Physics Beyond the Standard Model?

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Motivation for BSM Physics

Observational

- What is the observed Dark Matter?
- What generates the neutrino masses?
- What generates the Baryon Asymmetry of the Universe (BAU)?

Theoretical

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

Outline (Supersymmetry)

- Supersymmetry (SUSY) Basics
  - SUSY invariant theory
  - SUSY breaking
- Minimal Supersymmetric Standard Model (MSSM)
  - SUSY preserving Lagrangian and soft-breaking terms
    - R-parity
  - Superpartner Mixing
- Implications
  - Dark Matter
  - 125 GeV Higgs

Outline (Extra Dimensions)

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

Outline (Dark Matter)

- BSM DM Candidates
- DM Detection
  - Direct detection
  - Indirect detection
  - At colliders

SUPERSYMMETRY

Reviews: [Wess & Bagger] [Martin] [Drees]
[Drees, Godbole, Roy] [Baer, Tata]

Supersymmetry (SUSY)

Reviews: [Wess & Bagger]

Symmetry: Fermions $\Leftrightarrow$ Bosons

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

Q_α is a spinorial charge

SUSY algebra:

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

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

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

SUSY invariant theory

Under a SUSY transformation

$$\begin{aligned}\delta_\xi \phi &= \sqrt{2}\xi\psi \\ \delta_\xi \psi &= i\sqrt{2}\sigma^m\bar{\xi}\partial_m\phi + \sqrt{2}\xi F \\ \delta_\xi F &= i\sqrt{2}\bar{\xi}\bar{\sigma}^m\partial_m\psi\end{aligned}$$

$$\begin{aligned}\delta_\xi A_{mn} &= i\left[\left(\xi\sigma^n\partial_m\bar{\lambda} + \bar{\xi}\bar{\sigma}^n\partial_m\lambda\right) - (n \leftrightarrow m)\right] \\ \delta_\xi \lambda &= i\xi D + \sigma^{mn}\xi A_{mn} \\ \delta_\xi D &= \bar{\xi}\bar{\sigma}^m\partial_m\lambda - \xi\sigma^m\partial_m\bar{\lambda}\end{aligned}$$

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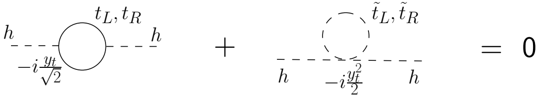
A SUSY invariant action: $S = \int d^4x\, \mathcal{L}$

$$\begin{aligned}\mathcal{L} =& |D_\mu\phi_i|^2 - i\bar{\psi}_i\sigma_\mu D^\mu\psi_i - g\sqrt{2}\left(\phi_i^* T^a\psi_i\lambda^a + \lambda^{a^\dagger}\psi^\dagger T^a\phi_i\right) \\ &- \left(\frac{1}{2}\frac{\partial^2\mathcal{W}(\phi_i)}{\partial\phi_j\partial\phi_k}\psi_j\psi_k + h.c.\right) - \left|\frac{\partial\mathcal{W}(\phi_i)}{\partial\phi_j}\right|^2 \\ &- \frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} - \frac{1}{2}\sum_a\left|g\phi_i^* T^a_{ij}\phi_j\right|^2 - i\lambda^{a^\dagger}\bar{\sigma}_\mu D^\mu\lambda_a\end{aligned}$$

$\mathcal{W}(\phi_i)$: Superpotential, a holomorphic function of the fields

Consequences

Solution to gauge hierarchy problem



Λ^2 divergence cancelled [Romesh Kaul, '81, '82] [Witten]

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

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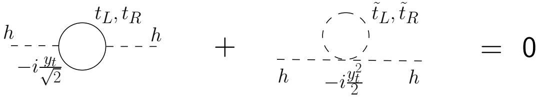

Λ^2 divergence cancelled [Romesh Kaul, '81, '82] [Witten]

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

- Lightest SUSY Particle (LSP) stable dark matter (if R_p conserved)
- Gauge Coupling Unification - SUSY $SO(10)$ GUT
  Includes $\nu_R \Rightarrow$ Neutrino mass via seesaw

SUSY breaking

- Exact SUSY $\Longrightarrow$ $M_\psi = M_\phi$; $M_A = M_{\tilde{\lambda}}$
  - So experiment $\Longrightarrow$ SUSY must be broken
- SUSY broken if and only if $\langle 0|H|0\rangle > 0$
  - Spontaneous SUSY breaking
    - O'Raifeartaigh F-term breaking
    - Fayet-Iliopoulos D-term breaking
  - $STr(M^2) = 0$ $\Longrightarrow$ cannot break SUSY spontaneously using SM superfield
    - Hidden sector breaking $\underset{Mediation}{\longleftrightarrow}$ Communicated to SM

      Spectrum depends on Mediation type + RGE
- In effective low-energy theory
  - Explicit soft-breaking terms, i.e., with dimensionful parameters

MSSM

The Minimal Supersymmetric Standard Model (MSSM)

Reviews: [Martin] [Drees] [Drees,Godbole,Roy] [Baer,Tata]

MSSM fields

To every SM particle, add a ***superpartner*** *(spin differs by* 1/2*)*

Matter fields (Chiral Superfields)

	$(SU(3), SU(2))_{U(1)}$	Components
Q	$(3, 2)_{1/6}$	$(\tilde{q}_L, q_L, F_Q)$; $\tilde{q}_L = \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$; $q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$
U^c	$(\bar{3}, 1)_{-2/3}$	$(\tilde{u}_R^*, u_R^c, F_U)$
D^c	$(\bar{3}, 1)_{1/3}$	$(\tilde{d}_R^*, d_R^c, F_D)$
L	$(1, 2)_{-1/2}$	$(\tilde{\ell}_L, \ell_L, F_L)$; $\tilde{\ell}_L = \begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$; $\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$
E^c	$(1, 1)_1$	$(\tilde{e}_R^*, e_R^c, F_E)$
(N^c)	$(1, 1)_0$	$(\tilde{\nu}_R^*, \nu_R^c, F_N)$

Gauge fields
(Vector Superfields)

	Components
$SU(3)$	$(g_\mu, \tilde{g}, D_3)$
$SU(2)$	$(W_\mu, \tilde{W}, D_2)$
$U(1)$	$(B_\mu, \tilde{B}, D_1)$

Higgs fields (Chiral Superfields)

	$(SU(3), SU(2))_{U(1)}$	Components
H_u	$(1, 2)_{1/2}$	$(h_u, \tilde{h}_u, F_{H_u})$; $h_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix}$; $\tilde{h}_u = \begin{pmatrix} \tilde{h}_u^+ \\ \tilde{h}_u^0 \end{pmatrix}$
H_d	$(1, 2)_{-1/2}$	$(h_d, \tilde{h}_d, F_{H_d})$; $h_d = \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix}$; $\tilde{h}_d = \begin{pmatrix} \tilde{h}_d^0 \\ \tilde{h}_d^- \end{pmatrix}$

MSSM Superpotential

Write most general $\mathcal{W}$ consistent with $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

- $\mathcal{W} = U^c y_u QH_u - D^c y_d QH_d - E^c y_e LH_d + \mu H_u H_d + (N^c y_n LH_u)$
- $\mathcal{W}_{\Delta L} = LH_u + LE^c L + QD^c L$; $\quad \mathcal{W}_{\Delta B} = U^c D^c D^c$
  - $\mathcal{W}_{\Delta L} + \mathcal{W}_{\Delta B}$ induce proton decay : $\quad \tau_p \sim 10^{-10} s$ for $\tilde{m} \sim 1$ TeV

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- $\mathcal{W}_{\Delta L} = L H_u + L E^c L + Q D^c L \; ; \qquad \mathcal{W}_{\Delta B} = U^c D^c D^c$
  - $\mathcal{W}_{\Delta L} + \mathcal{W}_{\Delta B}$ induce proton decay : $\quad \tau_p \sim 10^{-10} s$ for $\tilde{m} \sim 1$ TeV

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

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

$R_p(particle) = +1 \quad , \qquad R_p(sparticle) = -1$

Consequence : The Lightest SUSY Particle (LSP) is stable

- Cosmologically stable Dark Matter
- Missing Energy at Colliders

Soft SUSY breaking

Effective parametrization with explicit soft-SUSY-breaking terms

$$\mathcal{L}^{soft}_{SUSY\ Br} \supset -\tilde{Q}^\dagger \tilde{m}^2_Q \tilde{Q} - \tilde{u}^\dagger_R \tilde{m}^2_u \tilde{u}_R - \tilde{d}^\dagger_R \tilde{m}^2_d \tilde{d}_R - \tilde{L}^\dagger \tilde{m}^2_L \tilde{L} - \tilde{e}^\dagger_R \tilde{m}^2_e \tilde{e}_R - (\tilde{\nu}^\dagger_R \tilde{m}^2_\nu \tilde{\nu}_R)$$

$$- \frac{1}{2} M_1 \tilde{B}\tilde{B} - \frac{1}{2} M_2 \tilde{W}\tilde{W} - \frac{1}{2} M_3 \tilde{g}\tilde{g} + h.c.$$

$$- \tilde{u^c} A_u \tilde{Q} H_u + \tilde{d^c} A_d \tilde{Q} H_d + \tilde{e^c} A_e \tilde{L} H_d - (\tilde{\nu^c} A_\nu \tilde{L} H_u) + h.c.$$

$$- m^2_{H_u} H^\dagger_u H_u - m^2_{H_d} H^\dagger_d H_d - (B\mu H_u H_d + h.c.)$$

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$$- \frac{1}{2} M_1 \tilde{B}\tilde{B} - \frac{1}{2} M_2 \tilde{W}\tilde{W} - \frac{1}{2} M_3 \tilde{g}\tilde{g} + h.c.$$
$$- \tilde{u^c} A_u \tilde{Q} H_u + \tilde{d^c} A_d \tilde{Q} H_d + \tilde{e^c} A_e \tilde{L} H_d - (\tilde{\nu^c} A_\nu \tilde{L} H_u) + h.c.$$
$$- m_{H_u}^2 H_u^\dagger H_u - m_{H_d}^2 H_d^\dagger H_d - (B\mu H_u H_d + h.c.)$$

UV SUSY breaking and mediation dynamics will set these parameters

- Eg: Gravity Mediation (MSUGRA, CMSSM)
  - Inputs $\tilde{m}_0$,$M_{1/2}$, A_0, $\tan\beta$, sign(μ) at GUT scale
  - TeV scale values determined by RGE

Electroweak symmetry breaking (EWSB)

$$\langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix} \; ; \quad \langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}; \quad v^2 = v_u^2 + v_d^2; \qquad \tan\beta \equiv \frac{v_u}{v_d};$$

Physical Higgses: h^0, H^0, A^0, $H^\pm$

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Physical Higgses: h^0, H^0, A^0, $H^\pm$

$$\mathcal{V} = (|\mu|^2 + m_{H_u}^2)|h_u|^2 + (|\mu|^2 + m_{H_d}^2)|h_d|^2 - (b_\mu h_u h_d + h.c.) + \frac{1}{8}(g^2 + g'^2)(|h_u|^2 - |h_d|^2)^2$$

Minimization and EWSB

$$\sin(2\beta) = \frac{2b_\mu}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2} \qquad \text{and} \qquad m_Z^2 = \frac{|m_{H_d}^2 - m_{H_d}^2|}{\sqrt{1 - \sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

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- So we need μ^2 (SUSY preserving param) $\sim m^2$ (SUSY br param)! Why?
  - This is called the μ-problem

125 GeV Higgs

At 1-loop [Haber, Hempfling, Hoang ,1997]

$$m_h^2 \approx m_Z^2 \cos^2(2\beta) + \frac{3g_2^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right]$$

where $X_t = A_t - \mu \cot\beta$

- $m_h = 125$ GeV needs sizable loop contribution
  - Hard! Needs large $m_{\tilde{t}_1} m_{\tilde{t}_2}$ or large X_t^2
  - But $\delta m_{H_u}^2 \approx \frac{3g_2^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{X_t^2}{2m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{6 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right]$

    So fine-tuning necessary to keep m_Z^2 correct (*cf* previous EWSB relation)

    "Little hierarchy problem"

Neutralino mixing

Neutralino: Neutral EW gauginos $(\tilde{B}, \tilde{W}^3, \tilde{H}_u^0, \tilde{H}_d^0)$: Majorana states

$$\mathcal{L} \supset -\frac{1}{2} \left(\tilde{B}\ \tilde{W}^3\ \tilde{H}_u^0\ \tilde{H}_d^0 \right) \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_u^0 \\ \tilde{H}_d^0 \end{pmatrix}$$

Diagonalizing this $\begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_u^0 \\ \tilde{H}_d^0 \end{pmatrix} \to \begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix}$: the mass eigenstates

Chargino mixing

Chargino: Charged EW gauginos $(\tilde{W}^{\pm}, \tilde{H}^{\pm})$, $\quad \tilde{W}^{\pm} = \tilde{W}_1 \pm i\tilde{W}_2$

Form Dirac states $\tilde{W}^+ = \begin{pmatrix} \tilde{W}^+_\alpha \\ \tilde{W}^{-\dot{\alpha}} \end{pmatrix}; \quad \tilde{H}^+ = \begin{pmatrix} \tilde{H}^+_{u\,\alpha} \\ \tilde{H}_d^{-\dot{\alpha}} \end{pmatrix}$

$$\mathcal{L} \supset - \begin{pmatrix} \overline{\tilde{W}^+} & \overline{\tilde{H}^+} \end{pmatrix} \left(M_\chi P_L + M_\chi^\dagger P_R \right) \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}^+ \end{pmatrix} + h.c.$$

where $M_\chi = \begin{pmatrix} M_2 & \sqrt{2}\sin\beta\, m_W \\ \sqrt{2}\cos\beta\, m_W & \mu \end{pmatrix}$

Diagonalizing this $\begin{pmatrix} \tilde{W}^+ \\ \tilde{H}^+ \end{pmatrix} \to \begin{pmatrix} \tilde{\chi}_1^+ \\ \tilde{\chi}_2^+ \end{pmatrix}$: the mass eigenstates

Scalar mixing

Eg. stop sector $(\tilde{t}_L, \tilde{t}_R)$

$$\mathcal{L} \supset -\left(\tilde{t}_L^* \ \tilde{t}_R^*\right) \begin{pmatrix} \tilde{m}_{LL}^2 + m_t^2 + \Delta_L & (v_u A_t - \mu^* \cot\beta \, m_t)^* \\ (v_u A_t - \mu^* \cot\beta \, m_t) & \tilde{m}_{RR}^2 + m_t^2 + \Delta_R \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

where $\Delta = (T_3 - Q s_W^2) \cos(2\beta) \, m_Z^2$

Diagonalizing this $\begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \to \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix}$: the mass eigenstates

Flavor Probes

FCNC (Mixing, Rare decays) and Precision probes

- Kaon observable, B-factories (BaBar, Belle)
- $(g-2)_\mu$, EDM, ...

Flavor Problem

- In general $\tilde{m}_{ij}$ can have arbitrary flavor structure and phases (MSSM has 9 new phases + 1 CKM phase)
  - FCNC & EDM experiments severely constrain these
    - some deeper reason (in SUSY br mediation)?
  - Minimal Flavor Violation (MFV)
    - Only CKM phase
  - *Need experimental guidance*

EXTRA DIMENSION(S)

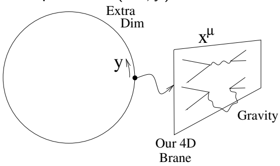
Large Extra Dimensions (LED, ADD)

[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
  $$\mathcal{S} = \int d^4x \, d^ny \left[\mathcal{L}_{\text{Bulk}} + \delta(\underline{y})\,\mathcal{L}_{Brane}\right]$$
- Gravitational potential modified to
  $$V(r) \sim 1/r^{n+1}$$

Example: 5-D : (x^μ, y)



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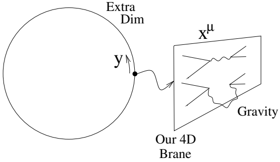


Some implications

- 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]

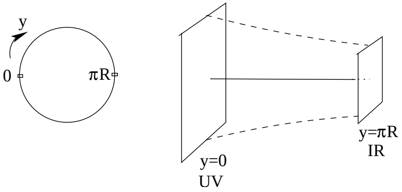
$$ds^2 = e^{-2k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2$$

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:

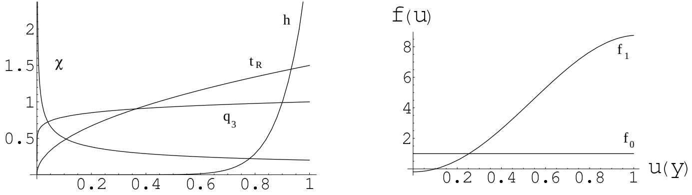
- IR localized Higgs : $M_{EW} \sim ke^{-k\pi R}$: Choose $k\pi R \sim 34$
  - CFT dual is a composite Higgs model

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]

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

$\mathcal{S} \supset \int d^4x\, \mathcal{O}_{CFT}(x)\, \phi_0(x)$	$\Gamma_{AdS}[\phi]$ 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

Kaluza-Klein (KK) expansion

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

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

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

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

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

Kaluza-Klein (KK) expansion

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

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

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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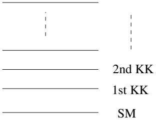
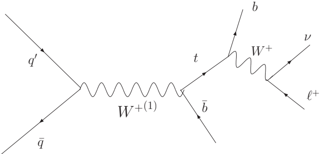
In summary

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

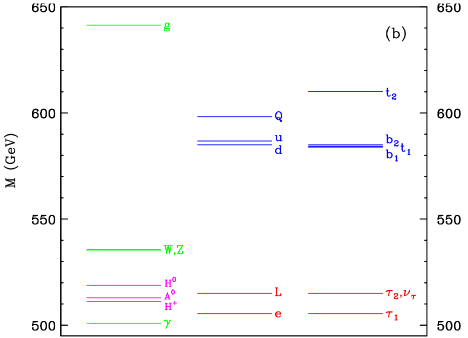


Example:



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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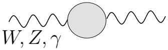
- SM strength: $t_L t_L A'$

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 $SU(2)_R \Leftrightarrow$ 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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[Agashe, Delgado, May, Sundrum 03]

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- 2 charged EW $(W_L^{\pm}, W_R^{\pm})$

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

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

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

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

---

- $h^{\mu\nu}_{(0)}\psi_{(0)}\psi_{(1)}$: 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 $pp \to h_{\mu\nu}^{(n)} \to \ell^+\ell^-$

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}

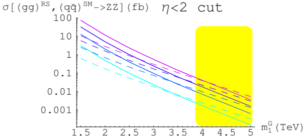
WED KK Graviton

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

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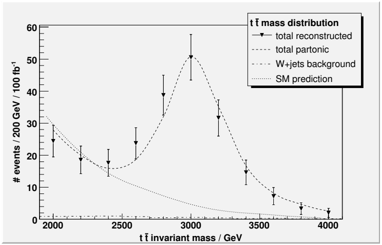
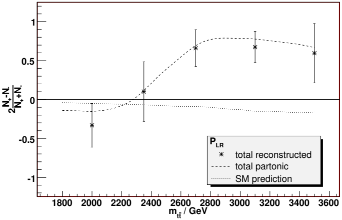




$$P_{LR} = 2\frac{N_+ - N_-}{N_+ + N_-} \qquad N_+ \text{ forward going } \ell \text{ wrt } k_t$$

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

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}

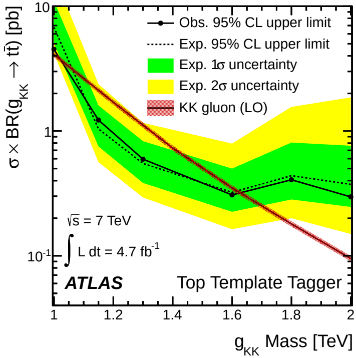
- $pp \to Z' \to W^+W^-$
  - Fully leptonic : $W \to \ell\nu$; $W \to \ell\nu$ — $\mathcal{L}$: (100; 1000) fb^{-1}
  - Semi leptonic : $W \to \ell\nu$; $W \to (jj)$ — $\mathcal{L}$: (100; 1000) fb^{-1}
- $pp \to Z' \to Z\,h$
  - $m_h = 120\text{GeV}$: $Z \to \ell^+\ell^-$; $h \to b\,\bar{b}$ — $\mathcal{L}$: (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 $0 < j_M < 75$ $\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

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

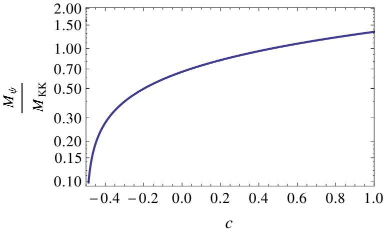
- SM fermions : $(+,+)$ BC $\rightarrow$ zero-mode
- "Exotic" fermions : $(-,+)$ BC $\rightarrow$ No zero-mode
  - 1^{st} KK vectorlike fermion

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

  c : Fermion bulk mass parameter

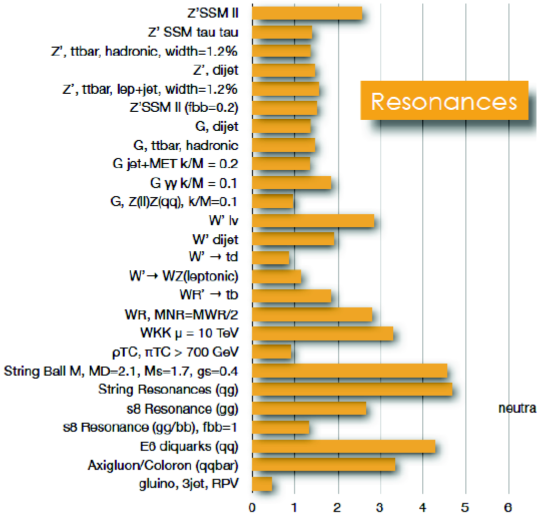
  [Choi, Kim, 2002] [Agashe, Delgado, May, Sundrum, 03]
  [Agashe, Perez, Soni, 04] [Agashe, Servant 04]

  - Look for it at the LHC

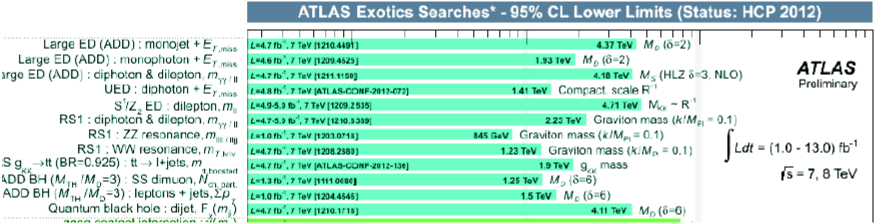


[Dennis et al, '07] [Carena et al, '07] [Contino, Servant, '08]
[Atre et al, '09, '11] [Aguilar-Saavedra, '09] [Mrazek, Wulzer, '09]
[SG, Moreau, Singh, '10] [SG, Mandal, Mitra, Tibrewala, '11] [SG, Mandal, Mitra, Moreau : '13]

CMS Resonances Limits (Moriond 2013)

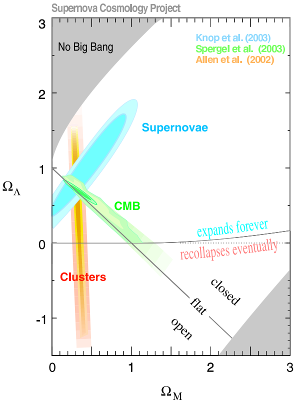


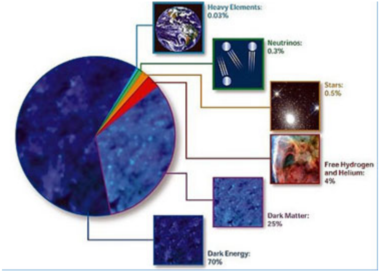
ATLAS Extra Dimensions Limits (Moriond 2013)



Dark Matter Candidates from BSM

Observations tell us





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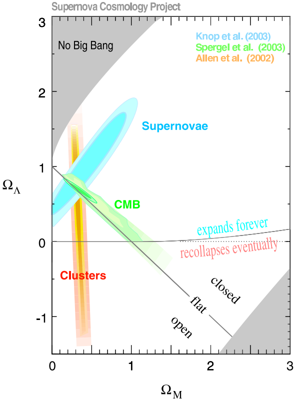

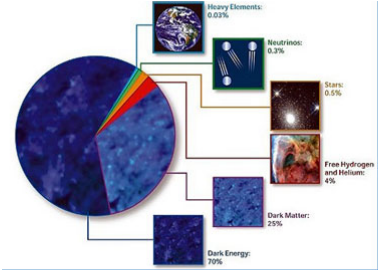

- **Flat** on large scales
- Expansion is **Accelerating**
- **95%** is unknown **dark matter** + **dark energy**
  - **What is it**??

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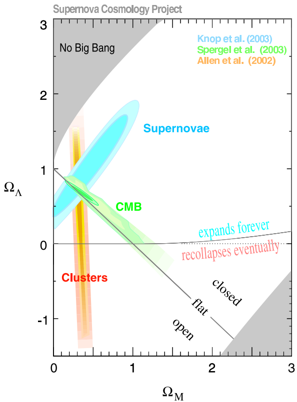

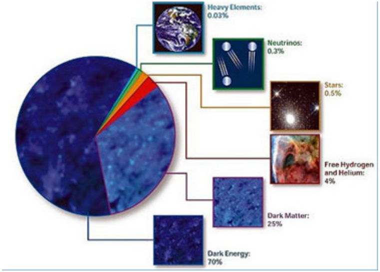

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The DARK SIDE rules!

What is the dark sector?

- Dark Matter
  - Astrophysical objects? (Disfavoured)
    - MAssive Compact Halo Objects (MACHO) or Black Holes or . . .
  - Particle dark matter? More on this...
    - Hot or Warm or Cold Dark Matter (CDM)

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- Dark energy

Particle DM Requirements

- Should be around for a long long long time ...
  - Absolutely stable : Conserved quantum number
    - e, p are stable, but not "dark"! So not possible
    - Active ν_L, disfavored. Sterile ν_R, possible
    - BSM particle with Z_2 symmetry
  - Decays, but with very very very long life-time
    - Very very very tiny coupling to other SM states

Particle Dark Matter

- Thermal Relic
  - In thermal equilibrium in early universe
  - Details of its origin do NOT matter
    - So most studied
- Nonthermal Relic
  - Never in thermal equilibrium
  - Details of its origin do matter

Particle DM Possibilities

- LSP - Lightest Supersymmetric Particle
  - $\tilde{\chi}_1^0$ Neutralino (SUSY partner of neutral gauge boson)
  - $\tilde{\nu}$ Sneutrino (SUSY partner of neutrino)
- SuperWIMP - Gravitino (SUSY partner of graviton)
- E-WIMP - Right-handed sneutrino (partner of neutrino)
- WIMPzilla - Extremely massive particle
- LKP - Lightest Kaluza-Klein Particle - Extra space dimensions
- LTP - Lightest T-odd Particle - Little-higgs theory with Z_2
- Hidden sector DM

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- Hidden sector DM
- Your candidate here

Thermal Relic

Thermal history of the Universe

Big Bang → Inflation → DM freeze-out→ BBN →γ decouples → Today

Hubble rate:

$$H \equiv \frac{\dot{a}}{a} \; ; \quad H^2 = \frac{8\pi G}{3}\rho$$

$$H = 1.66\sqrt{g_*}\frac{T^2}{M_{Pl}} \quad \text{(Rad Dom)}$$

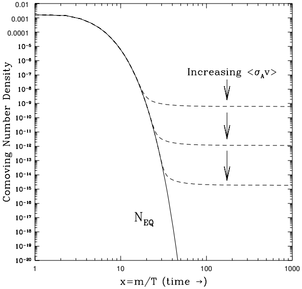
Boltzmann Equation

$$\frac{d}{dt}n = -3Hn - \langle\sigma v\rangle_{SI}\left(n^2 - n_{eq}^2\right) - \langle\sigma v\rangle_{CI}\left(nn_\phi - n_{eq}n_{\phi\, eq}\right) + C_\Gamma$$

Thermal equilibrium if

$$\langle\sigma v\rangle_{SI}\, n_{\tilde{\nu}_0} > 3H\ ; \qquad \langle\sigma v\rangle_{CI}\, n_\phi > 3H$$

Freeze-out



[Kolb & Turner, Early Universe]

Weakly Interacting Massive Particle (WIMP)

WIMP Cold dark matter - New BSM particle

- Mass: $M \sim 100\,\mathrm{GeV}$

$$\Omega_0 \equiv \frac{n_0 M}{\rho_c} \approx 4 \times 10^{-10} \left(\frac{\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

- Interaction strength: $g \sim g_{EW}$

Example: SUSY WIMP: If conserved R_p, Lightest Supersymmetric Particle (LSP) stable

- LSP (Eg: Neutralino) can be WIMP DM

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Example: SUSY WIMP: If conserved R_p, Lightest Supersymmetric Particle (LSP) stable

- LSP (Eg: Neutralino) can be WIMP DM
- Precisely the scale being explored at colliders!
  - DM at present colliders? (LHC connection)

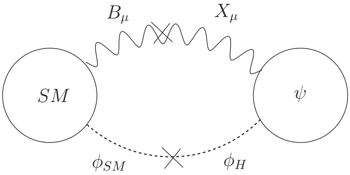
Hidden sector DM

Extend the SM to: SM $\times U(1)_X$

- $U(1)_X$ *sector* : *GaugeBoson*(X_μ), *Scalar*(Φ_H), *Fermion*(ψ)
  - If stable, can be DM

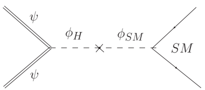
SM $\leftrightarrow U(1)_X$ communication

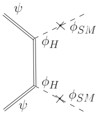
$$\mathcal{L} \supset -\alpha\ |\Phi_{SM}|^2|\Phi_H|^2 + \frac{\eta}{2}\ X_{\mu\nu}B^{\mu\nu}$$



Hidden Sector Relic Density

Self-annihilation

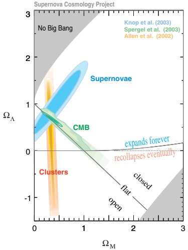




$$\Omega_0 h^2 = 10^{-29} x_f \left(\frac{eV^{-2}}{\langle \sigma v \rangle} \right)$$

$$\sigma v_{rel} = a + b \, v_{rel}^2 + O(v_{rel}^4)$$

$$\langle \sigma v \rangle = a + b/x_f \qquad x_f \equiv M_\psi / T_f \approx 25$$



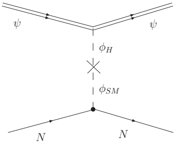
Observations : $\Omega_0 = 0.222 \pm 0.02$ [PDG '08]

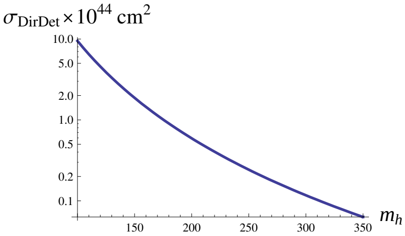
Channels $\psi\psi \to b\bar{b}, W^+W^-, ZZ, hh, t\bar{t}$

Dark Matter Detection

- Direct Detection
  - DM directly intereacts with a detector
- Indirect Detection
  - Look for indirect emmissions from DM
- Collider Detection
  - DM escapes as missing momentum at colliders

Direct Detection of Hidden sector





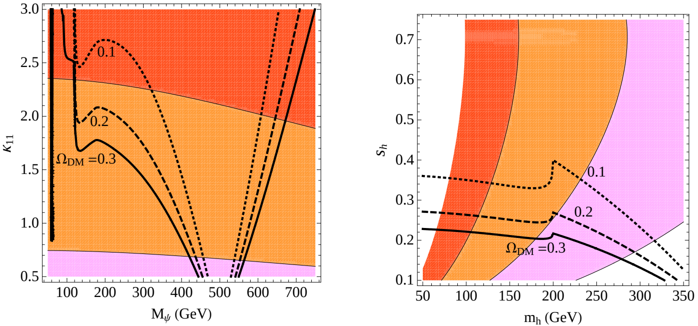
$M_\psi = 125\ GeV,\ \kappa_{11} = 1.5, s_h = 0.25$

Effective $h\bar{N}N$ coupling $\approx 2 \times 10^{-3}$ [Shifman, Vainshtein, Zakharov (1973)]

ψ- Nucleon c.s. :

$$\sigma\,(\psi N \to \psi N) \approx \frac{\kappa_{11}^2 s_h^2 c_h^2 \lambda_N^2}{8\pi v_{rel}} \frac{(|\mathbf{p}_\psi|^2 + m_N^2)}{(t - m_h^2)^2}$$

ψ Relic Density + Direct Detection



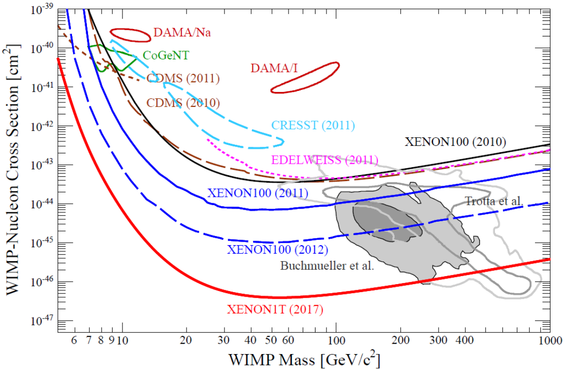
[SG, S.Lee, J.Wells 2009]

$M_\psi = 250 GeV, m_h = 120 GeV, \kappa_{11} = 2.0, s_h = 0.25, \kappa_{3\phi} = 1, m_H = 1 TeV$

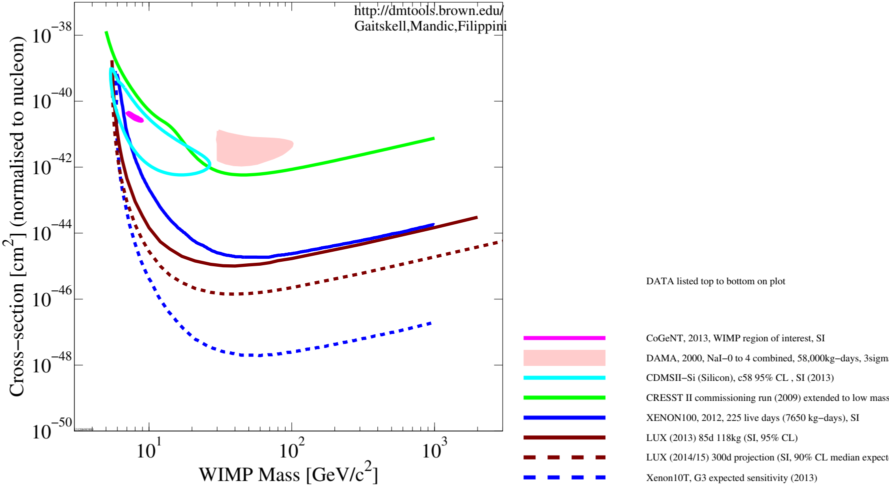
Shaded:

$\sigma_{Dir} \gtrsim 10^{-43}\ \mathrm{cm}^2$ (dark); $\gtrsim 10^{-44}\ \mathrm{cm}^2$ (medium); $\gtrsim 10^{-45}\ \mathrm{cm}^2$ (light)

Direct Detection Experimental Limits (Old)

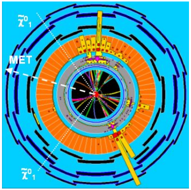


Direct Detection Experimental Limits

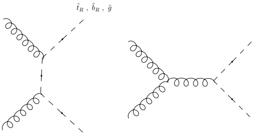


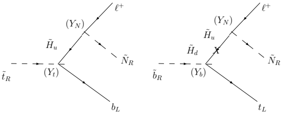
- DAMA vs. XENON/LUX puzzle
  - What's going on?

DM at Colliders II



- Example: Supersymmetry

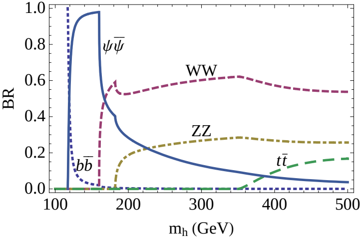


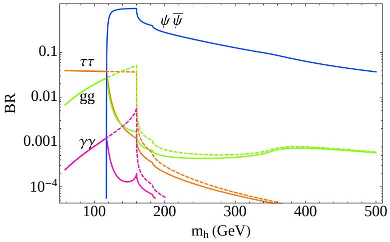


- LSP leads to "missing momentum"

Higgs decay to DM

- Higgs decay and BR
  - If $m_h > 2M_\psi$: $h \to \psi\overline{\psi}$ Invisible Decay!
    - Decay channels: $h \to \psi\bar{\psi}\,,\; b\bar{b}\,,\; WW\,,\; ZZ\,,\; t\bar{t}$





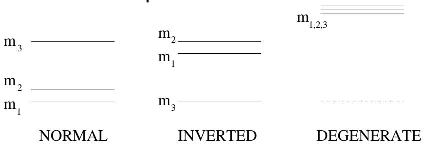
$$M_\psi \approx 59\,GeV, s_h = 0.25, \kappa_{11} = 2.0, \kappa_{3\phi} = 1.0, m_H = 1\,TeV$$

NB: Relic density not enforced

Neutrino Mass Generation

Questions

- What is the scale of m_ν
- Is the ν a DIRAC or MAJORANA particle? (Is $L_\#$ good?)
- Which mass spectrum?



- Is there CP violation in the lepton sector?

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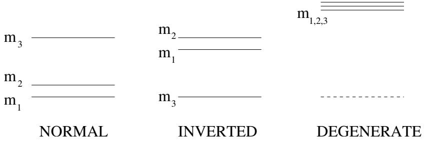

- Is there CP violation in the lepton sector?

Possible Answers

- Dirac ν : Add ν_R with TINY (10^{-12}) Yukawa coupling
- Type I seesaw: Add ν_R and a BIG (10^{11} GeV) mass
- Type II seesaw: Add SU(2) triplet scalar ξ with TINY (0.1 eV) VEV
- Type III seesaw: Add SU(2) triplet fermion Ξ
- Extra dimensions: Add BULK ν_R with BRANE coupling to ν_L

Conclusions

- Standard Model has shortcomings
  - Theoretical: Gauge (& flavor) hierarchy problem
  - Observational: DM, BAU
- Beyond the Standard Model physics can resolve these
  - Supersymmetry, Extra dimension(s), Strong dynamics, Little Higgs, ...
- Are any of these ideas realized in Nature?
  - *Desperately seeking experimental guidance*
  - Experiments poised for discovery?
    - LHC7,8 constraints already nontrivial.
      LHC14 high luminosity run crucial
    - DM Direct, Indirect detection
    - Flavor and precision probes

BACKUP SLIDES

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Yukawa Couplings

Yukawa Couplings

- No $Zb\bar{b}$ protection
  - DT $\mathcal{L}_{\rm Yuk} \supset \lambda_t \; \bar{Q}_L \Sigma \psi_{t_R} + \lambda_b \; \bar{Q}_L \Sigma \psi_{b_R} + h.c.$
- With $Zb\bar{b}$ protection
  - ST $\mathcal{L}_{\rm Yuk} \supset \lambda_t \; {\rm Tr}\left[\bar{Q}_L \Sigma\right] \; t_R + h.c.$
  - TT $\mathcal{L}_{\rm Yuk} \supset \lambda_t {\rm Tr}\left[\bar{Q}_L \Sigma \psi'_{t_R}\right] + \lambda'_t {\rm Tr}\left[\bar{Q}_L \Sigma \psi''_{t_R}\right] + h.c.$
  - 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 $Z_X|_{y=0} = 0\,;\ \partial_y Z_X\,|_{y=\pi R} = 0$

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

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

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

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

Gauge EW KK States

Gauge Boson

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

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

$$W_L^{(0)} \leftrightarrow W_L^{(1)} \;\; ; \;\; W_L^{(0)} \leftrightarrow W_R^{(1)} \;\; ; \;\; W_L^{(1)} \leftrightarrow W_R^{(1)}$$

Mass eigenstates :

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

Z' Overlap Integrals

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

Z' overlap with Higgs $\to \xi$

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

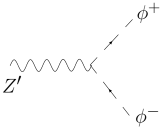
- Z' couplings to h enhanced (also V_L - Equivalence Theorem!)
- Z' couplings to t_R enhanced
- Z'couplings to χ suppressed

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

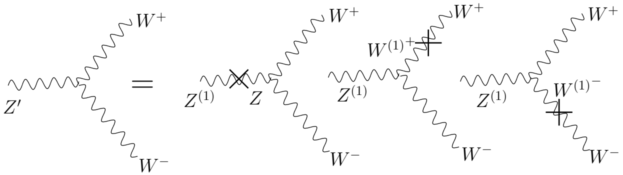
EWSB induced $Z'W^+W^-$ coupling

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

Using Goldstone equivalence:



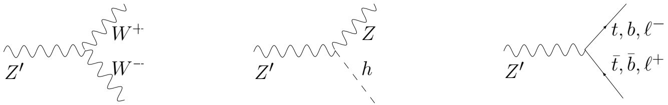
In Unitary Gauge:



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]]



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

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

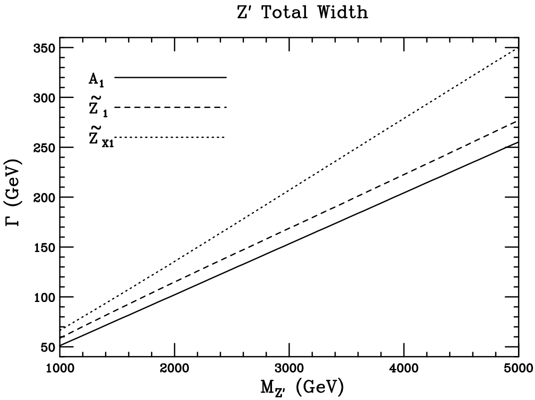
$$\Gamma(\tilde{Z}_1, \tilde{Z}_{X1} \to Z_L h) = \frac{g_Z^2 \kappa^2}{192\pi} M_{Z'} \; ; \quad \kappa \propto \sqrt{k\pi r_c} ,$$

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

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	

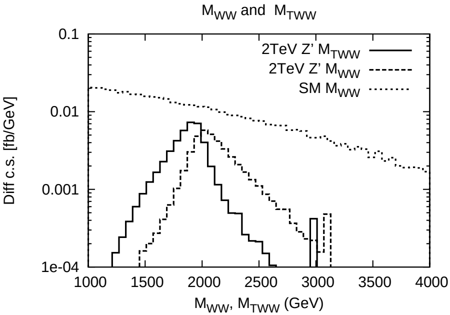
Total Widths



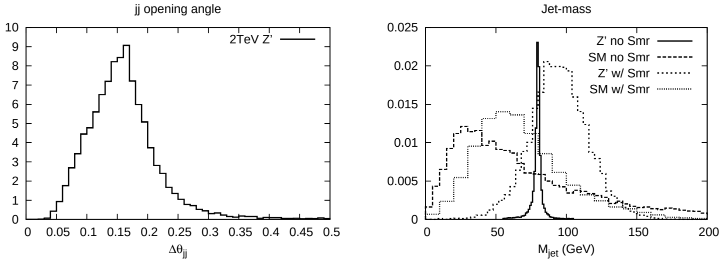
$M_{Z'} = 2\text{TeV}$	A_1	Z_1	Z_{X1}
Γ (GeV)	103.3	114.6	135.6

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

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



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

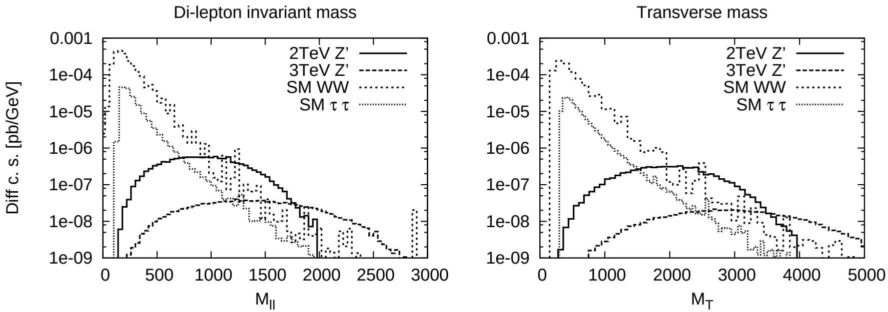
To account for (HCal) expt. uncert.

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}

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

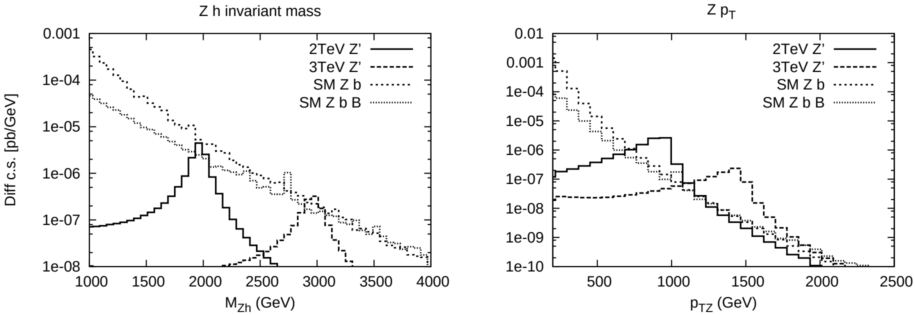
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ 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)

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

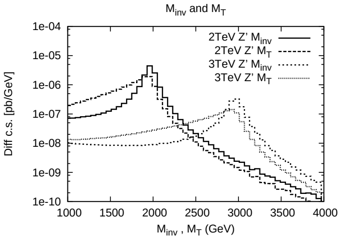
Cross-section (in fb) after cuts:

$M_{Z'} = 2$ 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}

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

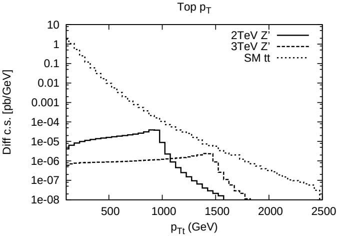
$M_{Z'} = 2$ TeV	Basic	$p_{T\ell}$	$M_{\ell\ell}$	# Evts	S/B	$S/\sqrt{B}$
Signal	0.1	0.09	0.06	60	0.3	4.2
SM $\ell\ell$	3×10^4	5.4	0.2	200		
SM WW	295	0.03	0.002	2		

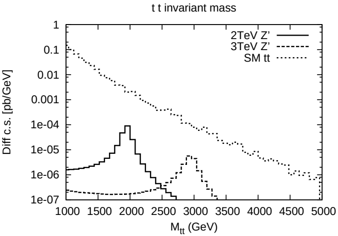
events above is for

- 2 TeV : 1000 fb^{-1}

Experimentally clean, but needs a LOT of luminosity

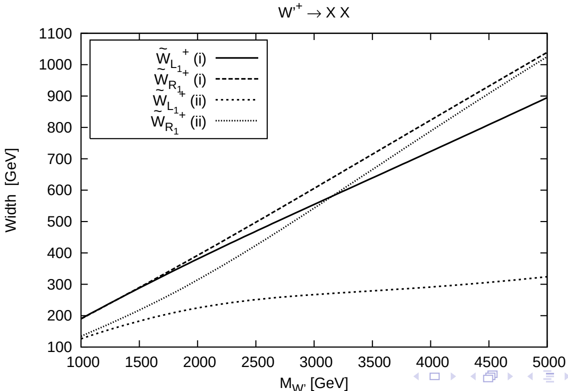
$pp \to Z' \to t\bar{t}$



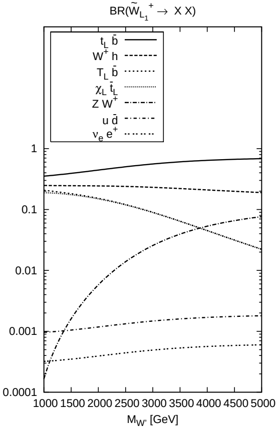


$M_{Z'} = 2$ TeV	Basic	$p_T > 800$	$1900 < M_{tt} < 2100$
Signal	17	7.2	5.6
SM $t\bar{t}$	1.9×10^5	31.1	19.1
$M_{Z'} = 3$ TeV	Basic	$p_T > 1250$	$2850 < M_{tt} < 310$
Signal	1.7	0.56	0.45
SM $t\bar{t}$	1.9×10^5	4.1	1.1

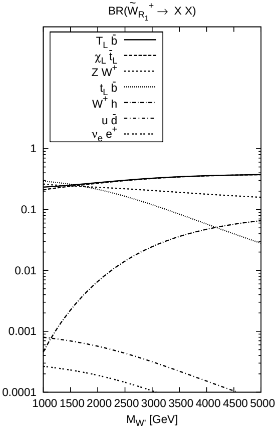
$W'^{\pm}$ width


W'+ → X X
Width [GeV]
M_W' [GeV]
W̃L1+ (i)
W̃R1+ (i)
W̃L1+ (ii)
W̃R1+ (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]



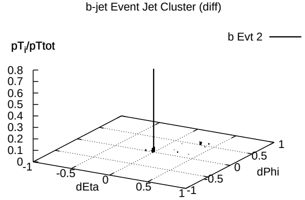
BR($\tilde{W}_{R_1}^{+} \to$ X X)
$T_L\ \bar{b}$
$\chi_L\ \bar{t}_L$
$Z\ W^+$
$t_L\ \bar{b}$
$W^+\ h$
$u\ \bar{d}$
$\nu_e\ e^+$
1
0.1
0.01
0.001
0.0001
1000 1500 2000 2500 3000 3500 4000 4500 5000
$M_{W'}$ [GeV]

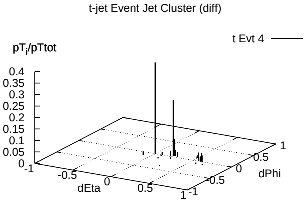
$W'^{\pm} \to t\,b \to \ell\nu b\,b$

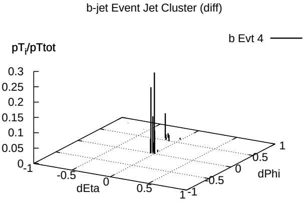
Signal c.s. $\sim 1 fb$

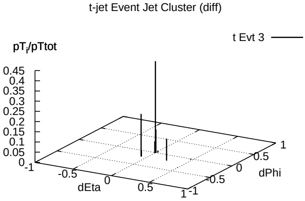
Bkgnd is single top + QCD W b b .... AND ...

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

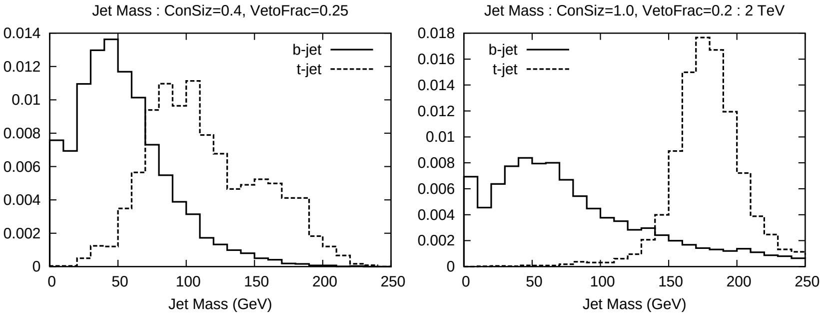








$W'^{\pm} \to t\,b \to \ell \nu b\,b$



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)

Warped States

- 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