Theories of Extra Dimensions

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Motivation

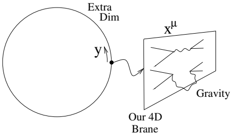
- SM hierarchy problem: $M_{EW} \ll M_{Pl}$
- SM flavor problem: $m_e \ll m_t$
- Explained by new dynamics?
    - **Extra dimensions** (Warped (AdS), Flat)
    - Supersymmetry
    - Strong dynamics
    - Little Higgs

Talk Outline

- Aspects of Extra Dimensional Theories
  - Large Extra Dimensions (LED) (aka ADD)
  - Universal Extra Dimensions (UED)
  - Warped Extra Dimensions (WED) - **Main Focus**
- Kaluza-Klein (KK) expansion
- LHC Signatures

Large Extra Dimensions (LED, ADD)

- Usual picture
  - 3 space + 1 time   Gravity scale $M_{pl} \sim 10^{19}$ GeV
- Large Extra Dimensions   [Arkani-Hamed, Dimopoulos, Dvali (ADD)]
  - n (compact) space extra dims   Radius R
  - Only fundamental scale $M_* \sim 10^3$ GeV
  - $M_{pl}^2 = M_*^{2+n} V_n \qquad V_n \sim R^n$
  - Gravity in bulk, SM on brane
  - $\mathcal{S} = \int d^4x \, d^ny \left[\mathcal{L}_{\rm Bulk} + \delta(\underline{y}) \, \mathcal{L}_{Brane}\right]$



Universal Extra Dimensions (UED)

[Appelquist, Cheng, Dobrescu] [Cheng, Matchev, Schmaltz] [Datta, Kong, Matchev]

All SM fields propagate in Extra Dimension(s)

- No solution to the hierarchy problem
- KK number conserved
- Orbifolding implies KK parity conservation
  - Relaxed constraints since no tree level contribution to EW precision obs
    - $M_{KK} \gtrsim 400\ GeV$
  - LKP stable!
    - Dark Matter [Servant, Tait]
    - Missing energy at Colliders

Warped Extra Dimensions (WED, RS)

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

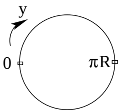
$$ds^2 = e^{-2k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2$$

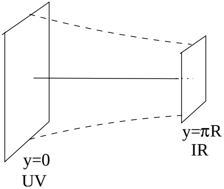
Z_2 orbifold fixed points:

- 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

AdS/CFT Correspondence

AdS/CFT Correspondence [Maldacena, 1997]

- A classical supergravity theory in $AdS_5 \times S_5$ at weak coupling is **dual** to a 4D large-N CFT at strong coupling
- The CFT is at the boundary of AdS [Witten 1998; Gubser, Klebanov, Polyakov 1998]

$$Z_{CFT}[\phi_0] = e^{-\Gamma_{AdS}[\phi_0]}$$

$\mathcal{L} \supset \int d^4x\, \mathcal{O}_{CFT}(x)\, \phi_0(x)$	$\Gamma_{AdS}[\phi]$ supergravity eff. action
Eg: $\langle \mathcal{O}(x_1)\, \mathcal{O}(x_2) \rangle = \frac{\delta^2 Z_{CFT}[\phi_0]}{\delta\phi_0(x_1)\delta(x_2)}$	$\phi(y,x)$ is a solution of the EOM ($\delta\Gamma = 0$)
with Z_{CFT} given by the RHS	for given bndry value $\phi_0(x) = \phi(y = y_0, x)$

4D Duals of Warped Models

[Arkani-Hamed, Porrati, Randall, 2000; Rattazzi, Zaffaroni, 2001]

- Dual of Randall-Sundrum model **RS1 (SM on IR Brane)**
  - Planck brane $\Longrightarrow$ UV Cutoff; Dynamical gravity in the 4D CFT
  - TeV (IR) brane $\Longrightarrow$ IR Cutoff; Conformal invariance broken below a TeV
    - All SM fields are composites of the CFT
- Dual of Warped Models with **Bulk SM**
  - UV localized fields are elementary
  - IR localized fields (Higgs) are composite
    - 4D dual is Composite Higgs model [Georgi, Kaplan 1984]
    - Shares many features with Walking Extended Technicolor
  - Partial Compositeness
    - AdS dual is weakly coupled and hence calculable!
  - KK states are dual to composite resonances

Eg: 5-Dimensional Theory

Bulk fields $\Phi(x,y) = \{A_M,\, \phi,\, \Psi, , ...\}$

$$\mathcal{S}^{(5)} = \int d^4x\, dy\ \mathcal{L}^{(5)} \quad ; \quad \mathcal{L}^{(5)} \supset \sqrt{|g|}\, M_*^3 \mathcal{R} + \mathcal{L}_A^{(5)} + \mathcal{L}_\Psi^{(5)} + \mathcal{L}_\phi^{(5)} + \mathcal{L}_{int}^{(5)}$$

$$\mathcal{L}_\psi^{(5)} \supset \sqrt{|g|}\ \left\{ \bar{\Psi} i \Gamma^M \partial_M \Psi + c_\psi\, k\, \bar{\Psi}\Psi \right\}$$

$$\mathcal{L}_\phi^{(5)} \supset \sqrt{|g|}\ \left\{ \partial^M \phi^\dagger\, \partial_M \phi + m_\phi^2\, \phi^\dagger \phi \right\};$$

$$\mathcal{L}_A^{(5)} \supset \sqrt{|g|}\ \left\{ -\tfrac{1}{4} F^{MN} F_{MN} \right\}$$

$$\mathcal{L}_{int}^{(5)} \supset \sqrt{|g|}\ \left\{ g_5 \bar{\Psi}\Gamma^M \Psi\, A_M\ + (\lambda_5\, \phi\, \bar{\Psi}_L \Psi_R + h.c.) - \mathcal{V}(\phi^\dagger \phi) \right\}$$

Kaluza-Klein (KK) expansion

$\delta S^{(5)} = 0 \quad \Longrightarrow$ Euler-Lagrange Equations of Motion (EOM)

- $\frac{\delta \mathcal{L}^{(5)}}{\delta \Phi} = \partial_M \frac{\delta \mathcal{L}^{(5)}}{\delta \partial_M \Phi}$

KK expansion: $\Phi(x,y) = \sum_{n=0}^{\infty} f^{\phi}_{(n)}(y)\, \phi^{(n)}(x)$ with $\int dy\, f^{\phi}_{(n)}(y)\, f^{\phi}_{(m)}(y) = \delta_{nm}$

Plug into EOM, y dependent piece is (for WED) [Gherghetta, Pomarol, 2000]

$$\left[-e^{sk|y|}\partial_5(e^{-sk|y|}\partial_5) + \hat{M}^2_\Phi\right] f_{(n)}(y) = e^{2k|y|} m_n^2 f_n(y)$$

$s = \{2, 4, 1\}; \quad \hat{M}^2_\Phi = \left\{0, ak^2, c(c \pm 1)k^2\right\}$

The solution is

$$f_{(n)}(y) = \frac{1}{N_n} e^{sk|y|/2} \left[J_\alpha\left(\frac{m_n}{k} e^{k|y|}\right) + b_\alpha Y_\alpha\left(\frac{m_n}{k} e^{k|y|}\right)\right]$$

Equivalent 4D theory

Plug KK expansion into $\mathcal{S}^{(5)}$ & integrate over $y \rightarrow$ *equivalent 4D theory*

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

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

Some 4D couplings

- Yukawas: $\lambda_{4D}^{(00)} = \lambda_{5D} \int dy \, f_0^{\psi_L} \; f_0^{\psi_R} \; f^H$
- Gauge couplings: $g_{4D}^{(001)} = g_{5D} \int dy \, f_0^{\psi} \; f_0^{\psi} \; f_1^A$

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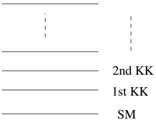
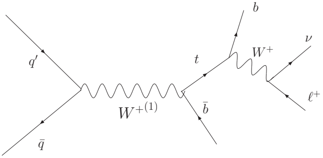
In summary

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

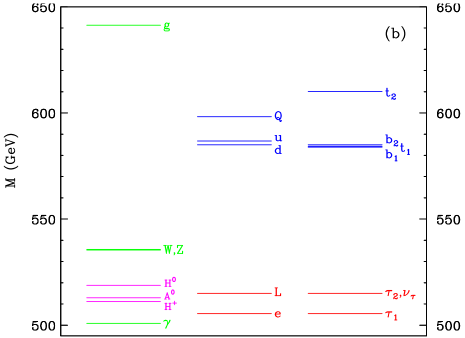


Example:



UED Spectrum

- All KK states degenerate at leading order
  - Loop corrections split this



[Cheng, Matchev, Schmaltz]

LHC SUSY $\leftrightarrow$ UED confusion!

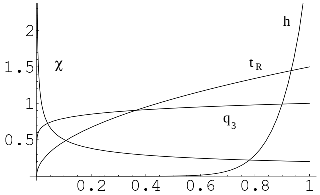
[Cheng, Matchev, Schmaltz: 2002]

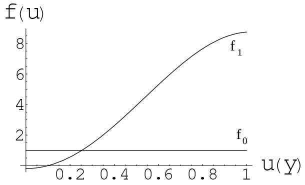
Explaining SM (gauge & mass) hierarchies (WED)

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

4-D KK couplings in WED

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

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: $t_L t_L A'$

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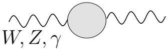
Effective coupling (Eg: Z'):

$$\mathcal{L}^{4D} \supset \bar{\psi}_{L,R}\gamma^{\mu}\left[eQ\mathcal{I}A_{1\ \mu} + g_Z\left(T^3_L - s^2_W T_Q\right)\mathcal{I}Z_{1\ \mu} + g_{Z'}\left(T^3_R - s'^2 T_Y\right)\mathcal{I}Z_{X1\ \mu}\right]\psi_{L,R}$$

Challenge I : Precision EW Constraints in WED



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]

WED 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: $A|_{y=0} = 0\,;\ \partial_y A\,|_{y=\pi R} = 0$
  - $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$
- By VEV of TeV brane Higgs — Higgs $\Sigma = (2,2)$
  - $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

Fermion representation : $Zb\bar{b}$ not protected

[Agashe, Delgado, May, Sundrum '03]

- Complete $SU(2)_R$ multiplet : Doublet t_R (DT) model
  - $Q_L \equiv (\mathbf{2}, \mathbf{1})_{1/6} = (t_L, b_L)$
    $\psi_{t_R} \equiv (\mathbf{1}, \mathbf{2})_{1/6} = (t_R, b')$
    $\psi_{b_R} \equiv (\mathbf{1}, \mathbf{2})_{1/6} = (T, b_R)$
    - "Project-out" b', T zero-modes by $(-,+)$ B.C.
    - New ψ_{VL} : b', T
- $b \leftrightarrow b'$ mixing
  - $Zb\bar{b}$ coupling shifted
    - So LEP constraint quite severe

Fermion representation : $Zb\bar{b}$ protected

- $Q_L = (2,2)_{2/3} = \begin{pmatrix} t_L & \chi \\ b_L & T \end{pmatrix}$ [Agashe, Contino, DaRold, Pomarol '06]
  - $Zb_L\overline{b_L}$ protected by custodial $SU(2)_{L+R} \otimes P_{LR}$ invariance
    Wt_Lb_L, Zt_Lt_L not protected, so shifts

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  - $Zb_L\overline{b_L}$ protected by custodial $SU(2)_{L+R} \otimes P_{LR}$ invariance
    $Wt_L b_L$, $Zt_L t_L$ not protected, so shifts

Two t_R possibilities:

1. Singlet t_R (ST) : $(1,1)_{2/3} = t_R$ New ψ_{VL} : χ, T
2. Triplet t_R (TT) :

$$(1,3)_{2/3} \oplus (3,1)_{2/3} = \psi'_{t_R} \oplus \psi''_{t_R} = \begin{pmatrix} \frac{t_R}{\sqrt{2}} & \chi' \\ b' & -\frac{t_R}{\sqrt{2}} \end{pmatrix} \oplus \begin{pmatrix} \frac{t''}{\sqrt{2}} & \chi'' \\ b'' & -\frac{t''}{\sqrt{2}} \end{pmatrix}$$

New ψ_{VL} : χ, T, χ', b', χ'', t'', b''

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)
- $W^{\pm}_{L(0)} \psi_{(0)} \psi_{(1)} \; : \; g \, V_{001} \; \left[f_{W^{(1)}} f_{\psi} f_{\psi^{(1)}} \right]$

Challenge II : Flavor Constraints in WED

- $K^0 \bar{K}^0$ 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 $g_{(1)}\, b\, s_{(1)}$ OR $\phi^{\pm}\, b\, s_{(1)}$
- $b \to s\, \ell^+ \ell^-$, $b \to s\, s\, \bar{s}$, $K \to \pi \nu \bar{\nu}$:
  - Tree level FCNC vertex $Z\, s\, d$

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]

[SG, A.Iyer, S.Vempati Ongoing]

LHC Phenomenology

LED KK Graviton @ LHC

Look for KK Gravitons ($h^{(n)}_{\mu\nu}$) : Missing energy (MET)
[Giudice, Rattazzi, Wells 1998][Hewett 1998] [Han, Lykken, Zhang 1998]

- Small KK spacing : sum over huge number of states
  - Cutoff dependence
- Final state Gravitons : $pp \to \gamma\, h^{(n)},\ j\, G^{(n)}$
- Virtual Gravitons : $pp \to h^{(n)} \to \ell^+\ell^-, \cdots$

LED LHC Limit $pp \to h^{(n)}_{\mu\nu} \to \ell^+\ell^-$

TABLE VIII. Observed 95% C.L. lower limits on M_S (in units of TeV), including systematic uncertainties, for ADD signal in the GRW, Hewett and HLZ formalisms with K factors of 1.6 and 1.7 applied to the signal for the dilepton and diphoton channels, respectively. Separate results are provided for the different choices of flat priors: $1/M_S^4$ and $1/M_S^8$.

Channel	Prior	GRW	Hewett	HLZ				
				n=3	n=4	n=5	n=6	n=7
ee	$1/M_S^4$	2.95	2.63	3.51	2.95	2.66	2.48	2.34
	$1/M_S^8$	2.82	2.67	3.08	2.82	2.68	2.59	2.52
$\mu\mu$	$1/M_S^4$	3.07	2.74	3.65	3.07	2.77	2.58	2.44
	$1/M_S^8$	2.82	2.67	3.08	2.82	2.68	2.59	2.52
$ee+\mu\mu$	$1/M_S^4$	3.27	2.92	3.88	3.27	2.95	2.75	2.60
	$1/M_S^8$	3.09	2.92	3.37	3.09	2.94	2.84	2.76
$ee+\mu\mu$	$1/M_S^4$	3.51	3.14	4.18	3.51	3.17	2.95	2.79
$+\gamma\gamma$	$1/M_S^8$	3.39	3.20	3.69	3.39	3.22	3.11	3.02

ATLAS : 1211.1150 : 7TeV, 5 fb^{-1}

WED KK Graviton

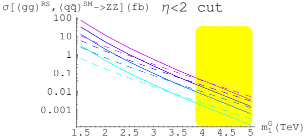
[Agashe et al, 07] [Fitzpatrick et al, 07]

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

- 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 $100 fb^{-1}$

- 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]

$m_n = x_n k e^{-k\pi r}$ $x_n \approx 2.45,\ 5.57,\ \ldots$ 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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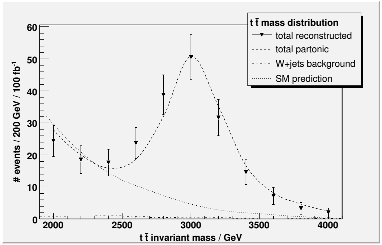
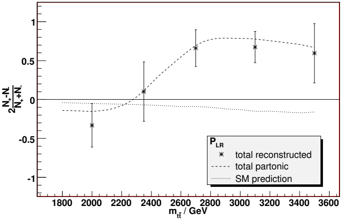
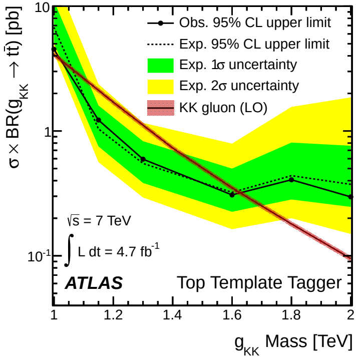




$P_{LR} = 2\frac{N_+ - N_-}{N_+ + N_-}$ N_+ forward going ℓ wrt k_t

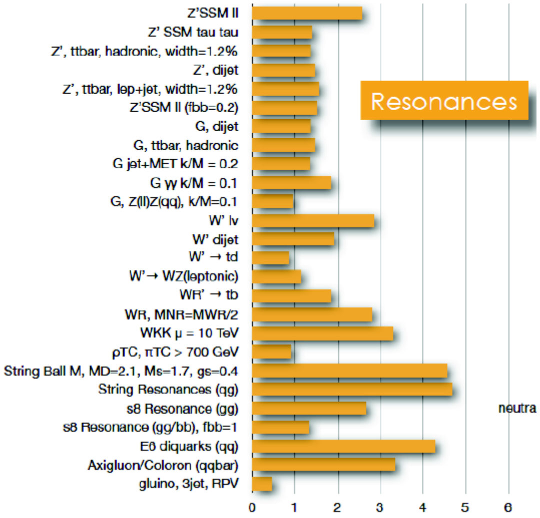
LHC reach: About 4 TeV with 100 fb^{-1}

LHC KK-gluon search

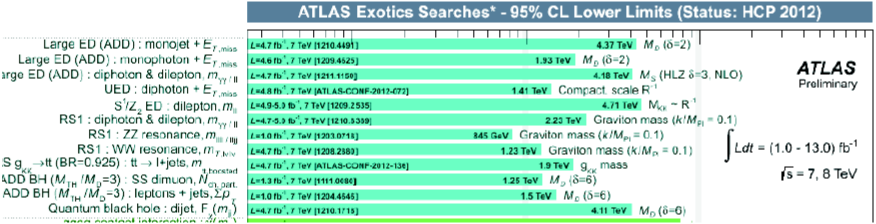


ATLAS JHEP01(2013) 116 : Limit (7 TeV, 4.7 fb^{-1}): $M_{KK} > 1.6\ TeV$ @ 95% CL

CMS Resonances Limits (Moriond 2013)

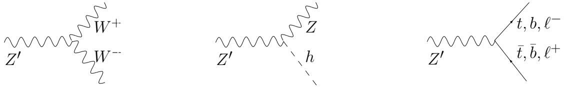


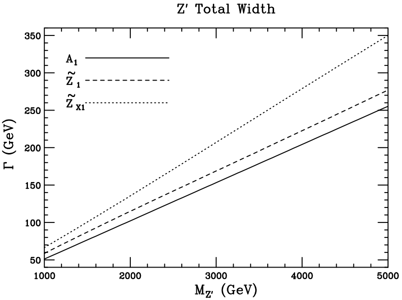
ATLAS Extra Dimensions Limits (Moriond 2013)



Z' decays in WED

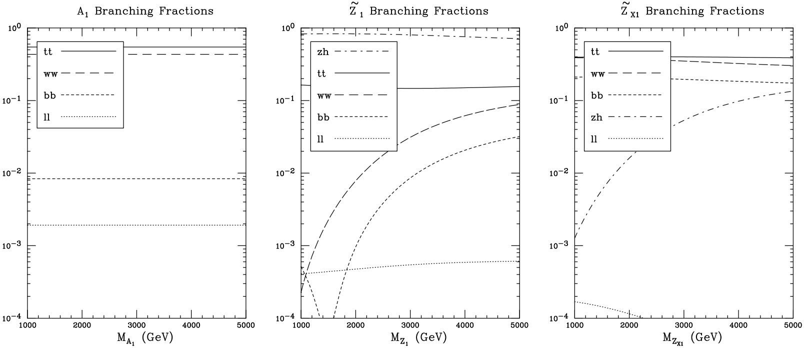
[Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni - arXiv:0709.0007 [hep-ph]]



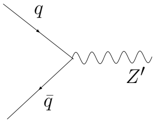


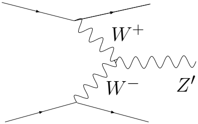
$M_{Z'} = 2$TeV	A_1	Z_1	Z_{X1}
Γ (GeV)	103.3	114.6	135.6

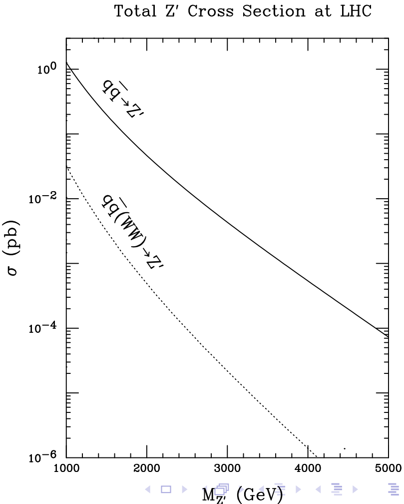
Z' Branching Ratios in WED



WED Z' production at the LHC







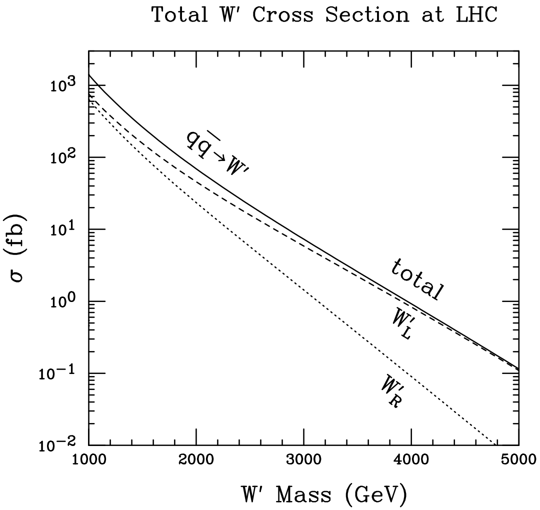
WED Z' channels summary

$(\mathcal{L}_{2\ TeV};\ \mathcal{L}_{3\ TeV})$ in fb^{-1}

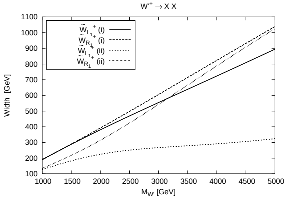
- $pp \to Z' \to W^+W^-$
  - Fully leptonic : $W \to \ell\nu\ ;\ W \to \ell\nu$ — $\mathcal{L}:\ (100;\ 1000)\ \ fb^{-1}$
  - Semi leptonic : $W \to \ell\nu\ ;\ W \to (jj)$ — $\mathcal{L}:\ (100;\ 1000)\ \ fb^{-1}$
- $pp \to Z' \to Z\,h$
  - $m_h = 120\text{GeV} : Z \to \ell^+\ell^-\ ;\ h \to b\,\bar{b}$ — $\mathcal{L}:\ (200;\ 1000)\ \ fb^{-1}$
  - $m_h = 150\text{GeV} : Z \to (jj)\ ;\ h \to W^+\,W^- \to (jj)\ \ell\nu$ — $\mathcal{L}:\ (75;\ 300)\ \ fb^{-1}$
- $pp \to Z' \to \ell^+\ell^-$ — $\mathcal{L}:\ (1000;\ -)\ \ fb^{-1}$
  - $BR_{\ell\ell} \sim 10^{-3}$ Tiny!
- $pp \to Z' \to t\,\bar{t}\ ,\ \ b\,\bar{b}$
  - KK gluon “pollution” — [Djouadi, Moreau, Singh 07]

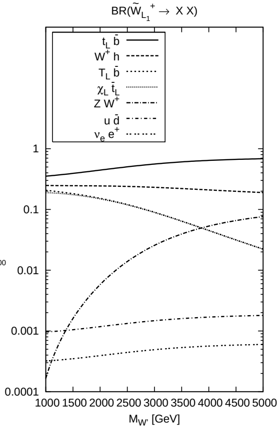
W' cross section

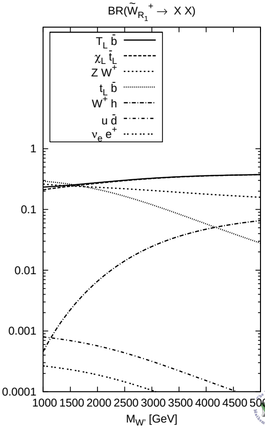
[Agashe, SG, Han, Huang, Soni, 08: arXiv:0810.1497]



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

A Model Independent Study

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

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

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

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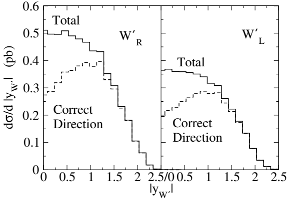
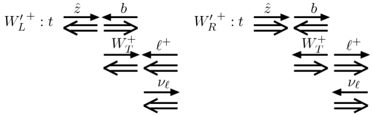
Need to fix u direction:

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



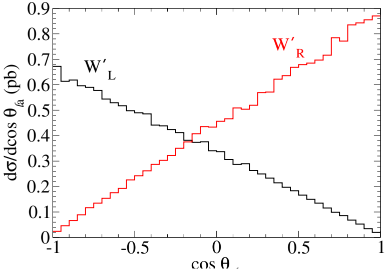
$\therefore$ direction of $y_{W'} > 0.8$ is u direction

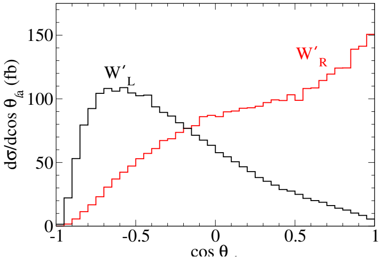
θ_ℓ distribution analyzes top polarization



Analyze in top rest frame

Measuring W' Chirality (Results)





WED KK Fermions @ LHC

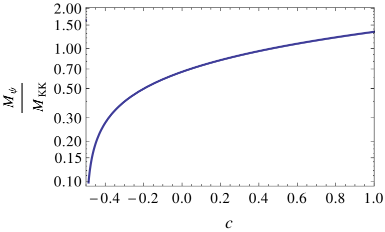
- SM fermions : $(+,+)$ BC $\rightarrow$ zero-mode
- "Exotic" fermions : $(-,+)$ BC $\rightarrow$ No zero-mode
  - 1^{st} KK vectorlike fermion

- Typical c_{t_R}, c_{t_L} : $(-,+)$ top-partners "light"

  c : Fermion bulk mass parameter

  [Choi, Kim, 2002] [Agashe, Delgado, May, Sundrum, 03] [Agashe, Perez, Soni, 04] [Agashe, Servant 04]

  - Look for it at the LHC

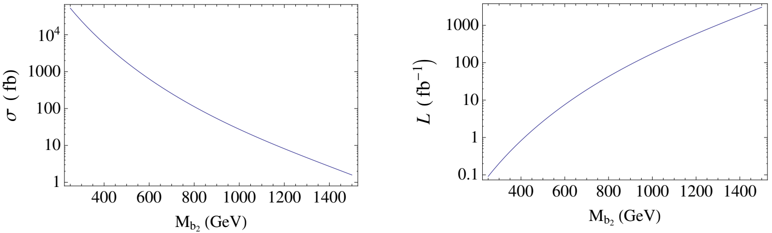


[Dennis et al, '07] [Carena et al, '07] [Contino, Servant, '08]
[Atre et al, '09, '11] [Aguilar-Saavedra, '09] [Mrazek, Wulzer, '09]
[SG, Moreau, Singh, '10] [SG, Mandal, Mitra, Tibrewala, '11] [SG, Mandal, Mitra, Moreau : Work In Progress]

b' Pair Production

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

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



Cuts:

Rapidity: $-2.5 < y_{b,j,Z} < 2.5$,
Transverse momentum: $p_{T\,b,j,Z} > 25$ GeV,
Invariant mass cuts:
$M_Z - 10\ \text{GeV} < M_{jj} < M_Z + 10\ \text{GeV}$,
$0.95 M_{b_2} < M_{(bZ)} < 1.05 M_{b_2}$.

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]

- b', t', χ (KK Fermions)
  [Agashe, Servant 04][Dennis et al 07][Contino, Servant 08][SG, Mandal, Mitra, Moreau ongoing]

- Radion

Little RS (LRS) ($Z' \to \ell^+\ell^-$)

$M_{EW} \sim k\, e^{-k\pi R}$; Vary $k,\ k\pi R$; $(k\pi R)_{LRS} < (k\pi R)_{RS} = 35$

- RS: $k \lesssim M_{pl}$
- LRS: $k \ll M_{pl}$; $k\pi R = 7 \implies k \approx 1000\ TeV$ [Davoudiasl, Perez, Soni 08]
- RS as a theory of flavor! (***give-up solution to hierarchy problem***)

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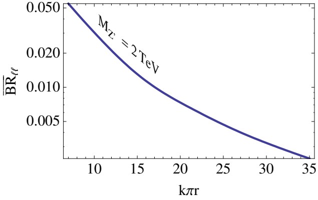

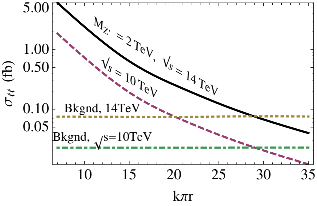

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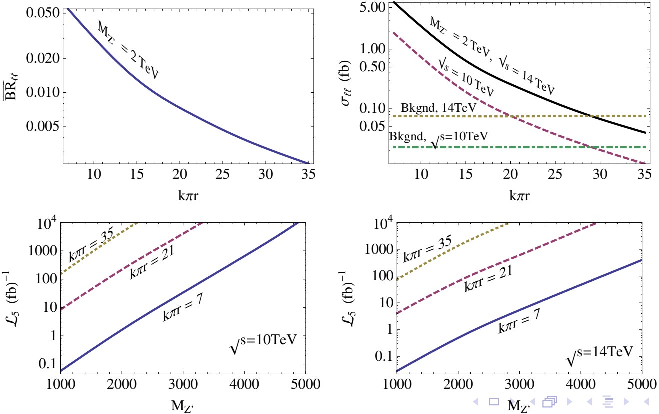


LED Bulk ν_R

[Dienes, Dudas, Gherghetta]
[Davoudiasl, Langacker, Perelstein]
[Cao,SG,Yuan 2003,2004]

- Introduce Bulk ν_R propagating in δ dimensions
- $\Psi^\alpha(x^\mu, y) = \begin{pmatrix} \psi_L^\alpha(x^\mu, y) \\ \psi_R^\alpha(x^\mu, y) \end{pmatrix} \qquad (\delta = 1) \qquad \alpha \to$ Generation
- $\mathcal{L}_{\rm Bulk} \supset \bar{\Psi}^\alpha \, i\Gamma^M D_M \Psi^\alpha$

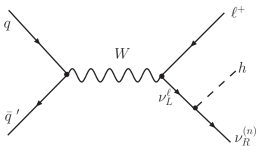
  $\mathcal{L}_{\rm Brane} \supset \mathcal{L}_{\rm SM} - \left(\frac{\Lambda^\nu_{\alpha\beta}}{\sqrt{M_*^\delta}} \, h \, \psi_R^\beta \, \nu_L^\alpha + h.c. \right)$
  - $\nu_L \to$ Usual SM left-handed neutrino
  - $\psi_R \to$ Bulk right-handed neutrino $\equiv \nu_R$
  - $\psi_L \to$ No direct coupling to SM

LED Bulk ν_R at colliders

- ν_R couples only to ν_L and h (Yukawa)
  - $\mathcal{L}^{(4)} \supset -\left[\frac{\bar{m}_\nu^{i\beta}}{v}\left(h\nu_R'^{i}\nu_L^{\beta} + \sum_{\hat{n}}\sqrt{2}h\nu_R'^{i(\hat{n})}\nu_L^{\beta}\right) + h.c.\right]$ $\qquad \bar{m}_\nu \equiv m_0 l^\dagger$
- New Higgs production mechanism (Signal)

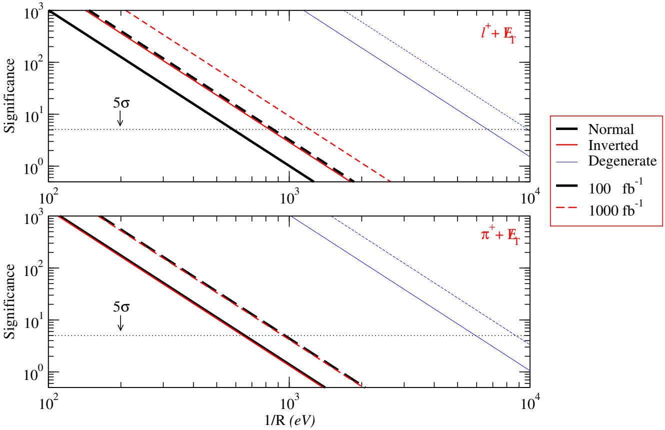
$$q\bar{q}' \to W^* \to \ell^+ h \nu_R^{(n)} \qquad (\ell = e, \mu, \tau)$$

  - Signal can be enhanced due to large number of final state $\nu_R^{(n)}$
- New Higgs decay mode
  - Invisible mode: $(h \to \nu_L \nu_R^{(n)})$
  - (SM: $h \to b\bar{b}$)



LED Bulk ν_R @ LHC

$$\delta = 3, \sqrt{S} = 14\ TeV$$



Conclusions

- LED recasts Heirarchy Problem statement
  - LHC Limits strong
- UED provides Dark Matter candidate
- Warped Models
  - Bulk fields limits weaker
  - **LHC14 high luminosity run crucial**
  - Possibly dual to 4D strongly coupled theory

BACKUP SLIDES

BACKUP SLIDES

Yukawa Couplings

- No $Zb\bar{b}$ protection
  - DT $\quad \mathcal{L}_{\rm Yuk} \supset \lambda_t\ \bar{Q}_L\Sigma\psi_{t_R} + \lambda_b\ \bar{Q}_L\Sigma\psi_{b_R} + h.c.$
- With $Zb\bar{b}$ protection
  - ST $\quad \mathcal{L}_{\rm Yuk} \supset \lambda_t\ {\rm Tr}[\bar{Q}_L\Sigma]\ t_R + h.c.$
  - TT $\quad \mathcal{L}_{\rm Yuk} \supset \lambda_t{\rm Tr}\left[\bar{Q}_L\Sigma\psi^{'}_{t_R}\right] + \lambda^{'}_t{\rm Tr}\left[\bar{Q}_L\Sigma\psi^{''}_{t_R}\right] + h.c.$
  - b Yukawa requires triplet b_R

$$(1,3)_{2/3} \oplus (3,1)_{2/3} = \psi^{'}_{b_R} \oplus \psi^{''}_{b_R} = \begin{pmatrix} \frac{t^{'}_b}{\sqrt{2}} & \chi^{'}_b \\ b_R & -\frac{t^{'}_b}{\sqrt{2}} \end{pmatrix} \oplus \begin{pmatrix} \frac{t^{''}_b}{\sqrt{2}} & \chi^{''}_b \\ b^{''}_b & -\frac{t^{''}_b}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{L}_{\rm Yuk} \supset \lambda_b{\rm Tr}\left[\bar{Q}_L\Sigma\psi^{'}_{b_R}\right] + \lambda^{'}_b{\rm Tr}\left[\bar{Q}_L\Sigma\psi^{''}_{b_R}\right] + h.c.$$

c_{b_R} such that new $\psi^{'}_b,\ \psi^{''}_b \gtrsim 3$ TeV, so ignore them

WED $pp \to g^{(1)} \to t\bar{t}$ (semi-leptonic)

!!!Warning!!! Very rough estimates!

- $\sigma(M_{g^{(1)}} = 2\,TeV,\ \sqrt{S} = 14\,TeV,\ k\pi R = 35) \ \approx\ 600\ fb$
  - $\mathcal{L}^{5\sigma}(M_{g^{(1)}} = 2\,TeV,\ \sqrt{S} = 14\,TeV,\ k\pi R = 35)\ =\ 1.2\ fb^{-1}$
- $14\ TeV \to 7\,TeV$: $\sigma(g^{(1)} = 2\,TeV)$ falls by a factor of 25
  - $\mathcal{L}^{5\sigma}(M_{g^{(1)}} = 2\,TeV,\ \sqrt{S} = 7\,TeV,\ k\pi R = 35)\ =\ 30\ fb^{-1}$

    (Assumed : Bkgnd falls with same factor)
- $\mathcal{L}^{5\sigma}(M_{g^{(1)}} = 2\,TeV,\ \sqrt{S} = 7\,TeV,\ k\pi R = 7)\ =\ 1\ fb^{-1}$

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

  - $SU(2)_R \times U(1)_X \to U(1)_Y$: $\quad (W_L^3, W_R^3, X) \to (W_L^3, B, Z_X)$

    $A \to (+,+)\,;\ Z \to (+,+)\,;\ Z_X \to (-,+)$
  - $Z_X \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_R W_R^3 - g_X X) \to (-,+) \quad ; \quad W_R^{\pm} \to (-,+)$
    - $B \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_X W_R^3 + g_R X) \to (+,+) \quad ; \quad W_L^{\pm} \to (+,+)$

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    $A \rightarrow (+,+)\,;\ Z \rightarrow (+,+)\,;\ Z_X \rightarrow (-,+)$
  - $Z_X \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_R W_R^3 - g_X X) \rightarrow (-,+)$; $W_R^{\pm} \rightarrow (-,+)$
  - $B \equiv \frac{1}{\sqrt{g_x^2+g_R^2}}(g_X W_R^3 + g_R X) \rightarrow (+,+)$; $W_L^{\pm} \rightarrow (+,+)$

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

Gauge EW KK States

Gauge Boson

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

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: $A, Z \quad ; \quad W^{\pm}$
- First KK modes: $A_1, \tilde{Z}_1, \tilde{Z}_{X_1} \quad \to Z' \quad ; \quad \tilde{W}_{L_1}, \tilde{W}_{R_1} \quad \to W'^{\pm}$

Z' Overlap Integrals

$$\text{Define: } \xi \equiv \sqrt{k\pi R} = 5.83$$

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

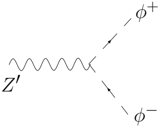
$$\bar{\psi}_{L,R}\gamma^{\mu}\Big[eQ\mathcal{I}A_{1\,\mu} + g_Z\left(T_L^3 - s_W^2 T_Q\right)\mathcal{I}Z_{1\,\mu} + g_{Z'}\left(T_R^3 - s'^2 T_Y\right)\mathcal{I}Z_{X1\,\mu}\Big]\psi_{L,R}$$

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

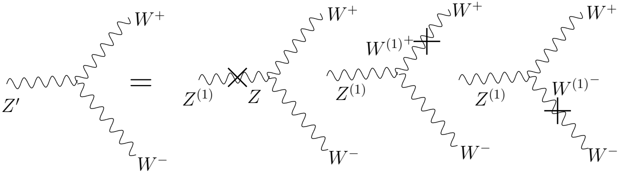
$Z^{(1)}V^{(0)}V^{(0)}$ is zero by orthogonality ...

... but induced after EWSB

Using Goldstone equivalence:



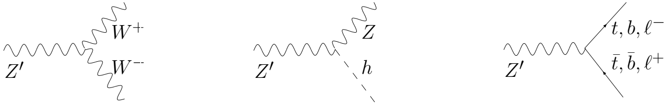
In Unitary Gauge:



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

Z' decays

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



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

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

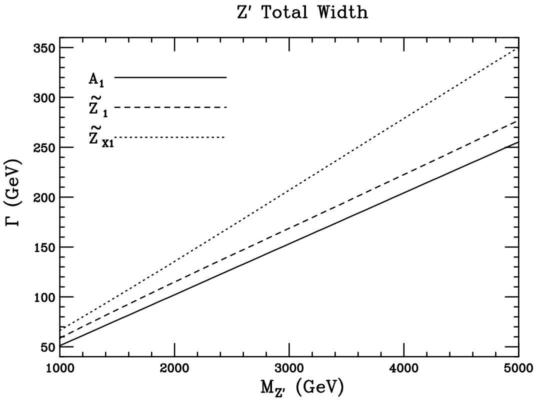
$$\Gamma(\tilde{Z}_1, \tilde{Z}_{X1} \to Z_L h) = \frac{g_Z^2\kappa^2}{192\pi} M_{Z'} \; ; \quad \kappa \propto \sqrt{k\pi r_c} ,$$

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

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	

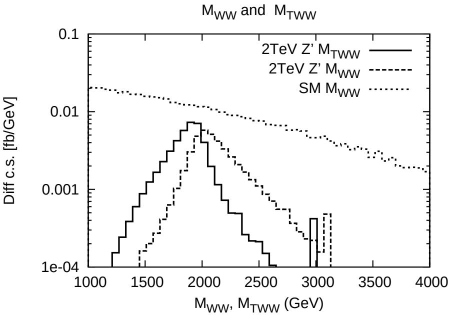
Total Widths



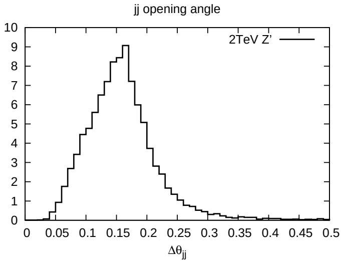
$M_{Z'} = 2\text{TeV}$	A_1	Z_1	Z_{X1}
Γ (GeV)	103.3	114.6	135.6

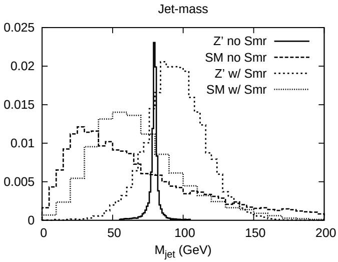
$pp \to Z' \to W^+W^- \to \ell\,\nu\; j\; j$

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



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

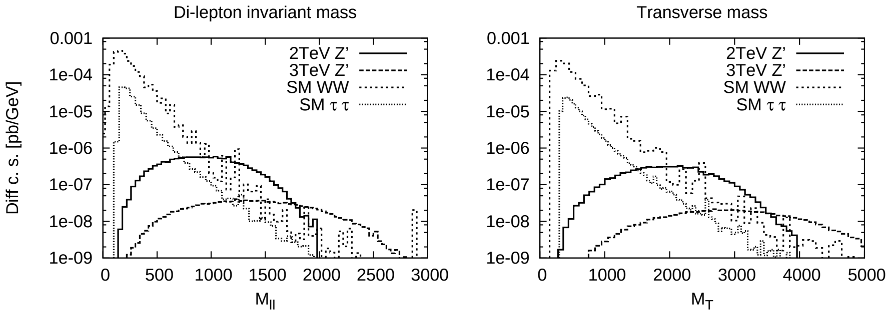
To account for (HCal) expt. uncert.

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

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

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

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	$\|\eta_\ell\| < 2$	$M_{eff} > 1$ 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}

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

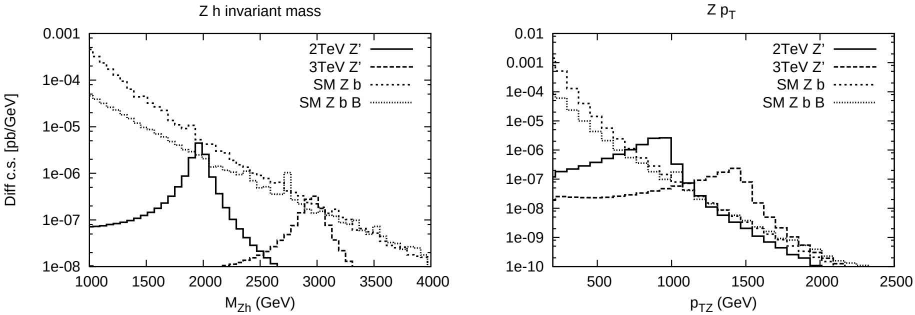
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ 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)

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

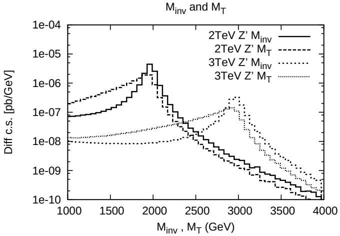
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ 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}

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



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

$M_{Z'} = 2$ TeV $\quad m_h = 150$ GeV	Basic	$p_T\,,\eta$	$\cos\theta$	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}

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

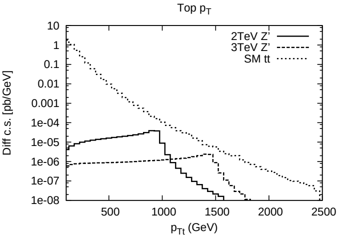
$M_{Z'} = 2$ TeV	Basic	$p_{T\ell}$	$M_{\ell\ell}$	# Evts	S/B	$S/\sqrt{B}$
Signal	0.1	0.09	0.06	60	0.3	4.2
SM $\ell\ell$	3×10^4	5.4	0.2	200		
SM WW	295	0.03	0.002	2		

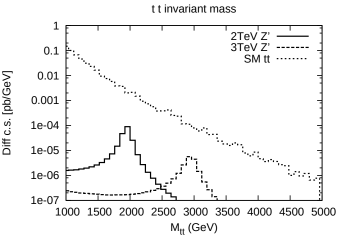
events above is for

- 2 TeV : 1000 fb^{-1}

Experimentally clean, but needs a LOT of luminosity

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

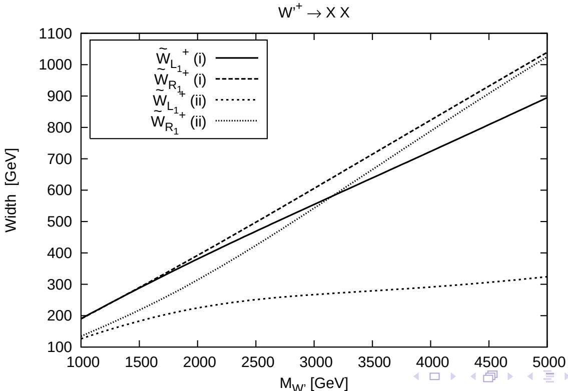




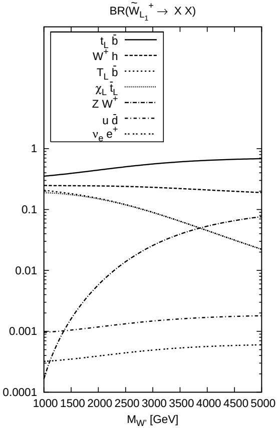
$M_{Z'} = 2$ TeV	Basic	$p_T > 800$	$1900 < M_{tt} < 2100$
Signal	17	7.2	5.6
SM $t\bar{t}$	1.9×10^5	31.1	19.1

$M_{Z'} = 3$ 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
Width [GeV]
M_W' [GeV]
(i)
(i)
(ii)
(ii)
1100
1000
900
800
700
600
500
400
300
200
100
1000
1500
2000
2500
3000
3500
4000
4500
5000

$W'^{\pm}$ BR



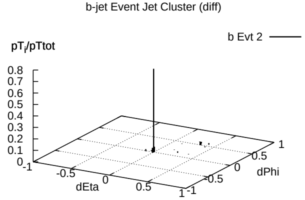
BR($\tilde{W}_{L_1}^+ \to$ X X)
$t_L\ \bar{b}$
W^+ h
$T_L\ \bar{b}$
$\chi_L\ \bar{t}_L$
Z W^+
u $\bar{d}$
$\nu_e\ e^+$
1
0.1
0.01
0.001
0.0001
1000 1500 2000 2500 3000 3500 4000 4500 5000
$M_{W'}$ [GeV]
BR($\tilde{W}_{R_1}^+ \to$ X X)
$T_L\ \bar{b}$
$\chi_L\ \bar{t}_L$
Z W^+
$t_L\ \bar{b}$
W^+ h
u $\bar{d}$
$\nu_e\ e^+$
1
0.1
0.01
0.001
0.0001
1000 1500 2000 2500 3000 3500 4000 4500 5000
$M_{W'}$ [GeV]

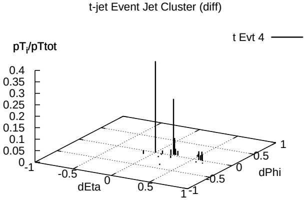
$W'^{\pm} \to t\,b \to \ell \nu b\, b$

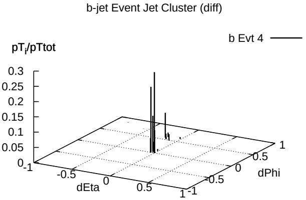
Signal c.s. $\sim 1fb$

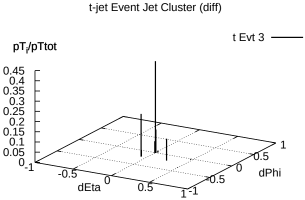
Bkgnd is single top + QCD W b b .... AND ...

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

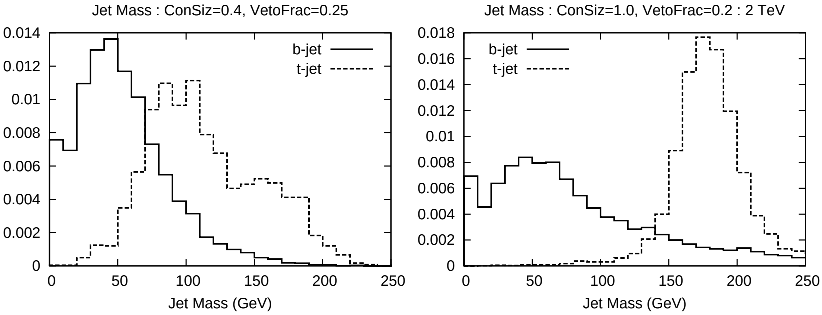








$W'^{\pm} \to t\, b \to \ell \nu b\, b$



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