

Heavy Electroweak Resonances at the LHC

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

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with

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...

...

Fermilab

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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

- Focus on heavy EW spin-1 resonances
- Warped (RS) model
 - $SU(3)_{QCD} \times SU(2)_L \times SU(2)_R \times U(1)_X$ bulk gauge group
 - Heavy EW gauge bosons : 3 neutral (Z') & 2 charged (W'^{\pm})
 - Precision electroweak observables require $M_{Z'}$, $M_{W'_1} \gtrsim 2$ TeV
 - Makes discovery challenging at the LHC
- What are general issues at the LHC?

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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.

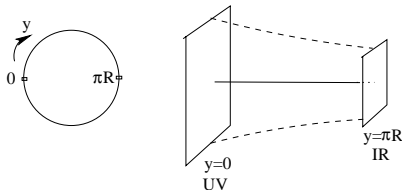
k : curvature

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 ψ , 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)

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- 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 $Z_X|_{y=0} = 0$; $\partial_y Z_X|_{y=\pi R} = 0$

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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

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: $A_1, \tilde{Z}_1, \tilde{Z}_{X1} \rightarrow Z'$; $\tilde{W}_{L1}, \tilde{W}_{R1} \rightarrow W'^\pm$

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

- $\Sigma = (2, 2)$

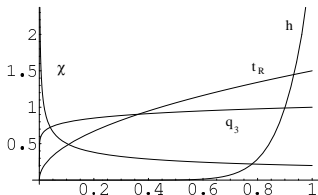
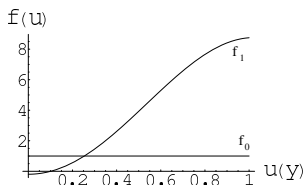
For these Reps

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

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' ANALYSIS

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	ξ	$-\frac{1}{\xi}$
\mathcal{I}^-	1	ξ	0

Compared to SM

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

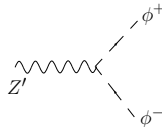
$$\bar{\psi}_{L,R} \gamma^\mu \left[e Q \mathcal{I} A_{1\mu} + g_Z (T_L^3 - s_W^2 T_Q) \mathcal{I} Z_{1\mu} + g_{Z'} (T_R^3 - s'^2 T_Y) \mathcal{I} Z_{X1\mu} \right] \psi_{L,R}$$

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

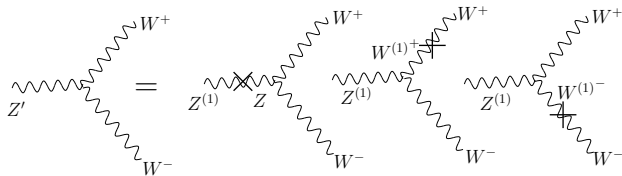
$Z^{(1)}V^{(0)}V^{(0)}$ is zero by orthogonality ...

... but induced after EWSB

Using Goldstone equivalence:

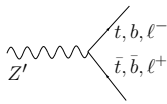
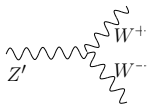


In Unitary Gauge:



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

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

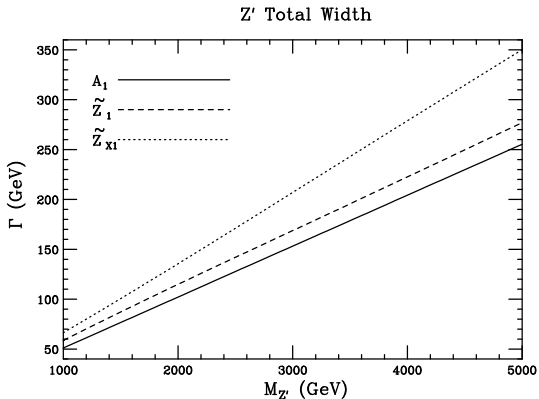


$$\Gamma(A_1 \rightarrow W_L W_L) = \frac{e^2 \kappa^2 M_{Z'}^5}{192\pi m_W^4}; \quad \kappa \propto \sqrt{k\pi r_c} \left(\frac{m_W}{M_{W_1^\pm}} \right)^2,$$

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

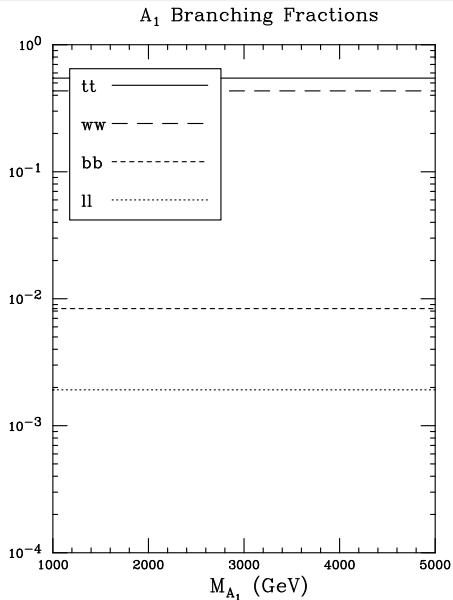
$$\Gamma(\tilde{Z}_1, \tilde{Z}_{X1} \rightarrow Z_L h) = \frac{g_Z^2 \kappa^2}{192\pi} M_{Z'}; \quad \kappa \propto \sqrt{k\pi r_c},$$

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

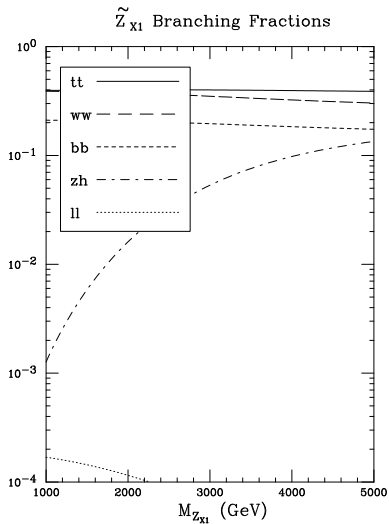
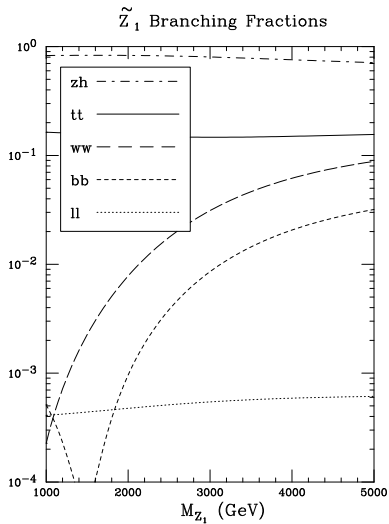


$M_{Z'} = 2\text{TeV}$	A_1	Z_1	Z_{X1}
Γ (GeV)	103.3	114.6	135.6

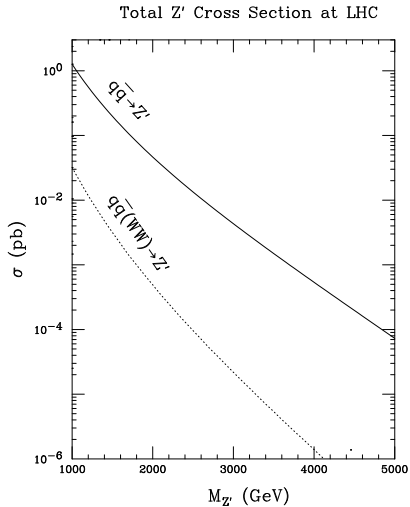
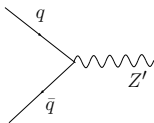
Z' Branching Ratios



Z' Branching Ratios (Contd.)



Z' production at the LHC

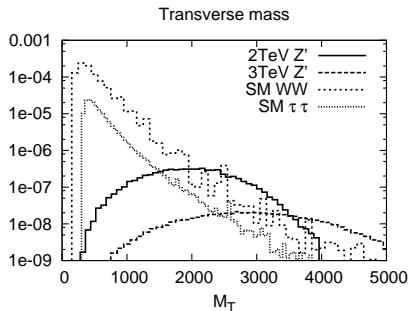
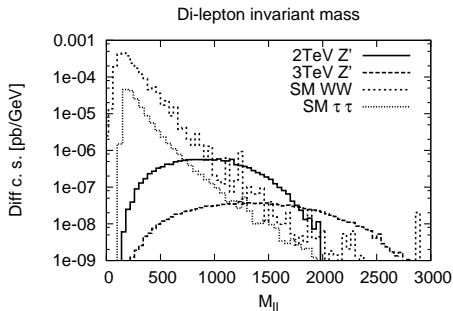


- $pp \rightarrow Z' \rightarrow W^+ W^-$
 - Fully leptonic : $W \rightarrow \ell\nu$; $W \rightarrow \ell\nu$
 - Semi leptonic : $W \rightarrow \ell\nu$; $W \rightarrow (jj)$
- $pp \rightarrow Z' \rightarrow Z h$
 - $m_h = 120\text{GeV}$: $Z \rightarrow \ell^+\ell^-$; $h \rightarrow b\bar{b}$
 - $m_h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

[Djouadi, Moreau, Singh - 07]

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

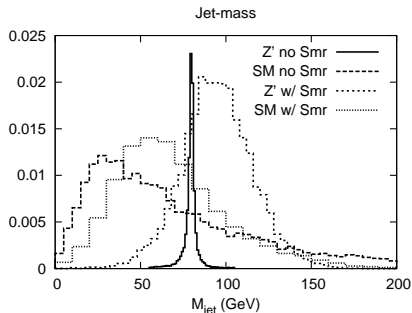
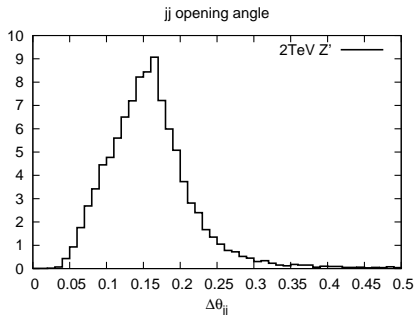
2 ν 's \Rightarrow cannot reconstruct event



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

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

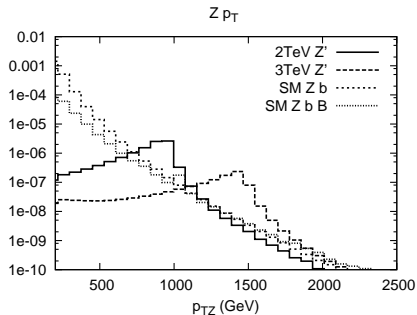
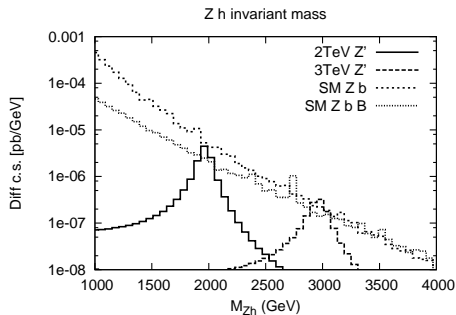
To account for (HCal) expt. uncert.

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 fb^{-1} (2 TeV) ; 1000 fb^{-1} (3 TeV)

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



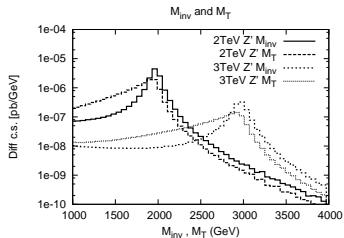
How well can we tag high p_T b's ?

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)

$pp \rightarrow Z' \rightarrow Zh : Z \rightarrow jj ; h \rightarrow W^+W^- \rightarrow jj \ell \nu$
 ($m_h = 150$ 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, η	$\cos \theta$	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	3×10^4	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	3×10^4		4.1	0.05	—	15		

events above is for

- 2 TeV : 100 fb⁻¹
- 3 TeV : 300 fb⁻¹

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

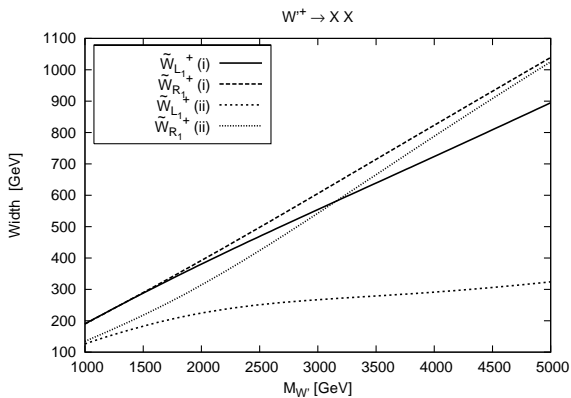
$M_{Z'} = 2 \text{ TeV}$	Basic	$p_{T\ell}$	$M_{\ell\ell}$	# Evts	S/B	S/\sqrt{B}
Signal	0.1	0.09	0.06	60	0.3	4.2
SM $\ell\ell$	3×10^4	5.4	0.2	200		
SM WW	295	0.03	0.002	2		

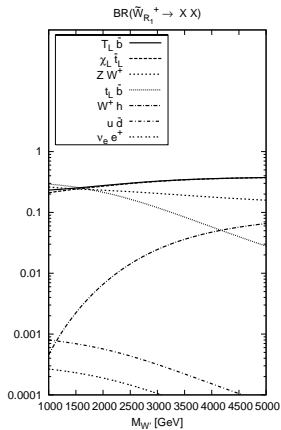
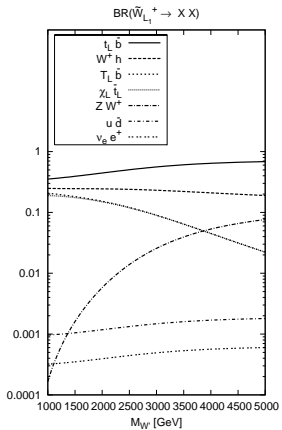
events above is for

- 2 TeV : 1000 fb^{-1}

Experimentally clean, but needs a LOT of luminosity

W'^{\pm} ANALYSIS (ongoing)



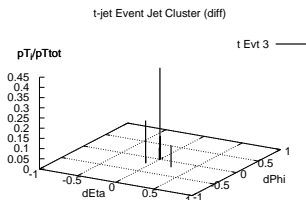
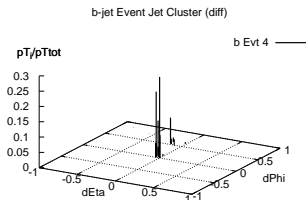
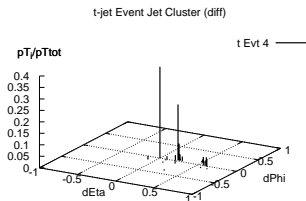
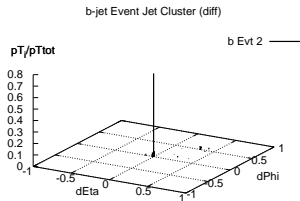


$$W'^{\pm} \rightarrow t b \rightarrow l \nu b b$$

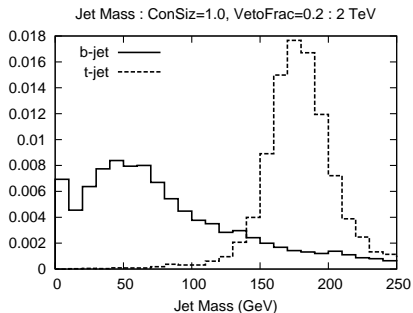
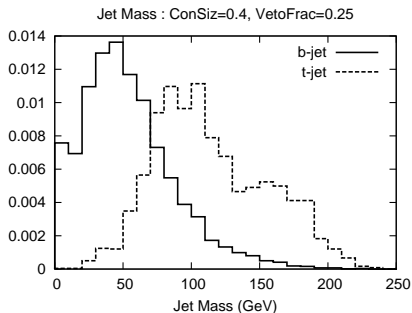
Signal c.s. $\sim 1fb$

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

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



$$W'^{\pm} \rightarrow t b \rightarrow l \nu b b$$



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

$W'^{\pm} \rightarrow Z W$ and $W h$

$W'^{\pm} \rightarrow Z W$:

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

$W'^{\pm} \rightarrow Z W$ and $W h$

$W'^{\pm} \rightarrow Z W$:

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

$W'^{\pm} \rightarrow W h$:

- $m_h \approx 120 : h \rightarrow b b$
 - 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 fb^{-1} (2TeV) ; 300 fb^{-1} (3TeV)

- LHC : $pp \rightarrow Z' \rightarrow W^+W^-, Zh, \ell^+\ell^-, (t\bar{t}, b\bar{b})$
 $pp \rightarrow W'^{\pm} \rightarrow tb, ZW, Zh, \ell\nu$ (ongoing work)
 $t\bar{t}$ bkgnd sneaks in
 - Probing electroweak KK sector challenging, but possible
- Warped model with $SU(2)_L \times SU(2)_R \times U(1)_X$
 $Z' : A_1, Z_1, Z_{X1}$ $W'^{\pm} : W_L, W_R$
- 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

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

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

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	8.7×10^{-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	

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

Cross-section (in fb) after cuts:

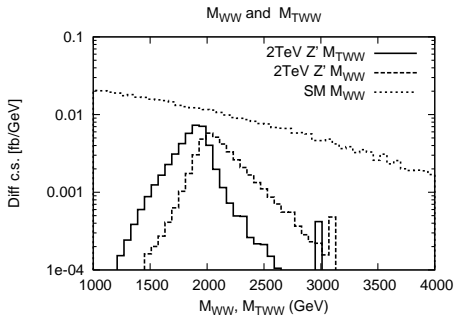
2 TeV	Basic cuts	$ \eta_\ell < 2$	$M_{eff} > 1$ TeV	$M_T > 1.75$ TeV	# Evts	S/B	S/\sqrt{B}
Signal	0.48	0.44	0.31	0.26	26	0.9	4.9
WW	82	52	0.4	0.26	26		
$\tau\tau$	7.7	5.6	0.045	0.026	2.6		
3 TeV	Basic cuts	$ \eta_\ell < 2$	$1.5 < M_{eff} < 2.75$	$2.5 < M_T < 5$	# Evts	S/B	S/\sqrt{B}
Signal	0.05	0.05	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 fb^{-1}
- 3 TeV : 1000 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	1.5×10^5	3.1×10^4	223.6	10.5	3.15	315		
WW	1.2×10^3	226	2.9	0.13	0.1	10		
$M_{Z'} = 3 \text{ TeV}$								
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}

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

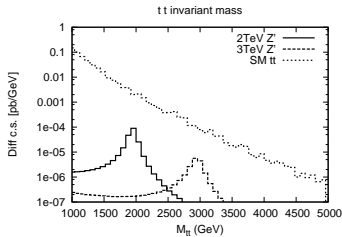
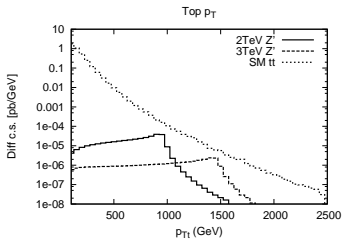
Cross-section (in fb) after cuts:

$M_{Z'} = 2 \text{ TeV}$	Basic	$p_{T, \eta}$	$\cos \theta_{Zh}$	M_{inv}	b-tag	# Evts	S/B	S/\sqrt{E}
$Z' \rightarrow hZ \rightarrow b\bar{b}\ell\ell$	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	3×10^{-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}

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



$M_{Z'} = 2 \text{ TeV}$	Basic	$p_T > 800$	$1900 < M_{t\bar{t}} < 2100$
Signal	17	7.2	5.6
SM $t\bar{t}$	1.9×10^5	31.1	19.1
$M_{Z'} = 3 \text{ TeV}$	Basic	$p_T > 1250$	$2850 < M_{t\bar{t}} < 3100$
Signal	1.7	0.56	0.45
SM $t\bar{t}$	1.9×10^5	4.1	1.1