LHC Search of Charged Electroweak Gauge Bosons in Warped Extra Dimensions

GuiYu Huang

University of California, Davis , Department of Physics

LHC Lunch Seminar at UC Davis, Physics

October 14, 2008

Kaustubh Agashe, Hooman Davoudiasl, Shrihari Gopalakrishna,
Tao Han, GH, Gilad Perez, Zong-Guo Si, Amarjit Soni
Phys. Rev. D **76**, 115015 (2007) arXiv:0709.0007

Agashe, Gopalakrishna, Han, GH, Soni arXiv:0810.1497

Kaluza-Klein Theory

pure 5D gravity

$$d\hat{s}^2 = \hat{g}_{\hat{\mu}\hat{\nu}} d\hat{x}^{\hat{\mu}} d\hat{x}^{\hat{\nu}}$$

$5 \to 4 + 1$ split, *e*.g.

$$\hat{g}_{\hat{\mu}\hat{\nu}} = e^{\phi/\sqrt{3}} \begin{pmatrix} g_{\mu\nu} + e^{-\sqrt{3}\phi} A_\mu A_\nu & e^{-\sqrt{3}\phi} A_\mu \\ e^{-\sqrt{3}\phi} A_\nu & e^{-\sqrt{3}\phi} \end{pmatrix}$$

$\hat{\mu} = 0, 1, 2, 3, 4$, and $\mu = 0, 1, 2, 3$
$\hat{x}^{\hat{\mu}} = (x^\mu, y)$

$g_{\mu\nu}(x)$, $A_\mu(x)$, $\phi(x)$

Klein's Compactification

- Non-observation of the extra dimension
- Suppression of field dependence on extra dimension

explained by a compact, small extra dimension

$$M^5 \rightarrow M^4 \times S^1$$

$$g_{\mu\nu}(x,y) = \sum g_{\mu\nu n}(x) e^{inky},$$

$$A_\mu(x,y) = \sum A_{\mu n}(x) e^{inky}$$

$$\phi(x,y) = \sum \phi_n e^{inky}, \ (kr = 1)$$

$\Longrightarrow$ Zero modes and infinite towers of excitations

Warped Extra Dimension

Randall-Sundrum Model

- Warping in the 5th Dim:

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

- Z_2 Orbifolding: Exponential scale factor between Planck Brane and TeV Brane
- Solves hierarchy problem with a warp factor from AdS background

$$e^{-k\pi R} \sim M_{EW}/M_{pl}$$

$$k\pi R \sim \log M_{pl}/\mathrm{TeV} \sim 34$$

R: size of extra dim.

k: curvature of extra dim.

Warped Extra Dimension

RS in the bulk

- Also explains flavor hierarchy with field profile (or wavefunction) in extra dimension
- Mass and couplings explained by overlappings of profiles

$$C^{FFG}_{mnq} = \int \frac{d\phi}{\sqrt{k}} \frac{e^{t\sigma} \ \chi_F^{(m)} \chi_F^{(n)} \chi_G^{(q)}}{\sqrt{R}} .$$

Collider Signature of RS

- KK-graviton: dilepton or diphoton signal, need high luminosity (hep-ph/0006041, hep-ph/0701150, hep-ph/0701186)
- KK-gluon: large cross section, $t\bar{t}$ final state (hep-ph/0612015, hep-ph/0701166, arXiv:0706.3960)
- KK-EW gauge boson: dominated by $t\bar{t}$. $\ell^+\ell^-$ suppressed. Other channels?
- KK-fermion (arXiv:0706.1281 arXiv:0712.0095)

Gauge Symmetry Breaking

Bulk Gauge Group

Neglecting $SU(3)_C$,

$$\begin{aligned} & SU(2)_L \times SU(2)_R \times U(1)_X \\ \Rightarrow \text{(viaBoundaryCondition) } & SU(2)_L \times U(1)_Y \\ \Rightarrow \text{(viaHiggsMechanism) } & U(1)_Q \end{aligned}$$

$$Y = T_{3R} + X, \; Q = T_{3L} + Y/2.$$

Gauge Bosons

- Charged: $W_L^\pm, W_R^\pm$
- Neutral:

$$\begin{aligned} & W_L^3, W_R^3, X \\ \Rightarrow & W_L^3, B, Z_X \\ \Rightarrow & A, Z, Z_X \end{aligned}$$

Only A, Z, W_L have zero-mode, W_R, Z_X don't. (-+) BC

Representations

Fermions

- $Q_L = (2,2) = \begin{pmatrix} t_L & \chi_L \\ b_L & T_L \end{pmatrix}$
- $t_R = (1,1)$ *or* $(1,3) \in (1,3) \oplus (3,1) = \begin{pmatrix} \chi''_R \\ t_R \\ B''_R \end{pmatrix} \oplus \begin{pmatrix} \chi'''_R \\ T'''_R \\ B'''_R \end{pmatrix}$

Higgs

- $\Sigma = (2,2)$

For these reps

- $Zb\bar{b}$: protected by custodial symmetry
  [Agashe,Contino,DaRold,Pomarol - 06]
- Precision EW constraints $\Rightarrow M_{Z'} \gtrsim 2 - 3\mathrm{TeV}$
  [Carena, Ponton, Santiago, Wagner - 06,07]

Two Cases We Consider

- Case (i): $t_R \rightarrow (1,1)$, $c_{Q_L^3} = 0$, $c_{t_R} = 0.4$.
- Case (ii): $t_R \rightarrow (1,3)$, $c_{Q_L^3} = 0.4$, $c_{t_R} = 0$.

Charged Gauge Bosons

Mass Spectrum

Mass term for zero mode and 1st excitations:

$$\begin{pmatrix} W_L^{+\,(0)} & W_{L_1}^{+} & W_{R_1}^{+} \end{pmatrix} \mathcal{M}_W^2 \begin{pmatrix} W_L^{-\,(0)} \\ W_{L_1}^{-} \\ W_{R_1}^{-} \end{pmatrix}$$

$$\mathcal{M}_W^2 =$$

$$\begin{pmatrix} m_W^2 & m_W^2\sqrt{k\pi R} & -m_W^2\sqrt{k\pi R}\,\frac{g_R}{g} \\ m_W^2\sqrt{k\pi R} & m_{KK}^2 + m_W^2 k\pi R & -m_W^2 k\pi R\,\frac{g_R}{g} \\ -m_W^2\sqrt{k\pi R}\,\frac{g_R}{g_L} & -m_W^2 k\pi R\,\frac{g_R}{g} & 0.963\ m_{KK}^2 + m_W^2 k\pi R\left(\frac{g_R}{g}\right)^2 \end{pmatrix}$$

$$m_{W_{1L}} \sim m_{KK}\,, \quad m_{W_{1R}} \sim 0.981 m_{KK}$$

Mixings

$$g' = \frac{g_X g_R}{\sqrt{g_R^2 + g_X^2}} \ , \ s' = \frac{g_X}{\sqrt{g_R^2 + g_X^2}} \ , \ c' = \sqrt{1 - s'^2} \ ,$$

$$e = \frac{g_L g'}{\sqrt{g'^2 + g_L^2}} \ , \ s_W = \frac{g'}{\sqrt{g'^2 + g_L^2}} \ , \ c_W = \sqrt{1 - s_W^2} \ ,$$

$$g_Z = g_L / c_W \ , \ g_{Z'} = g_R / c' \ .$$

For $g_R = g_L$, $s' = 0.55$, $c' = 0.84$.

$$\sin\theta_{01} \approx \left(\frac{M_Z}{M_{Z_1}}\right)^2 \sqrt{k\pi R}\ ,$$

$$\sin\theta_{01X} \approx -\left(\frac{M_Z}{M_{Z_{X1}}}\right)^2 \left(\frac{g_{Z'}}{g_Z}\right) c'^2 \sqrt{k\pi R}\ .$$

$$\sin\theta_{0L} \approx \left(\frac{M_W}{M_{W_{L_1}}}\right)^2 \sqrt{k\pi r_c}\ ,$$

$$\sin\theta_{0R} \approx -\left(\frac{M_W}{M_{W_{R_1}}}\right)^2 \left(\frac{g_R}{g_L}\right) \sqrt{k\pi r_c}\ .$$

For $m_{KK} = 2$ TeV

$s_{01} \sim 0.013$, $s_{01X} \sim -0.01$, $s_{0L} \sim 0.01$, $s_{0R} \sim -0.01$.

Mixings

$$\tan 2\theta_1 = \frac{-2M_Z^2 (g_{Z'}/g_Z) c'^2 k\pi R}{(M^2_{Z_{X1}} - M^2_{Z_1}) + M_Z^2 \left((g_{Z'}/g_Z)^2 c'^4 - 1\right) k\pi R}\,.$$

$$\tan 2\theta_1^c = \frac{-2M_W^2 (g_R/g_L) k\pi R}{(M^2_{W_{R_1}} - M^2_{W_{L_1}}) + M_W^2 \left((g_R/g_L)^2 - 1\right) k\pi R}\,.$$

For $m_{KK} = 2000$ GeV

$s_1 = 0.48, c_1 = 0.88; \quad s_1^c = 0.6, c_1^c = 0.8.$

W' Couplings

$$\frac{g_{\rm RS}^{q\bar{q},l\bar{l}A^{(1)}}}{g_{\rm SM}} \simeq -\xi^{-1} \approx -\frac{1}{5}$$

$$\frac{g_{\rm RS}^{Q^3\bar{Q}^3A^{(1)}}}{g_{\rm SM}}, \frac{g_{\rm RS}^{t_R\bar{t}_RA^{(1)}}}{g_{\rm SM}} \simeq 1 \text{ to } \xi\ (\approx 5)$$

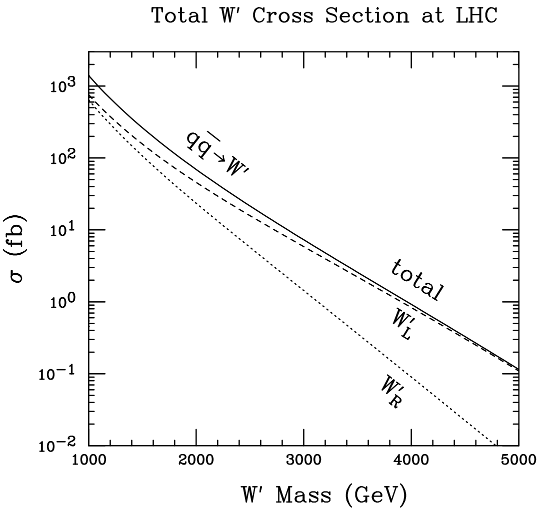
$$\frac{g_{\rm RS}^{HHA^{(1)}}}{g_{\rm SM}} \simeq \xi \approx 5 \quad (H = h, W_L, Z_L)$$

$$\frac{g_{\rm RS}^{A^{(0)}A^{(0)}A^{(1)}}}{g_{\rm SM}} \sim 0$$

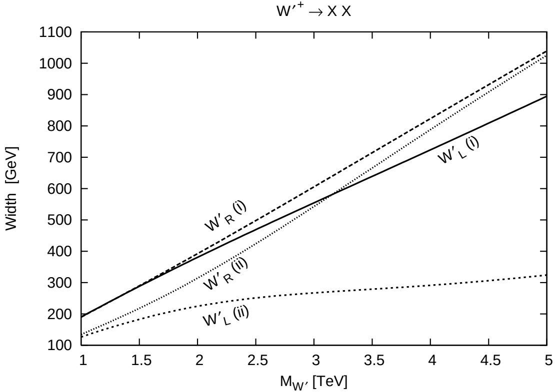
$c_{Q^3_L} = 0, c_{t_R} = 0.4$	Q^3_L	t_R	other fe
$\mathcal{I}^{++}_{++,++}$	$-\frac{1.13}{\xi} + 0.7\xi \approx 3.9$	$-\frac{1.13}{\xi} + 0.2\xi \approx 1$	$-\frac{1.13}{\xi}$
$\mathcal{I}^{++}_{-+,-+}$	ξ	ξ	$-$
$\mathcal{I}^{-+}_{++,-+}$	$0.8\xi \approx 4.6$	$0.4\xi \approx 2.3$	$\approx$
$c_{Q^3_L} = 0.4, c_{t_R} = 0$	Q^3_L	t_R	other fe
$\mathcal{I}^{++}_{++,++}$	$-\frac{1.13}{\xi} + 0.2\xi \approx 1$	$-\frac{1.13}{\xi} + 0.7\xi \approx 3.9$	$-\frac{1.13}{\xi}$
$\mathcal{I}^{++}_{-+,-+}$	ξ	ξ	$-$
$\mathcal{I}^{-+}_{++,-+}$	$0.4\xi \approx 2.3$	$0.8\xi \approx 4.6$	$\approx$

Table: Values of $\psi\psi W'^{\pm}$ overlap integrals. $\xi = \sqrt{k\pi r_c} = 5.83$. All SM fermions have (++) BC, "exotic" BSM fermions have $(-+)$, W_{L_1} has (++), and, W_{R_1} has $(-+)$ BC.

W' Drell-Yan Production



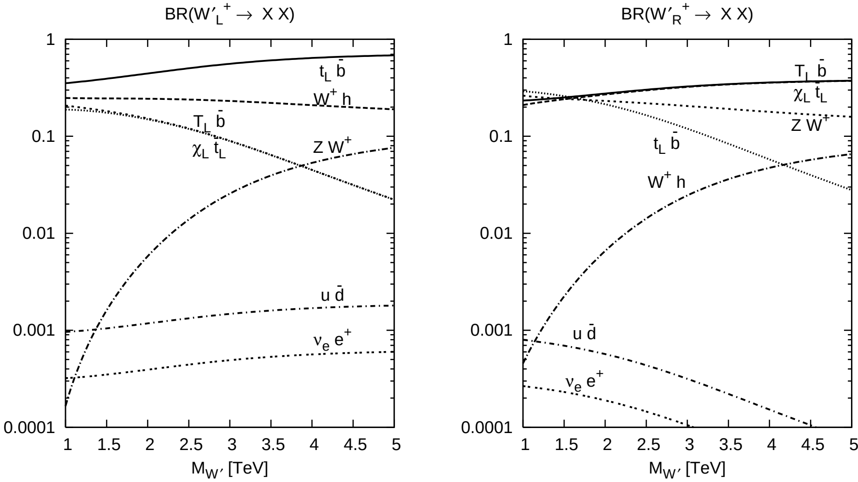
W' Decay Widths



Case (i): $t_R \to (1,1)$, $c_{Q_L^3} = 0$ and $c_{t_R} = 0.4$. All the other c's > 0.5

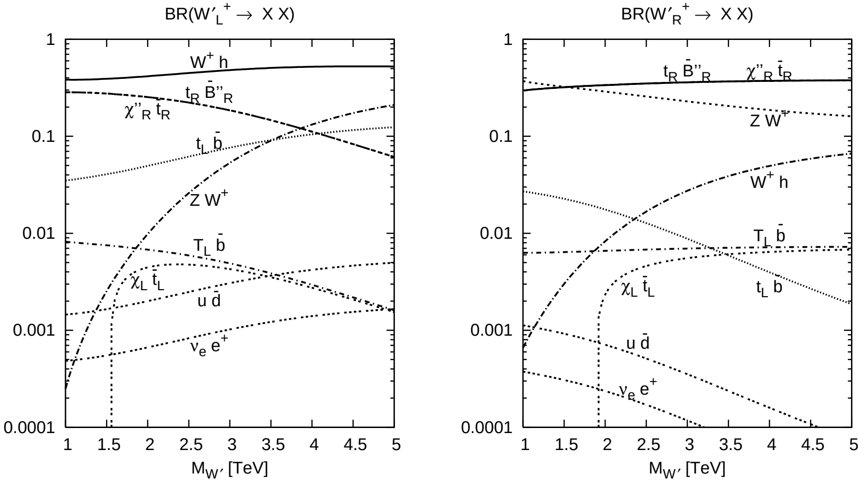
Case (ii): $t_R \to (1,3)$, $c_{Q_L^3} = 0.4$ and $c_{t_R} = 0$. All the other c's > 0.5

W' Branchings



Case (i)

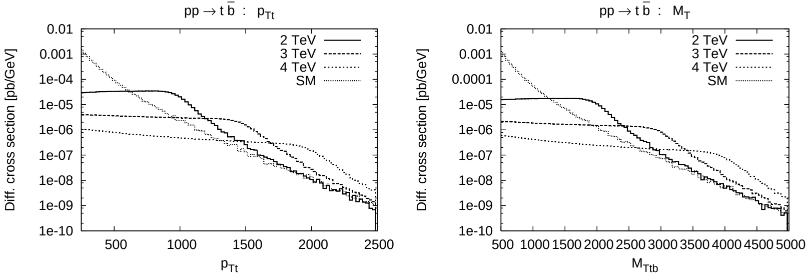
W' Branchings



Case (ii)

$W'^+ \to t\bar{b}$

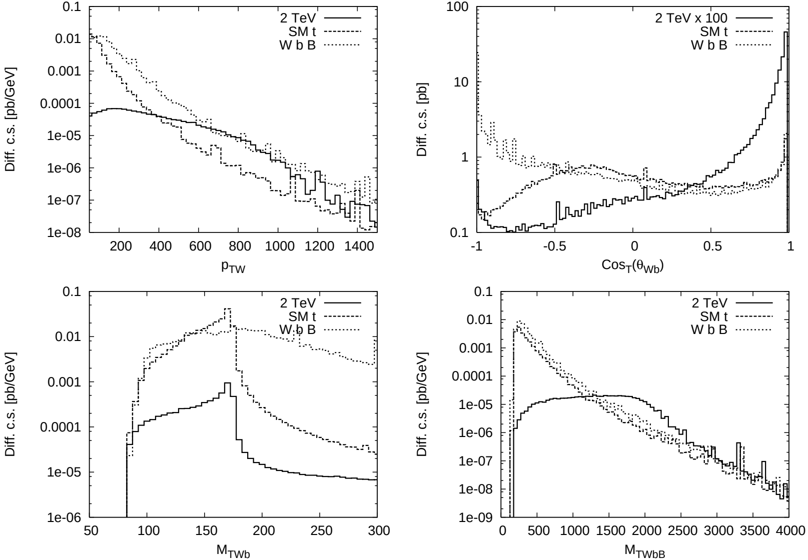
$$pp \to W'^+ \to t\bar{b} \to b\bar{b}\ell\bar{\nu}$$



$$M_{T\,Wb} = \left(\sqrt{p_{T\,W}^2 + m_W^2} + p_{T\,b}\right)^2 - \left|\mathbf{p}_{T_W} + \mathbf{p}_{T_b}\right|^2 ,$$

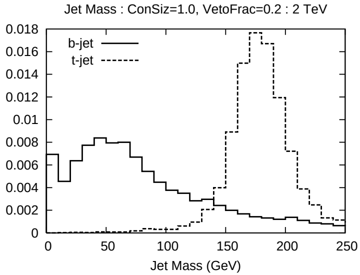
$$M_{T\,Wb\bar{b}} = p_{T\,b} + p_{T\,\bar{b}} + \sqrt{p_{T\,W}^2 + m_W^2} .$$

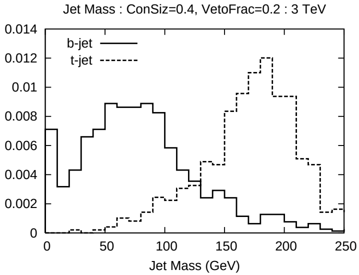
$W'^+ \to t\bar{b}$


Diff. c.s. [pb/GeV]
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
200 400 600 800 1000 1200 1400
p_TW
2 TeV
SM t
W b B
Diff. c.s. [pb]
100
10
1
0.1
-1 -0.5 0 0.5 1
Cos_T(θ_Wb)
2 TeV x 100
SM t
W b B
Diff. c.s. [pb/GeV]
0.1
0.01
0.001
0.0001
1e-05
1e-06
50 100 150 200 250 300
M_TWb
2 TeV
SM t
W b B
Diff. c.s. [pb/GeV]
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
0 500 1000 1500 2000 2500 3000 3500 4000
M_TWbB
2 TeV
SM t
W b B

$W'^{+} \to t\bar{b}$

To contend with $t\bar{t}$ background from SM and KK gluons:





Jet masses of top and bottom jets.

$W'^{+} \to t\bar{b}$

2 TeV	Basic	Wb cuts	b-tag	M_{TWbb}	j_M	# Evt	S/B	$S/\sqrt{B}$
Sig (i)	8.9	7	1.1	0.44	0.2	20	2.5 (1.4)	7 (5.3)
SM top	1431	372	60	0.09	0.04	4		
SM $W\,b\,\bar{b}$	517	66	10.6	9×10^{-3}	4×10^{-3}	0.4		
SM $W\,b\,j$	9×10^{3}	2×10^{3}	20	0.04	0.02	2		
SM $W\,c\,j$	4×10^{3}	700	4	10^{-3}	0.5×10^{-3}	0.05		
SM $W\,j\,j$	2×10^{5}	2×10^{4}	13	0.03	0.01	1		
SM $t\bar{t}$	4×10^{4}	10^{4}	2×10^{3}	4.5	0.02	2		
$G^{(1)}$ $t\bar{t}$ (i)	246	188	30	10	0.04	4		

3 TeV	Basic	Wb cuts	b-tag	M_{TWbb}	j_M	# Evt	S/B	CL
Sig (i)	1.5	1.1	0.18	0.04	0.02	7	5.8 (0.9)	0.995 (0.95)
SM top	1431	372	60	4×10^{-3}	2×10^{-3}	0.6		
SM $W\,b\,\bar{b}$	517	66	10.6	4×10^{-4}	2.3×10^{-4}	0.07		
SM $W\,b\,j$	9×10^{3}	2×10^{3}	20	10^{-3}	0.5×10^{-3}	0.2		
SM $W\,c\,j$	4×10^{3}	700	4	10^{-4}	0.5×10^{-4}	0.02		
SM $W\,j\,j$	2×10^{5}	2×10^{4}	13	2×10^{-3}	10^{-3}	0.3		
SM $t\bar{t}$	4×10^{4}	10^{4}	2×10^{3}	0.21	5.3×10^{-3}	1.6		
$G^{(1)}$ $t\bar{t}$ (i)	32	24	4	0.64	0.02	5		

Case (i). $\mathcal{L} = 100\,\mathrm{fb}^{-1}$ for $2\,\mathrm{TeV}$ and $\mathcal{L} = 300\,\mathrm{fb}^{-1}$ for $3\,\mathrm{TeV}$

$W'^+ \to t\bar{b}$

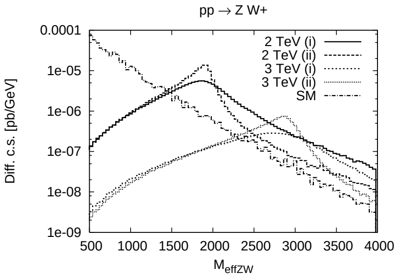
2 TeV	Basic	Wb cuts	b-tag	M_{TWbb}	j_M	# Evt	S/B	$S/\sqrt{B}$
Sig (ii)	0.75	0.6	0.1	0.05	0.03	30	0.38 (0.2)	3.4 (2.5)
SM top	1431	372	60	0.09	0.04	40		
SM Wj_1j_2	2.1×10^5	2.2×10^4	48	0.08	0.04	40		
SM $t\bar{t}$	4×10^4	10^4	2×10^3	4.5	0.02	20		
$G^{(1)}$ $t\bar{t}$ (ii)	207	180	29	12.8	0.05	50		

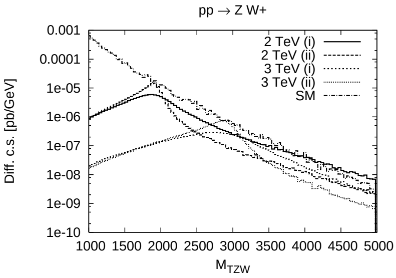
Case (ii). $\mathcal{L} = 1000\,\mathrm{fb}^{-1}$ for $2\,\mathrm{TeV}$
Small coupling to top

$W' \to ZW$

- fully leptonic. $Z \to \ell\ell,\ W \to \ell\nu$
- semi-leptonic.
  - $Z \to \ell\ell,\ W \to jj$
  - $Z \to jj,\ W \to \ell\nu$
- fully hadronic. $Z \to jj,\ W \to jj$. (BG too large)

$W' \rightarrow ZW$





$$M_{eff\,ZW} = p_{T\,Z} + p_{T\,W} \,,$$

$$M_{T\,ZW} = \sqrt{p_{T\,Z}^2 + M_Z^2} + \sqrt{p_{T\,W}^2 + M_W^2} \,.$$

$W' \to ZW \to (\ell\ell)(\ell\nu)$

2 TeV	Basic	M_{eff}	M_T	$\mathcal{L}$	# Evts	S/B	CL
Signal (i)	0.13	0.13	0.1	100	10	5	0.9995
Signal (ii)	0.17	0.16	0.13	100	13	6.5	> 0.9995
SM $Z\,W$	42	0.16	0.02		2		

3 TeV	Basic	M_{eff}	M_T	$\mathcal{L}$	# Evts	S/B	CL
Signal (i)	0.01	0.01	0.006	1000	6	6	0.99
Signal (ii)	0.014	0.01	0.01	1000	10	10	> 0.9995
SM $Z\,W$	42	0.05	0.001		1		

$M_{eff} > 1$ TeV (for 2 TeV) and $M_{eff} > 1.25$ TeV (for 3 TeV).

$1.5 < M_{T\,ZW} < 2.5$ TeV (for 2 TeV) and
$2.4 < M_{T\,ZW} < 3.6$ TeV (for 3 TeV).

Clean signal, large S/B, but limited statistics.

$W' \to ZW \to (\ell\ell)(jj)$

2 TeV	Basic	M_{eff}	M_{inv}	M_{jet}	$\mathcal{L}$	# Evts	S/B	$S/\sqrt{B}$
Sig (i)	0.4	0.4	0.16	0.13	1000	130	0.2	5
Sig (ii)	0.5	0.48	0.38	0.3	300	90	0.5	6.4
SM ZW	128	0.5	0.05	0.04		40, 12		
SM Z + 1j	3580	63	2.1	0.63		630, 189		

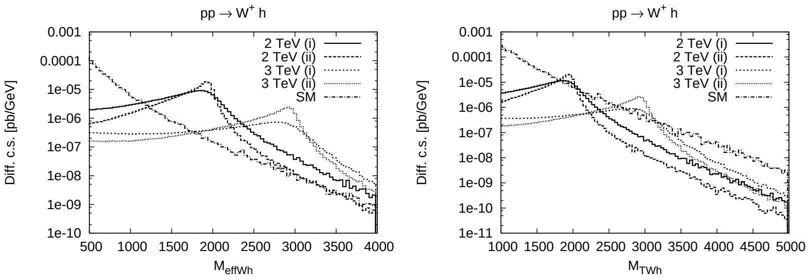
3 TeV	Basic	M_{eff}	M_{inv}	M_{jet}	$\mathcal{L}$	# Evts	S/B	$S/\sqrt{B}$
Sig (i)	0.03	0.03	0.01	–	1000	10	0.07	0.8
Sig (ii)	0.04	0.04	0.03	–	1000	30	0.22	2.6
SM ZW	128	0.16	0.006	–		6		
SM Z + 1j	3580	25	0.13	–		130		

$W' \to ZW \to (jj)(\ell\nu)$

2 TeV	Basic	M_{eff}	M_T	M_{jet}	$\mathcal{L}$	# Evts	S/B	$S/\sqrt{B}$
Sig (i)	1	1	0.38	0.3	1000	300	0.1	5.3
Sig (ii)	1.3	1.2	0.64	0.5	300	150	0.16	4.9
SM ZW	318	1.2	0.04	0.03		30, 9		
SM W + 1j	3.1×10^4	224	10.5	3.15		3150, 945		

3 TeV	Basic	M_{eff}	M_T	M_{jet}	$\mathcal{L}$	# Evts	S/B	$S/\sqrt{B}$
Sig (i)	0.08	0.08	0.016	–	1000	16	0.02	0.6
Sig (ii)	0.1	0.1	0.04	–	1000	40	0.06	1.5
SM ZW	318	0.4	0.002	–		2		
SM W + 1j	3.1×10^4	89	0.68	–		680		

$W' \to Wh$



$$M_{eff\,Wh} = p_{T\,W} + p_{T\,h}\,,$$
$$M_{T\,Wh} = \sqrt{p_{T\,W}^2 + M_W{}^2} + \sqrt{p_{T\,h}^2 + m_h{}^2}\,.$$

$m_h = 120$ GeV: $h \to b\bar{b}$, $W \to \ell\nu$
$m_h = 150$ GeV: $h \to WW \to \ell\nu jj$, $W \to jj$

$W' \to Wh \to \ell \not{E}_T b\bar{b}$

2 TeV	Basic	M_{eff}	M_T	b-tag	$\mathcal{L}$	# Evts	S/B	$S/\sqrt{B}$
Sig (i)	1.8	1.46	0.55	0.35	100	35	0.65	4.8
Sig (ii)	1.64	1.5	0.8	0.5	100	50	1	6.4
SM *Wh*	42.9	0.35	0.016	0.01		1		
SM *W* + 1j	3.1×10^4	224	10.5	0.53		53		

3 TeV	Basic	M_{eff}	M_T	b-tag	$\mathcal{L}$	# Evts	S/B	CL
Sig (i)	0.26	0.19	0.04	0.03	300	9	1	0.99
Sig (ii)	0.33	0.3	0.12	0.08	300	24	2.4	> 0.9995
SM *Wh*	42.9	0.13	0.001	6×10^{-4}		0.2		
SM *W* + 1j	3.1×10^4	89	0.68	0.03		9		

$W' \to Wh \to (jj)WW \to (jj)\ell \not{E}_T(jj)$

2 TeV	Basic	M_{eff}	M_T	M_{jet}	$\mathcal{L}$	# Evts	S/B	CL
Sig (i)	1.57	1.27	0.43	0.34	100	34	4	$\gg 0.9995$
Sig (ii)	2.1	1.9	0.9	0.7	100	70	7	$\gg 0.9995$
SM $W\,h$	25.63	0.31	0.014	0.01		1		
SM $h + 1j$	222.6	1.97	0.07	0.02		2		
SM $W + 2j$	3×10^4	35.5	0.62	0.06		6		

3 TeV	Basic	M_{eff}	M_T	M_{jet}	$\mathcal{L}$	# Evts	S/B	CL
Sig (i)	0.22	0.17	0.04	0.035	300	11	2	0.9987
Sig (ii)	0.3	0.26	0.1	0.09	300	27	4	$\gg 0.9995$
SM $W\,h$	25.63	0.12	8×10^{-4}	7×10^{-4}		0.2		
SM $h + 1j$	222.6	0.72	5×10^{-3}	2×10^{-3}		0.6		
SM $W + 2j$	3×10^4	4.1	0.05	0.015		4.5		

$W' \to W \to \ell \not{E}_T$

2 TeV	Basic	M_{eff}	M_T
Sig (i)	0.04	0.024	0.012
Sig (ii)	0.05	0.04	0.02
SM W	4×10^3	6.9	0.44

Branching too small.

RS W' at LHC

- Interesting phenomenology in multiple channels
- LHC a discovery machine for RS weak bosons of mass $\sim 2-3\,\mathrm{TeV}$ with integrated luminosity $\sim 100-1000\,\mathrm{fb}^{-1}$
- Higher mass range may require upgrade in luminosity
- Though some channels may be explored simultaneously, hard to extract precise coupling information
- Comparison to RS Z'
- Comparisons to 4D dual models?