Warped-space Phenomenology and LHC Signatures

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Motivation

- SM Hierarchy Problem: $M_{Pl} \leftrightarrow M_{EW}$
- New dynamics?
  - Extra dimensions (Warped, Flat)
  - Supersymmetry
  - Strong dynamics
  - Little Higgs
- AdS/CFT correspondence

Talk Outline

- Warped (Randall-Sundrum) model
  - 5-dimensional Anti deSitter (AdS) space
  - $SU(3)_{QCD} \times SU(2)_L \times SU(2)_R \times U(1)_X$ bulk gauge group
- Precision electroweak observables require $M_{Z'}$, $M_{W_1^\pm} \gtrsim 2$ TeV
  - Makes discovery challenging at the LHC
- LHC Signatures : New heavy particles
  - Graviton, Gauge bosons, Fermions, Radion

Warped Model

5D Warped Space [Randall, Sundrum, 99]

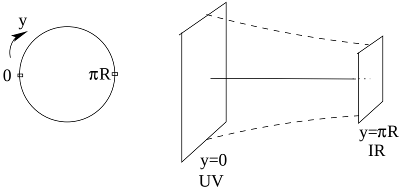
$ds^2 = e^{-2k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2$

Z_2 Orbifold -

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

R : radius of Ex. Dim.

k : curvature



Hierarchy prob soln:

- TeV Brane Higgs : $M_{EW} \sim k e^{-k\pi R}$: Choose $k\pi R \sim 34$

Warped Model

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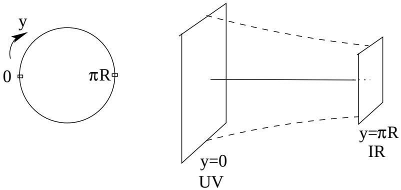

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AdS/CFT Correspondence [Maldacena]

- Gravity Theory in Anti-DeSitter (AdS) ↔ Conformal Field Theory (CFT)
  - I will use 5-D language

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

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

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

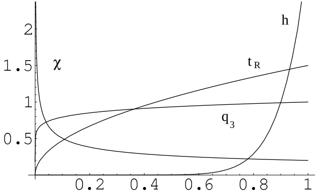
Flavor explanation

Bulk fermions explain standard model (SM) Mass hierarchy puzzle

Fermion profiles controlled by bulk mass

- $\mathcal{L} \supset c_\psi \, k \, \bar{\psi}\psi$

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



rescaled u(y) ⟶

FCNC under control

(New) Particles

- Bulk gravity
  - Graviton (spin 2)
  - Radion (spin 0)
- Bulk gauge sector : $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_X$
  - Colored gauge bosons (g)
  - Three neutral EW gauge bosons: (W_L^3, W_R^3, X)
  - Two charged EW gauge bosons: $(W_L^{\pm}, W_R^{\pm})$
- IR brane Higgs

KK Graviton

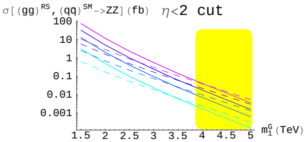
[Agashe et al, 07] [Fitzpatrick et al, 07]

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

- 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 100fb^{-1}

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

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



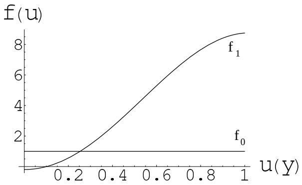
various $\frac{k}{M_p}$; SM dashed

[Agashe, Davoudiasl, Perez, Soni, 2007]

Wave functions

Bulk field EOM gives profiles in extra-dimension

Fermion bulk mass (c parameter) controls localization



Compute overlap integral of $f(y) \cdot g(y)$ to get 4D couplings

$$\mathcal{I}^{+,-} = \int [dy] g_\psi^2 f^{(++),(-+)}$$

Wave functions

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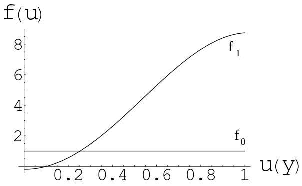

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$$\mathcal{I}^{+,-} = \int [dy] g_\psi^2 f^{(++),(-+)}$$

$$\frac{g^{f\bar{f}A^{(1)}}}{g_{\mathrm{SM}}} \simeq 1/\xi \ ; \quad \frac{g^{Q^3\bar{Q}^3A^{(1)}}}{g_{\mathrm{SM}}} \approx 1 \ ; \quad \frac{g^{t_R\bar{t}_RA^{(1)}}}{g_{\mathrm{SM}}} \simeq \xi \ ; \quad \frac{g^{A^{(0)}A^{(0)}A^{(1)}}}{g_{\mathrm{SM}}} \approx 0 \ ; \quad \frac{g^{HHA^{(1)}}}{g_{\mathrm{SM}}} \simeq \xi$$

KK Gluon

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

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

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

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

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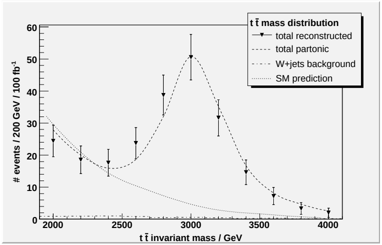

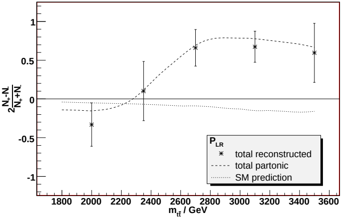

$$P_{LR} = 2\frac{N_+ - N_-}{N_+ + N_-} \qquad N_+ \text{ forward going } \ell \text{ wrt } k_t$$

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

(EW) Symmetry breaking

Symm breaking by BC: $Z_X(-,+)$ means $Z_X|_{y=0} = 0\,;\ \partial_y Z_X\,|_{y=\pi R} = 0$

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

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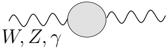
EWSB by TeV brane Higgs

- $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$: $\quad (W_L^3, B, Z_X) \rightarrow (A, Z, Z_X)$

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 $\sim (\frac{v}{M_{KK}})^2 log \frac{M_{Pl}}{M_{EW}}$ log enhanced [Csaki, Erlich, Terning - 02]
  - S parameter also log enhanced
- Bulk gauge symm - $SU(2)_R$ $\Leftrightarrow$ Custodial Symm (AdS/CFT)

  [Agashe, Delgado, May, Sundrum - 03]
  - T parameter - Protected
  - S parameter - log enhanced (with additional $\frac{1}{k\pi R}$ for bulk fermions)
  - $Zb\bar{b}$ shifted
- 3rd gen quarks (2,2) [Agashe, Contino, DaRold, Pomarol - 06]
  - $Zb\bar{b}$ coupling - Protected
  - Precision EW constraints $\Rightarrow M_{Z'} \gtrsim 2-3$ TeV

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

Representations (Custodial protection for $Zb\bar{b}$)

[Agashe, Contino, DaRold, Pomarol - 06]

Fermions

- $Q_L = (2,2) = \begin{pmatrix} t_L & \zeta_L \\ b_L & T_L \end{pmatrix}$
- $t_R \quad : \quad (1,1)$ OR $(1,3) \oplus (3,1)$
- $b_R \quad : \quad (1,1)$ OR $(1,3) \oplus (3,1)$

Higgs

- $\Sigma = (2,2)$

For these Reps

- $Zb\bar{b}$ coupling - Protected [Agashe, Contino, DaRold, Pomarol - 06]
- Precision EW constraints $\Rightarrow M_{Z'} \gtrsim 2 - 3$ TeV

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

Gauge Boson

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

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

Mass eigenstates :

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

Z', $W'^{\pm}$ Phenomenology

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

[Agashe, SG, Han, Huang, Soni - arXiv:0810.1497 [hep-ph]]

Z' couplings

- Z' overlap with Higgs : $\xi \equiv \sqrt{k\pi R} \approx 5$
- Z' overlap with fermions:

	Q_L^3	t_R	other fermions
$\mathcal{I}^+$	1	ξ	$-\frac{1}{\xi}$
$\mathcal{I}^-$	1	ξ	0

Compared to SM

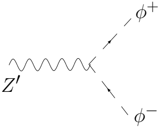
- Z' couplings to h enhanced (also V_L - Equivalence Theorem!)
- Z' couplings to t_R enhanced
- Z'couplings to light fermions suppressed

$$\bar{\psi}_{L,R}\gamma^{\mu}\left[eQ\mathcal{I}A_{1\ \mu} + g_Z\left(T_L^3 - s_W^2 T_Q\right)\mathcal{I}Z_{1\ \mu} + g_{Z'}\left(T_R^3 - s'^2 T_Y\right)\mathcal{I}Z_{X1\ \mu}\right]\psi_{L,R}$$

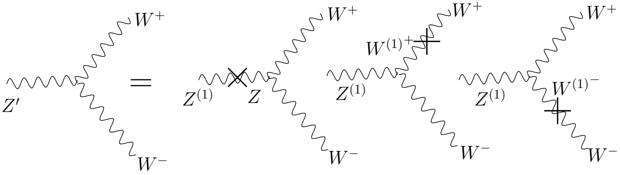
EWSB induced $Z'W^+W^-$ coupling

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

Using Goldstone equivalence:

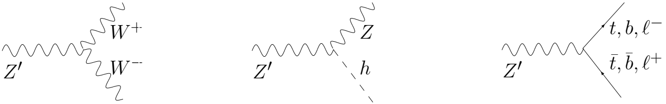


In Unitary Gauge:

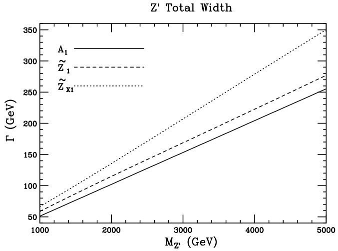


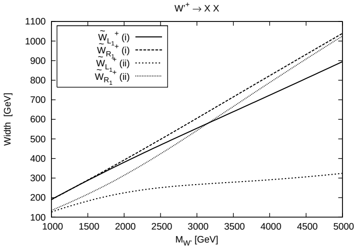
Even though $\xi \cdot (\frac{v}{M_{KK}})^2$ suppressed ...
... can be overcome by $(\frac{M_{KK}}{m_Z})^2$ (from long. pol. vectors)

Z' , W' decays



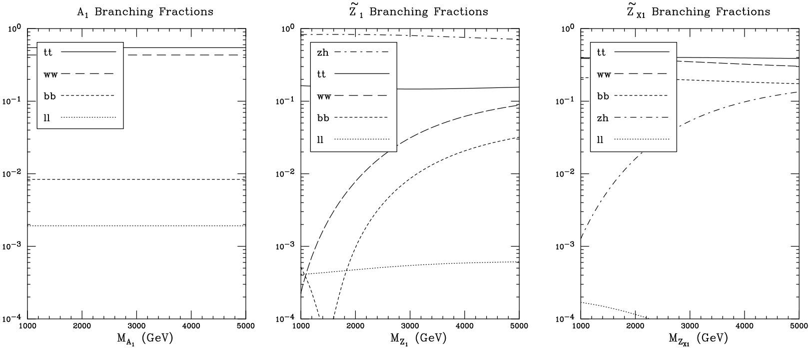
Z' , W' Total Widths



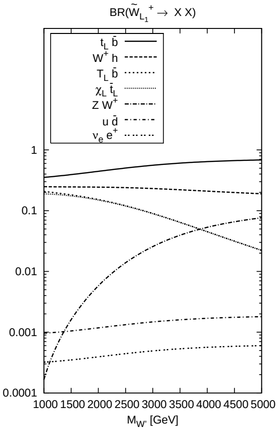


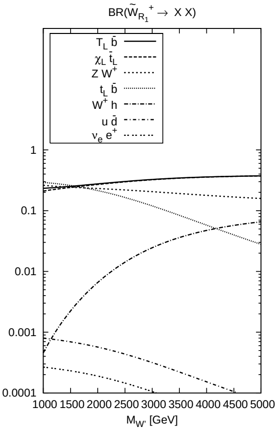
$M_{Z'} = 2$TeV	A_1	Z_1	Z_{X1}
Γ (GeV)	103.3	114.6	135.6

Z' Branching Ratios

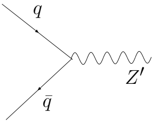


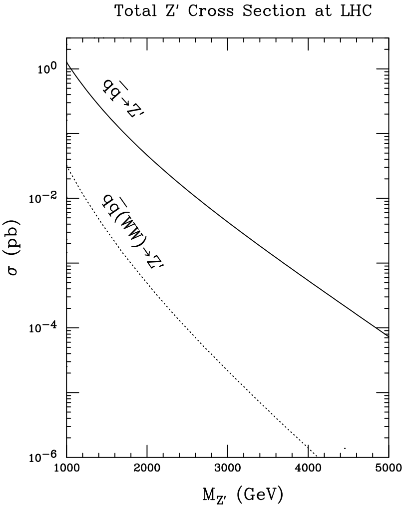
$W'^{\pm}$ Branching Ratios





Z'production at the LHC

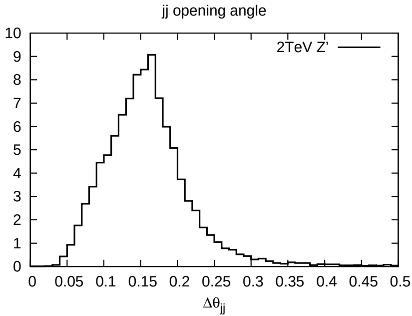


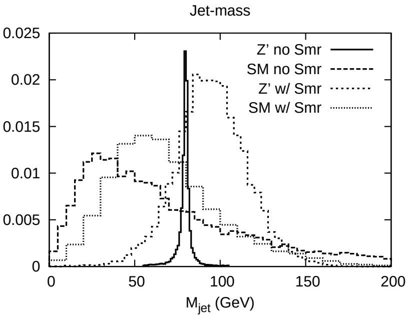


LHC Channels

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

- $pp \to Z' \to W^+ W^-$
  - Fully leptonic : $W \to \ell\nu$; $W \to \ell\nu$
  - Semi leptonic : $W \to \ell\nu$; $W \to (j\,j)$
- $pp \to Z' \to Z\,h$
  - $m_h = 120\text{GeV}$: $Z \to \ell^+\ell^-$; $h \to b\,\bar{b}$
  - $m_h = 150\text{GeV}$: $Z \to (j\,j)$; $h \to W^+\,W^- \to (j\,j)\ \ell\nu$
- $pp \to Z' \to \ell^+\ell^-$
  - Clean but needs high luminosity
- $pp \to Z' \to t\,\bar{t}\ ,\ \ b\,\bar{b}$ [Djouadi, Moreau, Singh - 07]
  - KK gluon "pollution"





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]

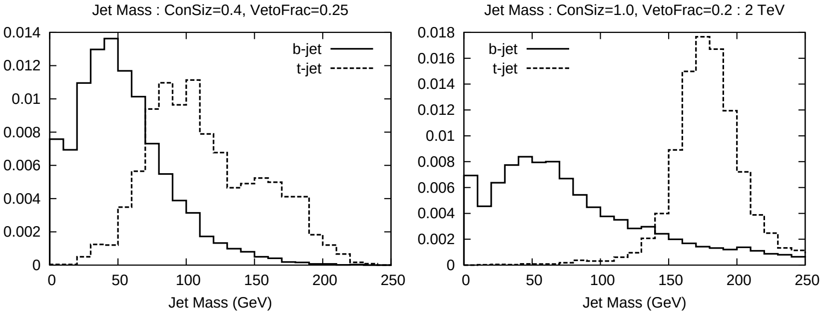
To account for (HCal) expt. uncert.

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

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

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

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



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)

Angular correlations in $W' \to tb$

[Work in progress: SG, Han, Lewis, Si, Zhou]

$$\mathcal{L} \supset \frac{1}{\sqrt{2}} \bar{\psi}_u \gamma_\mu \left(g_L P_L + g_R P_R \right) \psi_d \, {W'}^{+\mu} + \mathrm{h.c.}$$

LHC: $u\bar{d} \to W' \to t\bar{b}$ followed by $t \to Wb \to \ell \nu b$

Angular correlations in $W' \to tb$

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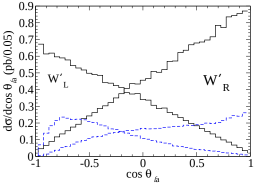
$$\mathcal{L} \supset \frac{1}{\sqrt{2}} \bar{\psi}_u \gamma_\mu \left(g_L P_L + g_R P_R \right) \psi_d \, {W'}^{+\mu} + \text{h.c.}$$

LHC: $u\bar{d} \to W' \to t\bar{b}$ followed by $t \to Wb \to \ell\nu b$
Determine $g_L^{u,d,t,b}$, $g_R^{u,d,t,b}$ from Angular Correlations

- g_L , g_R from $\cos\theta_t$ distribution
- g_L , g_R determines top polarization ; analyzed by ℓ angular distribution



Defining forward direction at the LHC

- pdf: $x_q > x_{\bar{q}} \Rightarrow$ more likely event boosted in q direction

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

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

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

- $m_h \approx 120$: $h \to b\,b$
  - 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)

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

$M_{Z'} = 2$ 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		

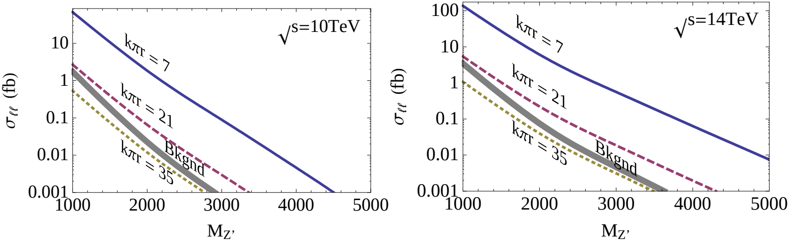
events above is for

- 2 TeV : $1000\ \mathrm{fb}^{-1}$

Experimentally clean, but needs a LOT of luminosity

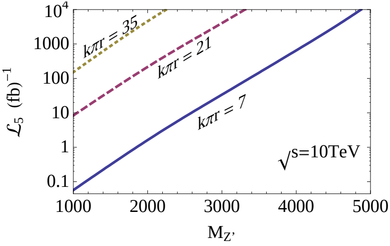
RS as a theory of flavor (No hierarchy problem solution) [Davoudiasl, Perez, Soni, 2008]

- Lower UV scale $y \equiv \frac{k\pi r\,|_{RS}}{k\pi r\,|_{LRS}} \Rightarrow BR^{LRS}_{\ell^+\ell^-} = y^2 BR^{RS}_{\ell^+\ell^-}$; $\frac{S}{B}\big|_{LRS} = y^4\, \frac{S}{B}\big|_{RS}$

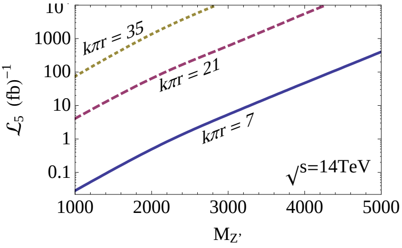


[Davoudiasl, SG, Soni, 2009]

LRS contd.



10^4
1000
100
10
1
0.1
1000
2000
3000
4000
5000
$M_{Z'}$
$\mathcal{L}_5\ (\text{fb})^{-1}$
$k\pi r = 35$
$k\pi r = 21$
$k\pi r = 7$
$\sqrt{s}$=10TeV



1000
100
10
1
0.1
1000
2000
3000
4000
5000
$M_{Z'}$
$\mathcal{L}_5\ (\text{fb})^{-1}$
$k\pi r = 35$
$k\pi r = 21$
$k\pi r = 7$
$\sqrt{s}$=14TeV

New fermion (b')

[Work in progress: SG, Moreau, Singh]

- Minimal rep (No custodial protection of $Zb\bar{b}$)

$$Q_L = (2,1)_{1/6} = (t_L, b_L)$$

$$Q_{b_R} = (1,2)_{1/6} = (t', b_R)$$

$$Q_{t_R} = (1,2)_{1/6} = (t_R, b')$$

b' has $(-,+)$ BC $\Rightarrow$ lightest BSM fermion

$$\mathcal{L}_{5D} \supset -\lambda_t \bar{Q}_L \Sigma Q_{t_R} - \lambda_b \bar{Q}_L \Sigma Q_{b_R}$$

After EWSB:

$$\mathcal{L}_{4D} \supset - \begin{pmatrix} \bar{b}_L & \bar{b'}_L \end{pmatrix} \begin{pmatrix} \lambda_b v \, f_{Q_L} f_{b_R} & \lambda_t v \, f_{Q_L} f_{b'} \\ 0 & m_{b'} \end{pmatrix} \begin{pmatrix} b_R \\ b'_R \end{pmatrix} + \mathrm{h.c.}$$

b'_R couplings:

- $b' b' g_\mu$, $b' b' A_\mu$
- diagonalizing leads to $t_L b'_L W_\mu$ & $bb' Z_\mu$ couplings $\longrightarrow$ single production!

Radion

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

Fluctuations of size of extra dimension $\longrightarrow$ 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

Things to do

- Can we tell longitudinal nature of W_L
- Probes of parity violation in KK gauge decays
- b' production and decay channels and LHC signatures
- Boosted W and t into jets. Clustering algorithms.

Conclusions

- Warped-space models explain gauge hierarchy problem
  - EWPT puts strong constraints
  - $SU(2)_L \times SU(2)_R \times U(1)_X$ bulk symmetry
  - $m_{KK} \gtrsim 2$ TeV
    - Some tension due to this
- Flavor hierachy can also be explained
  - Coupling of KK states to light states suppressed
  - LHC signals harder
- LHC signals: KK graviton, gluon, W, Z, A, ψ
- Other precision probes

BACKUP SLIDES

Z' Overlap Integrals

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

Z' overlap with Higgs $\rightarrow \xi$
Z' overlap with fermions:

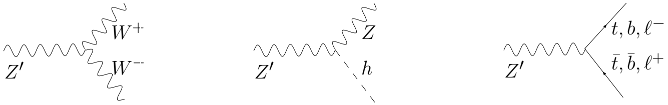
	Q_L^3	t_R	other fermions
$\mathcal{I}^+$	$-\frac{1.13}{\xi} + 0.2\xi \approx 1$	$-\frac{1.13}{\xi} + 0.7\xi \approx 3.9$	$-\frac{1.13}{\xi} \approx -0.2$
$\mathcal{I}^-$	$0.2\xi \approx 1.2$	$0.7\xi \approx 4.1$	0

Compared to SM

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

$$\bar{\psi}_{L,R}\gamma^\mu \Big[eQ\mathcal{I}A_{1\,\mu} + g_Z\left(T_L^3 - s_W^2 T_Q\right)\mathcal{I}Z_{1\,\mu} + g_{Z'}\left(T_R^3 - s'^2 T_Y\right)\mathcal{I}Z_{X1\,\mu}\Big]\psi_{L,R}$$

Z'decays



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

$$\Gamma(\tilde{Z}_1, \tilde{Z}_{X1} \to W_L W_L) = \frac{g_L^2 c_W^2 \kappa^2}{192\pi}\frac{M_{Z'}^5}{m_W^4} \; ; \quad \kappa \propto \sqrt{k\pi r_c}\left(\frac{m_Z}{(M_{Z_1}, M_{Z_{X_1}})}\right)^2 ,$$

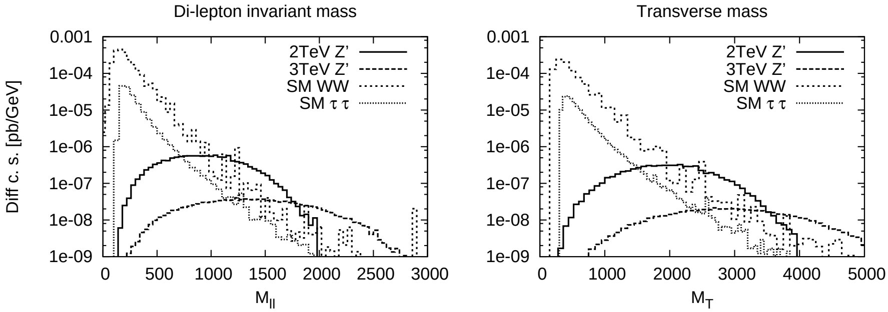
$$\Gamma(\tilde{Z}_1, \tilde{Z}_{X1} \to Z_L h) = \frac{g_Z^2\kappa^2}{192\pi} M_{Z'} \; ; \quad \kappa \propto \sqrt{k\pi r_c} ,$$

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

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	

2 ν's $\Rightarrow$ cannot reconstruct event



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

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

Cross-section (in fb) after cuts:

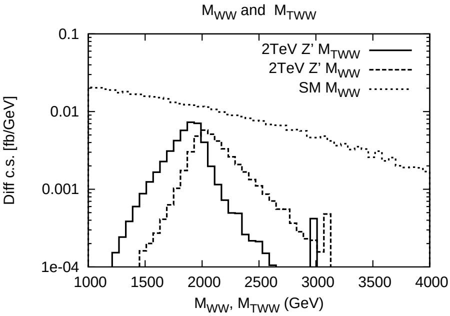
2 TeV	Basic cuts	$\|\eta_\ell\| < 2$	$M_{eff} > 1$ TeV	M_T >1.75 TeV	# Evts	S/B	$S/\sqrt{B}$
Signal	0.48	0.44	0.31	0.26	26	0.9	4.9
WW	82	52	0.4	0.26	26		
$\tau\tau$	7.7	5.6	0.045	0.026	2.6		
3 TeV	**Basic cuts**	$\|\eta_\ell\| < 2$	$1.5 < M_{eff} < 2.75$	$2.5 < M_T < 5$	**# Evts**	S/B	$S/\sqrt{B}$
Signal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

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

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



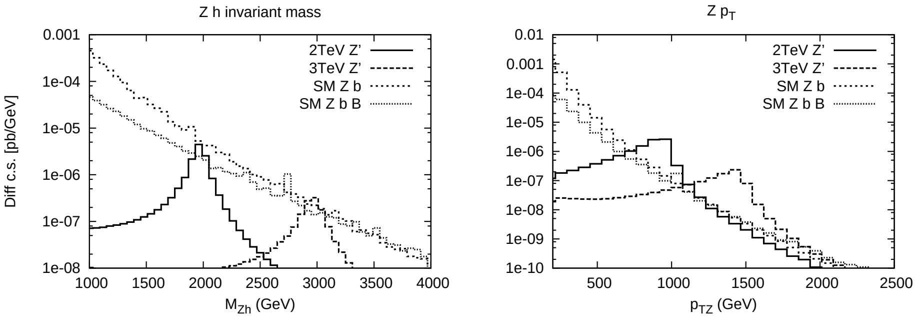
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ 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)

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

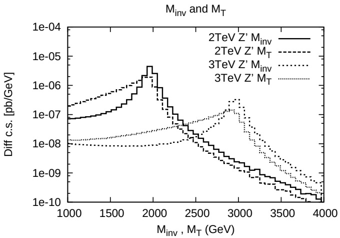
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ 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}

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



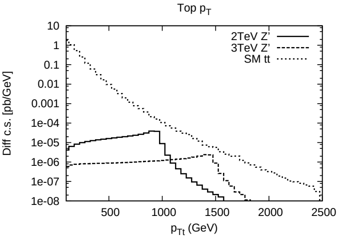
$$M_{T_{Zh}} \equiv \sqrt{p_{T_Z}^2 + m_Z^2} + \sqrt{p_{T_h}^2 + m_h^2}$$

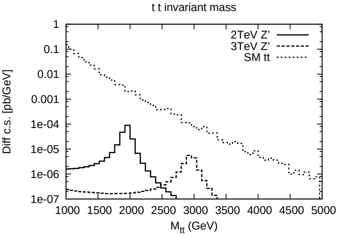
$M_{Z'} = 2$ TeV $m_h = 150$ GeV	Basic	p_T, η	$\cos\theta$	M_T	M_{jet}	# Evts	S/B	$S/\sqrt{B}$
$Z' \to hZ \to \ell \not{E}_T\,(jj)\,(jj)$	2.4	1.6	0.88	0.7	0.54	54	2.5	11.5
SM $W\,j\,j$	3×10^4	35.5	12.7	0.62	0.19	19		
SM $W\,Z\,j$	184	0.45	0.15	0.02	0.02	2		
SM $W\,W\,j$	712	0.54	0.2	0.02	0.01	1		
$M_{Z'}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

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





$M_{Z'} = 2$ 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

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

Signal c.s. $\sim 1fb$

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

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