Top-partners in (non-SUSY) models of electroweak symmetry breaking

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Workshop on Top Quark Physics at Present and Future Colliders

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Talk Outline

- Composite-Higgs, Little Higgs Models of EWSB (4D/5D Duals)
- Top and Top-partners: vector-like fermions - VLFs
- Electroweak precision & Higgs observables
- VLF LHC direct signatures
  - $t'_{(2/3)}$, $b'_{(-1/3)}$, $\chi_{(5/3)}$
  - present limits and prospects

General Idea of Composite Higgs

[Georgi, Kaplan 1984]

- Sector with global symmetry $\mathcal{G}$
  - Σ transforms under $\mathcal{G}$
- $\langle\Sigma\rangle \neq 0$ such that $\mathcal{G}$ broken to $\mathcal{H}$
  - **(massless) Goldstone Bosons (GB)** in coset $\mathcal{G}/\mathcal{H}$: π^a
    - π^a are $\{\phi^{1,2,3}, H, ...\}$
      ($\phi^{1,2,3}$ become $W^{\pm}_{longi}$, Z_{longi} after EWSB)
    - Note: **physical Higgs also a GB**
      (contrast with Technicolor where only $\phi^{1,2,3}$ are GB)
- Gauging $SU(2)_L \otimes U(1)_Y$ subgroup & writing Yukawa terms
  ($SU(3)_c$ always implied but not shown)
  - Explicitly breaks $\mathcal{G}$
    $\Longrightarrow$ **Higgs gets a mass (at loop level): Pseudo-GB (PGB)**
  - Analogy: (light) Pions are PGB of $SU(3)_L \otimes SU(3)_R \to SU(3)$

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4D model $\leftrightarrow$ Warped model Duality

[Maldacena, 1997] [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

AdS dual of MCHM and Higgs mass

- AdS/CFT Corrsp : $\mathcal{G}$ global symm of CFT $\leftrightarrow$ AdS gauge symm
  - Bulk gauge group : $SO(5) \otimes U(1)_X$ $\quad A_M = (A_\mu,\, A_5)$
- **Impose boundary condition (BC) to keep/break a symm**:
  - $(UV, IR) = (\pm, \pm)$: $+$ is Neumann, $-$ is Dirichlet
  - Dirichlet BC $(-)$ breaks a symmetry on that boundary
  - $A_{-+}(x, y)$ BC: $A|_{y=0} = 0$; $\partial_y A\,|_{y=\pi R} = 0$
- $A_5^{\hat{a}}(++)$ **dual of PNGB** $\pi^a = \{\phi^{1,2,3}, h\}$ [Contino, Nomura, Pomarol 2003]
  - **Gauge symmetry forbids tree-level mass**
  - **Mass at loop-level from gauge and top loops** [Hosotani 1983]
- Minimal Composite Higgs Model (MCHM) dual is [Agashe, Contino, Pomarol, 2004]

$[SO(5) \otimes U(1)_X]/[SO(4) \otimes U(1)_X]$	$A_\mu^{\hat{a}}(--),\ A_5^{\hat{a}}(++)$
$T_L,\ T_R^3 + X$	$A_\mu(++),\ A_5(--)$
$T_R^{\pm},\ T_R^3 - X$	$A_\mu(-+),\ A_5(+-)$

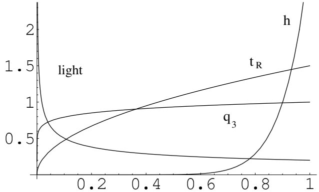
  - 1-loop effective potential gives: $m_h^2 \sim \frac{2N_c}{N} y_t^2 v^2$

Generating 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

Precision Electroweak Constraints

Precision Electroweak Constraints (S, T, $Zb\bar{b}$)
(perturbatively calculable on the warped side)

- Bulk gauge symm - $SU(2)_L \times U(1)$ (SM ψ, H on TeV Brane)
- T parameter $\sim (\frac{v}{M_{KK}})^2 (k\pi R)$ [Csaki, Erlich, Terning 02]
  - S parameter also $(k\pi R)$ enhanced
- AdS bulk gauge symm $SU(2)_R \quad \Leftrightarrow \quad$ CFT Custodial Symm

[Agashe, Delgado, May, Sundrum 03]

  - T parameter - Protected
  - S parameter - $\frac{1}{k\pi R}$ for light bulk fermions
  - Problem: $Zb\bar{b}$ shifted
- 3rd gen quarks (2,2) [Agashe, Contino, DaRold, Pomarol 06]
  - $Zb\bar{b}$ coupling - Protected
  - Precision EW constraints $\Rightarrow M_{KK} \gtrsim 1.5 - 2.5$ TeV

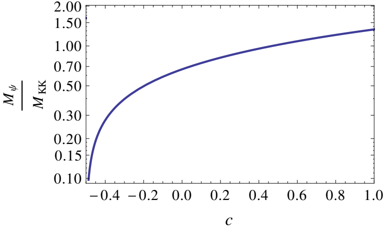
[Carena, Ponton, Santiago, Wagner 06,07]

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

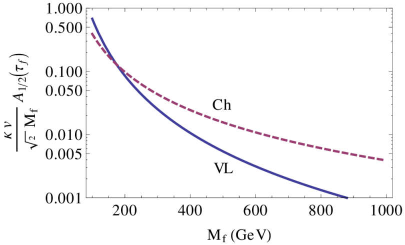
  [Choi, Kim, 2002] [Agashe, Delgado, May, Sundrum, 03] [Agashe, Perez, Soni, 04] [Agashe, Servant 04]
    - Look for it at the LHC



[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]

VLF decoupling

- VLF has independent source of mass M (not given by $m = \lambda v$)
  - Can make M arbitrarily large
    - Yukawa coupling can remain perturbative
    - As M increases, fine-tuning increases
  - Nice decoupling behavior : $S, T, U, h \to \gamma\gamma, gg \to h, \ldots$
    - For instance $h\gamma\gamma$, ggh couplings



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

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''

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   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 $\quad \mathcal{L}_{\rm Yuk} \supset \lambda_t \; {\rm Tr}[\bar{Q}_L \Sigma] \; t_R + h.c.$
  - TT Model $\quad \mathcal{L}_{\rm Yuk} \supset \lambda_t {\rm Tr}\left[\bar{Q}_L \Sigma \psi'_{t_R}\right] + \lambda'_t {\rm Tr}\left[\bar{Q}_L \Sigma \psi''_{t_R}\right] + h.c.$

ST model $W^\pm$ and Z VLF interactions

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

$$\mathcal{L}_{CC} \supset \frac{g_L}{\sqrt{2}} \left(c_L \bar{t}_{1L} \gamma^\mu b_L - s_L \bar{t}_{2L} \gamma^\mu b_L + s_L \bar{\chi}_L \gamma^\mu t_{1L} + c_L \bar{\chi}_L \gamma^\mu t_{2L} \right.$$
$$\left. + s_R \bar{\chi}_R t_{1R} + c_R \bar{\chi}_R t_{2R} \right) W^+_{L\ \mu} + h.c.$$

$$\begin{aligned}
\mathcal{L}_{NC} \supset \quad & e \left[\bar{\chi} \gamma^\mu \left(\frac{5}{3} \right) \chi + \bar{t}_1 \gamma^\mu \left(\frac{2}{3} \right) t_1 + \bar{t}_2 \gamma^\mu \left(\frac{2}{3} \right) t_2 + \bar{b} \gamma^\mu \left(-\frac{1}{3} \right) b \right] A_\mu \\
+ \quad & g_Z \left\{ \bar{t}_{1L} \gamma^\mu \left[\frac{1}{2} \cos 2\theta_L - \frac{2}{3} s_W^2 \right] t_{1L} + \bar{t}_{2L} \gamma^\mu \left[-\frac{1}{2} \cos 2\theta_L - \frac{2}{3} s_W^2 \right] t_{2L} \right. \\
+ \quad & \left[\bar{t}_{2L} \gamma^\mu \left(-\frac{1}{2} \sin 2\theta_L \right) t_{1L} + h.c. \right] \\
+ \quad & \bar{t}_{1R} \gamma^\mu \left[-\frac{1}{2} s_R^2 - \frac{2}{3} s_W^2 \right] t_{1R} + \bar{t}_{2R} \gamma^\mu \left[-\frac{1}{2} c_R^2 - \frac{2}{3} s_W^2 \right] t_{2R} \\
+ \quad & \left[\bar{t}_{2R} \gamma^\mu \left(-\frac{1}{2} s_R c_R \right) t_{1R} + h.c. \right] \\
+ \quad & \left. \bar{b}_L \gamma^\mu \left[-\frac{1}{2} - s_W^2 \left(-\frac{1}{3} \right) \right] b_L + \bar{\chi} \gamma^\mu \left[\frac{1}{2} - s_W^2 \left(\frac{5}{3} \right) \right] \chi \right\} Z_\mu ,
\end{aligned}$$

Sample points

$\mathcal{T}$	c_{q_L}	c_{t_R}	c_{b_R}	$\sin\theta_L$	$\sin\theta_R$
$\mathcal{T}_1$	-0.471	0.196	0.586	-0.167	-0.442
$\mathcal{T}_2$	-0.419	0.216	0.585	-0.062	-0.262
$\mathcal{T}_3$	-0.356	0.204	0.584	-0.034	-0.195
$\mathcal{T}_4$	-0.279	0.179	0.583	-0.022	-0.161
$\mathcal{T}_5$	-0.191	0.140	0.581	-0.016	-0.141
$\mathcal{T}_6$	-0.094	0.082	0.578	-0.013	-0.130

$\mathcal{T}$	M_{t_2}(GeV)	$\kappa_{t_{2L}t_{1R}h}$	$\kappa_{t_{1L}t_{2R}h}$	$\kappa_{t_{2R}t_{1R}Z}$	$\kappa_{t_{2L}t_{1L}Z}$
$\mathcal{T}_1$	500	0.806	0.277	0.148	0.123
$\mathcal{T}_2$	750	0.769	0.176	0.094	0.046
$\mathcal{T}_3$	1000	0.778	0.134	0.071	0.026
$\mathcal{T}_4$	1250	0.807	0.111	0.059	0.017
$\mathcal{T}_5$	1500	0.851	0.098	0.052	0.012
$\mathcal{T}_6$	1750	0.915	0.090	0.048	0.010

Table: For $\tilde{\lambda}_t = 1$, $\tilde{\lambda}_b = 1$ and $M_{KK} = 3$ TeV in the ST model.

LSS Little Higgs Model

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), 2002 :** $SU(6)/Sp(6)$

- Coset: $35 - 21 = 14$ →PNGB (Higgs included)
- Gauge sector:
  $SU(2)_1 \otimes SU(2)_2 \otimes U(1)_1 \otimes U(1)_2 \rightarrow SU(2)_L \otimes U(1)_Y$
- Vector-like fermions
  - SU(2) doublet: $Q' = \begin{pmatrix} t' \\ b' \end{pmatrix}$; SU(2) singlets: t'', b''
- Higgs sector is a 2HDM

$$V \supset m_1^2 \left|\phi_1\right|^2 + m_2^2 \left|\phi_2\right|^2 + \left(b^2 \phi_1^T \cdot \phi_2 + h.c.\right) + \lambda_5' \left|\phi_1^T \cdot \phi_2\right|^2$$

LSS model symmetry breaking, PNGB and VLF

$$\Sigma = \exp\left(\frac{i\pi^a X^a}{f}\right)\langle\Sigma\rangle\ ; \qquad \langle\Sigma\rangle = \begin{pmatrix} 0 & -\mathbb{1} \\ \mathbb{1} & 0 \end{pmatrix}$$

$$\pi^a X^a \supset \begin{pmatrix} \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \phi_2 & \begin{matrix} 0 & s \\ -s & 0 \end{matrix} & \phi_1 \\ \phi_2^\dagger & 0 & -\phi_1^T & 0 \\ \begin{matrix} 0 & -s^* \\ s^* & 0 \end{matrix} & -\phi_1^* & \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \phi_2^* \\ \phi_1^\dagger & 0 & \phi_2^T & 0 \end{pmatrix}$$

Gauge group: $SU(2)_1 \otimes SU(2)_2 \otimes U(1)_1 \otimes U(1)_2$ with $Q_1^a = \begin{pmatrix} \sigma^a & 0 \\ 0 & 0 \end{pmatrix}$; $Q_2^a = \begin{pmatrix} 0 & 0 \\ 0 & \sigma^a \end{pmatrix}$

$$\mathcal{L}_{Yuk} = y_1 f\ \left(Q'\ \psi_1\ (i\sigma^2 Q)^T\ 0\right)\ \Sigma^* \begin{pmatrix} 0 \\ t^c \end{pmatrix} + y_2 f\ \left(0\ 0\ Q^T\ 0\right)(\Sigma) \begin{pmatrix} i\sigma^2 Q'^{\,c} \\ \psi_1^c \\ 0 \\ \psi_2^c \end{pmatrix} + \text{h.c.}$$

BSM vector-like fermions: 1 VL doublet (Q') + 2 VL singlets (t'', b'')

1-loop effective potential $\Longrightarrow$ potential for PNGB, EWSB

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

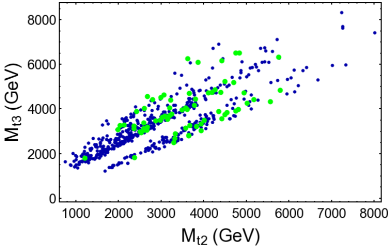
Scalars are: h, H, A, $H^{\pm}$; We focus on neutral scalars

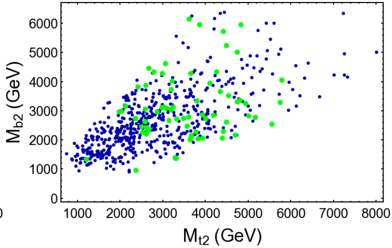
- Seek hWW, hZZ SM like
  - Alignment limit: $\cos(\beta - \alpha) \approx \frac{\pi}{2}$; [Gunion, Haber, 2002]
    - HWW, HZZ $\approx$ zero!
- Also seek htt SM like
- AWW, AZZ are zero at tree-level : $\mathcal{CP}$ inv

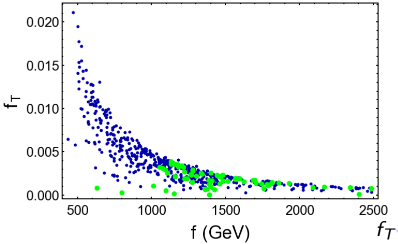
$$\langle \phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}; \quad \langle \phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_2 \\ 0 \end{pmatrix}; \quad \tan\beta = \frac{v_1}{v_2}$$

VLF properties and fine-tuning

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







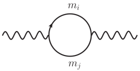
f_T : fine-tuning measure

VECTOR-LIKE FERMIONS IN ELECTROWEAK PRECISION & HIGGS OBSERVABLES

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

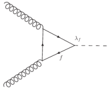
Observables

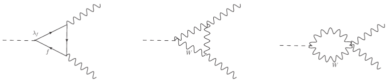
Precision electroweak observables (S, T, U)



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

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





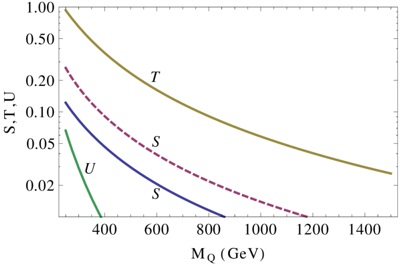
We compute ratios $\frac{\Gamma_{h\to gg}}{SM}$, $\frac{\Gamma_{h\to\gamma\gamma}}{SM}$ using leading-order expressions

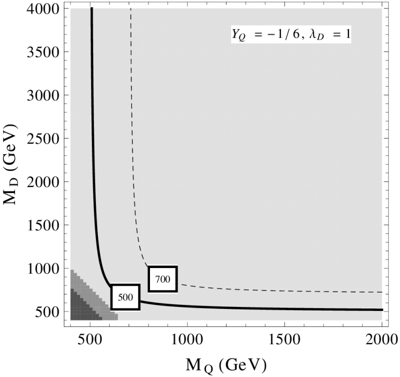
QCD corrections to ratios small: [Furlan '11] [Gori, Low '13]

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

$2\bar{2} + 1\bar{1}$ model

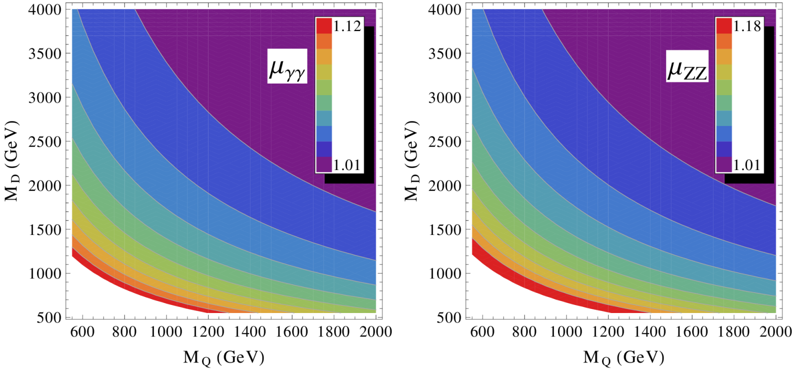
$Q + U$ model (ST Model like) : MVQD Model with $Y_\chi = -1/6$





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

$Q + U$ model



[Q+U model from MVQD model with $Y_\chi = -1/6$]

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]
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[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 $t'bW$
- VL Tree-level Decays
  - $b' \to tW$, $b' \to bZ$, $b' \to bh$
  - $t' \to bW$, $t' \to tZ$, $t' \to th$
  - $\chi \to tW$

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 $t'bW$

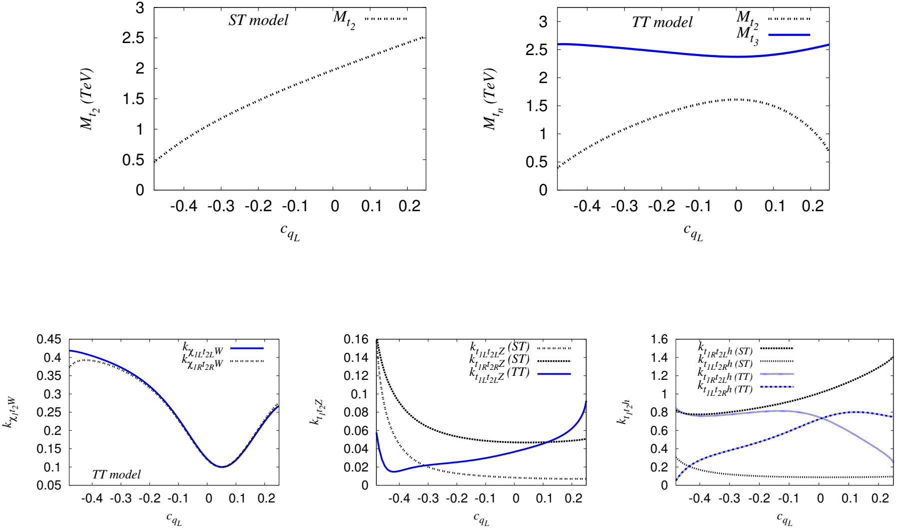
- VL Tree-level Decays
  - $b' \to tW$, $b' \to bZ$, $b' \to bh$
  - $t' \to bW$, $t' \to tZ$, $t' \to th$
  - $\chi \to tW$

t' Phenomenology at the LHC

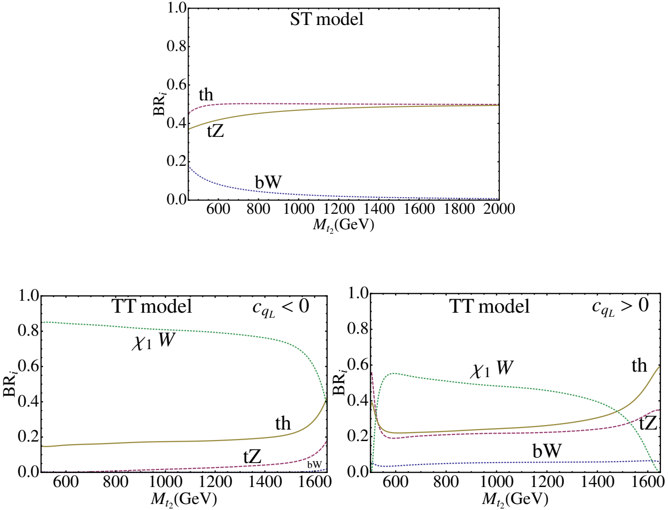
[SG, T. Mandal, S. Mitra, G. Moreau : arXiv:1306.2656, JHEP 1408 (2014) 079]

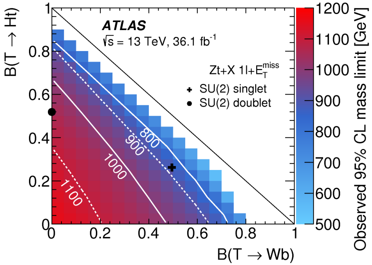
See also: [Harigaya et al., '12] [Giridhar, Mukhopadhyaya, 2012] [Azatov et al., '12] [Berger, Hubisz, Perelstein, '12] [Cacciapaglia et al., '10, '12] [Aguilar-Saavedra et al. '05]

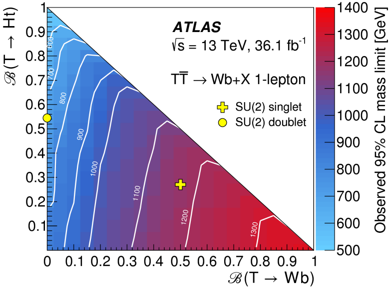
Warped model t' parameters



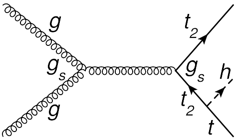
Warped model t' BR

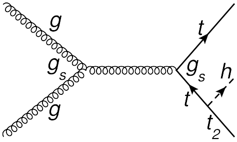



ATLAS
√s = 13 TeV, 36.1 fb-1
Zt+X 1l+E_T^miss
SU(2) singlet
SU(2) doublet
B(T → Ht)
B(T → Wb)
Observed 95% CL mass limit [GeV]


ATLAS
√s = 13 TeV, 36.1 fb-1
TT̄ → Wb+X 1-lepton
SU(2) singlet
SU(2) doublet
ℬ(T → Ht)
ℬ(T → Wb)
Observed 95% CL mass limit [GeV]

t' Double and Single Resonant channels

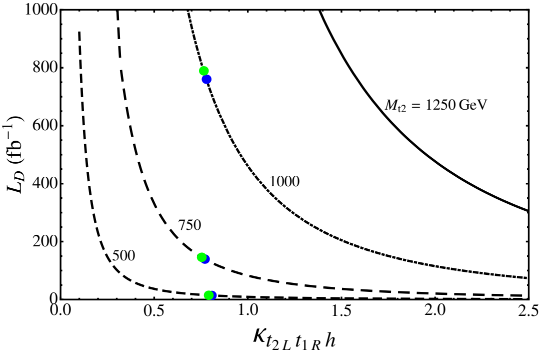




$$pp \to t_2 th \to thth \to tbbtbb \to 6\ b\ 4\ j \qquad \text{(4 b-tags)}$$

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

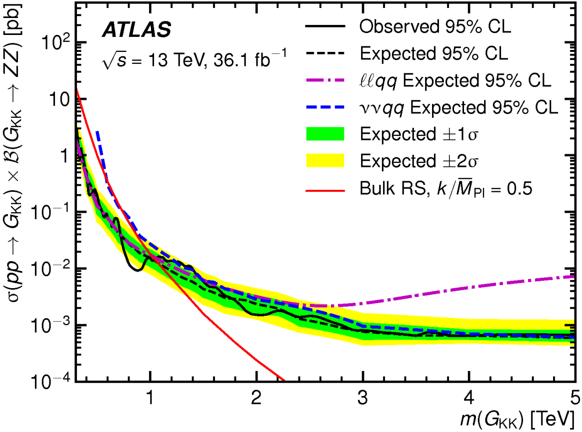


Blue Dots - ST Model   Green Dots - TT Model

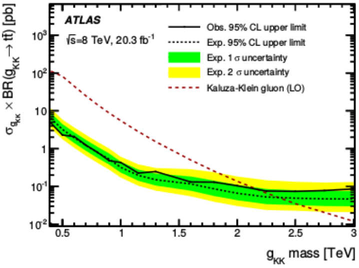
LHC Searches

LHC Searches

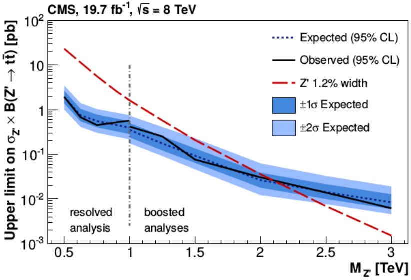
graviton$^{(1)} \to ZZ$ search



gluon$^{(1)} \to t\bar{t}$ search



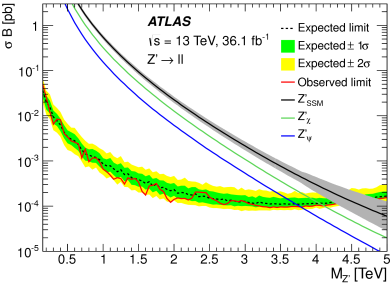
(b) $g_{\rm KK}$, resolved and boosted combination.

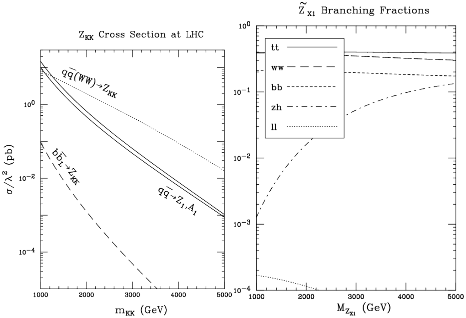


Limit: $M_{KK} > 2.2\ TeV$ @ 95% CL

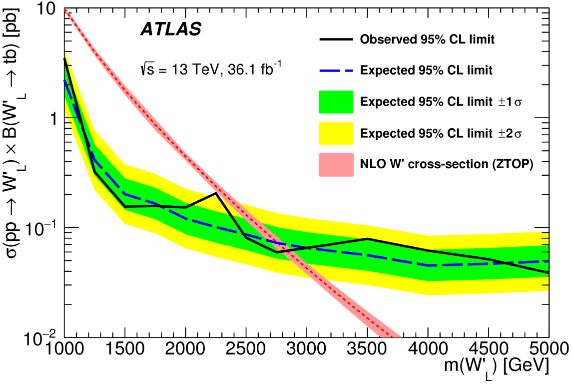
[ATLAS 1505.07018; CMS 1309.2030]

$Z' \to \ell^+ \ell^-$





[Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni - arXiv:0709.0007 [hep-ph]]



ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Observed 95% CL limit
Expected 95% CL limit
Expected 95% CL limit ±1σ
Expected 95% CL limit ±2σ
NLO W' cross-section (ZTOP)
σ(pp → W'_L) × B(W'_L → tb) [pb]
m(W'_L) [GeV]
10
1
10⁻¹
10⁻²
1000
1500
2000
2500
3000
3500
4000
4500
5000

Conclusions

- Top-partners (VLFs) play a crucial role in EWSB
  - Example: composite-Higgs, Little Higgs models
- Indirect probes of VLFs
  - hgg, $h\gamma\gamma$ couplings may show deviations in the future
    - if no deviation, constraint on parameter space
- Direct LHC signatures
  - Present limits on t', b', χ are in the 1 TeV range
  - Probing interesting region now!

BACKUP SLIDES

BACKUP SLIDES

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):

$$
\begin{array}{ll}
q_L = (3,2)_{1/6} & \text{No } (\bar{3},\bar{2})_{-1/6} \\
U_R = (3,1)_{+2/3} & \text{No } (\bar{3},1)_{-2/3} \\
D_R = (3,1)_{-1/3} & \text{No } (\bar{3},1)_{1/3}
\end{array}
$$

- 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 $\mathcal{X} \equiv \begin{pmatrix} \mathcal{X}_1 \\ \mathcal{X}_2 \end{pmatrix}$

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

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

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 $\phi_0(x) = \phi(y = y_0, x)$

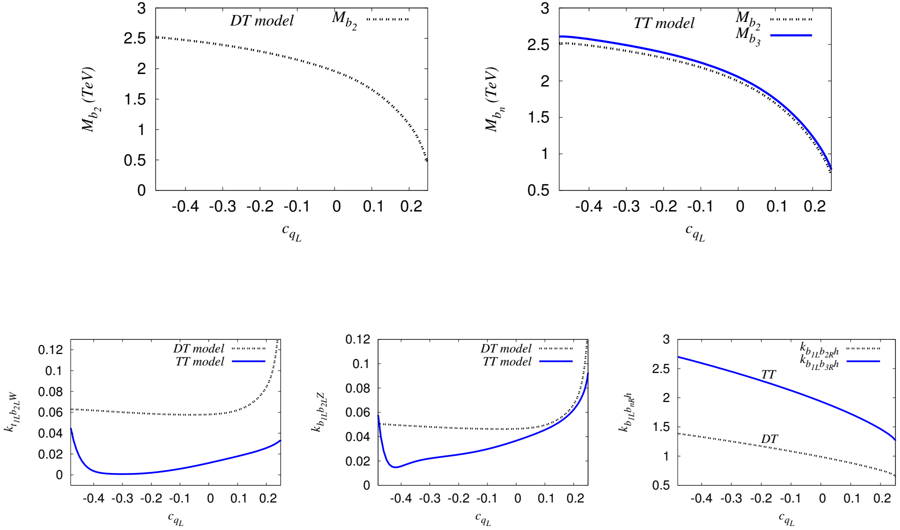
Warped Bulk Gauge Group

[Agashe, Delgado, May, Sundrum '03]

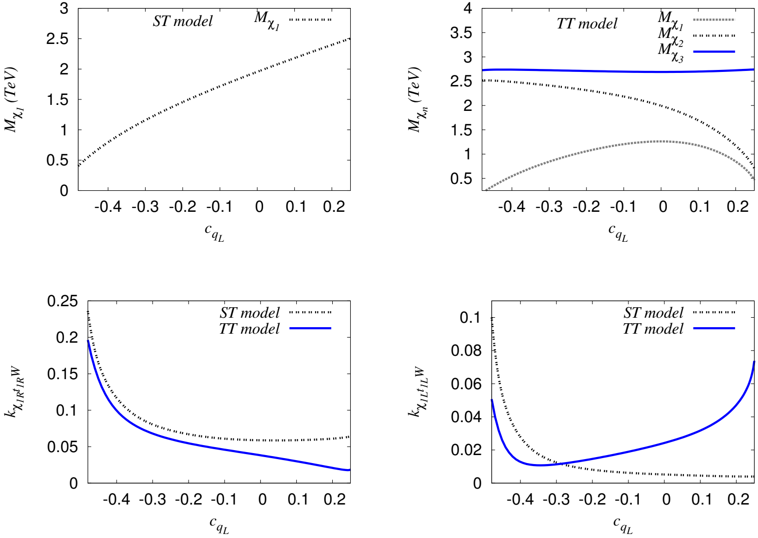
Bulk gauge group : $SU(3)_{QCD} \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_X$

- 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 $\Sigma = (2,2)_0$
    - $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

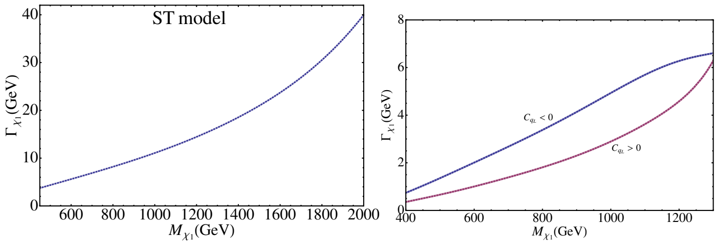
Warped model b' parameters



Warped model χ parameters



Warped model Γ_χ



ST Model

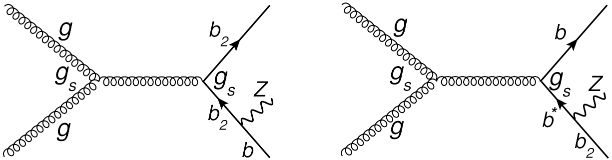
TT Model

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

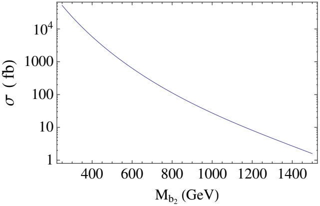


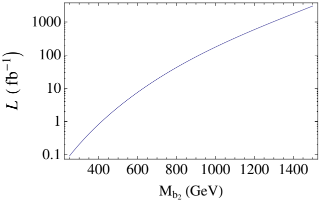
… followed by $b_2 \to bZ$

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



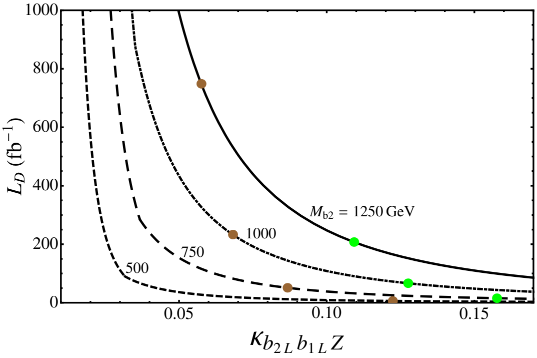


Cuts:

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

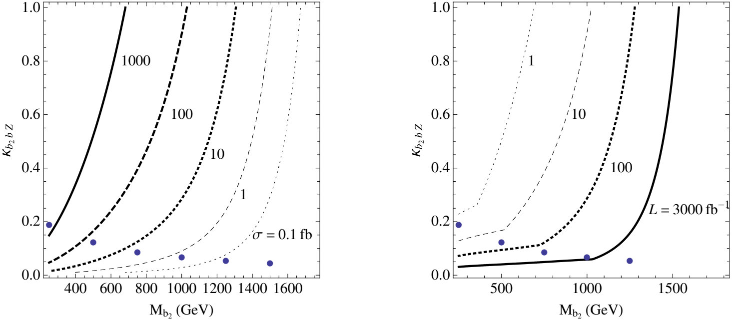
Single Resonant : $bg \to b' bZ \to bZbZ \to bbJJ\ell\ell$
Model Independent LHC-14 reach



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,
$0.95 M_{b_2} < M_{(bZ)\ OR\ (bjj)} < 1.05 M_{b_2}$.

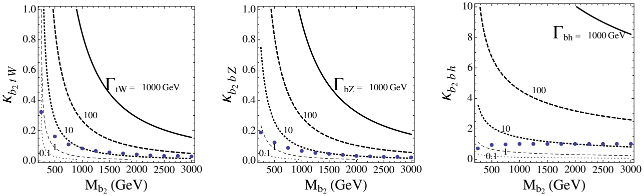
b' Pair Production Details

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

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)

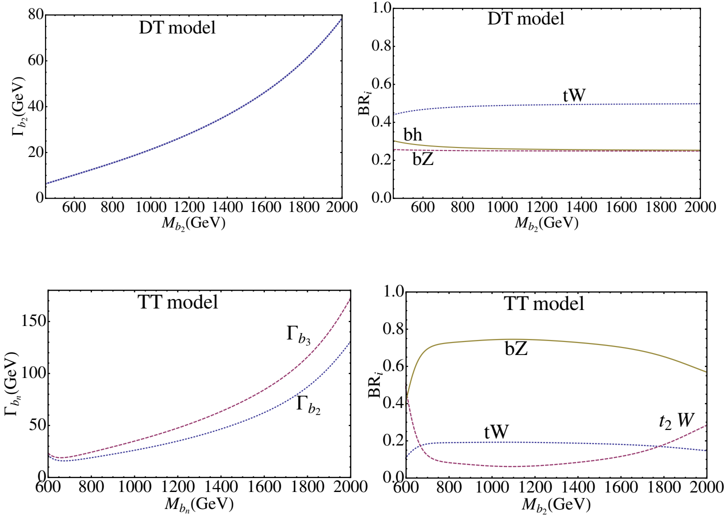


Benchmark Points (Model I):

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) $bjjZ$ Primary cuts	signal σ_s (in fb) $bjjZ$ all cuts	background σ_b (in fb) $(bjjZ)_{EW}$ Primary cuts	background σ_b (in fb) $(bjjZ)_{EW}$ all cuts	background σ_b (in fb) $(bjjZ)_{\rm QCD}$ Primary cuts	background σ_b (in fb) $(bjjZ)_{\rm QCD}$ all cuts	$\mathcal{L}_{\rm SemiLep}$ (fb^{-1})
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

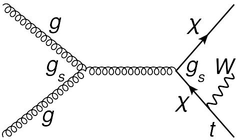
$M_{b'}$ (GeV)	QCD background (in fb) $bjjZ$	QCD background (in fb) $bjbZ$	QCD background (in fb) $bbbZ$
250	546.36	634.32	17.19
500	10.14	7.76	0.35
750	0.52	0.66	0.03
1000	0.02	0.06	0.002

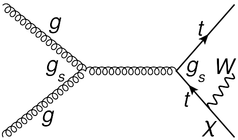
χ Phenomenology at the LHC

[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

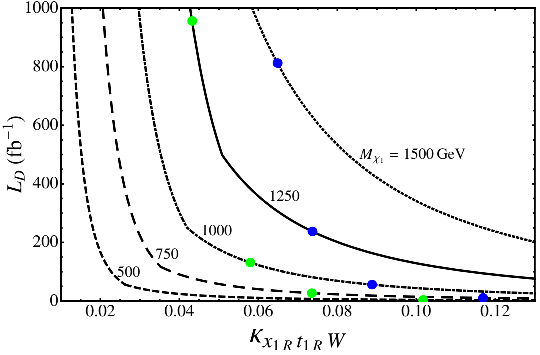




$$pp \to \chi t W \to tWtW \to tWt\ell\nu$$

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

Model: 2HDM-II + VLF

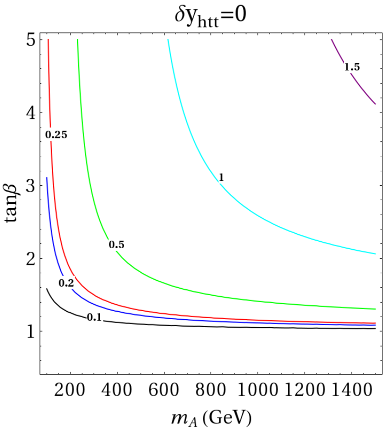
Model: 2HDM-II + VLF

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

LSS: constrain m_h =125 GeV

λ'_5 $\cos(\beta - \alpha)$

(preliminary plots - see new plots in the paper)



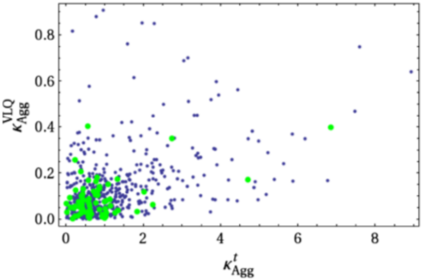
y_2 (Yukawa) κ_{Agg}

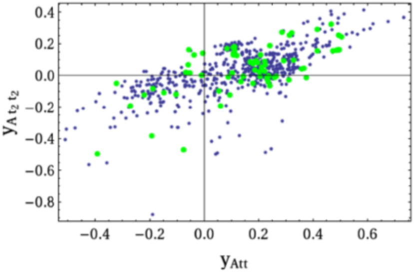
(preliminary plots - see new plots in the paper)

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

(preliminary plots - see new plots in the paper)

Effects from VLF on A, H





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]

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)

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

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

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

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

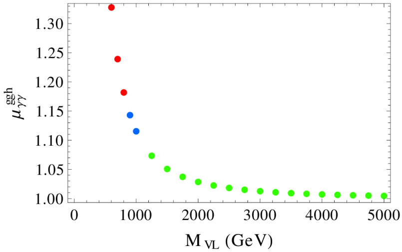
Y_χ	-1/2	-1/6	1/6	1/2
Q_1, Q_4	0	1/3	2/3	1
Q_2, Q_3	-1	-2/3	-1/3	0

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

Diagonalize and obtain W^a_μ, B_μ and h couplings

We assume tiny VL-SM mixing Yukawa terms

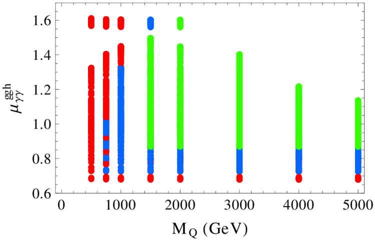
$2\bar{2} + 1\bar{1} + 1\bar{1}$: VSM



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

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

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

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

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

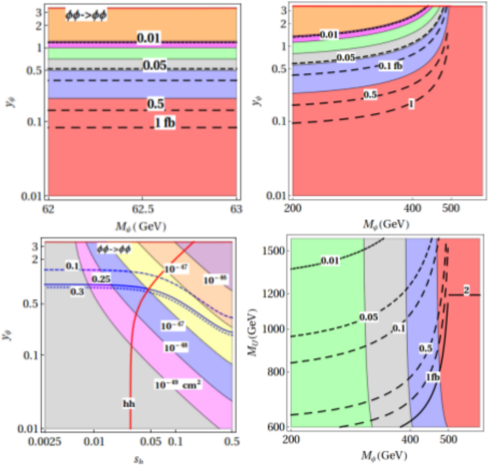


Figure 5: In the $SVU\psi$ model for $Y_\psi = 0$, $Y_U = 2/3$, the contours of $\sigma_\phi * BR_{\gamma\gamma}$ (in fb), and regions of $\kappa_\Gamma^2 < 0.1$ (red), $0.1 < \kappa_\Gamma^2 < 0.5$ (blue), $0.5 < \kappa_\Gamma^2 < 1$ (gray), $1 < \kappa_\Gamma^2 < 2$ (green), $2 < \kappa_\Gamma^2 < 3$ (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

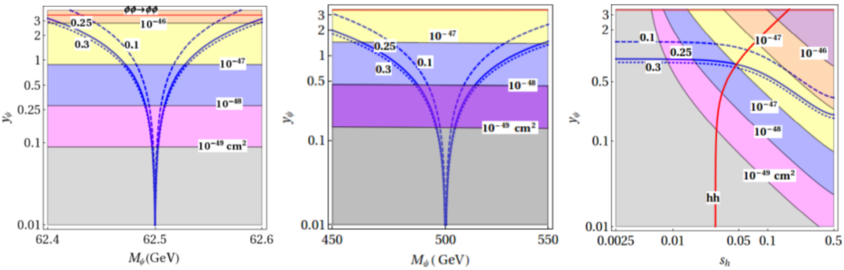
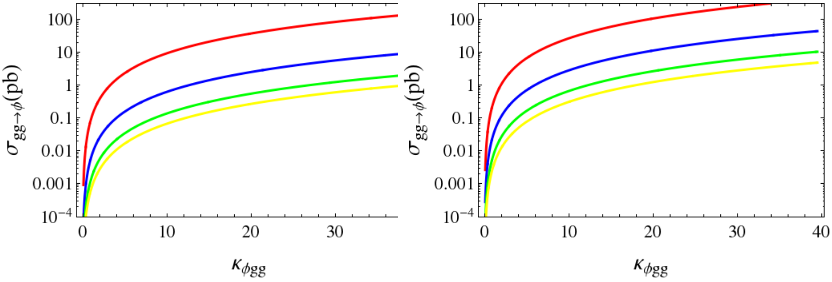


Figure 9: In the $SVU\psi$ model for $Y_\psi = 0$, $Y_U = 2/3$, $M_\phi = 1000$ GeV contours of $\Omega_{dm} = 0.1,\ 0.25,\ 0.3$, with the colored bands showing σ_{DD} as marked, for $y_U = 5$, $M_U = 1200$ GeV, and with the parameters not varied along the axes fixed at $s_h = 0.01$ and $M_\psi = 475$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

ASPECTS OF NEW SCALARS (IN 2HDM)

[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)

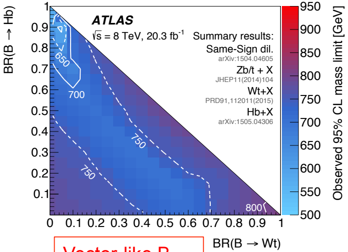
Effective Model: 2HDM-II + VLQ

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

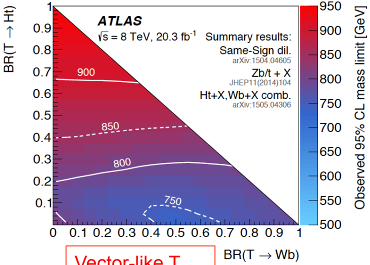
- $SU(2)$ doublet ψ + singlet ξ
  - Eg: $\mathcal{L} \supset y_1 \bar{\psi}_L \Phi_1^c \xi_R + \tilde{y}_1 \bar{\psi}_R \Phi_2 \xi_L + h.c.$

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

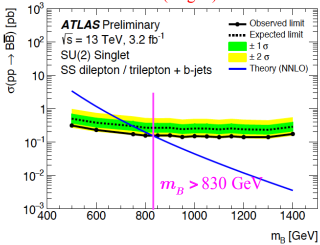


Vector-like T

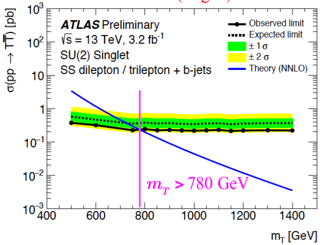
Limits for B and T VLQ's

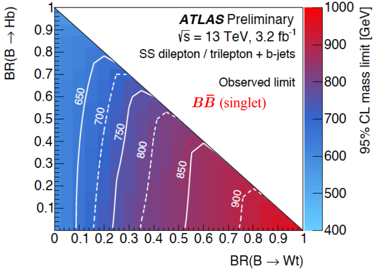
ATLAS-CONF-2016-032

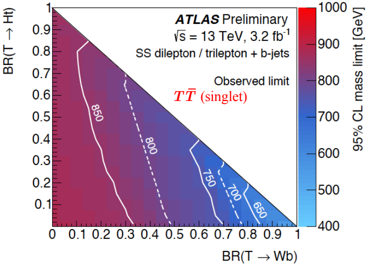
$B\bar{B}$ (singlet)



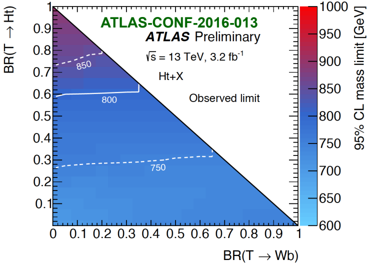
$T\bar{T}$ (singlet)







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



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

> 750 GeV (T singlet)

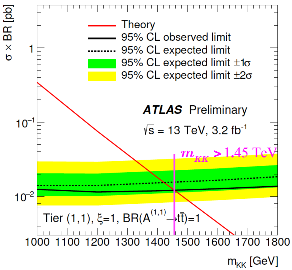
> 800 GeV (T in doublet)

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

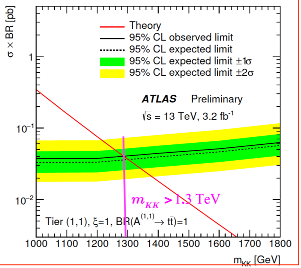
< 140 fb (contact interaction)

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

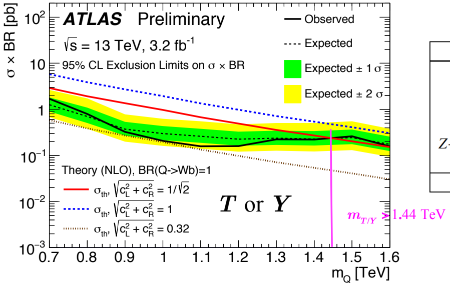
small- and large-R jets: **ATLAS-CONF-2016-013**



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

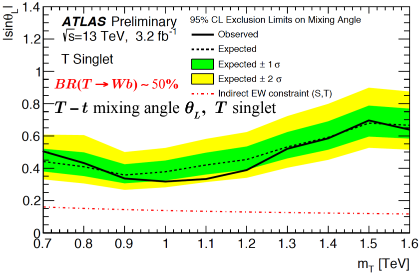


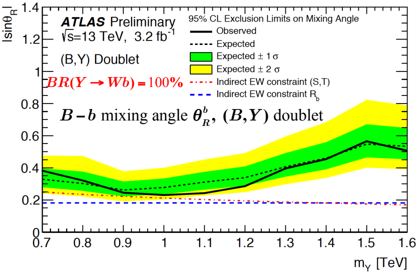
Limit on T, Y from single production



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

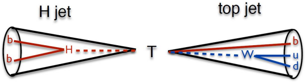




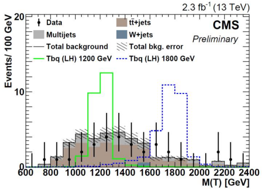
$T_{2/3} \rightarrow tH$: all hadronic

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



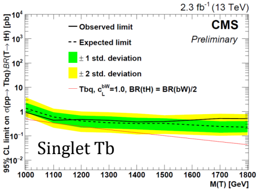
"ABCD method" for multijet background: three new regions from inverting tags

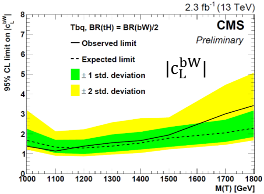
$$N_A/N_B = N_C/\mathbf{N_D}$$

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	**Signal Region** **D**

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

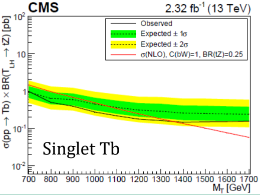


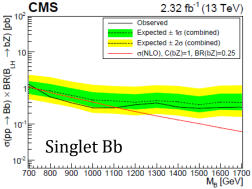


$T_{2/3} \rightarrow tZ$: dilepton

B2G-16-001

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