Phenomenology of Extra Dimensions

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Talk Outline

- Problems in the Standard Model (SM) of particle physics
  - Gauge hierarchy problem
- Extra Dimensional Proposal for solving this
  - Large Extra Dimensions (LED) (aka ADD)
  - Universal Extra Dimensions (UED)
  - Warped Extra Dimensions (WED)
- LHC Signatures

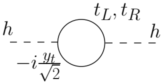
Standard Model (SM) problems

- Gauge hierarchy problem ($M_{EW} \ll M_{Pl}$)
  Electroweak scale : $M_{EW} = 10^3$ GeV Gravity scale : $M_{Pl} = 10^{19}$ GeV
  - Higgs sector unstable (quadratic divergence)
- Fermion mass hierarchy problem ($m_e \ll m_t$)
  - Flavor symmetry?
- What is the dark matter
- Inadequate source of CP violation for observed baryon asymmetry
- Cosmological constant problem

Gauge hierarchy problem in detail

$$\mathcal{L}_{SM} \supset -\frac{1}{2} m_h^2\, h^2 + \left(-\frac{y_t}{\sqrt{2}} h \bar{t}_R t_L + h.c.\right) + \ldots$$

Higgs mass is not protected by any symmetry!



$$\frac{\delta m_h^2}{2} = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$ (Λ is momentum cut-off)

Quadratic divergence! $\Longrightarrow$ unnatural (fine-tuning)

$m_h = 125$ GeV ; $\Lambda \sim M_{pl} = 10^{19}$ GeV

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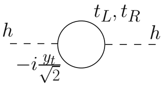

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New physics (BSM) restores naturalness?

Below what scale (Λ) should it appear?

Fine-tuning measure: $f_T \equiv \frac{m_h^2}{\delta m_h^2}$

$f_T > 0.1 \quad \Longrightarrow \quad \Lambda < 2\text{TeV}$ (for $m_h = 120$ GeV)

So expect new physics below 2 TeV scale

SM problems cured by Physics Beyond SM (BSM) ?

Some BSM proposals

- Supersymmetry
- Strong dynamics (Technicolor, Composite Higgs)
- **Extra dimensions**
  - Flat extra dims
  - Warped (AdS space) extra dim

    5-D gravity theory in AdS $\underset{DUAL}{\longleftrightarrow}$ 4-D conformal field theory (CFT)

    AdS/CFT correspondence [Maldacena 97]
- Little Higgs

Supersymmetry (SUSY)

Reviews: [Martin] [Dress]

Transforms Fermions ⇔ Bosons

- Minimal Supersymmetric Standard Model (MSSM)
  - To every SM particle, add **superpartner** (spin differs by 1/2)
    Particle spectrum doubled

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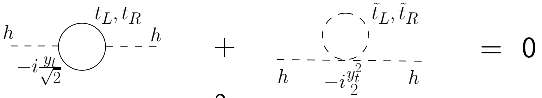
SUSY solves gauge hierarchy problem



Λ^2 divergence cancelled

[Romesh Kaul 1981, 82]

(Similarly $h, W^{\pm}, Z$ divergences cancelled by $\tilde{\lambda}$)

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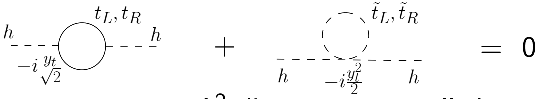

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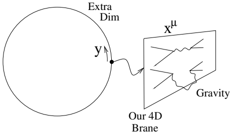
- SUSY $\Longrightarrow$ $M_\psi = M_\phi$; but experiment $\Longrightarrow$ SUSY broken
- Lightest SUSY Particle (LSP) stable dark matter (if R_p conserved)
- Gauge Coupling Unification - SUSY $SO(10)$ GUT

Large Extra Dimensions (LED, ADD)

[Arkani-Hamed, Dimopoulos, Dvali (ADD), 1998]

- n (compact) space extra dims with Radius R (in addition to the usual 3+1 dims)
  - Only fundamental scale $M_* \sim 1$ TeV
    $M_{pl}^2 = M_*^{2+n} V_n \qquad V_n \sim R^n$
  - Gravity in bulk, SM on brane
    $$\mathcal{S} = \int d^4x\ d^n y \left[\mathcal{L}_{\rm Bulk} + \delta(\underline{y})\, \mathcal{L}_{Brane}\right]$$
  - Gravitational potential modified to
    $V(r) \sim 1/r^{n+1}$

Example: 5-D : (x^μ, y)



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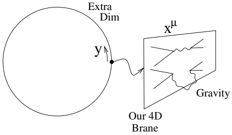


Some implications

- for $n = 1$, $R = 10^{11} m$
  - excluded by solar system tests!
- for $n = 2$, $R \sim 100\,\mu m$
  - Cavendish type experiments limit $M_* > 4\ TeV$

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 parity conserved
  - 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

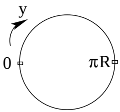
Warped Extra Dimensions (WED, RS)

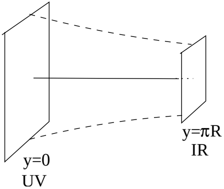
SM in background 5D warped AdS space [Randall, Sundrum 99]

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

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:

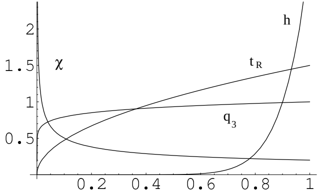
- IR localized Higgs : $M_{EW} \sim k e^{-k\pi R}$: Choose $k\pi R \sim 34$
  - CFT dual is a composite Higgs model

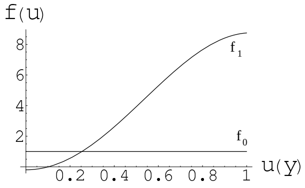
Explaining SM (gauge & mass) hierarchies (WED)

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

For details, see our review: [Davoudiasl, SG, Ponton, Santiago, New J.Phys.12:075011,2010. arXiv:0908.1968 [hep-ph]]

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]

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

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

Kaluza-Klein (KK) expansion

Eg: 5-Dimensional theory : Bulk fields : $\Phi(x,y) = \{A_M,\ \phi,\ \Psi,,\ldots\}$

$$\mathcal{S} = \int d^4x\, dy\, \mathcal{L}^{(5)} \quad ; \quad \mathcal{L}^{(5)}_{\phi} \supset \partial^M \phi^\dagger\, \partial_M \phi - m^2_\phi\, \phi^\dagger \phi$$

$\delta S^{(5)} = 0 \implies$ Euler-Lagrange Equations of Motion (EOM) : $\frac{\delta \mathcal{L}^{(5)}}{\delta \Phi} = \partial_M \frac{\delta \mathcal{L}^{(5)}}{\delta \partial_M \Phi}$

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KK expansion: expand in a complete set of states $f_n(y)$

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

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Plug into EOM, y dependent piece is $\left[-\partial_y^2 + \hat{M}_\Phi^2\right] f_{(n)}(y) = m_n^2 f_n(y)$

The solution is $f_{(n)}(y) = \frac{1}{N_n} e^{i m_n y} \quad ; \quad m_n = \frac{n}{R}$

Plug in the KK expansion into 5D action and integrate over y

$$\mathcal{S} = \int d^4x \left[\sum_{n=-\infty}^{\infty} \left(\partial^\mu \phi^{(n)*} \partial_\mu \phi^{(n)} - m_n^2 \phi^{(n)*} \phi^{(n)}\right)\right]$$

Is the equivalent 4D theory

with an infinite tower of states (the KK states)

Equivalent 4D theory (with interactions)

Similar procedure for interactions also

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

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

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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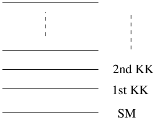
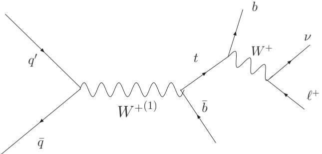
In summary

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

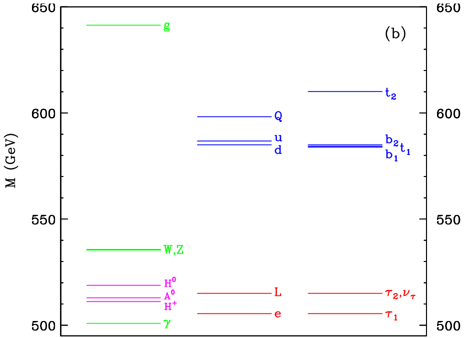


Example:



UED Spectrum

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



[Cheng, Matchev, Schmaltz]

LHC SUSY ↔ UED confusion!

[Cheng, Matchev, Schmaltz: 2002]

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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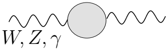
Effective coupling (Eg: Z'):

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

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
    $Wt_L b_L$, $Zt_L t_L$ not protected, so shifts

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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

[Giudice, Rattazzi, Wells 1998][Hewett 1998] [Han, Lykken, Zhang 1998]

Look for KK Gravitons ($h^{(n)}_{\mu\nu}$) : Missing energy (MET)

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

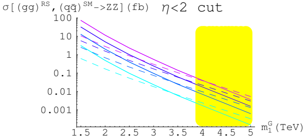
WED KK Graviton

[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]

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

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

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

KK Gluon

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

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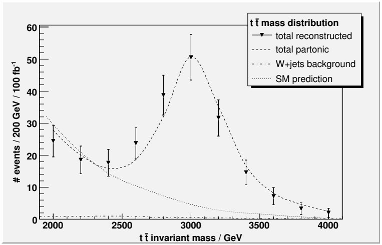
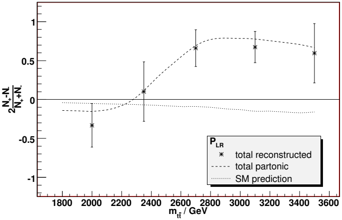




$P_{LR} = 2\frac{N_+ - N_-}{N_+ + N_-}$ N_+ forward going ℓ wrt k_t

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

WED Z' channels summary

[Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni - arXiv:0709.0007 [hep-ph]]
$(\mathcal{L}_{2\ TeV};\ \mathcal{L}_{3\ TeV})$ 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]

$W'^{\pm}$ Channels summary

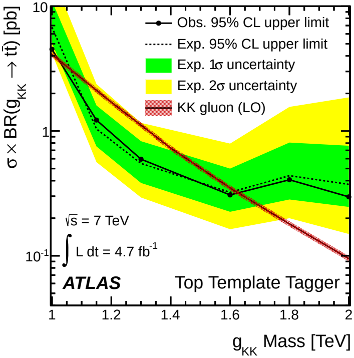
[Agashe, SG, Han, Huang, Soni, 08: arXiv:0810.1497]
$(\mathcal{L}_{2\ TeV};\ \mathcal{L}_{3\ TeV})$ in fb^{-1}

- $W'^{\pm} \to t\, b$:
  - 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 $0 < j_M < 75$ ⇒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

LHC KK-gluon search



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

WED KK Fermions @ LHC

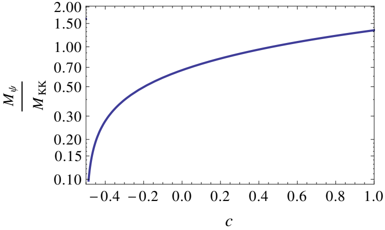
- SM fermions : $(+,+)$ BC $\rightarrow$ zero-mode
- "Exotic" fermions : $(-,+)$ BC $\rightarrow$ No zero-mode
  - 1^{st} KK vectorlike fermion

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

  c : Fermion bulk mass parameter

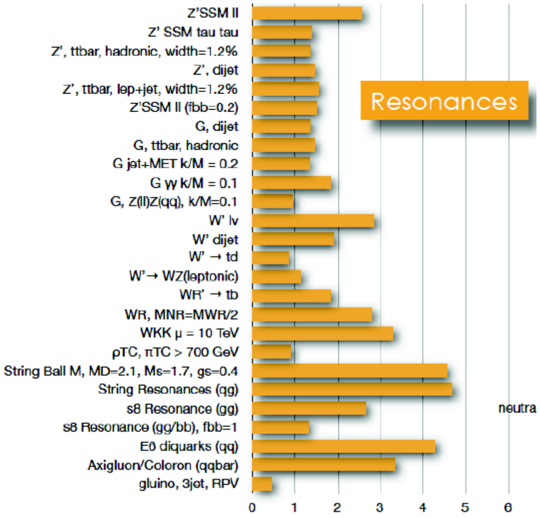
  [Choi, Kim, 2002] [Agashe, Delgado, May, Sundrum, 03] [Agashe, Perez, Soni, 04] [Agashe, Servant 04]

  - Look for it at the LHC

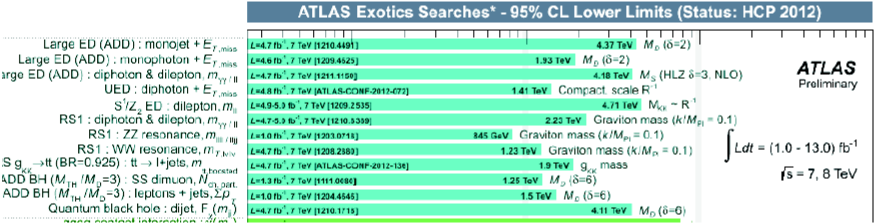


[Dennis et al, '07] [Carena et al, '07] [Contino, Servant, '08] [Atre et al, '09, '11] [Aguilar-Saavedra, '09] [Mrazek, Wulzer, '09] [SG, Moreau, Singh, '10] [SG, Mandal, Mitra, Tibrewala, '11] [SG, Mandal, Mitra, Moreau : '13]

CMS Resonances Limits (Moriond 2013)



ATLAS Extra Dimensions Limits (Moriond 2013)



Conclusions

- LED “solves” the Heirarchy Problem
  - Quantum gravity at the TeV scale
  - LHC limits already strong
- UED provides Dark Matter candidate
  - Does not solve the hierarchy problem
- WED (AdS) warped models dual to 4D strongly coupled theory
  - Model with bulk fields : limits weaker
  - **LHC 14TeV high luminosity run crucial**

BACKUP SLIDES

BACKUP SLIDES

KK decomposition : 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

$\delta S^{(5)} = 0 \implies$ 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

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

Supersymmetry (SUSY)

Reviews: [Martin] [Dress]

SUSY: Fermions ⇔ Bosons :
(Doubles particle spectrum)

$Q\ |\Phi\rangle = |\Psi\rangle \quad ; \quad Q\ |\Psi\rangle = |\Phi\rangle$

SUSY algebra:

$$\left\{Q_\alpha , \bar{Q}_{\dot\beta}\right\} = 2\sigma^\mu_{\ \alpha\dot\beta} P_\mu$$

$$\left\{Q_\alpha , Q_\beta\right\} = \left\{\bar{Q}_{\dot\alpha} , \bar{Q}_{\dot\beta}\right\} = 0$$

$$\left[P^\mu , Q_\alpha\right] = \left[P^\mu , \bar{Q}_{\dot\alpha}\right] = 0$$

Introduce fermionic (Grassmann) coordinate $\theta\ :\ \{\theta,\theta\} = \{\theta,\bar\theta\} = \{\bar\theta,\bar\theta\} = 0$

Superfield : $\Phi\ (x_\mu , \theta, \bar\theta)$

Chiral Superfield: $\bar{D}\Phi_L = 0 \ ; \ D\Phi_R = 0$

$\Phi_L = \phi(x) + \sqrt{2}\theta\psi(x) + \theta\theta F(x)$

Vector Superfield: $V = V^\dagger$

$$V(x,\theta,\bar\theta) = -\theta\sigma_\mu\bar\theta A^\mu(x) + i\theta\theta\bar\theta\bar\lambda(x) - \bar\theta\bar\theta\theta\lambda(x) + \tfrac{1}{2}\theta\theta\bar\theta\bar\theta D(x)$$

Minimal Supersymmetric Standard Model (MSSM)

MSSM Superpotential : $\mathcal{W} = y_u U^c Q H_u - y_d D^c Q H_d - y_e E^c L H_d + \mu H_u H_d$

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Chiral Superfield: $\bar{D}\Phi_L = 0 \ ; \ D\Phi_R = 0$

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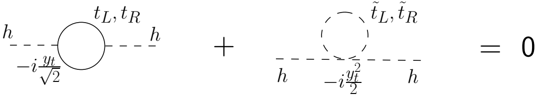
Minimal Supersymmetric Standard Model (MSSM)

MSSM Superpotential : $\mathcal{W} = y_u U^c Q H_u - y_d D^c Q H_d - y_e E^c L H_d + \mu H_u H_d$

SUSY $\Longrightarrow M_\psi = M_\phi$ Experiment $\Longrightarrow$ SUSY broken

SUSY solves gauge hierarchy problem

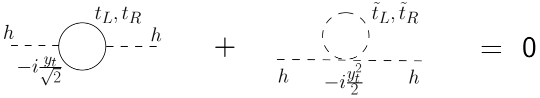


Λ^2 divergence cancelled

[Romesh Kaul 1981, 82]

Similarly $h, W^{\pm}, Z$ divergences cancelled by $\tilde{\lambda}$

SUSY solves gauge hierarchy problem



Λ^2 divergence cancelled

[Romesh Kaul 1981, 82]

Similarly $h, W^{\pm}, Z$ divergences cancelled by $\tilde{\lambda}$

Gauge Coupling Unification - GUT SUSY $SO(10)$

Includes $\nu_R \Rightarrow$ Neutrino seesaw mass

SUSY breaking

SUSY has to be broken

- Spectrum depends on SUSY Breaking/Mediation + RGE
- Minimal Supersymmetric SM (MSSM) general parametrization

$$\mathcal{L}^{soft}_{SUSY\ Br} \supset -\frac{1}{2} M_{\tilde{\lambda}} \tilde{\lambda}\tilde{\lambda} - \tilde{u}^c a_u \tilde{Q} H_u - \tilde{Q}^\dagger \tilde{m}^2_Q \tilde{Q} - m^2_H H^* H - b\mu H_u H_d + \cdots$$

MSSM predicts a LIGHT Higgs. At tree level: $m_h < m_Z$.

- But LEP bound $m_h \gtrsim 114\,\text{GeV}$
- Sizable one loop correction: $\delta m_h^2 \lesssim \frac{3}{4\pi^2}\, y_t^2\, m_t^2\, log\, \frac{\tilde{m}_1 \tilde{m}_2}{m_t^2}$
  - LEP Higgs bound needs heavy stop ⇒ "Little hierarchy problem"

R-parity

SM gauge symmetry allows

$$W_{\Delta L} = LH_u + LE^cL + QD^cL \ ; \qquad W_{\Delta B} = U^cD^cD^c$$

These induce proton decay : $\tau_p \sim 10^{-10} s$ for $\tilde{m} \sim 1$ TeV

Impose Matter Parity $R_M = (-1)^{3(B-L)}$ to forbid ΔL *and* ΔB terms

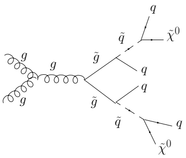
For components this implies : R-parity $R_p = (-1)^{3(B-L)+2s}$

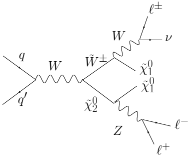
Consequence : The Lightest SUSY Particle (LSP) is stable

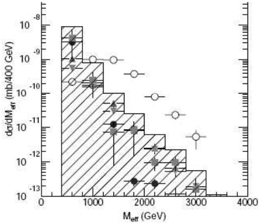
- Cosmologically stable Dark Matter
- Missing Energy at Colliders

SUSY at LHC

- Cascade decays
- Missing energy signals



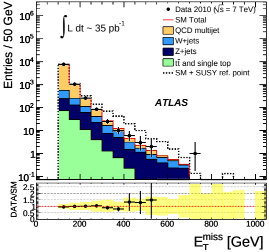


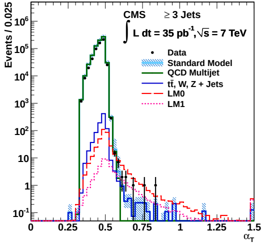


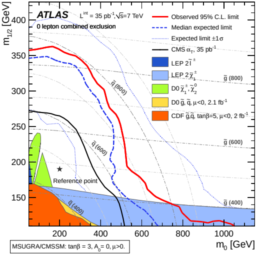
[ATLAS Physics TDR]

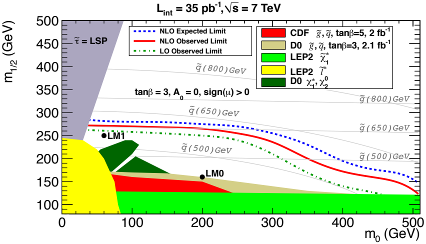
- Can we determine the spin and couplings to show SUSY?
    - Angular distributions

LHC Data ! (SUSY jets + MET)









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 $\quad \mathcal{L}_{\rm Yuk} \supset \lambda_t \, {\rm Tr}\left[\bar{Q}_L \Sigma\right] t_R + h.c.$
  - 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 ψ'_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 $Z_X|_{y=0} = 0\,;\; \partial_y Z_X\,|_{y=\pi R} = 0$

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

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

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

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

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

Gauge EW KK States

Gauge Boson

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

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: $A_1, \tilde{Z}_1, \tilde{Z}_{X_1} \;\to Z'$; $\tilde{W}_{L_1}, \tilde{W}_{R_1} \;\to W'^{\pm}$

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

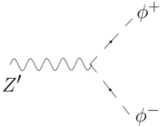
- Z' couplings to h enhanced (also V_L - Equivalence Theorem!)
- Z' couplings to t_R enhanced
- Z'couplings to χ suppressed

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

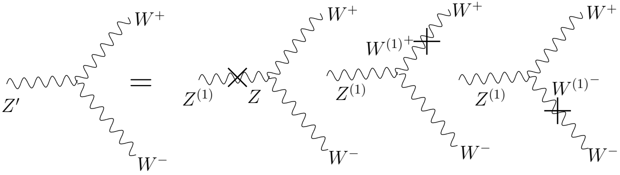
EWSB induced $Z'W^+W^-$ coupling

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

Using Goldstone equivalence:



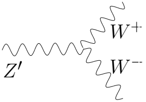
In Unitary Gauge:

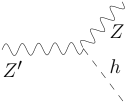


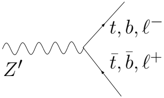
Even though $\xi \cdot (\frac{v}{M_{KK}})^2$ suppressed ...

Z' decays

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







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

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

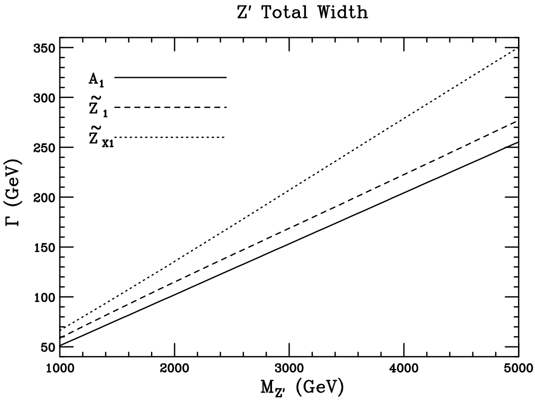
$$\Gamma(\tilde{Z}_1, \tilde{Z}_{X1} \to Z_L h) = \frac{g_Z^2\kappa^2}{192\pi} M_{Z'} \; ; \quad \kappa \propto \sqrt{k\pi r_c} ,$$

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

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	

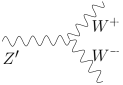
Total Widths

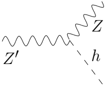


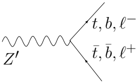
$M_{Z'} = 2\text{TeV}$	A_1	Z_1	Z_{X1}
Γ (GeV)	103.3	114.6	135.6

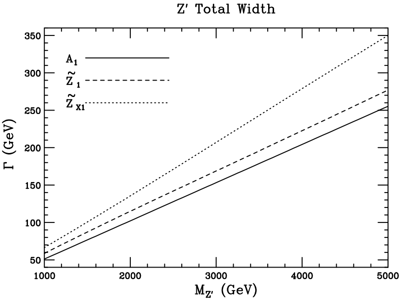
Z' decays in WED

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



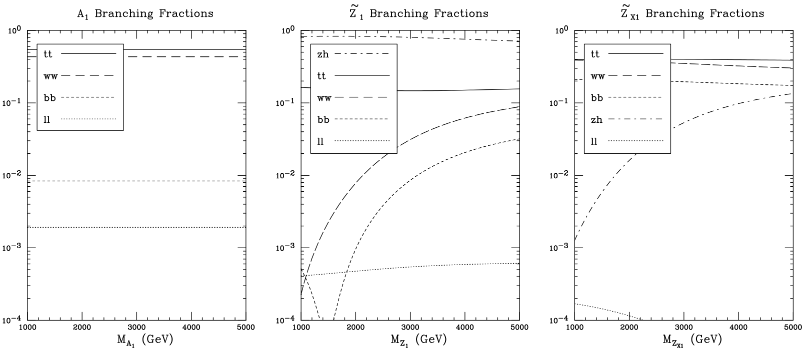




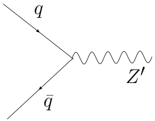


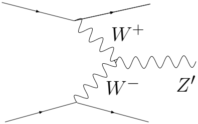
$M_{Z'}$ = 2TeV	A_1	Z_1	Z_{X1}
Γ (GeV)	103.3	114.6	135.6

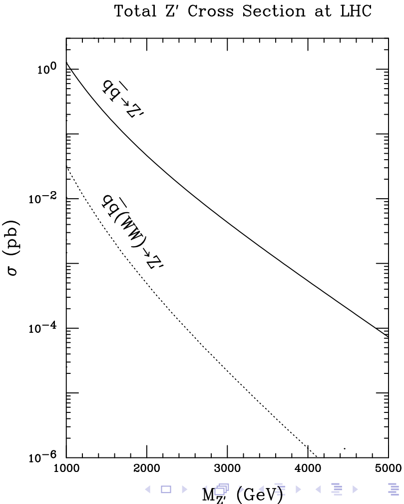
Z' Branching Ratios in WED



WED Z' production at the LHC

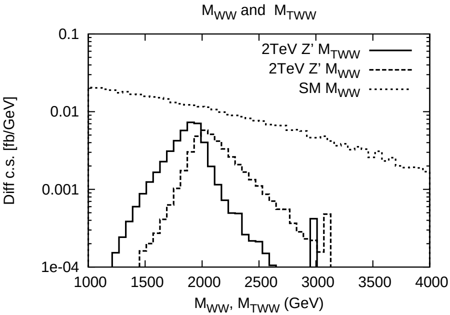




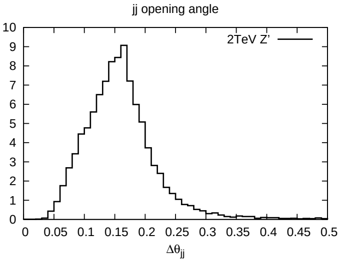


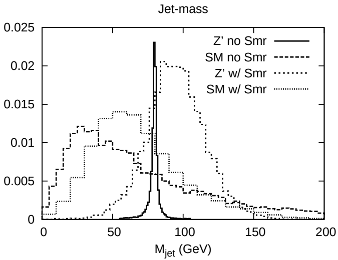
$pp \to Z' \to W^+W^- \to \ell\,\nu\,j\,j$

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



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

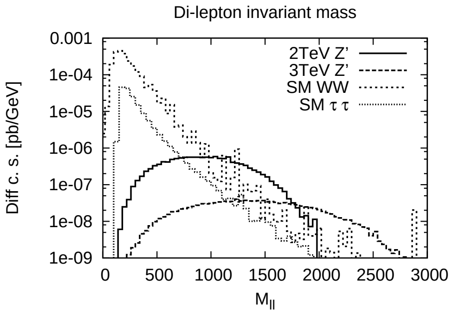
To account for (HCal) expt. uncert.

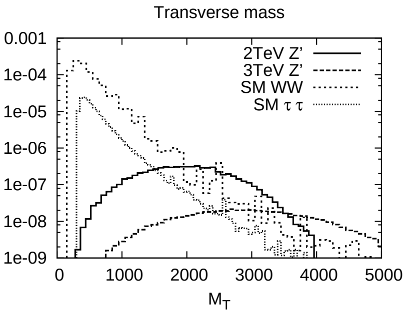
Smearing by $\delta E = 80\%/\sqrt{E}$; $\delta\eta, \delta\phi = 0.05$

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

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

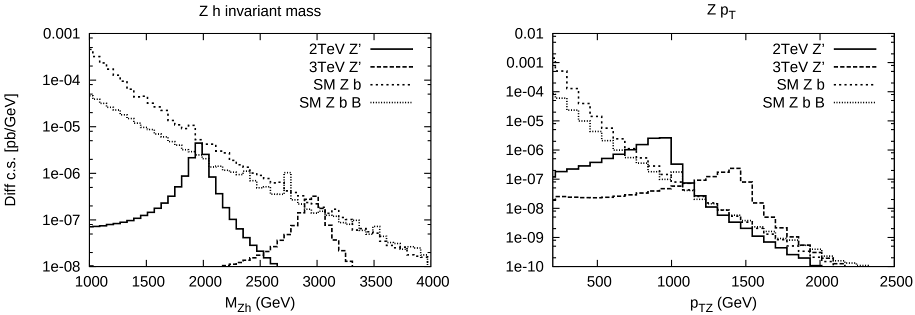
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ 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)

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

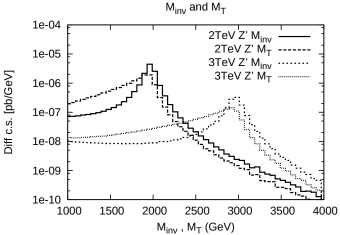
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ 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}

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



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

$M_{Z'} = 2$ TeV $m_h = 150$ 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 $m_h = 150$ 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}

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

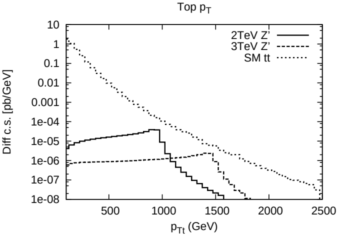
$M_{Z'} = 2$ TeV	Basic	$p_{T\ell}$	$M_{\ell\ell}$	# Evts	S/B	$S/\sqrt{B}$
Signal	0.1	0.09	0.06	60	0.3	4.2
SM $\ell\ell$	3×10^4	5.4	0.2	200		
SM WW	295	0.03	0.002	2		

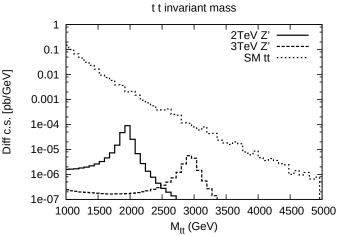
events above is for

- 2 TeV : 1000 fb^{-1}

Experimentally clean, but needs a LOT of luminosity

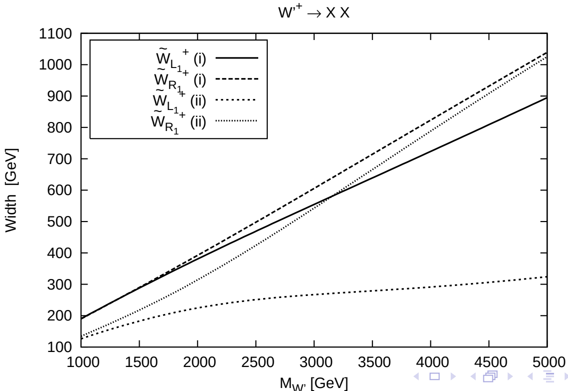
$pp \to Z' \to t\bar{t}$



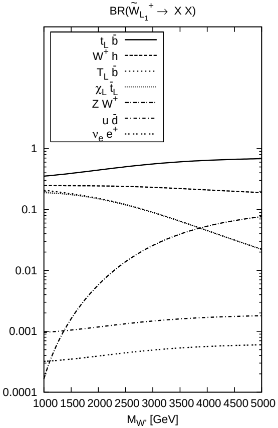


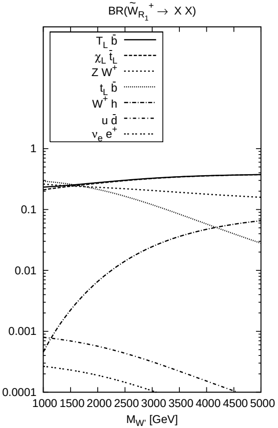
$M_{Z'} = 2$ TeV	Basic	$p_T > 800$	$1900 < M_{tt} < 2100$
Signal	17	7.2	5.6
SM $t\bar{t}$	1.9×10^5	31.1	19.1
$M_{Z'} = 3$ TeV	Basic	$p_T > 1250$	$2850 < M_{tt} < 310$
Signal	1.7	0.56	0.45
SM $t\bar{t}$	1.9×10^5	4.1	1.1

$W'^{\pm}$ width


W'+ → X X
Width [GeV]
M_W' [GeV]
W̃_L1+ (i)
W̃_R1+ (i)
W̃_L1+ (ii)
W̃_R1+ (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]

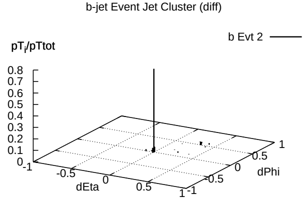

BR($\tilde{W}_{R_1}^{+} \to$ X X)
$T_L\ \bar{b}$
$\chi_L\ \bar{t}_L$
Z W^+
$t_L\ \bar{b}$
W^+ h
u $\bar{d}$
$\nu_e\ e^+$
1
0.1
0.01
0.001
0.0001
1000 1500 2000 2500 3000 3500 4000 4500 5000
$M_{W'}$ [GeV]

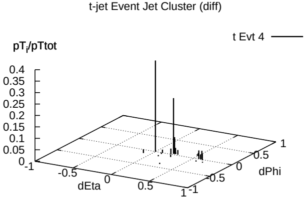
$W'^{\pm} \rightarrow t\, b \rightarrow \ell \nu\, b\, b$

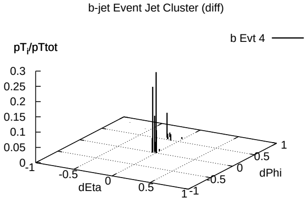
Signal c.s. $\sim 1fb$

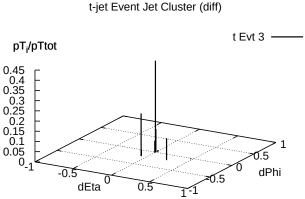
Bkgnd is single top + QCD W b b .... AND ...

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

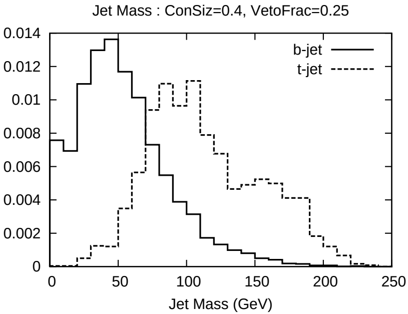


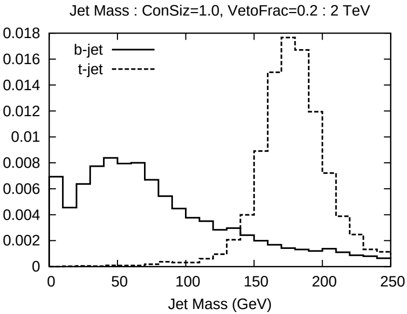






$W'^{\pm} \to t\, b \to \ell \nu b\, b$





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)
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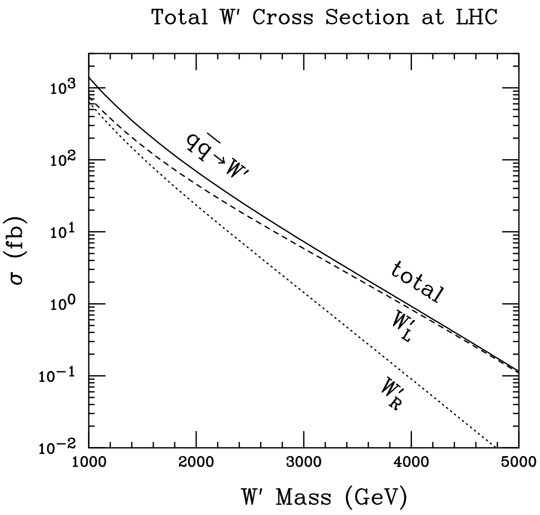
$W'^{\pm} \to W\,h$:

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

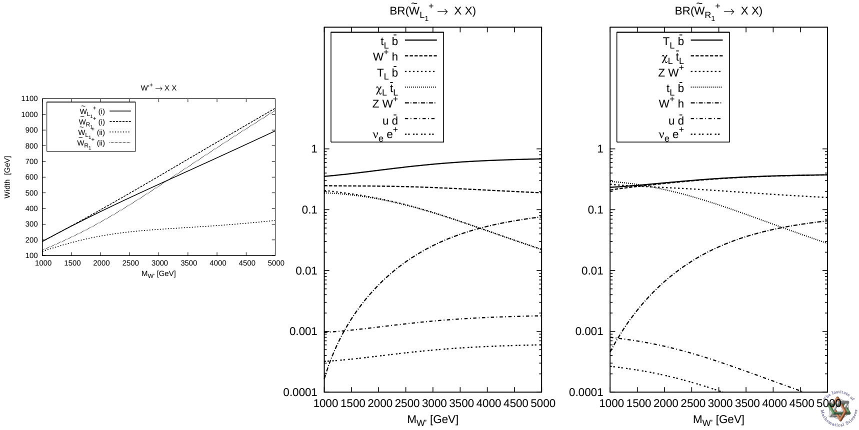
$\mathcal{L}$ needed: 100 fb^{-1}(2TeV) ; 300 fb^{-1} (3TeV)

W' cross section

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



$W'^{\pm}$ Width and BR



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]

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

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

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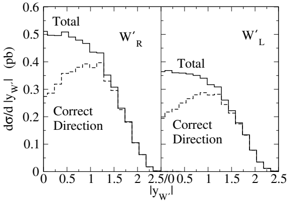
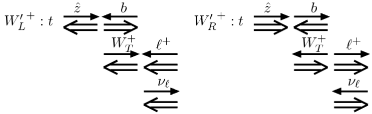
Need to fix u direction:

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



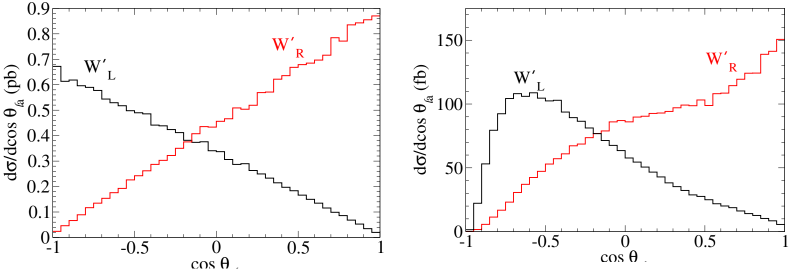
$\therefore$ direction of $y_{W'} > 0.8$ is u direction

θ_ℓ distribution analyzes top polarization



Analyze in top rest frame

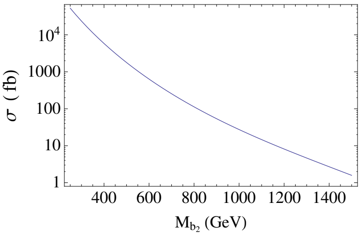
Measuring W' Chirality (Results)

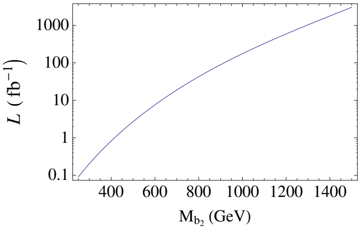


b' Pair Production

[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:
$M_Z - 10\ \mathrm{GeV} < M_{jj} < M_Z + 10\ \mathrm{GeV}$,
$0.95 M_{b_2} < M_{(bZ)} < 1.05 M_{b_2}$.

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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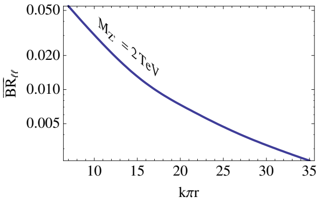
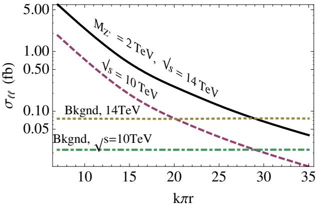
$pp \to {Z'}_{LRS} \to \ell^+\ell^-$ [Davoudiasl, SG, Soni 09; arXiv:0908.1131]





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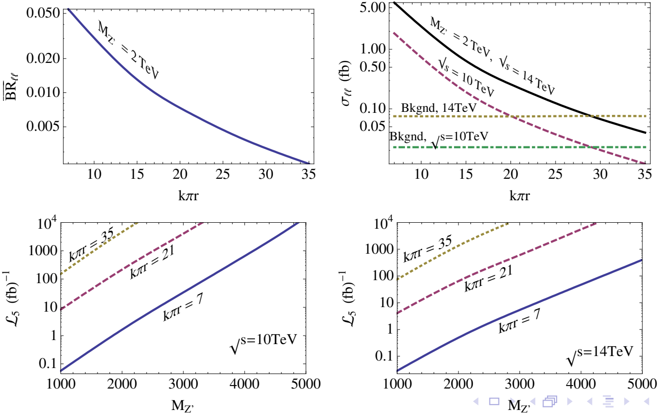


LED Bulk ν_R

[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
- $\mathcal{L}_{\rm Bulk} \supset \bar{\Psi}^\alpha \, i\Gamma^M D_M \Psi^\alpha$

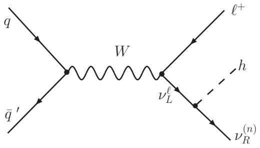
  $\mathcal{L}_{\rm Brane} \supset \mathcal{L}_{\rm SM} - \left(\frac{\Lambda^\nu_{\alpha\beta}}{\sqrt{M_*^\delta}} \, h \, \psi_R^\beta \, \nu_L^\alpha + h.c. \right)$
  - $\nu_L \to$ Usual SM left-handed neutrino
  - $\psi_R \to$ Bulk right-handed neutrino $\equiv \nu_R$
  - $\psi_L \to$ No direct coupling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

LED Bulk ν_R at colliders

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

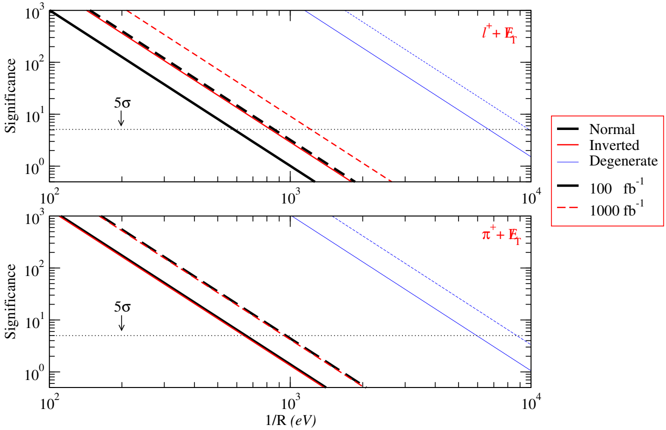
$$q\bar{q}' \to W^* \to \ell^+ h\,\nu_R^{(n)} \qquad (\ell = e, \mu, \tau)$$

  - 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

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



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