Unusual Higgs Decays

from

Gauge Mediated Supersymmetry Breaking

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with

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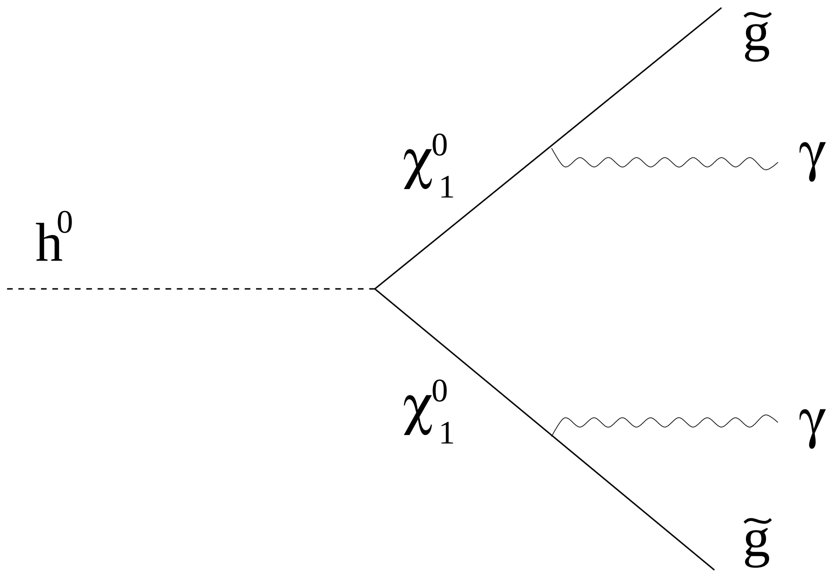
The Big Picture

- 

- $$h^0 \rightarrow \chi_1^0 \chi_1^0$$

  $\chi_1^0 \rightarrow \tilde{g}\,\gamma$ promptly in low-scale GMSB

$\Rightarrow$ collider signal of $\gamma\gamma + \not{E}_T$

Motivation

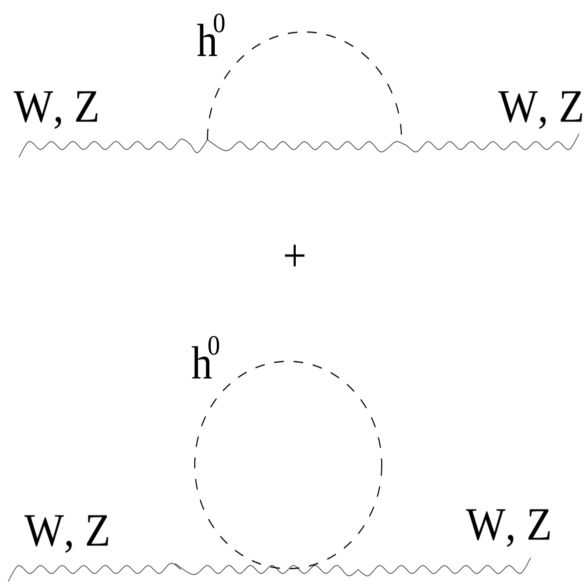
- We really want to find the Higgs!

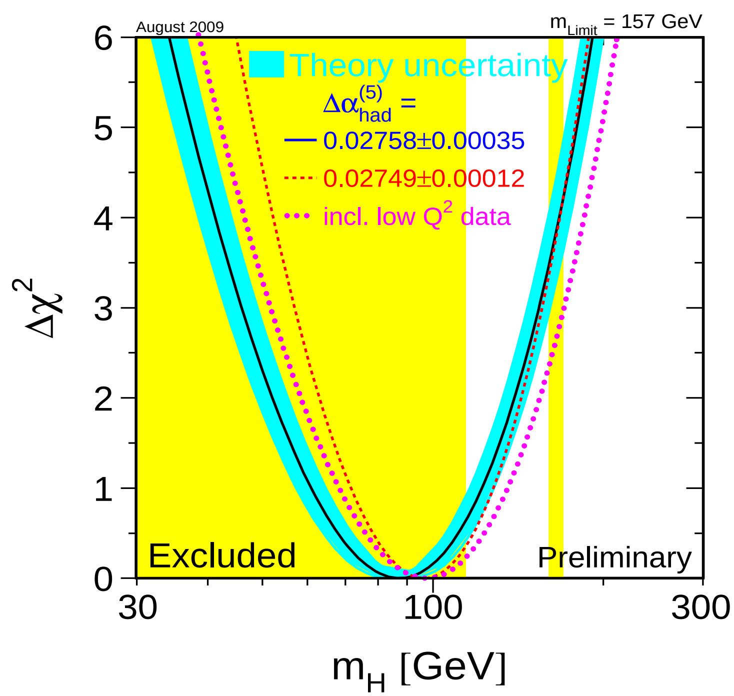
  (Or convince ourselves it's not there.)

$$SU(2)_L \times U(1)_Y \to U(1)_{em} \quad \text{when} \quad \langle H \rangle \neq 0$$

- Lower mass bound: $m_h > 114.4\,\text{GeV}$ (LEP – SM Higgs).

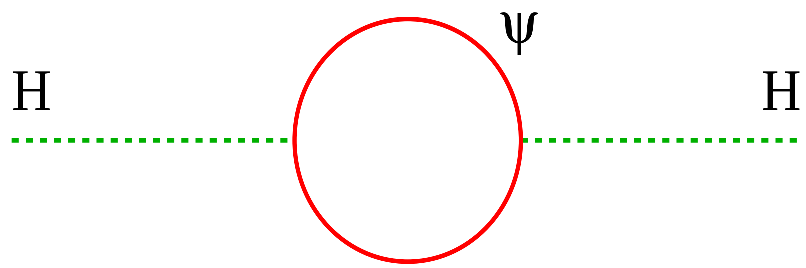
- Indirect evidence from precision electroweak constraints:





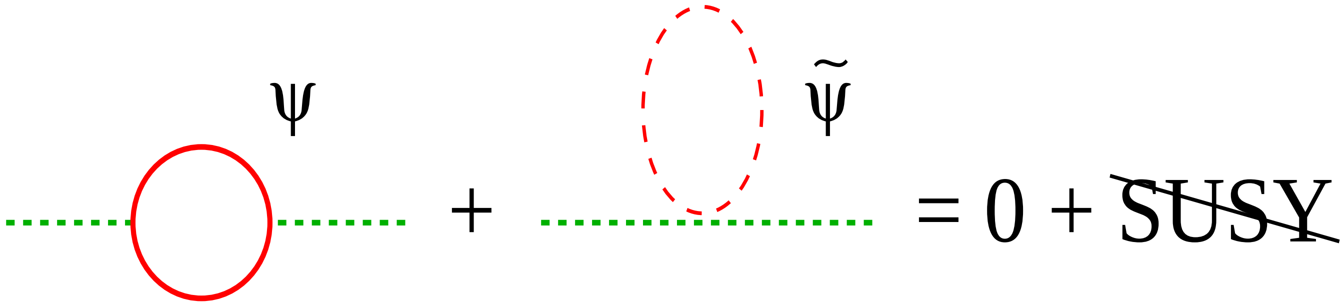
Higgs Puzzles and Supersymmetry

- The Higgs potential inducing $\langle H \rangle = v = 174\,\mathrm{GeV}$ is unstable under quantum corrections:



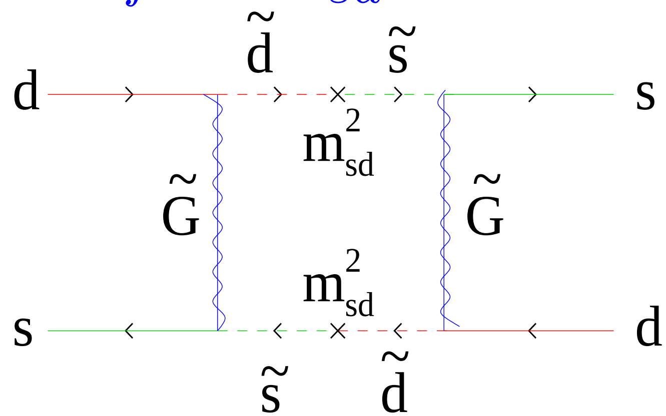
$$\Delta v^2 \sim \frac{g_\psi^2}{(4\pi)^2} M_\psi^2 .$$

- Supersymmetry (SUSY) fixes this:



SUSY Complications

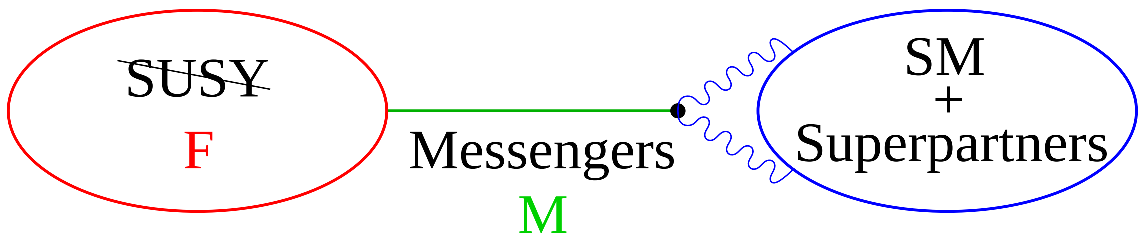
- Supersymmetry must be broken.
- If SUSY breaking is *soft* with $m_{soft} \lesssim 1000\,\mathrm{GeV}$, the Higgs potential is still protected by SUSY.
- Flavour Problem: $-\mathcal{L}_{soft} \supset m^2_{sd}\,\tilde{s}^*\tilde{d} + h.c.$



$$\Rightarrow \quad \frac{|m^2_{\tilde{sd}}|}{m^2_{soft}} \lesssim 10^{-3}$$ [Ciuchini *et al.* '96]

- SUSY breaking must have special properties . . .

Gauge Mediated SUSY Breaking (GMSB)



$$m_{soft} \sim \frac{g^2}{(4\pi)^2}\frac{F}{M} \qquad \text{(SM superpartners)}$$

$$m_{3/2} \sim \frac{F}{M_{\mathsf{Pl}}} \qquad \text{(Gravitino)}$$

- Gauge interactions are the same for all flavours.
  $\Rightarrow$ soft masses are flavour-independent! (up to CKM)
- The gravitino is the lightest superpartner (LSP) if

$$M \ll \frac{g^2}{(4\pi)^2} M_{\mathsf{Pl}}.$$

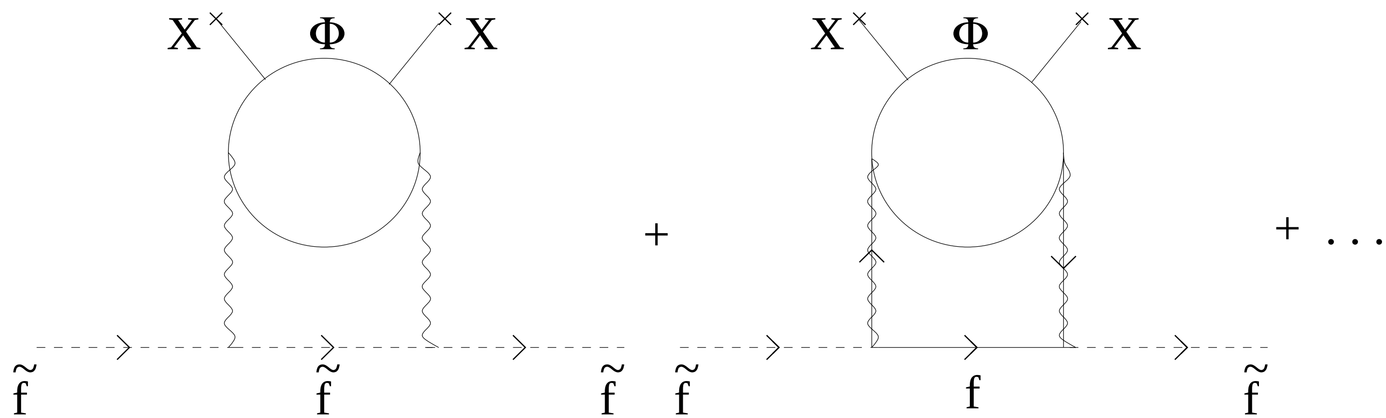
Minimal Implementation of Gauge Mediation

- $W \supset \lambda\, X\, \Phi^c \Phi$

  $X \to \langle X \rangle = M + F\,\theta^2 \to$ SUSY breaking in a hidden sector

  $\Phi,\ \Phi^c = \mathbf{5},\ \bar{\mathbf{5}} \in SU(5) \supset SU(3)_c \times SU(2)_L \times U(1)_Y$

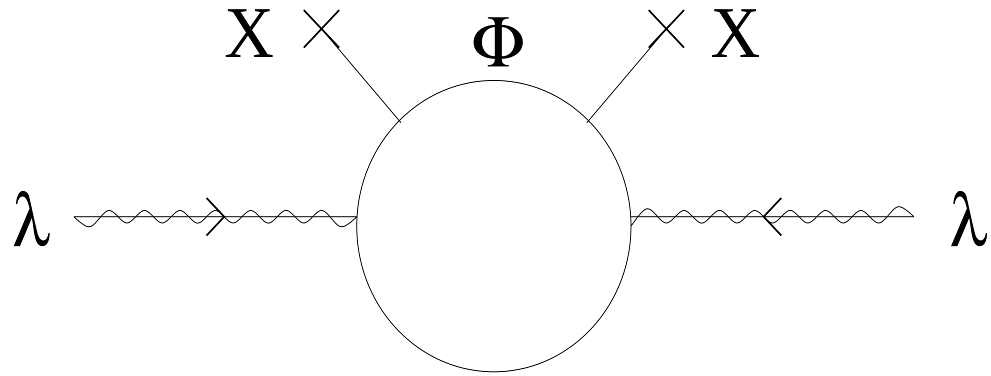
- Scalar Superpartner Soft Masses:



$$m_i^2 \simeq \sum_{a=1}^{3} \frac{2\, g_a^4}{(4\pi)^4}\, C_a^i \left|\frac{F}{M}\right|^2$$

$\Rightarrow$ flavour-universal and diagonal

- Gaugino Superpartner Soft Masses:



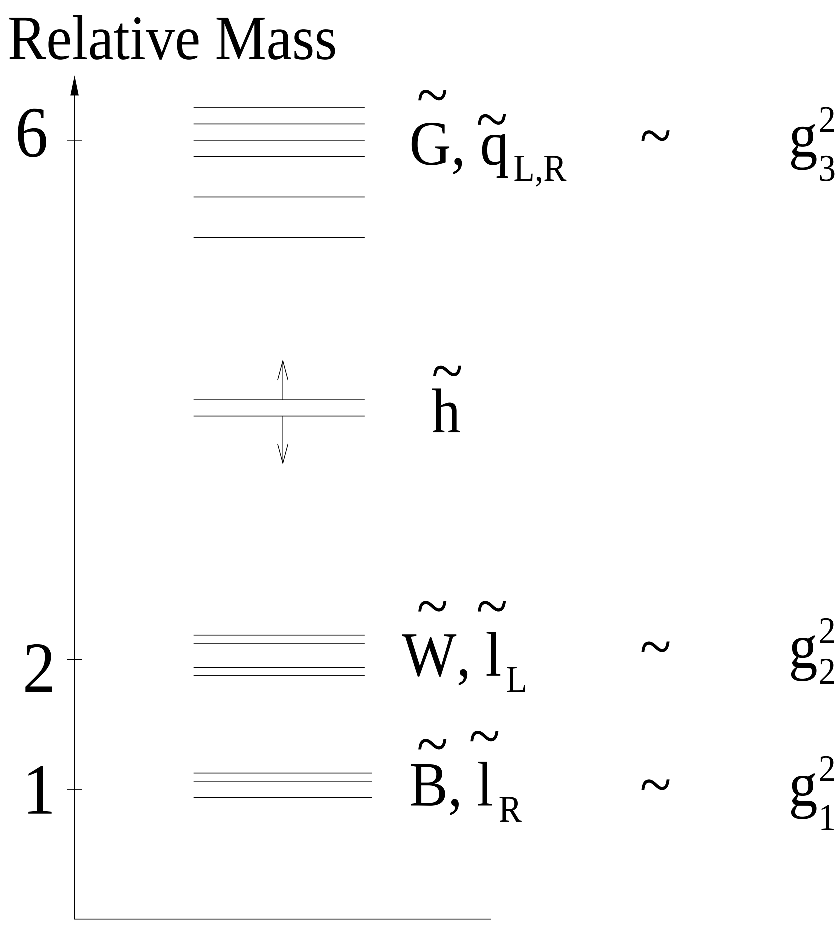
$$M_a \simeq \frac{g_a^2}{(4\pi)^2}\frac{F}{M}$$

Minimal GMSB Spectra

- Soft masses go like g_a^2.

  $M_1 \sim \sqrt{m^2_{\tilde{\ell}_R}}$ are the smallest soft masses: $g_1 < g_2 < g_3$.

  $\Rightarrow$ get a light mostly-Bino neutralino and light sleptons



- Mass Bounds:

$$m_{\tilde{\ell}_R} \gtrsim 100\,\mathrm{GeV} \quad \text{from LEP searches}$$
$$\simeq m_{\chi_1^0} \quad \text{in minimal GMSB}$$
$$m_{h^0} \lesssim 135\,\mathrm{GeV} \quad \text{for } m_{soft} \lesssim 2\,\mathrm{TeV}$$

$\Rightarrow$ can't have $h^0 \to \chi_1^0 \chi_1^0$ in minimal GMSB

(H^0, $A^0 \to \chi_1^0 \chi_1^0$ is possible [Diáz-Cruz,Ghosh,Moretti '03])

- But this is only the minimal case!

  Things can be much more complicated . . .

General Gauge Mediation and Beyond

- GGMSB parametrizes "all" possibilities.

  [Meade,Seiberg,Shih '08]

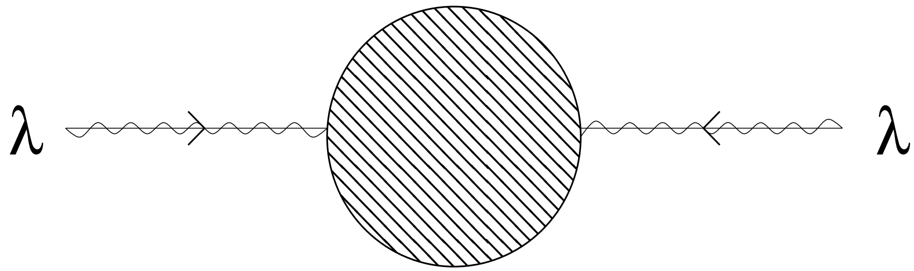
- Assumptions:

  1. $m_{soft} \to 0$ as $g_{SM} \to 0$
  2. g_{SM} remains weakly coupled

- Expand "blobs" in powers of g_{SM}.

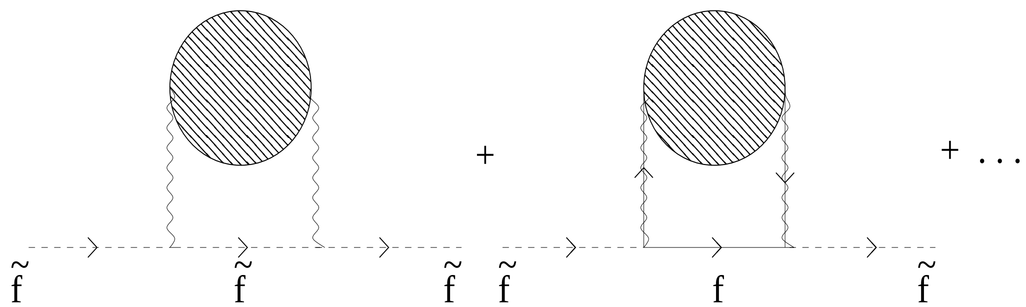
  Symmetries, SUSY lead to a finite set of basis functions.

- Gaugino Mass Blob:



$$M_a = g_a^2\, B_a$$

- Scalar Mass Blob:



$$m_i^2 = \Sigma_{a=1}^3\, g_a^4 C_a^i A_a$$

- Basis functions $\{A_a,\, B_a\}$ depend only on the gauge group, and are mutually independent.

  $\Rightarrow$ 3 distinct complex B_a for gaugino masses

  $\Rightarrow$ 3 distinct real A_a for scalar masses

- Models can be constructed that span this set. [Buican *et al.* '09]

- M_1 and $m^2_{\tilde{\ell}_R}$ are independent in GGMSB.

  $\Rightarrow$ can have a light neutralino and heavier sleptons

  $\Rightarrow$ $h^0 \to \chi^0_1 \chi^0_1$ could be possible

- High-scale GMSB: χ^0_1 is metastable

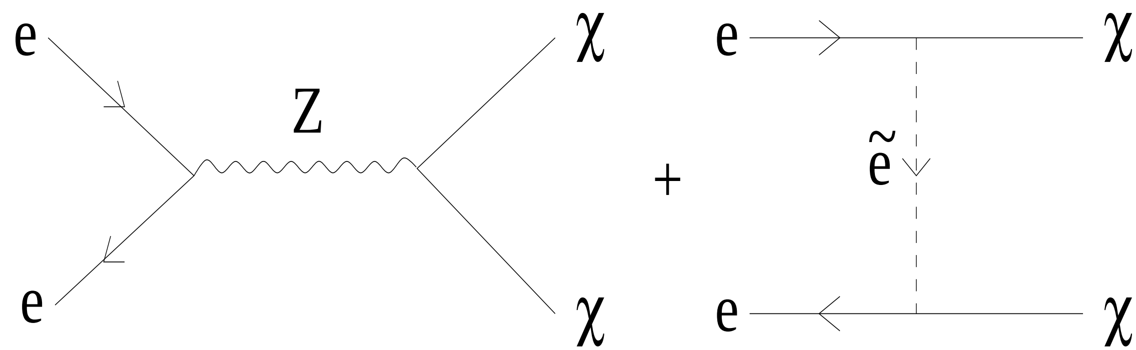
  $\to$ invisible Higgs decays [Éboli+Zeppenfeld '00]

- Low-scale GMSB: $\chi^0_1 \to \tilde{g}\,\gamma$ promptly

  $\to$ new signatures

LEP Bounds on a Light Neutralino

- LEP: e^+e^- with $\sqrt{s} \leq 209\,\text{GeV}$
- Main production modes:



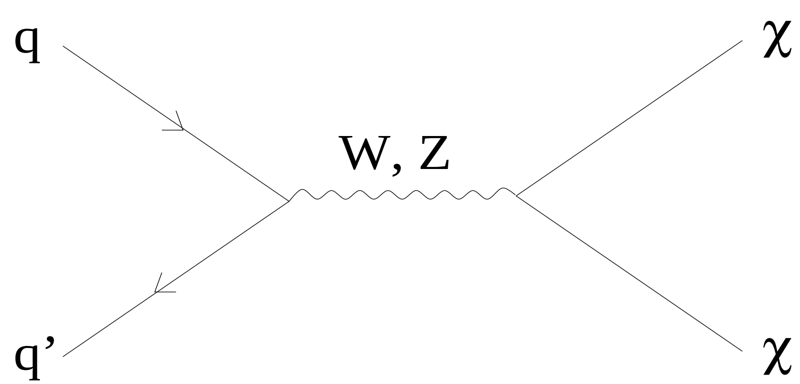
- $\sigma(e^+e^- \to \chi_1^0\chi_1^0 \to \gamma\gamma + \not{E}_T) < 10 fb$
- $BR(Z^0 \to \chi_1^0\chi_1^0 \to \gamma\gamma + \not{E}_T) < 3 \times 10^{-6}$

$\Rightarrow$ need small neutralino couplings to gauge bosons.

Tevatron Bounds on a Light Neutralino

- Tevatron: $p\bar{p}$ with $\sqrt{s} = 1.96\,\text{TeV}$

- Main SUSY Production Modes:



- CDF GMSB search:

$$\sigma_{tot}(p\bar{p} \to \chi_i^{0,\pm}\chi_j^{0,\mp} \to X + \gamma\gamma + \not{E}_T) < 20\,fb$$

$\Rightarrow$ need small neutralino couplings to gauge bosons.

Higgs Decays to Neutralinos

- LEP+Tevatron $\Rightarrow$ light neutralino must be mostly Bino:

  $\tilde{B}^0$ doesn't couple directly to gauge bosons,

  $\tilde{H}_u$, $\tilde{H}_d$, $\tilde{W}^3$ do couple directly.

$$\chi_1^0 \simeq \tilde{B}^0 - \epsilon\, \tilde{H}, \quad \text{with} \quad \epsilon \sim s_\beta c_\beta \left(\frac{v}{\mu}\right)$$

- Higgs-neutralino couplings come from

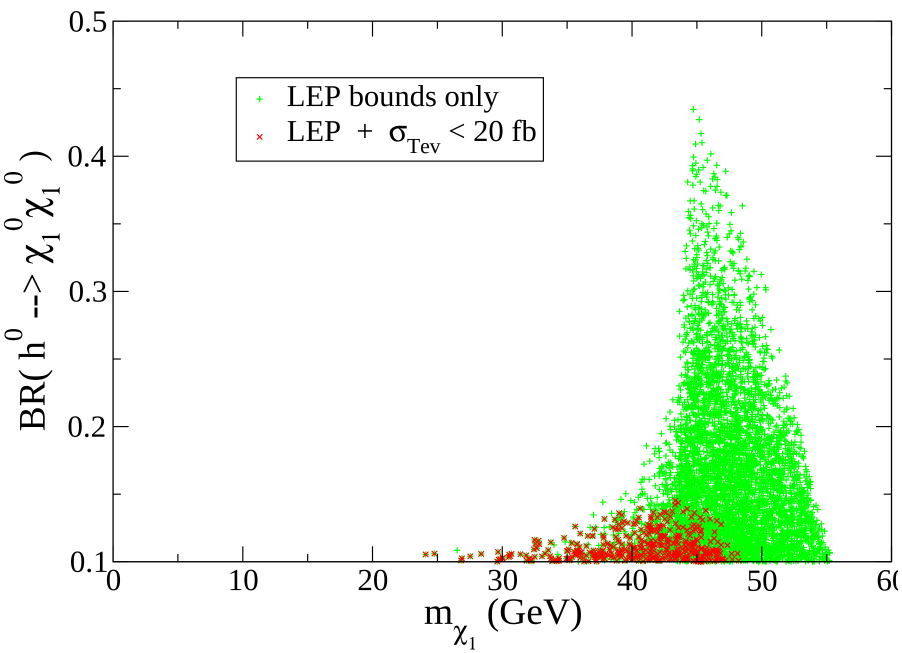
$$-\mathcal{L} \supset \pm \frac{1}{\sqrt{2}}\, g_Y\, \tilde{B}_0 \tilde{H}_i\, H_i^0$$

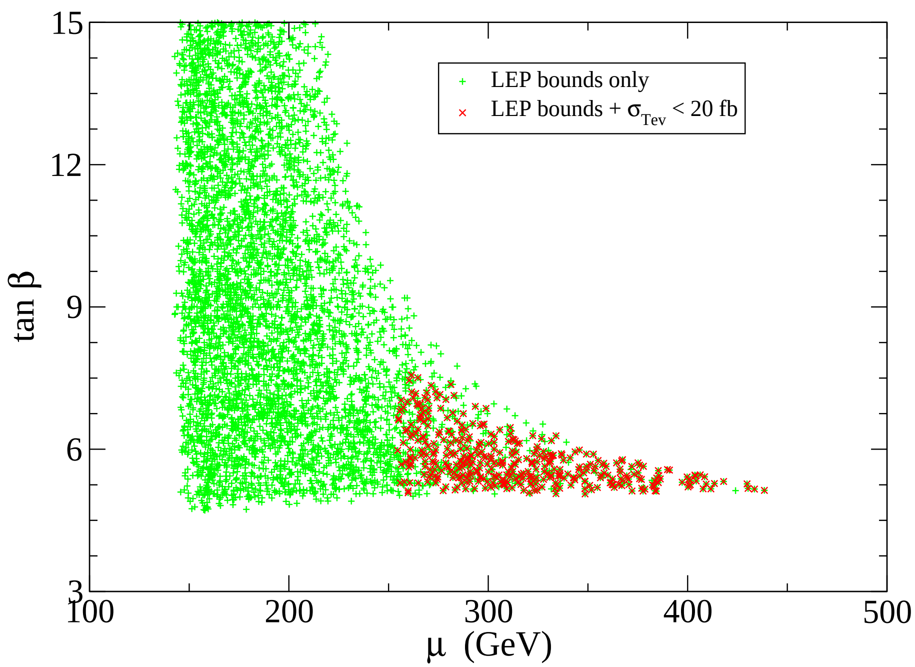
- $W^\pm/Z^0\, \chi_1^0 \chi_1^0$ coupling $\propto \epsilon^2$

- $h^0\, \chi_1^0 \chi_1^0$ coupling $\propto \epsilon$

  $\Rightarrow h^0 \to \chi_1^0 \chi_1^0$ can compete with $h^0 \to b\bar{b}$

Parameter Scans





- $BR(h^0 \to \chi_1^0 \chi_1^0) \simeq 0.15$ is possible.

  Maximal for small $\tan\beta$, $|\mu|$.

- Tevatron bounds limit $|\mu| \gtrsim 250\,\text{GeV}$.

Neutralino Decays to Photons and Gravitinos

- Gravitino = mixture of the gravitino and the goldstino.

- Goldstino Equivalence Theorem: [Fayet '76]

  "longitudinal" $s = 1/2$ goldstino components couple as $1/F$

  "transverse" $s = 3/2$ SUGRA components couple as $1/M_{\mathrm{Pl}}^2$

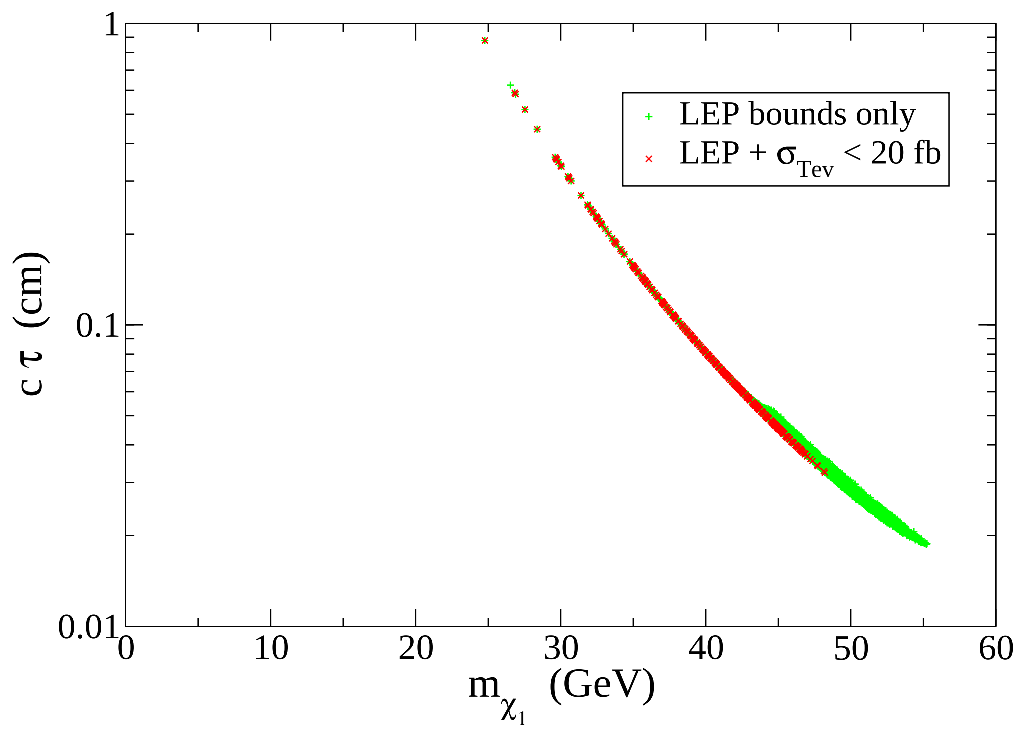
- Effective Goldstino Coupling:

$$\mathcal{L} \supset \frac{1}{4\sqrt{2}F} \bar{\lambda} \gamma^{\alpha} \sigma_{\mu\nu} \partial_{\alpha} \tilde{g} F^{\mu\nu} + \ldots$$

- This leads to

$$c\tau(\chi_1^0 \to \tilde{g}\gamma) \simeq \frac{48\pi}{c_W^2} \frac{m_{3/2}^2 M_{\mathrm{Pl}}^2}{m_{\chi_1^0}^5},$$

- $m_{3/2} \simeq 0.6\,\text{eV}$ ($F \simeq 50\,\text{TeV}$) gives "prompt" decays:



- $D\emptyset$ ECAL can "point" photons to within $2cm$.
  (CDF does slightly worse.)

Tevatron Higgs Searches

- $BR(h^0 \to \gamma\gamma) \simeq 2 \times 10^{-3}$ in the SM

  Tevatron searches limit $(\sigma BR) \lesssim 15\,(\sigma BR)_{SM}$.

- $BR(h^0 \to \chi_1^0 \chi_1^0 \to \gamma\gamma \not{E}_T) \simeq 0.15$ is possible.

  A potential signal?

- Study Sample Point:

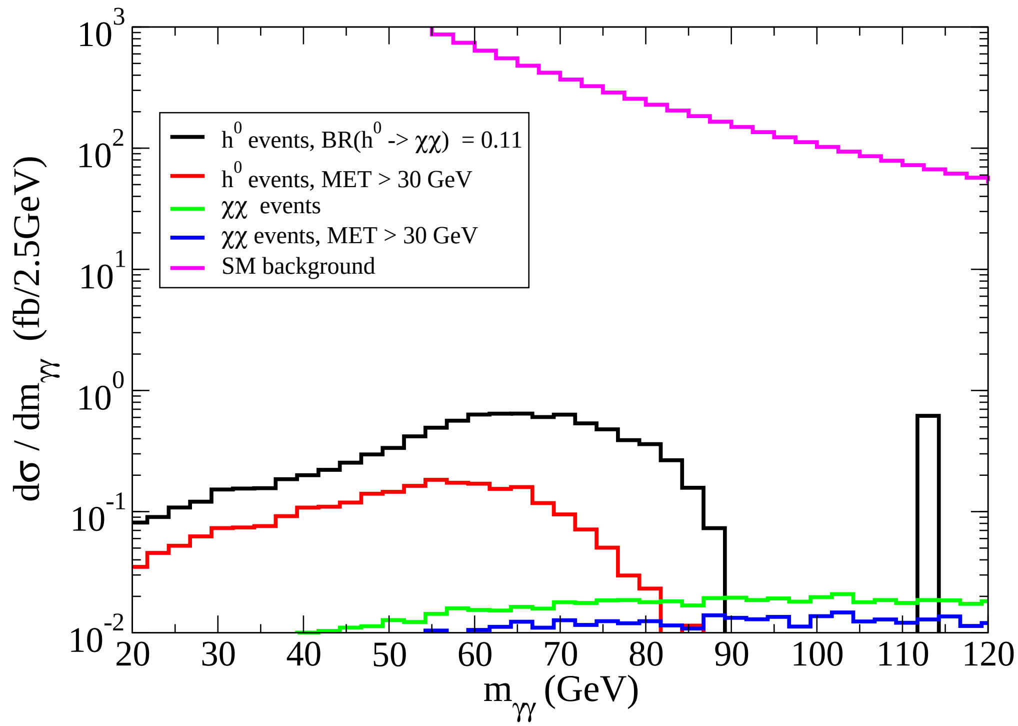
$$M_1 = 50\,\text{GeV},\;\; \mu = 300\,\text{GeV},\;\; \tan\beta = 5.5,$$

$$m_{\tilde{t}} \simeq 2000\,\text{GeV}, \quad A_t = 0, \quad m_{A^0} = 1000\,\text{GeV}.$$

This is consistent with LEP+Tevatron and gives

$$BR(h^0 \to \chi_1^0 \chi_1^0) \simeq 0.11,\;\; m_{h^0} \simeq 114.7\,\text{GeV},\;\; m_{\chi_1^0} \simeq 46.6\,\text{GeV}.$$

- Tevatron (DØ) search: $p_T^\gamma > 25\,\text{GeV},\ |\eta| < 1.1$



- This inclusive channel is swamped by background.

- Kinematic End-Point:

$$m_{\gamma\gamma} \leq \frac{2\,m_{\chi_1^0}^2}{m_h - \sqrt{m_h^2 - 4m_{\chi_1^0}^2}}.$$

Tevatron (DØ) GMSB Searches

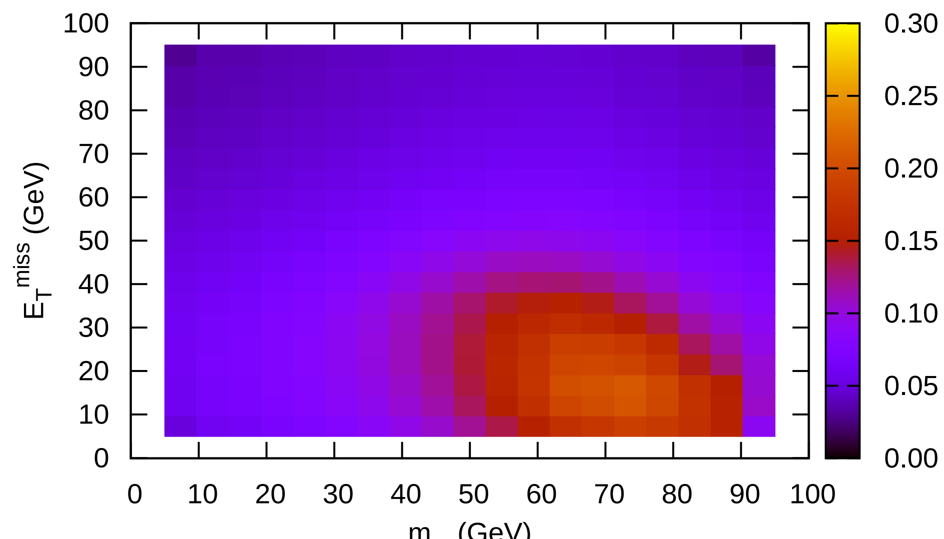
- Cuts: $p_T^\gamma > 25\,\mathrm{GeV}$, $|\eta| < 1.1$, $\not{E}_T > 30, 60\,\mathrm{GeV}$.
- With $\not{E}_T > 30\,\mathrm{GeV}$,

$$S \simeq 2.7/fb^{-1}, \quad B \simeq 10/fb^{-1}$$

$\Rightarrow S/\sqrt{B} \simeq 3$ with $10\,fb^{-1}$ of data

$\Rightarrow$ better than SM Higgs sensitivity for $m_h \lesssim 125\,\mathrm{GeV}$

- Could be improved with smarter cuts:



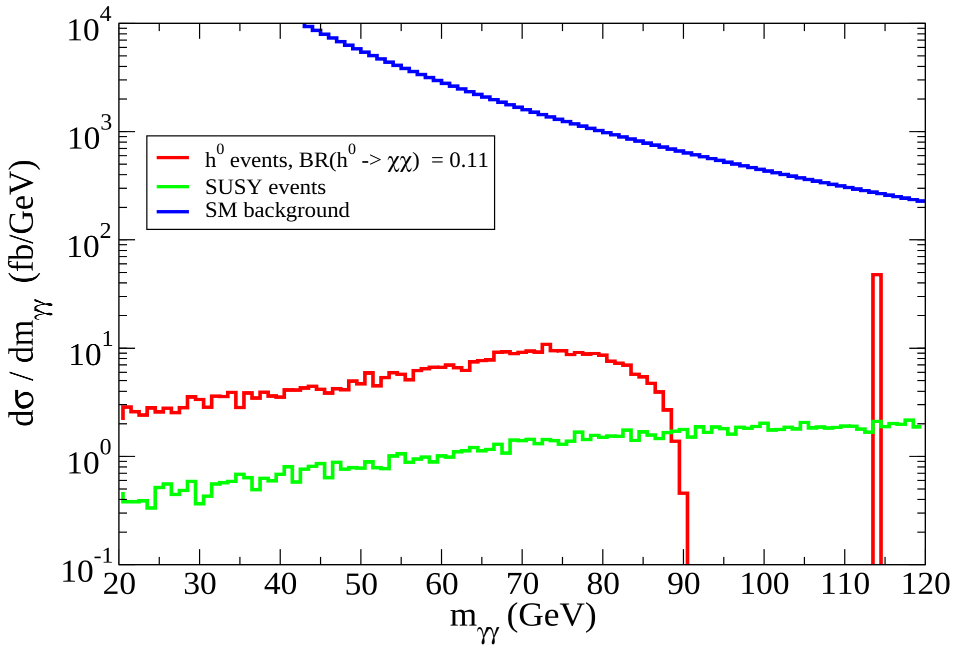
LHC Higgs Searches

- Inclusive $h^0 \to \gamma\gamma$ is the best LHC search mode for a SM Higgs with $m_{h^0} \lesssim 135\,\mathrm{GeV}$.
- Discovery requires about $15\, fb^{-1}$ of data.
- With $h^0 \to \chi_1^0 \chi_1^0 \to \gamma\gamma \not{E}_T$ there are more photonic events.
- We study the same sample point as before:

$$BR(h^0 \to \chi_1^0 \chi_1^0) \simeq 0.11, \;\; m_{h^0} \simeq 114.7\,\mathrm{GeV}, \;\; m_{\chi_1^0} \simeq 46.6\,\mathrm{GeV}.$$

LHC Inclusive Diphotons

- ATLAS Inclusive Higgs: $p_T^\gamma > 40,\ 25\,\mathrm{GeV},\ |\eta| < 2.5$

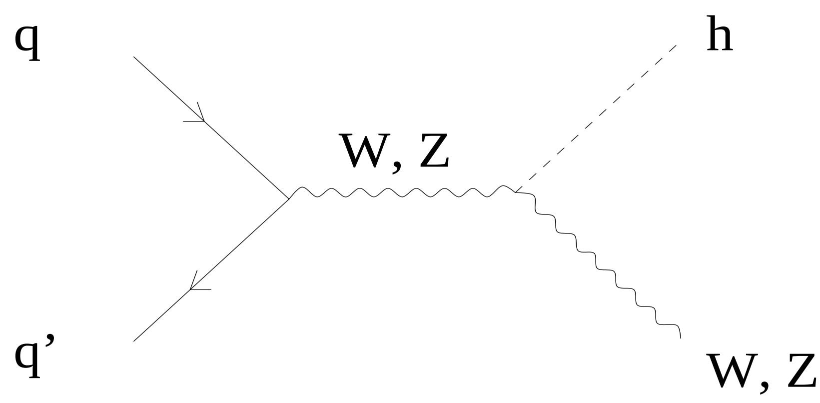


- Requiring $60\,\mathrm{GeV} < m_{\gamma\gamma} < 90\,\mathrm{GeV}$ gives

$$S/\sqrt{B} = 1.1 \quad \text{with } 1\,fb^{-1} \quad (S/B \sim 5 \times 10^{-4})$$

$\Rightarrow$ 20 fb^{-1} needed for discovery (but systematics . . .)

Exclusive $(W/Z)\,h^0 \to \gamma\gamma + n\,\ell$

- 

- Requiring a lepton from the W/Z makes this channel clean.

- CMS Search: $p_T^\gamma = 35$, $20\,\mathrm{GeV}$, $|\eta| < 2.5$, $N_\ell \geq 1$, $\ldots$

- With $20\,\mathrm{GeV} < m_{\gamma\gamma} < 90\,\mathrm{GeV}$ we find (after cuts)

$$S \simeq 7\,fb,\ B \simeq 28\,fb \quad \Rightarrow S/\sqrt{B} \simeq 1.26 \quad \text{with } 1\,fb^{-1}.$$

$\Rightarrow$ discovery with about $16\,fb^{-1}$ of data

Unexpected New Physics

- $h^0 \to \chi_1^0 \chi_1^0 \to \gamma\gamma \not{E}_T$ is not a generic SUSY signal, but it is not so crazy either.

- Planned $D\emptyset$ searches for GMSB and ATLAS searches for $(W/Z)\, h^0 \to \gamma\gamma$ are potentially sensitive to this mode.

- CDF GMSB searches use a cut $H_T = \sum_i p_T^i + \not{E}_T > 200\,\mathrm{GeV}$ which eliminates this signal.

- ATLAS non-inclusive $h^0 \to \gamma\gamma$ searches apply $p_T^{\gamma_1} \gtrsim 50\,\mathrm{GeV}$ which removes most of this signal.

- It is important to search broadly in LHC data!

Summary

- $h^0 \to \chi_1^0 \chi_1^0$ with $\chi_1^0 \to \gamma\,\tilde{g}$ promptly.
- This does not occur in minimal MSSM GMSB.

  It is possible in generalized GMSB scenarios.
- Could be visible at the Tevatron and the LHC.
- Future Directions:
  - Non prompt $\chi_1^0 \to \gamma\,\tilde{g}$ decays.
  - NMSSM #1: larger $BR(h^0 \to \chi_1^0 \chi_1^0)$ with smaller $\tan\beta$.
  - NMSSM #2: $h^0 \to \chi_1^0 \chi_1^0$ with $\chi_1^0 \to a^0 \tilde{g}$ and $a^0 \to b\bar{b}$, $\tau\bar{\tau}$.
  - NMSSM #3: $h^0 \to \chi_2^0 \chi_2^0$ with $\chi_2^0 \to \chi_1^0 X$ and $\chi_1^0 \to \gamma\tilde{g}$.