Warped extra dimensions and LHC signatures

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Mahabaleswar
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Motivation

- SM hierarchy problem: $M_{EW} \ll M_{Pl}$
- SM flavor problem: $m_e \ll m_t$
- Explained by new dynamics?
  - **Extra dimensions** (**Warped** (AdS), Flat)
  - Supersymmetry
  - Strong dynamics
  - Little Higgs
- AdS/CFT correspondence [Maldacena 97]
  - 5-D gravity theory in AdS $\underset{DUAL}{\longleftrightarrow}$ 4-D conformal field theory

Talk Outline

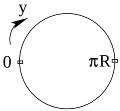
- Introduction to Warped-space (Randall-Sundrum) scenario
  - $SU(3)_{QCD} \times SU(2)_L \times SU(2)_R \times U(1)_X$ bulk gauge group
  - Phenomenological Implications
    - Collider signals
    - Flavor aspects
- Signals of Kaluza-Klein (KK) particles at the LHC
  - Graviton_{KK} ; Gluon_{KK} , $W^{\pm}_{KK}$, Z_{KK}; Fermion_{KK}
  - Little RS (LRS) : $Z' \to \ell^+\ell^-$
- Angular correlation in $W^{\pm}_{KK} \to t\, b$
- Recent LHC Results

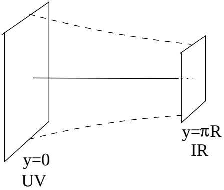
Warped Model

SM in background 5D warped AdS space [Randall, Sundrum 99]

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

Z_2 orbifold fixed points:





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

R : radius of Ex. Dim.

k : AdS curvature scale ($k \lesssim M_{pl}$)

Hierarchy prob soln:

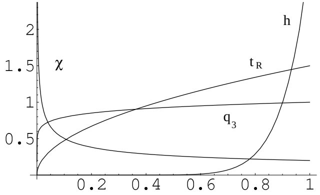
- IR localized Higgs : $M_{EW} \sim ke^{-k\pi R}$: Choose $k\pi R \sim 34$
  - CFT dual is a composite Higgs model

Explaining SM mass hierarchy

Bulk Fermions explain SM mass hierarchy [Gherghetta, Pomarol 00][Grossman, Neubert 00]

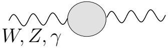
$$\mathcal{S}^{(5)} \supset \int d^4x\, dy \;\left\{ c_\psi \, k\, \overline{\Psi}(x,y)\, \Psi(x,y) \right\}$$

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 $SU(2)_R \quad \Leftrightarrow \quad$ 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): $A_{-+}(x,y)$ BC: $A|_{y=0} = 0\,;\ \partial_y A\,|_{y=\pi R} = 0$
  - $SU(2)_R \times U(1)_X \to U(1)_Y$
- By VEV of TeV brane Higgs Higgs $\Sigma = (2,2)$
  - $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

Fermion reps (Model I)

[Agashe, Delgado, May, Sundrum 03]

- Complete $SU(2)_R$ multiplet
  - $Q_L \equiv (\mathbf{2},\mathbf{1})_{1/6} = (t_L, b_L)$
  - $Q_{t_R} \equiv (\mathbf{1},\mathbf{2})_{1/6} = (t_R, b'_R)$
  - $Q_{b_R} \equiv (\mathbf{1},\mathbf{2})_{1/6} = (t'_R, b_R)$
- "Project-out" b', t' zero-modes by $(-,+)$ B.C.
- $b \leftrightarrow b'$ mixing
  - $Zb\bar{b}$ coupling shifted!
    - So severe constraints (LEP)

Fermion reps (Model II)

[Agashe, Contino, DaRold, Pomarol 06]

Custodial protection for $Zb_L\overline{b_L}$ coupling

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

Fermions:

- $Q_L = (2,2) = \begin{pmatrix} t_L & \zeta_L \\ b_L & T_L \end{pmatrix}$

  $t_R : (1,1)$ OR $(1,3) \oplus (3,1) = \begin{pmatrix} \chi'_R \\ t_R \\ b'_R \end{pmatrix} \oplus \begin{pmatrix} \chi''_R \\ t''_R \\ b''_R \end{pmatrix}$; $b_R : (1,1)$ OR $(1,3) \oplus (3,1)$

- $Zb_L\overline{b_L}$ coupling protected! Note: Wt_Lb_L, Zt_Lt_L not protected, so expect shifts

New "exotic" fermions ζ_L, T_L, χ'_R, b'_R, ...

- No zero-mode. $(-,+)$ BC $\Longrightarrow M_{\psi'} < M_{A'}$ [Agashe, Servant 04]
- Promising LHC signatures

Kaluza-Klein (KK) expansion

[See for example: Gherghetta, Pomarol, 2000]

$$S_5 = -\int d^4x \int dy \sqrt{-g} \left[\frac{1}{4g_5^2} F_{MN}^2 + |\partial_M \phi|^2 + i\bar{\Psi}\gamma^M D_M \Psi + m_\phi^2 |\phi|^2 + i m_\Psi \bar{\Psi}\Psi \right]$$

EOM:

$$\left[e^{2\sigma} \eta^{\mu\nu} \partial_\mu \partial_\nu + e^{s\sigma} \partial_5 (e^{-s\sigma} \partial_5) - M_\Phi^2 \right] \Phi(x^\mu, y) = 0$$

Kaluza-Klein expansion

$$\Phi(x^\mu, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=0}^{\infty} \Phi^{(n)}(x^\mu) f_n(y)$$

Orthonormality relation:

$$\frac{1}{2\pi R} \int_{-\pi R}^{\pi R} dy \, e^{(2-s)\sigma} f_n(y) f_m(y) = \delta_{nm}$$

EOM implies

$$\left[-e^{s\sigma} \partial_5 (e^{-s\sigma} \partial_5) + \widehat{M}_\Phi^2 \right] f_n = e^{2\sigma} m_n^2 f_n$$

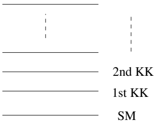
Solution is

$$f_n(y) = \frac{e^{s\sigma/2}}{N_n} \left[J_\alpha\left(\frac{m_n}{k} e^\sigma\right) + b_\alpha(m_n) \, Y_\alpha\left(\frac{m_n}{k} e^\sigma\right) \right]$$

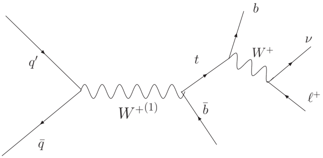
$\Phi^{(n)} \rightarrow$KK tower with mass m_n. Equivalent 4D theory

Kaluza-Klein (KK) decomposition

- 5D (compact) field $\leftrightarrow$ Infinite tower of 4D fields
- Look for this tower
  - at the LHC
  - in FCNCs



Example LHC:



Look for heavy Kaluza-Klein (KK) states : KK $h^{(1)}_{\mu\nu}$, $g^{(1)}_{\mu}$, $W^{(1)}_{\mu}$, $Z^{(1)}_{\mu}$, $b^{(1)}_{\alpha}$, ...

LEP precision electroweak constraints $\Rightarrow W^{(1)}_{\mu}, Z^{(1)}_{\mu} \gtrsim 2$ *TeV*

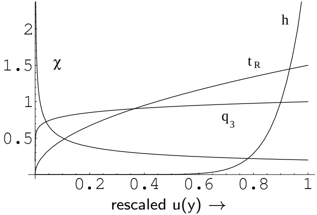
Explaining Flavor in a Warped extra dimension

Bulk fermions explain standard model (SM) Mass hierarchy puzzle

Fermion profiles controlled by bulk mass ($c_{L,R}$)

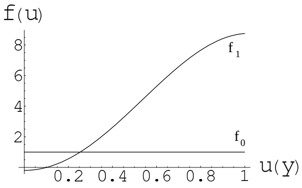
$$\mathcal{L}^{(5)}_{Yuk} \supset \sqrt{|g|}\,\left\{c_L k\,\bar{\psi}_L\psi_L + c_R k\,\bar{\psi}_R\psi_R + \left(\lambda_5\,\bar{\psi}_R\psi_L H + h.c.\right)\right\}$$

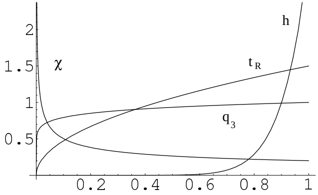
$$\Psi_L(x,y) = \frac{e^{(2-c)\sigma}}{\sqrt{2\pi R}N_0}\Psi_L^{(0)}(x) + \ldots \qquad N_0^2 = \frac{e^{2\pi kR(1/2-c)} - 1}{2\pi kR(1/2-c)}$$



FCNC under control

4-D KK couplings





Integrate $\mathcal{S}^{(5)}$ over y → **equivalent 4D theory**

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

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

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

4-D couplings

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

Compare to SM couplings:

- 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: $t_L t_L A'$

4-D couplings

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Effective coupling (Eg: Z'):

$$\mathcal{L}^{4D} \supset \bar{\psi}_{L,R}\gamma^{\mu}\left[eQ\mathcal{I}A_{1\ \mu} + g_Z\left(T_L^3 - s_W^2 T_Q\right)\mathcal{I}Z_{1\ \mu} + g_{Z'}\left(T_R^3 - s'^2 T_Y\right)\mathcal{I}Z_{X1\ \mu}\right]\psi_{L,R}$$

Flavor structure

[Agashe, Perez, Soni, 04]

$$\mathcal{L} \supset \bar{\Psi}^i i\Gamma^\mu D_\mu \Psi^i + M_{ij}\bar{\Psi}^i\Psi^j + y_{ij}^{5D} H\bar{\Psi}^i\Psi^j + h.c.$$

- Basis choice: M_{ij} diagonal $\equiv M_i$
    - All flavor violation from y_{ij}^{5D}
    - KK decompose and go to mass basis
        - $\Longrightarrow g\,\bar{\Psi}^i_{(n)} W_\mu^{(k)} \Psi^j_{(m)}$ off-diagonal in flavor (due to non-degenerate f^i i.e. M^i)
- 5D fermion Ψ is vector-like
    - M_{ij} is independent of $\langle H \rangle = v$
    - But zero-mode made chiral (SM)

FCNC couplings

- $h^{\mu\nu}_{(0)}\psi_{(0)}\psi_{(0)}$: diagonal
- $\{A_{(0)}, g_{(0)}\}\ \psi_{(0)}\psi_{(0)}$: diagonal (unbroken gauge symmetry)
- $\{Z_{(0)}, Zx_{(0)}\}\ \psi_{(0)}\psi_{(0)}$: almost diagonal (non-diagonal due to EWSB effect)
- $h\,\psi_{(0)}\psi_{(0)}$: diagonal (only source of mass is $\langle h \rangle = v$)

- $h^{\mu\nu}_{(1)}\psi_{(0)}\psi_{(0)}$: off-diagonal
- $\{A_{(1)}, g_{(1)}\}\ \psi_{(0)}\psi_{(0)}$: off-diagonal (i=1,2 almost diagonal)
- $\{Z_{(1)}, Zx_{(1)}\}\ \psi_{(0)}\psi_{(0)}$: off-diagonal

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- $h^{\mu\nu}_{(0)}\psi_{(0)}\psi_{(1)}$: 0
- $\{A_{(0)}, g_{(0)}\}\ \psi_{(0)}\psi_{(1)}$: 0 (unbroken gauge symmetry)
- $\{Z_{(0)}, Zx_{(0)}\}\ \psi_{(0)}\psi_{(1)}$: off-diagonal (EWSB effect)
- $h\,\psi_{(0)}\psi_{(1)}$: off-diagonal (since M_ψ is extra source of mass)

$\psi_{(0)} \leftrightarrow \psi_{(1)}$ mixing due to EWSB

FCCC couplings

- $W^{\pm}_{L(0)} \psi^{i}_{(0)} \psi^{j}_{(0)}$: $g\, V^{ij}_{CKM}$
- $\left\{ W^{\pm}_{L(1)}, W^{\pm}_{R(1)} \right\} \psi_{(0)} \psi_{(0)}$: $g\, V_{100}\ [f_{W^{(1)}} f_{\psi} f_{\psi}]$
  - [...] suppressed for $i = 1, 2$; (Not suppr for b_L, t_L, t_R)
- $W^{\pm}_{L(0)} \psi_{(0)} \psi_{(1)}$: $g\, V_{001}\ \left[f_{W^{(1)}} f_{\psi} f_{\psi^{(1)}} \right]$

KK states at the LHC

- $h^{(1)}_{\mu\nu}$ (KK Graviton) $gg \to h^{(1)} \to t\bar{t}$

  $L = 300\ fb^{-1}$ LHC reach is about 2 TeV [Agashe, Davoudiasl, Perez, Soni 07] [Fitzpatrick, Kaplan, Randall, Wang 07]

- $g^{(1)}_{\mu}$ (KK Gluon) $q\bar{q} \to g^{(1)} \to t\bar{t}$

  $L = 100\ fb^{-1}$ LHC reach is 4 TeV [Agashe, Belyaev, Krupovnickas,Perez,Virzi 06] [Lillie, Randall, Wang, 07] [Lillie, Shu, Tait 07]

- $Z^{(1)}_{\mu}$, $W^{(1)\pm}_{\mu}$ $(Z_{KK} \equiv Z'\ ,\ W^{\pm}_{KK} \equiv W')$ $q\bar{q} \to Z', W' \to XX$

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

- $\psi^{(1)}$ (KK Fermion) [Agashe, Servant 04][Dennis et al 07][Contino, Servant 08][SG et al ongoing]

- Radion

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

Example FCNC processes

- $K^0 \bar{K}^0$ mixing:
  - Tree-level FCNC vertex $g_{(1)} d\, s \propto V_L^{d\dagger} \begin{pmatrix} [g_{(1)} d\, d] & 0 \\ 0 & [g_{(1)} s\, s] \end{pmatrix} V_L^d$
- $b \to s\gamma$:
  - No tree-level contribution to helicity flip dipole operator
  - So 1-loop with $g^{(1)}\, b\, s$ OR $\phi\, b\, s^{(1)}$
- $b \to s\, \ell^+ \ell^-$, $b \to s\, s\, \bar{s}$, $K \to \pi \nu \bar{\nu}$:
  - Tree level FCNC vertex $Z\, s\, d$, $Z\, b\, s$

Bound : $m_{KK} \gtrsim$ *few* TeV [Agashe et al][Buras et al][Neubert et al][Csaki et al]

Relaxed with flavor alignment : MFV, NMFV, flavor symmetries, ...
[Fitzpatrick et al][Agashe et al]

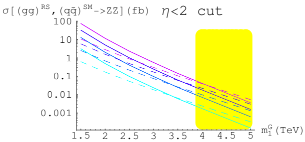
KK Graviton

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

$$m_n = x_n k e^{-k\pi r} \quad x_n = 3.83, 7.02, \ldots$$
$$\mathcal{L} \supset -\frac{C^{ffG}}{\Lambda} T^{\alpha\beta} h^{(n)}_{\alpha\beta} \quad \Lambda = \bar{M}_P e^{-k\pi r}$$

- SM on IR brane
  - CDF & D0 bounds : $m_1 > 300 - 900$ GeV for $\frac{k}{M_p}$ =0.01-0.1
  - ATLAS & CMS reach : 3.5 TeV with 100fb^{-1}
- SM in Bulk (flavor)
  - light fermion couplings highly suppressed
  - gauge field couplings $\frac{1}{k\pi r}$ suppressed
  - Decays dominantly to $t,\ h,\ V_{Long}$

$$gg \to h^{(1)} \to ZZ \to 4\ell$$



various $\frac{k}{M_p}$; SM dashed

[Agashe, Davoudiasl, Perez, Soni, 2007]

KK Gluon

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

$m_n = x_n k e^{-k\pi r}$ $\quad x_n \approx 2.45,\ 5.57,\ \ldots$ $\quad$ Width $\Gamma \approx \frac{M}{6}$

$g^{(1)} t\bar{t}$: parity violating couplings!

$$\text{LHC: } q\bar{q} \to g^{(1)} \to t\bar{t}$$

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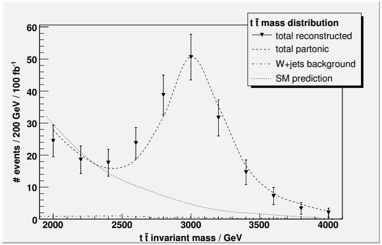
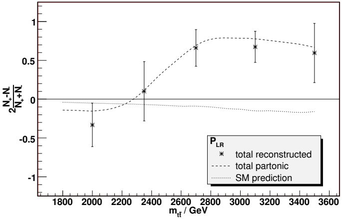
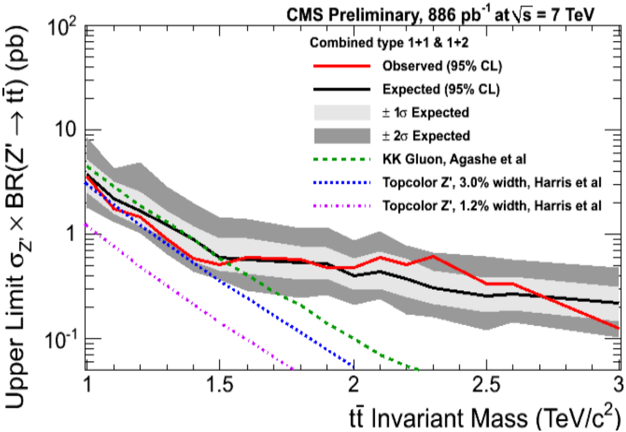




$$P_{LR} = 2\frac{N_+ - N_-}{N_+ + N_-} \qquad N_+ \text{ forward going } \ell \text{ wrt } k_t$$

LHC reach: About 4 TeV with 100 fb^{-1}

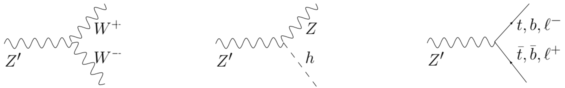
LHC KK-gluon search

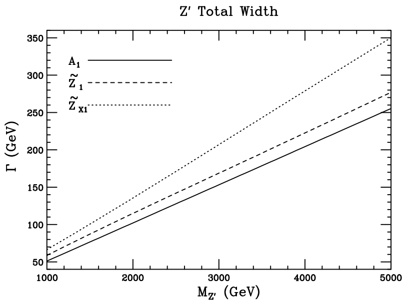


CMS Limit: $M_{KK} > 1.5\,TeV$ @ 95% CL
(with 886 pb^{-1} at $\sqrt{s} = 7\,TeV$) [Sunanda Banerjee's talk @ WHEPP-12]

Z'decays

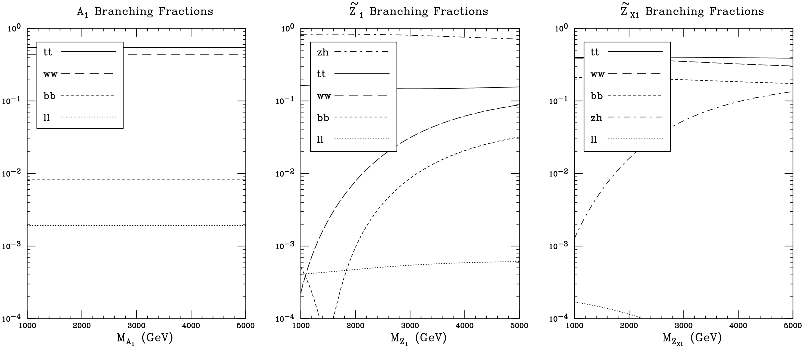
[Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni - arXiv:0709.0007 [hep-ph]]



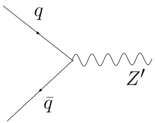


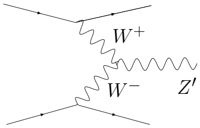
$M_{Z'} = 2$TeV	A_1	Z_1	Z_{X1}
Γ (GeV)	103.3	114.6	135.6

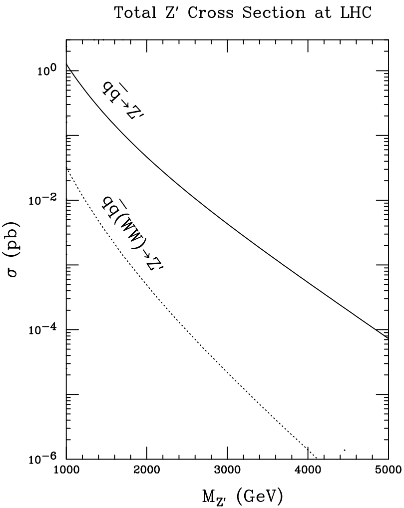
Z' Branching Ratios



Z' production at the LHC

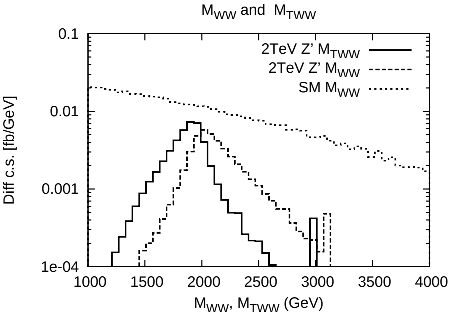




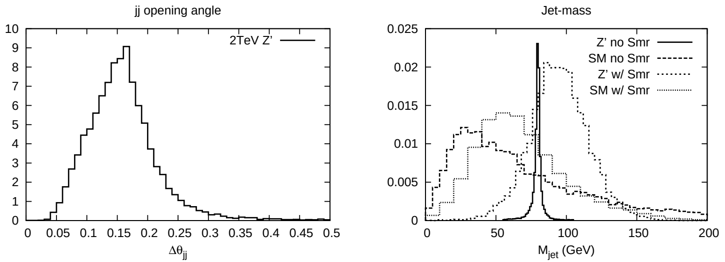


$pp \to Z' \to W^+W^- \to \ell\,\nu\,j\,j$

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



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

- $pp \to Z' \to W^+W^-$
  - 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}
- $pp \to Z' \to Z\,h$
  - $m_h = 120\text{GeV}$: $Z \to \ell^+\ell^-$; $h \to b\,\bar{b}$ — $\mathcal{L}$: (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}
- $pp \to Z' \to \ell^+\ell^-$ — $\mathcal{L}$: (1000; $-$) fb^{-1}
  - $BR_{\ell\ell} \sim 10^{-3}$ Tiny!
- $pp \to Z' \to t\,\bar{t}\ ,\ b\,\bar{b}$
  - 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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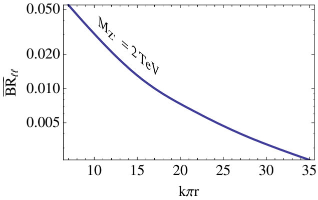

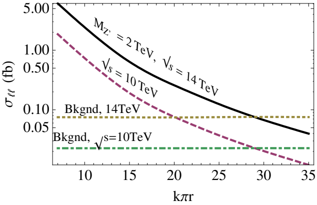

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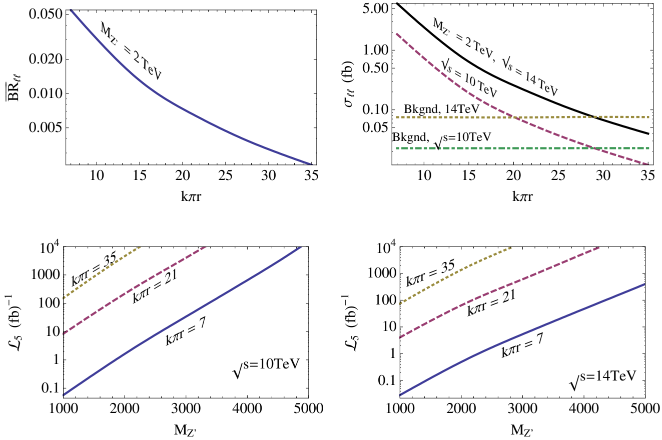
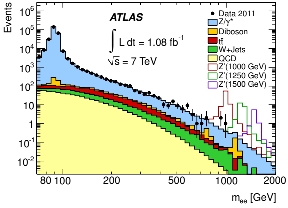
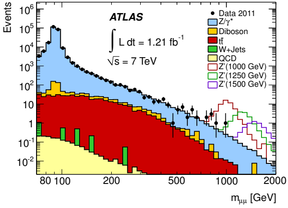
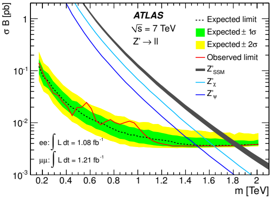
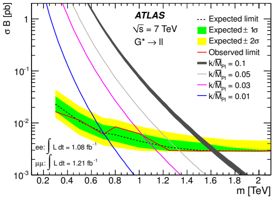


LHC Data ($Z' \to \ell\ell$)



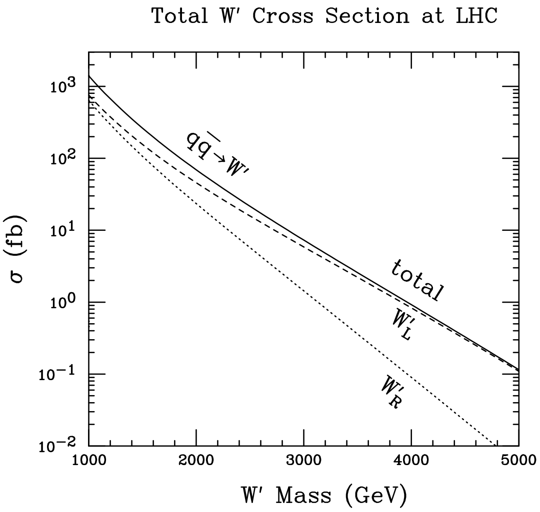




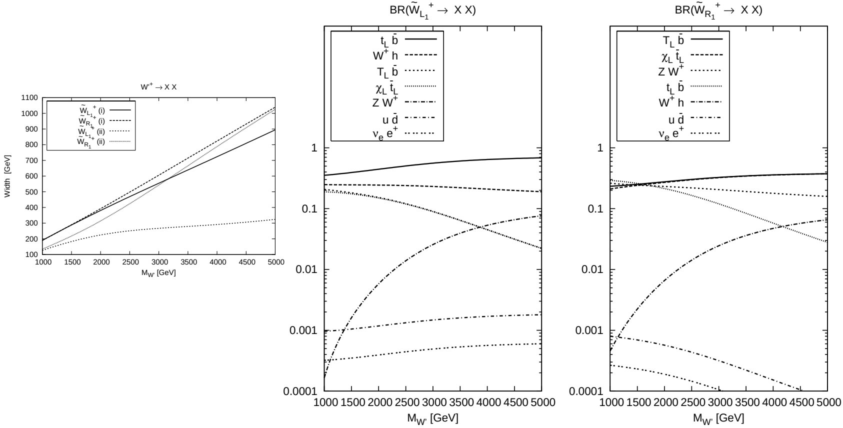


W' cross section

[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}

- $W'^{\pm} \to t\, b$:
  - 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 $0 < j_M < 75$ $\Rightarrow$0.4% of *tops* fake b

- $W'^{\pm} \to Z\, W$:
  - Fully leptonic $\mathcal{L}$: (100; 1000) fb^{-1}
  - Semi leptonic $\mathcal{L}$: (300; $-$) fb^{-1}

- $W'^{\pm} \to W\, h$: $\mathcal{L}$: (100; 300) fb^{-1}
  - $m_h \approx 120$: $h \to b\, b$
    - What is b-tagging eff at large p_{T_b}?
  - $m_h \approx 150$: $h \to W\, W$
    - Use W jet-mass to reject light jet

Measuring Chirality in (pp) $u\bar{d} \to W'^{+} \to t\,\bar{b} \to \ell^{+}\nu b\bar{b}$

A Model Independent Study

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

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

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

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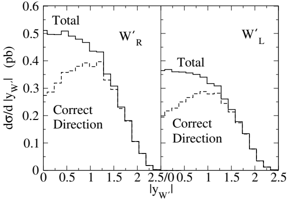
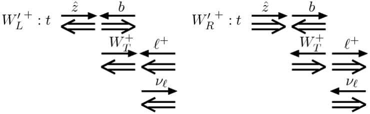
1. Need to fix u direction:

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



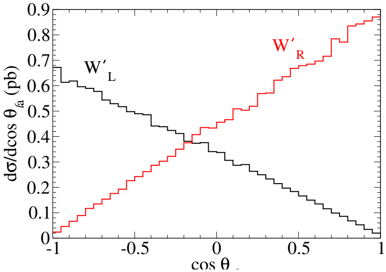
   $\therefore$ direction of $y_{W'} > 0.8$ is u direction

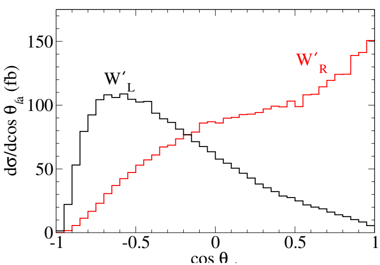
2. θ_ℓ distribution analyzes top polarization



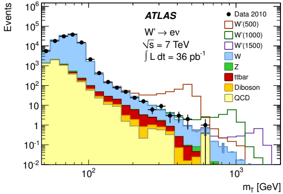
Analyze in top rest frame

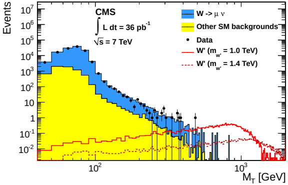
Measuring Chirality (Results)

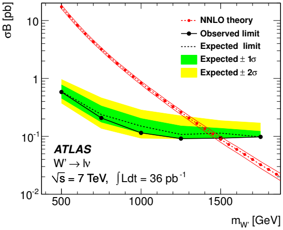


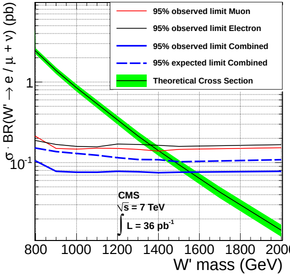


LHC Data ($W' \to \ell\nu$)





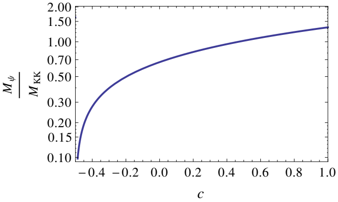




Vector-like ψ (KK Fermion)

[Dennis et al, 2007] [Carena et al, 2007] [Contino, Servant, 2008] [Atre et al, 2009] [Aguilar-Saavedra, 2009] [SG, Moreau, Singh, 2010] [Work In Progress]

- Custodial partner of t_R "light"
  - Look for at the LHC



b' as an example

[SG, T.Mandal, S.Mitra, R.Tibrewala, arXiv:1107.4306]

- KK Fermion is Vector-like! Differences from Chrial (4-gen) b' :
  - Separate mass (M_{KK}) independent of $\langle H \rangle$
    - Can be arbitrarily heavy w/o Landau pole of Yukawa coupling
    - In addition to $b' \to tW$, also $b' \to bZ$, bh at tree-level

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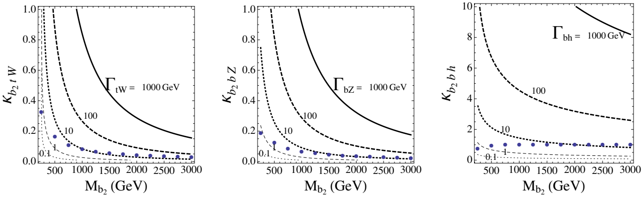
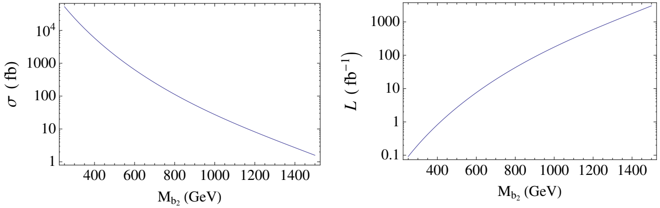


b' LHC Signals

Pair Production : $pp \to b'\bar{b}' \to bZ\bar{b}Z \to bjj\bar{b}\ell\ell$



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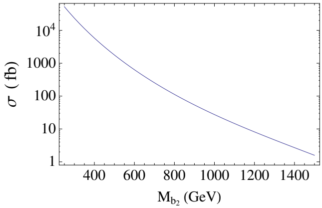
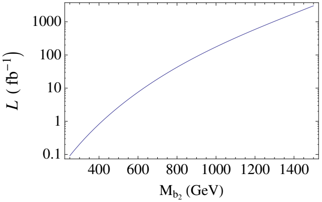
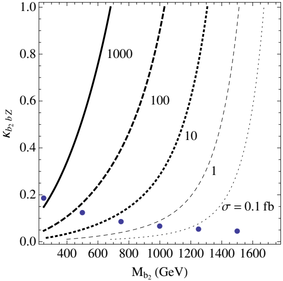
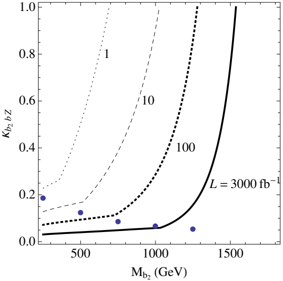




Single Production : $bg \to b'Z \to bZZ \to bjj\ell\ell$





Radion

[Csaki et al, 2001, 2007] [Gunion et al, 2004]

Fluctuations of size of extra dimension $\rightarrow$ scalar d.o.f

$$\mathcal{L} \supset \frac{r}{\Lambda} T^{\mu}_{\mu}$$

- SM on IR brane

$$\mathcal{L} \supset -\frac{r}{\Lambda_r}\left(2M_W^2 W^+_\mu W^{-\,\mu} + M_Z^2 Z_\mu Z^\mu\right)$$

- SM in bulk

$$\mathcal{L} \supset -\frac{1}{2\Lambda_r}\left[\frac{1}{(k\pi R)}+\epsilon\right] rW^-_{\mu\nu}W^{+\,\mu\nu} - \frac{1}{4\Lambda_r}\left[\frac{1}{(k\pi R)}+\epsilon\right] rZ_{\mu\nu}Z^{\mu\nu} - \frac{1}{4\Lambda_r}\left[\frac{1}{(k\pi R)}+\epsilon\right] rF_{\mu\nu}F^{\mu\nu}$$
$$-\frac{2M_W^2}{\Lambda_r}\left[1-\frac{1}{2}M_W^2 R'^2(k\pi R)-\frac{\epsilon}{2}\right] rW^+_\mu W^{-\,\mu} - \frac{M_Z^2}{\Lambda_r}\left[1-\frac{1}{2}M_Z^2 R'^2(k\pi R)-\frac{\epsilon}{2}\right] rZ_\mu Z^\mu$$

- Curvature-scalar mixing

$\mathcal{L} \supset \xi\,\mathcal{R}\,H^\dagger H$ leads to $r \leftrightarrow h$ mixing

Example LHC flavor changing processes

- Tree-level FCNC $t \to c\,h$ OR $h \to t\,c$ [Agashe, Contino 09]
  - $BR(t \to c\,h) \sim 10^{-4}$
  - $BR(h \to t\,c) \sim 5 \times 10^{-3}$
- Tree-level FCNC $BR(t \to c\,Z) \sim 10^{-5}$ [Agashe, Perez, Soni 06]
- Loop FCNC $t \to c\,\gamma$

Conclusions

- Warped models solve SM hierarchy and flavor problems
  - KK couplings to light fermions suppressed
  - KK couplings to heavy fermions, A_L, h enhanced
- Precision electroweak constraints imply $M_{KK} \gtrsim 2\ TeV$
  - Requires large $\mathcal{L}$ at LHC
  - Boosted W, Z, $top \Rightarrow$ collimation of decay products
    - QCD bkgnd becomes significant
- Chirality of W' : using θ_ℓ as analyzer of top polarization
- Little-RS (LRS) has good $Z' \to \ell^+ \ell^-$
- Tools used:
  - 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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    $A \to (+,+)\,;\ Z \to (+,+)\,;\ Z_X \to (-,+)$
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  - $B \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_X W_R^3 + g_R X) \to (+,+)$; $W_L^{\pm} \to (+,+)$

- 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: $A^{(0)}, Z^{(0)}$; $W_L^{(0)}$
- 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: $A_1, \tilde{Z}_1, \tilde{Z}_{X_1} \rightarrow Z'$; $\tilde{W}_{L_1}, \tilde{W}_{R_1} \rightarrow W'^{\pm}$

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

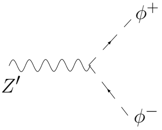
$$\bar{\psi}_{L,R}\gamma^{\mu}\Big[eQ\mathcal{I}A_{1\,\mu} + g_Z\left(T_L^3 - s_W^2 T_Q\right)\mathcal{I}Z_{1\,\mu} + g_{Z'}\left(T_R^3 - s'^2 T_Y\right)\mathcal{I}Z_{X1\,\mu}\Big]\psi_{L,R}$$

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

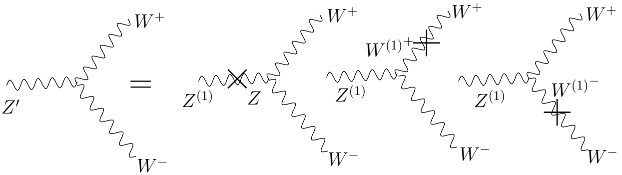
$Z^{(1)}V^{(0)}V^{(0)}$ is zero by orthogonality ...

... but induced after EWSB

Using Goldstone equivalence:



In Unitary Gauge:

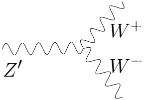


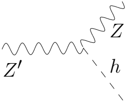
Even though $\xi \cdot (\frac{v}{M_{KK}})^2$ suppressed ...

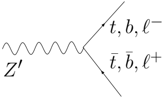
... can be overcome by $(\frac{M_{KK}}{m_Z})^2$ (from long. pol. vectors)

Z' decays

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







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

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

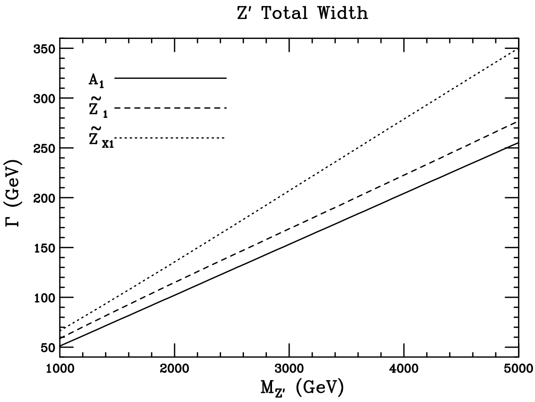
$$\Gamma(\tilde{Z}_1, \tilde{Z}_{X1} \to Z_L h) = \frac{g_Z^2 \kappa^2}{192\pi} M_{Z'} \; ; \quad \kappa \propto \sqrt{k\pi r_c} ,$$

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

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	

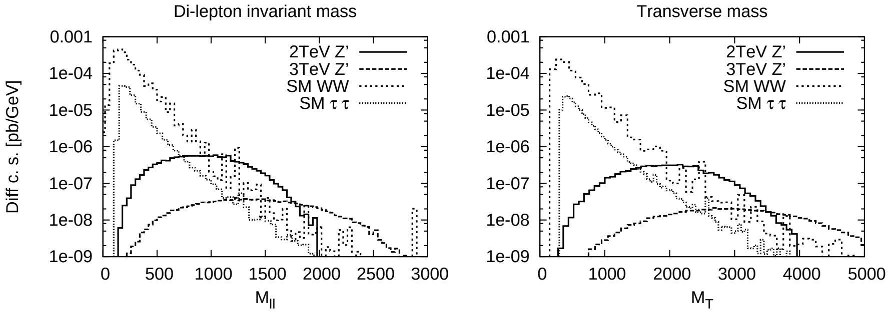
Total Widths



$M_{Z'} = 2$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}

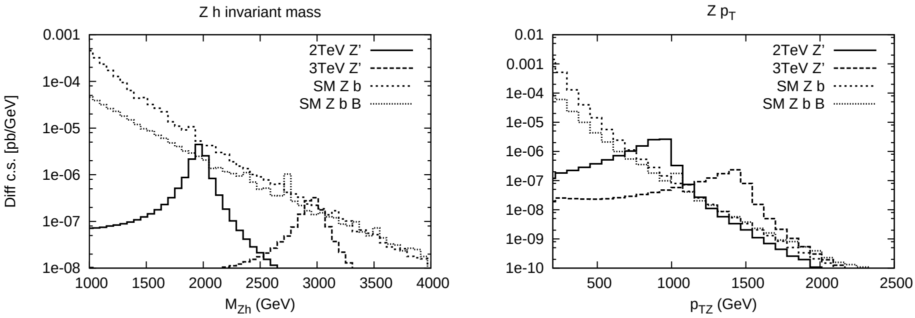
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ 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}

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



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)

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

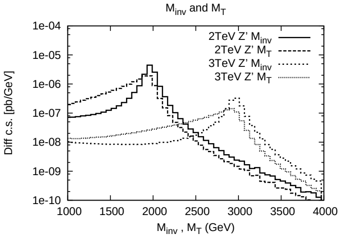
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ 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}

$pp \to Z' \to Z\,h$: $\quad Z \to j\,j$; $\quad h \to W^+W^- \to j\,j\,\ell\,\nu$ $(m_h = 150$ 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 $\quad m_h = 150$ 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 $\quad m_h = 150$ 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}

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

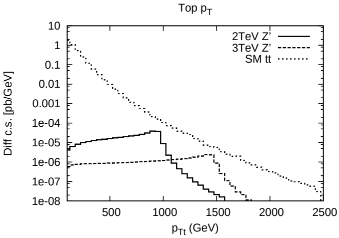
$M_{Z'} = 2$ TeV	Basic	$p_{T\ell}$	$M_{\ell\ell}$	# Evts	S/B	$S/\sqrt{B}$
Signal	0.1	0.09	0.06	60	0.3	4.2
SM $\ell\ell$	3×10^4	5.4	0.2	200		
SM WW	295	0.03	0.002	2		

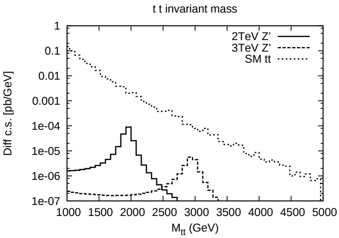
events above is for

- 2 TeV : 1000 fb^{-1}

Experimentally clean, but needs a LOT of luminosity

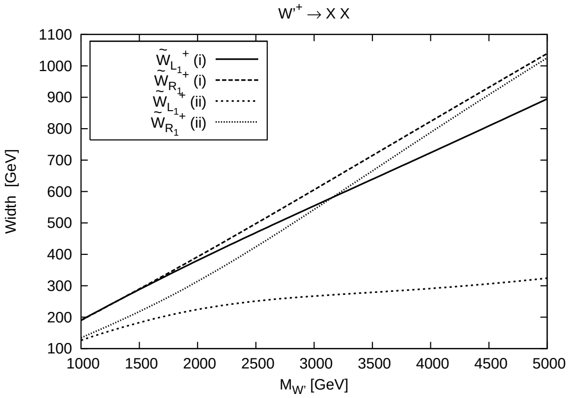
$pp \to Z' \to t\bar{t}$





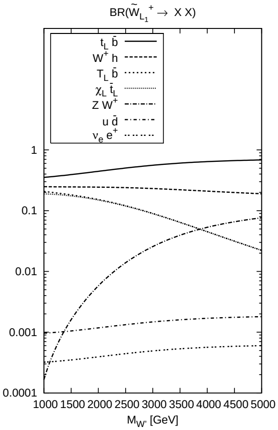
$M_{Z'} = 2$ TeV	Basic	$p_T > 800$	$1900 < M_{tt} < 2100$
Signal	17	7.2	5.6
SM $t\bar{t}$	1.9×10^5	31.1	19.1
$M_{Z'} = 3$ TeV	Basic	$p_T > 1250$	$2850 < M_{tt} < 310$
Signal	1.7	0.56	0.45
SM $t\bar{t}$	1.9×10^5	4.1	1.1

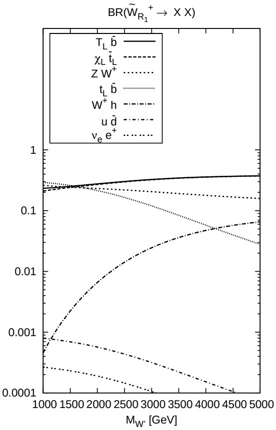
$W'^{\pm}$ width



W'+ → X X
W̃L1+ (i)
W̃R1+ (i)
W̃L1+ (ii)
W̃R1+ (ii)
Width [GeV]
MW' [GeV]
1100
1000
900
800
700
600
500
400
300
200
100
1000
1500
2000
2500
3000
3500
4000
4500
5000

$W'^{\pm}BR$

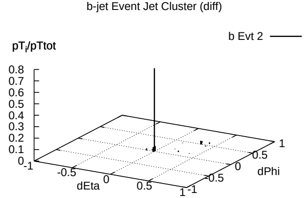

BR($\tilde{W}_{L_1}^{+} \to$ X X)
$t_L\ \bar{b}$
$W^+\ h$
$T_L\ \bar{b}$
$\chi_L\ \bar{t}_L$
$Z\ W^+$
$u\ \bar{d}$
$\nu_e\ e^+$
1
0.1
0.01
0.001
0.0001
1000 1500 2000 2500 3000 3500 4000 4500 5000
$M_{W'}$ [GeV]

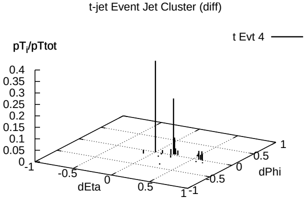

BR($\tilde{W}_{R_1}^{+} \to$ X X)
$T_L\ \bar{b}$
$\chi_L\ \bar{t}_L$
$Z\ W^+$
$t_L\ \bar{b}$
$W^+\ h$
$u\ \bar{d}$
$\nu_e\ e^+$
1
0.1
0.01
0.001
0.0001
1000 1500 2000 2500 3000 3500 4000 4500 5000
$M_{W'}$ [GeV]

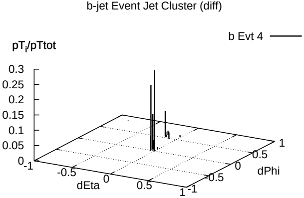
Signal c.s. $\sim 1fb$

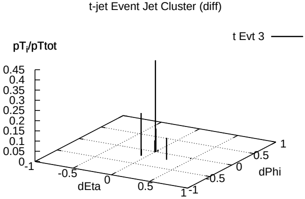
Bkgnd is single top + QCD W b b .... AND ...

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

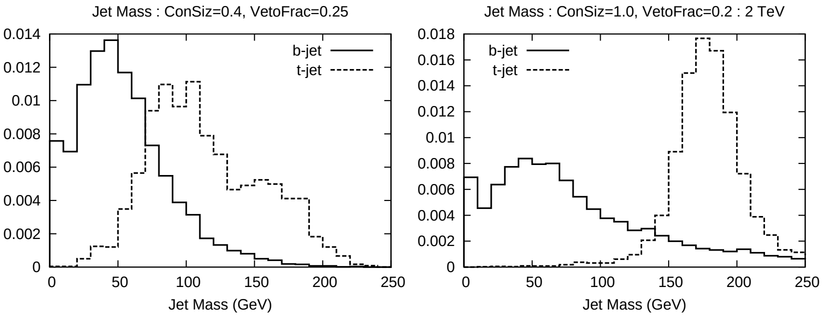








$W'^{\pm} \to t\, b \to \ell \nu b\, b$



Jet-mass cut: cone size 1.0 and $0 < j_M < 75 \Rightarrow$0.4% of *top* fakes *b*

$\mathcal{L}$ needed: 100 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