Higgs sector of the E6 inspired SUSY model with an extra $U(1)_N$ factor

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I. Introduction

- One of the strongest arguments in favour of SUSY is that the local version of SUSY (SUGRA) leads to a partial unification of the SM gauge interactions with gravity.

- However the origin of the μ–term remains unclear in SUGRA models. Indeed
$$W_{SUGRA} = W_0(h_m) + \mu(h_m)(\hat{H}_d\hat{H}_u) + ...$$
where
$$\mu(h_m) \sim M_{Pl} \qquad \text{or} \qquad \mu(h_m) = 0.$$

- The correct pattern of electroweak symmetry breaking requires
$$\mu(h_m) \sim 100 - 1000\,\text{GeV}\,.$$

- Since SUGRA is non–renormalizable theory it should be considered as an effective one.

- Nowadays the best candidate for underlying theory is superstring theory.

- The enlarged gauge symmetry in the superstring inspired E_6 models forbids any bilinear terms in the superpotential allowing interaction

$$W_{E_6} = \lambda S(H_d H_u) + \dots .$$

- By means of the Hosotani mechanism E_6 may be broken to

$$E_6 \to SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_\psi \times U(1)_\chi \,,$$

where $U(1)_\psi$ and $U(1)_\chi$ are defined as

$$E_6 \to SO(10) \times U(1)_\psi, \qquad SO(10) \to SU(5) \times U(1)_\chi.$$

- The obtained rank–6 model can be reduced further to rank–5 model that contains only one extra $U(1)'$ factor

$$U(1)' = U(1)_\chi \cos\theta + U(1)_\psi \sin\theta \,.$$

- At the electroweak or SUSY breaking scale field S acquires VEV breaking $U(1)'$ and providing natural solution of the μ–problem

$$\mu_{eff} = \lambda < S > \; .$$

II. Exceptional SUSY model

- For a special value of θ

$$\theta = \arctan\sqrt{15}$$

  that corresponds to $U(1)_N$ symmetry, right handed neutrino remains sterile after the breakdown of E_6.

- Only in this exceptional SUSY model (ESSM) right handed neutrino can be superheavy.

- Anomalies in the ESSM are cancelled automatically if the particle contents form complete fundamental 27 representations of E_6.

- To ensure the gauge coupling unification $SU(2)$ doublet and anti doublet from extra 27 and $\overline{27}$ (H' and $\overline{H}'$) should be introduced.

- Together with survivors the particle contents of the ESSM becomes

$$3\left[(Q_i,\, u^c_i,\, d^c_i,\, L_i,\, e^c_i)\right] + 3(D_i,\, \overline{D}_i) +$$
$$+3(H_{2i}) + 3(H_{1i}) + 3(S_i) + 3(N^c_i) + H' + \overline{H}',$$

  where D_i and $\overline{D}_i$ are exotic quarks, H_{1i} and H_{2i} are either Higgs or exotic $SU(2)$ doublets.

- To prevent rapid proton decay the invariance under some discrete symmetry should be imposed.

- The straightforward generalization of R–parity definition
$$R = (-1)^{3(B-L)+2S}$$
assuming $B_D = 1/3$ and $B_{\overline{D}} = -1/3$ ensures that the lightest exotic quark is stable.

- The existence of stable exotic quarks is ruled out by different experiments.

- There are two different ways to impose an appropriate Z_2 symmetry leading to the baryon and lepton number conservation which imply
  - $\overline{D}$ and D are diquark and anti diquark, i.e.
  $$B_{\overline{D}} = 2/3\,, \qquad B_D = -2/3\,;$$
  - exotic quarks are leptoquarks, i.e.
  $$B_D = 1/3\,, \qquad L_D = 1\,,$$
  $$B_{\overline{D}} = -1/3\,, \qquad L_{\overline{D}} = -1\,.$$

- Different generalizations of R–parity result in different ESSM superpotentials

$$\begin{array}{lrcl} i) & W_{ESSMI} & = & \frac{1}{2}M_{ij}N_i^cN_j^c + W_0 + W_1\,, \\ ii) & W_{ESSMII} & = & \frac{1}{2}M_{ij}N_i^cN_j^c + W_0 + W_2. \end{array}$$

  where

$$\begin{array}{rcl} W_0 & = & \lambda_{ijk}S_i(H_{1j}H_{2k}) + \kappa_{ijk}S_i(D_j\overline{D}_k) + h^N_{ijk}N_i^c(H_{2j}L_k) + \\ & + & h^U_{ijk}u_i^c(H_{2j}Q_k) + h^D_{ijk}d_i^c(H_{1j}Q_k) + h^E_{ijk}e_i^c(H_{1j}L_k)\,, \\ W_1 & = & g^Q_{ijk}D_i(Q_jQ_k) + g^q_{ijk}\overline{D}_id_j^cu_k^c\,, \\ W_2 & = & g^N_{ijk}N_i^cD_jd_k^c + g^E_{ijk}e_i^cD_ju_k^c + g^D_{ijk}(Q_iL_j)\overline{D}_k\,. \end{array}$$

- The ESSM superpotentials involve a lot of new Yukawa interactions that contribute to the amplitude of $K^0-\overline{K}^0$ oscillations and give rise to $\mu\to e^-e^+e^-$.

- To suppress flavour changing processes one can postulate Z_2^H symmetry under which all superfields except $H_d\equiv H_{13}$, $H_u\equiv H_{23}$ and $S\equiv S_3$ are odd.

- The Z_2^H symmetry simplifies the structure of interactions in the ESSM superpotentials

$$\begin{array}{c} \lambda_{ijk}S_i(H_{1j}H_{2k}) + \kappa_{ijk}S_i(D_j\overline{D}_k) \longrightarrow \lambda_iS(H_{1i}H_{2i}) + \\ +\kappa_iS(D_i\overline{D}_i) + f_{\alpha\beta}S_\alpha(H_dH_{2\beta}) + \tilde{f}_{\alpha\beta}S_\alpha(H_{1\beta}H_u)\,, \end{array}$$

  where $\alpha,\beta=1,2$ and $i=1,2,3$.

- But Z_2^H symmetry can only be approximate since it forbids all terms in W_1 and W_2 that would allow the exotic quarks to decay.

- In order to provide the correct breakdown of gauge symmetry and to suppress FCNC processes we assume that

  - only one field $S = S_3$ may have appreciable couplings to the exotic quarks and $SU(2)$ doublets H_{1i} and H_{2i} and the structure of the corresponding Yukawa interactions is flavor diagonal ;

  - only one pair of $SU(2)$ doublets H_d and H_u is allowed to have Yukawa couplings of the order of unity ;

  - the Yukawa couplings of exotic particles to the quarks and leptons of the first two generations are less than 10^{-4} and 10^{-3} respectively ;

  - the Yukawa couplings of exotic particles to the quarks and leptons of the third generation as well as to the fields S_1 and S_2 are smaller than 0.1 .

III. The analysis of RG flow

- According to our assumptions the superpotential of the ESSM can be written as

$$W_{ESSM} \simeq \lambda S(H_d H_u) + \kappa_i S(D_i \overline{D}_i) + h_t(H_u Q)t^c + \\ + h_b(H_d Q)b^c + h_\tau (H_d L)\tau^c + \ldots,$$

- We assume that this superpotential is formed near the Planck scale and RG equations should be used to compute the gauge and Yukawa couplings at $Q \simeq M_Z$.

- The inclusion of loop effects induces mixing between $U(1)_N$ and $U(1)_Y$ in the gauge kinetic part of the Lagrangian

$$\mathcal{L}_{kin} = -\frac{1}{4}\left(F^Y_{\mu\nu}\right)^2 - \frac{1}{4}\left(F^N_{\mu\nu}\right)^2 - \frac{\sin\chi}{2} F^Y_{\mu\nu} F^N_{\mu\nu} - \ldots .$$

- It can be eliminated by a non–unitary transformation

$$B^Y_\mu = B_{1\mu} - B_{2\mu}\tan\chi\,, \qquad B^N_\mu = B_{2\mu}/\cos\chi\,.$$

  which changes the interaction between the $U(1)_N$ gauge field and matter fields so that

$$D_\mu = \partial_\mu - i g_1 Q^Y_i B_{1\mu} - i(g'_1 Q^N_i + g_{11} Q^Y_i) B_{2\mu} - \ldots,$$

  where

$$g_1 = g_Y\,, \quad g'_1 = g_N/\cos\chi\,, \quad g_{11} = -g_Y\tan\chi\,.$$

- The RG flow of the gauge couplings is affected by the kinetic term mixing

$$\frac{dg_2}{dt} = \frac{\beta_2 g_2^3}{(4\pi)^2}\,, \qquad\qquad \frac{dg_3}{dt} = \frac{\beta_3 g_3^3}{(4\pi)^2}\,,$$

$$\begin{aligned} \frac{dG}{dt} &= G \times B\,, \qquad G = \begin{pmatrix} g_1 & g_{11} \\ 0 & g_1' \end{pmatrix}, \\ B &= \frac{1}{(4\pi)^2}\begin{pmatrix} \beta_1 g_1^2 & 2g_1 g_1' \beta_{11} + 2g_1 g_{11}\beta_1 \\ 0 & g_1'^2\beta_1' + 2g_1' g_{11}\beta_{11} + g_{11}^2\beta_1 \end{pmatrix}, \end{aligned}$$

$$\beta_3 = 0\,, \quad \beta_2 = 4\,, \quad \beta_1 = \frac{48}{5}\,, \quad \beta_1' = \frac{47}{5}\,, \quad \beta_{11} = -\frac{\sqrt{6}}{5}\,.$$

- In the E_6 inspired models one can expect that

$$g_3(M_X) = g_2(M_X) = g_1(M_X) = g_1'(M_X) = g_0\,,$$
$$g_{11}(M_X) = 0\,.$$

- The hypothesis of the gauge coupling unification permits to evaluate

$$\begin{aligned} g_0 &\simeq 1.21\,, \qquad && M_X \simeq 2\cdot 10^{16}\,\mathrm{GeV}\,, \\ \frac{g_1(M_Z)}{g_1'(M_Z)} &\simeq 0.99\,, \qquad && g_{11}(M_Z) \simeq 0.020\,. \end{aligned}$$

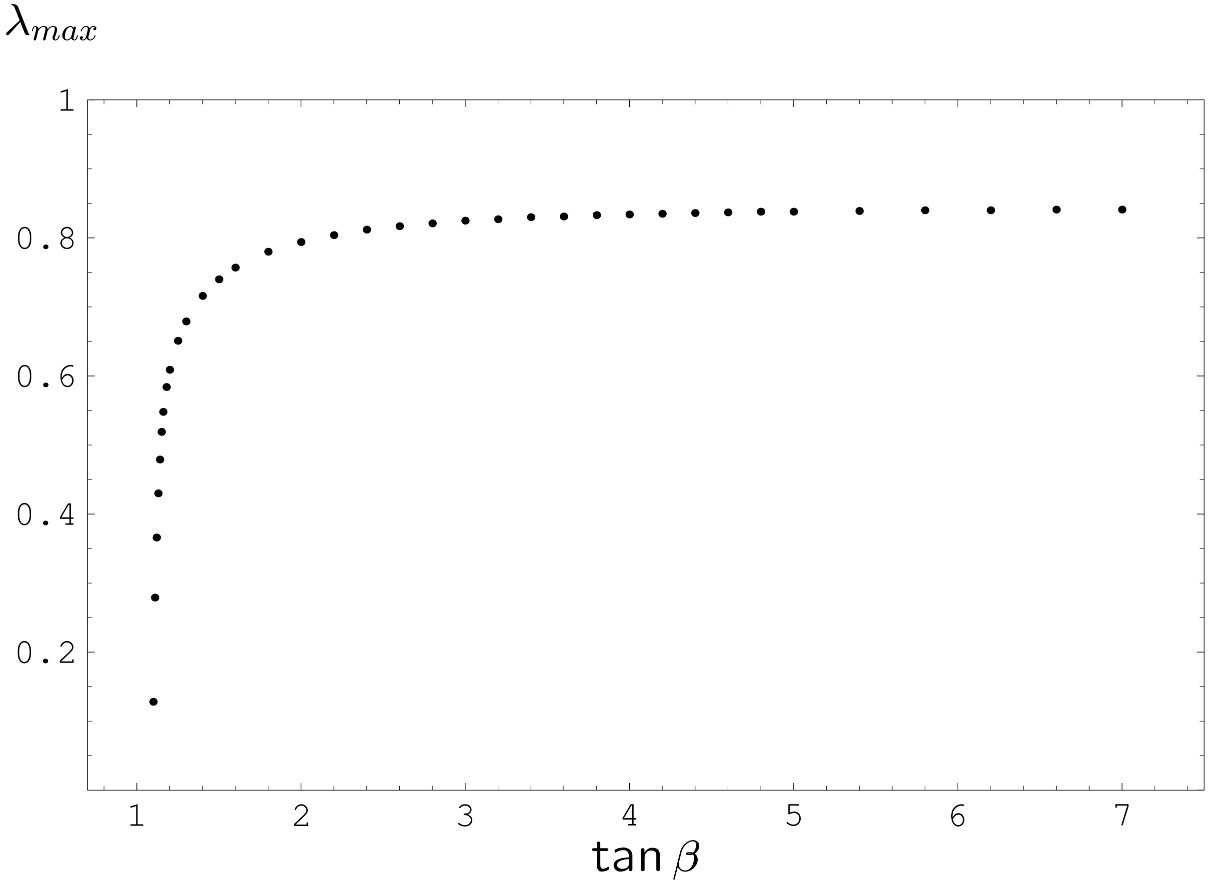
- The running of the Yukawa couplings obeys the RG equations

$$\begin{aligned} \frac{dh_t}{dt} &= \frac{h_t}{(4\pi)^2}\left[\lambda^2 + 6h_t^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2 - \frac{3}{10}g_1^{'2}\right], \\ \frac{d\lambda}{dt} &= \frac{\lambda}{(4\pi)^2}\left[4\lambda_i^2 + 3\Sigma_\kappa + 3h_t^2 - 3g_2^2 - \frac{3}{5}g_1^2 - \frac{19}{10}g_1^{'2}\right], \\ \frac{d\kappa_i}{dt} &= \frac{\kappa_i}{(4\pi)^2}\left[2\kappa_i^2 + 2\lambda^2 + 3\Sigma_\kappa - \frac{16}{3}g_3^2 - \frac{4}{15}g_1^2 - \frac{19}{10}g_1^{'2}\right], \end{aligned}$$

$$\Sigma_\kappa = \kappa_1^2 + \kappa_2^2 + \kappa_3^2\,, \qquad i = 1,\,2,\,3\,.$$

- The requirement of validity of perturbation theory up to $Q \simeq M_X$ restricts the interval of variations of Yukawa couplings at $Q \simeq M_t$.

- Whereas the restrictions on κ_i do not change much when $\tan\beta$ varies the upper limit on λ depends rather strongly on $\tan\beta$.



IV. Spectrum of the Higgs bosons

- The Higgs boson potential of the ESSM is given by

$$
\begin{aligned}
V &= V_F + V_D + V_{soft} + \Delta V\,, \\
V_F &= \lambda^2|S|^2(|H_d|^2+|H_u|^2) + \lambda^2|(H_d H_u)|^2\,, \\
V_D &= \frac{g_2^2}{8}\Big(H_d^+\sigma_a H_d + H_u^+\sigma_a H_u\Big)^2 + \frac{g'^2}{8}\Big(|H_d|^2-|H_u|^2\Big)^2 \\
&\quad + \frac{g_1^{'2}}{2}\Big(\tilde{Q}_1|H_d|^2 + \tilde{Q}_2|H_u|^2 + \tilde{Q}_S|S|^2\Big)^2\,, \\
V_{soft} &= m_S^2|S|^2 + m_1^2|H_d|^2 + m_2^2|H_u|^2 + \\
&\qquad + \Big[\lambda A_\lambda S(H_u H_d) + h.c.\Big]\,,
\end{aligned}
$$

  where $g' = \sqrt{3/5}\cdot g_1(M_Z)$.

- At the tree level it contains five fundamental parameters

$$\lambda\,, \quad m_1^2\,, \quad m_2^2\,, \quad m_S^2\,, \quad A_\lambda\,.$$

- At the physical vacuum

$$H_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \quad H_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \quad S = \frac{s}{\sqrt{2}},$$

$$v^2 = v_1^2 + v_2^2 = (246\,GeV)^2\,, \quad \tan\beta = v_2/v_1\,.$$

- From the conditions for the extrema

$$\frac{\partial V}{\partial v_1} = \frac{\partial V}{\partial v_2} = \frac{\partial V}{\partial s} = 0$$

  one can express soft masses m_1^2, m_2^2, m_s^2 via $\tan\beta$, s and v.

- Then tree level masses of the Higgs bosons depend on four variables:

$$\lambda\,, \qquad \tan\beta\,, \qquad s\,, \qquad A_\lambda\ (\text{or } m_A^2)\,.$$

- After the gauge symmetry breaking four goldstone modes are absorbed by W, Z and Z'.
- Thus the Higgs sector of the ESSM involves
  - one pseudoscalar $\qquad m_A^2 \simeq \dfrac{\sqrt{2}\lambda A_\lambda}{\sin 2\beta}\, s\,,$
  - two charged states $\qquad m_{H^\pm}^2 \simeq m_A^2\,,$
  - three scalars

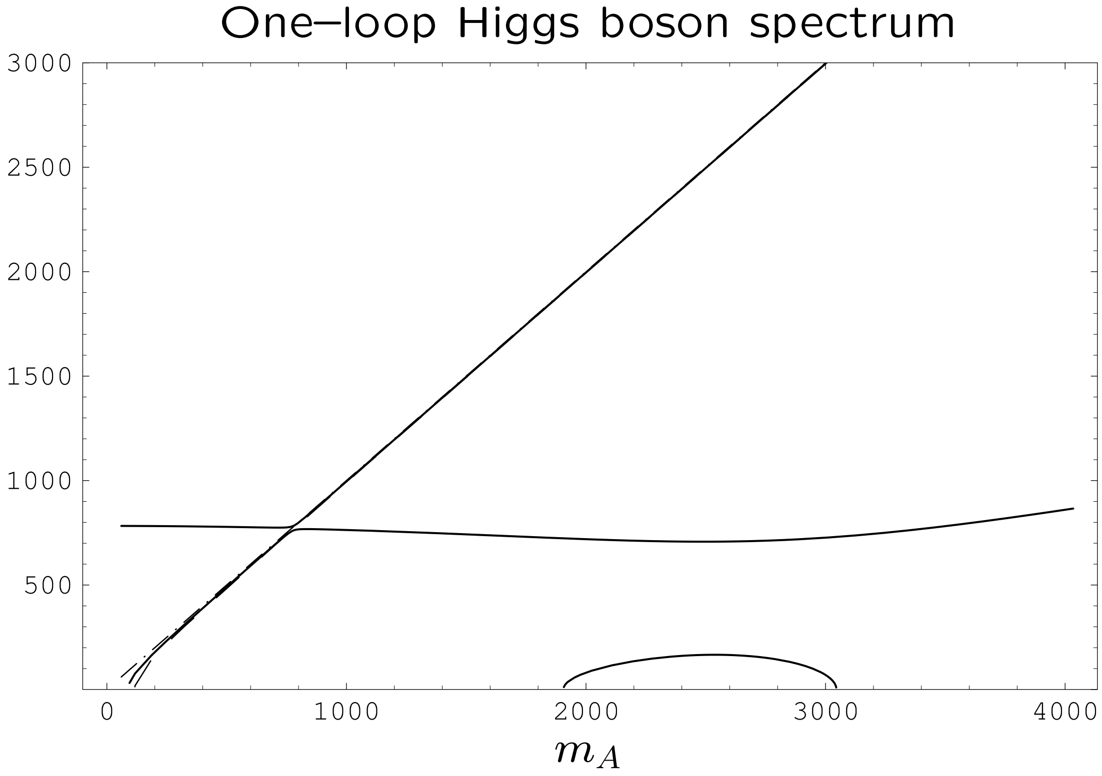
$$\begin{aligned} m_{h_1}^2 &\approx g_1^{'2}\tilde{Q}_S^2 s^2 \simeq M_{Z'}^2\,, \\ m_{h_2}^2 &\approx m_A^2\,, \\ m_{h_3}^2 &\leq \frac{\lambda^2}{2} v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \\ &\qquad + g_1^{'2} v^2 \Big(\tilde{Q}_1 \cos^2\beta + \tilde{Q}_2 \sin^2\beta\Big)^2\,. \end{aligned}$$

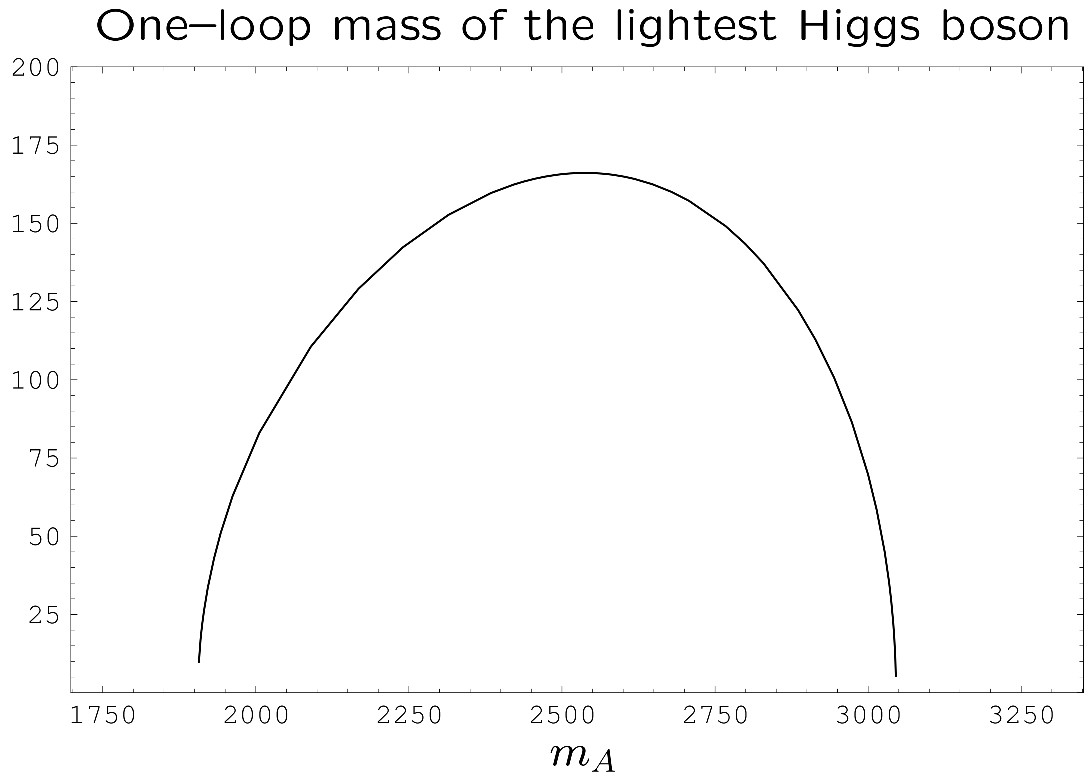
- One CP–even Higgs boson is always heavy because it has almost the same mass as Z'. From the direct searches at the Tevatron

$$M_{Z'} > 500 - 600\,\text{GeV}\,.$$

- Masses of another CP–even, CP–odd and charged Higgs bosons are very close to m_A.

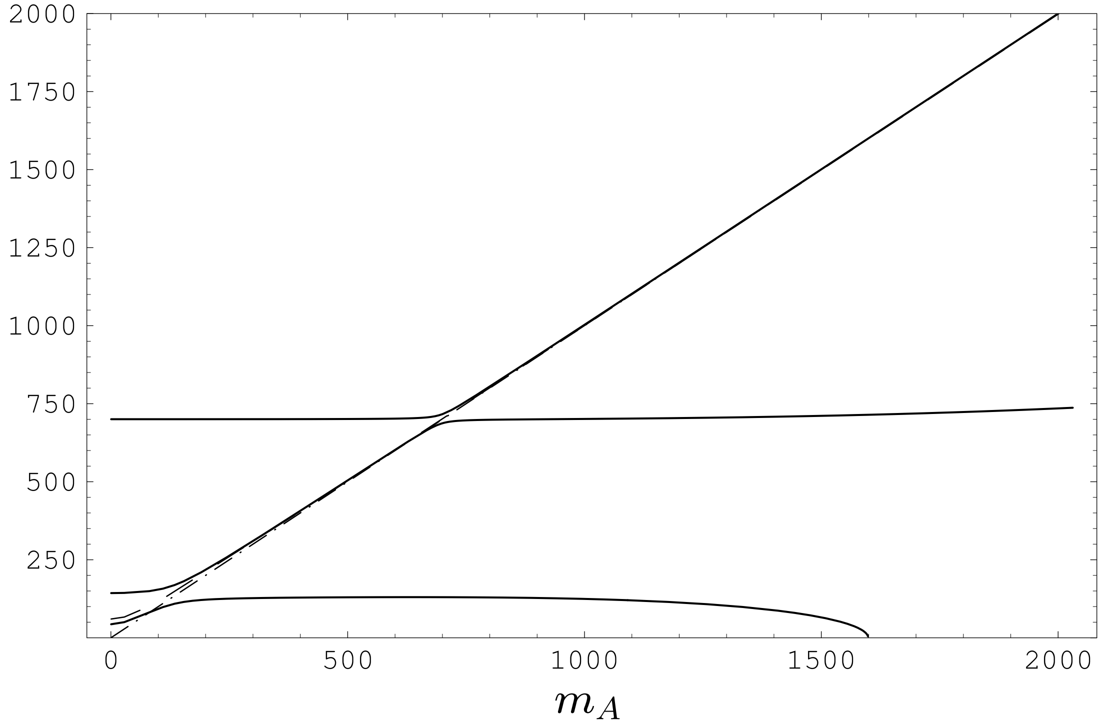
- When $\lambda > g_1^{'}$ the parameter of m_A is limited from below and above so that the Higgs spectrum has a hierarchical structure. For $\lambda = 0.79$, $\tan\beta = 2$, $X_t = \sqrt{6}M_S$ and $M_{Z'} = M_S = 700\,\text{GeV}$ we get


One–loop Higgs boson spectrum

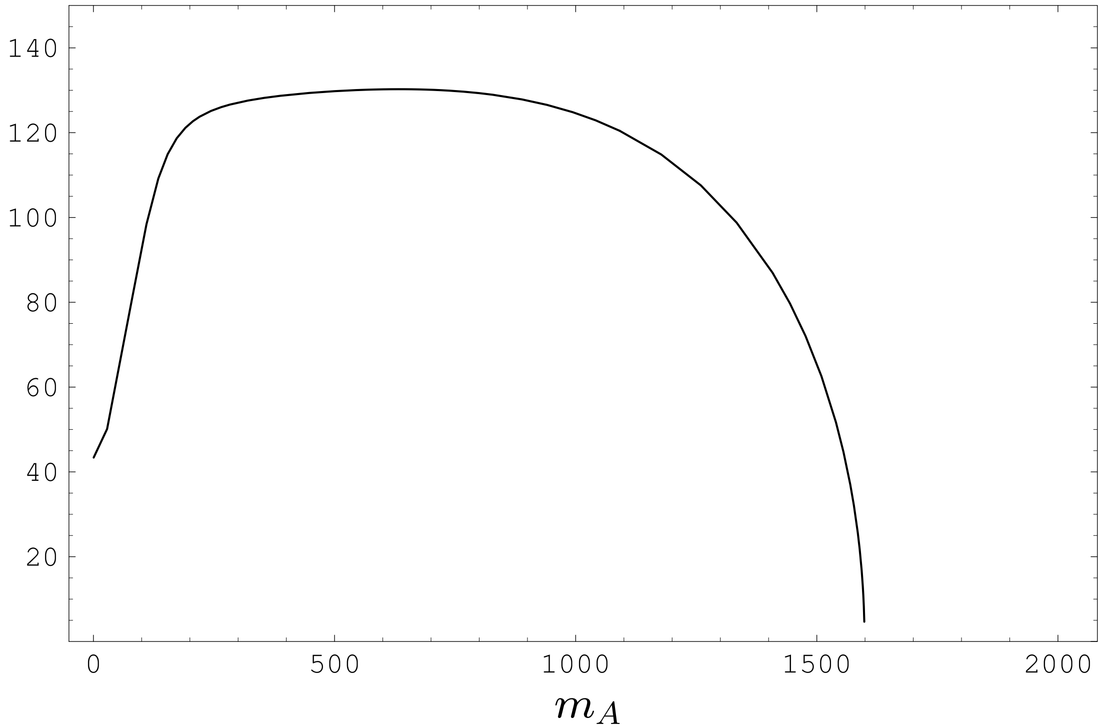

One–loop mass of the lightest Higgs boson

- For small values of λ ($\lambda < g_1^{'}$) m_A is bounded from above only so that some of the Higgs states may gain masses below 1 TeV. If $\lambda = 0.3$, $\tan\beta = 2$, $X_t = \sqrt{6} M_S$ and $M_{Z'} = M_S = 700\,\mathrm{GeV}$ we have

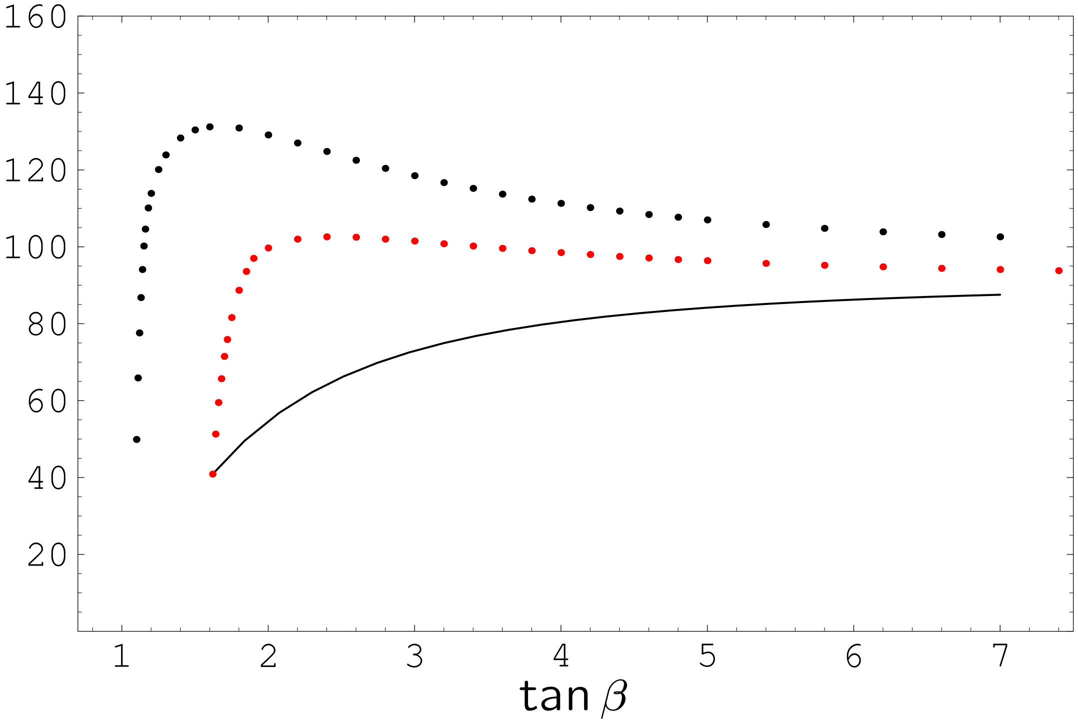
One–loop Higgs boson spectrum



One–loop mass of the lightest Higgs boson

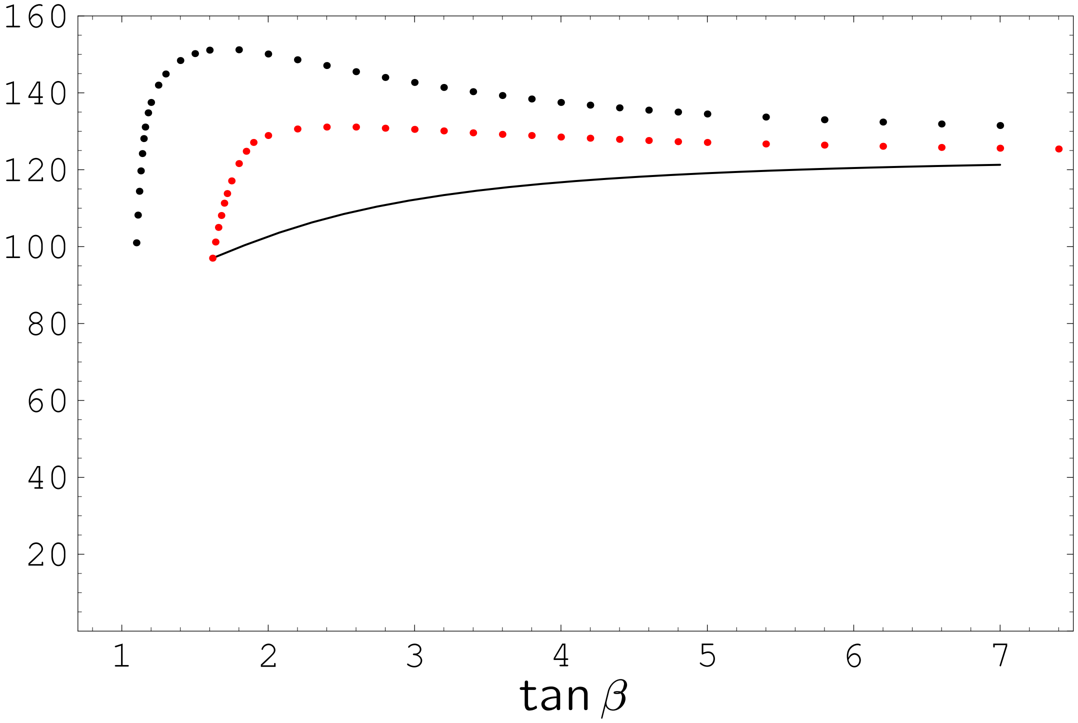


- Even at the tree level the lightest Higgs scalar in the ESSM can be heavier 120 GeV.



Tree level upper bound on m_{h_1}

- Two–loop theoretical restriction on m_{h_1} in the ESSM does not exceed $150-155$ GeV.



Two–loop upper bound on m_{h_1}

V. Collider phenomenology

- Z', exotic quarks and leptons may be produced at future colliders.

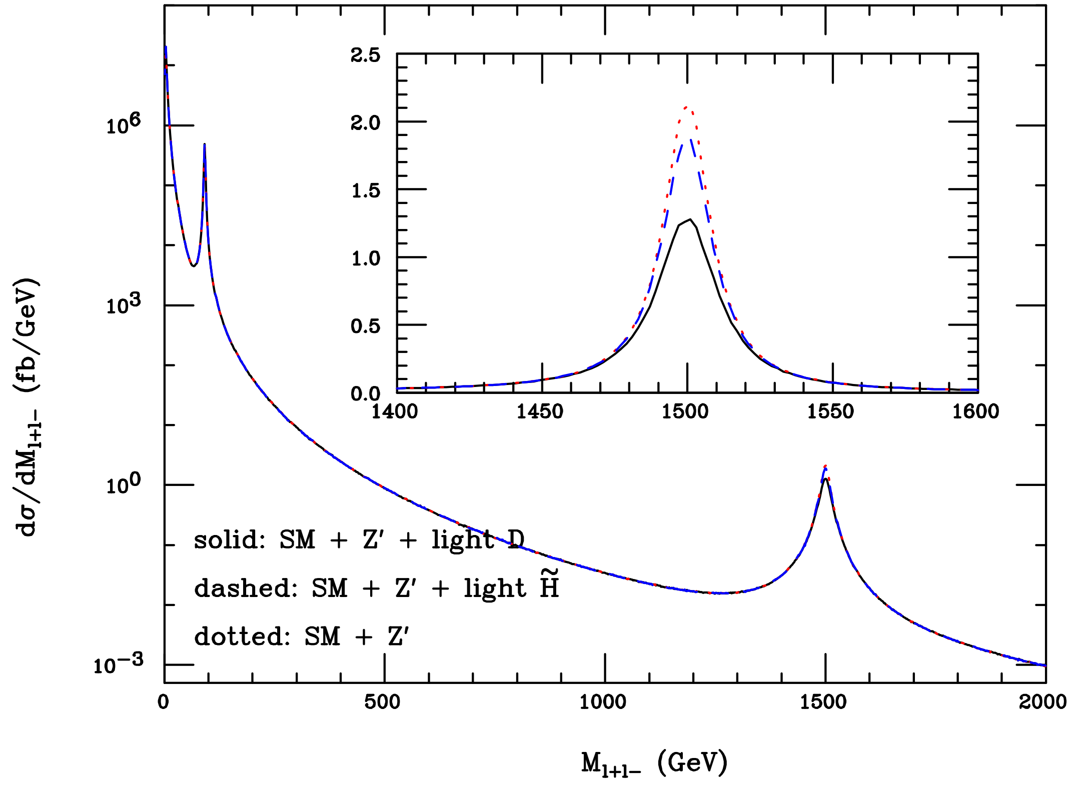
- At the LHC the Z' boson can be discovered if it has a mass below $4 - 4.5\,\text{TeV}$.

A.Leike, Phys.Rept. 317 (1999) 143;
J.Kang, P.Langacker, Phys.Rev.D 71 (2005) 035014.

- Its diagnostic via asymmetries should be possible up to $M_{Z'} \simeq 2 - 2.5\,\text{TeV}$.

M.Dittmar, A.Nicollerat, A-S.Djouadi, Phys.Lett.B 583 (2004) 111.

Cross section for Drell-Yan production at the LHC



- The hierarchical structure of the Yukawa interactions in the ESSM implies that exotic particles decay predominantly into the quarks and leptons of the third generation.

- The exotic quarks decay either via

  $$\overline{D} \to t + \tilde{b}\,, \qquad \overline{D} \to b + \tilde{t}$$

  if exotic quarks $\overline{D}_i$ are diquarks or via

  $$\begin{array}{ll} D \to t + \tilde{\tau}\,, & D \to \tau + \tilde{t}\,, \\ D \to b + \tilde{\nu}_{\tau}\,, & D \to \nu_{\tau} + \tilde{b}\,, \end{array}$$

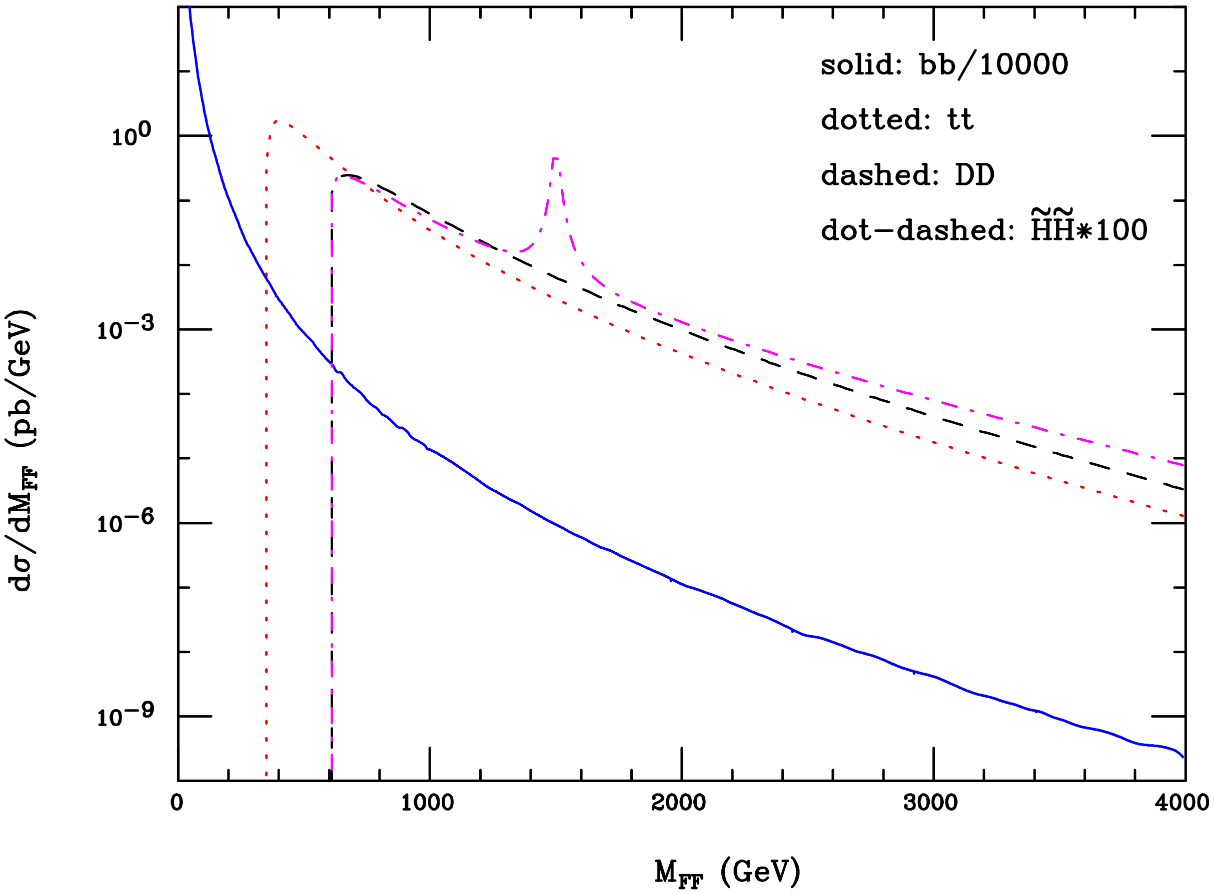
  if exotic quarks D_i are leptoquarks.

- The non–Higgsino decay modes are

  $$\begin{array}{ll} \tilde{H}^0 \to t + \tilde{\bar{t}}\,, & \tilde{H}^0 \to \bar{t} + \tilde{t}\,, \\ \tilde{H}^0 \to b + \tilde{\bar{b}}\,, & \tilde{H}^0 \to \bar{b} + \tilde{b}\,, \\ \tilde{H}^0 \to \tau + \tilde{\bar{\tau}}\,, & \tilde{H}^0 \to \bar{\tau} + \tilde{\tau}\,, \\ \tilde{H}^- \to b + \tilde{\bar{t}}\,, & \tilde{H}^- \to \bar{t} + \tilde{b}\,, \\ \tilde{H}^- \to \tau + \tilde{\bar{\nu}}_{\tau}\,, & \tilde{H}^- \to \bar{\nu}_{\tau} + \tilde{\tau}\,. \end{array}$$

- Assuming that $\tilde{f} \to f + \chi^0$ the exotic quark will produce either t– and b–quarks or t–quark and τ–lepton in the final state with rather high probability.

Cross section for pair production of b, t and exotic particles at the LHC



- Since $\sigma(pp \to D\overline{D} + X)$ may be comparable with $\sigma(pp \to t\bar{t} + X)$ the presence of light exotic quark will result in appreciable enhancement of the cross section of either

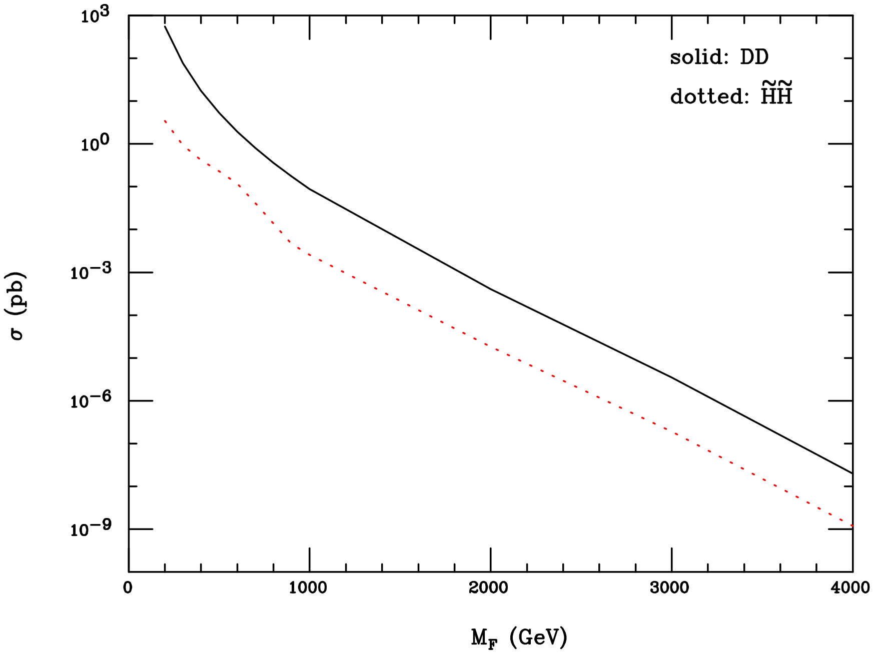
$$pp \to t\bar{t}b\bar{b} + X\,, \qquad pp \to b\bar{b}b\bar{b} + X$$

if exotic quarks are diquarks or

$$pp \to t\bar{t}l\bar{l} + X\,, \qquad pp \to b\bar{b}l\bar{l} + X$$

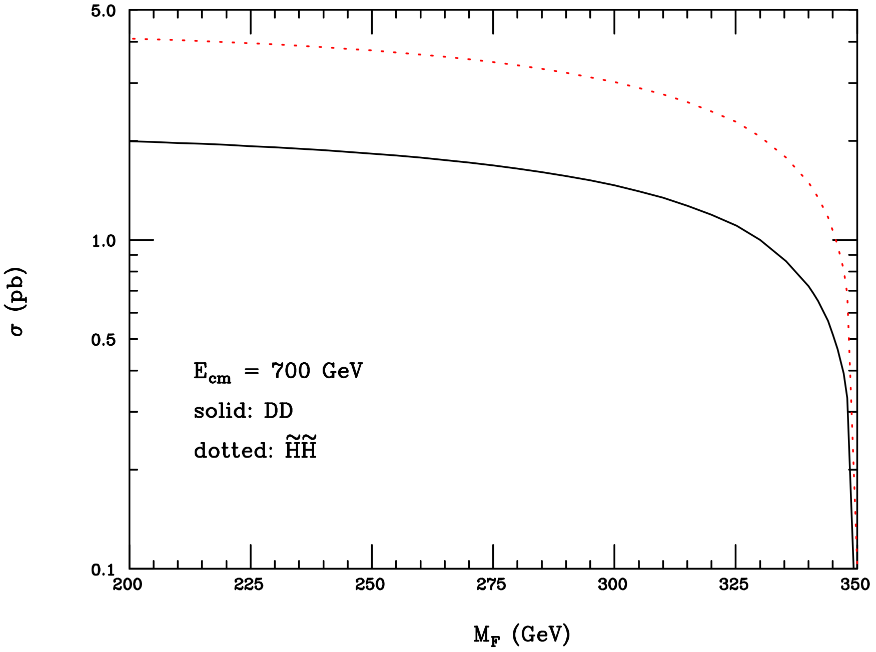
if new quark states are leptoquarks.

Cross section for pair production of exotic particles at the LHC



- While at the LHC $\sigma(pp \to \tilde{H}\overline{\tilde{H}} + X)$ is expected to be considerably smaller than $\sigma(pp \to D\overline{D} + X)$ they become comparable at the ILC.

Cross section for pair production of exotic quarks and leptons at future ILC



VI. Conclusions

- We have presented a self–consistent supersymmetric model with additional $U(1)_N$ factor which naturally arises after the breakdown of E_6 symmetry.

- The SM like Higgs boson in the ESSM is lighter than $150 - 155\,\text{GeV}$ and can be considerably heavier than in the MSSM and NMSSM.

- When the lightest Higgs scalar is relatively heavy the masses of the charged, CP–odd and heaviest CP–even Higgs states are almost degenerate and very large

$$m_{H^{\pm}} \simeq m_A \simeq m_H \gtrsim 1\,\text{TeV}\,.$$

- The possible manifestations of the considered model at the LHC are enhanced production of $l^{+}l^{-}$, $t\bar{t}$ or $b\bar{b}$ pairs coming from either Z' boson or exotic particle decays.

- The discovery at future colliders of the exotic particles and extra Z' boson predicted by the ESSM would provide circumstantial evidence for superstring theory.