Why the cNMSSM?
Low energy phenomenology and possible signatures at the LHC

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In collaboration with **A. Djouadi** and **U. Ellwanger**, arXiv:**0803.0253** [hep-ph]
0811.2699 [hep-ph]

The Next-to-Minimal Supersymmetric Standard Model

By adding a **singlet** superfield $\hat{S}$ to the **MSSM** $\Rightarrow$ **NMSSM**

★ **Elegant solution to the μ-problem of the MSSM**

$$\mu\,\hat{H}_u\,\hat{H}_d \quad \longrightarrow \quad \lambda\,\hat{S}\,\hat{H}_u\,\hat{H}_d$$

$\Rightarrow$ dynamically generated μ: $\quad \langle S \rangle \sim \mathcal{O}(M_{\text{SUSY}}) \;\rightsquigarrow\; \mu_{\text{eff}} = \lambda \langle S \rangle$

$\Rightarrow$ Scale-invariant superpotential: **EW, SUSY scale only** appearing via $\mathcal{L}_{\text{soft}}$

★ NMSSM

$\rightsquigarrow$ **Simplest** extension of the SM where the **only scale** is M_{SUSY}

$\rightsquigarrow$ **Original SUSY/SUGRA** extensions of the SM of this type [Fayet, Nilles, ...]

NMSSM new features

$$W = Y_u \hat{H}_u \hat{Q} \hat{u} + Y_d \hat{H}_d \hat{Q} \hat{d} + Y_e \hat{H}_d \hat{L} \hat{e} - \boldsymbol{\lambda} \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \boldsymbol{\kappa} \hat{S}^3$$

$$-\mathcal{L}_{\text{soft}}^{\text{Higgs}} = m_{H_i}^2 H_i^* H_i + \boldsymbol{m_S^2} S^* S + \left(-\boldsymbol{\lambda} \boldsymbol{A_\lambda} S H_u H_d + \frac{1}{3} \boldsymbol{\kappa} \boldsymbol{A_\kappa} S^3 + \text{H.c.}\right)$$

Neutralino sector:

- 5 Majorana fermions (χ^0_{1-5})
- $\tilde{\chi}_1^0 = N_{11} \tilde{B}^0 + N_{12} \tilde{W}_3^0 + N_{13} \tilde{H}_d^0 + N_{14} \tilde{H}_u^0 + N_{15} \tilde{S}$

Neutral Higgs sector:

- 2 pseudoscalar (a_1^0, a_2^0) and 3 **scalar bosons** (h_1^0, h_2^0, h_3^0)
- $h_1^0 = S_{11} H_d^0 + S_{12} H_u^0 + S_{13} S$

$\Rightarrow$ **NMSSM: Richer, more complex phenomenology**

LEP and the NMSSM

★ In the NMSSM **less severe** "Higgs - little fine tuning problem"

Theoretically higher upper bound on $m_{h_1^0}$

Additional contributions to $m_{h_1^0}$, low $\tan\beta$ regime $\Rightarrow$ $m_{h_1^0} \sim 145$ GeV

Experimentally "invisible" h_1^0 (escaped LEP detection)

$\Rightarrow$ **NMSSM light Higgs** ($m_{h_1^0} \lesssim 114$ GeV) **still allowed by LEP data:**

(i) $\boldsymbol{Z - Z - h_1^0}$ coupling is heavilly **suppressed**

$\rightsquigarrow$ **singlet** dominated $\boldsymbol{h_1^0}$; SM-like $\boldsymbol{h_2^0}$

(ii) $\boldsymbol{m_{a_1^0} \lesssim 11}$ **GeV** allowing for $m_{h_1^0} \lesssim 86$ GeV

$\rightsquigarrow$ SM-like $\boldsymbol{h_1^0}$ dominant **decay** $\boldsymbol{h_1^0 \to a_1^0\, a_1^0}$;

$\rightsquigarrow$ **Forbidden** $a_1^0 \to b\,\bar{b}$ only $a_1^0 \to 2\,\tau$

$\Rightarrow$ **Enlarge window for $\boldsymbol{m_{h_1^0}}$!**

NMSSM with universal soft terms at GUT scale

Supergravity mediated $\Rightarrow$ flavour blind (universal), CP conserving, SUSY soft breaking terms! (at corresponding mass scale)

mSUGRA-like NMSSM: $M_i = M_{1/2}$; $(m_0^{\tilde{F},\phi})_{ij} = m_0$; $(A_0^{\tilde{F},\phi})_{ij} = A_0$

$$\Rightarrow m_{H_u} = m_{H_d} = m_S = m_0,\ A_\lambda = A_\kappa = A_0$$

cNMSSM: $M_{1/2}$, m_0, A_0, λ, κ $\Rightarrow$ 5 continuous parameters

Analogous to the cMSSM: $M_{1/2}$, m_0, A_0, μ, $B\mu$

- ⋆ Requiring correct M_Z $\Leftrightarrow$ 4 parameters
- ⋆ **Practical purposes** (RGE's, numerics, ...) $\kappa \leftrightsquigarrow \tan\beta$

constrained NMSSM: $M_{1/2}$, m_0, A_0, λ

NMSSMTools [Ellwanger, Hugonie]

Constraining the cNMSSM: scalar potential & LEP

★ **Phenomenologically acceptable minimum** of Higgs potential: $s = \langle S \rangle \neq 0$

$$V_{\text{Higgs}} \sim \kappa^2 s^4 + \frac{2}{3}\kappa A_\kappa s^3 + m_S^2 s^2 + \ldots$$

⋆ **Non vanishing s:** $\Rightarrow \; m_0 \lesssim \frac{1}{3}|A_0|$

cMSSM: low m_0 disfavoured (charged slepton LSP)

cNMSSM: low m_0 required to generate $< S >$; **singlino LSP**

⋆ **Absence of pseudoscalar tachyons:** $\Rightarrow \; A_\kappa \sim A_0 < 0$

★ **LEP constraints** $\rightsquigarrow$ **upper bound** on λ: typically $\Rightarrow \; \lambda \lesssim 0.02$

★ $(g-2)_\mu$: *favours* **low $M_{1/2}$ regime** $M_{1/2} \lesssim 1$ TeV

Constraining the cNMSSM: dark matter

★ **Comply with WMAP constraints on the relic density**

$$0.094 \lesssim \Omega_{\chi_1^0} h^2 \lesssim 0.136 \qquad (\,\text{at}\, 2\,\sigma)$$

MicrOmegas [Belanger et al]

⋆ **"Assisted" $\tilde{\tau}_1$ annihilation:** nearly **degenerate LSP and NLSP**

$m^2_{\chi S} \sim m^2_{\tilde{\tau}_R}$ $\Rightarrow\ m_0 \lesssim \frac{1}{10} M_{1/2}$ **small/vanishing m_0**

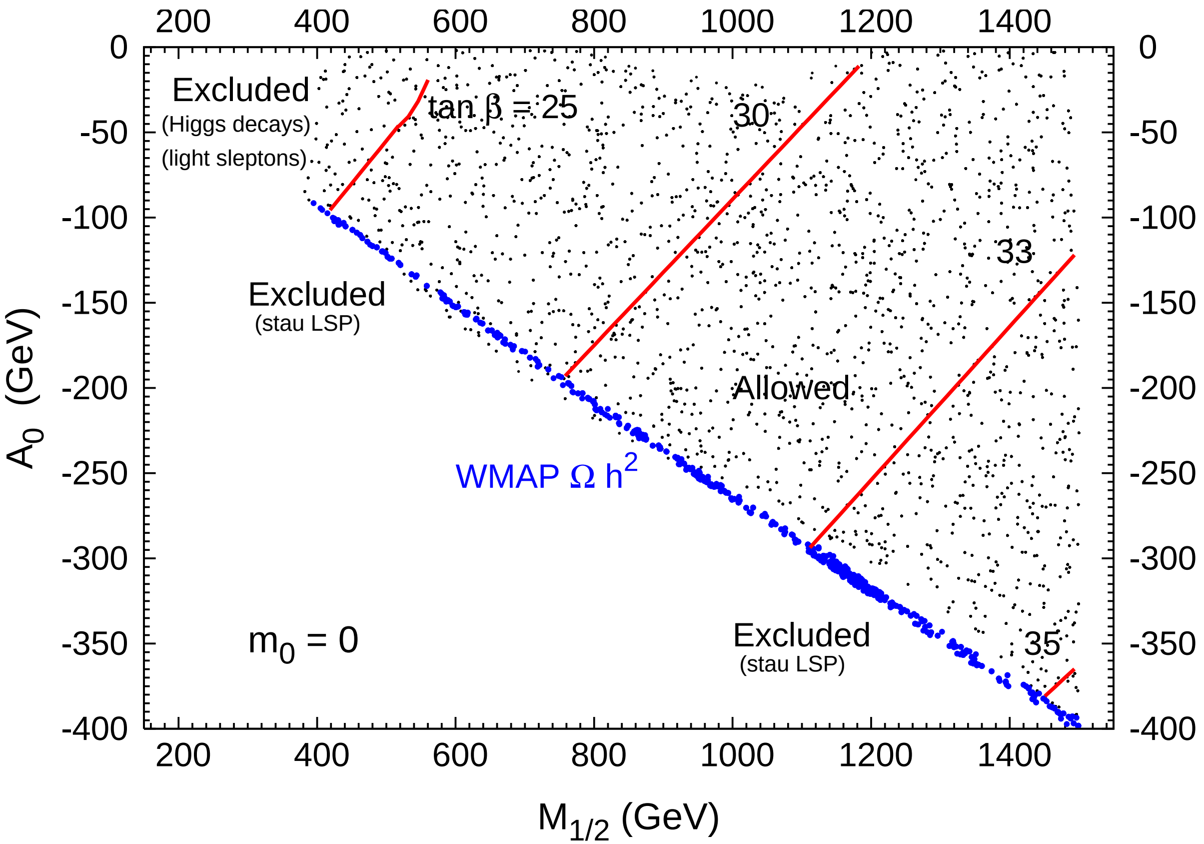
small A_0, determined by $M_{1/2}$ $\Rightarrow\ A_0 \sim -\frac{1}{4} M_{1/2}$

⋆ Diluting LSP density: LSP-NLSP **thermal equilibrium**

for very **small λ** $\rightsquigarrow$ **decoupled** LSP $\Rightarrow\ \lambda \gtrsim 10^{-5}$

⋆ σ_{annih} decreases with $m_{\text{NLSP}} \propto M_{1/2} \Rightarrow M_{1/2}$ not too large ($\lesssim 2-3$ TeV)

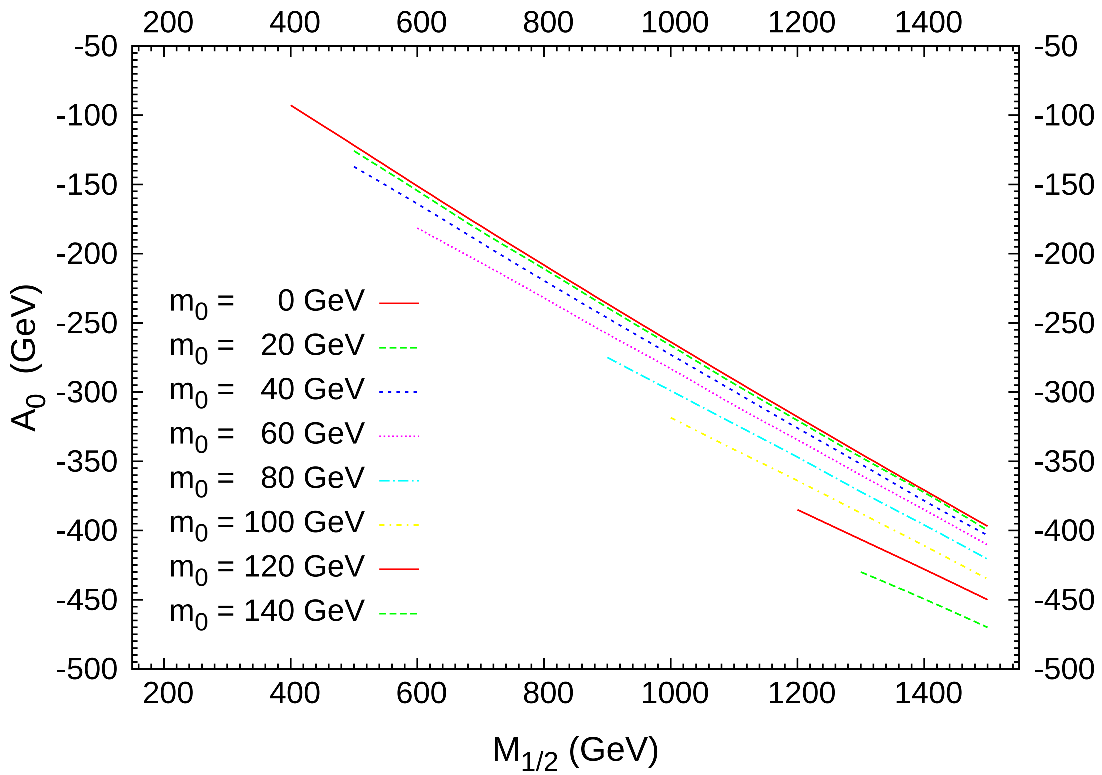
The allowed cNMSSM parameter space



★ **Allowed parameter space: "line" in $[M_{1/2}, A_0]$ plane !**

Small m_0 $\Rightarrow$ **cNMSSM: cNMSSM ($M_{1/2}$)**

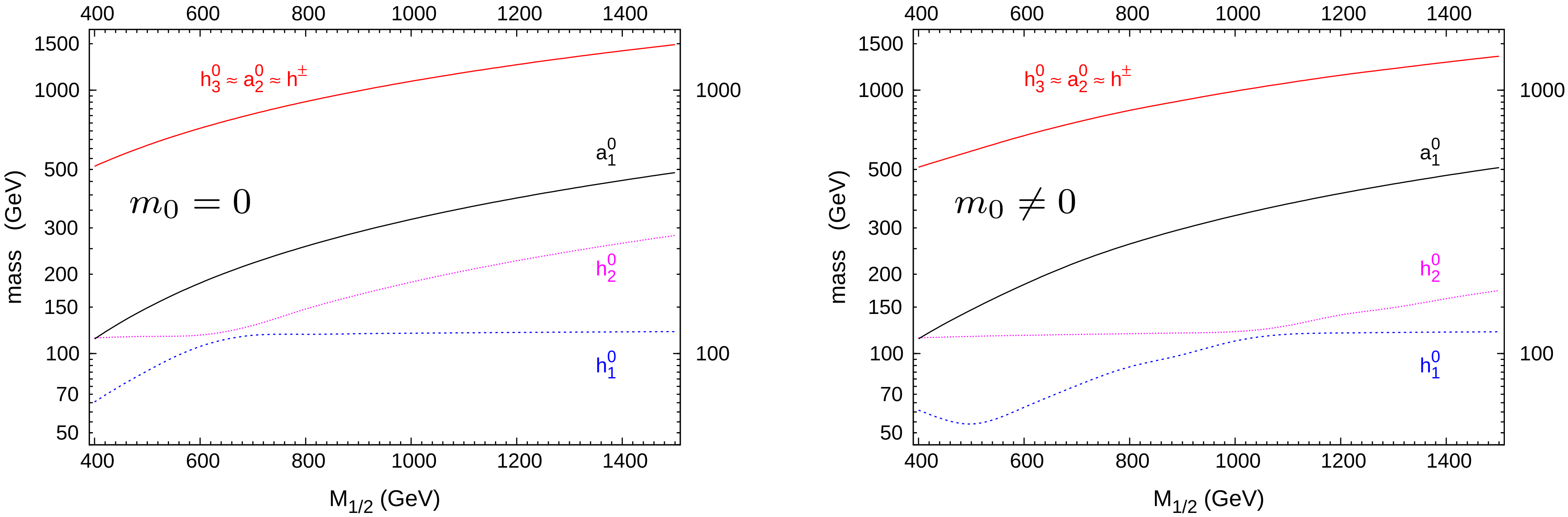
The allowed cNMSSM parameter space



★ **Allowed parameter space: "lines" in $[M_{1/2}, A_0]$ plane !**

Small m_0 $\Rightarrow$ **cNMSSM: cNMSSM ($M_{1/2}$)**

Higgs spectrum



- $\boldsymbol{M_{1/2}} \lesssim \begin{pmatrix} 660 \\ 1100 \end{pmatrix}$ singlet like h_1^0 SM-like $\boldsymbol{h_2^0}$; $\boldsymbol{M_{1/2}} \gtrsim \begin{pmatrix} 660 \\ 1100 \end{pmatrix}$ SM-like $\boldsymbol{h_1^0}$ singlet like h_2^0

- **"Cross-over":** **small** mass **splitting**; similar **components**; similar couplings

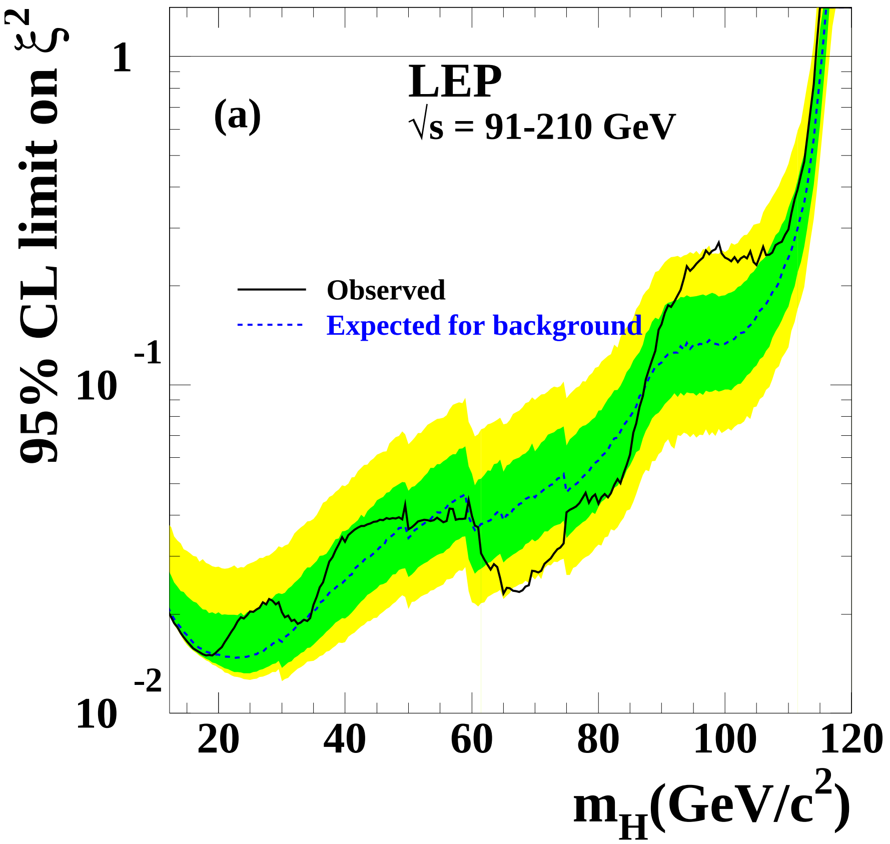
- **Decays:**
  - **SM-like** $h^0_{1,2}$: $b\bar{b}$ (70%) ; BR$(h^0_{1,2} \to \gamma\gamma) \approx$ BR$^{\text{SM}} \approx 2 \times 10^{-3}$
  - **Singlet like**: $b\bar{b}$ and $\tau^+\tau^-$ (as well as h_3^0,a_2^0, $h^\pm$)
  - **Higgs-to-Higgs:** possible but NOT typical

Explaining LEP?

Back to LEP2: combined results from all Higgs searches $(e^+ e^- \to h\,Z;\ h \to b\bar{b})$

- Observed **excesses:** $\begin{cases} m_h \sim \mathbf{115}\ \text{GeV}\ (\mathbf{1.7}\boldsymbol{\sigma}) \\ m_h \sim \mathbf{98}\ \text{GeV}\ (\mathbf{2.3}\,\boldsymbol{\sigma}) \end{cases}$

- Number of **events** $\sim$ **10%** of $\boldsymbol{h}^{\text{SM}}$ expected



- reduced coupling to SM gauge bosons

  $C_h^V = g_{hZZ}/g_{h^{\text{SM}}ZZ} \approx \mathcal{O}(\sqrt{0.1})$

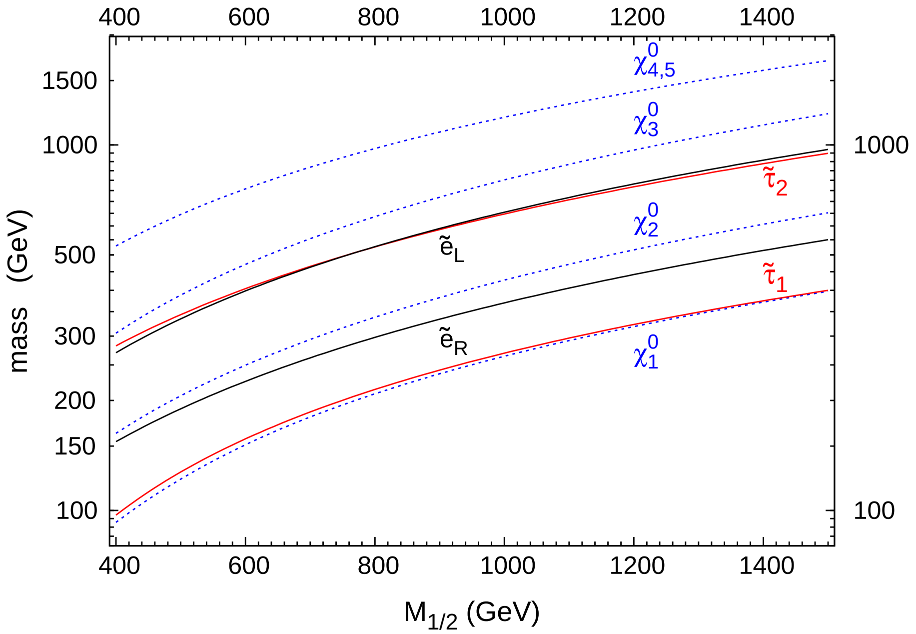
- $C_h^V \sim 1$, but reduced BR$(h \to b\bar{b})$

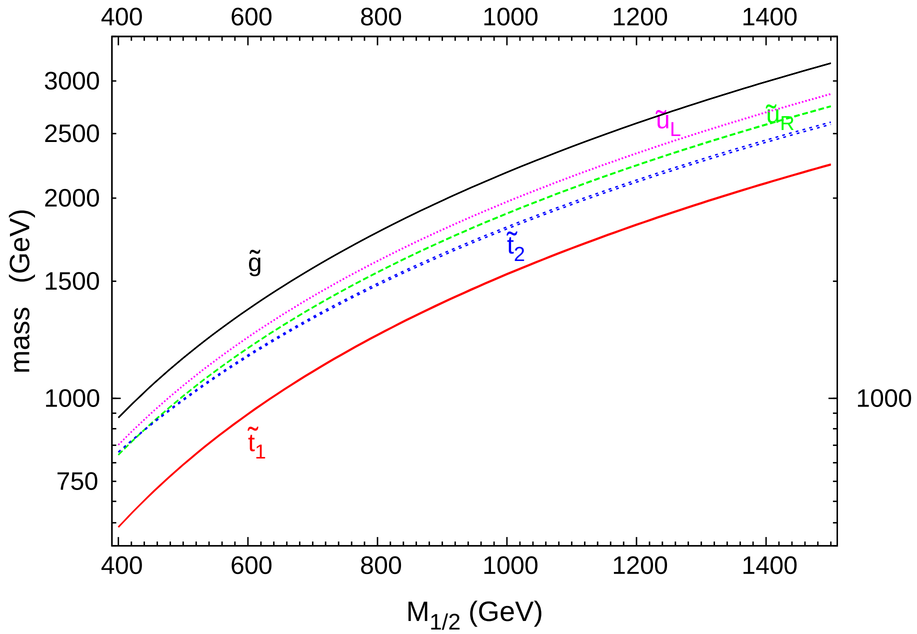
★ **cNMSSM** (cross over regions):

97 GeV $\lesssim \boldsymbol{m_{h_1^0}} \lesssim$ **101 GeV** ; $\boldsymbol{m_{h_2^0}} \approx$ **117 GeV**; $0.28 \lesssim |C^V_{h_1^0}| \lesssim 0.33$

cNMSSM (low $M_{1/2}$): constrained model accounting for LEP!

Sparticle spectrum





- **Neutralino sector:**

  Singlino **LSP** - nearly degenerate with $\tilde{\tau}_1$

  Bino-like χ_2^0; Wino-like χ_3^0; Higgsino-like $\chi_{4,5}^0$: $M_{\chi_{4,5}^0} \approx \mu_{\text{eff}}$

- **Squarks & gluinos:**

  Gluino heavier than all squarks and sleptons (m_0 is small!)

cNMSSM at the LHC: sparticle decay chains

- ⋆ $\tilde{g} \to \tilde{q}\, q \qquad (m_{\tilde{g}} \gtrsim m_{\tilde{q}})$
- ⋆ $\tilde{q} \to \chi^{0(\pm)}\, q\, (q') \begin{cases} \tilde{q}_L \to \chi_3^0\, q & (33\%) \\ \tilde{q}_L \to \chi_1^{\pm}\, q' & (66\%) \end{cases} \qquad \tilde{q}_R \to \chi_2^0\, q$
- ⋆ $\tilde{l}_L \to \chi_2^0\, l\,; \qquad \tilde{l}_R \to l\, \tilde{\tau}_1\, \tau\, (\gtrsim 99\%)$
- ⋆ $\chi_3^0 (\chi_1^{\pm}) \to \tilde{l}\, l^{(\prime)}\, (\sim 50\%)\,; \qquad \chi_3^0 (\chi_1^{\pm}) \to \tilde{\tau}_1\, \tau\,,\, \tilde{\nu}_\tau\, \nu_\tau\, (\sim 50\%)$
- ⋆ $\chi_2^0 \to \tilde{\tau}_1\, \tau$

cNMSSM: Almost all sparticle decay chains contain $\tilde{\tau}_1$ NLSP !

- ⋆ $\tilde{\tau}_1 \to \chi_1^0\, \tau\,;$ **stable** χ_1^0

cNMSSM: **subdominant** cascade decays with **lepton** final states ...

cNMSSM "smoking gun": possibly displaced vertices

cNMSSM: singlino LSP (χ_1^0), mostly right-handed NLSP ($\tilde{\tau}_1$) $\Rightarrow$ **Long-lived $\tilde{\tau}_1$!**

$$\Gamma(\tilde{\tau}_1 \to \chi_1^0 \tau) \approx \lambda^2 \frac{\sqrt{\Delta m^2 - m_\tau^2}}{4\pi m_{\tilde{\tau}_1}} (\alpha \Delta m - \rho\, m_\tau)$$

$\Delta m \equiv m_{\tilde{\tau}_1} - m_{\chi_1^0}$;

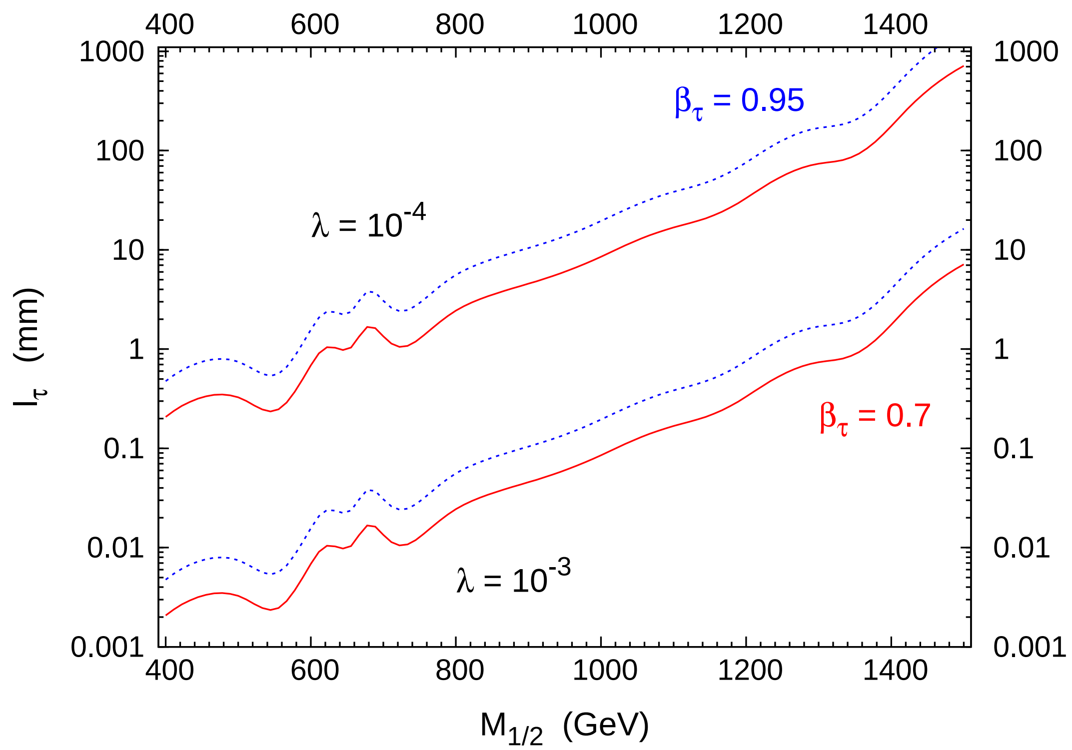
$\alpha(M_{1/2}), \rho(M_{1/2}) \in [10^{-2}, 10^{-4}]$

Realistic $l_{\tilde{\tau}_1}$ in the lab frame

$\Rightarrow \beta_{\tilde{\tau}_1} = v_{\tilde{\tau}_1}/c$ ($\tilde{\tau}_1$ **production**)

$$l_{\tilde{\tau}_1} = \frac{\hbar c}{\Gamma(\tilde{\tau}_1 \to \chi_1^0 \tau)} \sqrt{\frac{\beta_{\tilde{\tau}_1}^2}{1-\beta_{\tilde{\tau}_1}^2}}$$

GMSB ATLAS studies: $\beta_{\tilde{\tau}_1} \gtrsim 0.7$



cNMSSM: $\tilde{\tau}_1$ length of flight $\rightsquigarrow$ $\mathcal{O}$(few centimeters)

cNMSSM prospects for the LHC

Sparticle production:

dominant **production** $\rightsquigarrow$ $\tilde{q}\tilde{g}$, $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{q}^*$

Low $M_{1/2}$ **regime:** $\sigma \sim 0.5$ pb

$\mathcal{L} = 100\ \mathrm{pb}^{-1} \Rightarrow 10^4 - 10^5$ events

Simplest decay cascade: $\tilde{q}_R \to \chi_2^0\, q\,;\quad \chi_2^0 \to \tilde{\tau}_1\, \tau\,;\quad \tilde{\tau}_1 \to \chi_1^0\, \tau$

3 jets $/\tilde{q}_R$ (one hard quark + 2 τ jets) & long lived $\tilde{\tau}_1$

$\Rightarrow$ **complicated measurements of sparticle spectra**

Higgs production:

$h_{1,2}^{\text{SM-like}}$ $\rightsquigarrow$ gluon-gluon & vector boson fusion $\quad h_{1,2} \to \gamma\gamma$

heavier Higgses $\rightsquigarrow$ associated $b\bar{b}\,(tb)$ $\qquad$ low $M_{1/2}$

singlet-like $\rightsquigarrow$ inaccessible

Higgs cross-over region: two nearly **degenerate**, **same couplings** states

sum behaves as ONE SM Higgs - resolve $\gamma\gamma$ peak?

Concluding remarks & outlook

- Why the NMSSM?? **simple** and very attractive **SUSY extension** of the SM

  A lot of work to be done (especially experimental simulations)!

- cNMSSM allowed parameter space: described by **ONE parameter!**

  Very low m_0, small A_0 values, and $M_{1/2} \lesssim 1$ TeV; $\tan\beta \sim 30$

  Satisfy observed Higgs excesses at LEP and $(g-2)_\mu$ deviation from SM

- cNMSSM - different spectra from cMSSM!

  $m_{\tilde{g}} \gtrsim m_{\tilde{q}}$; $\boldsymbol{\tilde{\tau}_1}$ in **all** decay **cascades** (possibly long lived)

- **Dark matter** detection prospects: well below experimental capabilities ...

- **Testable** at LHC, but **ILC required** for precision measurements

Additional slides

NMSSM: $\tilde{\chi}^0$ and scalar Higgs mass matrices

CP-even Higgs

$$\mathcal{M}^2_{S,11} = M_Z^2 \cos^2\beta + \lambda s \tan\beta (A_\lambda + \kappa s)$$
$$\mathcal{M}^2_{S,22} = M_Z^2 \sin^2\beta + \lambda s \cot\beta (A_\lambda + \kappa s)$$
$$\mathcal{M}^2_{S,33} = 4\kappa^2 s^2 + \kappa A_\kappa s + \frac{\lambda}{s} A_\lambda v_1 v_2$$
$$\mathcal{M}^2_{S,12} = \left(\lambda^2 v^2 - \frac{M_Z^2}{2}\right) \sin 2\beta - \lambda s (A_\lambda + \kappa s)$$
$$\mathcal{M}^2_{S,13} = 2\lambda^2 v_1 s - \lambda v_2 (A_\lambda + 2\kappa s)$$
$$\mathcal{M}^2_{S,23} = 2\lambda^2 v_2 s - \lambda v_1 (A_\lambda + 2\kappa s)$$

$$h_a^0 = S_{ab} H_b^0$$

CP-odd Higgs

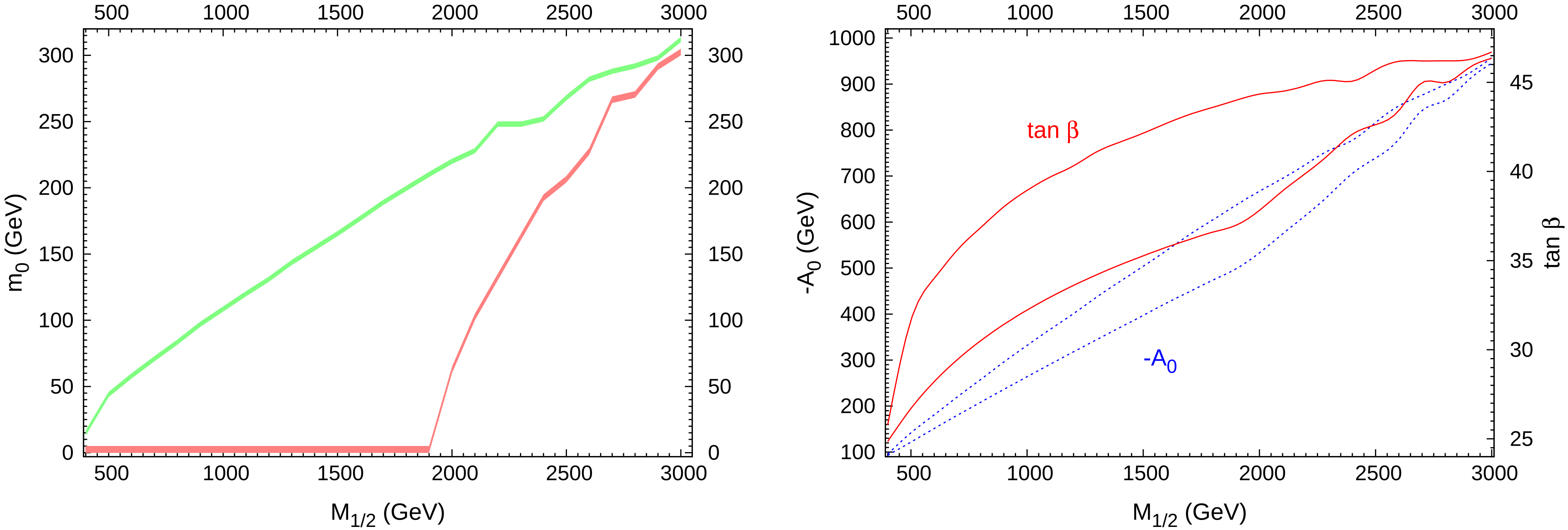
$$\mathcal{M}^2_{P,11} = \frac{2\lambda s}{\sin 2\beta} (\kappa s + A_\lambda)$$
$$\mathcal{M}^2_{P,22} = \lambda \left(2\kappa + \frac{A_\lambda}{2s}\right) v^2 \sin 2\beta - 3\kappa A_\kappa s$$
$$\mathcal{M}^2_{P,12} = \lambda v (A_\lambda - 2\kappa s)$$

$$a_i^0 = P_{ij} P_j^0$$

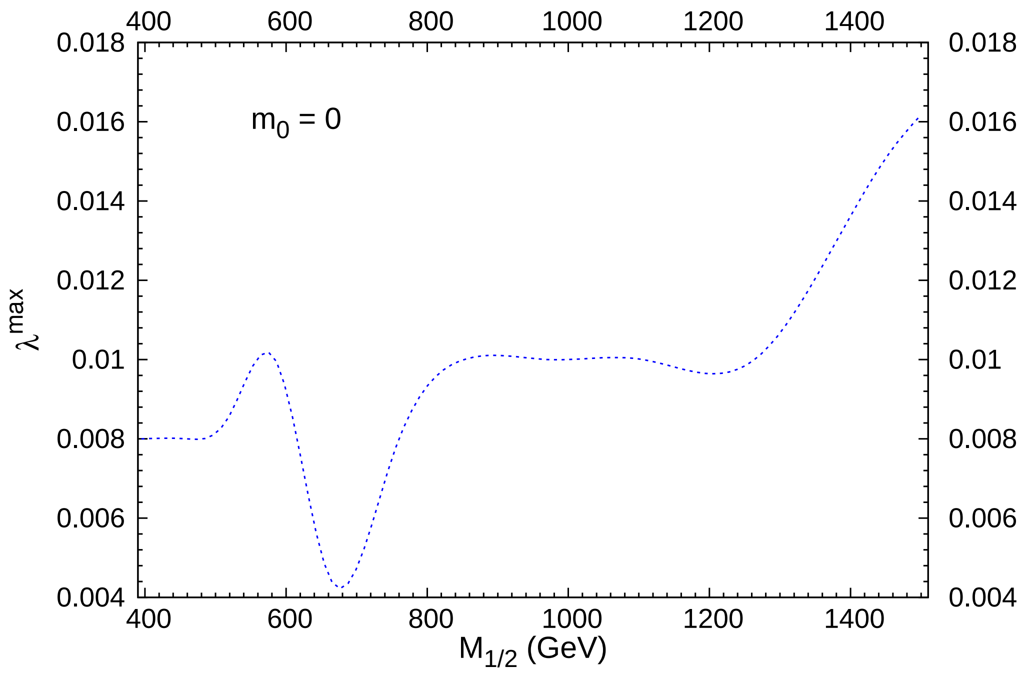
Neutralino Sector

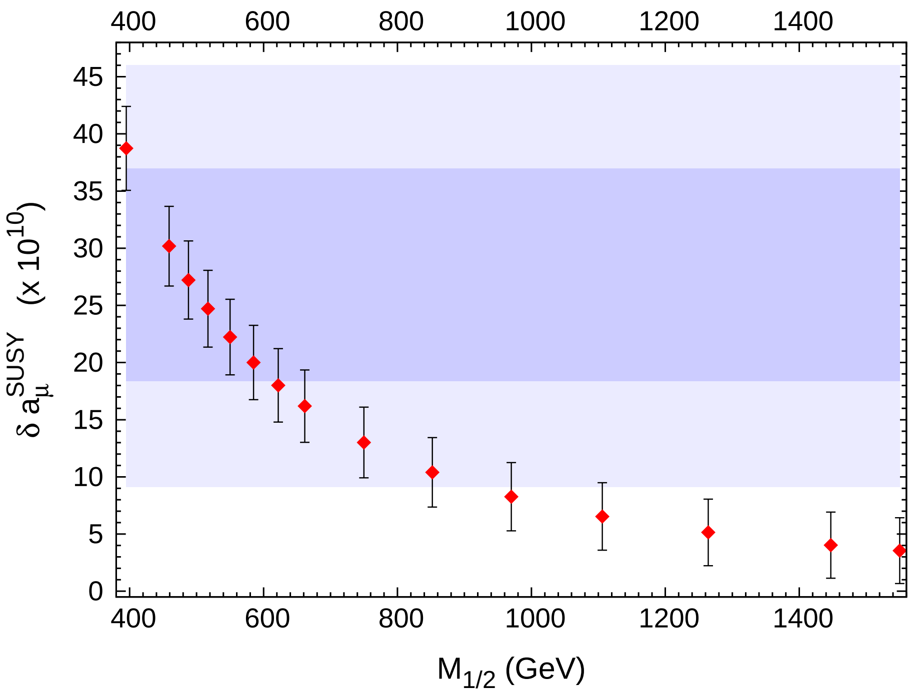
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta & 0 \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta & 0 \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\lambda s & -\lambda v_2 \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\lambda s & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 & -\lambda v_1 & 2\kappa s \end{pmatrix}$$

Ranges



Additional phenomenology





Tables: Spectra

	P1	P2
$M_{1/2}$ (GeV)	500	1000
m_0 (GeV)	0	0
A_0 (GeV)	-122	-263
$\tan\beta$	26.7	32.2
$\mu_{\rm eff}$ (GeV)	640	1185
M_2 (GeV)	390	790
$m_{h_1^0}$ (GeV)	86	119
$m_{h_2^0}$ (GeV)	116	187
$m_{h_3^0}$ (GeV)	610	1073
$m_{a_1^0}$ (GeV)	149	323

	P1	P2
$M_{1/2}$ (GeV)	500	1000
$m_{\chi_1^0}$ (GeV)	122	264
$m_{\chi_2^0}$ (GeV)	206	427
$m_{\chi_3^0}$ (GeV)	388	802
$m_{\chi_{4,5}^0}$ (GeV)	645	1190
$m_{\chi_1^\pm}$ (GeV)	388	801
$m_{\chi_2^\pm}$ (GeV)	658	1198
$m_{\tilde{g}}$ (GeV)	1150	2187
$m_{\tilde{u}_L}$ (GeV)	1044	1973
$m_{\tilde{u}_R}$ (GeV)	1007	1895
$m_{\tilde{t}_1}$ (GeV)	795	1539
$m_{\tilde{t}_2}$ (GeV)	997	1810
$m_{\tilde{b}_1}$ (GeV)	931	1760
$m_{\tilde{b}_2}$ (GeV)	983	1817
$m_{\tilde{e}_L}$ (GeV)	334	654
$m_{\tilde{e}_R}$ (GeV)	190	370
$m_{\tilde{\nu}_l}$ (GeV)	325	650
$m_{\tilde{\tau}_1}$ (GeV)	127	269
$m_{\tilde{\tau}_2}$ (GeV)	343	647
$m_{\tilde{\nu}_\tau}$ (GeV)	318	631

	P1′	P2′
$M_{1/2}$ (GeV)	500	1000
m_0 (GeV)	40	107
A_0 (GeV)	-137	-327
$\tan\beta$	30.2	38.4
$\mu_{\rm eff}$ (GeV)	642	1192
M_2 (GeV)	390	791
$m_{h_1^0}$ (GeV)	64	116
$m_{h_2^0}$ (GeV)	116	127
$m_{h_3^0}$ (GeV)	588	989
$m_{a_1^0}$ (GeV)	149	333
$m_{\chi_1^0}$ (GeV)	107	226
$m_{\tilde{\tau}_1}$ (GeV)	112	235

Tables: Production and Decays

σ (pb)	P1	P2
$\tilde{g}\,\tilde{g}$	9.5×10^{-2}	2.14×10^{-4}
$\tilde{g}\,\tilde{q}$	0.668	4.28×10^{-3}
$\tilde{q}\,\tilde{q}$	0.436	9.21×10^{-3}
$\tilde{q}\,\tilde{q}^*$	0.221	1.64×10^{-3}
$\tilde{t}_1\,\tilde{t}_1^*$	3.69×10^{-2}	2.63×10^{-4}
$\tilde{l}_L\,\tilde{l}_L^*$	3.4×10^{-3}	1.62×10^{-3}
$\tilde{l}_R\,\tilde{l}_R^*$	1.17×10^{-2}	8.87×10^{-4}
$\tilde{\nu}_l\,\tilde{\nu}_l^*$	3.58×10^{-3}	1.53×10^{-4}
$\tilde{\tau}_1\,\tilde{\tau}_l^*$	4.8×10^{-2}	3.46×10^{-3}
$\chi_2^0\,\chi_2^0$	1.1×10^{-3}	6.22×10^{-5}
$\chi_2^0\,\chi_3^0$	1.73×10^{-4}	8.67×10^{-6}
$\chi_2^0\,\chi_1^\pm$	5.37×10^{-4}	6.53×10^{-5}
$\chi_3^0\,\chi_3^0$	1.79×10^{-3}	5.74×10^{-5}
$\chi_3^0\,\chi_1^\pm$	6.51×10^{-2}	7.49×10^{-3}
$\chi_1^+\,\chi_1^-$	3.53×10^{-2}	1.17×10^{-3}

BR (%)	P1	P2
$\tilde{g} \to \tilde{q}_L\,\bar{q}$	17.7	14.4
$\tilde{g} \to \tilde{q}_R\,\bar{q}$	33.6	27.5
$\tilde{g} \to \tilde{b}_1\,\bar{b}$	16.5	12.8
$\tilde{g} \to \tilde{b}_2\,\bar{b}$	10.9	10.3
$\tilde{g} \to \tilde{t}_1\,\bar{t}$	21.2	22.4
$\tilde{g} \to \tilde{t}_2\,\bar{t}$	–	12.5
$\tilde{q}_L \to \chi_3^0\,q$	31.7	32.3
$\tilde{q}_L \to \chi_1^\pm\,q'$	62.7	64.3
$\tilde{q}_R \to \chi_2^0\,q$	99.7	99.9
$\tilde{l}_L \to \chi_2^0\,l$	100	100
$\tilde{l}_R \to l\,\tilde{\tau}_1\,\tau$	$\gtrsim 95$	$\gtrsim 99$
$\tilde{\nu}_l \to \chi_2^0\,\nu_l$	100	100
$\tilde{\nu}_\tau \to \chi_2^0\,\nu_\tau$	13.8	6.8
$\tilde{\nu}_\tau \to \tilde{\tau}_1\,W$	86.2	93.2

BR (%)	P1	P2
$\chi_2^0 \to \tilde{\tau}_1\,\tau$	88.3	74.3
$\chi_2^0 \to \tilde{l}_R\,l$	11.7	25.7
$\chi_3^0 \to \tilde{l}_L\,l$	22.1	28.4
$\chi_3^0 \to \tilde{\nu}_l\,\nu_l$	27.1	29.2
$\chi_3^0 \to \tilde{\tau}_1\,\tau$	24.9	8.8
$\chi_3^0 \to \tilde{\tau}_2\,\tau$	6.9	14.8
$\chi_3^0 \to \tilde{\nu}_\tau\,\nu_\tau$	16.9	18.3
$\chi_1^\pm \to \tilde{\nu}_l\,l$	29.3	29.9
$\chi_1^\pm \to \tilde{l}\,\nu_l$	20.8	27.8
$\chi_1^\pm \to \tilde{\nu}_\tau\,\tau$	18.4	18.9
$\chi_1^\pm \to \tilde{\tau}_1\,\nu_\tau$	24	8.7
$\chi_1^\pm \to \tilde{\tau}_2\,\nu_\tau$	–	14.3