Light higgsino model and parameter determination

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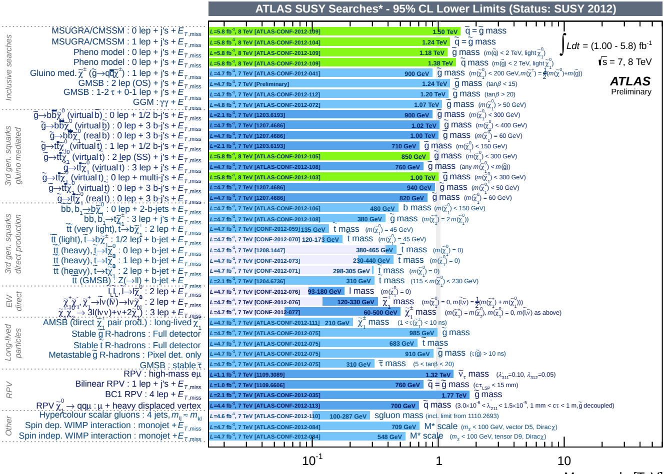
SUSY @ LHC

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



*Only a selection of the available mass limits on new states or phenomena 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

Outline

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 μ is special: supersymmetric

A priori μ is unrelated to the scale of SUSY breaking

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

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

Naturalness wants μ 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.

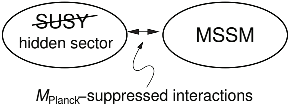
Motivates studying scenarios where higgsinos are light (EW scale) while everything else is heavy (multi-TeV) except maybe 3rd generation

light higgsinos = near-degenerate χ_1^0, $\chi_1^\pm$, χ_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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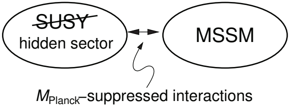
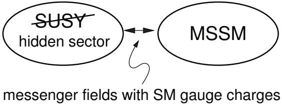


Gauge med.: $\mu = 0$,

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



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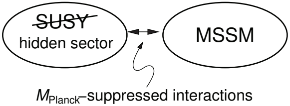

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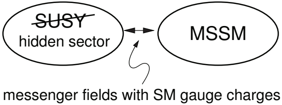

Models with GUT-scale extra dimensions:

- 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: $\rightarrow$ 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
χ_1^0	164
$\chi_1^\pm$	166
χ_2^0	167
χ_3^0	2700
χ_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

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

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

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

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

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

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

Outline

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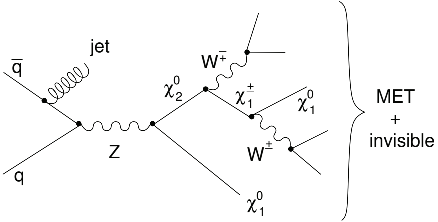
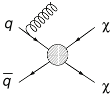
Higgsinos + monojets



- 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!

Detailed parameter measurements require linear collider

$\rightarrow$ 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
μ	160

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
μ	160

- 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 $\Rightarrow$ pions, soft γs

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 τ 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

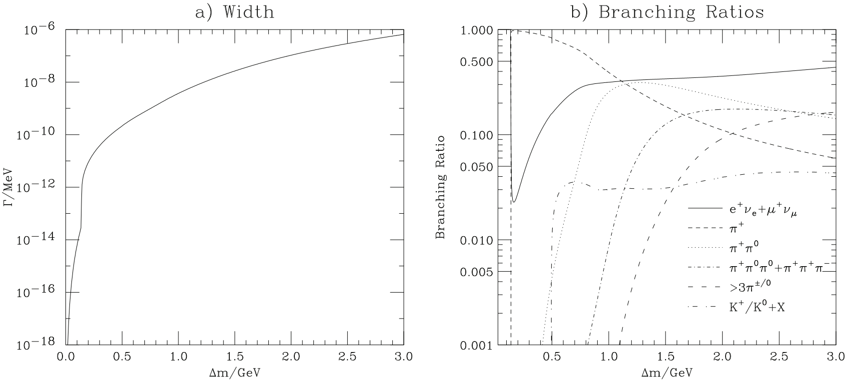
decay	Pythia	Herwig++
$\tilde{\chi}_1^0 \ell \nu$	39%	29%
$\tilde{\chi}_1^0 \pi^+$	11%	60%
$\tilde{\chi}_1^0 \pi^+ \pi^0$	23%	7%
$\tilde{\chi}_1^0 K^+$	0%	3.5%

$m_h = 124$ 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++

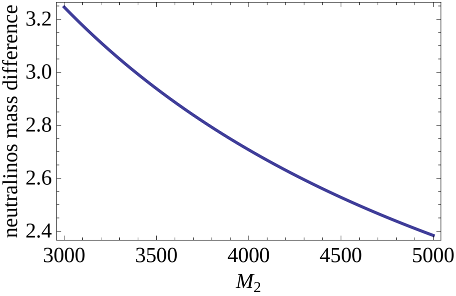


Grellscheid, Richardson arXiv:0710.1951

Measurements at the ILC

- cross sections: $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^0\tilde{\chi}_2^0$, $\sqrt{s} = 350, 500\ \mathrm{GeV}$
  $\Rightarrow$ accuracy 10%
- mass differences: $\Delta m(\tilde{\chi}_1 - \tilde{\chi}_1^0)$, $\Delta m(\tilde{\chi}_2^0 - \tilde{\chi}_1^0)$
  $\Rightarrow$ accuracy $20\ \mathrm{MeV}$
- chargino/neutralino masses from recoil against ISR
  $\Rightarrow$ accuracy $1\ \mathrm{GeV}$

$\Rightarrow$ more details in the next talk by Jenny



Parameter determination

- $\tan\beta$ unconstrained in both scenarios

scenario 1, $m_h = 124$ GeV

M_1	1700^{+300}_{-200}
M_2	4300^{+800}_{-400}
μ	166^{+2}_{-1}

scenario 2, $m_h = 127$ GeV

M_1	5400^{+800}_{-500}
M_2	> 8000
μ	166^{+3}_{-1}

- precise mass difference measurements crucial for determination of M_1 and M_2
- cross sections constrain μ value

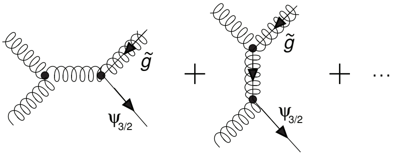
Summary

- Light higgsinos = near-degenerate χ_1^0, $\chi_1^\pm$, χ_2^0 around $100 - 200$ GeV
- Motivated from naturalness
- Motivated from model-building
  E.g. hybrid gauge-gravity mediation: μ gravity-mediated, soft masses gauge-mediated
- Higgsinos hard to see: mass degeneracy $\Rightarrow$ 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 $\Rightarrow$ Jenny's talk

Cosmology

Gravitino LSP is natural dark matter candidate

Gravitinos produced thermally during reheating at large T_R:



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

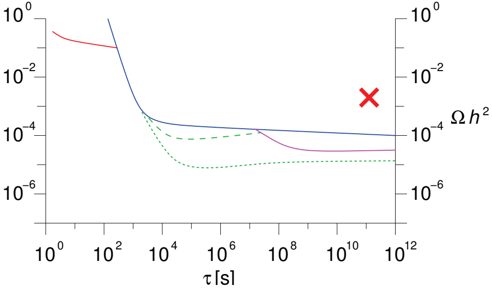
see e.g. $\rightarrow$ Bolz, Brandenburg, Buchmüller '00

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

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

Cosmology

Problem: χ_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?