# Light higgsino models and parameter determination

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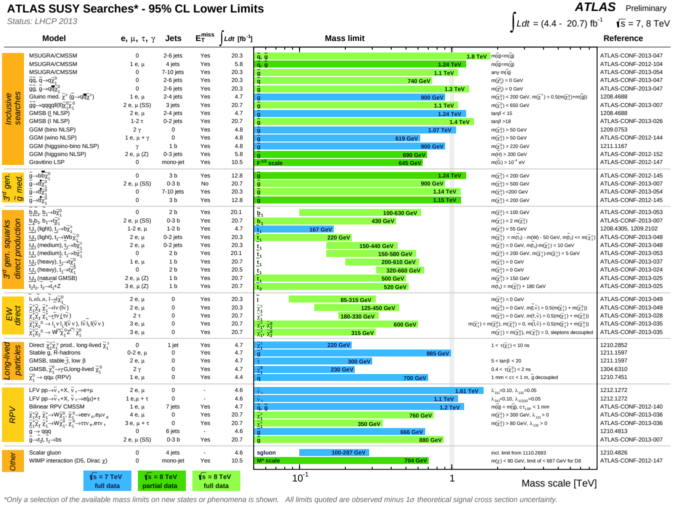
# SUSY @ LHC

- What does LHC tell us about $1^{\mathrm{st}}/2^{\mathrm{nd}}$ gen. squarks? → quite heavy
- Gaugino and stop searches model dependent – limits weaker



**ATLAS SUSY Searches* - 95% CL Lower Limits**

*Status: LHCP 2013*

***ATLAS*** Preliminary

$\int Ldt = (4.4 - 20.7)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

| | Model | $e, \mu, \tau, \gamma$ | Jets | $E_T^{\mathrm{miss}}$ | $\int Ldt\ [\mathrm{fb}^{-1}]$ | Mass limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Inclusive searches | MSUGRA/CMSSM | 0 | 2-6 jets | Yes | 20.3 | $\tilde{q}, \tilde{g}$ 1.8 TeV | $m(\tilde{q})=m(\tilde{g})$ | ATLAS-CONF-2013-047 |
| | MSUGRA/CMSSM | 1 e, μ | 4 jets | Yes | 5.8 | $\tilde{q}, \tilde{g}$ 1.24 TeV | $m(\tilde{q})=m(\tilde{g})$ | ATLAS-CONF-2012-104 |
| | MSUGRA/CMSSM | 0 | 7-10 jets | Yes | 20.3 | $\tilde{g}$ 1.1 TeV | any $m(\tilde{q})$ | ATLAS-CONF-2013-054 |
| | $\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{q}$ 740 GeV | $m(\tilde{\chi}_1^0) = 0$ GeV | ATLAS-CONF-2013-047 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{g}$ 1.3 TeV | $m(\tilde{\chi}_1^0) = 0$ GeV | ATLAS-CONF-2013-047 |
| | Gluino med. $\tilde{\chi}^\pm$ ($\tilde{g}\to q\bar{q}\tilde{\chi}^\pm$) | 1 e, μ | 2-4 jets | Yes | 4.7 | $\tilde{g}$ 900 GeV | $m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}^\pm) = 0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ | 1208.4688 |
| | $\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$ | 2 e, μ (SS) | 3 jets | Yes | 20.7 | $\tilde{g}$ 1.1 TeV | $m(\tilde{\chi}_1^0) < 650$ GeV | ATLAS-CONF-2013-007 |
| | GMSB ($\tilde{\ell}$ NLSP) | 2 e, μ | 2-4 jets | Yes | 4.7 | $\tilde{g}$ 1.24 TeV | $\tan\beta < 15$ | 1208.4688 |
| | GMSB ($\tilde{\ell}$ NLSP) | 1-2 τ | 0-2 jets | Yes | 20.7 | $\tilde{g}$ 1.4 TeV | $\tan\beta > 18$ | ATLAS-CONF-2013-026 |
| | GGM (bino NLSP) | 2 γ | 0 | Yes | 4.8 | $\tilde{g}$ 1.07 TeV | $m(\tilde{\chi}_1^0) > 50$ GeV | 1209.0753 |
| | GGM (wino NLSP) | 1 e, μ + γ | 0 | Yes | 4.8 | $\tilde{g}$ 619 GeV | $m(\tilde{\chi}_1^0) > 50$ GeV | ATLAS-CONF-2012-144 |
| | GGM (higgsino-bino NLSP) | γ | 1 b | Yes | 4.8 | $\tilde{g}$ 900 GeV | $m(\tilde{\chi}_1^0) > 220$ GeV | 1211.1167 |
| | GGM (higgsino NLSP) | 2 e, μ (Z) | 0-3 jets | Yes | 5.8 | $\tilde{g}$ 690 GeV | $m(\tilde{H}) > 200$ GeV | ATLAS-CONF-2012-152 |
| | Gravitino LSP | 0 | mono-jet | Yes | 10.5 | $F^{1/2}$ scale 645 GeV | $m(\tilde{G}) > 10^{-4}$ eV | ATLAS-CONF-2012-147 |
| $3^{rd}$ gen. $\tilde{g}$ med. | $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 b | Yes | 12.8 | $\tilde{g}$ 1.24 TeV | $m(\tilde{\chi}_1^0) < 200$ GeV | ATLAS-CONF-2012-145 |
| | $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 2 e, μ (SS) | 0-3 b | No | 20.7 | $\tilde{g}$ 900 GeV | $m(\tilde{\chi}_1^0) < 500$ GeV | ATLAS-CONF-2013-007 |
| | $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0 | 7-10 jets | Yes | 20.3 | $\tilde{g}$ 1.14 TeV | $m(\tilde{\chi}_1^0) <200$ GeV | ATLAS-CONF-2013-054 |
| | $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0 | 3 b | Yes | 12.8 | $\tilde{g}$ 1.15 TeV | $m(\tilde{\chi}_1^0) < 200$ GeV | ATLAS-CONF-2012-145 |
| $3^{rd}$ gen. squarks direct production | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$ | 0 | 2 b | Yes | 20.1 | $\tilde{b}_1$ 100-630 GeV | $m(\tilde{\chi}_1^0) < 100$ GeV | ATLAS-CONF-2013-053 |
| | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$ | 2 e, μ (SS) | 0-3 b | Yes | 20.7 | $\tilde{b}_1$ 430 GeV | $m(\tilde{\chi}_1^\pm) = 2\, m(\tilde{\chi}_1^0)$ | ATLAS-CONF-2013-007 |
| | $\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 1-2 e, μ | 1-2 b | Yes | 4.7 | $\tilde{t}_1$ 167 GeV | $m(\tilde{\chi}_1^0) = 55$ GeV | 1208.4305, 1209.2102 |
| | $\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ | 2 e, μ | 0-2 jets | Yes | 20.3 | $\tilde{t}_1$ 220 GeV | $m(\tilde{\chi}_1^0) = m(\tilde{t}_1) - m(W) - 50$ GeV, $m(\tilde{t}_1) << m(\tilde{\chi}_1^\pm)$ | ATLAS-CONF-2013-048 |
| | $\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 2 e, μ | 0-2 jets | Yes | 20.3 | $\tilde{t}_1$ 150-440 GeV | $m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^\pm) = 10$ GeV | ATLAS-CONF-2013-048 |
| | $\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 0 | 2 b | Yes | 20.1 | $\tilde{t}_1$ 150-580 GeV | $m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^\pm) = 5$ GeV | ATLAS-CONF-2013-053 |
| | $\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 1 e, μ | 1 b | Yes | 20.7 | $\tilde{t}_1$ 200-610 GeV | $m(\tilde{\chi}_1^0) = 0$ GeV | ATLAS-CONF-2013-037 |
| | $\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 0 | 2 b | Yes | 20.5 | $\tilde{t}_1$ 320-660 GeV | $m(\tilde{\chi}_1^0) = 0$ GeV | ATLAS-CONF-2013-024 |
| | $\tilde{t}_1\tilde{t}_1$ (natural GMSB) | 2 e, μ (Z) | 1 b | Yes | 20.7 | $\tilde{t}_1$ 500 GeV | $m(\tilde{\chi}_1^0) > 150$ GeV | ATLAS-CONF-2013-025 |
| | $\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$ | 3 e, μ (Z) | 1 b | Yes | 20.7 | $\tilde{t}_2$ 520 GeV | $m(\tilde{t}_1) = m(\tilde{\chi}_1^0) + 180$ GeV | ATLAS-CONF-2013-025 |
| EW direct | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 e, μ | 0 | Yes | 20.3 | $\tilde{\ell}$ 85-315 GeV | $m(\tilde{\chi}_1^0) = 0$ GeV | ATLAS-CONF-2013-049 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ | 2 e, μ | 0 | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 125-450 GeV | $m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{\ell},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$ | ATLAS-CONF-2013-049 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$ | 2 τ | 0 | Yes | 20.7 | $\tilde{\chi}_1^\pm$ 180-330 GeV | $m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{\tau},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$ | ATLAS-CONF-2013-028 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to \tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ | 3 e, μ | 0 | Yes | 20.7 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV | $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0) = 0$, $m(\tilde{\ell},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$ | ATLAS-CONF-2013-035 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to W^{(*)}\tilde{\chi}_1^0 Z^{(*)}\tilde{\chi}_1^0$ | 3 e, μ | 0 | Yes | 20.7 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV | $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0) = 0$, sleptons decoupled | ATLAS-CONF-2013-035 |
| Long-lived particles | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | 0 | 1 jet | Yes | 4.7 | $\tilde{\chi}_1^\pm$ 220 GeV | $1 < \tau(\tilde{\chi}_1^\pm) < 10$ ns | 1210.2852 |
| | Stable $\tilde{g}$, R-hadrons | 0-2 e, μ | 0 | Yes | 4.7 | $\tilde{g}$ 985 GeV | | 1211.1597 |
| | GMSB, stable $\tilde{\tau}$, low β | 2 e, μ | 0 | Yes | 4.7 | $\tilde{\tau}$ 300 GeV | $5 < \tan\beta < 20$ | 1211.1597 |
| | GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 γ | 0 | Yes | 4.7 | $\tilde{\chi}_1^0$ 230 GeV | $0.4 < \tau(\tilde{\chi}_1^0) < 2$ ns | 1304.6310 |
| | $\tilde{\chi}_1^0 \to qq\mu$ (RPV) | 1 e, μ | 0 | Yes | 4.4 | $\tilde{q}$ 700 GeV | 1 mm < cτ < 1 m, $\tilde{g}$ decoupled | 1210.7451 |
| RPV | LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$ | 2 e, μ | 0 | - | 4.6 | $\tilde{\nu}_\tau$ 1.61 TeV | $\lambda'_{311}=0.10$, $\lambda_{132}=0.05$ | 1212.1272 |
| | LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$ | 1 e,μ + τ | 0 | - | 4.6 | $\tilde{\nu}_\tau$ 1.1 TeV | $\lambda'_{311}=0.10$, $\lambda_{1(2)33}=0.05$ | 1212.1272 |
| | Bilinear RPV CMSSM | 1 e, μ | 7 jets | Yes | 4.7 | $\tilde{q}, \tilde{g}$ 1.2 TeV | $m(\tilde{q}) = m(\tilde{g})$, $c\tau_{LSP} < 1$ mm | ATLAS-CONF-2012-140 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$ | 4 e, μ | 0 | Yes | 20.7 | $\tilde{\chi}_1^\pm$ 760 GeV | $m(\tilde{\chi}_1^0) > 300$ GeV, $\lambda_{121} > 0$ | ATLAS-CONF-2013-036 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$ | 3 e, μ + τ | 0 | Yes | 20.7 | $\tilde{\chi}_1^\pm$ 350 GeV | $m(\tilde{\chi}_1^0) > 80$ GeV, $\lambda_{133} > 0$ | ATLAS-CONF-2013-036 |
| | $\tilde{g} \to qqq$ | 0 | 6 jets | - | 4.6 | $\tilde{g}$ 666 GeV | | 1210.4813 |
| | $\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$ | 2 e, μ (SS) | 0-3 b | Yes | 20.7 | $\tilde{g}$ 880 GeV | | ATLAS-CONF-2013-007 |
| Other | Scalar gluon | 0 | 4 jets | - | 4.6 | sgluon 100-287 GeV | incl. limit from 1110.2693 | 1210.4826 |
| | WIMP interaction (D5, Dirac χ) | 0 | mono-jet | Yes | 10.5 | M* scale 704 GeV | $m(\chi) < 80$ GeV, limit of < 687 GeV for D8 | ATLAS-CONF-2012-147 |

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*

# Outline

1. Light higgsinos from gauge-gravity mediation

2. Light higgsinos at colliders

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# Light higgsinos

$$\mathcal{L}_{\text{MSSM}} = \mu\, \tilde{H}_u \tilde{H}_d + \text{h.c.} + \left(m_{H_u}^2 + |\mu|^2\right)\, |H_u|^2 + \left(m_{H_d}^2 + |\mu|^2\right)\, |H_d|^2 + \ldots$$

- Higgsino mass parameter $\mu$ is special: supersymmetric

A priori $\mu$ is unrelated to the scale of SUSY breaking

- $\mu$ cannot be too small (LEP chargino bound: $m_{\chi_1^\pm} \gtrsim 100$ GeV)
- $\mu$ should not be too large:

$$m_Z^2 = -2\, m_{H_u}^2 - 2|\mu|^2 + \mathcal{O}(\cot^2\beta)$$

If $|m_{H_u}^2|,\ |\mu|^2 \gg m_Z^2 \Rightarrow$ large cancellation needed $\Rightarrow$ Fine-tuning!

# Light higgsinos

**Two approaches:**

- $\mu$ generated supersymmetrically, around EW scale by coincidence
- effective $\mu$ generated by SUSY breaking
  in calculable models: $\mu/B_\mu$ problem $\Rightarrow$ $\mu$ still special

**Naturalness wants $\mu$ around 100 GeV**:

$$m_Z^2 = -2\,m_{H_u}^2 - 2|\mu|^2 + \mathcal{O}(\cot^2\beta)$$

**LHC bounds want squarks and gluinos above 1 TeV.**

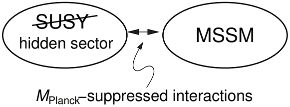
Motivates studying scenarios where higgsinos are light (EW scale) while everything else is heavy (multi-TeV) except maybe 3rd generation

**light higgsinos** = near-degenerate $\chi_1^0$, $\chi_1^\pm$, $\chi_2^0$ around 100–200 GeV

# Light higgsinos from hybrid gauge-gravity mediation

**Gravity med.**: $\mu \sim m_{3/2}$, → Giudice/Masiero '88

$$m_{\text{soft}} \sim m_{3/2}$$



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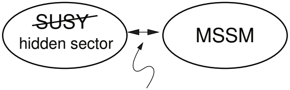
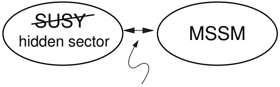


$M_{\text{Planck}}$–suppressed interactions

**Gauge med.**: $\mu = 0$,

$$m_{\text{soft}} \sim m_{3/2} \cdot N_{\text{mess.}} \cdot \frac{M_{\text{Planck}}}{M_{\text{mess.}}} \cdot \frac{g^2}{16\pi^2}$$



messenger fields with SM gauge charges

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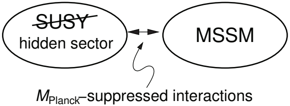

~~SUSY~~ hidden sector

MSSM

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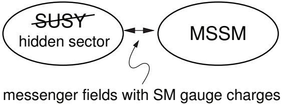

~~SUSY~~ hidden sector

MSSM

messenger fields with SM gauge charges

**Models with GUT-scale extra dimensions:**

- typically include superheavy "exotic matter": candidate messengers
- masses: $M_{\text{mess.}} \approx M_{\text{GUT}} \approx M_{\text{Planck}} \cdot \frac{g^2}{16\pi^2}$
- multiplicities: $N_{\text{mess.}} \sim \mathcal{O}(\text{few tens})$

Hybrid gauge-gravity mediation in higher-dim. GUTs:→ Brümmer,Buchmüller '11,'12

$$\mu \sim m_{3/2} \sim \mathcal{O}(100\,\text{GeV}), \qquad m_{\text{soft}} \sim N_{\text{mess.}} \cdot m_{3/2} \sim \mathcal{O}(\text{TeV})$$

# A mass spectrum from hybrid gauge-gravity mediation

| particle | mass [GeV] |
|---|---|
| $h^0$ | $124$ |
| $\chi_1^0$ | $164$ |
| $\chi_1^\pm$ | $166$ |
| $\chi_2^0$ | $167$ |
| $\chi_3^0$ | $2700$ |
| $\chi_4^0$ | $4100$ |
| $\chi_2^\pm$ | $4100$ |
| $H_0$ | $2200$ |
| $A_0$ | $2200$ |
| $H^\pm$ | $2200$ |
| $\tilde{g}$ | $4200$ |
| $\tilde{\tau}_1$ | $1900$ |
| other sleptons | $2500-3600$ |
| squarks | $2700-5000$ |

$$\tan\beta = 44$$

# Quick recap: chargino and neutralino Sector

$$\begin{aligned}\mathcal{L}_{\tilde{\chi}} =&\overline{\tilde{\chi}_i^-}(\not{p}\delta_{ij} - \omega_L(U^* X V^\dagger)_{ij} - \omega_R(V X^\dagger U^T)_{ij})\tilde{\chi}_j^- \\ &+ \frac{1}{2}\overline{\tilde{\chi}_i^0}(\not{p}\delta_{ij} - \omega_L(N^* Y N^\dagger)_{ij} - \omega_R(N Y^\dagger N^T)_{ij})\tilde{\chi}_j^0\end{aligned}$$

$$X = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin\beta \\ \sqrt{2}M_W \cos\beta & \mu \end{pmatrix}$$

diagonalised via $\mathbf{M}_{\tilde{\chi}^+} = U^* X V^\dagger$

---

[0] where we define $\omega_{L/R} = \frac{1}{2}(1 \mp \gamma_5)$

# Quick recap: chargino and neutralino Sector

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$$X = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin\beta \\ \sqrt{2}M_W \cos\beta & \mu \end{pmatrix}$$

diagonalised via
$\mathbf{M}_{\tilde{\chi}^+} = U^* X V^\dagger$

$$Y = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

diagonalised via
$\mathbf{M}_{\tilde{\chi}^0} = N^* Y N^\dagger$

$M_1, M_2 \sim \mathcal{O}(\mathrm{TeV})$, $\mu \sim \mathcal{O}(100\ \mathrm{GeV})$

---

[0] where we define $\omega_{L/R} = \frac{1}{2}(1 \mp \gamma_5)$

# Approximate mass eigenstates

$$\tilde{\chi}_1^0 = \frac{1}{\sqrt{2}}\left(\tilde{h}_d^0 - \tilde{h}_u^0\right) + \frac{\sin\beta + \cos\beta}{\sqrt{2}}\frac{m_Z}{M_1}\sin\theta_w\ \widetilde{B} - \frac{\sin\beta + \cos\beta}{\sqrt{2}}\frac{m_Z}{M_2}\cos\theta_w\ \widetilde{W}^0$$

$$\tilde{\chi}_2^0 = \frac{1}{\sqrt{2}}\left(\tilde{h}_d^0 + \tilde{h}_u^0\right) - \frac{\sin\beta - \cos\beta}{\sqrt{2}}\frac{m_Z}{M_1}\sin\theta_w\ \widetilde{B} + \frac{\sin\beta - \cos\beta}{\sqrt{2}}\frac{m_Z}{M_2}\cos\theta_w\ \widetilde{W}^0$$

$$\tilde{\chi}_1^+ = \tilde{h}_u^+ - \sqrt{2}\,\sin\beta\frac{m_W}{M_2}\ \widetilde{W}^+$$

with masses given by

$$M_{\tilde{\chi}_{1,2}^0} = |\mu| \mp \frac{m_Z^2}{2}\left(\cos\beta \pm \mathrm{sign}(\mu)\sin\beta\right)^2\left(\frac{\sin^2\theta_w}{M_1} + \frac{\cos^2\theta_w}{M_2}\right)$$

$$M_{\tilde{\chi}_1^\pm} = |\mu| - \sin 2\beta\ \mathrm{sign}(\mu)\ \cos^2\theta_w\ \frac{m_Z^2}{M_2}$$

and the mass difference between chargino $\tilde{\chi}_1^\pm$ and the LSP

$$M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0} = m_Z^2\left[\frac{\sin 2\beta}{2}\left(\frac{\sin^2\theta_w}{M_1} - \frac{\cos^2\theta_w}{M_2}\right) + \frac{1}{2}\left(\frac{\sin^2\theta_w}{M_1} + \frac{\cos^2\theta_w}{M_2}\right) + \mathcal{O}\left(\frac{\mu}{M_i^2}\right)\right]$$

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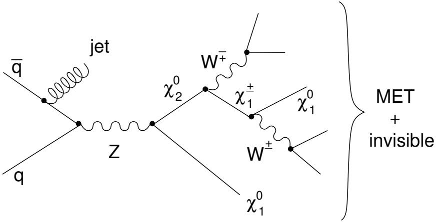
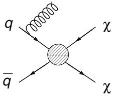
1. Light higgsinos from gauge-gravity mediation

2. Light higgsinos at colliders

# Higgsinos + monojets



- Monojet (and -photon) signal at ATLAS and CMS
- Usual interpretation of j+MET: generic WIMP with contact interaction



- Should also provide mass limits for higgsinos!

# Linear collider

**Detailed parameter measurements require linear collider**

→ Baer/Barger/Huang ’11; Berggren/Brümmer/List/Moortgat-Pick/Rolbiecki/Sert, in preparation

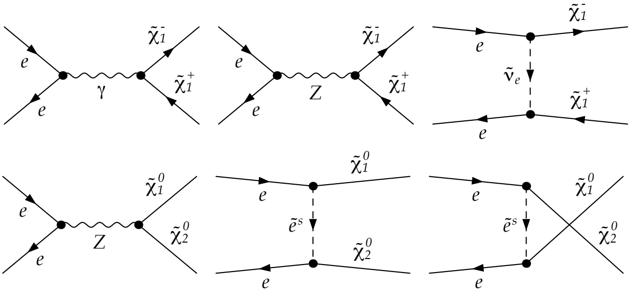
Two benchmark scenarios with hybrid gauge-gravity mediation:

| | |
|---|---|
| $m_{h^0}$ | 124 |
| $m_{\chi_1^0}$ | 164.2 |
| $m_{\chi_1^\pm}$ | 165.8 |
| $m_{\chi_2^0}$ | 166.9 |
| $M_1$ | 1700 |
| $M_2$ | 4400 |
| $\mu$ | 166 |

| | |
|---|---|
| $m_{h^0}$ | 127 |
| $m_{\chi_1^0}$ | 166.6 |
| $m_{\chi_1^\pm}$ | 167.4 |
| $m_{\chi_2^0}$ | 167.6 |
| $M_1$ | 5300 |
| $M_2$ | 9500 |
| $\mu$ | 166 |

- production of $\tilde{\chi}_1^+\tilde{\chi}_1^-$ and $\tilde{\chi}_2^0\tilde{\chi}_1^0$ already at $\sqrt{s} = 350$ GeV
- small mass splittings ⇒ pions, soft $\gamma$s

# Production at the ILC



- only $\tilde{\chi}_1^0\tilde{\chi}_2^0$ produced: $Z$ couplings forbid $\tilde{\chi}_1^0\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0\tilde{\chi}_2^0$ for higgsinos
- the $t$ and $u$ slepton exchange proportional to Yukawa coupling
  ⇒ negligible for higgsinos
  ⇒ heavy sleptons in our scenarios but even for light ones they would not contribute

# Higgsino decays

- neutralino decays via off-shell $Z$ boson or two-body $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$
- for low mass difference the latter loop induced dominates
- chragino decays with off-shell $W$ boson $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^* \to \tilde{\chi}_1^0 f f'$
- lifetime up to $\sim 10^{-12}$ s $\Rightarrow$ decay length $c\tau \sim 10^{-3}$ m
- in scenarios with small mass difference one can look for displaced vertices
- two approaches to calculate decay modes:
  - calculate parton level matrix element (e.g. with `Whizard`) and hadronize with `Pythia`
  - use hadronic currents like for $\tau$ decays, implemented in `Herwig++`
  - give very different results...

# Chargino decays

`Pythia` hadronization vs `Herwig++` hadronic currents

$m_h = 127$ GeV; $\Delta m = 0.7$ GeV

| decay | `Pythia` | `Herwig++` |
|---|---|---|
| $\tilde{\chi}_1^0 \ell \nu$ | 39% | 29% |
| $\tilde{\chi}_1^0 \pi^+$ | 11% | 60% |
| $\tilde{\chi}_1^0 \pi^+ \pi^0$ | 23% | 7% |
| $\tilde{\chi}_1^0 K^+$ | 0% | 3.5% |

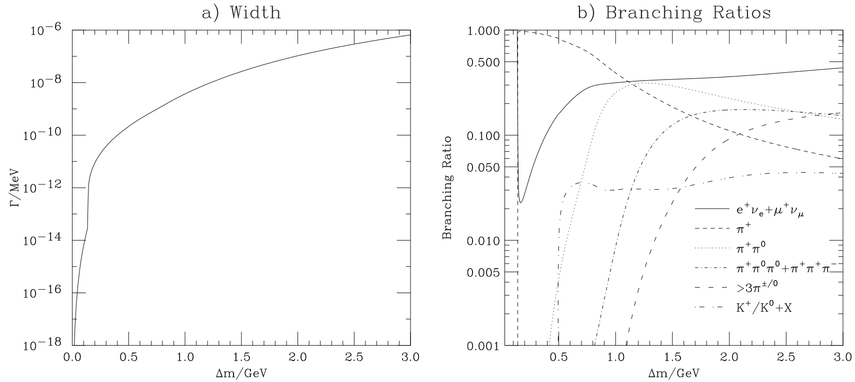
$m_h = 124$ GeV; $\Delta m = 1.6$ GeV

| decay | `Pythia` | `Herwig++` |
|---|---|---|
| $\tilde{\chi}_1^0 \ell \nu$ | 40% | 33% |
| $\tilde{\chi}_1^0 \pi^+$ | 10% | 17% |
| $\tilde{\chi}_1^0 \pi^+ \pi^0$ | 20% | 29% |
| $\tilde{\chi}_1^0 \pi^+ \pi^0 \pi^0$ | 6% | 8% |
| $\tilde{\chi}_1^0 \pi^+ \pi^+ \pi^-$ | 6% | 7% |
| $\tilde{\chi}_1^0 \pi^+ \pi^+ \pi^- \pi^0$ | 11% | 2.5% |

- `Pythia` also predicts decay modes not present in `Herwig++` that should otherwise be highly suppressed
- to be fair, `Herwig++` hadronization is not doing much better here...

# Chargino decay modes from `Herwig++`

Grellscheid, Richardson arXiv:0710.1951



⇒ note that radiative corrections to the mass difference (typically $\sim 200$ MeV) will have a profound effect on branching ratios if the tree level difference $\lesssim 1$ GeV

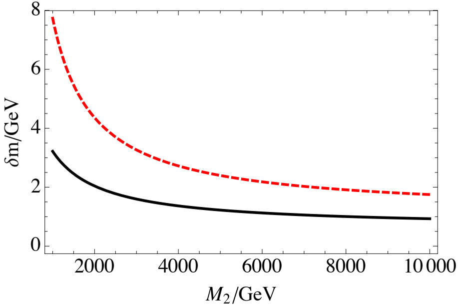
# Neutralino decays

| Decay mode<br>$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \ldots$ | $m_h = 124$ GeV | $m_h = 127$ GeV |
|---|---|---|
| $\gamma$ | $23.6\%$ | $74.0\%$ |
| $\nu\bar{\nu}$ | $21.9\%$ | $9.7\%$ |
| $e^+e^-$ | $3.7\%$ | $1.6\%$ |
| $\mu^+\mu^-$ | $3.7\%$ | $1.5\%$ |
| hadrons | $44.9\%$ | $12.7\%$ |
| $\chi_1^\pm + X$ | $1.9\%$ | $0.4\%$ |

- radiative decay to $\tilde{\chi}_1^0\gamma$ dominates for small mass differences
- cleanest experimentally
- for $m_h = 124$ GeV scenario hadronic decay modes become important giving low mass jets

# Measurements at the ILC

- cross sections: $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^0\tilde{\chi}_2^0$, $\sqrt{s} = 350, 500$ GeV
  $\Rightarrow$ accuracy 1.5%–6%
- mass differences: $\Delta m(\tilde{\chi}_1^\pm - \tilde{\chi}_1^0)$
  $\Rightarrow$ accuracy 20–70 MeV



- chargino/neutralino masses from recoil against ISR
  $\Rightarrow$ accuracy 1.5–3.5 GeV

$\Rightarrow$ more details in Hale's talk

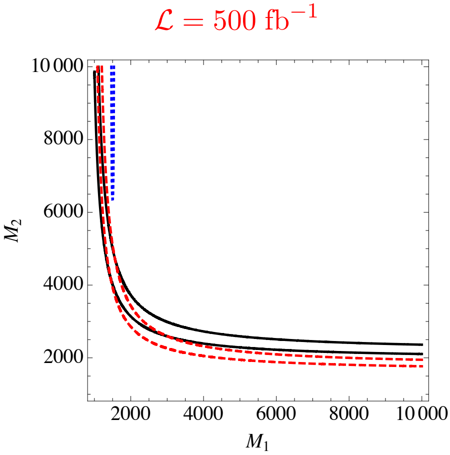
# Parameter determination

- four fitted parameters:
  $\Rightarrow M_1$, $M_2$, $\mu$ and $\tan\beta$
- perform a $\chi^2$ fit

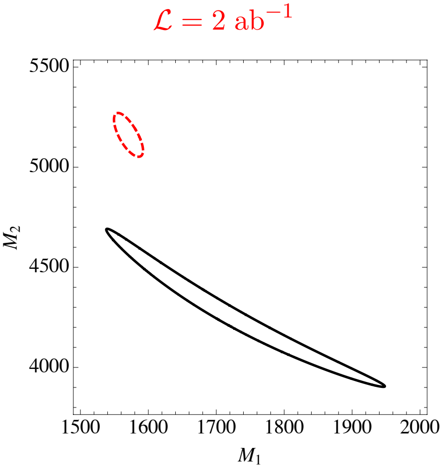
$$\chi^2 = \sum_i \left| \frac{\mathcal{O}_i^{\rm exp} - \bar{\mathcal{O}}_i^{\rm th}}{\delta \mathcal{O}_i^{\rm exp}} \right|^2$$

- $\tan\beta$ remains unconstrained, will be varied in $[1, 60]$ range
- $mu$ constrained by cross sections and absolute masses:
  $\Rightarrow$ in $m_h = 124$ GeV scenario $\mu = 167^{+2.1}_{-1.5}$ GeV
  $\Rightarrow$ in $m_h = 127$ GeV scenario $\mu = 166 \pm 1$ GeV
- mass difference between chargino and LSP strongly constraints $M_1$ and $M_2$

# $\chi^2$ contours $m_h = 124$ GeV scenario



$\tan\beta = 50$, $\tan\beta = 10$, $\tan\beta = 1$



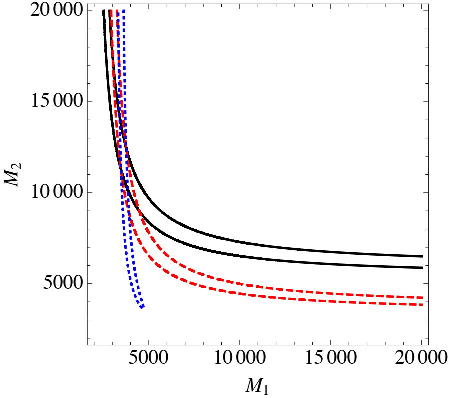
$\tan\beta = 50$, $\tan\beta = 1$

errors halved

includes $\Delta m = m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$

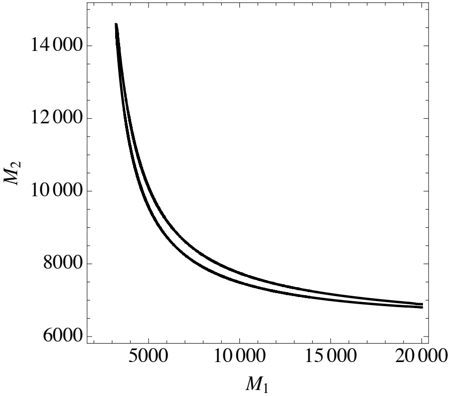
# $\chi^2$ contours $m_h = 127$ GeV scenario

$\mathcal{L} = 500\ \mathrm{fb}^{-1}$



$\tan\beta = 50$, $\tan\beta = 5$, $\tan\beta = 2$

$\mathcal{L} = 2\ \mathrm{ab}^{-1}$



$\tan\beta = 50$

errors halved

includes $\Delta m = m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$

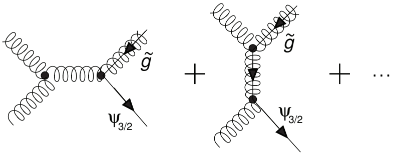
# Summary

- Light higgsinos = near-degenerate $\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ around $100 - 200$ GeV
- Motivated from naturalness
- Motivated from model-building
  E.g. hybrid gauge-gravity mediation: $\mu$ gravity-mediated, soft masses gauge-mediated
- Higgsinos hard to see: mass degeneracy ⇒ soft decay products
- Difficult to see at LHC if everything else heavy
- Good case for linear collider
- With precise measurements multi-TeV parameters could be resolved
- Experimental analysis ongoing ⇒ Hale's talk

# Cosmology

Gravitino LSP is natural dark matter candidate

Gravitinos produced thermally during reheating at large $T_R$:



$$\Omega_{\psi_{3/2}} h^2 \approx 0.21 \left( \frac{T_R}{10^{10}\ \text{GeV}} \right) \left( \frac{100\ \text{GeV}}{m_{3/2}} \right) \left( \frac{m_{\tilde{g}}}{1\ \text{TeV}} \right)^2$$

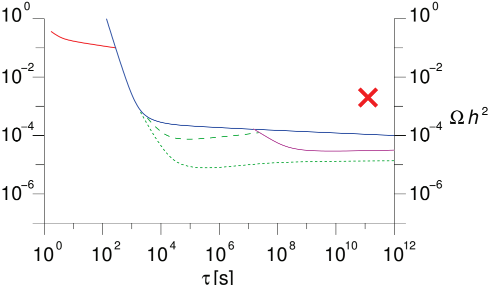
see e.g. → Bolz, Brandenburg, Buchmüller '00

$T_R \approx 10^{10}$ GeV:

- Nicely compatible with leptogenesis
- Right order of magnitude for DM abundance

# Cosmology

**Problem:** $\chi_1^0$ NLSP long-lived, decays after BBN
Energetic decay products destroy nuclei, distorting light element abundances



Bounds from → Jedamzik '06:
NLSP relic density vs. lifetime
(assuming large hadronic BR)

$^4$He, $^2$H, $^3$He, (Li)

- Higgsino NLSP relic density low: coannihilation with $\chi_1^\pm$ (recall first spectrum, $m_{\chi_1^0} = 137$ GeV, $m_{\chi_1^\pm} = 140$ GeV):

$$\Omega_{\chi_1^0} h^2 = 3 \cdot 10^{-3}$$

- . . . but still in conflict with BBN bounds
- (Small) R-parity violation? Additional entropy production?