Current Status of Extra Dimension (inspired) Models

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Workshop on High Energy Physics Phenomenology XIV
IIT Kanpur
Dec 2015

Motivation

- SM hierarchy problem: $M_{EW} \ll M_{Pl}$
- SM flavor problem: $m_e \ll m_t$
- Explained by new dynamics?
  - **Extra dimensions** (**Warped** (AdS), Flat)
  - Supersymmetry
  - Strong dynamics
  - Little Higgs
- AdS/CFT correspondence [Maldacena 97]
  - 5-D gravity theory in AdS $\underset{DUAL}{\longleftrightarrow}$ 4-D conformal field theory

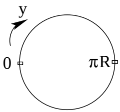
Warped Model

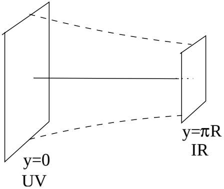
SM in background 5D warped AdS space [Randall, Sundrum 99]

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

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 $k\pi R \sim 34$
  - CFT 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 $\phi_0(x) = \phi(y = y_0, x)$

$4D \leftrightarrow 5D$ descriptions

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

- Dual of Randall-Sundrum model **RS1 (SM on IR Brane)**
  - Planck brane $\implies$ UV Cutoff; Dynamical gravity in the 4D CFT
  - TeV (IR) brane $\implies$ 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 ↔ Minimal Composite Higgs Model [SO(5)/SO(4)]

[Agashe, Contino, Pomarol, 2004]

- AdS/CFT Corrsp : $\mathcal{G}$ global symm of CFT ↔ AdS gauge symm
  - Bulk gauge group : $SO(5) \otimes U(1)_X$ $\qquad A_M = (A_\mu, A_5)$
- **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: $A|_{y=0} = 0\,;\ \partial_y A\,|_{y=\pi R} = 0$
- Minimal Composite Higgs Model (MCHM) dual is

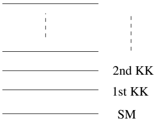
$$\begin{array}{cc} [SO(5) \otimes U(1)_X]/[SO(4) \otimes U(1)_X] & A_\mu^{\hat{a}}(--),\ A_5^{\hat{a}}(++) \\ T_L,\ T_R^3 + X & A_\mu(++),\ A_5(--) \\ T_R^{\pm},\ T_R^3 - X & A_\mu(-+),\ A_5(+-) \end{array}$$

- $A_5^{\hat{a}}(++)$ **dual of 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]

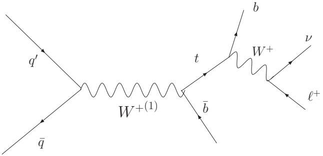
Kaluza-Klein (KK) tower

Kaluza-Klein (KK) decomposition

- 5D (compact) field $\leftrightarrow$ Infinite tower of 4D fields
- Look for this tower
  - at the LHC
  - in Precision-EW obs, Flavor Changing NC, CC



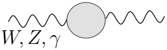
Example LHC:



Look for heavy Kaluza-Klein (KK) states : KK $h^{(1)}_{\mu\nu}$, $g^{(1)}_{\mu}$, $W^{(1)}_{\mu}$, $Z^{(1)}_{\mu}$, $b^{(1)}_{\alpha}$, ...

LEP precision electroweak constraints $\Rightarrow W^{(1)}_{\mu}, Z^{(1)}_{\mu} \gtrsim 2$ TeV

Precision EW Constraints



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

- 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 $\Rightarrow M_{KK} \gtrsim 2-3$ TeV

[Carena, Ponton, Santiago, Wagner 06,07] [Bouchart, Moreau-08] [Djouadi, Moreau, Richard 06]

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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- 2 charged EW $(W_L^{\pm}, W_R^{\pm})$

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 TeV brane Higgs Higgs $\Sigma = (2,2)$
  - $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

Fermion reps (Model II)

[Agashe, Contino, DaRold, Pomarol 06]

Custodial protection for $Zb_L\overline{b_L}$ coupling

Impose custodial $SU(2)_{L+R} \otimes P_{LR}$ invariance

Fermions:

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

  $t_R : (1,1)$ OR $(1,3) \oplus (3,1) = \begin{pmatrix} \chi'_R \\ t_R \\ b'_R \end{pmatrix} \oplus \begin{pmatrix} \chi''_R \\ t''_R \\ b''_R \end{pmatrix}$; $b_R : (1,1)$ OR $(1,3) \oplus (3,1)$
- $Zb_L\overline{b_L}$ coupling protected! Note: Wt_Lb_L, Zt_Lt_L not protected, so expect shifts

New "exotic" fermions ζ_L, T_L, χ'_R, b'_R, ...

- No zero-mode. $(-,+)$ BC $\Longrightarrow M_{\psi'} < M_{A'}$ [Agashe, Servant 04]
- Promising LHC signatures

4-D couplings

$$\xi \equiv \sqrt{k\pi R} \approx 5$$

Compare to SM couplings:

- ξ enhanced: $t_R t_R A'$, hhA', $\phi\phi A'$ (Equivalence Theorem $\Rightarrow$ $\phi \leftrightarrow A_L$)
- $1/\xi$ suppressed: $\psi_{light}\, \psi_{light}\, A'_{++}$ Note: $\psi_{light}\, \psi_{light}\, A'_{-+} = 0$
- SM strength: $t_L t_L A'$

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Effective coupling (Eg: Z'):

$$\mathcal{L}^{4D} \supset \bar{\psi}_{L,R} \gamma^{\mu} \left[eQ\mathcal{I} A_{1\,\mu} + g_Z \left(T_L^3 - s_W^2 T_Q \right) \mathcal{I} Z_{1\,\mu} + g_{Z'} \left(T_R^3 - s'^2 T_Y \right) \mathcal{I} Z_{X\,1\,\mu} \right] \psi_{L,R}$$

KK states (heavy resonances) 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* 07, 08]

- $\psi^{(1)}$ (KK Fermion) [Agashe, Servant 04][Dennis et al 07][Contino, Servant 08] [SG, Moreau, Singh, 10][SG, Mandal, Mitra, Moreau, Tibrewala 11, 14]
- Radion [Csaki et al, 2001, 2007] [Gunion et al, 2004]
- Extended Higgs sector [T. Mukherjee, S. Sadhukhan, SG: In progress]

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

ATLAS Exotics searches

ATLAS Exotics Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.7 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

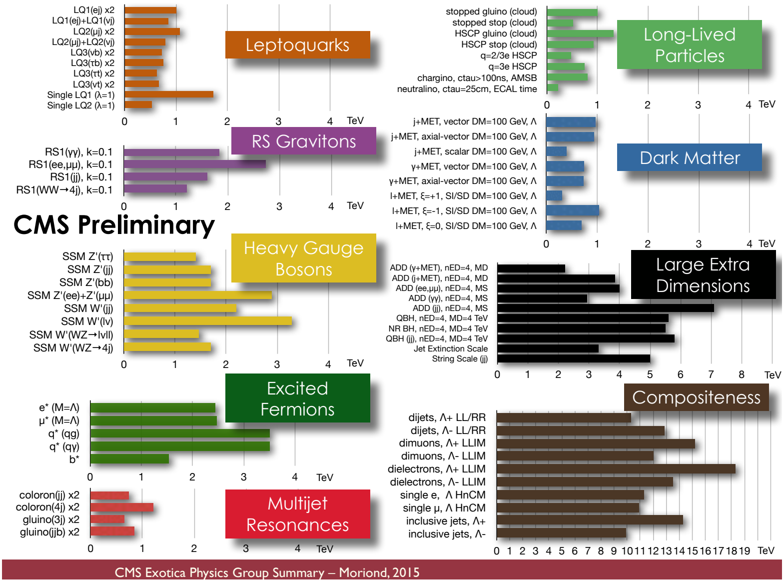
	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D 5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	2e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1503.08988
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	2 j / 1 J	Yes	20.3	W' mass 760 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 500-720 GeV	$k/\overline{M}_{Pl} = 1.0$	1506.00285
	Bulk RS $g_{KK} \to t\bar{t}$	1 e, μ	≥ 1 b, $\geq$ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV		1504.04605
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	20.3	W' mass 3.24 TeV		1407.7494
	EGM $W' \to WZ \to \ell\nu\ell'\ell'$	3 e, μ	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W' mass 1.59 TeV		1409.6190
	EGM $W' \to WZ \to qqqq$	–	2 J	–	20.3	W' mass 1.3-1.5 TeV		1506.00962
	HVT $W' \to WH \to \ell\nu bb$	1 e, μ	2 b	Yes	20.3	W' mass 1.47 TeV	$g_V = 1$	1503.08089
	LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	Λ 12.0 TeV	$\eta_{LL} = -1$	1504.00357
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.3 TeV	$\lvert C_{LL}\rvert = 1$	1504.04605
DM	EFT D5 operator (Dirac)	0 e, μ	≥ 1 j	Yes	20.3	M_* 974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	20.3	LQ mass 1.05 TeV	$\beta = 1$	Preliminary
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	20.3	LQ mass 1.0 TeV	$\beta = 1$	Preliminary
	Scalar LQ 3rd gen	1 e, μ	$\geq$1 b, $\geq$3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	Preliminary
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	$T_{5/3} \to Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	20.3	q* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1407.1376
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
	Excited lepton $\nu^* \to \ell W, \nu Z$	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2 e, μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	Preliminary

$\sqrt{s} = 7$ TeV $\sqrt{s} = 8$ TeV

10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

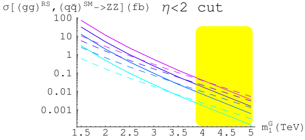
CMS Exotics searches



KK-graviton

$$m_n = x_n k e^{-k\pi r} \qquad x_n = 3.83, 7.02, \ldots$$
$$\mathcal{L} \supset -\frac{C^{ffG}}{\Lambda} T^{\alpha\beta} h^{(n)}_{\alpha\beta} \qquad \Lambda = \bar{M}_P e^{-k\pi r}$$

$$gg \to h^{(1)} \to ZZ \to 4\ell$$

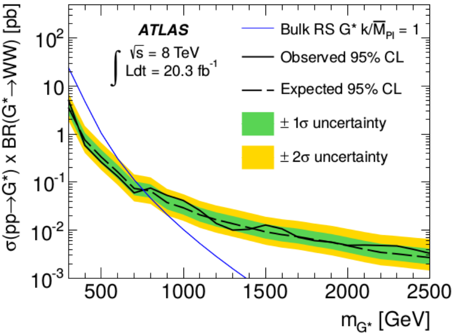


various $\frac{k}{M_p}$; SM dashed

[Agashe, Davoudiasl, Perez, Soni, 2007]

[Agashe et al, 07] [Fitzpatrick et al, 07]

- SM in Bulk (flavor)
  - light fermion couplings highly suppressed
  - gauge field couplings $\frac{1}{k\pi r}$ suppressed
  - Decays dominantly to t, h, V_{Long}



KK-gluon

[Agashe et al, 06] [Lillie et al, 07]

$m_n = x_n k e^{-k\pi r}$ $\quad x_n \approx 2.45,\ 5.57,\ \ldots$ $\quad$ Width $\Gamma \approx \frac{M}{6}$

$g^{(1)} t\bar{t}$: parity violating couplings!

$$\text{LHC: } q\bar{q} \to g^{(1)} \to t\bar{t}$$

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[Agashe et al, 06] [Lillie et al, 07]

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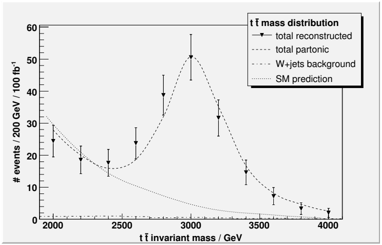
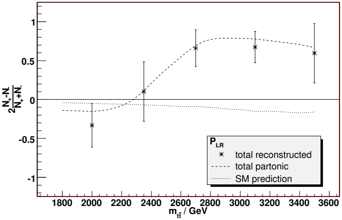
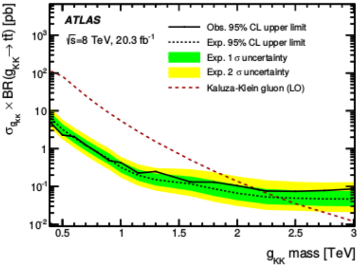




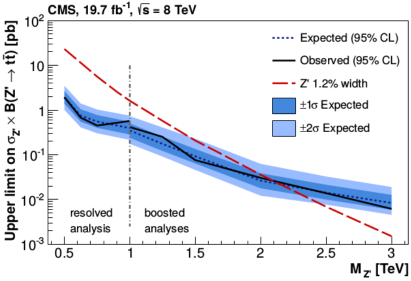
$P_{LR} = 2\frac{N_+ - N_-}{N_+ + N_-}$ N_+ forward going ℓ wrt k_t

LHC reach: About 4 TeV with 100 fb^{-1}

LHC KK-gluon $\to t\bar{t}$ search



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

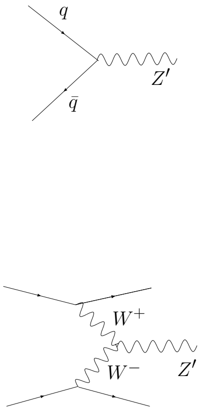


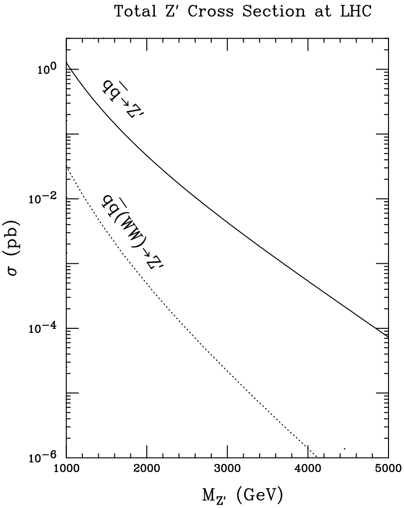
Limit: $M_{KK} > 2.2$ TeV @ 95% CL

[ATLAS 1505.07018; CMS 1309.2030]

Z' production at the LHC

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





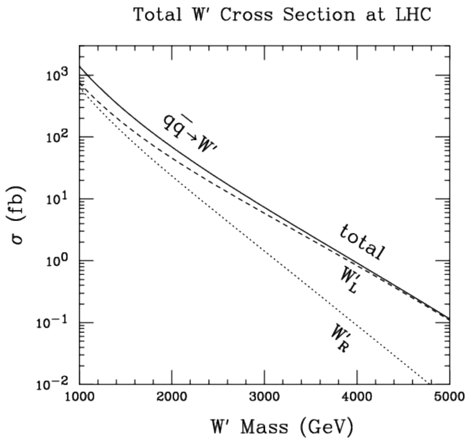
Z' channels summary

[Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni: 0709.0007]

- $pp \to Z' \to W^+ W^-$ — $(\mathcal{L}_{2\ TeV};\ \mathcal{L}_{3\ TeV})$ in fb^{-1}
- 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' cross section

[Agashe, SG, Han, Huang, Soni, 0810.1497]



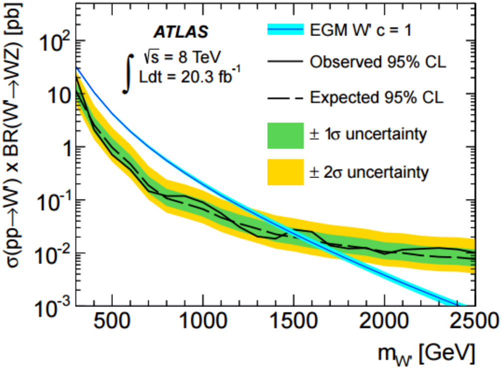
$W'^{\pm}$ channels summary

[Agashe, SG, Han, Huang, Soni, 0810.1497]

$(\mathcal{L}_{2\ TeV};\ \mathcal{L}_{3\ TeV})$ in fb^{-1}

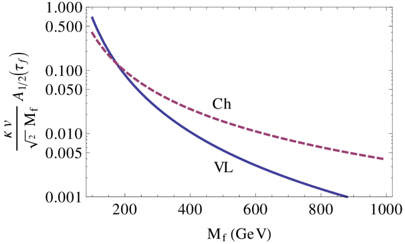
- $W'^{\pm} \to t\, b$:
  - Leptonic — $\mathcal{L}$: (100; 1000) fb^{-1}
- $W'^{\pm} \to Z\, W$:
  - Fully leptonic — $\mathcal{L}$: (100; 1000) fb^{-1}
  - Semi leptonic — $\mathcal{L}$: (300; −) fb^{-1}
- $W'^{\pm} \to W\, h$: — $\mathcal{L}$: (100; 300) fb^{-1}

LHC Data ($W' \to WZ$)



Vector-like 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



Warped vectorlike fermions

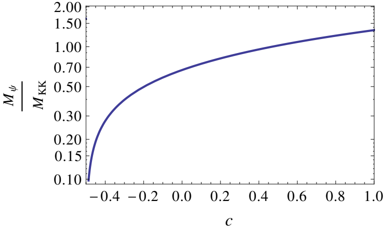
- SM fermions : $(+,+)$ BC $\rightarrow$ zero-mode
- "Exotic" fermions : $(-,+)$ BC $\rightarrow$ No zero-mode
    - 1^{st} KK vectorlike fermion

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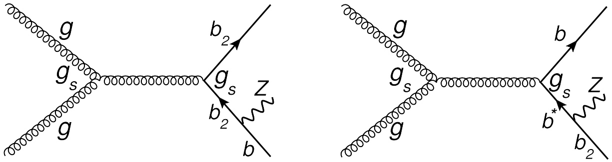
  - $g_Z \neq g'_Z$ leads to $b'bZ$ coupling
  - Similarly $t'tZ$, $t'th$ couplings also, in addition to $t'bW$
- VL Tree-level Decays
  - $b' \to tW$, $b' \to bZ$, $b' \to bh$
  - $t' \to bW$, $t' \to tZ$, $t' \to th$
  - $\chi \to tW$

b' Single & Double Resonant channels

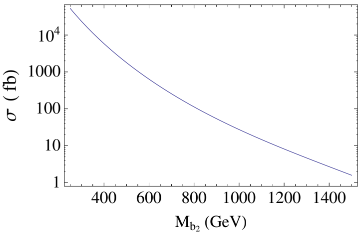


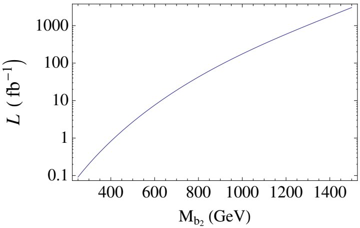
... followed by $b_2 \to bZ$

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





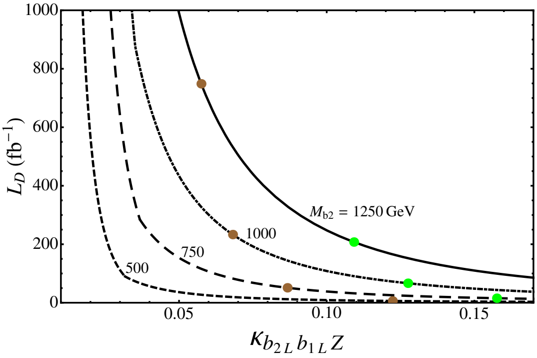
Cuts:

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

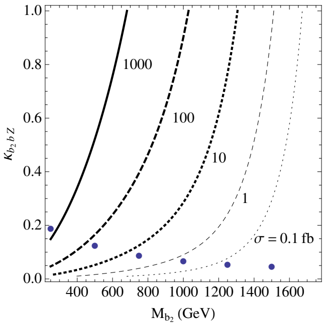
Model Independent LHC-14 reach

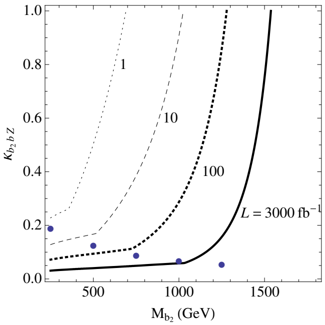


Brown dots : DT Model Green dots : TT Model

b' Single Production - II

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





Cuts:

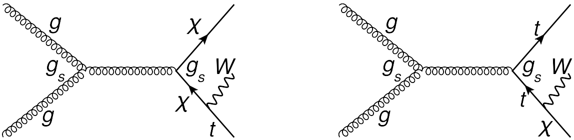
Rapidity: $-2.5 < y_{b,j,Z} < 2.5$,
Transverse momentum: $p_{T\,b,j,Z} > 0.1 M_{b_2}$,
Invariant mass cuts:
$M_Z - 10\ \mathrm{GeV} < M_{jj} < M_Z + 10\ \mathrm{GeV}$,
$0.95 M_{b_2} < M_{(bZ)\ OR\ (bjj)} < 1.05 M_{b_2}$.

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]

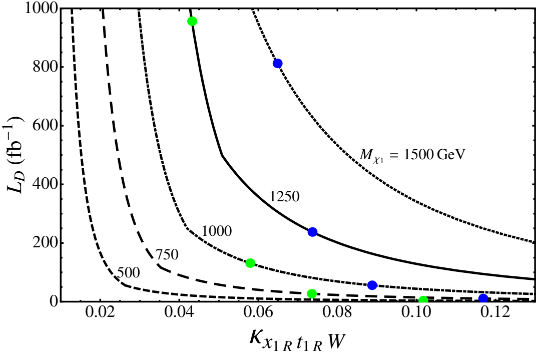
χ Double and Single Resonant channels



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

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

χ Single Resonant Channel



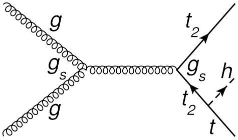
Blue Dots - ST Model Green Dots - TT Model

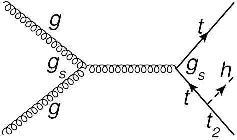
t' Phenomenology at the LHC

[SG, 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

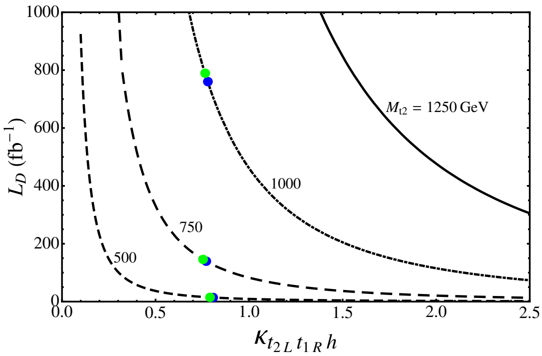




$$pp \to t_2 th \to thth \to tbbtbb \to 6\ b\ 4\ j \qquad \text{(4 b-tags)}$$

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



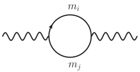
Blue Dots - ST Model Green Dots - TT Model

VL fermions in EWPT and Higgs Observables

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

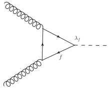
[S.Ellis, R.Godbole, SG, J.Wells; 1404.4398 [hep-ph], JHEP 1409 (2014) 130]

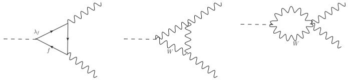
Precision electroweak observables (S, T, U)



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

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





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]

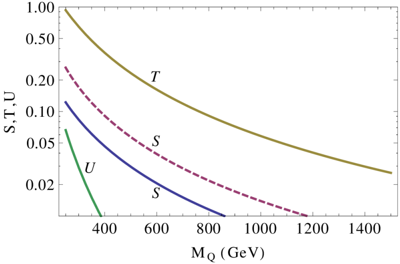
$$\mu^{VBF}_{\gamma\gamma} \approx \frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} \; ; \quad \mu^{ggh}_{ZZ} \approx \frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} \; ; \quad \mu^{ggh}_{\gamma\gamma} \approx \frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} \frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}}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

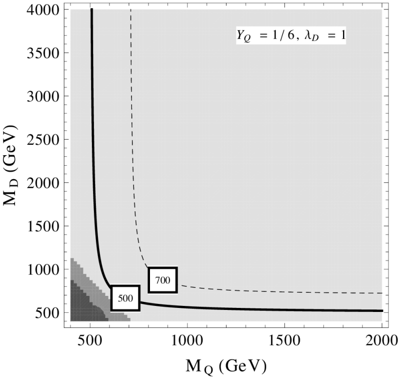
SM-like vectorlike fermions

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)

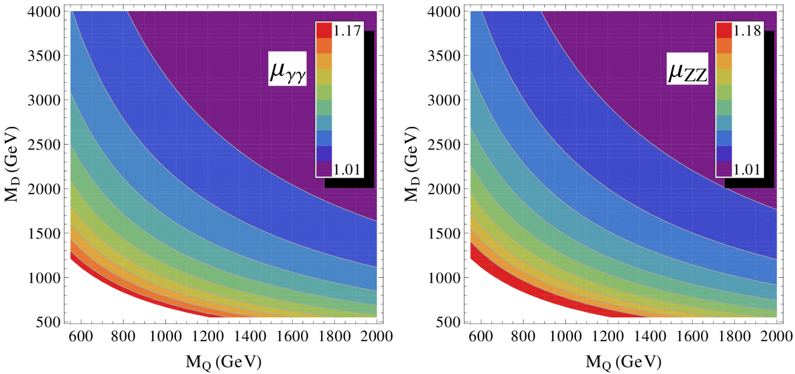
$2\bar{2} + 1\bar{1}$: MVQD





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

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



Heavy 2HDM Scalars (in SU(6)/Sp(6) Little-Higgs)

[SG, Soumya Sadhukhan, Tuhin S. Mukherjee: on-going]

Low, Skiba, Smith (LSS) Model (2002) : SU(6)/Sp(6)

$$\Sigma = \exp\{\frac{i\pi^a X^a}{f}\}\,\langle\Sigma\rangle \; ; \qquad \langle\Sigma\rangle = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}_{6\times 6} \; ; \qquad \pi^a X^a \supset \begin{pmatrix} \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \phi_2 & \begin{matrix} 0 & s \\ -s & 0 \end{matrix} & \phi_1 \\ \phi_2^\dagger & 0 & -\phi_1^T & 0 \\ \begin{matrix} 0 & -s^* \\ s^* & 0 \end{matrix} & -\phi_1^* & \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \phi_2^* \\ \phi_1^\dagger & 0 & \phi_2^T & 0 \end{pmatrix}$$

$$\text{2HDM:} \quad \mathcal{V}_{LSS} = m_1^2|\phi_1|^2 + m_2^2|\phi_2|^2 + (b^2\phi_1^T\cdot\phi_2 + \mathrm{h.c.}) + \lambda_5'|\phi_1^T\cdot\phi_2|^2$$

Take "Alignment limit"

Heavy 2HDM Scalars (in SU(6)/Sp(6) Little-Higgs)

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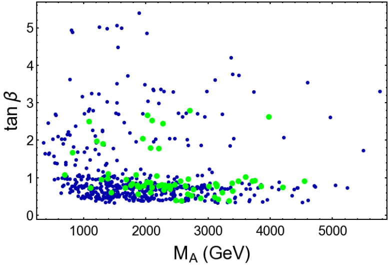
$$\text{2HDM:} \quad \mathcal{V}_{LSS} = m_1^2|\phi_1|^2 + m_2^2|\phi_2|^2 + (b^2\phi_1^T\cdot\phi_2 + \text{h.c.}) + \lambda_5'|\phi_1^T\cdot\phi_2|^2$$

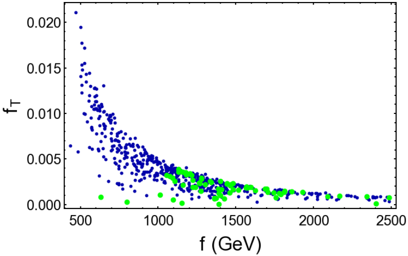
Take "Alignment limit"

Table 1: The experimental constraints at about the 2 to 3 σ level.

Quantity	Constraint	Reference
Top mass (MSbar)	$158 < m_t^{MS} < 168.7$ GeV	Ref. [13]
Higgs VEV	$v \equiv 246$ GeV	
Higgs mass	$123 < m_h < 127$ GeV	Ref. [14]
Higgs Yukawa	$0.63 < \lvert\kappa_{htt}\rvert < 1.2$	Table 15 of Ref. [15]
hW^+W^- coupling	$\lvert\cos(\beta-\alpha)\rvert < 0.4$	Table 15 of Ref. [15]
VLQ mass	$M_{t',b'} > 750$ GeV	Refs. [16], [17]

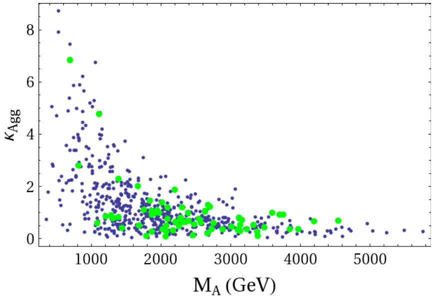
LSS model scan; fine-tuning

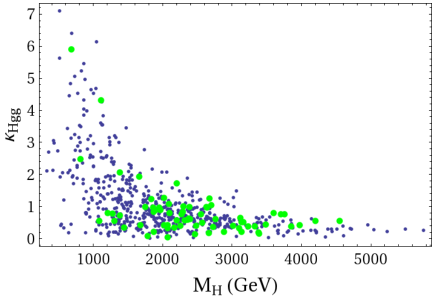




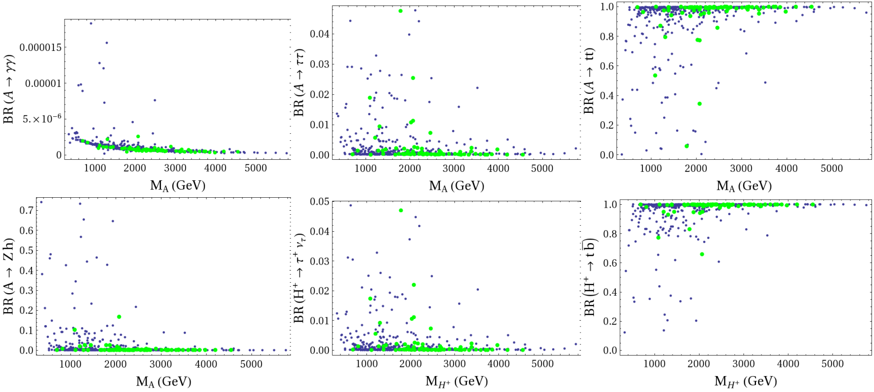
LSS model ϕgg effective coupling ($\phi = A, H$)

$$\mathcal{L} = \frac{\kappa_{\phi gg}}{64\pi^2 \, (1\ TeV)} \phi GG$$



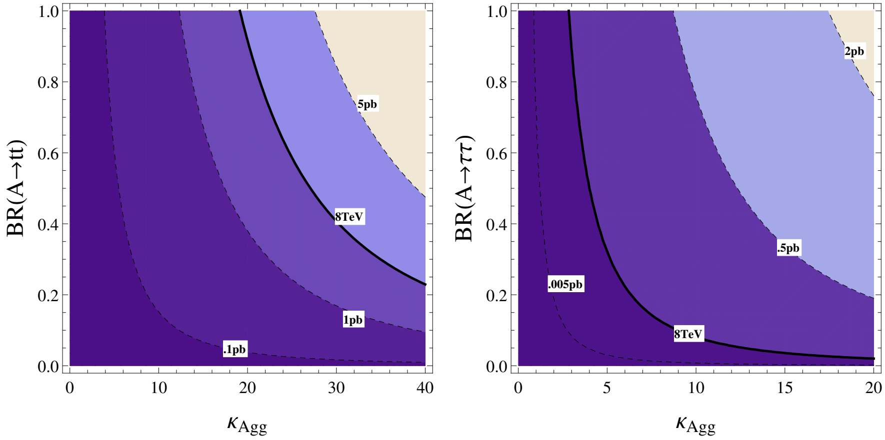


LSS model BRs



Model Independent LHC Limits/Prospects

[SG, Soumya Sadhukhan, Tuhin Subhra Mukherjee: 1504.01074]



Flavor structure

[Agashe, Perez, Soni, 04]

$$\mathcal{L} \supset \bar{\Psi}^i i\Gamma^\mu D_\mu \Psi^i + M_{ij}\bar{\Psi}^i\Psi^j + y_{ij}^{5D} H\bar{\Psi}^i\Psi^j + h.c.$$

- Basis choice: M_{ij} diagonal $\equiv M_i$
  - All flavor violation from y_{ij}^{5D}
  - KK decompose and go to mass basis
    - $\Longrightarrow g\,\bar{\Psi}^i_{(n)} W^{(k)}_\mu \Psi^j_{(m)}$ off-diagonal in flavor (due to non-degenerate f^i i.e. M^i)
- 5D fermion Ψ is vector-like
  - M_{ij} is independent of $\langle H\rangle = v$
  - But zero-mode made chiral (SM)

Example FCNC processes

- $K^0 \bar{K}^0$ mixing:
  - Tree-level FCNC vertex $g_{(1)} d\, s \propto V_L^{d\dagger} \begin{pmatrix} [g_{(1)} d\, d] & 0 \\ 0 & [g_{(1)} s\, s] \end{pmatrix} V_L^d$
- $b \to s\gamma$:
  - No tree-level contribution to helicity flip dipole operator
  - So 1-loop with $g^{(1)}\, b\, s$ OR $\phi\, b\, s^{(1)}$
- $b \to s\, \ell^+ \ell^-$, $b \to s\, s\, \bar{s}$, $K \to \pi \nu \bar{\nu}$:
  - Tree level FCNC vertex $Z\, s\, d$, $Z\, b\, s$

Bound : $m_{KK} \gtrsim$ *few* TeV [Agashe et al][Buras et al][Neubert et al][Csaki et al]

Relaxed with flavor alignment : MFV, NMFV, flavor symmetries, ...
[Fitzpatrick et al][Agashe et al]

Example LHC flavor changing processes

- Tree-level FCNC $t \to c\, h$ [Agashe, Contino 09]
  - $BR(t \to c\, h) \sim 10^{-4}$
- Tree-level FCNC $BR(t \to c\, Z) \sim 10^{-5}$ [Agashe, Perez, Soni 06]
- Loop FCNC $t \to c\, \gamma$

Conclusions

- In Warped models or Composite-Higgs models: SM + Heavy states
  - Spin-2 ($h_{\mu\nu}$), Vectors ($g^{(1)}, Z', W'$), Fermions (b', t', χ), Scalars (2HDM?)
  - LHC direct and indirect probes
- Precision electroweak constraints imply $M_{KK} \gtrsim 2\ TeV$
- Now LHC has entered the game!

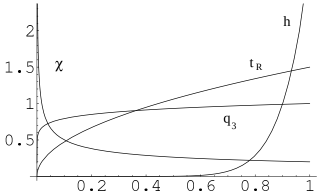
BACKUP SLIDES

Explaining SM mass hierarchy

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

$$\mathcal{S}^{(5)} \supset \int d^4x\, dy\ \left\{ c_\psi\, k\, \overline{\Psi}(x,y)\, \Psi(x,y) \right\}$$

Fermion bulk mass (c_ψ parameter) controls $f^\psi(y)$ localization



RS-GIM keeps FCNC under control

Kaluza-Klein (KK) expansion

[See for example: Gherghetta, Pomarol, 2000]

$$S_5 = -\int d^4x \int dy \sqrt{-g} \left[\frac{1}{4g_5^2} F_{MN}^2 + |\partial_M \phi|^2 + i\bar{\Psi}\gamma^M D_M \Psi + m_\phi^2 |\phi|^2 + i m_\Psi \bar{\Psi}\Psi \right]$$

EOM:

$$\left[e^{2\sigma} \eta^{\mu\nu} \partial_\mu \partial_\nu + e^{s\sigma} \partial_5 (e^{-s\sigma} \partial_5) - M_\Phi^2 \right] \Phi(x^\mu, y) = 0$$

Kaluza-Klein expansion

$$\Phi(x^\mu, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=0}^{\infty} \Phi^{(n)}(x^\mu) f_n(y)$$

Orthonormality relation:

$$\frac{1}{2\pi R} \int_{-\pi R}^{\pi R} dy \, e^{(2-s)\sigma} f_n(y) f_m(y) = \delta_{nm}$$

EOM implies

$$\left[-e^{s\sigma} \partial_5 (e^{-s\sigma} \partial_5) + \widehat{M}_\Phi^2 \right] f_n = e^{2\sigma} m_n^2 f_n$$

Solution is

$$f_n(y) = \frac{e^{s\sigma/2}}{N_n} \left[J_\alpha\left(\frac{m_n}{k} e^\sigma\right) + b_\alpha(m_n) \, Y_\alpha\left(\frac{m_n}{k} e^\sigma\right) \right]$$

$\Phi^{(n)}$ →KK tower with mass m_n. Equivalent 4D theory

Bulk EW Gauge Sector

Bulk EW Gauge group : $SU(2)_L \times SU(2)_R \times U(1)_X$

- Three neutral gauge bosons: (W_L^3, W_R^3, X)
- Two charged gauge bosons: $(W_L^{\pm}, W_R^{\pm})$

Symmetry Breaking:

- By Boundary Condition (BC):

$$Z_X(-,+) \text{ means } Z_X|_{y=0} = 0\,;\ \partial_y Z_X\,|_{y=\pi R} = 0$$

  - $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$: $\quad (W_L^3, W_R^3, X) \rightarrow (W_L^3, B, Z_X)$
    $A \rightarrow (+,+)\,;\ Z \rightarrow (+,+)\,;\ Z_X \rightarrow (-,+)$
  - $Z_X \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_R W_R^3 - g_X X) \rightarrow (-,+) \quad ; \quad W_R^{\pm} \rightarrow (-,+)$
    - $B \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_X W_R^3 + g_R X) \rightarrow (+,+) \quad ; \quad W_L^{\pm} \rightarrow (+,+)$

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  - $SU(2)_R \times U(1)_X \to U(1)_Y$: $(W_L^3, W_R^3, X) \to (W_L^3, B, Z_X)$

    $A \to (+,+)\,;\ Z \to (+,+)\,;\ Z_X \to (-,+)$
  - $Z_X \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_R W_R^3 - g_X X) \to (-,+)$; $W_R^{\pm} \to (-,+)$
    - $B \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_X W_R^3 + g_R X) \to (+,+)$; $W_L^{\pm} \to (+,+)$

- By VEV of TeV brane Higgs
  - $SU(2)_L \times U(1)_Y \to U(1)_{EM}$: $(W_L^3, B, Z_X) \to (A, Z, Z_X)$

Gauge KK States

Gauge Boson

- "Zero" modes: $A^{(0)}, Z^{(0)} \quad ; \quad W_L^{(0)}$
- First KK modes: $A^{(1)}, Z^{(1)}, Z_X^{(1)} \quad \to \; Z' \quad ; \quad W_L^{(1)}, \; W_R^{(1)}$

EWSB mixes : $\quad Z^{(0)} \leftrightarrow Z^{(1)} \;\; ; \;\; Z^{(0)} \leftrightarrow Z_X^{(1)} \;\; ; \;\; Z^{(1)} \leftrightarrow Z_X^{(1)}$

$W_L^{(0)} \leftrightarrow W_L^{(1)} \;\; ; \;\; W_L^{(0)} \leftrightarrow W_R^{(1)} \;\; ; \;\; W_L^{(1)} \leftrightarrow W_R^{(1)}$

Mass eigenstates :

- "Zero" modes: $A, Z \quad ; \quad W^{\pm}$
- First KK modes: $A_1, \tilde{Z}_1, \tilde{Z}_{X_1} \quad \to Z' \quad ; \quad \tilde{W}_{L_1}, \tilde{W}_{R_1} \quad \to W'^{\pm}$

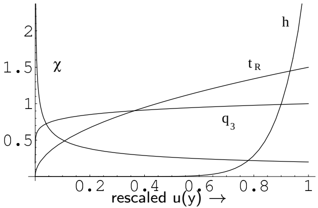
Explaining Flavor in a Warped extra dimension

Bulk fermions explain standard model (SM) Mass hierarchy puzzle

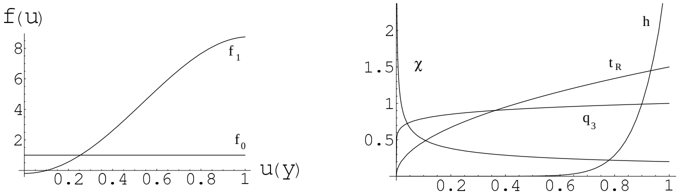
Fermion profiles controlled by bulk mass ($c_{L,\,R}$)

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

$$\Psi_L(x,y) = \frac{e^{(2-c)\sigma}}{\sqrt{2\pi R}N_0}\Psi_L^{(0)}(x) + \ldots \qquad N_0^2 = \frac{e^{2\pi kR(1/2-c)} - 1}{2\pi kR(1/2-c)}$$



4-D KK couplings



Integrate $\mathcal{S}^{(5)}$ over y $\rightarrow$ **equivalent 4D theory**

$$\mathcal{S}^{(4)} = \int d^4x \sum m_n^2 \phi^{(n)}\phi^{(n)} \; + \; g_{4D}^{(nml)} \psi^{(n)}\psi^{(m)} A^{(l)} \; + \; \lambda_{4D}^{(nm)} \, \psi_L^{(n)} \psi_R^{(m)} \, H$$

$\phi^{(n)}$ $\rightarrow$KK tower with mass m_n ; Denote $\phi^{(1)} \equiv \phi'$; $m_1 \equiv m_{KK} \sim$TeV

Compute overlap integral over y to get 4D couplings

- Yukawas: $\lambda_{4D}^{(00)} = \lambda_{5D} \int dy \, f_0^{\psi_L} \, f_0^{\psi_R} \, f^H$
- Gauge couplings: $g_{4D}^{(001)} = g_{5D} \int dy \, f_0^{\psi} \, f_0^{\psi} \, f_1^A$

Fermion reps (Model I)

[Agashe, Delgado, May, Sundrum 03]

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

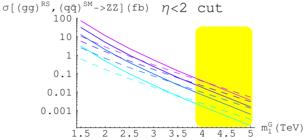
KK Graviton

[Agashe et al, 07] [Fitzpatrick et al, 07]

$$m_n = x_n k e^{-k\pi r} \qquad x_n = 3.83, 7.02, \ldots$$
$$\mathcal{L} \supset -\frac{C^{ffG}}{\Lambda} T^{\alpha\beta} h^{(n)}_{\alpha\beta} \qquad \Lambda = \bar{M}_P e^{-k\pi r}$$

- SM on IR brane
  - CDF & D0 bounds : $m_1 > 300 - 900$ GeV for $\frac{k}{M_p}$ =0.01-0.1
  - ATLAS & CMS reach : 3.5 TeV with $100 fb^{-1}$
- SM in Bulk (flavor)
  - light fermion couplings highly suppressed
  - gauge field couplings $\frac{1}{k\pi r}$ suppressed
  - Decays dominantly to t, h, V_{Long}

$$gg \to h^{(1)} \to ZZ \to 4\ell$$



various $\frac{k}{M_p}$; SM dashed

[Agashe, Davoudiasl, Perez, Soni, 2007]

Z' Overlap Integrals

$$\text{Define: } \xi \equiv \sqrt{k\pi R} = 5.83$$

Z' overlap with Higgs $\rightarrow \xi$

Z' overlap with fermions:

	Q^3_L	t_R	other fermions
$\mathcal{I}^+$	$-\frac{1.13}{\xi} + 0.2\xi \approx 1$	$-\frac{1.13}{\xi} + 0.7\xi \approx 3.9$	$-\frac{1.13}{\xi} \approx -0.2$
$\mathcal{I}^-$	$0.2\xi \approx 1.2$	$0.7\xi \approx 4.1$	0

Compared to SM

- Z' couplings to h enhanced (also V_L - Equivalence Theorem!)
- Z' couplings to t_R enhanced
- Z'couplings to χ suppressed

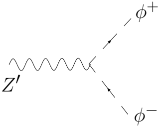
$$\bar{\psi}_{L,R}\gamma^\mu \Big[eQ\mathcal{I}A_{1\,\mu} + g_Z \left(T^3_L - s^2_W T_Q \right) \mathcal{I}Z_{1\,\mu} +$$

$$g_{Z'} \left(T^3_R - s'^2 T_Y \right) \mathcal{I}Z_{X1\,\mu} \Big] \psi_{L,R}$$

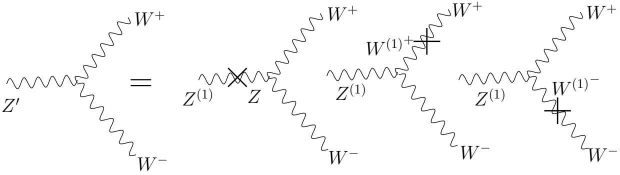
EWSB induced $Z'W^+W^-$ coupling

$Z^{(1)}V^{(0)}V^{(0)}$ is zero by orthogonality ...
... but induced after EWSB

Using Goldstone equivalence:



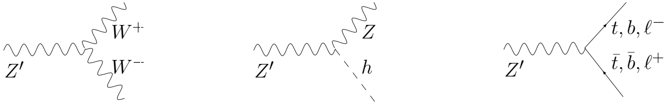
In Unitary Gauge:



Even though $\xi \cdot (\frac{v}{M_{KK}})^2$ suppressed ...

Z' decays

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



$$\Gamma(A_1 \to W_L W_L) = \frac{e^2\kappa^2}{192\pi}\frac{M_{Z'}^5}{m_W^4} \; ; \quad \kappa \propto \sqrt{k\pi r_c}\left(\frac{m_W}{M_{W_1^\pm}}\right)^2 ,$$

$$\Gamma(\tilde{Z}_1, \tilde{Z}_{X1} \to W_L W_L) = \frac{g_L^2 c_W^2 \kappa^2}{192\pi}\frac{M_{Z'}^5}{m_W^4} \; ; \quad \kappa \propto \sqrt{k\pi r_c}\left(\frac{m_Z}{(M_{Z_1}, M_{Z_{X1}})}\right)^2 ,$$

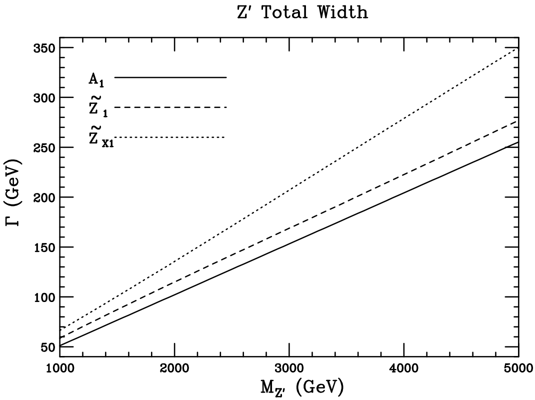
$$\Gamma(\tilde{Z}_1, \tilde{Z}_{X1} \to Z_L h) = \frac{g_Z^2\kappa^2}{192\pi} M_{Z'} \; ; \quad \kappa \propto \sqrt{k\pi r_c} ,$$

$$\Gamma(Z' \to f\bar{f}) = \frac{(e^2, g_Z^2)}{12\pi}\left(\kappa_V^2 + \kappa_A^2\right) M_{Z'} \; .$$

Widths & BR's (For $M_{Z'} = 2$TeV)

	A_1		$\tilde{Z}_1$		$\tilde{Z}_{X1}$	
	Γ(GeV)	BR	Γ(GeV)	BR	Γ(GeV)	BR
$\bar{t}t$	55.8	0.54	18.3	0.16	55.6	0.41
$\bar{b}b$	0.9	8.7×10^{-3}	0.12	10^{-3}	28.5	0.21
$\bar{u}u$	0.28	2.7×10^{-3}	0.2	1.7×10^{-3}	0.05	4×10^{-4}
$\bar{d}d$	0.07	6.7×10^{-4}	0.25	2.2×10^{-3}	0.07	5.2×10^{-4}
$\ell^+\ell^-$	0.21	2×10^{-3}	0.06	5×10^{-4}	0.02	1.2×10^{-4}
$W_L^+ W_L^-$	45.5	0.44	0.88	7.7×10^{-3}	50.2	0.37
$Z_L h$	-	-	94	0.82	2.7	0.02
Total	103.3		114.6		135.6	

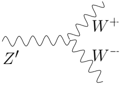
Total Widths

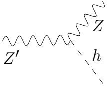


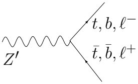
$M_{Z'} = 2\text{TeV}$	A_1	Z_1	Z_{X1}
Γ (GeV)	103.3	114.6	135.6

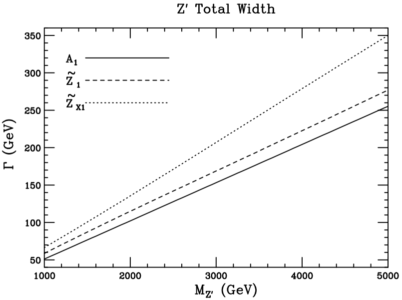
Z' decays

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



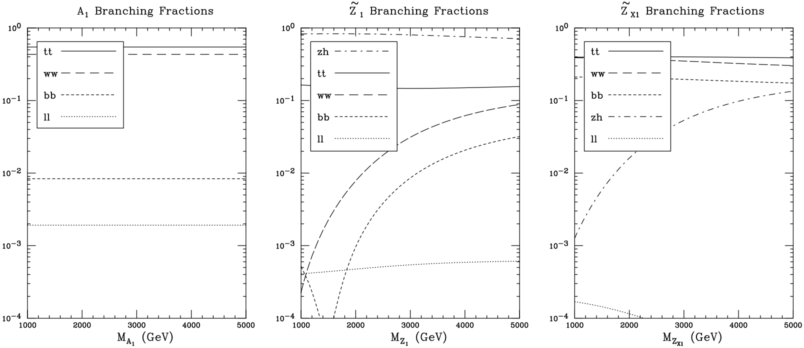






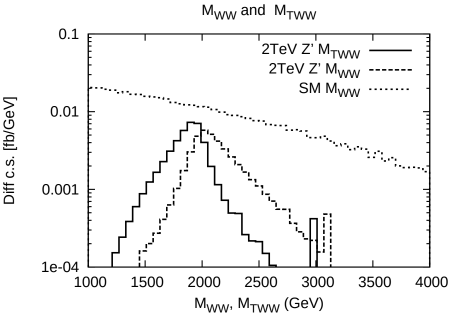
$M_{Z'} = 2$TeV	A_1	Z_1	Z_{X1}
Γ (GeV)	103.3	114.6	135.6

Z' Branching Ratios

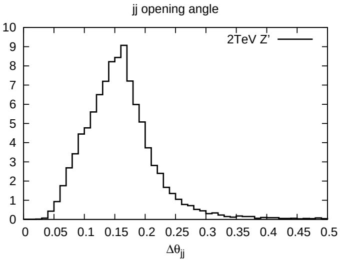


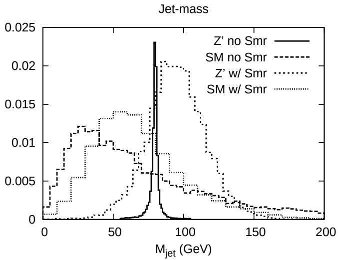
$pp \to Z' \to W^+W^- \to \ell\,\nu\,j\,j$

$$M_{eff} \equiv p_{T_{jj}} + p_{T_\ell} + \not{p}_T \qquad M_{T_{WW}} \equiv 2\sqrt{p_{T_{jj}}^2 + m_W^2}$$



$pp \to Z' \to W^+W^- \to \ell\,\nu\,j\,j$ (Boosted $W \to (jj)$)





j j Collimation implies forming m_W nontrivial : use jet-mass

In our study: Jet-mass after Parton shower in Pythia

[Thanks to Frank Paige for discussions]

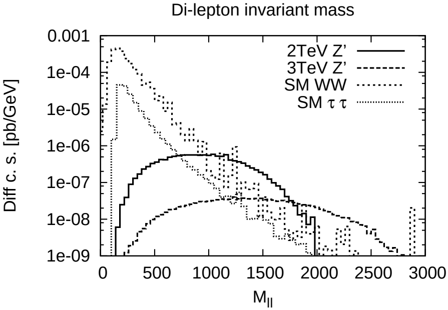
To account for (HCal) expt. uncert.

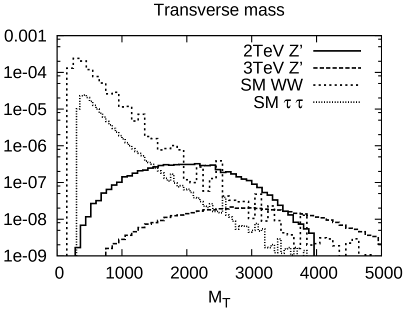
Smearing by $\delta E = 80\%/\sqrt{E}$; $\delta\eta, \delta\phi = 0.05$

Tracker + ECal (2 cores?) have better resolutions [F. Paige; M. Strassler]

$pp \to Z' \to W^+W^- \to \ell\,\nu\,\ell\,\nu$

2 ν's $\Rightarrow$ cannot reconstruct event





$$M_{eff} \equiv p_{T_{\ell_1}} + p_{T_{\ell_2}} + \not{p}_T \qquad M_{T_{WW}} \equiv 2\sqrt{p^2_{T_{\ell\ell}} + M^2_{\ell\ell}}$$

$\mathcal{L}$ needed: 100 fb^{-1} (2 TeV) ; 1000 fb^{-1} (3 TeV)

$pp \to Z' \to W^+W^- \to \ell\,\nu\,\ell\,\nu$

Cross-section (in fb) after cuts:

2 TeV	Basic cuts	$\|\eta_\ell\| < 2$	$M_{eff} > 1$ TeV	M_T >1.75 TeV	# Evts	S/B	$S/\sqrt{B}$
Signal	0.48	0.44	0.31	0.26	26	0.9	4.9
WW	82	52	0.4	0.26	26		
$\tau\tau$	7.7	5.6	0.045	0.026	2.6		
3 TeV	**Basic cuts**	$\|\eta_\ell\| < 2$	$1.5 < M_{eff} < 2.75$	$2.5 < M_T < 5$	**# Evts**	S/B	$S/\sqrt{B}$
Signal	0.05	0.05	0.03	0.025	25		
WW	82	52	0.08	0.04	40	0.6	3.8
$\tau\tau$	7.7	5.6	0.015	0.003	3		

events above is for

- 2 TeV : 100 fb^{-1}
- 3 TeV : 1000 fb^{-1}

$pp \to Z' \to W^+W^- \to \ell\,\nu\,j\,j$

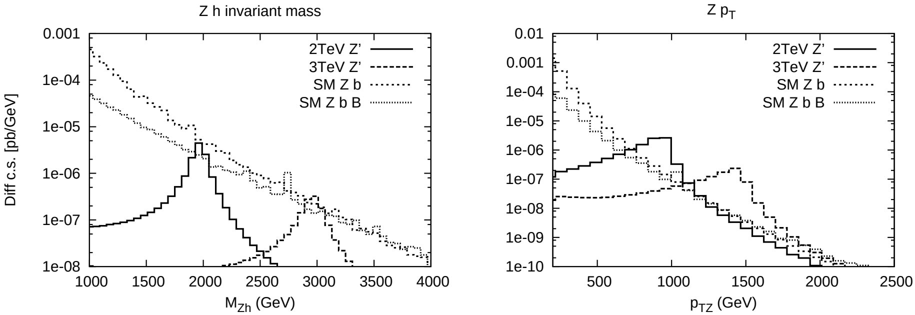
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ TeV	p_T	$\eta_{\ell,j}$	M_{eff}	$M_{T_{WW}}$	M_{jet}	# Evts	S/B	$S/\sqrt{B}$
Signal	4.5	2.40	2.37	1.6	1.25	125	0.39	6.9
W+1j	1.5×10^5	3.1×10^4	223.6	10.5	3.15	315		
WW	1.2×10^3	226	2.9	0.13	0.1	10		
$M_{Z'} = 3$ TeV								
Signal	0.37	0.24	0.24	0.12	-	120	0.17	4.6
W+1j	1.5×10^5	3.1×10^4	88.5	0.68	-	680		
WW	1.2×10^3	226	1.3	0.01	-	10		

events above is for

- 2 TeV : 100 fb^{-1}
- 3 TeV : 1000 fb^{-1}

$pp \to Z' \to Z\,h \to \ell^+\ell^-\ \ b\,\bar{b} \quad (m_h = 120\ \text{GeV})$



How well can we tag high p_T b's ?

For $\epsilon_b = 0.4$, expect $R_j \approx 20 - 50$; $R_c = 5$

Two b's close : $\Delta R_{bb} \sim 0.16$

$\mathcal{L}$ needed: $200\, fb^{-1}$ (2 TeV) ; $1000\, fb^{-1}$ (3 TeV)

$pp \to Z' \to Z\,h \to \ell^+\ell^- \;\; b\,\bar{b} \quad (m_h = 120 \text{ GeV})$

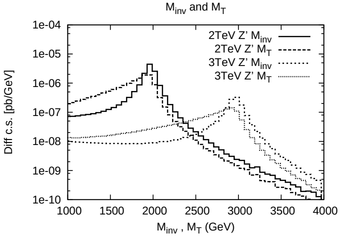
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ TeV	Basic	p_T, η	$\cos\theta_{Zh}$	M_{inv}	b-tag	# Evts	S/B	$S/\sqrt{B}$
$Z' \to hZ \to b\bar{b}\ell\ell$	0.81	0.73	0.43	0.34	0.14	27	1.1	5.3
SM $Z + b$	157	1.6	0.9	0.04	0.016	3		
SM $Z + b\bar{b}$	13.5	0.15	0.05	0.01	0.004	0.8		
SM $Z + q_l$	2720	48	22.4	1.5	0.08	15		
SM $Z + g$	505.4	11.2	5.8	0.5	0.025	5		
SM $Z + c$	184	1.9	1.1	0.05	0.01	2		
$M_{Z'} = 3$ TeV								
$Z' \to hZ \to b\bar{b}\ell\ell$	0.81	0.12	0.05	0.04	0.016	16	2	5.7
SM $Z + b$	157	0.002	0.001	3×10^{-4}	1.2×10^{-4}	0.12		
SM $Z + b\bar{b}$	13.5	0.018	0.014	0.002	0.001	1		
SM $Z + q_l$	2720	1.1	0.7	0.1	0.005	5		
SM $Z + g$	505.4	0.3	0.2	0.03	0.0015	1.5		
SM $Z + c$	183.5	0.03	0.02	0.002	4×10^{-4}	0.4		

events above is for

- 2 TeV : 200 fb^{-1}
- 3 TeV : 1000 fb^{-1}

$pp \to Z' \to Z\,h\;:\quad Z \to j\,j\;;\quad h \to W^+W^- \to j\,j\,\ell\,\nu$ $(m_h = 150\text{ GeV})$



$$M_{T_{Zh}} \equiv \sqrt{p_{T_Z}^2 + m_Z^2} + \sqrt{p_{T_h}^2 + m_h^2}$$

$M_{Z'} = 2$ TeV $\quad m_h = 150$ GeV	Basic	$p_T\,,\,\eta$	$\cos\theta$	M_T	M_{jet}	# Evts	S/B	$S/\sqrt{B}$
$Z' \to hZ \to \ell\,\not{E}_T\,(jj)\,(jj)$	2.4	1.6	0.88	0.7	0.54	54	2.5	11.5
SM $W\,j\,j$	3×10^4	35.5	12.7	0.62	0.19	19		
SM $W\,Z\,j$	184	0.45	0.15	0.02	0.02	2		
SM $W\,W\,j$	712	0.54	0.2	0.02	0.01	1		
$M_{Z'} = 3$ TeV $\quad m_h = 150$ GeV								
$Z' \to hZ \to \ell\,\not{E}_T\,(jj)\,(jj)$	0.26	0.2	0.14	0.06	—	18	1.2	4.7
SM $W\,j\,j$	3×10^4		4.1	0.05	—	15		

events above is for

- 2 TeV : 100 fb^{-1}
- 3 TeV : 300 fb^{-1}

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

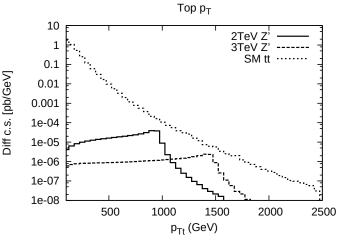
$M_{Z'} = 2$ TeV	Basic	$p_{T\ell}$	$M_{\ell\ell}$	# Evts	S/B	$S/\sqrt{B}$
Signal	0.1	0.09	0.06	60	0.3	4.2
SM $\ell\ell$	3×10^4	5.4	0.2	200		
SM WW	295	0.03	0.002	2		

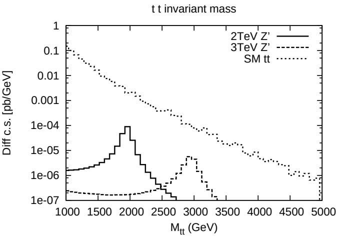
events above is for

- 2 TeV : 1000 fb^{-1}

Experimentally clean, but needs a LOT of luminosity

$pp \rightarrow Z' \rightarrow t\bar{t}$





$M_{Z'} = 2$ TeV	Basic	$p_T > 800$	$1900 < M_{tt} < 2100$
Signal	17	7.2	5.6
SM $t\bar{t}$	1.9×10^5	31.1	19.1
$M_{Z'} = 3$ TeV	Basic	$p_T > 1250$	$2850 < M_{tt} < 310$
Signal	1.7	0.56	0.45
SM $t\bar{t}$	1.9×10^5	4.1	1.1

Little RS (LRS) ($Z' \to \ell^+\ell^-$)

Vary $k\pi R$: $(k\pi R)_{LRS} < (k\pi R)_{RS} = 35$ [Davoudiasl, Perez, Soni 08]

- $M_{EW} \sim k\, e^{-k\pi R}$; RS: $k \lesssim M_{pl}$; LRS: $k \ll M_{pl}$
- RS as a theory of flavor! (***give-up solution to hierarchy problem***)

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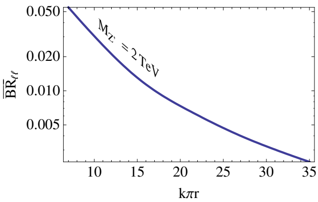
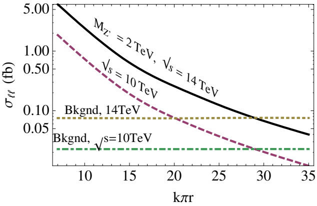
$pp \to Z'_{LRS} \to \ell^+\ell^-$ [Davoudiasl, SG, Soni 09; arXiv:0908.1131]





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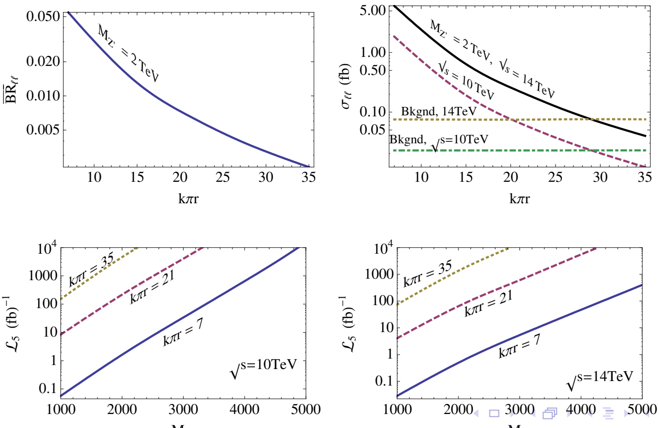
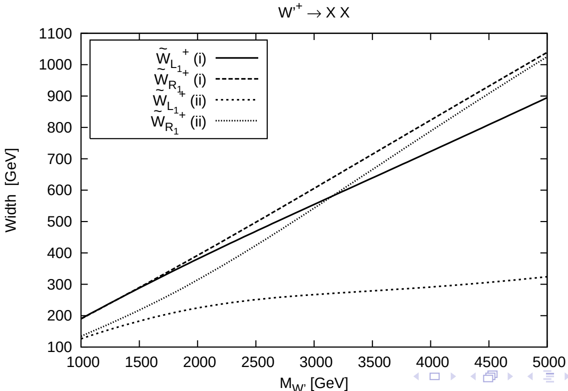
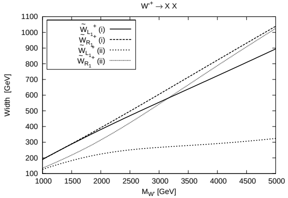


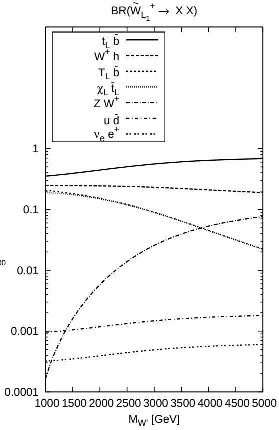
$W'^{\pm}$ width

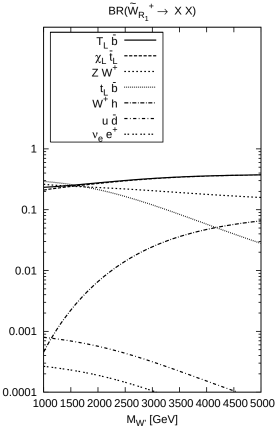


W'+ → X X
Width [GeV]
M_W' [GeV]
W̃L1+ (i)
W̃R1+ (i)
W̃L1+ (ii)
W̃R1+ (ii)
1100
1000
900
800
700
600
500
400
300
200
100
1000
1500
2000
2500
3000
3500
4000
4500
5000

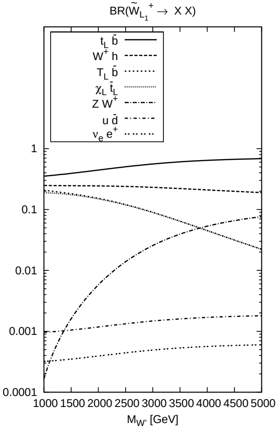
$W'^{\pm}$ width and BR

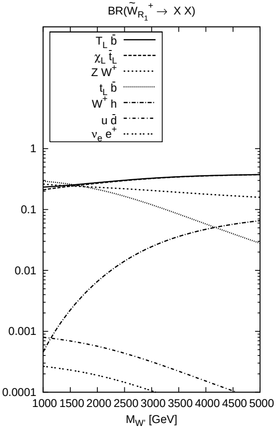






$W'^{\pm}$ BR


BR(W̃L1+ → X X)
tL b̄
W+ h
TL b̄
χL t̄L
Z W+
u d̄
νe e+
1
0.1
0.01
0.001
0.0001
1000 1500 2000 2500 3000 3500 4000 4500 5000
MW' [GeV]

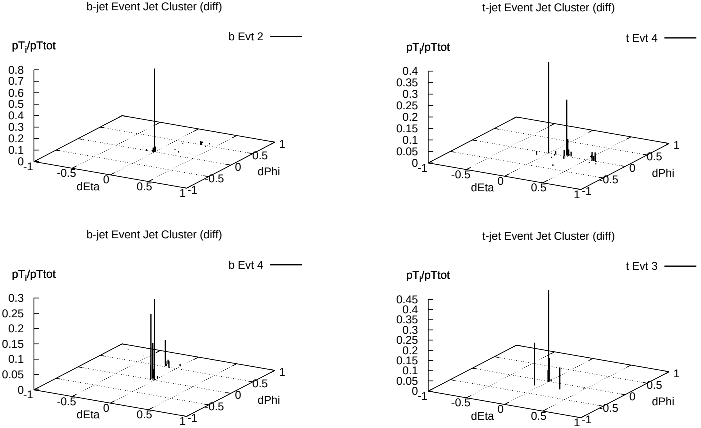

BR(W̃R1+ → X X)
TL b̄
χL t̄L
Z W+
tL b̄
W+ h
u d̄
νe e+
1
0.1
0.01
0.001
0.0001
1000 1500 2000 2500 3000 3500 4000 4500 5000
MW' [GeV]

$W'^{\pm} \to t\, b \to \ell \nu\, b\, b$

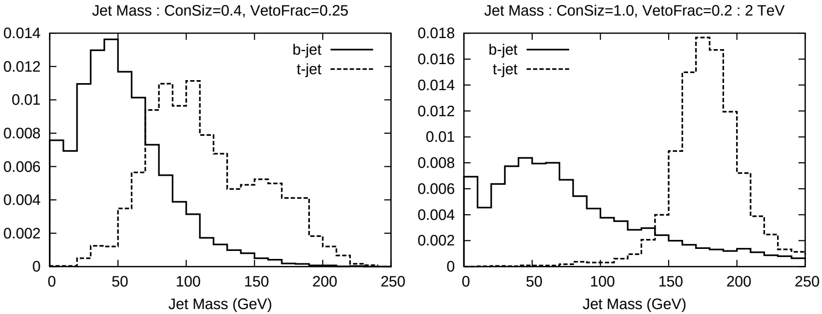
Signal c.s. $\sim 1 fb$

Bkgnd is single top + QCD W b b .... AND ...

$t\bar{t}$: hadronically decaying top can fake a b



$W'^{\pm} \to t\, b \to \ell \nu b\, b$



Jet-mass cut: cone size 1.0 and $0 < j_M < 75 \Rightarrow 0.4\%$ of *top* fakes *b*

$\mathcal{L}$ needed: 100 fb^{-1} (2 TeV)

$W'^{\pm} \to Z\,W$ and $W\,h$

$W'^{\pm} \to Z\,W$:

- Fully leptonic $\to \mathcal{L}$: 100 fb^{-1} (2 TeV) ; 1000 fb^{-1} (3 TeV)
- Semi leptonic $\to \mathcal{L}$: 300 fb^{-1} (2 TeV) (SM $W/Z + 1j$ large)

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- Semi leptonic $\to \mathcal{L}$: 300 fb^{-1} (2 TeV) (SM $W/Z + 1j$ large)

$W'^{\pm} \to W\, h$:

- $m_h \approx 120$: $h \to b\, b$
  - What is b-tagging eff?
- $m_h \approx 150$: $h \to W\, W$
  - Use W jet-mass to reject light jet

$\mathcal{L}$ needed: 100 fb^{-1}(2TeV) ; 300 fb^{-1} (3TeV)

Measuring Chirality in (pp) $u\bar{d} \to W'^{+} \to t\,\bar{b} \to \ell^{+}\nu b\bar{b}$

A Model Independent Study

[SG, Han, Lewis, Si, Zhou, 2010: arXiv:1008.3508]

$$L \supset \bar{\psi}_u \,(g_L P_L + g_R P_R)\, \psi_d \; W'$$

- Can we measure $g^{ud}_{L,R}$, $g^{tb}_{L,R}$?
- Yes, encoded in **top polarization**!

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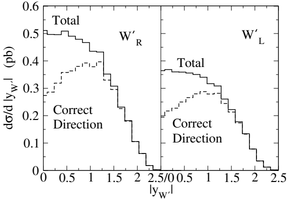
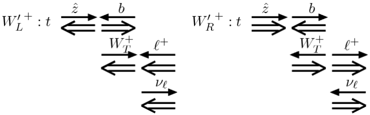
1. Need to fix u direction:

   Statistical only: On avg u carries higher momentum fraction than $\bar{d}$

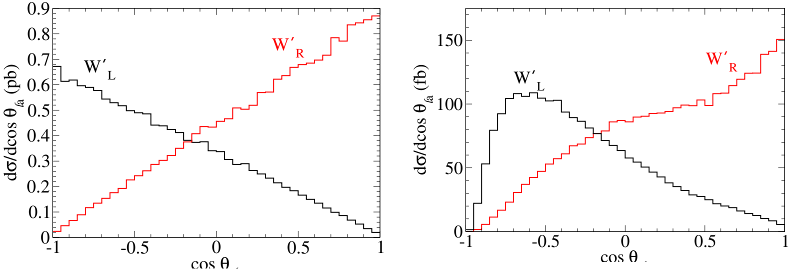


   $\therefore$ direction of $y_{W'} > 0.8$ is u direction

2. θ_ℓ distribution analyzes top polarization



Measuring Chirality (Results)



FCNC couplings

- $h^{\mu\nu}_{(0)}\psi_{(0)}\psi_{(0)}$: diagonal
- $\{A_{(0)}, g_{(0)}\}\,\psi_{(0)}\psi_{(0)}$: diagonal (unbroken gauge symmetry)
- $\{Z_{(0)}, Zx_{(0)}\}\,\psi_{(0)}\psi_{(0)}$: almost diagonal (non-diagonal due to EWSB effect)
- $h\,\psi_{(0)}\psi_{(0)}$: diagonal (only source of mass is $\langle h\rangle = v$)

- $h^{\mu\nu}_{(1)}\psi_{(0)}\psi_{(0)}$: off-diagonal
- $\{A_{(1)}, g_{(1)}\}\,\psi_{(0)}\psi_{(0)}$: off-diagonal (i=1,2 almost diagonal)
- $\{Z_{(1)}, Zx_{(1)}\}\,\psi_{(0)}\psi_{(0)}$: off-diagonal

---

- $h^{\mu\nu}_{(0)}\psi_{(0)}\psi_{(1)}$: 0
- $\{A_{(0)}, g_{(0)}\}\,\psi_{(0)}\psi_{(1)}$: 0 (unbroken gauge symmetry)
- $\{Z_{(0)}, Zx_{(0)}\}\,\psi_{(0)}\psi_{(1)}$: off-diagonal (EWSB effect)
- $h\,\psi_{(0)}\psi_{(1)}$: off-diagonal (since M_ψ is extra source of mass)

$\psi_{(0)} \leftrightarrow \psi_{(1)}$ mixing due to EWSB

FCCC couplings

- $W^{\pm}_{L(0)}\psi^{i}_{(0)}\psi^{j}_{(0)}\ :\ g\ V^{ij}_{CKM}$
- $\left\{W^{\pm}_{L(1)}, W^{\pm}_{R(1)}\right\}\psi_{(0)}\psi_{(0)}\ :\ g\ V_{100}\ [f_{W^{(1)}} f_{\psi} f_{\psi}]$
  - [...] suppressed for $i = 1, 2$; (Not suppr for b_L, t_L, t_R)
- $W^{\pm}_{L(0)}\psi_{(0)}\psi_{(1)}\ :\ g\ V_{001}\ \left[f_{W^{(1)}} f_{\psi} f_{\psi^{(1)}}\right]$

Radion

[Csaki et al, 2001, 2007] [Gunion et al, 2004]

Fluctuations of size of extra dimension $\rightarrow$ scalar d.o.f

$$\mathcal{L} \supset \frac{r}{\Lambda} T^{\mu}_{\mu}$$

- SM on IR brane

$$\mathcal{L} \supset -\frac{r}{\Lambda_r}\left(2M_W^2 W^+_\mu W^{-\,\mu} + M_Z^2 Z_\mu Z^\mu\right)$$

- SM in bulk

$$\mathcal{L} \supset -\frac{1}{2\Lambda_r}\left[\frac{1}{(k\pi R)} + \epsilon\right] r W^-_{\mu\nu} W^{+\,\mu\nu} - \frac{1}{4\Lambda_r}\left[\frac{1}{(k\pi R)} + \epsilon\right] r Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4\Lambda_r}\left[\frac{1}{(k\pi R)} + \epsilon\right] r F_{\mu\nu} F^{\mu\nu}$$
$$- \frac{2M_W^2}{\Lambda_r}\left[1 - \frac{1}{2} M_W^2 R'^2 (k\pi R) - \frac{\epsilon}{2}\right] r W^+_\mu W^{-\,\mu} - \frac{M_Z^2}{\Lambda_r}\left[1 - \frac{1}{2} M_Z^2 R'^2 (k\pi R) - \frac{\epsilon}{2}\right] r Z_\mu Z^\mu$$

- Curvature-scalar mixing

$\mathcal{L} \supset \xi \mathcal{R} H^\dagger H$ leads to $r \leftrightarrow h$ mixing