X}}\cdot H^*U - \lambda'_{D}\bar{\mathcal{X}}HD + h.c.$$

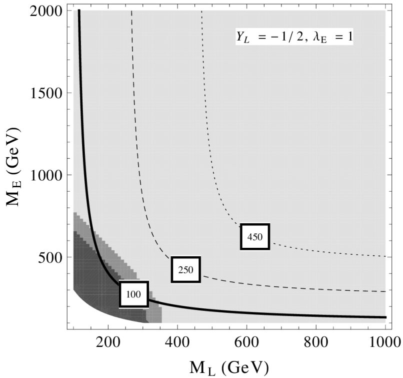
similarly for the VL-leptons

- 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]

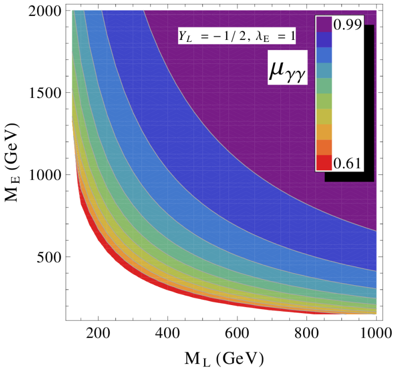
$2\bar{2} + 1\bar{1}$: MVLE



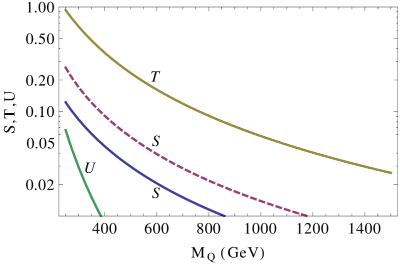


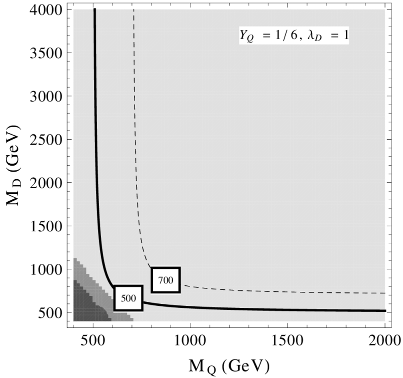
$\lambda_E = 1,\ M_E = M_L,\ Y_L = (-1/2, 1/2)$ (solid,dashed)

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



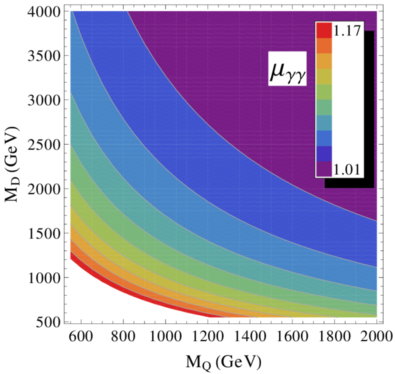
$2\bar{2} + 1\bar{1}$: MVQD





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

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



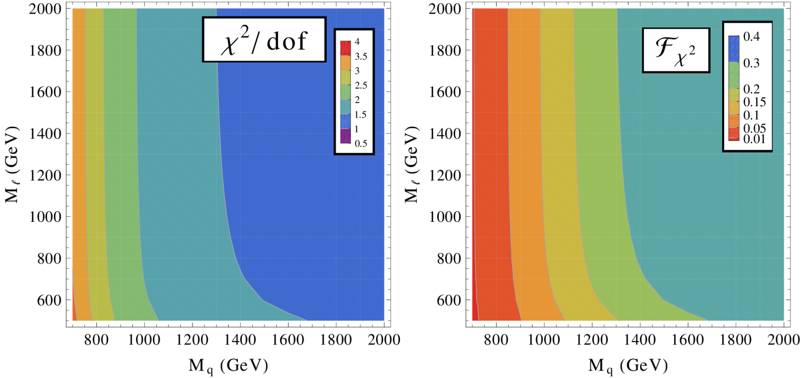
χ^2 fit to the LHC Data

[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

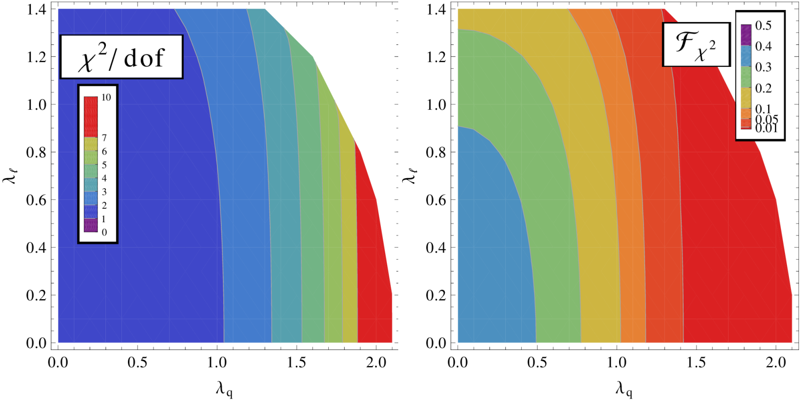
$$\chi^2 = \sum_{i=1}^{4} \left(\kappa_i^{\mathrm{Exp}} - \kappa_i^{\mathrm{Th}}\right)^2 / \left(\sigma_i^{\mathrm{Exp}}\right)^2$$

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



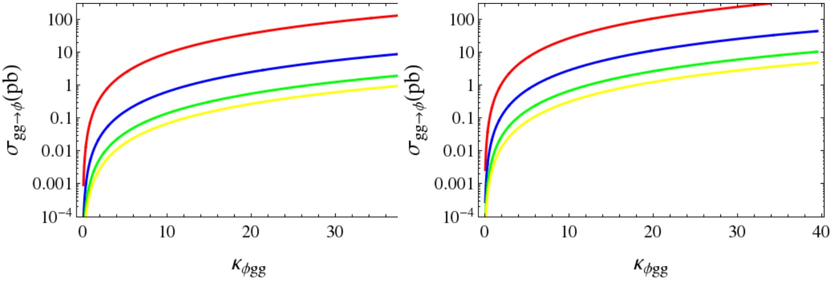
$$Y_Q = 1/6,\ Y_L = -1/2, \lambda_q = 1, \lambda_\ell = 1$$

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



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

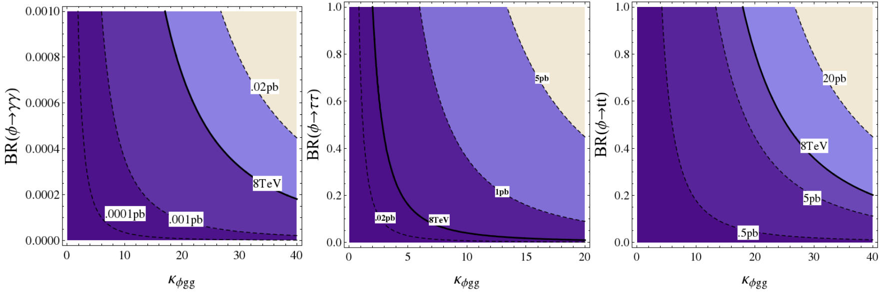
$\sigma(gg \to \phi)$ at 8, 14 TeV LHC



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)

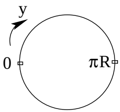
Warped Model

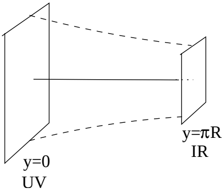
SM in background 5D warped AdS space [Randall, Sundrum '99]

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

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:

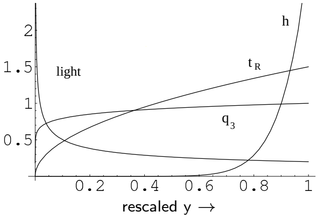
- IR localized Higgs : $M_{EW} \sim k e^{-k\pi R}$: Choose $k\pi R \sim 34$
  - Gauge-theory dual is a composite Higgs model

Explaining SM mass hierarchy

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

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

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



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

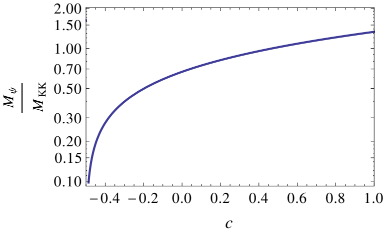
- SM fermions : $(+,+)$ BC $\rightarrow$ zero-mode
- "Exotic" fermions : $(-,+)$ BC $\rightarrow$ No zero-mode
    - 1^{st} KK vectorlike fermion

- 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:

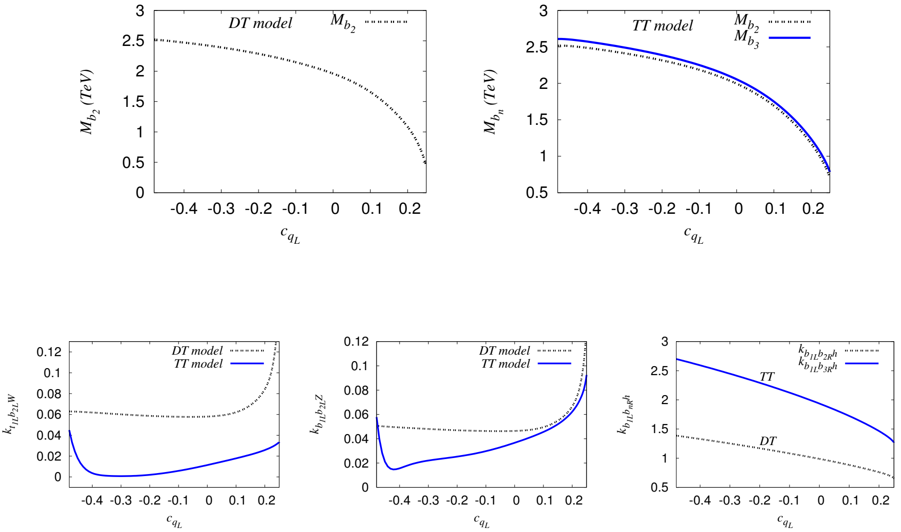
1. Singlet t_R (ST Model) : $(1,1)_{2/3} = t_R$ New ψ_{VL} : χ, T
2. Triplet t_R (TT Model) :
   $$(1,3)_{2/3} \oplus (3,1)_{2/3} = \psi'_{t_R} \oplus \psi''_{t_R} = \begin{pmatrix} \frac{t_R}{\sqrt{2}} & \chi' \\ b' & -\frac{t_R}{\sqrt{2}} \end{pmatrix} \oplus \begin{pmatrix} \frac{t''}{\sqrt{2}} &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

Yukawa Couplings

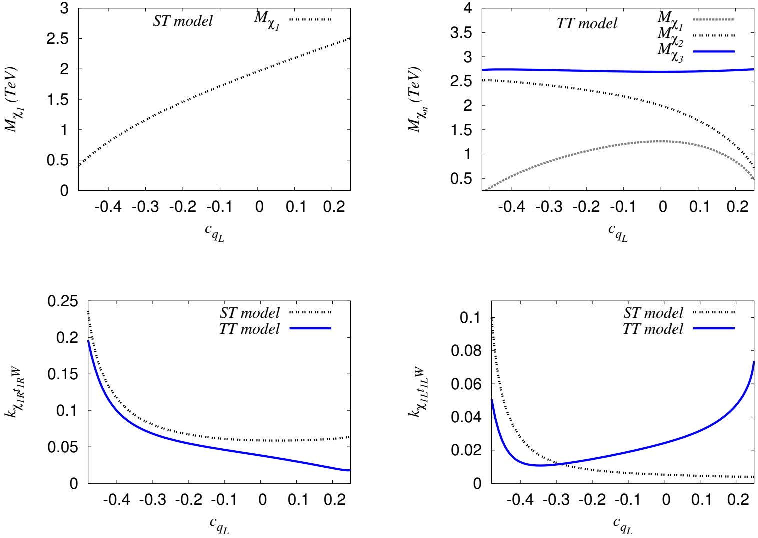
Yukawa Couplings

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

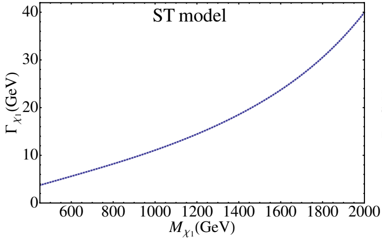
Warped model b' parameters

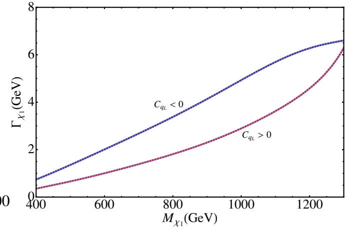


Warped model χ parameters



Warped model Γ_χ





ST Model

TT Model

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]

t' Phenomenology at the LHC

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

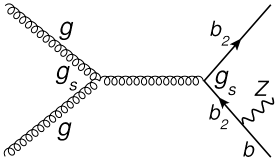
See also: [Harigaya et al., '12] [Giridhar, Mukhopadhyaya, 2012] [Azatov et al., '12] [Berger, Hubisz, Perelstein, '12] [Cacciapaglia et al., '10, '12] [Aguilar-Saavedra et al. '05]

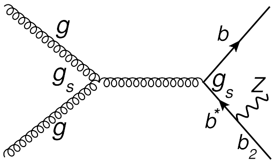
b' Phenomenology at the LHC

[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



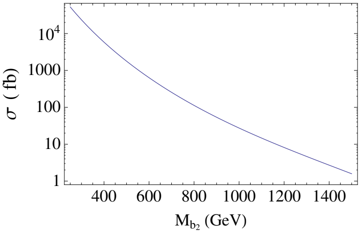


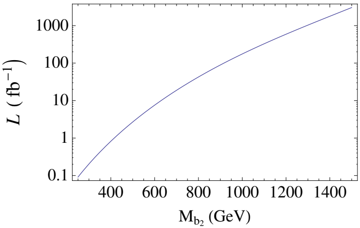
... followed by $b_2 \to bZ$

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





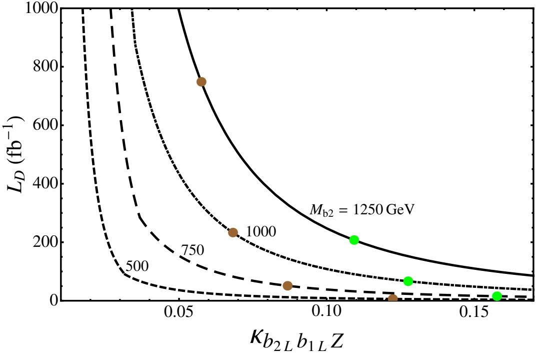
Cuts:

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 : $bg \to b' bZ \to bZbZ \to bbJJ\ell\ell$

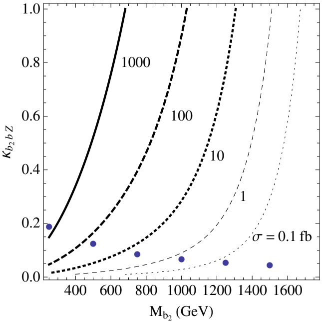
Model Independent LHC-14 reach

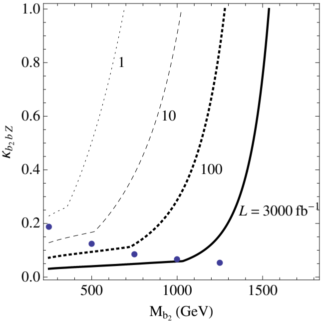


Brown dots : DT Model Green dots : TT Model

b' Single Production - II

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



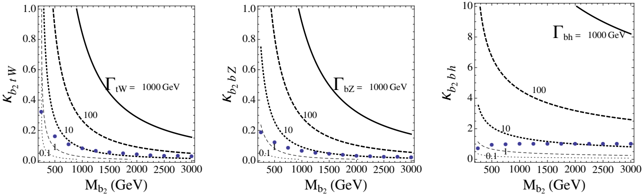


Cuts:

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

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

b' Signature (Model Independent)

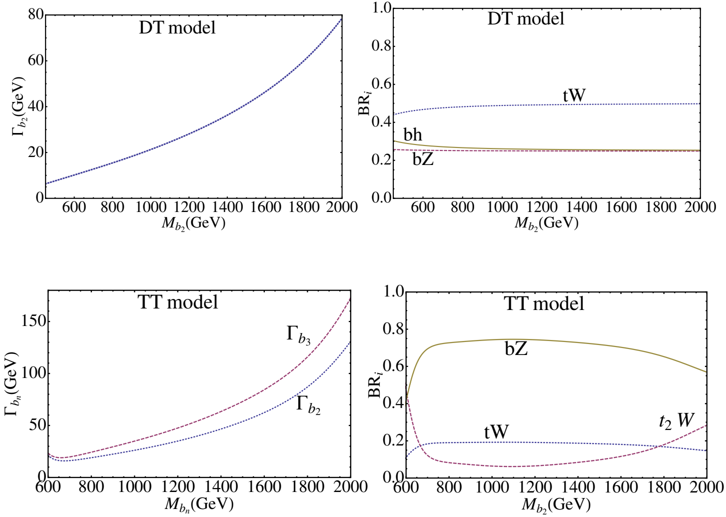


Benchmark Points (Model I):

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

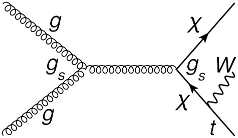
$M_{b'}$ (GeV)	QCD background (in fb)		
	$bjjZ$	$bjbZ$	$bbbZ$
250	546.36	634.32	17.19
500	10.14	7.76	0.35
750	0.52	0.66	0.03
1000	0.02	0.06	0.002

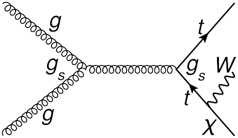
χ Phenomenology at the LHC

[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

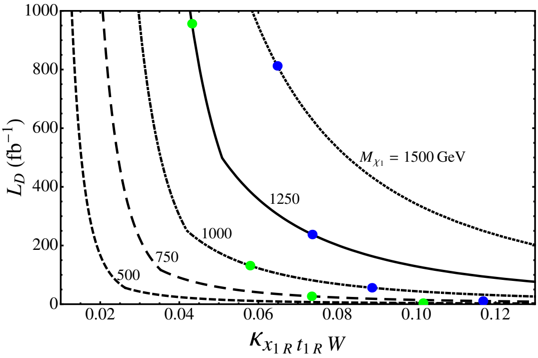




$$pp \to \chi tW \to tWtW \to tWt\ell\nu$$

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