Collider Phenomenology of a SUSY Randall-Sundrum Scenario

BSM Meeting, Sussex 26^{th} Sept. 2003

1. Motivation
2. 4-D Effective Theory
3. Phenomenology
4. Conclusions

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Hierarchy problem

1. Fine tuning problem: tuning of 1-loop Higgs mass corrections counterterms to 1 part in 10^{17};

2. Why is $\frac{M_{EW}}{M_{Pl}}$ so tiny? *i.e.* natural values for the Higgs and Planck masses ought to be similar.

Solutions?

1. SUSY: Add new degrees of freedom s.t. divergent diagrams contributing to M_H^2 exactly cancel order by order $\Rightarrow$ no need to fine-tune;

2. RS:$\frac{M_{EW}}{M_{Pl}}$ *isn't* tiny - *observed* M_{Pl} orders of magnitude larger than M_{Pl}^{true} due to warped background geometry.

But, these scenarios have their own problems...

MSSM: μ-problem

- Two mass scales in low energy SUSY:

1. SUSY soft scale m_{soft} - gives soft masses to superscalars, gauginos.

2. μ-term in superpotential $W \supset \mu H_1 \cdot H_2$ - controls gauge symmetry breaking.

E-W precision data $\Rightarrow \mu$, $m_{\text{soft}} \sim$ TeV.

- Unrelated parameters: Why are they both small (and similar) *cf.* Planck scale?

Existing possible solutions:

- Set $\mu = 0$ at tree level *i.e.* no ‘by hand’ small mass scale, generate it radiatively;

- Use non-renormalizeable superpotential;

- Giudice-Masiero mechanism.

Radion Stabilization

Compactification radius r_c $\sim$ arbitrary integration constant of Einstein eqns.

- Must be small (precision GR tests) - Why?

- Must protect hierarchy from radiative corrections.

- Cosmological constraints.

Existing possible solutions:

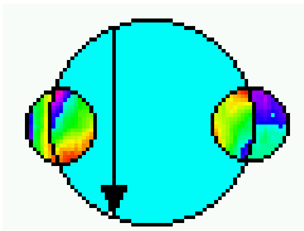
- Goldberger-Wise mechanism.

The Model

Casas, Espinosa, Navarro: Nucl.Phys. B620 (2002) 195-236

- Start from 5-D, $\mathcal{N} = 2$ supergravity realized on $\mathcal{M}_4 \otimes S_1/Z_2$.

- Add constant brane energy densities at Z_2 fixed points.



- Randall-Sundrum metric is a solution of 5-D Einstein eqns:

$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2.$$

- 5-D, $\mathcal{N} = 2$ SUSY in bulk $\longrightarrow$ 4-D, $\mathcal{N} = 1$ on brane by localized energy densities and orbifold projection.

• Give modulus field for 5$^{\mathrm{th}}$ dimension (T) a VEV:

$$\langle T + T^\dagger \rangle = \log \left[\frac{3M_p^2}{\Lambda^2} \right] \; ; \;\; T = \langle T \rangle + \frac{t}{\Lambda}$$

(defining Λ).

• $\sim$ MSSM with some important differences.

• Use standard MSSM superpotential:

$$\begin{aligned} W &= h_U^{ij} Q_{Li} \cdot H_2 U_{Rj} + h_D^{ij} H_1 \cdot Q_{Li} D_{Rj} \\ &+ h_E^{ij} H_1 \cdot L_{Li} E_{Rj} + \mu H_1 \cdot H_2 . \end{aligned}$$

with μ-term modified - see later.

• Non-minimal effective Kähler potential K_{eff};

(Obtain by integrating action over compactified dimension, compare curvature term with 4-D SUGRA $\equiv$ imposing *separate* 4- and 5-D Poincaré invariance).

• Extra neutral scalar t mixes with neutral Higgses.

• Fermionic superpartner χ_t mixes with neutral gauginos, Higgsinos $\longrightarrow$ 5 neutralinos, *cf.* 4 in MSSM.

$$K_{\text{eff}} = \Lambda^2 \exp\left\{ -\frac{t+t^*}{\Lambda} + \frac{1}{\Lambda^2}\sum_i |\phi_i|^2 + (\lambda H_1 \cdot H_2 + \text{h.c.}) \right\}$$

where:

- Λ = effective theory cutoff;
- t = radion;
- ϕ_i represent all matter + Higgs scalars;
- λ = parameter allowing "chiral" Higgs terms* in K.

*("$\cdot$" = $SU(2)$ product $H_1 \cdot H_2 = H_1^0 H_2^0 - H_1^- H_2^+$.)

• λ contributes to μ-paramter in superpotential:

$$\mu = \mu_0 + \lambda m_{3/2},$$

via G-M mechanism.

• Can remove μ_0 entirely, $\rightarrow$ $\mu \sim m_{3/2}$, or leave it in at $\mathcal{O}(M_P)$, warped down to $\mathcal{O}(\Lambda)$.

• 'Free' parameters: $\Lambda, \lambda, \mu_0, m_{3/2}$ constrained by EWSB (CaEsNa01):

$$\lambda \sim \frac{-1}{3+\sqrt{3}} \left\{ 1 - (1+\sqrt{3})\frac{\mu}{m_{3/2}} + \frac{\mu^2}{m_{3/2}^2} \right\}.$$

• MSSM parameter $\tan\beta = 1$ after EWSB.

Scalar kinetic terms

$$\sim \frac{\partial^2 K}{\partial \phi_I \partial \phi_J^*} D_\mu \phi_I D^\mu \phi_J \equiv K_{IJ} D_\mu \phi_I D^\mu \phi_J.$$

• For $K = \sum_i |\phi_i|^2$ (minimal K), $K_{IJ} = \delta_{IJ}$;

• Non-minimal $K \to$ non-diagonal $K_{IJ} \Rightarrow$ *kinetic mixing*.

• Perform field redefinition to return kinetic terms to canonical form.

• Effect least suppressed in neutral scalar and neutralino sector, (holomorphic) transformations take the form ($\mathcal{O}(1/\Lambda)$):

$$\begin{pmatrix} H_1^0 \\ H_2^0 \\ t \end{pmatrix} \to \begin{pmatrix} 1 & 0 & \frac{1+\lambda}{4}\frac{v}{\Lambda} \\ 0 & 1 & \frac{1+\lambda}{4}\frac{v}{\Lambda} \\ \frac{1+\lambda}{4}\frac{v}{\Lambda} & \frac{1+\lambda}{4}\frac{v}{\Lambda} & 1 \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \\ t \end{pmatrix}$$

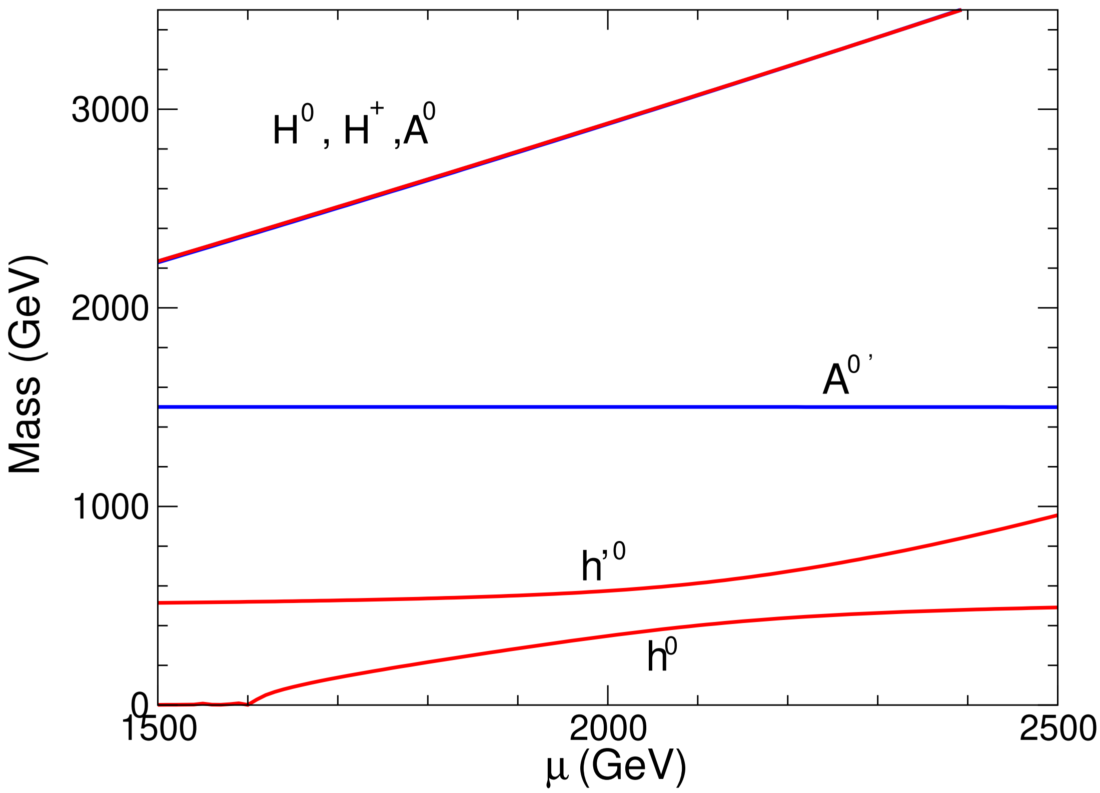
diagonalizing kinetic terms and rescaling fields.

• 2 levels of mixing: above + normal weak mixing of neutral d.o.f.'s

Leads to (CP-even scalar) mass matrix...

$$
\begin{aligned}
M_R^{11} &= -M_R^{12} = -M_R^{21} = M_R^{22} \\
&= \frac{1}{2}v^2\left(g^2 + g'^2\right) \\
&+ 4\left[\zeta\mu m_{3/2} - \lambda(2+\zeta)m_{3/2}^2\right], \\
M_R^{13} &= M_R^{23} = M_R^{31} = M_R^{32} \\
&= 2\, m_{3/2}^2\frac{v}{\Lambda}[-\frac{3}{2} - \frac{13}{2} \\
&+ 3\zeta)\lambda + (1+3\zeta)\frac{\mu}{m_{3/2}} - 4\frac{\mu^2}{m_{3/2}^2}], \\
M_R^{33} &= 4m_{3/2}^2.
\end{aligned}
$$

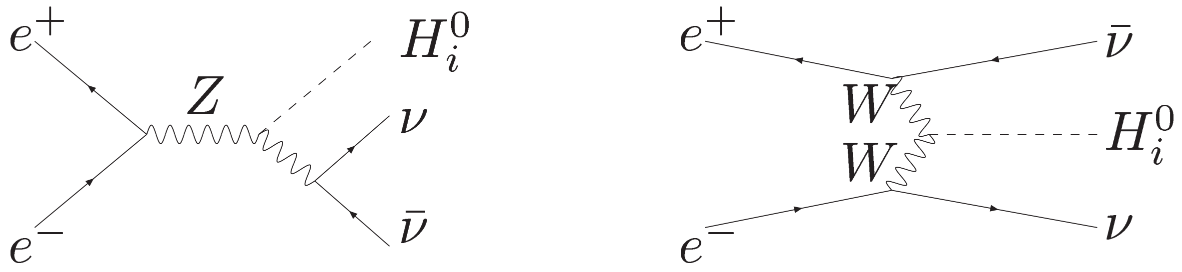
- Lightest Higgs can be up to ~ 700GeV.



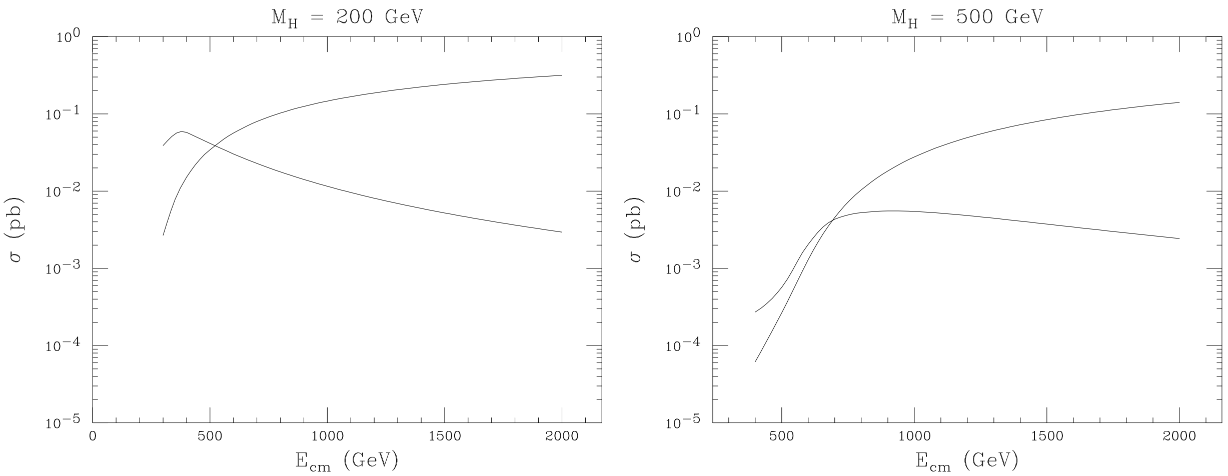
Shows masses of scalar/pseudoscalar sector vs. value of $\mu = \mu_0 + \lambda m_{3/2}$. ($\Lambda = 4$ TeV, $m_{3/2} =$ 500 GeV.(Casas et al, Nucl.Phys. B620 (2002) 195-236))

SUSY Higgs production in W^+W^- fusion

SM/MSSM tree-level diagrams:

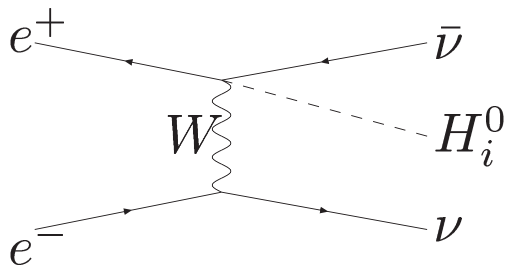


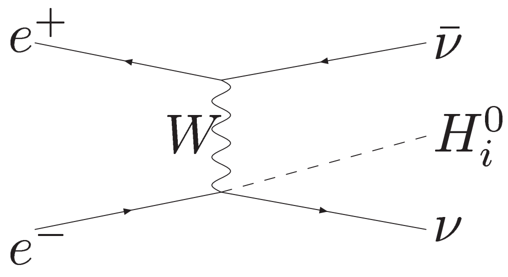
• Neglect Higgsstrahlung diagram at high $\sqrt{s}$, as t-channel $\ln s$ growth dominates.



• Neglect Higgs radiation off e^+, e^- due to small Yukawas.

Additional diagrams from 4-D effective interaction Lagrangian:



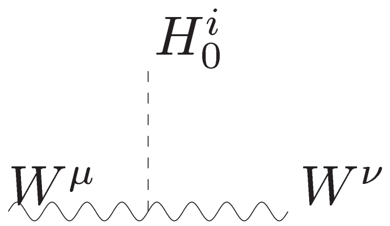


- Extra ($\frac{1}{\Lambda}$-suppressed) diagrams come from

$$\mathcal{L} \sim \left(1 - \frac{t + t^*}{\Lambda}\right) \times \mathcal{L}_{\mathrm{MSSM}}^{\mathrm{kinetic}}$$

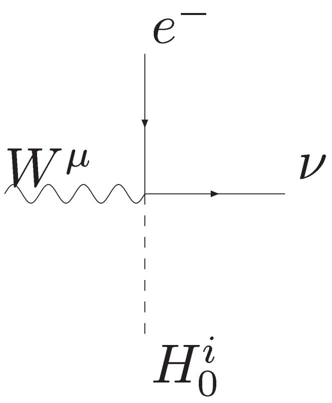
structure in effective Lagrangian.

WWH vertex modified:

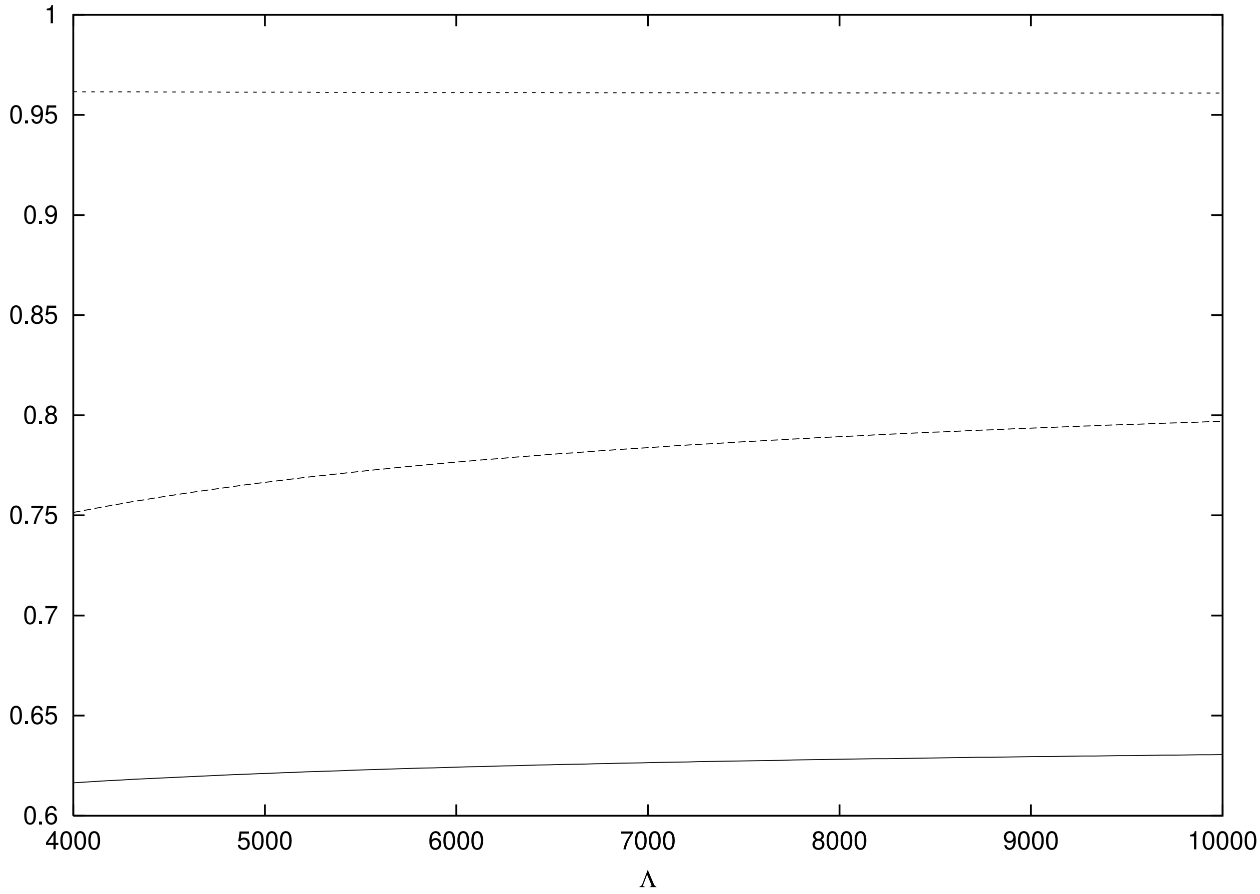


$$\frac{ie^2}{2\sin^2\theta_W}\left\{v(Z_R^{1i}+Z_R^{2i})+\frac{1-2\sqrt{2}+\lambda}{2}\frac{v^2}{\Lambda}Z_R^{3i}\right\}g^{\mu\nu}.$$

New adjacency 4 vertex:



$$\frac{ie}{\Lambda\sin\theta_W}\gamma^\mu P_L Z_R^{3i}$$



Shows ratio $\sigma/\sigma_{\rm SM}$.

$\mu = 1500$GeV, $m_{3/2} = 1000$GeV

$\mu = 2500$GeV, $m_{3/2} = 500$GeV

$\mu = 1500$GeV, $m_{3/2} = 500$GeV.

Outlook

- Phenomenology of SUSY warped geometry under investigation.

- Modified vertices predict suppressed cross-sections.

- Higher-order (in Λ^{-1}) effects may be important.

- LEP II bounds on Λ (hence r_c) needed.

- Detailed predictions for NLC, LHC underway.