

# LHC Signals for Warped Electroweak Gauge Bosons

(arXiv:0709.0007 + 0810.1497 [hep-ph])

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*with*

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ILC Workshop 08, UIC

Nov. 2008

- Focus on Electroweak gauge KK resonances
- Warped (RS) model
  - $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$  bulk gauge group
  - Heavy EW gauge bosons : 3 neutral ( $Z'$ ) & 2 charged ( $W'$ )
  - Precision electroweak observables require  $M_{Z'}, M_{W_1^\pm} \gtrsim 2$  TeV
    - Makes discovery challenging at LHC, ILC
- What are general issues at colliders?

- Focus on Electroweak gauge KK resonances
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Not discussed here:

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

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

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

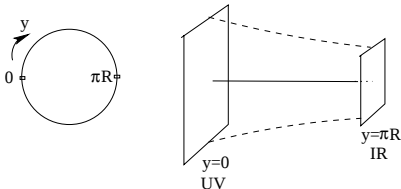
$k$  : curvature

## 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  $\Rightarrow M_{Z'} \gtrsim 2 - 3 \text{ TeV}$
- [Carena, Ponton, Santiago, Wagner - 06,07]

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

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- $SU(2)_R \times U(1)_X \rightarrow U(1)_Y : (W_L^3, W_R^3, X) \rightarrow (W_L^3, B, Z_X)$ 
  - By Boundary Conditions:  $Z_X, W_R^\pm$  massive

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

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

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

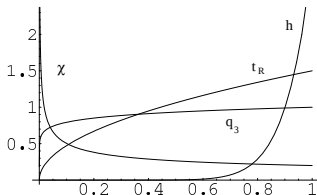
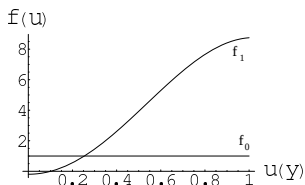
## Mass eigenstates :

- “Zero” modes:  $A, Z$  ;  $W^\pm$
- First KK modes:  $A_1, \tilde{Z}_1, \tilde{Z}_{X1} \rightarrow Z'$  ;  $\tilde{W}_{L1}, \tilde{W}_{R1} \rightarrow W'$

# 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

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

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

# $Z'$ couplings

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

$Z'$ ,  $W'$  overlap with Higgs  $\rightarrow \xi$

$Z'$ ,  $W'$  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, the  $Z'$ ,  $W'$  couplings to :

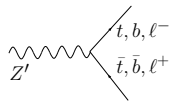
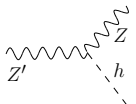
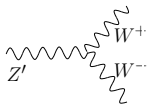
- $h$  enhanced (also  $W_{longi}$  by Equivalence Theorem!)
- $t_R$  enhanced
- $q_L^3$  unchanged
- light fermions suppressed

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

# $Z'$ ANALYSIS

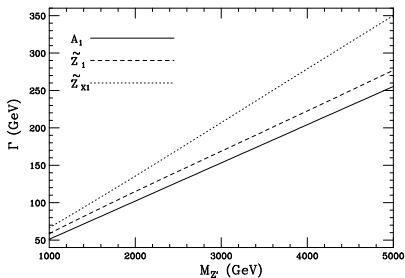
[Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni - arXiv:0709.0007 [hep-ph]]

# $Z'$ decays



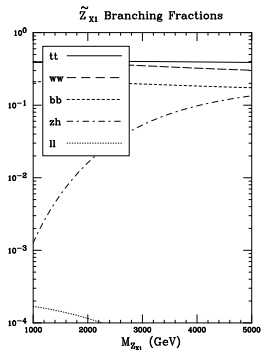
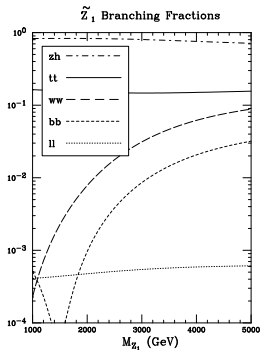
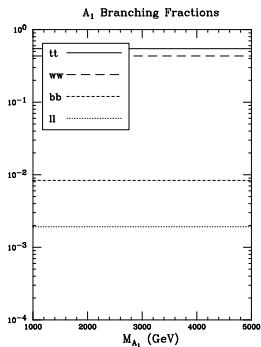
$Z'$  Total Width

Total Widths

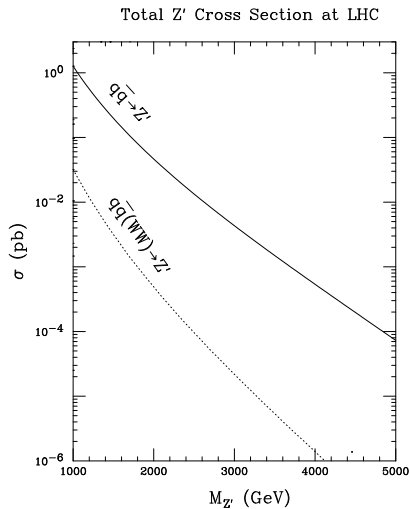
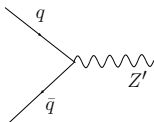


| $M_{Z'} = 2\text{TeV}$ | $A_1$ | $Z_1$ | $Z_{X1}$ |
|------------------------|-------|-------|----------|
| $\Gamma$ (GeV)         | 103.3 | 114.6 | 135.6    |

# Z' Branching Ratios



# $Z'$ production at the LHC

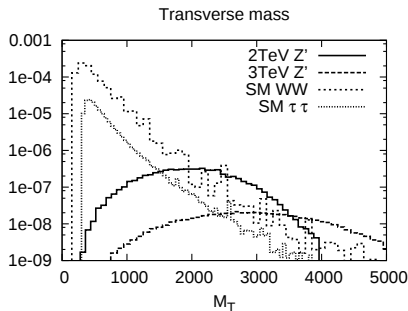
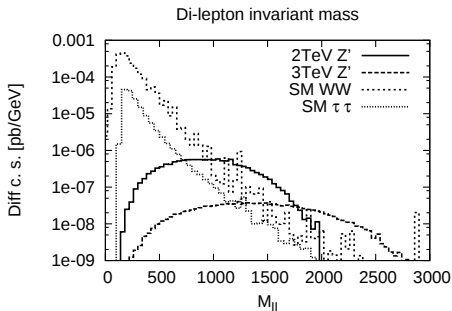


$\mathcal{L}$  needed :  $(\dots, \dots) \text{ fb}^{-1}$  for (2 TeV, 3 TeV) is shown below

- $pp \rightarrow Z' \rightarrow W^+ W^-$  (100, 1000)  $\text{fb}^{-1}$ 
  - Fully leptonic :  $W \rightarrow \ell \nu$  ;  $W \rightarrow \ell \nu$
  - Semi leptonic :  $W \rightarrow \ell \nu$  ;  $W \rightarrow (jj)$
- $pp \rightarrow Z' \rightarrow Z h$ 
  - $m_h = 120\text{GeV}$  :  $Z \rightarrow \ell^+ \ell^-$  ;  $h \rightarrow b \bar{b}$  (200, 1000)  $\text{fb}^{-1}$
  - $m_h = 150\text{GeV}$  :  
 $Z \rightarrow (jj)$  ;  $h \rightarrow W^+ W^- \rightarrow (jj) \ell \nu$  ( $< 100, 300$ )  $\text{fb}^{-1}$
- $pp \rightarrow Z' \rightarrow \ell^+ \ell^-$ 
  - Clean but needs high luminosity (1000, -)  $\text{fb}^{-1}$
- $pp \rightarrow Z' \rightarrow t \bar{t}, b \bar{b}$  [Djouadi, Moreau, Singh - 07]
  - KK gluon “pollution”

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

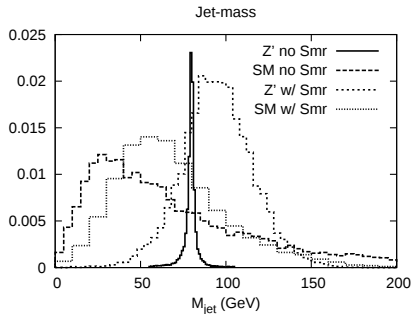
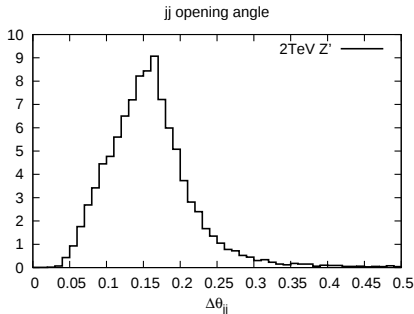
2  $\nu$ 's  $\Rightarrow$  cannot reconstruct event



$$M_{eff} \equiv p_{T_{\ell_1}} + p_{T_{\ell_2}} + \cancel{p}_T \quad M_{T_{WW}} \equiv 2\sqrt{p_{T_{\ell\ell}}^2 + M_{\ell\ell}^2}$$

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

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



$jj$  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]

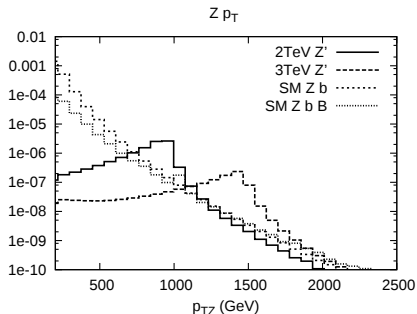
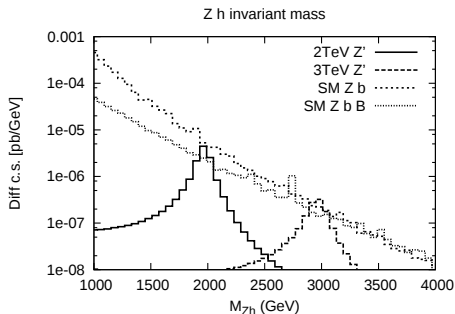
To account for (HCal) expt. uncert.

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

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

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

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



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

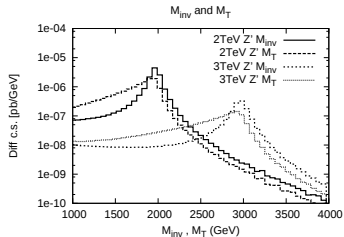
For  $\epsilon_b = 0.4$ , expect  $R_i \approx 20 - 50$ ;  $R_c = 5$

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

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

$$pp \rightarrow Z' \rightarrow Z h : \quad Z \rightarrow jj ; \quad h \rightarrow W^+ W^- \rightarrow jj \ell \nu$$

$$(m_h = 150 \text{ GeV})$$



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

| $M_{Z'} = 2 \text{ TeV} \quad m_h = 150 \text{ GeV}$        | 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 $W jj$                                                   | $3 \times 10^4$ | 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      |       |              |
| $M_{Z'} = 3 \text{ TeV} \quad m_h = 150 \text{ GeV}$        |                 |             |               |       |           |        |       |              |
| $Z' \rightarrow hZ \rightarrow \ell \cancel{E}_T (jj) (jj)$ | 0.26            | 0.2         | 0.14          | 0.06  | —         | 18     | 1.2   | 4.7          |
| SM $W jj$                                                   | $3 \times 10^4$ |             | 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

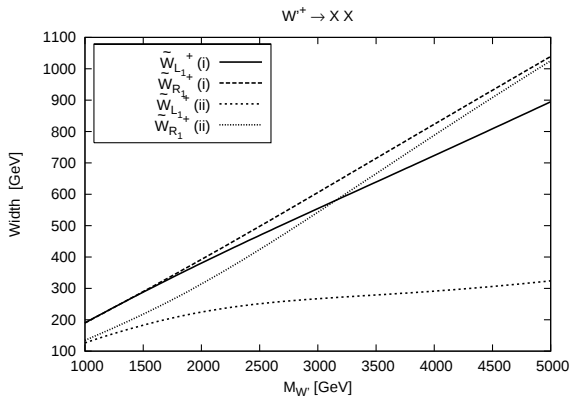
● 2 TeV :  $1000 \text{ fb}^{-1}$

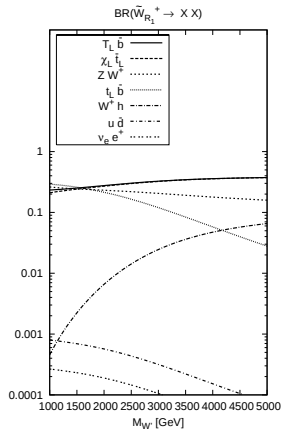
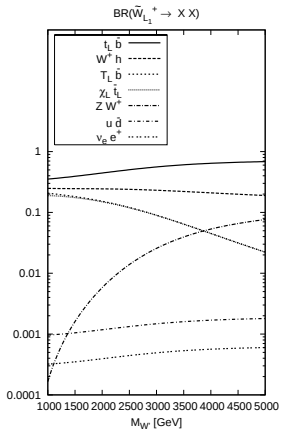
Experimentally clean, but needs a LOT of luminosity

# $W'$ ANALYSIS

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

# $W'$ width



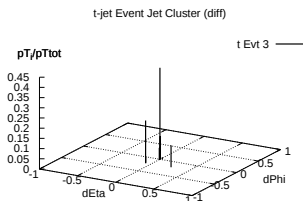
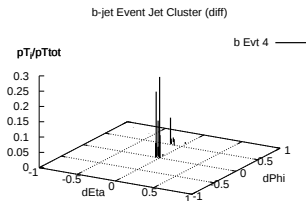
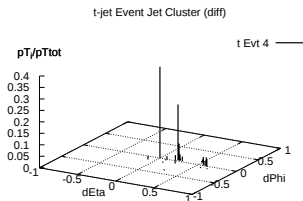
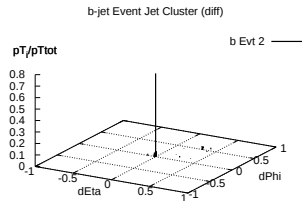


$$W' \rightarrow t b \rightarrow \ell \nu b b$$

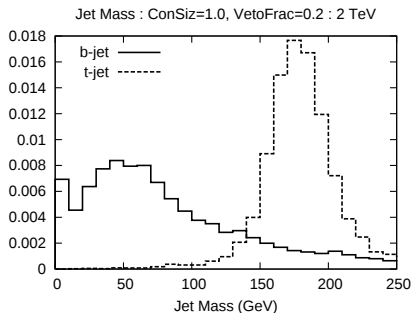
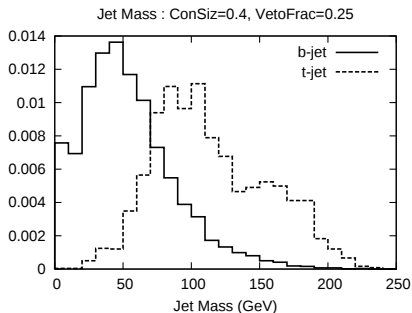
Signal c.s.  $\sim 1fb$

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

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



$$W' \rightarrow t b \rightarrow \ell \nu b b$$



Jet-mass cut: cone size 1.0 and  $0 < j_M < 75 \Rightarrow 0.4\%$  of *top* fakes *b*  
 $\mathcal{L}$  needed:  $100 \text{ fb}^{-1}$  (2 TeV)

# $W' \rightarrow Z W$ and $W h$

$W' \rightarrow Z W$ :

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

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$W' \rightarrow W h$ :

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

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

| Case (i): Channel                                  | $M_{W_1^\pm}$ (TeV) | $\mathcal{L}$ ( $\text{fb}^{-1}$ ) | $S/B$     | $S/\sqrt{B}$       |
|----------------------------------------------------|---------------------|------------------------------------|-----------|--------------------|
| $t b \rightarrow \ell \nu b \bar{b}$               | 3                   | 300                                | 5.8 (0.9) | 0.995 (0.95) CL    |
| $Z W \rightarrow \ell \ell \ell \nu$               | 3                   | 1000                               | 6         | 0.99 CL            |
| $m_h = 120$ : $W h \rightarrow \ell \nu b \bar{b}$ | 3                   | 300                                | 1         | 0.99 CL            |
| $m_h = 150$ : $W h \rightarrow (jj) \ell \nu (jj)$ | 3                   | 300                                | 2         | 0.9987 CL          |
| Case (ii): Channel                                 | $M_{W_1^\pm}$ (TeV) | $\mathcal{L}$ ( $\text{fb}^{-1}$ ) | $S/B$     | $S/\sqrt{B}$       |
| $t b \rightarrow \ell \nu b \bar{b}$               | 2                   | 1000                               | 0.4 (0.2) | 3.4 (2.5) $\sigma$ |
| $Z W \rightarrow \ell \ell \ell \nu$               | 3                   | 1000                               | 10        | $> 0.9995$ CL      |
| $m_h = 120$ : $W h \rightarrow \ell \nu b \bar{b}$ | 3                   | 300                                | 2.4       | $> 0.9995$ CL      |
| $m_h = 150$ : $W h \rightarrow (jj) \ell \nu (jj)$ | 3                   | 300                                | 4         | $\gg 0.9995$ CL    |

CM Energy known : One  $\nu$  final state fully reconstructible  
QCD background limits LHC significance  
Detector resolutions (for jet mass) better?

## Challenges:

- EWPT pushes masses to few TeV

- $e^+$ ,  $e^-$  couplings to  $Z'$ ,  $W'$  suppressed

- BR to more complicated final states ( $t\bar{t}$ ,  $WW$ ,  $Z h$ ;  $t\bar{b}$ ,  $WZ$ ,  $W h$ )

## Testing RS at ILC :

- Radion (mixes with the Higgs)

- Exotic  $(-, +)$  fermions within kinematic reach?

- Loop shifts in observables

- FCNC,  $A_{FB}$ , ...

- LHC : Electroweak gauge KK needs  $\sim 300 \text{ fb}^{-1}$  (3 TeV)  
 $pp \rightarrow Z' \rightarrow W^+ W^-, Z h, (t \bar{t}), (b \bar{b}), (\ell^+ \ell^-)$   
 $pp \rightarrow W' \rightarrow t b, Z W, Z h, \ell \nu$
- ILC : Loop effects, radion, exotic (light) fermions, FCNC,  $A_{FB}$ , ...
- 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

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

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

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

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

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

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

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

[Agashe, Contino, DaRold, Pomarol - 06]

## Fermions

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

## Higgs

- $\Sigma = (2, 2)$

## For these Reps

- $Zb\bar{b}$  coupling - Protected
- Precision EW constraints  $\Rightarrow M_{Z'} \gtrsim 2 - 3 \text{ TeV}$

[Agashe, Contino, DaRold, Pomarol - 06]

[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

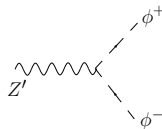
$$\bar{\psi}_{L,R} \gamma^\mu \left[ eQ\mathcal{I}A_{1\mu} + g_Z (T_L^3 - s_W^2 T_Q) \mathcal{I}Z_{1\mu} + g_{Z'} (T_R^3 - s'^2 T_Y) \mathcal{I}Z_{X1\mu} \right] \psi_{L,R}$$

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

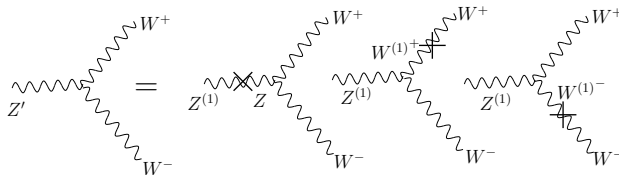
$Z^{(1)}V^{(0)}V^{(0)}$  is zero by orthogonality ...

... but induced after EWSB

Using Goldstone equivalence:



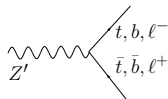
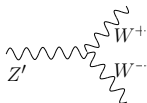
In Unitary Gauge:



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



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

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

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

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

# 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                |                      |

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

Cross-section (in fb) after cuts:

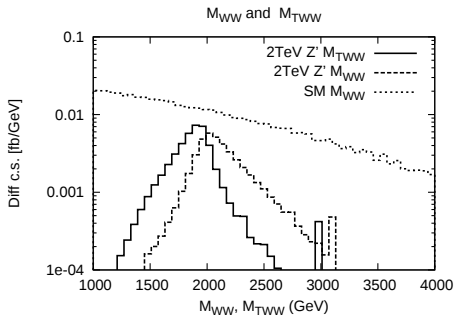
| 2 TeV      | Basic cuts | $ \eta_\ell  < 2$ | $M_{eff} > 1 \text{ TeV}$ | $M_T > 1.75 \text{ TeV}$ | # Evts | $S/B$ | $S/\sqrt{B}$ |
|------------|------------|-------------------|---------------------------|--------------------------|--------|-------|--------------|
| Signal     | 0.48       | 0.44              | 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 :  $1000 \text{ fb}^{-1}$

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

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



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

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

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

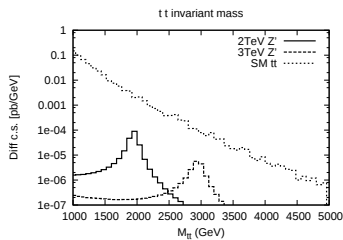
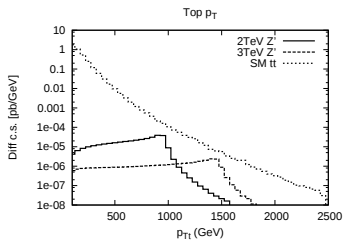
Cross-section (in fb) after cuts:

| $M_{Z'} = 2 \text{ TeV}$                         | 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 :  $1000 \text{ fb}^{-1}$

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



|                          |                   |              |                              |
|--------------------------|-------------------|--------------|------------------------------|
| $M_{Z'} = 2 \text{ TeV}$ | Basic             | $p_T > 800$  | $1900 < M_{t\bar{t}} < 2100$ |
| 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             | $p_T > 1250$ | $2850 < M_{t\bar{t}} < 310$  |
| Signal                   | 1.7               | 0.56         | 0.45                         |
| SM $t\bar{t}$            | $1.9 \times 10^5$ | 4.1          | 1.1                          |