Supersymmetric extensions of the Standard Model

M. Maniatis

Cosmoconce Concepción 2013

Motivation for SUSY

- Every fermion is paired with a boson and vice versa.
- SUSY is the invariance of the Lagrangian under
  $Q\,|boson\rangle = |fermion\rangle, \qquad Q\,|fermion\rangle = |boson\rangle.$
- Boson–fermion pairs build supermultiplets with same behavior under gauge groups.
- Non-gauge interactions are determined by one function, the superpotential.

- Local SUSY connected to gravity.
- Unification of couplings at scale $m_{GUT} \approx 2 \times 10^{16}$ GeV.
- *Lightest Supersymmetric Particle* (LSP) candidate for dark matter.
- Solution for the naturalness problem

- In the SM we have one Higgs doublet.

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

- SM Higgs potential.

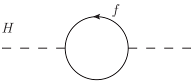
$$V = -m_H^2 (H^\dagger H) + \lambda (H^\dagger H)^2$$

- Spontaneously broken symmetry
  for $m_H^2 > 0$ and $\lambda > 0$,

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v = \sqrt{m_H^2/(2\lambda)}$$

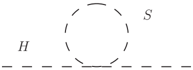
- Electroweak data $v \approx 246$ GeV.
  We expect m_H at electroweak scale.

- Quantum corrections to Higgs-boson mass:
- A fermion loop with $\mathcal{L} = -\lambda_f H \bar{f} f$ gives



$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2} \left[-2\Lambda_{UV}^2 + 6 m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots \right]$$

- A scalar boson loop with $\mathcal{L} = -\lambda_S |H|^2 |S|^2$



$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \left[\Lambda_{UV}^2 - 2 m_S^2 \ln(\Lambda_{UV}/m_S) + \ldots \right]$$

- A fermion loop and two corresponding boson loops $\Delta m_H^2 = \frac{1}{8\pi^2} \left(\lambda_S - |\lambda_f|^2 \right) \Lambda_{UV}^2 + \ldots .$
- For $\lambda_S \overset{!}{=} |\lambda_f|^2$ quadratic divergences cancel!

The MSSM

- SM extended by minimal number of *superpartners*.
- Particle content, chiral- and gauge- supermultiplets

chiral supermultiplets		spin-0	spin-1/2	$SU_C(3)$	$SU_L(2)$	$U_Y(1)$
quark–squark	$\hat{Q}$	$\tilde{Q} = (\tilde{u}_L,\ \tilde{d}_L)^{\mathrm{T}}$	$Q = (u_L,\ d_L)^{\mathrm{T}}$	**3**	**2**	$1/6$
	$\hat{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	**3**	**1**	$-2/3$
	$\hat{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	**3**	**1**	$1/3$
lepton–slepton	$\hat{L}$	$\tilde{L} = (\tilde{\nu}_e,\ \tilde{e}_L)^{\mathrm{T}}$	$L = (\nu_e,\ e_L)^{\mathrm{T}}$	**1**	**2**	$-1/2$
	$\hat{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	**1**	**1**	1
Higgs–Higgsino	$\hat{H}_u$	$H_u = (H_u^+,\ H_u^0)^{\mathrm{T}}$	$\tilde{H}_u = (\tilde{H}_u^+,\ \tilde{H}_u^0)^{\mathrm{T}}$	**1**	**2**	$1/2$
	$\hat{H}_d$	$H_d = (H_d^0,\ H_d^-)^{\mathrm{T}}$	$\tilde{H}_d = (\tilde{H}_d^0,\ \tilde{H}_d^-)^{\mathrm{T}}$	**1**	**2**	$-1/2$

gauge supermultiplets	spin-1/2	spin-1	$SU_C(3)$	$SU_L(2)$	$U_Y(1)$
gluon–gluino	$\tilde{g}$	g	**8**	**1**	0
W-boson–wino	$\tilde{W}^\pm,\ \tilde{W}^0$	$W^\pm,\ W^0$	**1**	**3**	0
B-boson–bino	$\tilde{B}^0$	B^0	**1**	**1**	0

- Two Higgs doublets needed to give masses to up- and down-type fermions.
- Two doublets

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

correspond after EWSB to physical Higgs bosons

$$H_1, H_2, A, H^\pm$$

The μ problem in the MSSM

- MSSM superpotential

$$W = \hat{u} y_u \hat{Q} \hat{H}_u - \hat{d} y_d \hat{Q} \hat{H}_d - \hat{e} y_e \hat{L} \hat{H}_d + \mu \hat{H}_u \hat{H}_d$$

- The parameter μ has mass dimension.
- In the MSSM, μ has to be adjusted to EW scale before EWSB occurs.

- Lightest CP-even Higgs boson mass bound

$$m_{H_1}^2 < m_Z^2 \cos^2(2\beta)$$

- With regard to LHC

$$m_{H_1} \approx 126 \text{ GeV}$$

- Even taking quantum corrections into account

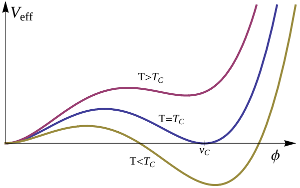
$$\Delta m_{H_1}^2 = c \frac{m_t^4}{v^2} \ln \left(\frac{m_{\tilde{t}_L} m_{\tilde{t}_R}}{m_t^2} \right)$$

very large masses $m_{\tilde{t}_{L/R}}$ required!

Baryogenesis via EWPT

- Absence of antimatter may be generated by strong EWPT.

  V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, PLB155, '85 M.E. Shaposhnikov, NPB287, '87
- Phase transitions are characterized by an *order parameter* which changes at a critical temperature T_c.
- First order electroweak phase transitions.



- *Strong* EWPT avoid a wash-out of generated baryon asymmetry. $\frac{v_c}{T_c} > \xi \approx 1$ M. Dine et al.,PLB283, '92 M. Dine et al.,PRD46, '92

- Consider effective Higgs potential

$$V_{\text{eff}} = m^2\phi^2 - \alpha\phi^3 + \beta\phi^4$$

- Degenerate minima with symmetry breaking minimum at v_c for

$$v_c = \frac{\alpha}{2\beta}$$

- Cubic α-term needed.
- In the SM only generically small loop contributions give a cubic term. The strong condition $v_c/T_c > 1$ translates to

$$m_H^{\text{SM}} < 32 \text{ GeV}$$

- Similar in MSSM: strong EWPT rely on loop contributions. It turns out this can only happen for J.M. Cline, G.D. Moore, PRL81, '98 M.S. Carena, M. Quiros, C.E.M. Wagner, PLB380, '96

$$m_{\tilde{t}_R} < m_t << m_{\tilde{t}_L}$$

- Unnatural mass hierarchy!

The NMSSM

- Additional Higgs singlet $\hat{S}$.

  P. Fayet, NPB90 '75 M. Dine, W. Fischler, M. Srednicki, PLB104, '81
  H.P. Nilles, M. Srednicki, D. Wyler, PLB120, '83

  For reviews see: M. Maniatis IJMPA, '10 or U. Ellwanger et al, PR496 '10

$$W_{\text{NMSSM}} = \hat{u} y_u \hat{Q} \hat{H}_u - \hat{d} y_d \hat{Q} \hat{H}_d - \hat{e} y_e \hat{L} \hat{H}_d + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3$$

- Spontaneous broken $\langle S \rangle = v_S$ gives required $\mu_{\mathit{eff}} = \lambda v_S$.
- κ term to avoid additional $U(1)'$.

The NMSSM

- Additional Higgs singlet $\hat{S}$.

P. Fayet, NPB90 '75 M. Dine, W. Fischler, M. Srednicki, PLB104, '81
H.P. Nilles, M. Srednicki, D. Wyler, PLB120, '83

For reviews see: M. Maniatis IJMPA, '10 or U. Ellwanger et al, PR496 '10

$$W_{\text{NMSSM}} = \hat{u} y_u \hat{Q} \hat{H}_u - \hat{d} y_d \hat{Q} \hat{H}_d - \hat{e} y_e \hat{L} \hat{H}_d + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3$$

- Spontaneous broken $\langle S \rangle = v_S$ gives required $\mu_{eff} = \lambda v_S$.
- κ term to avoid additional $U(1)'$.

The NMSSM

- Additional Higgs singlet $\hat{S}$.

  P. Fayet, NPB90 '75 M. Dine, W. Fischler, M. Srednicki, PLB104, '81
  H.P. Nilles, M. Srednicki, D. Wyler, PLB120, '83

  For reviews see: M. Maniatis IJMPA, '10 or U. Ellwanger et al, PR496 '10

$$W_{\text{NMSSM}} = \hat{u} y_u \hat{Q} \hat{H}_u - \hat{d} y_d \hat{Q} \hat{H}_d - \hat{e} y_e \hat{L} \hat{H}_d + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3$$

- Spontaneous broken $\langle S \rangle = v_S$ gives required $\mu_{eff} = \lambda v_S$.
- κ term to avoid additional $U(1)'$.

- Two doublets and one singlet

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \qquad S$$

correspond after EWSB to physical Higgs bosons

$$H_1, H_2, H_3, H_4, H_5, H^{\pm}.$$

Particle content, chiral- and gauge- supermultiplets

chiral supermultiplets		spin-0	spin-1/2	$SU_C(3)$	$SU_L(2)$	$U_Y(1)$
quark–squark	$\hat{Q}$	$\tilde{Q} = (\tilde{u}_L,\ \tilde{d}_L)^{\mathrm{T}}$	$Q = (u_L,\ d_L)^{\mathrm{T}}$	**3**	**2**	$1/6$
	$\hat{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	**3**	**1**	$-2/3$
	$\hat{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	**3**	**1**	$1/3$
lepton–slepton	$\hat{L}$	$\tilde{L} = (\tilde{\nu}_e,\ \tilde{e}_L)^{\mathrm{T}}$	$L = (\nu_e,\ e_L)^{\mathrm{T}}$	**1**	**2**	$-1/2$
	$\hat{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	**1**	**1**	1
Higgs–Higgsino	$\hat{H}_u$	$H_u = (H_u^+,\ H_u^0)^{\mathrm{T}}$	$\tilde{H}_u = (\tilde{H}_u^+,\ \tilde{H}_u^0)^{\mathrm{T}}$	**1**	**2**	$1/2$
	$\hat{H}_d$	$H_d = (H_d^0,\ H_d^-)^{\mathrm{T}}$	$\tilde{H}_d = (\tilde{H}_d^0,\ \tilde{H}_d^-)^{\mathrm{T}}$	**1**	**2**	$-1/2$
	$\hat{S}$	S	$\tilde{S}$	**1**	**1**	0

gauge supermultiplets	spin-1/2	spin-1	$SU_C(3)$	$SU_L(2)$	$U_Y(1)$
gluon–gluino	$\tilde{g}$	g	**8**	**1**	0
W-boson–wino	$\tilde{W}^\pm,\ \tilde{W}^0$	$W^\pm,\ W^0$	**1**	**3**	0
B-boson–bino	$\tilde{B}^0$	B^0	**1**	**1**	0

1 The NMSSM solves μ-problem.

$$W_{\text{NMSSM}} = \hat{u} y_u \hat{Q} \hat{H}_u - \hat{d} y_d \hat{Q} \hat{H}_d - \hat{e} y_e \hat{L} \hat{H}_d + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3$$

Spontaneous broken $\langle S \rangle = v_S$ gives required $\mu_{eff} = \lambda v_S$.

2 Lower upper mass bound in the NMSSM

$$(m_{H_1}^{\text{NMSSM}})^2 < m_Z^2 \left(\cos^2(2\beta) + \frac{2\lambda^2 \sin^2(2\beta)}{g_1^2 + g_2^2} \right)$$

3 EWPT possible in the NMSSM

- Consider effective Higgs potential

$$V_{\text{eff}} = m^2\phi^2 - \alpha\phi^3 + \beta\phi^4$$

- Degenerate minima with symmetry breaking minimum at v_c for

$$v_c = \frac{\alpha}{2\beta}$$

- Cubic α-term needed.
- We have cubic terms at tree level M. Pietroni, NPB402, '93

$$V_{\text{soft, trilinear}} = \lambda A_\lambda (H_u^{\mathrm{T}} \epsilon H_d) S + \frac{\kappa}{3} A_\kappa S^3 + c.c.$$

- From parameter scans it is found

$$m_{H_1}^{\text{NMSSM}} < 170 \text{ GeV}$$

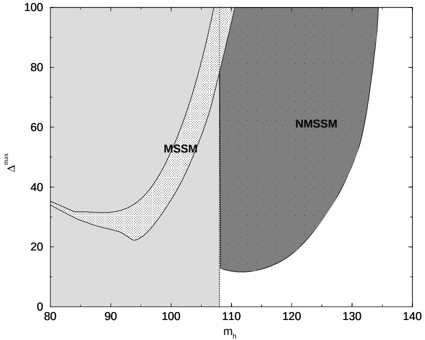
4 In general much less fine tuning

- Quantification of fine tuning R. Barbieri, G.F. Giudice, NPB306, '88

$$\Delta^{\max} = \max_{a_i} \left| \frac{a_i}{m_Z^2(a_i)} \frac{\mathrm{d}\, m_Z^2}{\mathrm{d}\, a_i} \right| ,$$

a_i denotes all soft-breaking parameters.

- Comparison of $\Delta^{\max}$ at $\tan(\beta) = 3$. M. Bastero-Gil et al.,PLB489, '00



Oblique parameters S, T, U

- Confront NMSSM with EW precision measurements.

- EW sector parameterized by 3 oblique parameters S, T, U under condtions:

  M. E. Peskin, T. Takeuchi PRL65, '90 D. C. Kennedy, P. Langacker, PRL65, '90

  - New model obeys $SU(2)_L \otimes U(1)_Y$ gauge symmetry.
  - Couplings of new particles to light fermions suppressed.
  - New physics enters far beyond EW scale

- Last condition may be dropped (V, W, X).

- Explicit expressions for S, T, U

$$S = \frac{4s_W^2 c_W^2}{\alpha}\left[\frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} - \frac{c_W^2 - s_W^2}{s_W c_W}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right]$$

$$T = \frac{1}{\alpha}\left[\frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}\right],$$

$$U = \frac{4s_W^2}{\alpha}\left[\frac{\Pi_{WW}(m_W^2) - \Pi_{WW}(0)}{m_W^2} - c_W^2\frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} - 2s_W c_W \Pi'_{Z\gamma}(0) - s_W^2\Pi'_{\gamma\gamma}(0)\right]$$

with $\Pi_{G_1G_2}(s) = \Pi^{\text{new}}_{G_1G_2}(s) - \Pi^{\text{SM}}_{G_1G_2}(s)$ and $G_{1/2} \in \{\gamma, W, Z\}$

- EW Precision Measurements for S, T, U J. Beringer et al., PRD86 '12

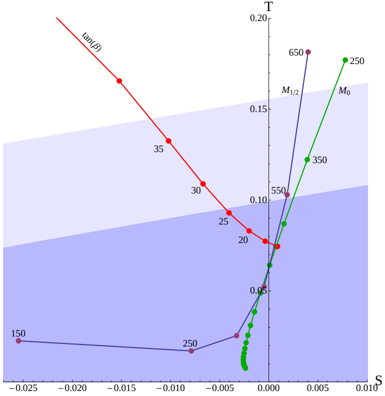
$$S = 0.01 \pm 0.1, \quad T = 0.03 \pm 0.11, \quad \rho = 0.87.$$

- Calculation of S, T, U (V, W, X) in the NMSSM

  M. Maniatis, Y. Schröder, AHEP '13

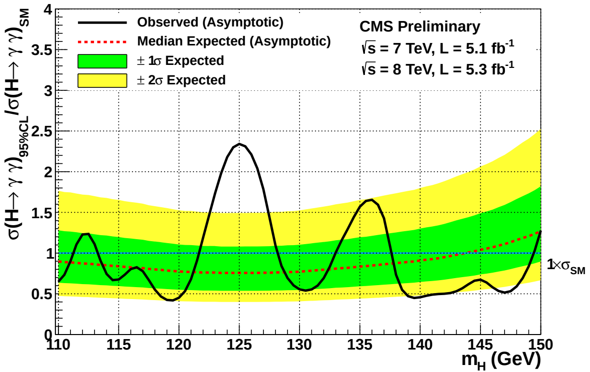
- Example of parameters

M_0^{GUT}	$M_{1/2}^{\text{GUT}}$	A_0^{GUT}	A_κ^{GUT}	$\tan(\beta)^{\text{MSUSY}}$	$\text{sgn}(\mu)$	λ^{MSUSY}
500	500	-800	-100	5	$+$	0.15



- Enhancement of the $H \to \gamma\gamma$ channel observed.

CMS PAS HIG-12-015, ’12



Conclusions

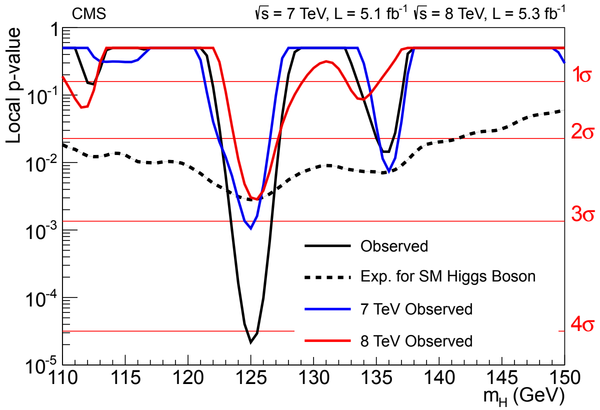
- Supersymmetry is an appealing extension.
- The MSSM in unsatisfactory.
- The NMSSM could be realized by Nature!
- Thank you very much for your attention!

- What are the consequences of the singlet $\hat{S}$?
- After mixing, taking singlet $\hat{S}$ into account.

bosons	gauge eigenstates	mass eigenstates
sleptons	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_e$ $\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_\mu$ $\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_\tau$	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_e$ $\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_\mu$ $\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_\tau$
squarks	$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$ $\tilde{c}_L, \tilde{c}_R, \tilde{s}_L, \tilde{s}_R$ $\tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R$	$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$ $\tilde{c}_L, \tilde{c}_R, \tilde{s}_L, \tilde{s}_R$ $\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$
Higgs bosons	H_d^0, H_u^0, S H_d^-, H_u^+	H_1, H_2, H_3, H_4, H_5 $(H_1, H_2, H_3, A_1, A_2)$ $H^\pm$
fermions		
neutralinos	$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0, \tilde{S}$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$
charginos	$\tilde{W}^\pm, \tilde{H}_d^-, \tilde{H}_u^+$	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$
gluino	$\tilde{g}$	$\tilde{g}$

- Enhancement of the $H \to \gamma\gamma$ channel observed.

CMS PAS HIG-12-015, '12



Matter parity

- Most general superpotential W introduces lepton and baryon number violating terms.
- Matter parity/ R-parity $P_R = (-1)^{3(B-L)+2s}$,
- Consequences of R-parity
  - LSP stable.
  - Signatures of missing E_T
- SUSY breaking with $\mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{soft}$, Mass terms, couplings with positive mass dimension.
- Additional radiative corrections $\Delta m_H^2 = m_{soft}^2 \left[\frac{\lambda}{16\pi^2} \ln(\Lambda_{UV}/m_{soft}) + \ldots\right]$

Superpotential

- All non-gauge interactions determined by one function W, the superpotential.

$$W = \frac{1}{2}\mu^{ij}\phi_i\phi_j + \frac{1}{6}\lambda^{ijk}\phi_i\phi_j\phi_k$$

$$\mathcal{L}_{\text{chiral, int}} = -\frac{1}{2}W^{ij}\psi_i\psi_j - W^i W_i + c.c.$$

with

$$W^i = \frac{\delta W}{\delta \phi_i} = \mu^{ij}\phi_j + \frac{1}{2}\lambda^{ijk}\phi_j\phi_k\ , \quad W^{ij} = \frac{\delta^2 W}{\delta\phi_i\delta\phi_j} = \mu^{ij} + \lambda^{ijk}\phi_k$$

- 2002: *"Establishing a No-Lose Theorem for NMSSM Higgs Boson Discovery at the LHC"*

  U. Ellwanger, J.F. Gunion, C. Hugonie, hep-ph/0111179

1) $gg \to H \to \gamma\gamma$,
2) WH or $t\bar{t}H$ production with $\gamma\gamma l^{\pm}$ in the final state ,
3) $t\bar{t}H$ with $H \to b\bar{b}$,
4) $gg \to H/A$ or $b\bar{b}H/A$ production with $H/A \to \tau\bar{\tau}$,
5) $gg \to H \to ZZ^* \to$ 4 leptons ,
6) $gg \to H \to WW^* \to l^+ l^- \nu\bar{\nu}$,
7) at LEP2: $e^+e^- \to ZH$ and $e^+e^- \to HA$,
8) $WW \to H \to \tau\bar{\tau}$,
9) $WW \to H \to WW^*$,

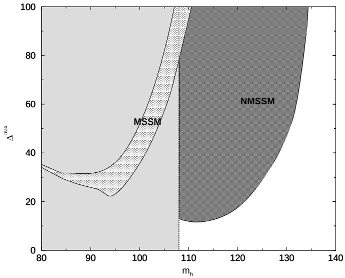
with $H \in \{H_1, H_2, H_3\}$ and $A \in \{A_1, A_2\}$.

- Based on these channels, they state:
  At least one Higgs at 300 fb^{-1} with 5-σ.

- But, certain decay channels are suppressed in their analysis:
  $H \to HH/AA/H^+H^-/AZ$,
  $A \to HA/HZ$,
  $H/A \to H^\pm W^\mp/t\bar{t}$,
  $t \to H^+ b$.
- 2003: *"Towards a no-lose theorem for NMSSM Higgs discovery at the LHC"* U. Ellwanger, hep-ph/0305109
  Added channel $WW \to H \to AA$.

- 2005: *"Difficult scenarios for NMSSM Higgs discovery at the LHC"* U. Ellwanger, J.F. Gunion, C. Hugonie, JHEP07, '05
  Parameter scan with
  $m_{H^\pm} > 155$ GeV to suppress $t \to H^\pm b$,
  High universal soft-breaking masses.
- Sets not belonging not 1) - 9) found, where no detection is possible.
- Example 1
  - Dominant $\mathrm{BR}(H_2 \to H_1 H_1) = 0.93$
  - H_1 is mostly H_u^0-like and thus ~~$H_1 \to b\bar{b}/\tau^+\tau^-$~~.
  - Therefore ~~$WW \to H_2 \to 2j\ \tau^+\tau^-$~~
  - $WW \to H_2 \to 4j$
- Example 2
  - Dominant $\mathrm{BR}(H_1 \to A_1 A_1)$ with $m_{A_1} \approx 1$ GeV.

- 2008: *"Reinstating the 'no-lose' theorem for NMSSM Higgs discovery at the LHC"* J.R. Forshaw et al., JHEP04, '08
  Additional assumption: absence of large fine-tuning.
- Quantification of fine-tuning R. Barbieri, G.F. Giudice, NPB306, '88
  $\Delta^{\text{max}} = \max_{a_i} \left| \frac{a_i}{m_Z^2(a_i)} \frac{\mathrm{d}\, m_Z^2}{\mathrm{d}\, a_i} \right| ,$
  a_i denotes all soft-breaking parameters.
- Comparison of Δ^{max} at $\tan(\beta) = 3$. M. Bastero-Gil et al.,PLB489, '00



The fifth neutralino $\tilde{S}$

- One more neutralino in the NMSSM, the $\tilde{S}$.
- Mixing in the basis $\psi^0 = (\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})^{\mathrm{T}}$,

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z & 0 \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z & 0 \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\lambda v_s/\sqrt{2} & -\lambda v_u/\sqrt{2} \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\lambda v_s/\sqrt{2} & 0 & -\lambda v_d/\sqrt{2} \\ 0 & 0 & -\lambda v_u/\sqrt{2} & -\lambda v_d/\sqrt{2} & \sqrt{2}\kappa v_s \end{pmatrix}$$

- Mass eigenstates are ordered, $m_{\tilde{\chi}_1^0} < \ldots < m_{\tilde{\chi}_5^0}$.
- Detection of a fifth neutralino is clear signal for extension of MSSM.
- In case of small mixing of $\tilde{S}$ with Higgsinos, $\tilde{S}$ decouples, $m_{\tilde{S}}^2 \approx 2\kappa^2 v_s^2$.
- For large $m_{\tilde{S}}$, detection difficult.

SUSY Generators

- Possible forms of supersymmetry operators restricted by Haag-Lopuszanski-Sohnius extension of Coleman-Mandula theorem.

Coleman, Mandula, 1967; Haag, Lopuszanski, Sohnius, 1975

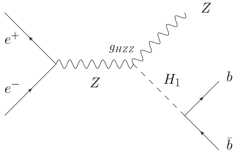
$$
\begin{aligned}
\{Q_a, \bar{Q}_b\} &= 2\,\gamma^{\mu}_{ab} P_{\mu} \\
[P^{\mu}, Q_a] &= 0 \\
[M^{\mu\nu}, Q_a] &= -\Sigma^{\mu\nu}_{ab}\; Q_b
\end{aligned}
$$

  - SUSY is connected to space-time TL.
  - Q's transform as spinors under Lorentz TF.
  - # bosonic d.o.f = # fermionic d.o.f

- Measurement gives in addition a weaker bound in the NMSSM OPAL Coll., EPJC27, '03

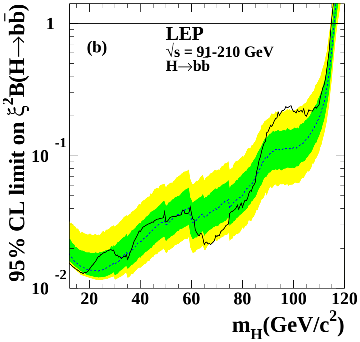
$$m_{H_1}^{\text{(N)MSSM, exp}} > 82 \text{ GeV}$$

- Detection is based on b-tagging in SM/MSSM



- In NMSSM, new decay channels $H_1 \to A_1 A_1$.
- In case of $m_{A_1} < 2m_b$, $A_1 \not\to b\bar{b}$, but $A_1 \to \tau^+\tau^- / q\bar{q}$

- Upper limit on ratio $\xi^2 = \left(\frac{g_{HZZ}}{g_{HZZ}^{SM}}\right)^2$ depending on m_H.



- Excess may originate in NMSSM from $m_{H_1} \approx 98$ GeV $\mathrm{BR}(H_1 \to b\bar{b}) \approx 0.08$ and $\mathrm{BR}(H_1 \to A_1 A_1) \approx 0.9$.

R. Dermisek, J.F. Gunion, PRL95, '05 R. Dermisek, J.F. Gunion, PRD73, '06