Composite Higgs

(Warped extradimensional analogues & LHC Signatures)

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Talk Outline

- $4D$ composite Higgs model
  - The Minimal Composite Higgs Model (MCHM)
- Motivations from AdS/CFT correspondence
- $5D$ AdS (warped) extradimensional analogue
- Phenomenology
  - Precision electroweak constraints
  - LHC Direct production
    - Z'_μ, W'_μ
    - $b'_{(-1/3)}$, $t'_{(2/3)}$, $\chi_{(5/3)}$
  - LHC Higgs observables

General Idea of Composite Higgs

[Georgi, Kaplan 1984]

- Sector with global symmetry $\mathcal{G}$
  - Σ transforms under $\mathcal{G}$

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  - **(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)

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    - 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 $SU(3)_L \otimes SU(3)_R \to SU(3)$

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)**

Structure of MCHM

- Strongly coupled (CFT) sector (with $\mathcal{G}$ global symmetry) condenses at a scale $\Lambda > 1$ TeV
  - The "low" energy theory has composite GB: $\pi^a = \{\phi^{1,2,3}, H\}$
    - $\Sigma = exp\left(-i\pi^{\hat{a}} T^{\hat{a}} / f_\pi\right)$
  - **SM fields W_μ, ψ are elementary states external to the CFT**

$$\mathcal{L} = \mathcal{L}_{CFT}(\Sigma) + \mathcal{L}_{SM\,(No\,H)} + J_\mu(\Sigma)\, W^\mu + \lambda \mathcal{O}^\alpha_{CFT}\, \psi_\alpha$$

- **SM ψ_α fermions mix with CFT fermionic operators**
  - So low energy mass eigen-states are admixtures of elementary and composite states $\rightarrow$ "partial compositeness"
- Anomolous dimension γ of $\mathcal{O}^\alpha_{CFT}$ dictates running of λ : **generates Hierarchical Yukawas**
  - Addresses flavor hierarchy puzzle of the SM!

Structure of MCHM

- Strongly coupled sector contributions cannot be computed perturbatively
- So parametrize in terms of **effective form-factors** $\Pi(p)$
  - In terms of these, write low energy theory $\mathcal{L}_{eff}$
- **AdS side is weakly coupled, and** $\Pi(p)$ **computed there**

Higgs potential

- Gauging a subgroup + Yukawa Interactions explicity breaks $\mathcal{G} = SO(5) \otimes U(1)_X$
  - generates a potential for the Higgs (so pseudo-GB composite Higgs)
  - **Coleman-Weinberg effective potential**
    - Gauge bosons + top loop contributions
  - Cannot compute $\mathcal{V}(\Sigma)$
- $\mathcal{H} = SO(4) \otimes U(1)_X \sim SU(2)_L \otimes SU(2)_R \otimes U(1)_X$
  - So $SU(2)_R$ **custodial symmetry present**
    - T-parameter under control

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

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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 $SO(4) \sim SU(2)_L \otimes SU(2)_R$):

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

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]

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

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

$4D \leftrightarrow 5D$ descriptions

[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

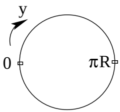
Randall-Sundrum Model

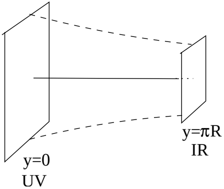
SM in background 5D warped AdS space [Randall, Sundrum '99]

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

Z_2 orbifold fixed points:

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





R : radius of Ex. Dim.

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

Hierarchy prob soln:

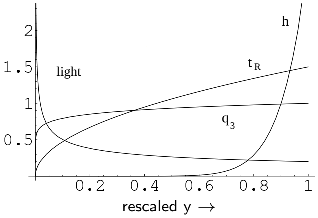
- IR localized Higgs : $M_{EW} \sim k e^{-k\pi R}$: Choose $k\pi R \sim 34$
  - Gauge-theory dual is a composite Higgs model

Explaining SM mass hierarchy

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

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

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



FCNC largely under control, but still strong constraints

AdS dual of MCHM

[Agashe, Contino, Pomarol, 2004]

- 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: $A|_{y=0} = 0$; $\partial_y A\,|_{y=\pi R} = 0$
- MCHM dual is

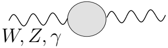
$$\begin{array}{cc} [SO(5) \otimes U(1)_X]/[SO(4) \otimes U(1)_X] & A_\mu^{\hat{a}}(--),\ A_5^{\hat{a}}(++) \\ T_L,\ T_R^3 + X & A_\mu(++),\ A_5(--) \\ T_R^\pm,\ T_R^3 - X & A_\mu(-+),\ A_5(+-) \end{array}$$

- $A_5^{\hat{a}}(++)$ **dual of PGB** $\pi^a = \{\phi^{1,2,3},\ H\}$! [Contino, Nomura, Pomarol 2003]
  - **Gauge symmetry forbids tree-level mass**
  - **Mass at loop-level from gauge and top loops** [Hosotani 1983]

Precision Electroweak Constraints

Precision Electroweak Constraints (S, T, $Zb\bar{b}$)

(perturbatively calculable on the warped side)

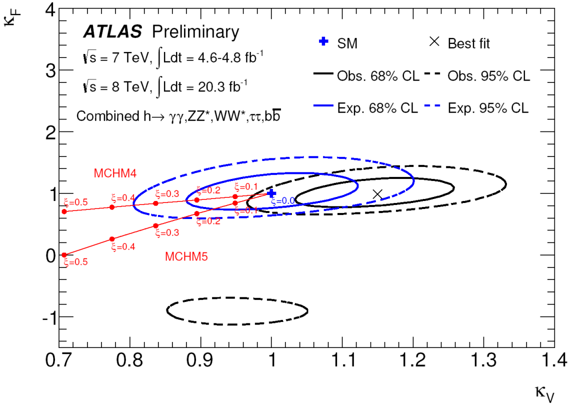


- Bulk gauge symm - $SU(2)_L \times U(1)$ (SM ψ, H on TeV Brane)
  - T parameter $\sim (\frac{v}{M_{KK}})^2 (k\pi R)$ [Csaki, Erlich, Terning 02]
  - S parameter also $(k\pi R)$ enhanced
- AdS bulk gauge symm $SU(2)_R$ $\Leftrightarrow$ CFT Custodial Symm [Agashe, Delgado, May, Sundrum 03]
  - T parameter - 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]

ATLAS limit on MCHM

Constraints from 125 GeV Higgs coupling measurements



(Note: $\xi \equiv v^2/f^2$) [ATLAS-CONF-2014-010]

At 95 % CL, $\xi < 0.12 \quad \Longrightarrow \quad f > 710$ GeV; $m_\rho > 9/\sqrt{N}$ TeV

KK states at the LHC

- $h^{(1)}_{\mu\nu}$ (KK Graviton) $gg \to h^{(1)} \to t\bar{t}$

  $L = 300\, fb^{-1}$ LHC reach is about 2 TeV
  [Agashe, Davoudiasl, Perez, Soni 07]
  [Fitzpatrick, Kaplan, Randall, Wang 07]

- $g^{(1)}_{\mu}$ (KK Gluon) $q\bar{q} \to g^{(1)} \to t\bar{t}$

  $L = 100\, fb^{-1}$ LHC reach is 4 TeV
  [Agashe, Belyaev, Krupovnickas,Perez,Virzi 06]
  [Lillie, Randall, Wang, 07] [Lillie, Shu, Tait 07]

- $Z^{(1)}_{\mu}$, $W^{(1)\pm}_{\mu}$ $(Z_{KK} \equiv Z'\ ,\ W^{\pm}_{KK} \equiv W')$ $q\bar{q} \to Z', W' \to XX$

  [*Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni* 0709.0007 & 0810.1497]

- $\psi^{(1)}$ (KK Fermion) [Agashe, Servant 04][Dennis et al 07][Contino, Servant 08]
  [Mandal, Mitra, Moreau, SG, Tibrewala '11, '13]

- Radion [Csaki, Hubisz, Lee, '07]

Review: [Davoudiasl, SG, Ponton, Santiago, New J.Phys.12:075011,2010. arXiv:0908.1968 [hep-ph]]

Bulk Gauge Group

[Agashe, Delgado, May, Sundrum 03]

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

- 8 gluons
- 3 neutral EW (W_L^3, W_R^3, X)
- 2 charged EW $(W_L^\pm, W_R^\pm)$

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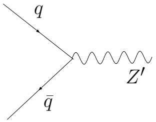
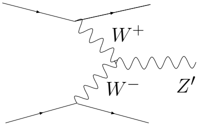
Gauge Symmetry breaking:

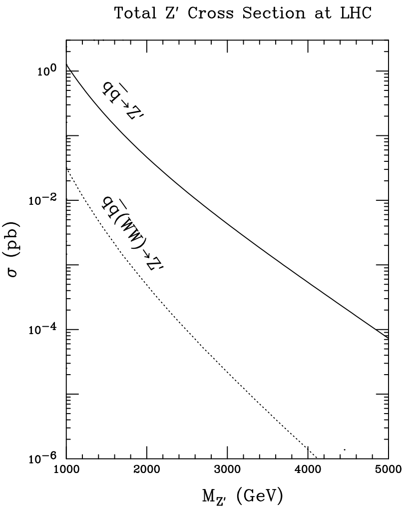
- By Boundary Condition (BC): $A_{-+}(x,y)$ BC: $A|_{y=0} = 0\,;\ \partial_y A\,|_{y=\pi R} = 0$
  - $SU(2)_R \times U(1)_X \to U(1)_Y$
- By VEV of TeV brane Higgs — Higgs $\Sigma = (2,2)$
  - $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

Z' production at the LHC

[*Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni* 0709.0007 & 0810.1497]







Z' channels summary

[*Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni* 0709.0007]
$(\mathcal{L}_{2\ TeV};\ \mathcal{L}_{3\ TeV})$ in fb^{-1}

- $pp \to Z' \to W^+W^-$
  - Fully leptonic : $W \to \ell\nu$; $W \to \ell\nu$ — $\mathcal{L}$: (100; 1000) fb^{-1}
  - Semi leptonic : $W \to \ell\nu$; $W \to (j\,j)$ — $\mathcal{L}$: (100; 1000) fb^{-1}
- $pp \to Z' \to Z\,h$
  - $Z \to \ell^+\ell^-$; $h \to b\,\bar{b}$ — $\mathcal{L}$: (200; 1000) fb^{-1}
- $pp \to Z' \to \ell^+\ell^-$ — $\mathcal{L}$: (1000; −) fb^{-1}
  - $BR_{\ell\ell} \sim 10^{-3}$ Tiny!
- $pp \to Z' \to t\,\bar{t}\ ,\ \ b\,\bar{b}$
  - KK gluon "pollution" — [Djouadi, Moreau, Singh 07]

$W'^{\pm}$ channels summary

[*Agashe, SG, Han, Huang, Si, Soni* 0810.1497]
$(\mathcal{L}_{2\ TeV};\ \mathcal{L}_{3\ TeV})$ in fb^{-1}

- $W'^{\pm} \to t\, b$:
  - Leptonic — $\mathcal{L}:\ (100;\ 1000)\ \ fb^{-1}$
    - $t\,\bar{t}$ becomes (reducible) bkgnd since collimated t can fake a b-jet
      Jet-mass cut : cone size 1.0 and $0 < j_M < 75$ ⇒0.4% of *tops* fake b

- $W'^{\pm} \to Z\, W$:
  - Fully leptonic — $\mathcal{L}:\ (100;\ 1000)\ \ fb^{-1}$
  - Semi leptonic — $\mathcal{L}:\ (300;\ -)\ \ fb^{-1}$

- $W'^{\pm} \to W\, h$: — $\mathcal{L}:\ (100;\ 300)\ \ fb^{-1}$
  - $h \to b\, b$

Warped vectorlike fermions

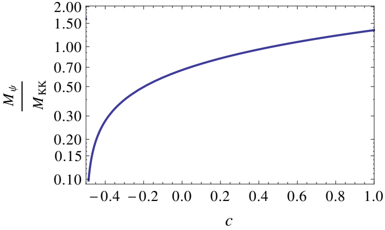
- SM fermions : $(+,+)$ BC $\rightarrow$ zero-mode
- "Exotic" fermions : $(-,+)$ BC $\rightarrow$ No zero-mode
    - 1^{st} KK vectorlike fermion

- 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



[Contino, da Rold, Pomarol, '06]

t', b', $\chi_{5/3}$ Vectorlike fermions at the LHC

Model independent analysis,

motivated by *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 (a partial list!): [Dennis et al, '07] [Carena et al, '07] [Contino, Servant, '08]
[Atre et al, '08, '09, '11] [Aguilar-Saavedra, '09] [Mrazek, Wulzer, '09] [Han et al. '10]
[SG, Moreau, Singh, '10] [Bini et al. '12][Buchkremer et al. '13]
[Delaunay et al. '14][Flacke et al. '14] [Backovic et al. '14]

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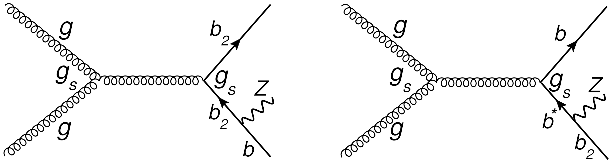
- VL Tree-level Decays
  - $b' \to tW$, $b' \to bZ$, $b' \to bh$
  - $t' \to bW$, $t' \to tZ$, $t' \to th$
  - $\chi \to tW$

b' Single & Double Resonant channels

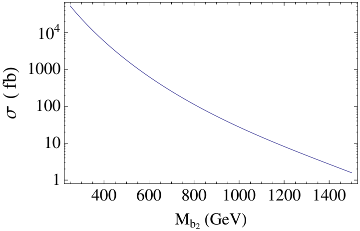


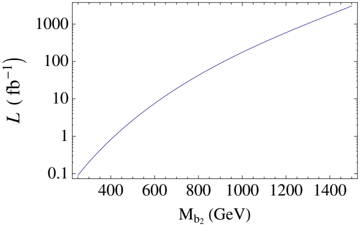
... followed by $b_2 \to bZ$

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





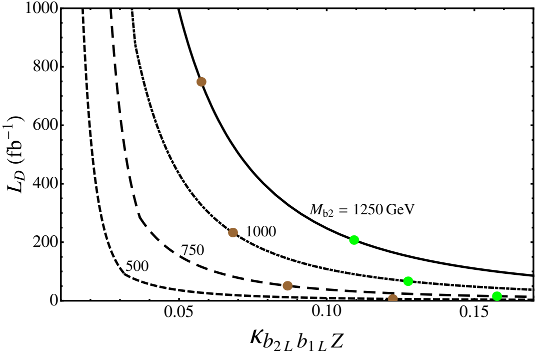
Cuts:

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

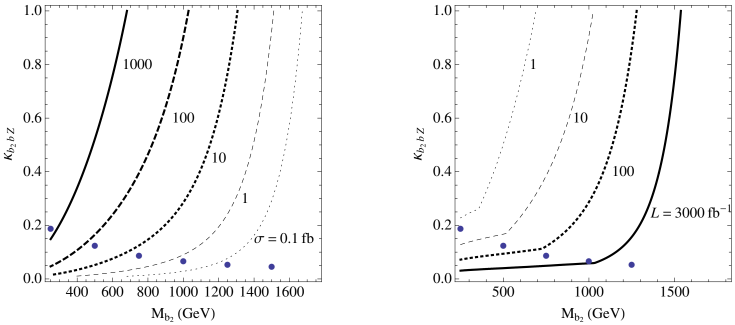
Model Independent LHC-14 reach



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:

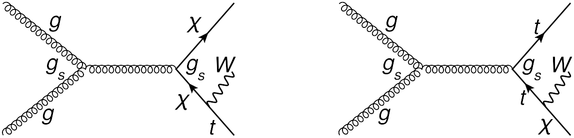
Rapidity: $-2.5 < y_{b,j,Z} < 2.5$,
Transverse momentum: $p_{T\,b,j,Z} > 0.1 M_{b_2}$,
Invariant mass cuts:
$M_Z - 10\ \mathrm{GeV} < M_{jj} < M_Z + 10\ \mathrm{GeV}$,
$0.95 M_{b_2} < M_{(bZ)\ OR\ (bjj)} < 1.05 M_{b_2}$.

χ Phenomenology at the LHC

[SG, T.Mandal, S.Mitra, G.Moreau : arXiv:1306.2656]

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

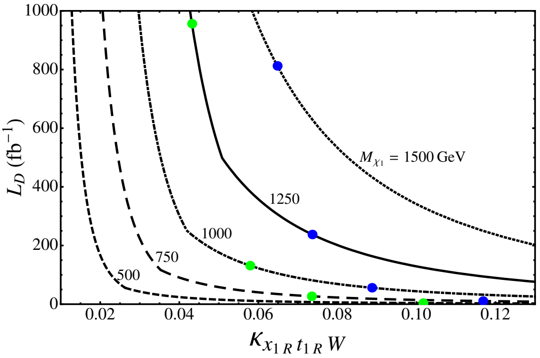
χ Double and Single Resonant channels



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

X	M_X (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



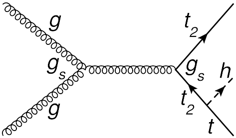
Blue Dots - ST Model   Green Dots - TT Model

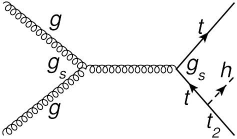
t' Phenomenology at the LHC

[SG, Tanumoy Mandal, Subhadip Mitra, Gregory Moreau : arXiv:1306.2656]

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

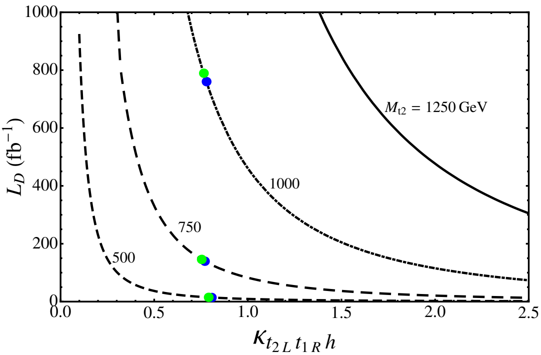




$$pp \to t_2 th \to thth \to tbbtbb \to 6\ b\ 4\ j \qquad \text{(4 b-tags)}$$

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

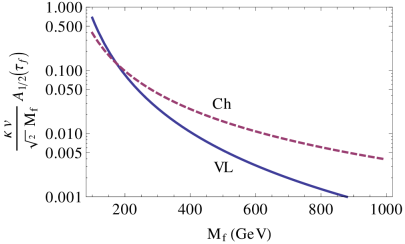
t' Single Resonant channel



Blue Dots - ST Model   Green Dots - TT Model

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: ExtraDim Th $M = M_{KK} \sim TeV$, SUSY solutions to μ problem
  - Decoupling behavior : S, T, U, $h \to \gamma\gamma$, $gg \to h$, ...
    - For instance $h\gamma\gamma$, ggh couplings

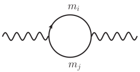


VL fermions in EWPT and Higgs Observables

Survey of vector-like fermion extensions of the Standard Model and their phenomenological implications

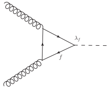
[S.Ellis, R.Godbole, SG, J.Wells; 1404.4398 [hep-ph], JHEP 1409 (2014) 130]

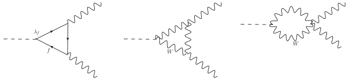
Precision electroweak observables (S, T, U)



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

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





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]

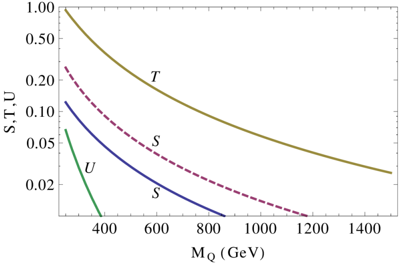
$$\mu^{VBF}_{\gamma\gamma} \approx \frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} \; ; \quad \mu^{ggh}_{ZZ} \approx \frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} \; ; \quad \mu^{ggh}_{\gamma\gamma} \approx \frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} \frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}}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

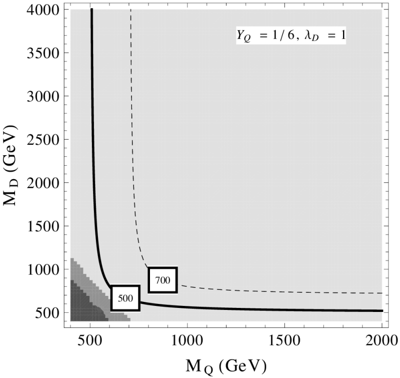
SM-like vectorlike fermions

Simple VL extensions of SM (No mixing to SM fermions)

- $1\bar{1}$: $SU(2)$ 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)

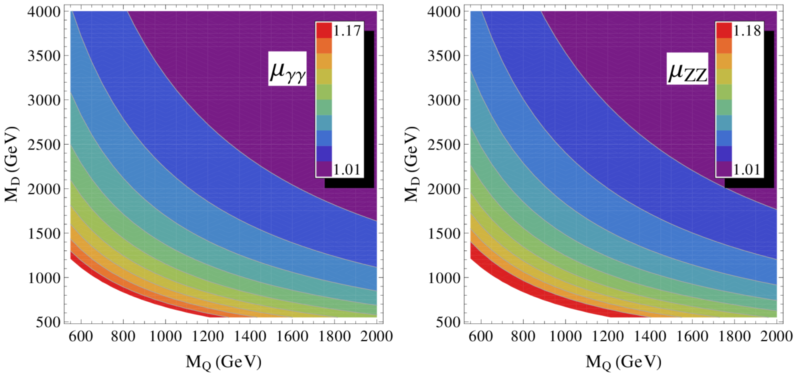
$2\bar{2} + 1\bar{1}$: MVQD





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

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



Conclusions

- Minimal Composite Higgs Model (MCHM) as a paradigm
- Warped extradimensional theory is a calculable analogue
- Probe these in
  - precision EW and Flavor observables
  - h couplings shifts
  - direct LHC searches for: $V'_\mu, \psi', h'_{\mu\nu}, \phi'$
- Upcoming LHC run exciting!

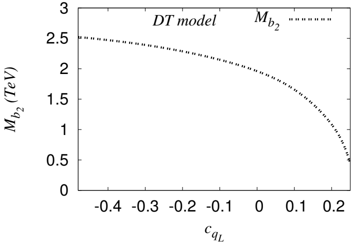
BACKUP SLIDES

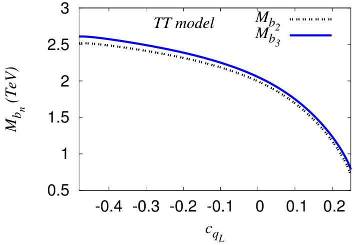
Yukawa Couplings

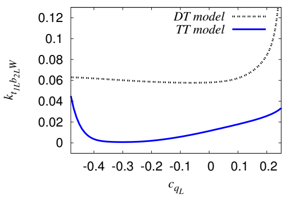
Yukawa Couplings

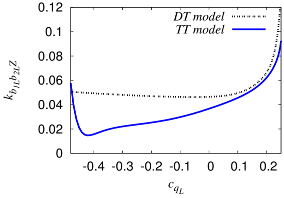
- No $Zb\bar{b}$ protection
  $$\mathcal{L}_{\rm Yuk} \supset \lambda_t\ \bar{Q}_L \Sigma \psi_{t_R} + \lambda_b\ \bar{Q}_L \Sigma \psi_{b_R} + h.c.$$
- With $Zb\bar{b}$ protection
  - ST Model $\quad \mathcal{L}_{\rm Yuk} \supset \lambda_t\ {\rm Tr}[\bar{Q}_L \Sigma]\ t_R + h.c.$
  - TT Model $\quad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

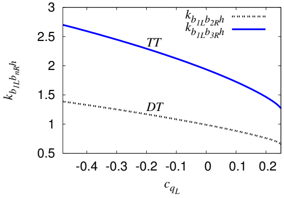
Warped model b' parameters



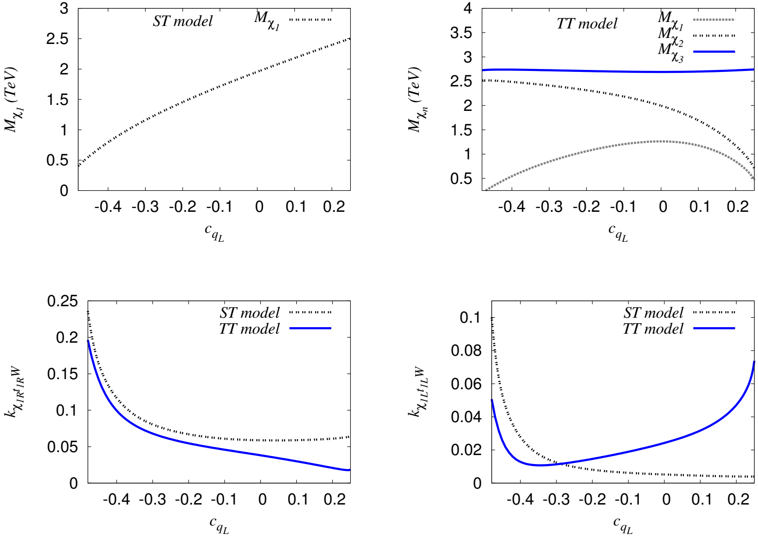




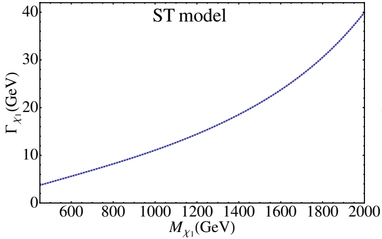


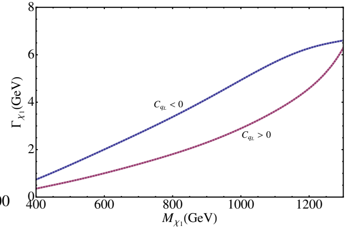


Warped model χ parameters



Warped model Γ_χ

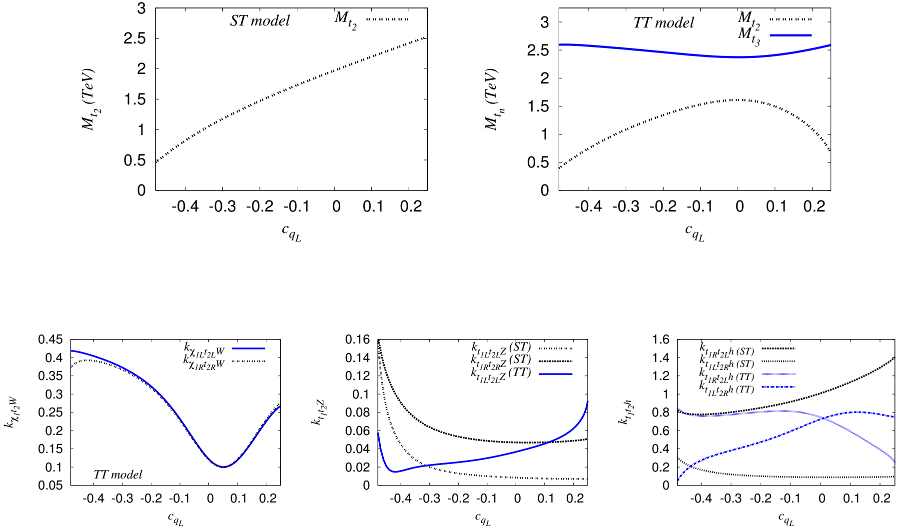




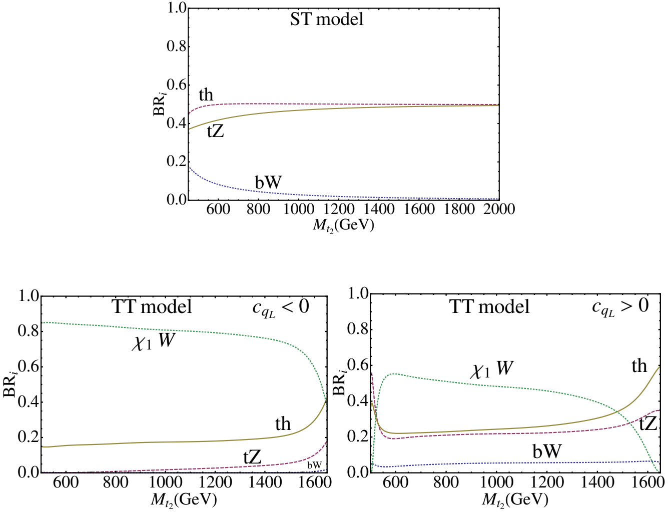
ST Model

TT Model

Warped model t' parameters



Warped model t' BR



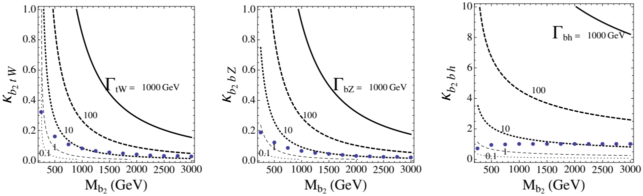
b' Pair Production Details

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

M_{b_2} (GeV)	Signal σ_s (in fb) $bZbZ$		Background σ_b (in fb) $bZbZ$		Background σ_b (in fb) $(bjjbZ)_{\rm tot}$		$\mathcal{L}$ (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) $bjjbZ$		QCD background (in fb) $bbjbZ$		QCD background (in fb) $bbbbZ$	
	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)

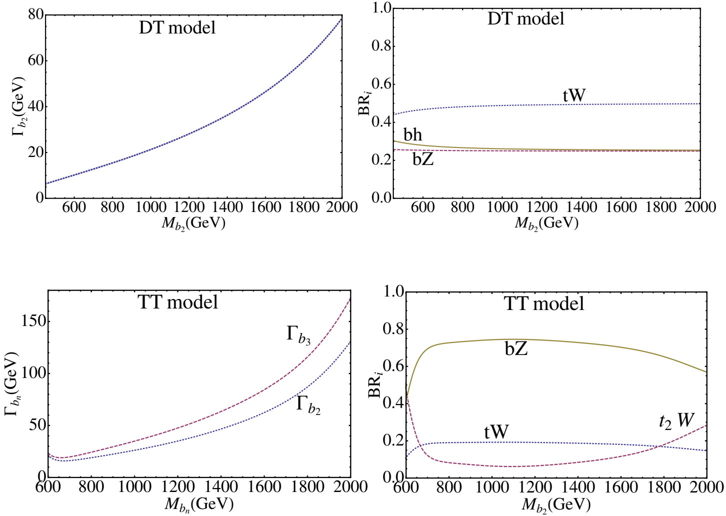


Benchmark Points (Model I):

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)				$\mathcal{L}_{\rm SemiLep}$ (fb^{-1})
	$bjjZ$		$(bjjZ)_{EW}$		$(bjjZ)_{\rm QCD}$		
	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

Vectorlike fermions

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

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

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

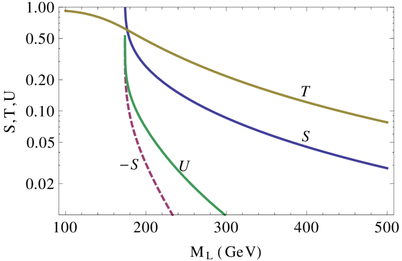
$$\mathcal{L}_{\rm Yuk} \supset -\lambda'_\xi \bar{Q} \cdot H^* \xi - \lambda'_\Upsilon \bar{Q} H \Upsilon - \lambda'_U \bar{\mathcal{X}} \cdot H^* U - \lambda'_D \bar{\mathcal{X}} H D + h.c.$$

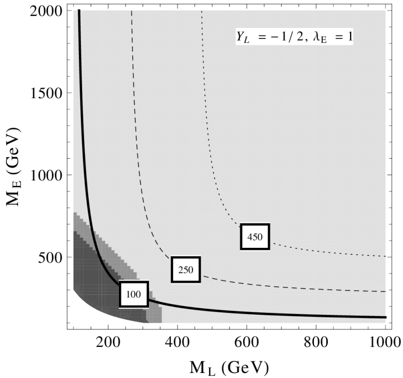
similarly for the VL-leptons

- 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]

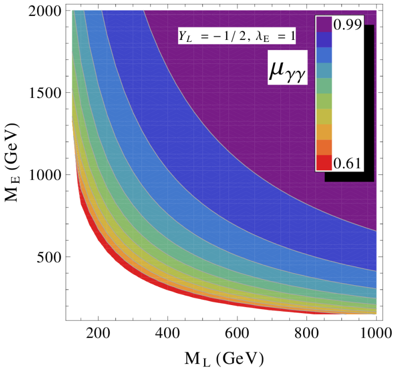
$2\bar{2} + 1\bar{1}$: MVLE



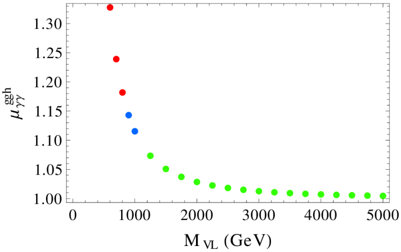


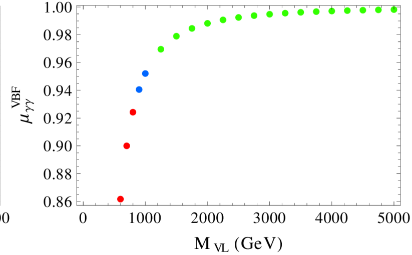
$\lambda_E = 1,\ M_E = M_L,\ Y_L = (-1/2, 1/2)$ (solid,dashed)

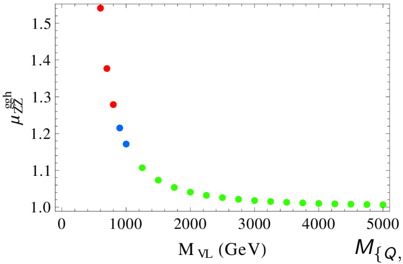
$2\bar{2} + 1\bar{1}$: MVLE



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



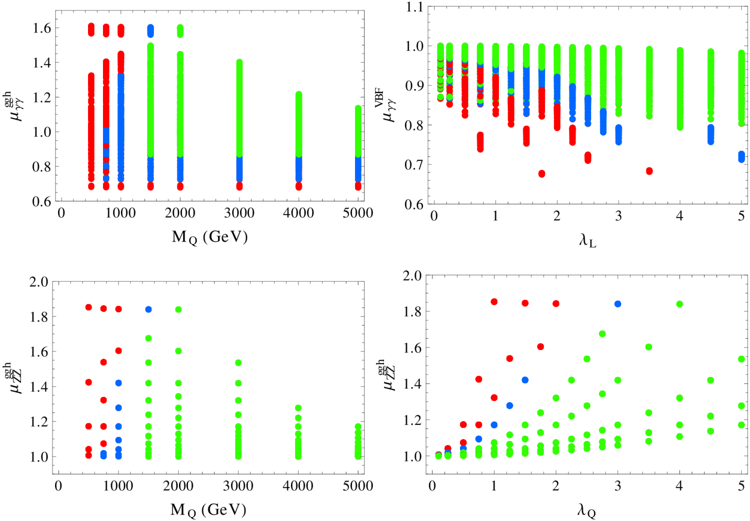




Category	M_q(Gev)	M_ℓ (GeV)	Color
Light	≤ 700	≤ 450	Red
Medium	(700, 1000)	(450, 750)	Blue
Heavy	> 1000	> 750	Green

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

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



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

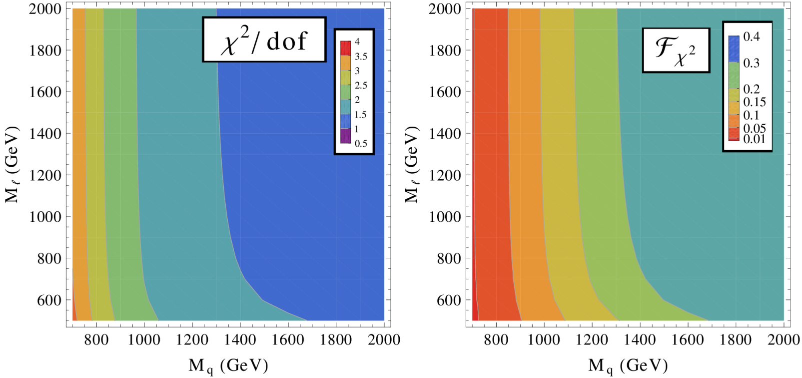
χ^2 fit to the LHC Data

[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

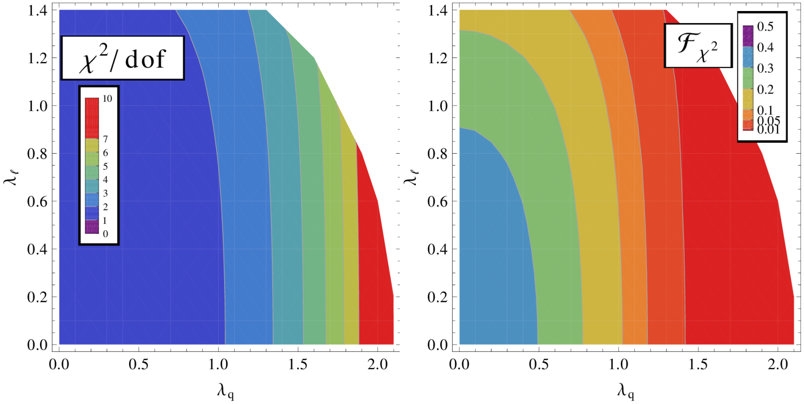
$$\chi^2 = \sum_{i=1}^{4} \left(\kappa_i^{\mathrm{Exp}} - \kappa_i^{\mathrm{Th}}\right)^2 / \left(\sigma_i^{\mathrm{Exp}}\right)^2$$

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



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