

# Warped-space Electroweak Neutral Gauge Bosons at the LHC

(arXiv:0709.0007)

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UMass, Amherst

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

- Details of Warped Randall-Sundrum (RS) model
  - $SU(3)_{QCD} \times SU(2)_L \times SU(2)_R \times U(1)_X$  bulk gauge group
  - Focus on 3 Electroweak neutral gauge bosons ( $Z'$ )
- LHC signals of  $Z'$

- Details of Warped Randall-Sundrum (RS) model
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- LHC signals of  $Z'$

Not discussed here:

- KK Gluon ( $SU(3)_{QCD}$ ) at LHC
- KK Graviton at LHC

[Agashe, Belyaev, Krupovnickas, Perez, Virzi, 06]

[Agashe, Davoudiasl, Perez, Soni, 07]

# 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.

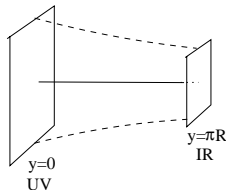
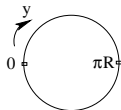
$k$  : curvature

## Hierarchy prob soln:

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

Bulk fields  $\rightarrow$  AdS/CFT

- Bulk Fermions explain flavor (FCNC's safe)



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

- Bulk gauge symm -  $SU(2)_L \times U(1)$  (SM  $\psi$ , H on TeV Brane)
    - T parameter -  $\log \frac{M_{Pl}}{M_{EW}}$  enhanced [Csaki, Erlich, Terning - 02]
    - S parameter - 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]

# Gauge Sector

Bulk 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:  $(W_L^\pm, W_R^\pm)$

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

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



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

Kaluza-Klein (KK) expansion:  $A(x, y) = \sum_0^\infty f_n(y) A^{(n)}(x)$   
 $A^{(n)} \rightarrow$  KK tower with mass  $m_n$ . Equivalent 4D theory

## Gauge Boson

- “Zero” modes:  $A^{(0)}, Z^{(0)}, Z_X^{(0)}$ . Since  $Z_X(-+) : Z_X^{(0)} \equiv 0$
- First KK modes:  $A^{(1)}, Z^{(1)}, Z_X^{(1)} \rightarrow Z'$

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

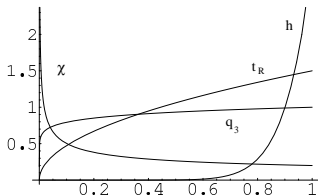
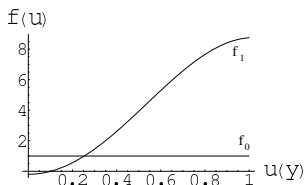
## Mass eigenstates :

- “Zero” modes:  $A, Z$
- First KK modes:  $A_1, \tilde{Z}_1, \tilde{Z}_{X_1} \rightarrow Z'$  collectively

# 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

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

- $A \rightarrow (+, +)$ ;  $Z \rightarrow (+, +)$ ;  $Z_X \rightarrow (-, +)$

# Z' Overlap Integrals

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

Z' overlap with Higgs  $\rightarrow \xi$

Z' overlap with fermions:

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

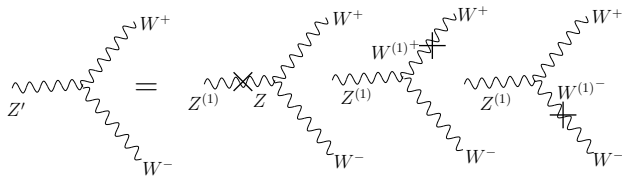
Compared to SM

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

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

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

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



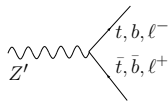
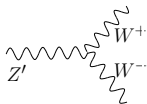
Even though  $\xi \cdot \left(\frac{v}{M_{KK}}\right)^2$  suppressed ...

... can be overcome by  $\left(\frac{M_{KK}}{m_Z}\right)^2$  (from long. pol. vectors)

Hence important to keep

# Z' decays

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

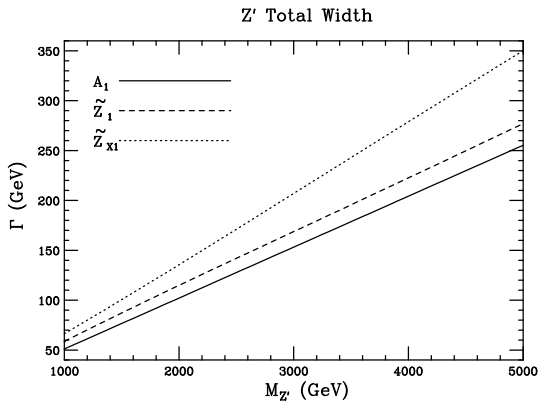


$$\Gamma(A_1 \rightarrow W_L W_L) = \frac{e^2 \kappa^2 M_{Z'}^5}{192\pi m_W^4}; \quad \kappa \propto \sqrt{k\pi r_c} \left( \frac{m_W}{M_{W_1^\pm}} \right)^2,$$

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

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

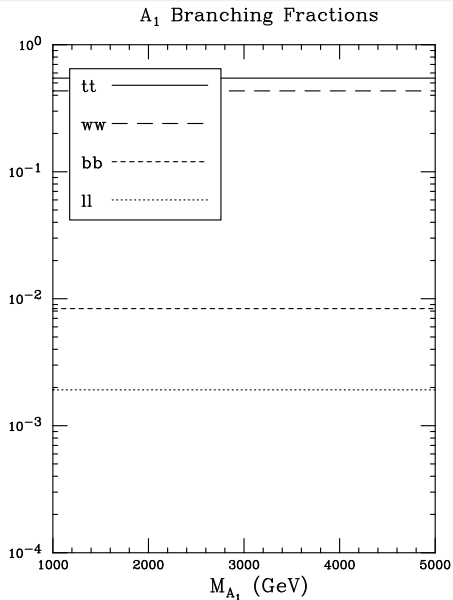
$$\Gamma(Z' \rightarrow f\bar{f}) = \frac{(e^2, g_Z^2)}{12\pi} (\kappa_V^2 + \kappa_A^2) M_{Z'}.$$



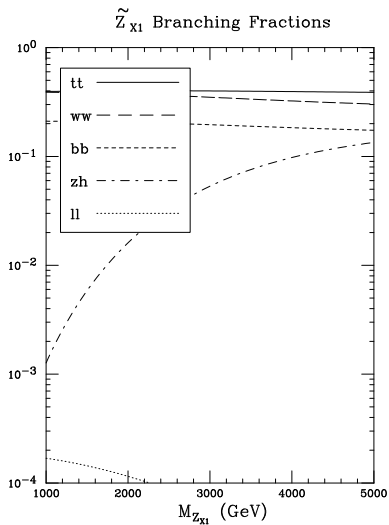
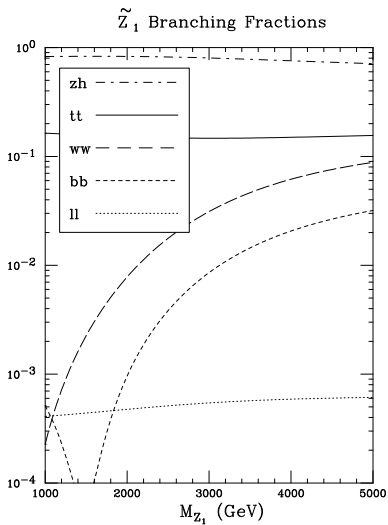
$M_{Z'} = 2\text{TeV}$	$A_1$	$Z_1$	$Z_{X1}$
$\Gamma$ (GeV)	103.3	114.6	135.6



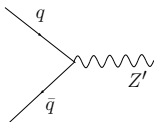
# Z' Branching Ratios



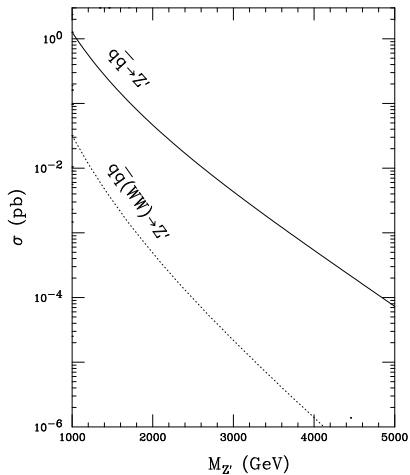
# Z' Branching Ratios (Contd.)



# $Z'$ production at the LHC



Total  $Z'$  Cross Section at LHC

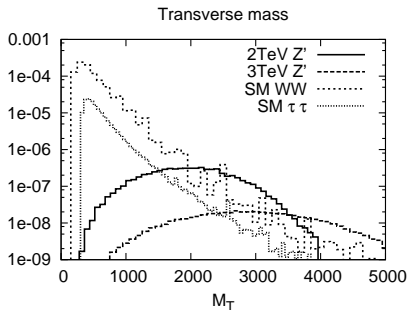
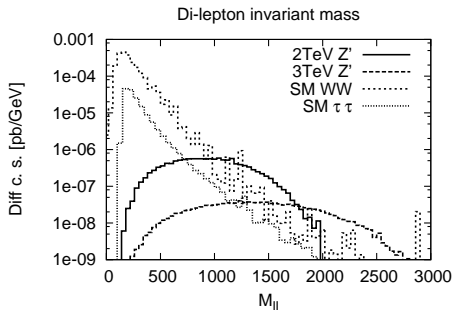


- $pp \rightarrow Z' \rightarrow W^+ W^-$ 
  - Fully leptonic :  $W \rightarrow \ell\nu$  ;  $W \rightarrow \ell\nu$
  - Semi leptonic :  $W \rightarrow \ell\nu$  ;  $W \rightarrow (jj)$
- $pp \rightarrow Z' \rightarrow Z h$ 
  - $m_h = 120\text{GeV}$  :  $Z \rightarrow \ell^+\ell^-$  ;  $h \rightarrow b\bar{b}$
  - $m_h = 150\text{GeV}$  :  $Z \rightarrow (jj)$  ;  $h \rightarrow W^+ W^- \rightarrow (jj) \ell\nu$
- $pp \rightarrow Z' \rightarrow \ell^+\ell^-$ 
  - Clean but needs high luminosity
- $pp \rightarrow Z' \rightarrow t\bar{t}, b\bar{b}$ 
  - KK gluon “pollution”

[Djouadi, Moreau, Singh - 07]

$$pp \rightarrow Z' \rightarrow W^+W^- \rightarrow \ell\nu\ell\nu$$

2  $\nu$ 's  $\Rightarrow$  cannot reconstruct event



$$M_{eff} \equiv p_{T_{\ell_1}} + p_{T_{\ell_2}} + \cancel{p}_T$$

$$M_{T_{WW}} \equiv 2\sqrt{p_{T_{\ell\ell}}^2 + M_{\ell\ell}^2}$$

$$pp \rightarrow Z' \rightarrow W^+ W^- \rightarrow \ell \nu \ell \nu$$

Cross-section (in fb) after cuts:

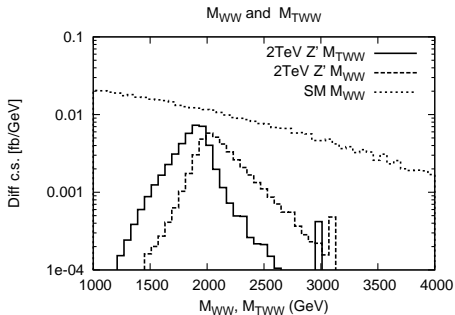
2 TeV	Basic cuts	$ \eta_\ell  < 2$	$M_{eff} > 1$ TeV	$M_T > 1.75$ TeV	# Evts	S/B	$S/\sqrt{B}$
Signal	0.48	0.44	0.31	0.26	26	0.9	4.9
WW	82	52	0.4	0.26	26		
$\tau\tau$	7.7	5.6	0.045	0.026	2.6		
3 TeV	Basic cuts	$ \eta_\ell  < 2$	$1.5 < M_{eff} < 2.75$	$2.5 < M_T < 5$	# Evts	S/B	$S/\sqrt{B}$
Signal	0.05	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

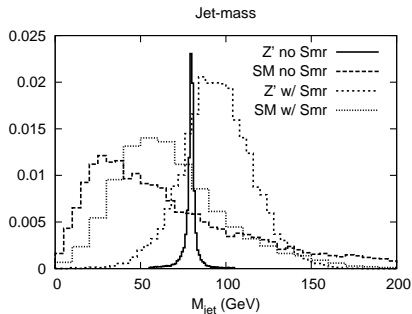
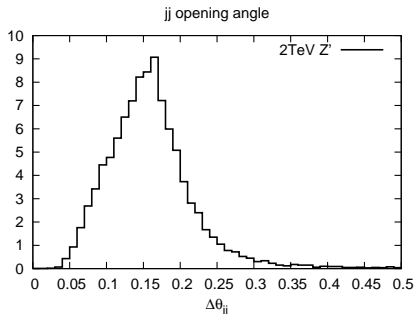
- 2 TeV :  $100 \text{ fb}^{-1}$
- 3 TeV :  $1000 \text{ fb}^{-1}$

$$pp \rightarrow Z' \rightarrow W^+W^- \rightarrow \ell \nu jj$$

$$M_{\text{eff}} \equiv p_{T_{jj}} + p_{T_\ell} + \cancel{p}_T \quad M_{T_{WW}} \equiv 2\sqrt{p_{T_{jj}}^2 + m_W^2}$$



$$pp \rightarrow Z' \rightarrow W^+W^- \rightarrow \ell \nu jj$$



jj 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]



$$pp \rightarrow Z' \rightarrow W^+W^- \rightarrow \ell \nu jj$$

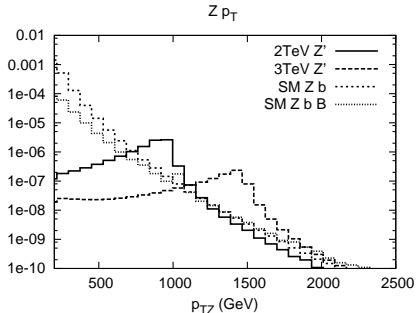
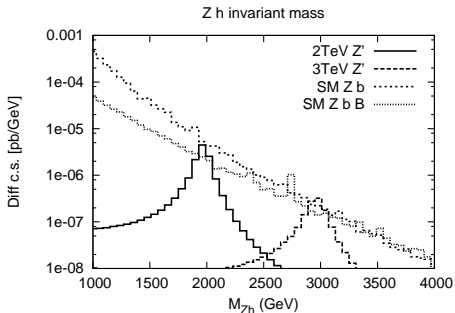
Cross-section (in fb) after cuts:

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

# events above is for

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

# $pp \rightarrow Z' \rightarrow Zh \rightarrow \ell^+ \ell^- b \bar{b}$ ( $m_h = 120$ GeV)



How well can we tag high  $p_T$  b's ?

We use:  $\epsilon_b = 0.4$  ;  $R_u = 20$  ;  $R_c = 5$

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

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

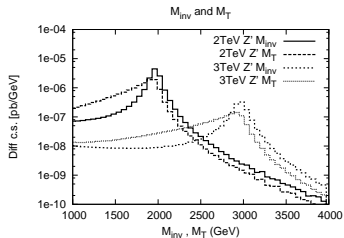
Cross-section (in fb) after cuts:

$M_{Z'} = 2 \text{ TeV}$	Basic	$p_{T, \eta}$	$\cos \theta_{Zh}$	$M_{inv}$	b-tag	# Evts	$S/B$	$S/\sqrt{B}$
$Z' \rightarrow hZ \rightarrow b\bar{b}\ell\ell$	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		
$M_{Z'} = 3 \text{ TeV}$								
$Z' \rightarrow hZ \rightarrow b\bar{b}\ell\ell$	0.81	0.12	0.05	0.04	0.016	16	2	5.7
SM $Z + b$	157	0.002	0.001	$3 \times 10^{-4}$	$1.2 \times 10^{-4}$	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	$4 \times 10^{-4}$	0.4		

# events above is for

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

$pp \rightarrow Z' \rightarrow Zh : Z \rightarrow jj ; h \rightarrow W^+W^- \rightarrow jj \ell \nu$   
 ( $m_h = 150$  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	$p_T, \eta$	$\cos \theta$	$M_T$	$M_{jet}$	# EvtS	$S/B$	$S/\sqrt{B}$
$Z' \rightarrow hZ \rightarrow \ell \cancel{E}_T (jj) (jj)$	2.4	1.6	0.88	0.7	0.54	54	2.5	11.5
SM $Wjj$	$3 \times 10^4$	35.5	12.7	0.62	0.19	19		
SM $WZj$	184	0.45	0.15	0.02	0.02	2		
SM $WWj$	712	0.54	0.2	0.02	0.01	1		
$M_{Z'} = 3$ TeV $m_h = 150$ GeV								
$Z' \rightarrow hZ \rightarrow \ell \cancel{E}_T (jj) (jj)$	0.26	0.2	0.14	0.06	—	18	1.2	4.7
SM $Wjj$	$3 \times 10^4$		4.1	0.05	—	15		

# events above is for

- 2 TeV : 100 fb<sup>-1</sup>
- 3 TeV : 300 fb<sup>-1</sup>

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

$M_{Z'} = 2 \text{ TeV}$	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 $\ell\ell$	$3 \times 10^4$	5.4	0.2	200		
SM $WW$	295	0.03	0.002	2		

# events above is for

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

Experimentally clean, but needs a LOT of luminosity

- Warped model with  $SU(2)_L \times SU(2)_R \times U(1)_X$ 
  - $A_1$  ,  $Z_1$  ,  $Z_{X1}$  neutral Gauge Bosons ( $Z'$ )
- LHC :  $pp \rightarrow Z' \rightarrow W^+W^-$ ,  $Z h$ ,  $\ell^+\ell^-$ ,  $t\bar{t}$ ,  $b\bar{b}$ 
  - Probing electroweak KK sector challenging, but possible
- Ongoing work -  $W'$  signatures
  - $W' \rightarrow tb$  no "QCD" background ?
  - $W' \rightarrow W Z$  fully leptonic has only one  $\nu$
- Thanks to:
  - Colleagues at BNL : Bill Kilgore, Frank Paige
  - CalcHEP (help from Alaxender Belyaev)
  - Pythia (help from Steve Mrenna, Peter Skands)
  - MadGraph (help from Rikkert Frederix)
  - Bridge (help from Matt Reece)

BACKUP SLIDES

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

[Agashe, Contino, DaRold, Pomarol - 06]

## Fermions

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

## Higgs

- $\Sigma = (2, 2)$

## For these Reps

- $Zb\bar{b}$  coupling - Protected [Agashe, Contino, DaRold, Pomarol - 06]
- Precision EW constraints  $\Rightarrow M_{Z'} \gtrsim 2 - 3 \text{ TeV}$   
[Carena, Ponton, Santiago, Wagner - 06,07]



# 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

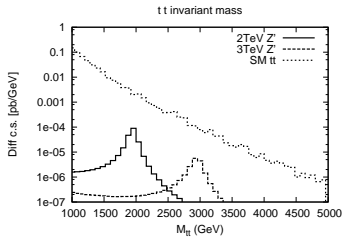
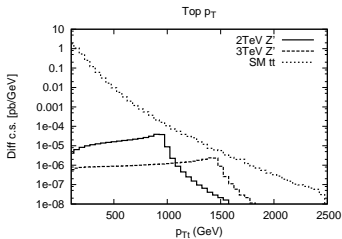
- Z' couplings to  $h$  enhanced (also  $V_L$  - Equivalence Theorem!)
- Z' couplings to  $t_R$  enhanced
- Z' couplings to  $\chi$  suppressed

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

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

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

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



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