Higgs Production in a SUSY Randall-Sundrum Scenario

CPV/NSH Meeting, CERN May 2004

1. Motivation
2. The model
3. $e^+e^- \to \bar{\nu}\nu H$
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 $M_{Pl}^{\rm true}$ 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 $m_{\rm soft}$ - 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 $\Rightarrow$ μ, $m_{\rm soft} \sim$ 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.

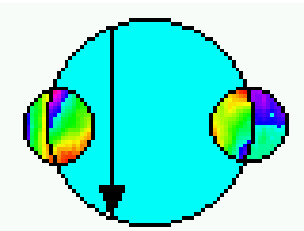
(Adds a scalar to the bulk)

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 $5^{\rm th}$ 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 $K_{\rm eff}$;

(Obtain by integrating action over compactified dimension, compare curvature term with 4-D SUGRA).

• 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 $K \rightarrow$ non-diagonal $K_{I\,J} \Rightarrow$ *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 ($\mathcal{O}(1/\Lambda)$):

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

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...

The mass matrix of the model under consideration takes the form

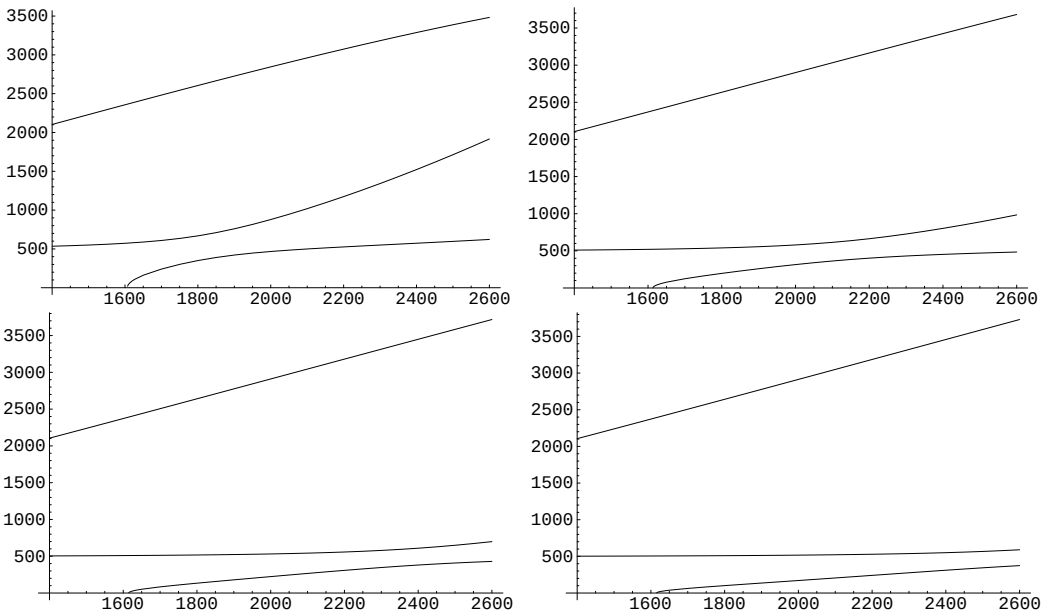
$$M = \begin{pmatrix} A + B/\Lambda^2 & 0 & 0 \\ 0 & C/\Lambda^2 & D/\Lambda \\ 0 & D/\Lambda & E + F/\Lambda^2 \end{pmatrix}$$

with A to F depending in other scales in the theory, $v, m_{3/2}, \mu$.

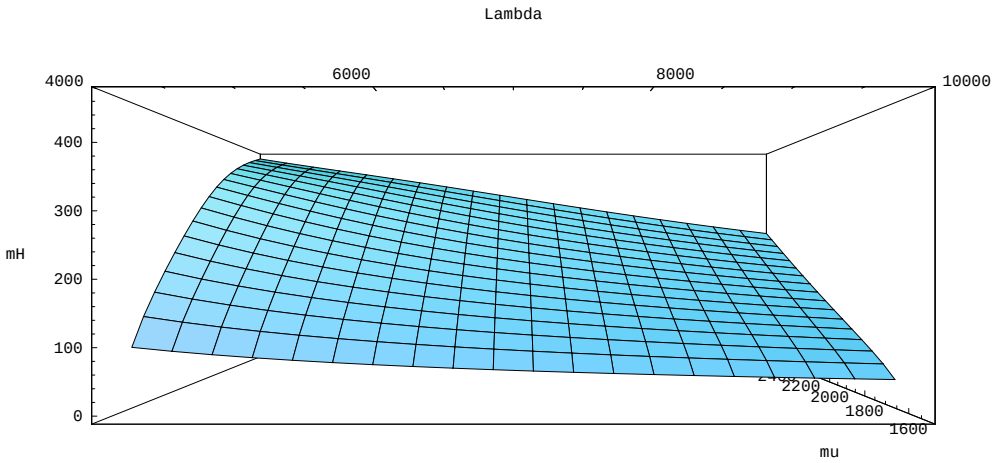
- First scalar still exact eigenstate - no 1-2, 1-3 mixing;

- $\tan\beta = 1 \Rightarrow$ D-flat direction if $\Lambda \to \infty$, massless scalar in this limit;

- Lightest Higgs can be up to ~ 700GeV.



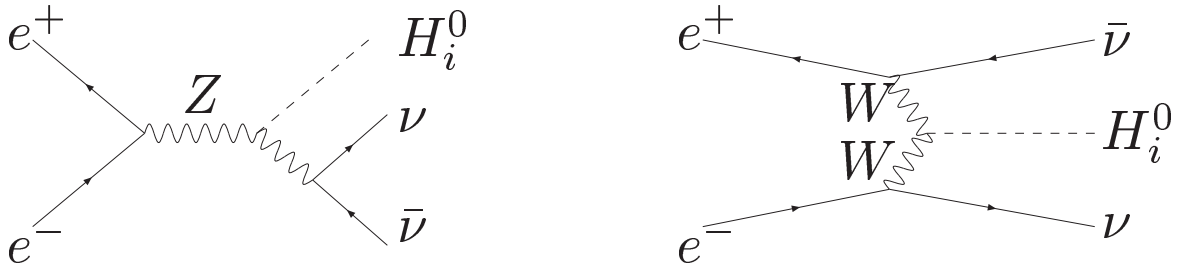
Shows masses of scalar sector vs. value of $\mu = \mu_0 + \lambda m_{3/2}$. ($\Lambda$ = 2,4,6,8 TeV, $m_{3/2} = 500$ GeV).



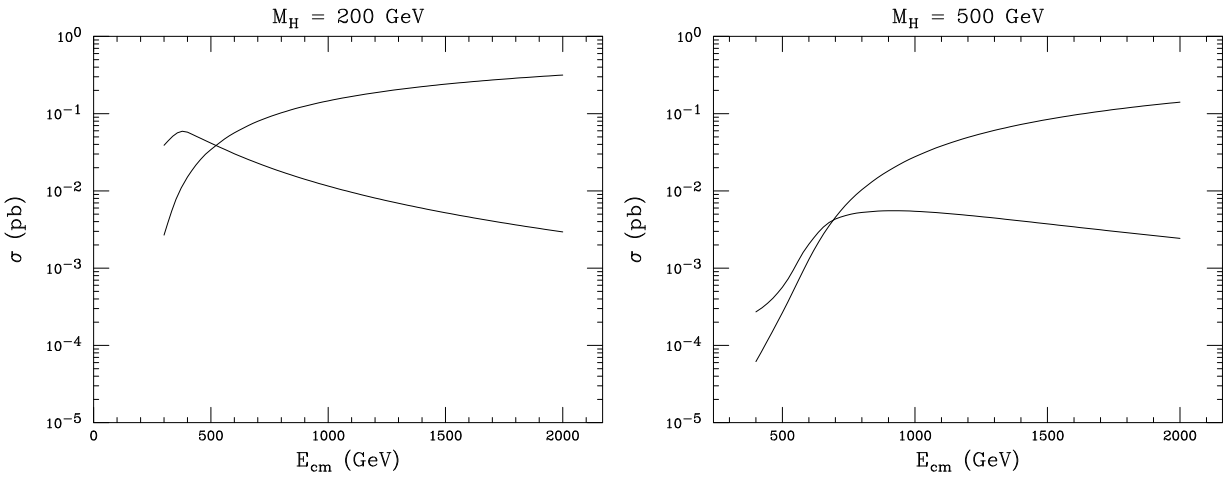
Leads to *upper* bound on Λ $4.4 - 9.5$ TeV from $m_H > 114$ GeV (from breaking of D-flatness by Λ-suppressed terms).

SUSY Higgs production in W^+W^- fusion

SM/MSSM tree-level diagrams:

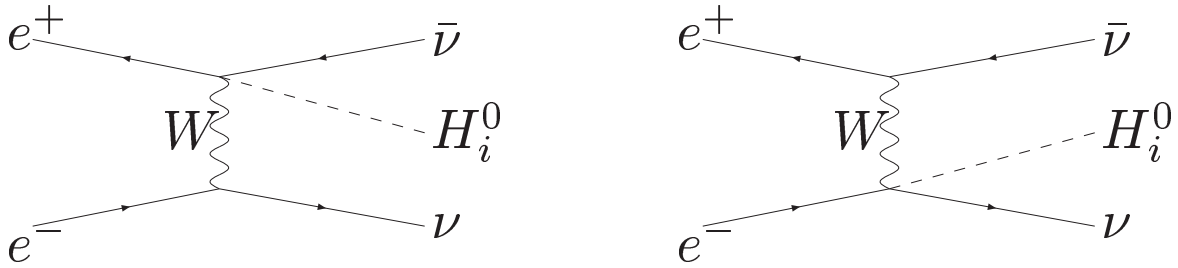


• Neglect Higgsstrahlung diagram at high $\sqrt{s}$, as t-channel $\ln s$ growth dominates.



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

Additional diagrams from 4-D effective interaction Lagrangian:

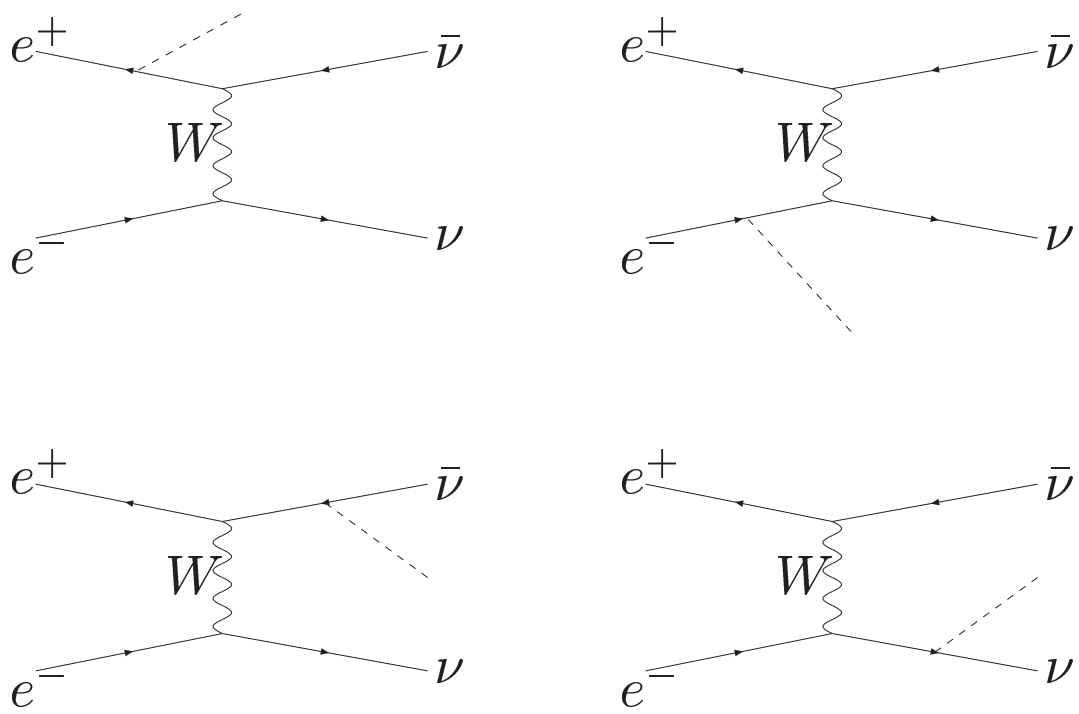


- Extra ($\frac{1}{\Lambda}$-suppressed) diagrams come from

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

structure in effective Lagrangian.

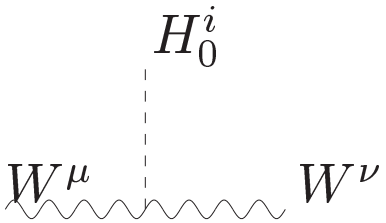
Also, contribution from term $(1/\Lambda)\bar{\chi}\sigma^{\mu}\chi\partial_{\mu}t$ gives correction to Yukawas, hence following diagrams:



- Contributions cancel exactly in matix element.

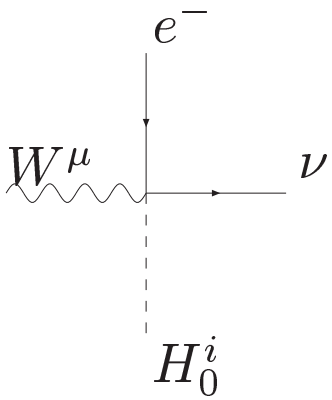
- Any potentially large effects on the decays, say, $\sqrt{s}/\Lambda$, say, cancel, leaving observables unaffected to $\mathcal{O}(m_f/\Lambda)$

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:

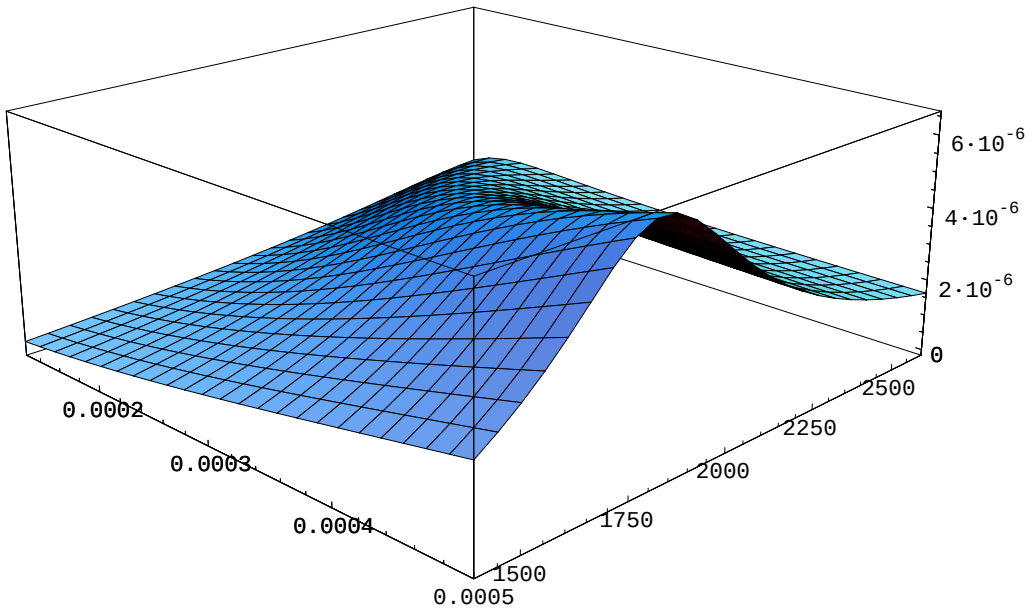


$$\frac{ie}{\Lambda\sin\theta_W}\gamma^\mu P_L Z_R^{3i}$$

Parameterize matrix element as

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2\{R_1 + R_2 + R_3(p_1 \cdot p_1' + p_2 \cdot p_2' + m_W^2)\}$$

- R_1 : like $\sin^2(\beta - \alpha)$ in MSSM.
- R_2 : Correction to WWH vertex.
- R_3 : Contribution from new diagrams...



- Dominant effect from the WWH vertex modification.

• Can it be distinguished from mSUGRA?

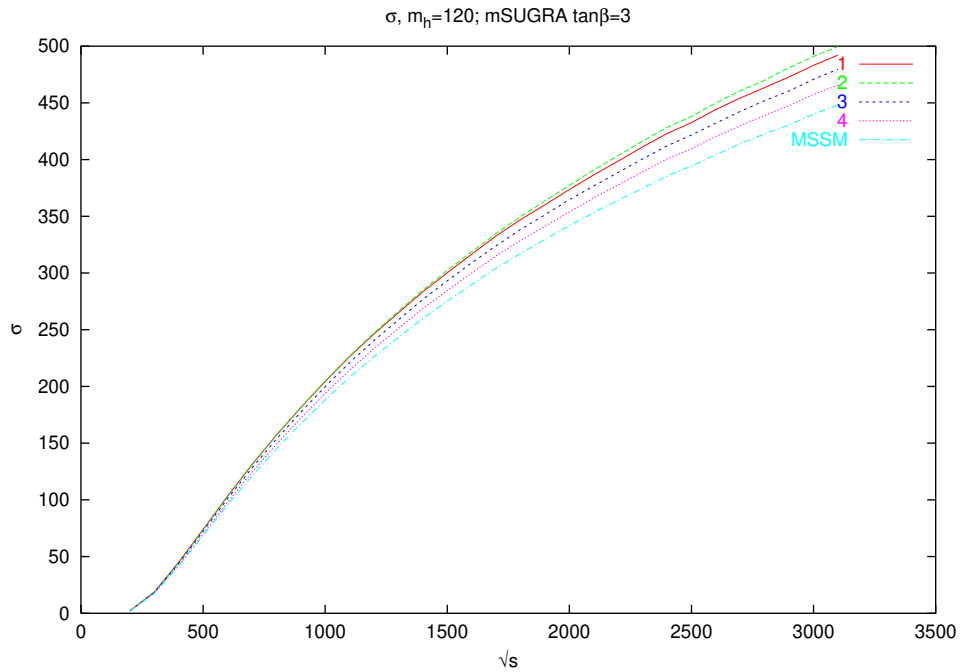
• Pick Higgs mass 120 GeV - assume known from LHC.

• Mixing matrices, and hence normalization, will differ...

In the following...

	Point 1	Point 2	Point 3	Point 4
Λ (GeV)	4000	4000	8000	8000
$m_{3/2}$ (GeV)	500	350	500	350
$R_1 + R_2$	0.97	0.96	0.99	0.92
R_3	-8E-7	-1.9E-6	-5.5E-7	-7E-7
μ	1695	1234	1853	1401

and the mSUGRA point used has lightest scalar at 120 GeV, $\tan\beta = 3$ (using low energy mass matrix, β, m_A, m_Z)


σ, m_h=120; mSUGRA tanβ=3
σ
√s
1
2
3
4
MSSM
0
50
100
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300
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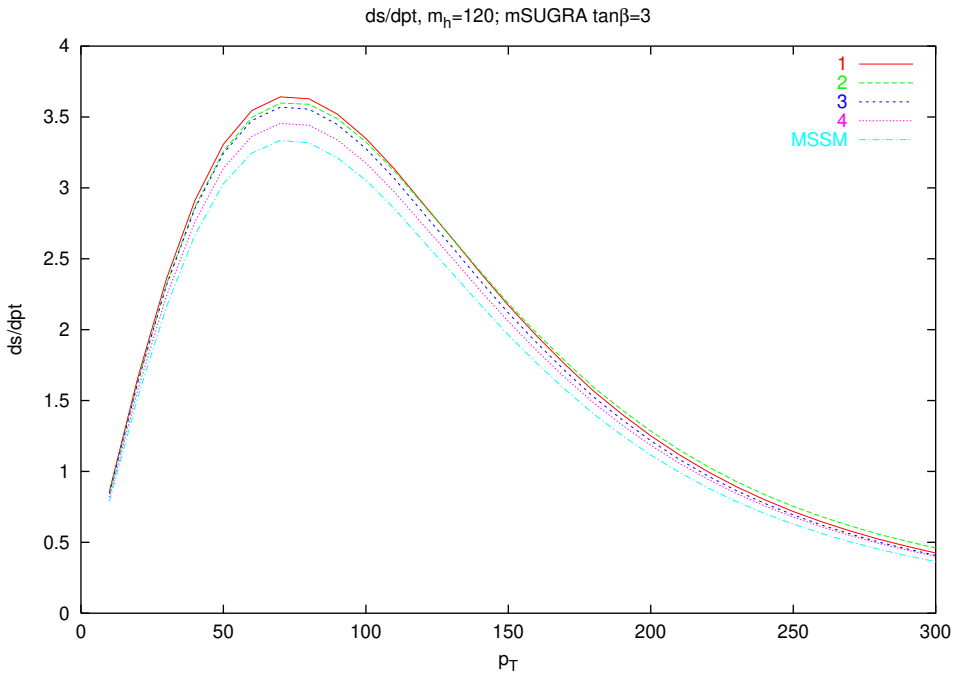
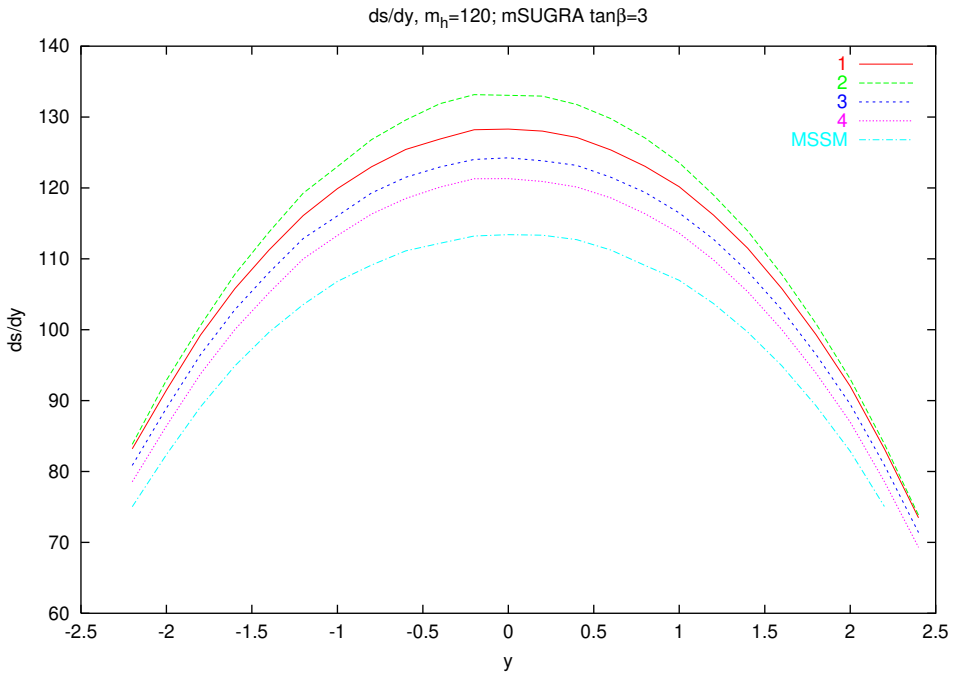

ds/dpt, m_h=120; mSUGRA tanβ=3
ds/dpt
p_T
1
2
3
4
MSSM
0
0.5
1
1.5
2
2.5
3
3.5
4
0
50
100
150
200
250
300



- But not by much! $\sim 10\%$. ("Worst case scenario")

- More likely scenario would be heavier lightest scalar.

Outlook

- Phenomenology of SUSY warped geometry under investigation.

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

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

- Neutralino phenomenology may have large effect - decay chains?