Warped-space 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

- Introduction to Warped-space (Randall-Sundrum) scenario
  - $SU(3)_{QCD} \times SU(2)_L \times SU(2)_R \times U(1)_X$ bulk gauge group
  - Phenomenological Implications
- Kaluza-Klein (KK) particles at the LHC
  - $\mathrm{Graviton}_{KK}$; Gluon_{KK} , $W^{\pm}_{KK}$, Z_{KK}; $\mathrm{Fermion}_{KK}$
  - Angular correlation in $W^{\pm}_{KK} \to t\, b$
- Little RS (LRS)
- Some general issues at the LHC

5D Warped Space

[Randall, Sundrum 99]

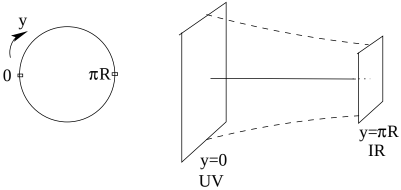
$ds^2 = e^{-2k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2$

Z_2 Orbifold -

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

R : radius of Ex. Dim.

k : AdS curvature scale



Hierarchy prob soln:

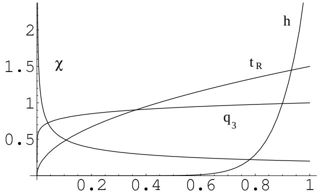
- IR localized Higgs : $M_{EW} \sim k e^{-k\pi R}$: Choose $k\pi R \sim 34$
  - CFT dual is a composite Higgs model

[Gherghetta, Pomarol 00][Grossman, Neubert 00]

Bulk Fermions explain SM mass hierarchy

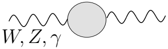
$\mathcal{S}^{(5)} \supset \int d^4x\, dy\ \left\{ -c_\psi\, k\, \overline{\Psi}(x,y)\, \Psi(x,y) \right\}$

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



RS-GIM keeps FCNC under control

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 $SU(2)_R$ $\Leftrightarrow$ 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 $\Rightarrow M_{KK} \gtrsim 2 - 3$ 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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Gauge Symmetry breaking:

- By Boundary Condition (BC):

$$A_{-+}(x,y):\ A|_{y=0} = 0\,;\ \partial_y A\,|_{y=\pi R} = 0$$

  - $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$
- By VEV of TeV brane Higgs
  - $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

Fermion reps (Custodial protection for $Zb_L\overline{b_L}$)

[Agashe, Contino, DaRold, Pomarol 06]

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

Higgs $\Sigma = (2,2)$

Fermions

- $Q_L = (2,2) = \begin{pmatrix} t_L & \zeta_L \\ b_L & T_L \end{pmatrix}$
- t_R : $(1,1)$ OR $(1,3) = \begin{pmatrix} \chi'_R \\ t_R \\ b'_R \end{pmatrix} \oplus \begin{pmatrix} \chi''_R \\ t''_R \\ b''_R \end{pmatrix}$
- b_R : $(1,1)$ OR $(1,3)$
    - New $(-,+)$ fermions with no zero-modes: ζ_L, T_L, χ'_R, b'_R, ...

Note: Wt_Lb_L, Zt_Lt_L not protected, so expect shifts

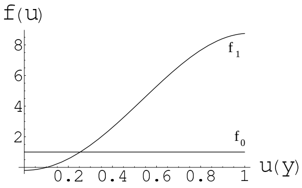
Kaluza Klein (KK) decomposition

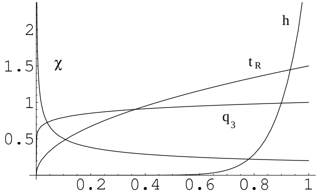
Bulk fields $\Phi(x,y) = \Psi,\ A,\ \ldots$

$$\mathcal{S}^{(5)} = \int d^4x dy\ \mathcal{L}^{(5)} \quad ; \quad \mathcal{L}^{(5)} \supset \sqrt{|g|}\left(M_*^3\mathcal{R}\ + c_\psi \Psi\Psi\ + g_5 \Psi\Psi\, A\ + \lambda_5\, \Psi_L \Psi_R\, H\right)$$

Kaluza-Klein (KK) expansion: $\Phi(x,y) = \sum_{n=0}^{\infty} f_{(n)}^{\phi}(y)\, \phi^{(n)}(x)$

Bulk Equations of Motion give profiles $f^{\phi}(y)$





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

Plug this in $\mathcal{S}^{(5)}$ and integrate over y to get Equivalent 4D theory

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

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

4-D KK couplings (Ratio to SM)

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

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: $g_{4D}^{(001)} = g_{5D} \int dy\, f_0^{\psi}\, f_0^{\psi}\, f_1^A$
  - 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:

$$\mathcal{L}^{4D} \supset \bar{\psi}_{L,R}\gamma^{\mu}\left[eQ\mathcal{I}A_{1\,\mu} + g_Z\left(T_L^3 - s_W^2 T_Q\right)\mathcal{I}Z_{1\,\mu} + g_{Z'}\left(T_R^3 - s'^2 T_Y\right)\mathcal{I}Z_{X_1\,\mu}\right]\psi_{L,R}$$

KK states at the LHC

- $h^{(1)}_{\mu\nu}$ KK Graviton

  $L = 300\ fb^{-1}$ LHC reach is about 2 TeV

  [Agashe, Davoudiasl, Perez, Soni 07]
  [Fitzpatrick, Kaplan, Randall, Wang 07]

- $g^{(1)}_{\mu}$ KK Gluon

  $L = 100\ fb^{-1}$ LHC reach is 4 TeV

  [Agashe, Belyaev, Krupovnickas,Perez,Virzi 06]
  [Lillie, Randall, Wang, 07] [Lillie, Shu, Tait 07]

- $Z^{(1)}_{\mu}$ and $W^{(1)\pm}_{\mu}$ KK Z and $W^{\pm}$ (Denote as Z' and W')

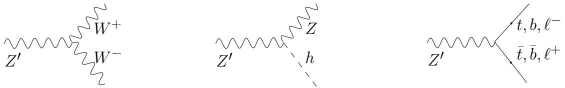
  [*Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni* 0709.0007 & 0810.1497]

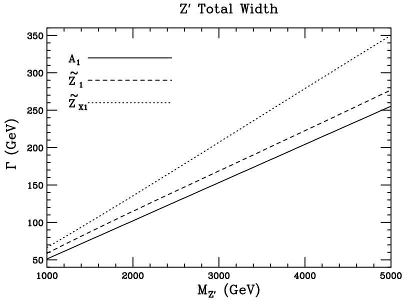
- $\psi^{(1)}$ KK Fermion [*Work in progress*]
- Radion

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

Z_{KK} (Z') phenomenology

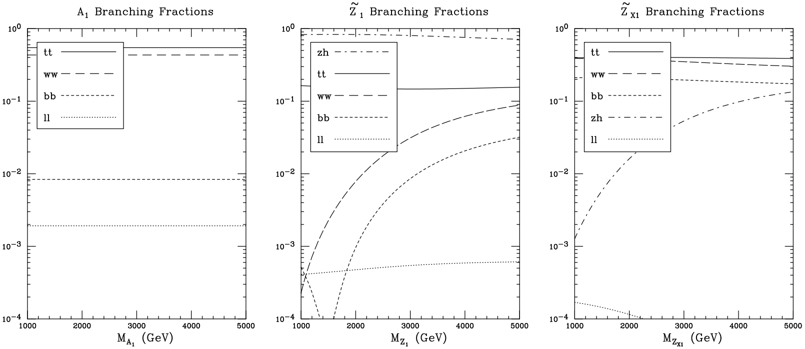
[Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni - arXiv:0709.0007 [hep-ph]]



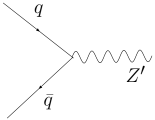


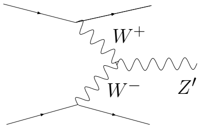
$M_{Z'}$ = 2TeV	A_1	Z_1	$Z_{X\,1}$
Γ (GeV)	103.3	114.6	135.6

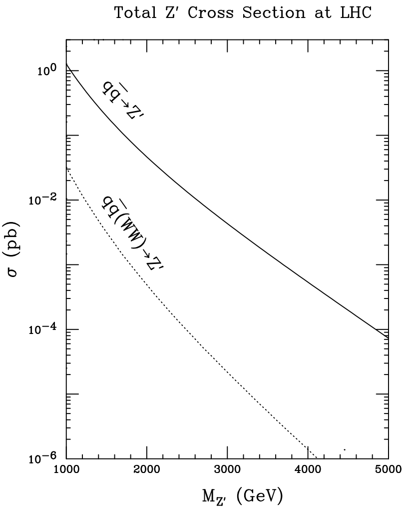
Z' Branching Ratios



Z' production at the LHC

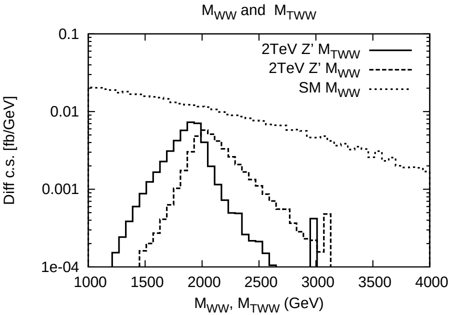




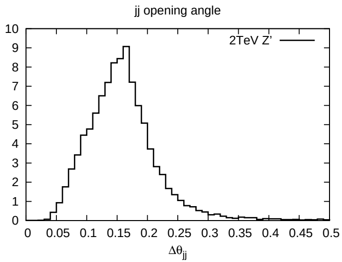


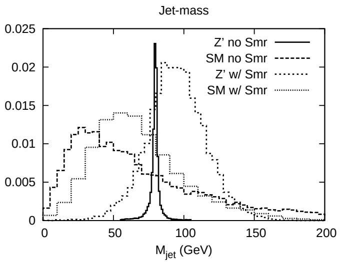
$pp \to Z' \to W^+W^- \to \ell\,\nu\, j\, j$

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



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

Z' channels summary

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

- $pp \longrightarrow Z' \longrightarrow W^+W^-$
    - 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}
- $pp \longrightarrow Z' \longrightarrow Z\,h$
    - $m_h = 120\text{GeV}$: $Z \to \ell^+\ell^-$; $h \to b\,\bar{b}$ — $\mathcal{L}$: (200; 1000) fb^{-1}
    - $m_h = 150\text{GeV}$: $Z \to (j\,j)$; $h \to W^+\,W^- \to (j\,j)\ \ell\nu$ — $\mathcal{L}$: (75; 300) fb^{-1}
- $pp \longrightarrow Z' \longrightarrow \ell^+\ell^-$ — $\mathcal{L}$: (1000; —) fb^{-1}
    - $BR_{\ell\ell} \sim 10^{-3}$ Tiny!
- $pp \longrightarrow Z' \longrightarrow t\,\bar{t}\ ,\ b\,\bar{b}$
    - KK gluon "pollution" — [Djouadi, Moreau, Singh 07]

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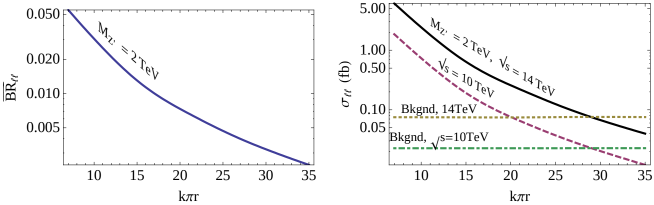
$pp \to Z'_{LRS} \to \ell^+\ell^-$ [Davoudiasl, SG, Soni 09; arXiv:0908.1131]



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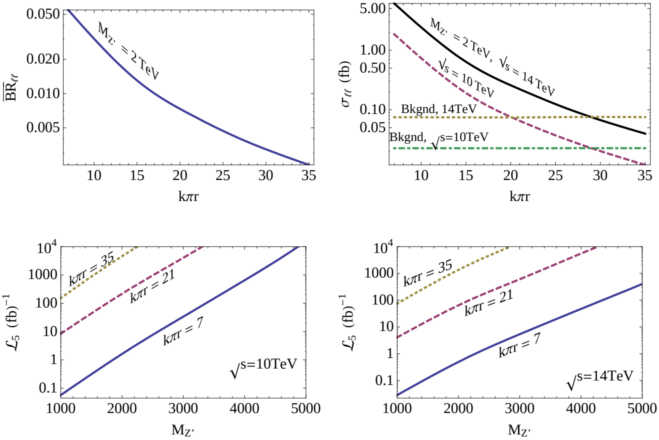
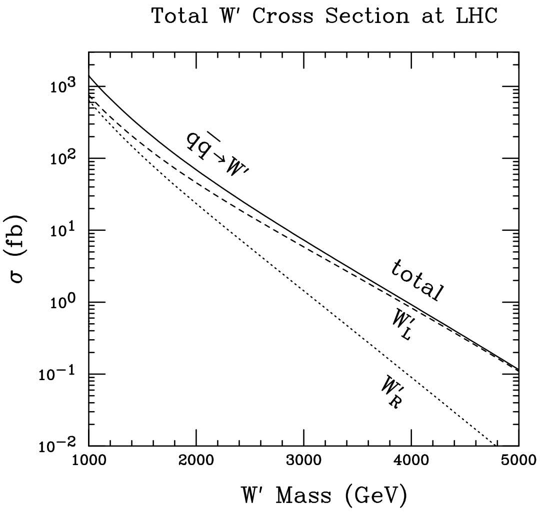


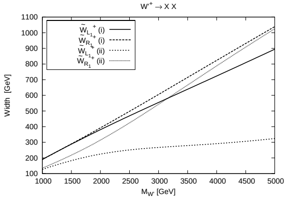
$W^{\pm}_{KK}$ ($W'^{\pm}$) phenomenology

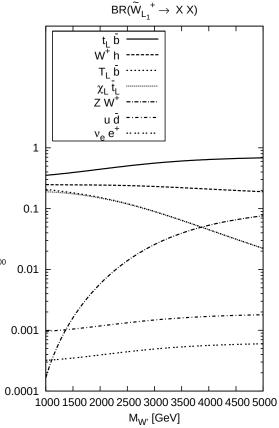
W' cross section

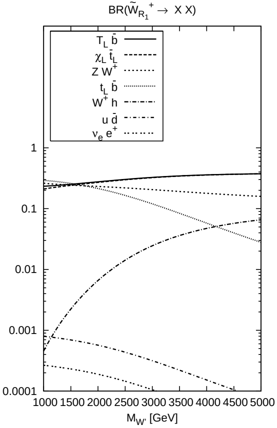
[Agashe, SG, Han, Huang, Soni, 08: arXiv:0810.1497]



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







$W'^{\pm}$ channels summary

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

- $W'^{\pm} \rightarrow t\, b$:
  - 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
- $W'^{\pm} \rightarrow Z\, W$:
  - Fully leptonic — $\mathcal{L}$: (100; 1000) fb^{-1}
  - Semi leptonic — $\mathcal{L}$: (300; −) fb^{-1}
- $W'^{\pm} \rightarrow W\, h$: — $\mathcal{L}$: (100; 300) fb^{-1}
  - $m_h \approx 120$: $h \rightarrow b\, b$
    - What is b-tagging eff at large p_{T_b}?
  - $m_h \approx 150$: $h \rightarrow W\, W$
    - Use W jet-mass to reject light jet

A Model Independent Study

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

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

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

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- Can we measure $g^{ud}_{L,R}$, $g^{tb}_{L,R}$?
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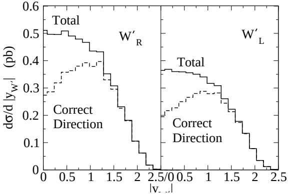
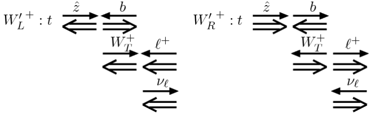
1. Need to fix u direction:

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



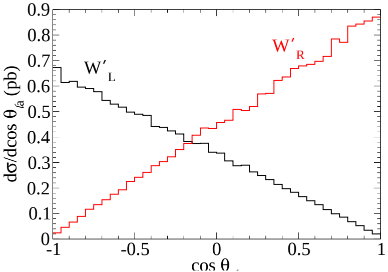
   $\therefore$ direction of $y_{W'} > 0.8$ is u direction

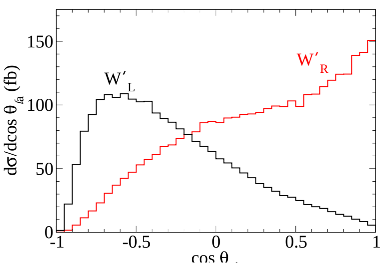
2. θ_ℓ distribution analyzes top polarization



Analyze in top rest frame

Measuring Chirality (Results)





Conclusions

- Warped-space addresses SM hierarchy and flavor problems
  - KK mode couplings to light fermions suppressed, heavy fermions enhanced
  - Requires high $\mathcal{L}$ at LHC
- Precision electroweak constraints imply $M_{KK} \gtrsim 2\ TeV$
  - Boosted W, Z, top $\Rightarrow$ collimation of decay products
    - picks up QCD bkgnd
- Chirality of W' : using θ_ℓ as analyzer of top polarization
- Little-RS (LRS) has good $Z' \to \ell^+\ell^-$
- Thanks to:
  - CalcHEP (help from Alaxender Belyaev)
  - Pythia (help from Steve Mrenna, Peter Skands)
  - MadGraph (help from Rikkert Frederix)
  - Bridge (help from Matt Reece)

BACKUP SLIDES

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):
  $Z_X(-,+)$ means $Z_X|_{y=0} = 0\,;\ \partial_y Z_X\,|_{y=\pi R} = 0$
  - $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$: $(W_L^3, W_R^3, X) \rightarrow (W_L^3, B, Z_X)$
    $A \rightarrow (+,+)\,;\ Z \rightarrow (+,+)\,;\ Z_X \rightarrow (-,+)$
  - $Z_X \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_R W_R^3 - g_X X) \rightarrow (-,+)$; $W_R^\pm \rightarrow (-,+)$
    - $B \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_X W_R^3 + g_R X) \rightarrow (+,+)$; $W_L^\pm \rightarrow (+,+)$

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Symmetry Breaking:

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

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

- 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: $A^{(1)}, Z^{(1)}, Z_X^{(1)} \quad \longrightarrow \ Z' \quad ; \quad W_L^{(1)}, \ W_R^{(1)}$

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

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

Mass eigenstates :

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

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

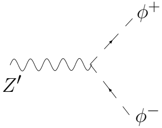
- Z' couplings to h enhanced (also V_L - Equivalence Theorem!)
- Z' couplings to t_R enhanced
- Z'couplings to χ suppressed

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

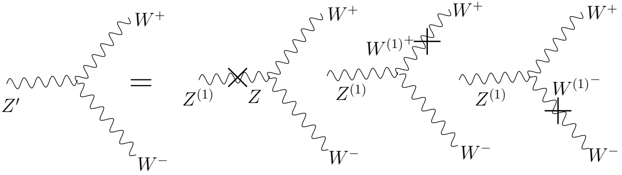
EWSB induced $Z'W^+W^-$ coupling

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

Using Goldstone equivalence:



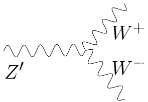
In Unitary Gauge:

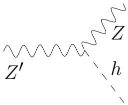


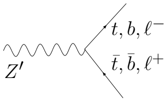
Even though $\xi \cdot (\frac{v}{M_{KK}})^2$ suppressed ...
... can be overcome by $(\frac{M_{KK}}{m_Z})^2$ (from long. pol. vectors)

Z' decays

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





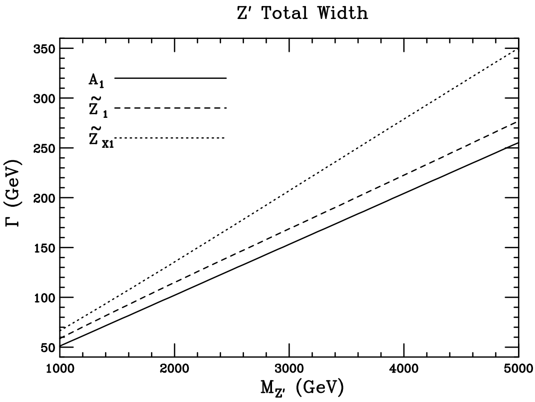


$$
\begin{aligned}
\Gamma(A_1 \to W_L W_L) &= \frac{e^2 \kappa^2}{192\pi} \frac{M_{Z'}^5}{m_W^4} \; ; \quad \kappa \propto \sqrt{k\pi r_c} \left(\frac{m_W}{M_{W_1^\pm}} \right)^2 , \\
\Gamma(\tilde{Z}_1, \tilde{Z}_{X1} \to W_L W_L) &= \frac{g_L^2 c_W^2 \kappa^2}{192\pi} \frac{M_{Z'}^5}{m_W^4} \; ; \quad \kappa \propto \sqrt{k\pi r_c} \left(\frac{m_Z}{(M_{Z_1}, M_{Z_{X1}})} \right)^2 , \\
\Gamma(\tilde{Z}_1, \tilde{Z}_{X1} \to Z_L h) &= \frac{g_Z^2 \kappa^2}{192\pi} M_{Z'} \; ; \quad \kappa \propto \sqrt{k\pi r_c} , \\
\Gamma(Z' \to f\bar{f}) &= \frac{(e^2, g_Z^2)}{12\pi} \left(\kappa_V^2 + \kappa_A^2 \right) M_{Z'} \; .
\end{aligned}
$$

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	

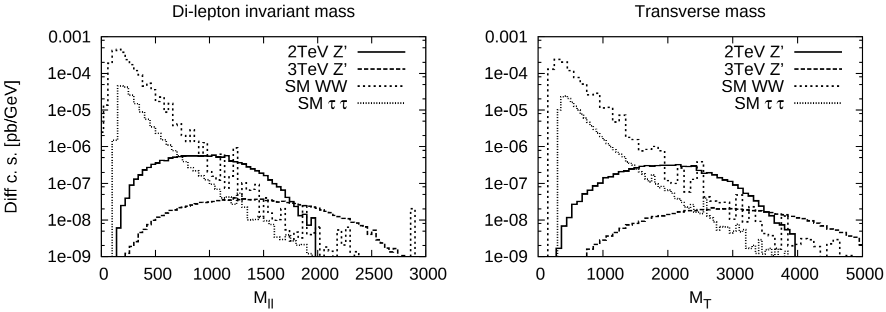
Total Widths



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

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

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	$\lvert\eta_\ell\rvert < 2$	$M_{eff} > 1$ 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	$\lvert\eta_\ell\rvert < 2$	$1.5 < M_{eff} < 2.75$	$2.5 < M_T < 5$	# 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}

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

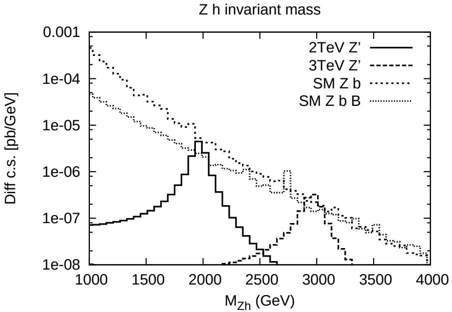
Cross-section (in fb) after cuts:

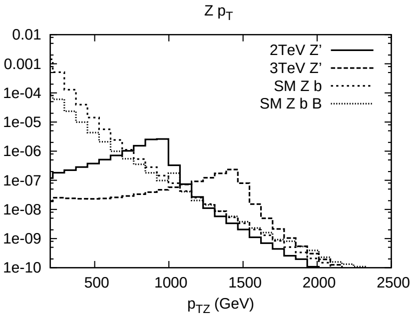
$M_{Z'} = 2$ TeV	p_T	$\eta_{\ell,j}$	M_{eff}	$M_{T_{WW}}$	M_{jet}	# Evts	S/B	$S/\sqrt{B}$
Signal	4.5	2.40	2.37	1.6	1.25	125	0.39	6.9
W+1j	1.5×10^5	3.1×10^4	223.6	10.5	3.15	315		
WW	1.2×10^3	226	2.9	0.13	0.1	10		
$M_{Z'} = 3$ TeV								
Signal	0.37	0.24	0.24	0.12	-	120	0.17	4.6
W+1j	1.5×10^5	3.1×10^4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

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





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)

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

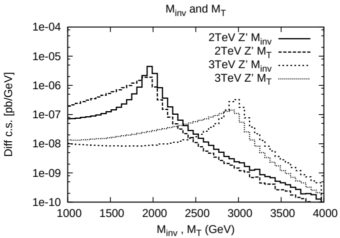
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ 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}

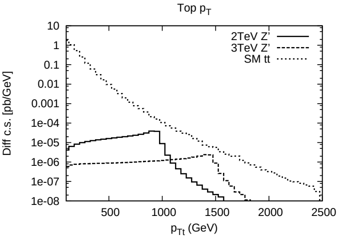
$M_{Z'} = 2$ TeV	Basic	$p_{T\ell}$	$M_{\ell\ell}$	# Evts	S/B	$S/\sqrt{B}$
Signal	0.1	0.09	0.06	60	0.3	4.2
SM $\ell\ell$	3×10^4	5.4	0.2	200		
SM WW	295	0.03	0.002	2		

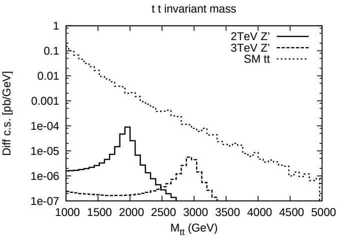
events above is for

- 2 TeV : 1000 fb^{-1}

Experimentally clean, but needs a LOT of luminosity

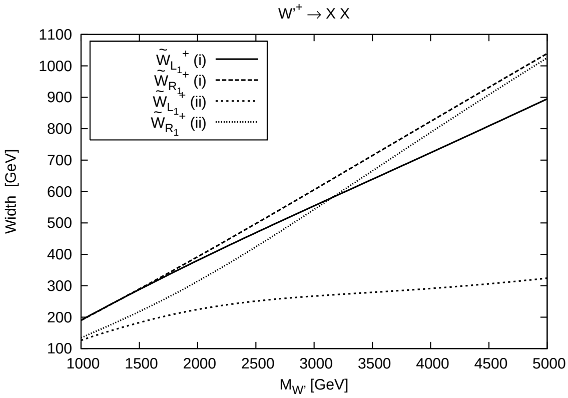
$pp \longrightarrow Z' \longrightarrow t\bar{t}$



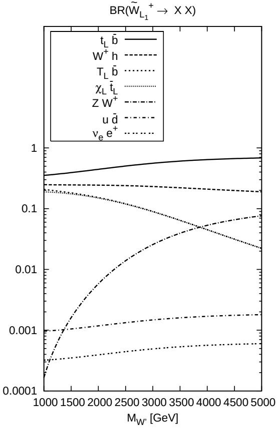


$M_{Z'} = 2$ TeV	Basic	$p_T > 800$	$1900 < M_{tt} < 2100$
Signal	17	7.2	5.6
SM $t\bar{t}$	1.9×10^5	31.1	19.1
$M_{Z'} = 3$ TeV	Basic	$p_T > 1250$	$2850 < M_{tt} < 310$
Signal	1.7	0.56	0.45
SM $t\bar{t}$	1.9×10^5	4.1	1.1

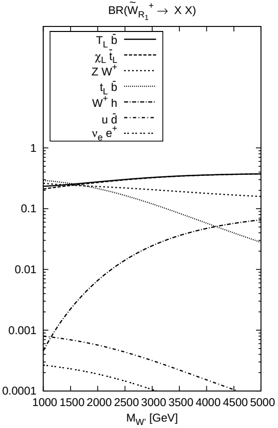
$W'^{\pm}$ width


W'+ → X X
Width [GeV]
M_W' [GeV]
1100
1000
900
800
700
600
500
400
300
200
100
1000
1500
2000
2500
3000
3500
4000
4500
5000
W̃_L1+ (i)
W̃_R1+ (i)
W̃_L1+ (ii)
W̃_R1+ (ii)

$W'^{\pm}$ BR



BR($\tilde{W}_{L_1}{}^+ \to$ X X)
$t_L\ \bar{b}$
$W^+\ h$
$T_L\ \bar{b}$
$\chi_L\ \bar{t}_L$
$Z\ W^+$
$u\ \bar{d}$
$\nu_e\ e^+$
1
0.1
0.01
0.001
0.0001
1000 1500 2000 2500 3000 3500 4000 4500 5000
$M_{W'}$ [GeV]



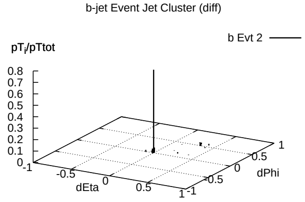
BR($\tilde{W}_{R_1}{}^+ \to$ X X)
$T_L\ \bar{b}$
$\chi_L\ \bar{t}_L$
$Z\ W^+$
$t_L\ \bar{b}$
$W^+\ h$
$u\ \bar{d}$
$\nu_e\ e^+$
1
0.1
0.01
0.001
0.0001
1000 1500 2000 2500 3000 3500 4000 4500 5000
$M_{W'}$ [GeV]

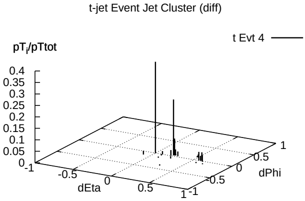
$W'^{\pm} \to t\, b \to \ell \nu\, b\, b$

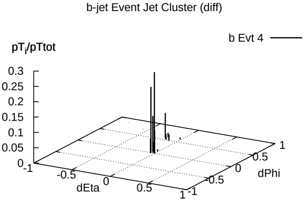
Signal c.s. $\sim 1 fb$

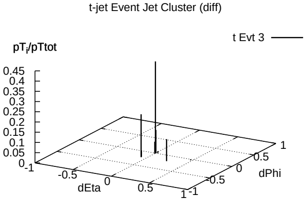
Bkgnd is single top + QCD W b b .... AND ...

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

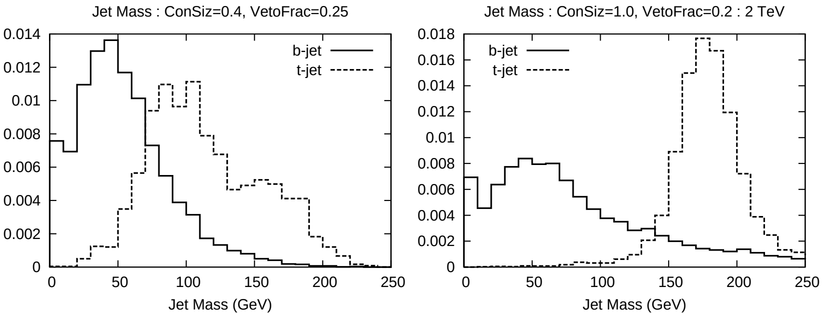








$W'^{\pm} \to t\, b \to \ell \nu b\, b$



Jet-mass cut: cone size 1.0 and $0 < j_M < 75$ ⇒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)

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

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

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

Storage Area

- Warped (RS) model
- Heavy EW gauge bosons : 3 neutral (Z') & 2 charged ($W'^{\pm}$)
  - Precision electroweak observables require $M_{Z'}$, $M_{W_1^{\pm}} \gtrsim 2$ TeV
    - Makes discovery challenging at the LHC