

Title: Unusual Higgs Decays in Low-Scale Gauge Mediation

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Abstract: In generalized models of gauge-mediated supersymmetry breaking, a standard model-like Higgs boson can decay to pairs of neutralino superpartners. If the energy scale of supersymmetry breaking is very low, each of these neutralinos will subsequently decay promptly to a photon and a gravitino. This process gives rise to a collider signal consisting of a pair of photons and missing energy. In this talk I will describe scenarios of supersymmetry breaking that can give rise this signature and other non-standard Higgs decay modes, and discuss how it might be discovered with upcoming data from the Tevatron and the LHC.

Unusual Higgs Decays
in
Low-Scale Gauge Mediation

David Morrissey

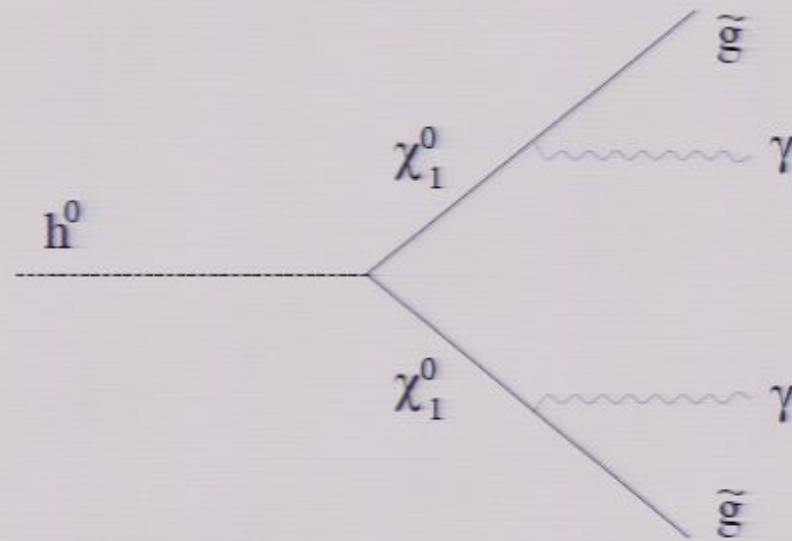
TRIUMF

with

John Mason and David Poland

The Big Picture

-



-

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

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

\Rightarrow collider signal of $\gamma\gamma + \cancel{E}_T$

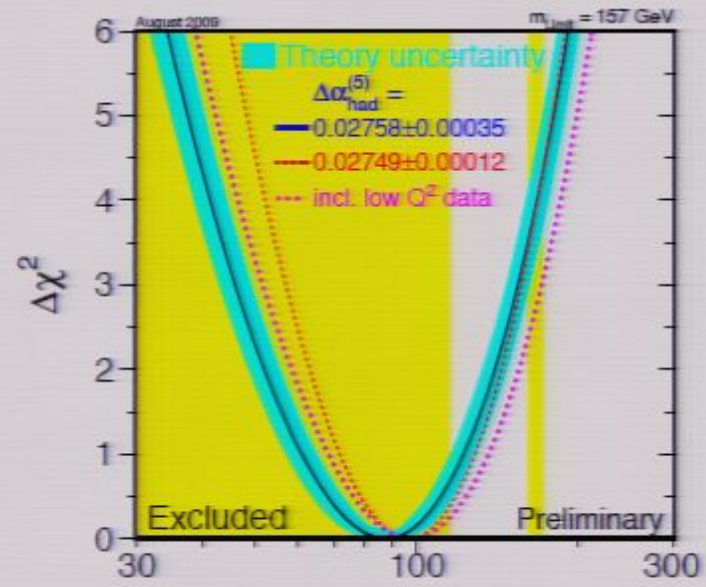
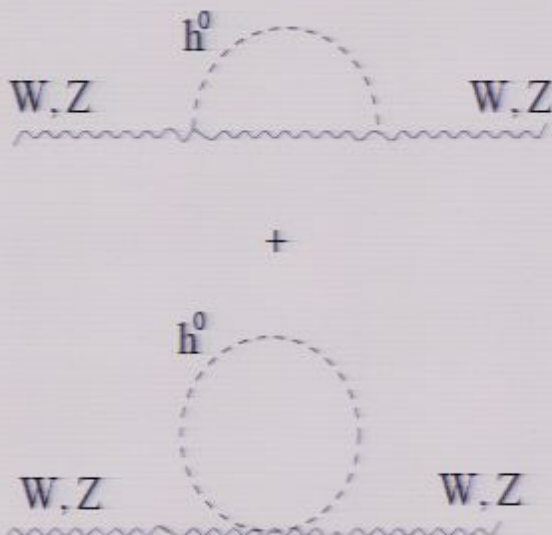
Motivation

- We really want to find the Higgs!

(Or convince ourselves it's not there.)

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

- 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 $\langle H \rangle = v = 174 \text{ GeV}$ is unstable under quantum corrections:



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

- Supersymmetry (SUSY) fixes this:



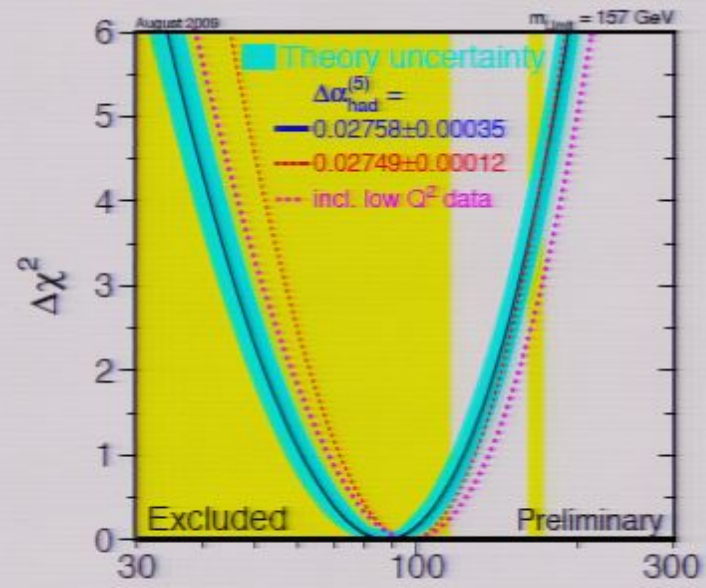
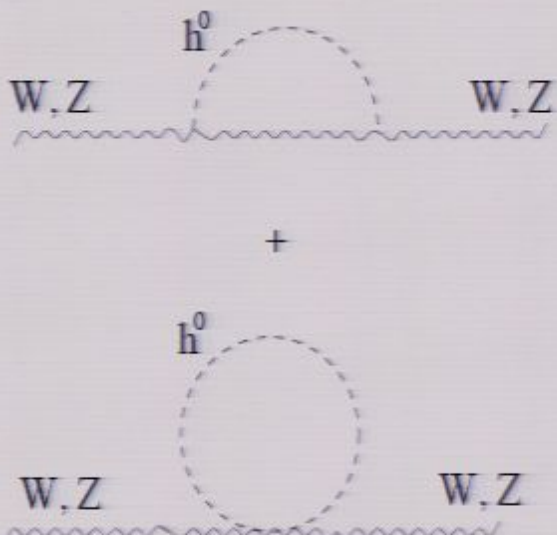
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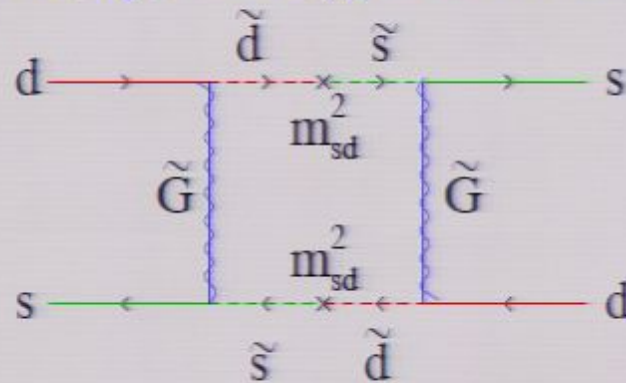
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SUSY Complications

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



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

- SUSY breaking must have special properties ...

Gauge Mediated SUSY Breaking (GMSB)

→ SUSY breaking communicated by SM gauge interactions

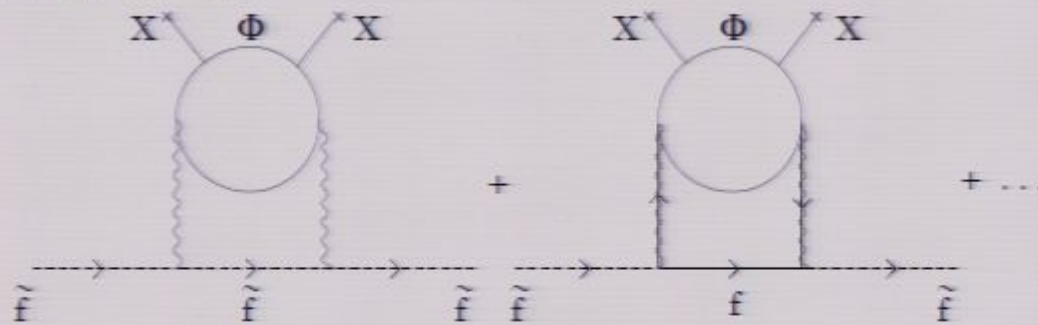
- Minimal Implementation:

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

$X = M + F \theta^2 \rightarrow$ SUSY breaking in a hidden sector

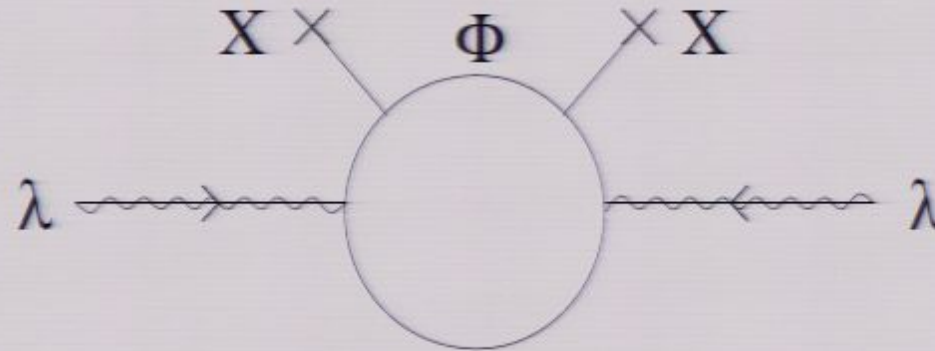
$$\Phi, \Phi^c = \mathbf{5}, \bar{\mathbf{5}} \in SU(5) \supset SU(3)_c \times SU(2)_L \times U(1)_Y$$

- Scalar Soft Masses:



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

- Gaugino Soft Masses:



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

- Gravitino Mass:

$$m_{3/2} = \frac{F}{\sqrt{3}M_{\text{Pl}}}$$

- The gravitino is the lightest superpartner (LSP) if

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

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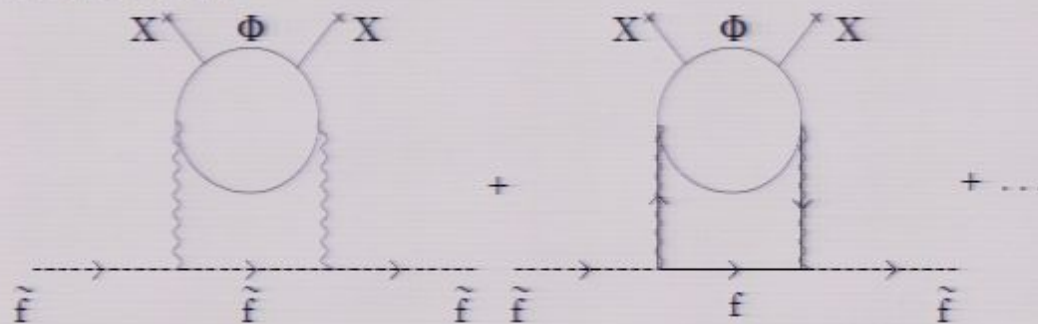
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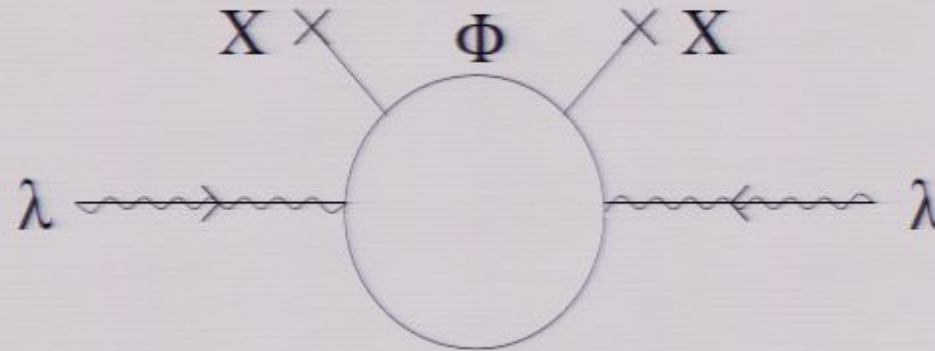
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Minimal GMSB Spectra

- $M_1 \sim \sqrt{m_{\tilde{\ell}_R}^2}$ are the smallest soft masses: $g_1 < g_2 < g_3$.
 \Rightarrow get a light mostly-Bino neutralino and light sleptons
- Mass Bounds:

$$m_{\tilde{\ell}_R} \gtrsim 100 \text{ GeV} \quad \text{from LEP searches}$$

$$\simeq m_{\chi_1^0} \quad \text{in minimal GMSB}$$

$$m_{h^0} \lesssim 135 \text{ GeV} \quad \text{for } m_{\text{soft}} \lesssim 2 \text{ TeV}$$

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

($H^0, A^0 \rightarrow \chi_1^0 \chi_1^0$ 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. $m_{soft} \rightarrow 0$ as $g_{SM} \rightarrow 0$

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:



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

- 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]

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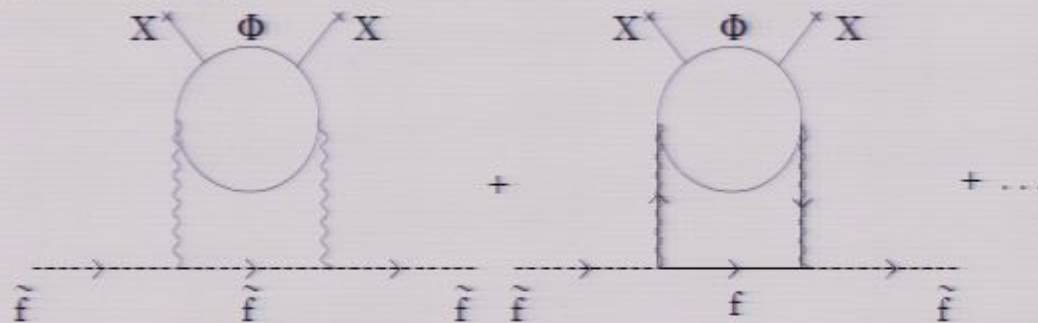
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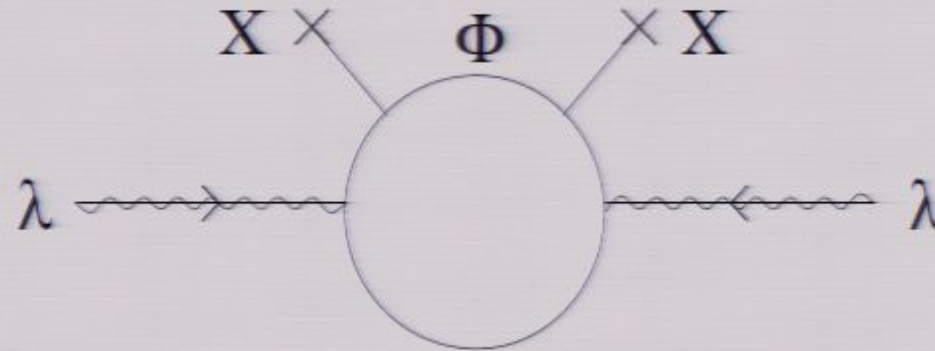
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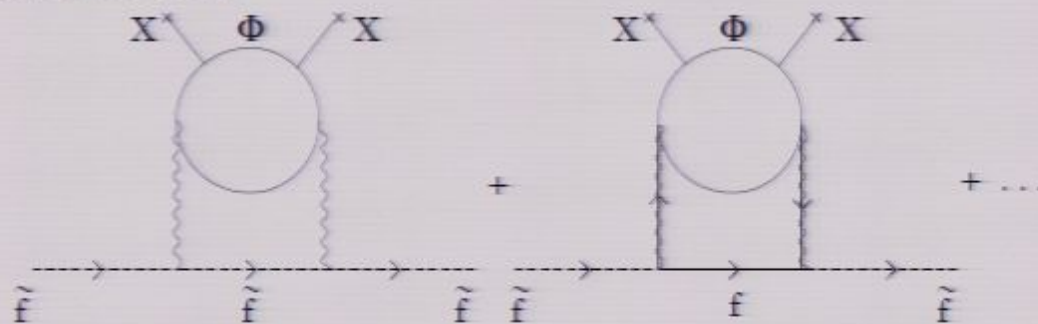
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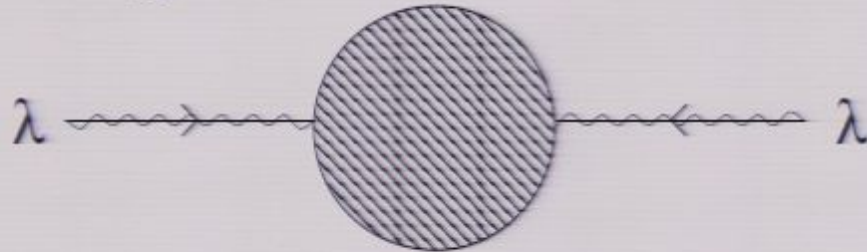
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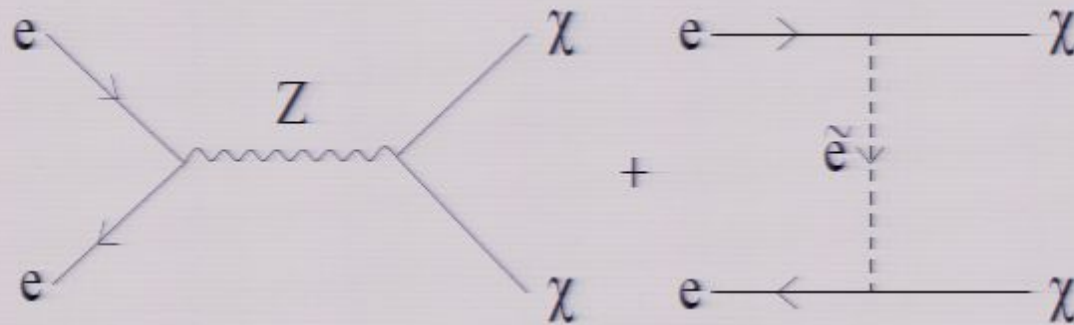
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- Models can be constructed that span this set. [Buican *et al.* '09]

- Many possibilities beyond GGMSB:
 - more couplings in the Higgs sector for μ [Komargodski+Seiberg '08]
 - direct singlet-messenger couplings [Delgado, Giudice, Slavich '07]
 - D -terms for hypercharge: $m_i^2 \rightarrow m_i^2 + Y \xi$ [Carpenter *et al.* '08]
- M_1 and $m_{\tilde{\ell}_R}^2$ are independent in GGMSB.
 - \Rightarrow can have a light neutralino and heavier sleptons
 - $\Rightarrow h^0 \rightarrow \chi_1^0 \chi_1^0$ could be possible
- High-scale GMSB: χ_1^0 is metastable
 - \rightarrow invisible Higgs decays [Éboli+Zeppenfeld '00]
- Low-scale GMSB: $\chi_1^0 \rightarrow \tilde{g} \gamma$ promptly
 - \rightarrow new signatures

LEP Bounds on a Light Neutralino

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

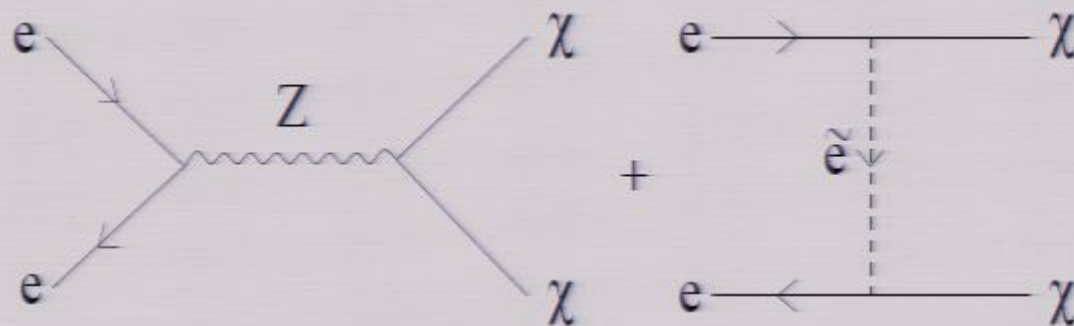


- $\sigma(e^+e^- \rightarrow \chi_1^0\chi_1^0 \rightarrow \gamma\gamma + \cancel{E}_T) < 10 \text{ fb}$
- $BR(Z^0 \rightarrow \chi_1^0\chi_1^0 \rightarrow \gamma\gamma + \cancel{E}_T) < 3 \times 10^{-6}$

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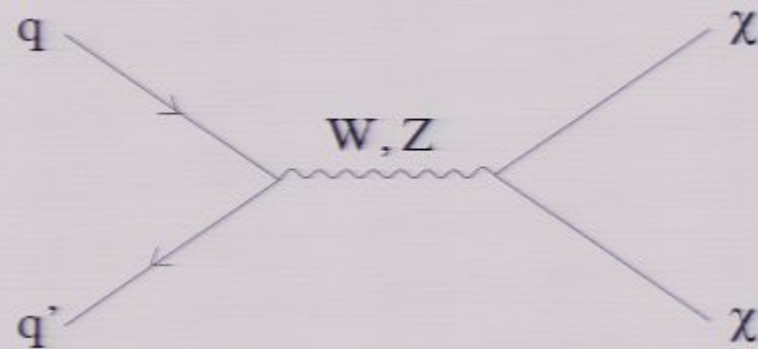
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Tevatron Bounds on a Light Neutralino

- Tevatron: $p\bar{p}$ with $\sqrt{s} = 1.96$ TeV
- Main SUSY Production Modes:



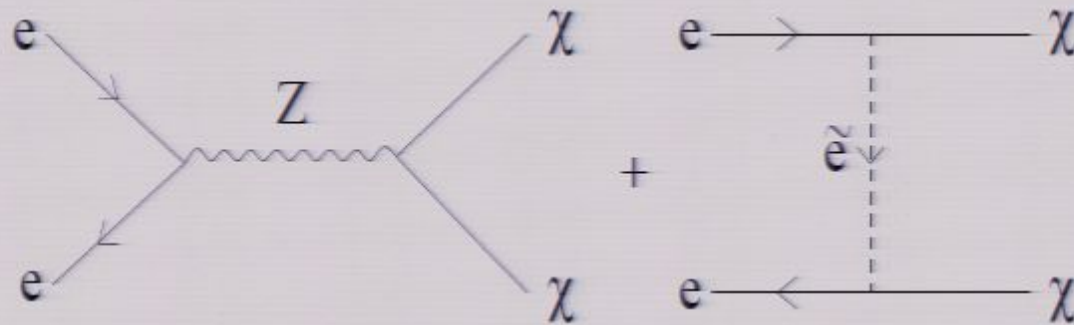
- CDF GMSB search:

$$\sigma_{tot}(p\bar{p} \rightarrow \chi_i^{0,\pm} \chi_j^{0,\mp} \rightarrow X + \gamma\gamma + \cancel{E}_T) < 20 \text{ fb}$$

\Rightarrow need small neutralino couplings to gauge bosons.

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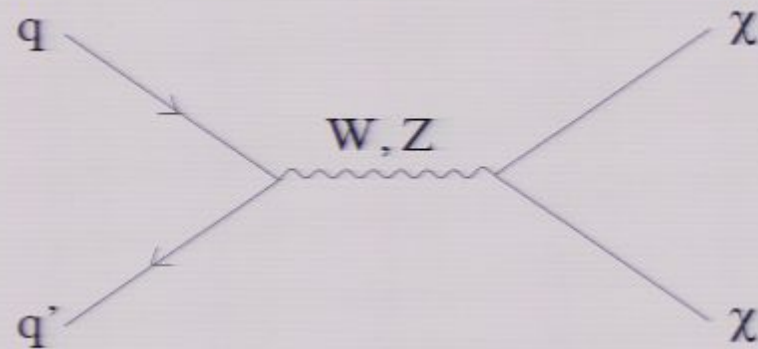
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Higgs Decays to Neutralinos

- 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

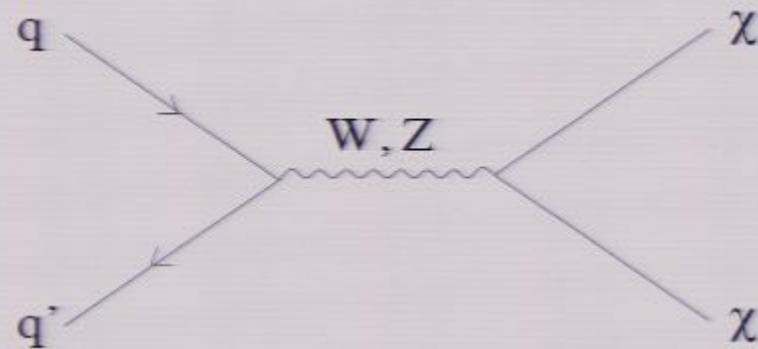
$$-\mathcal{L} \supset \pm \frac{1}{\sqrt{2}} g_Y \tilde{B}_0 \tilde{H}_i H_i^0$$

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

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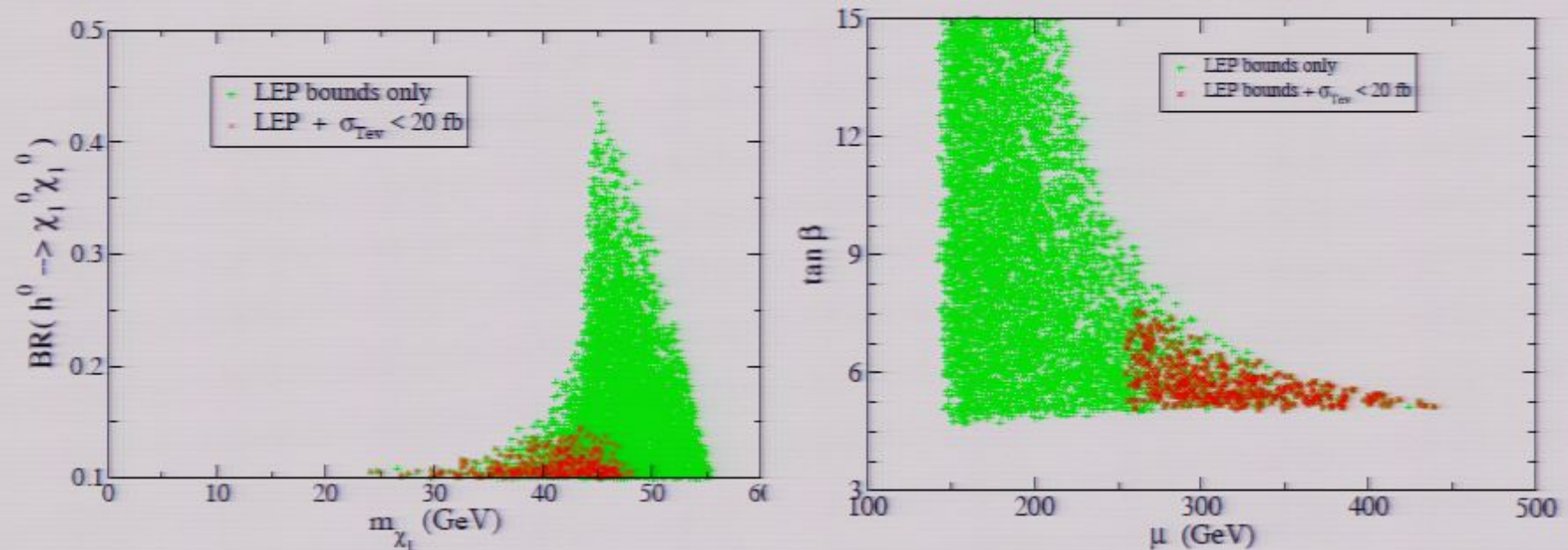
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Parameter Scans



- $BR(h^0 \rightarrow \chi_1^0 \chi_1^0) \simeq 0.15$ is possible.
Maximal for small $\tan \beta$, $|\mu|$.
- Tevatron bounds limit $|\mu| \gtrsim 250$ GeV.

Neutralino Decays to Photons and Gravitinos

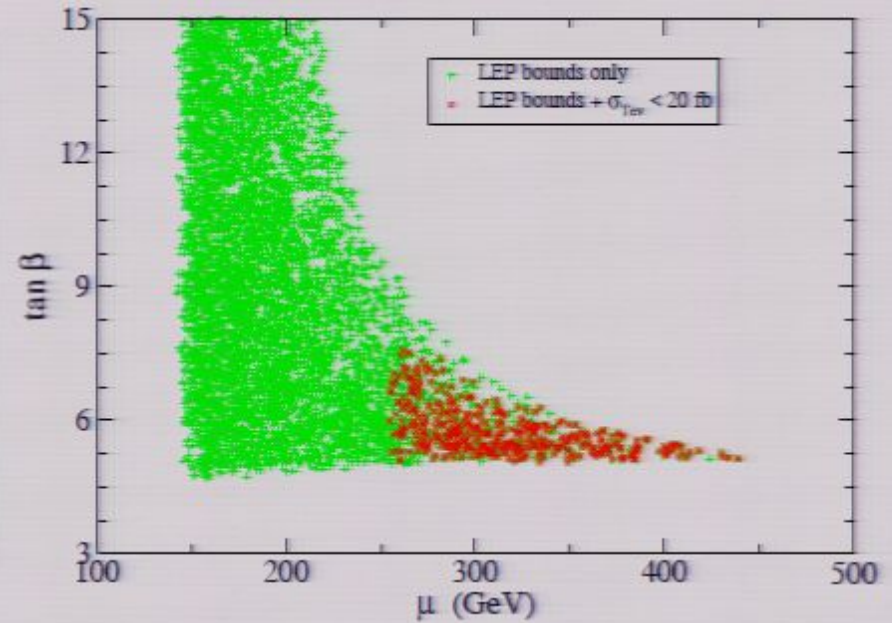
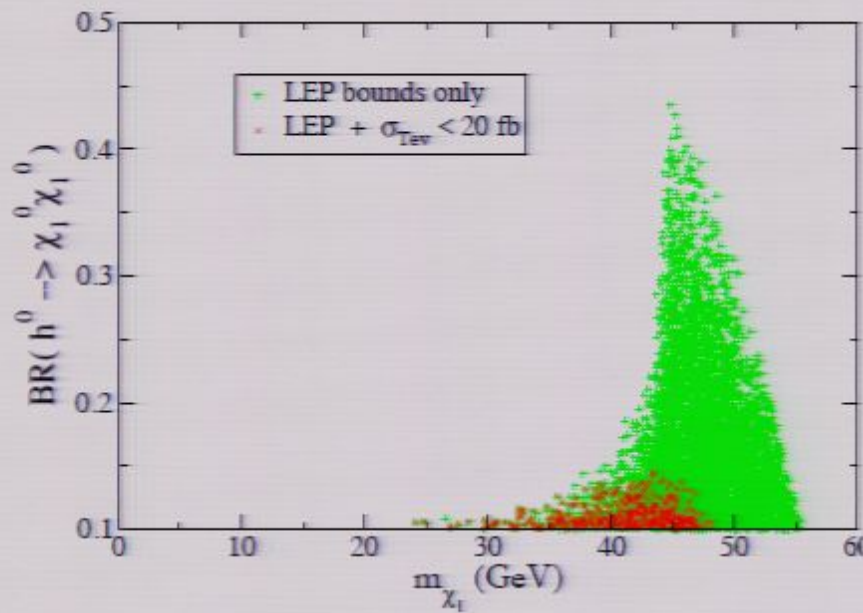
- Gravitino = mixture of the gravitino and the goldstino.
- Goldstino Equivalence Theorem: [Fayet '76]
 - “longitudinal” $s = 1/2$ goldstino components couple as $1/F$
 - “transverse” $s = 3/2$ SUGRA components couple as $1/M_{\text{Pl}}^2$
- Effective Goldstino Coupling:

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

- This leads to

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

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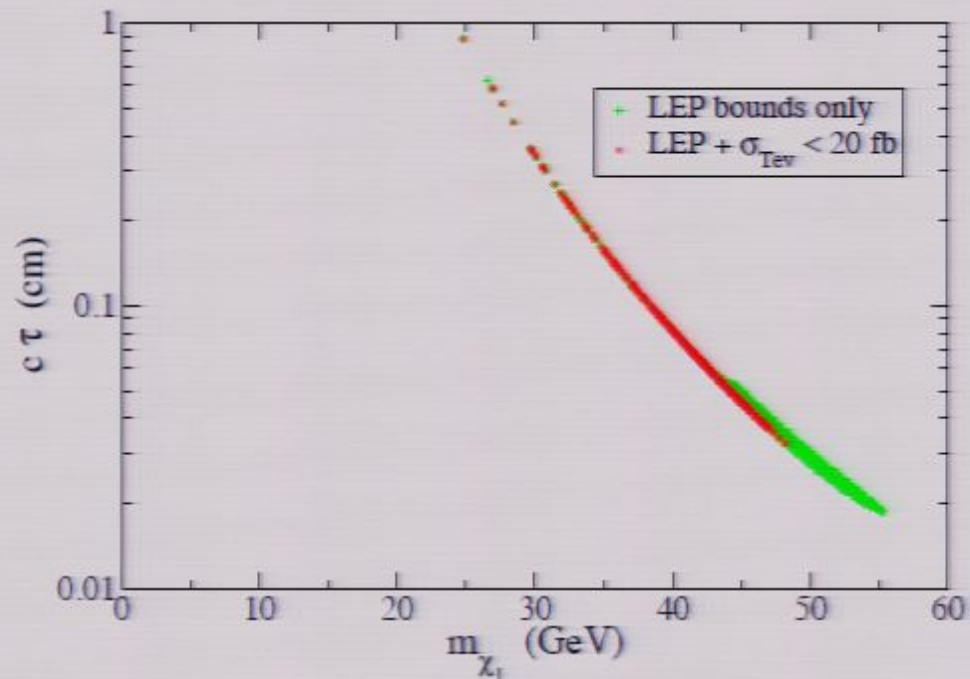
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- $m_{3/2} \simeq 0.6 \text{ eV}$ ($F \simeq 50 \text{ TeV}$) gives “prompt” decays:



- $D\phi$ ECAL can “point” photons to within 2cm .
(CDF does slightly worse.)

Tevatron Higgs Searches

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

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

- $BR(h^0 \rightarrow \chi_1^0 \chi_1^0 \rightarrow \gamma\gamma + E_T) \simeq 0.15$ is possible.

A potential signal?

- Study Sample Point:

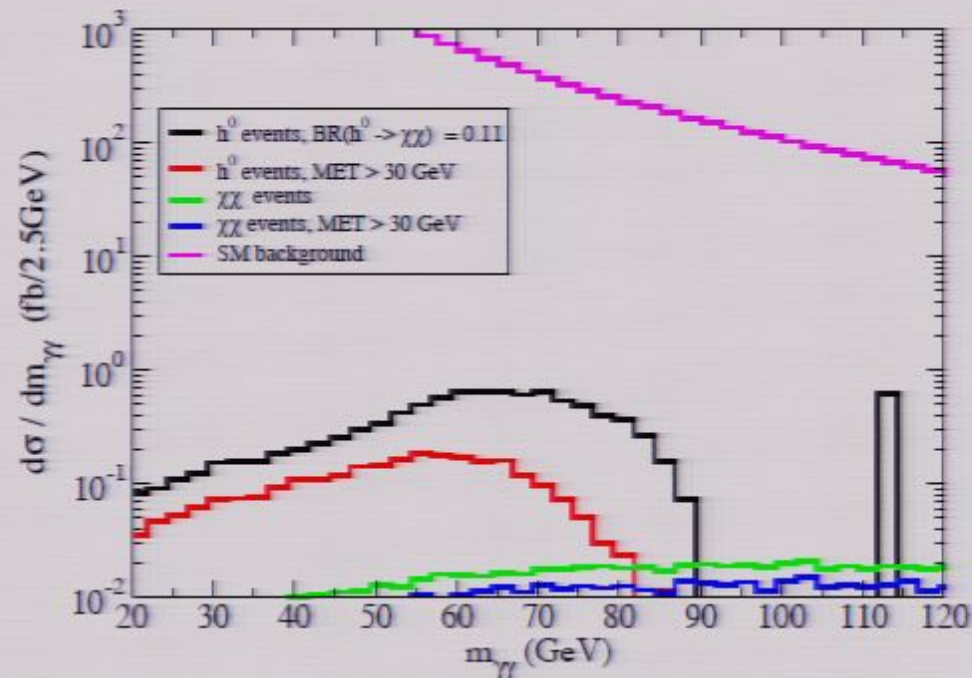
$$M_1 = 50 \text{ GeV}, \quad \mu = 300 \text{ GeV}, \quad \tan \beta = 5.5,$$

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

This is consistent with LEP+Tevatron and gives

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

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



- This inclusive channel is swamped by background.
- Kinematic End-Point:

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

Tevatron (DØ) GMSB Searches

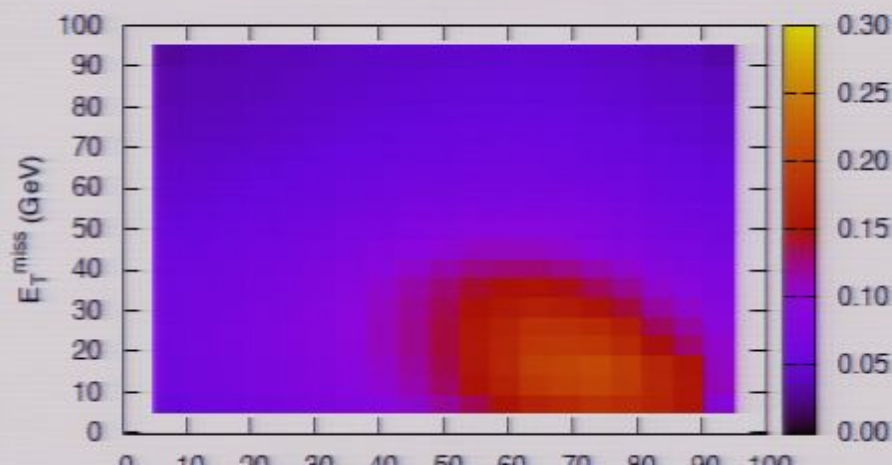
- Cuts: $p_T^\gamma > 25 \text{ GeV}$, $|\eta| < 1.1$, $\cancel{E}_T > 30, 60 \text{ GeV}$.
- With $\cancel{E}_T > 30 \text{ GeV}$,

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

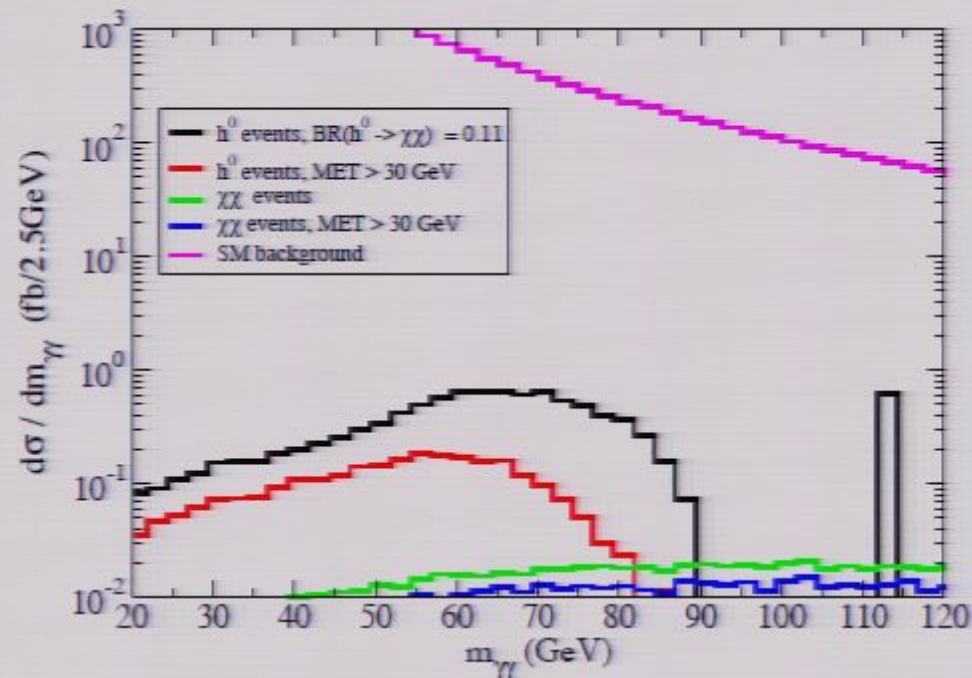
$\Rightarrow S/\sqrt{B} \simeq 3$ with $10 fb^{-1}$ of data

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

- Could be improved with smarter cuts:



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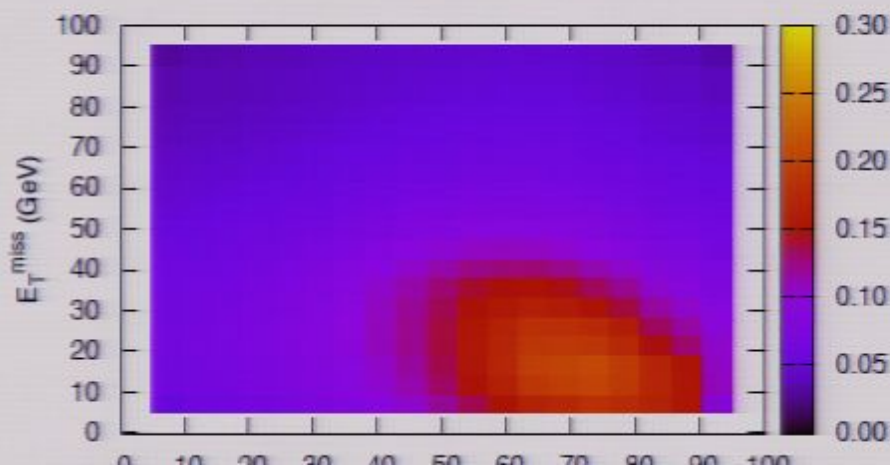
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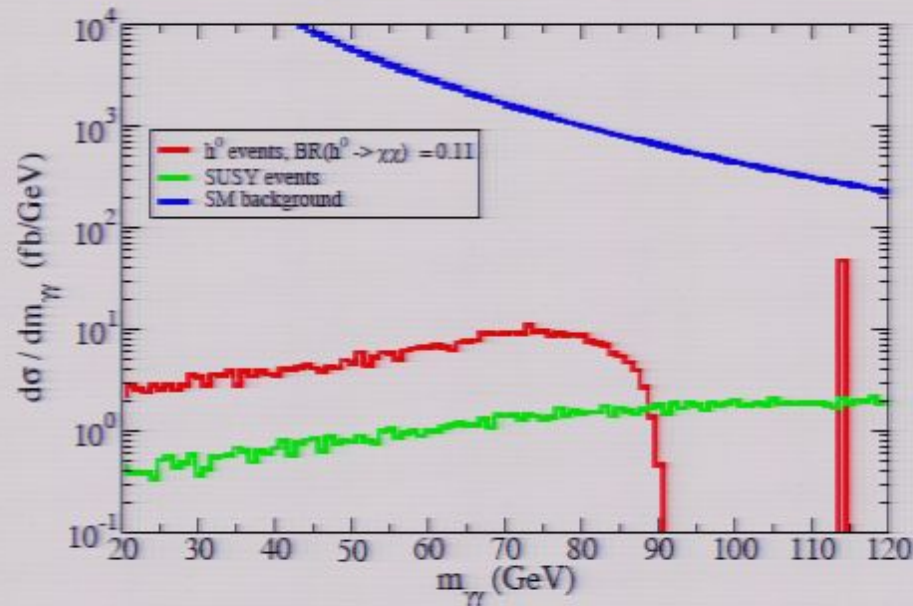
LHC Higgs Searches

- Inclusive $h^0 \rightarrow \gamma\gamma$ is the best LHC search mode for a SM Higgs with $m_{h^0} \lesssim 135$ GeV.
- Discovery requires about 15 fb^{-1} of data.
- With $h^0 \rightarrow \chi_1^0 \chi_1^0 \rightarrow \gamma\gamma \cancel{E}_T$ there are more photonic events.
- We study the same sample point as before:

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

LHC Inclusive Diphotons

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



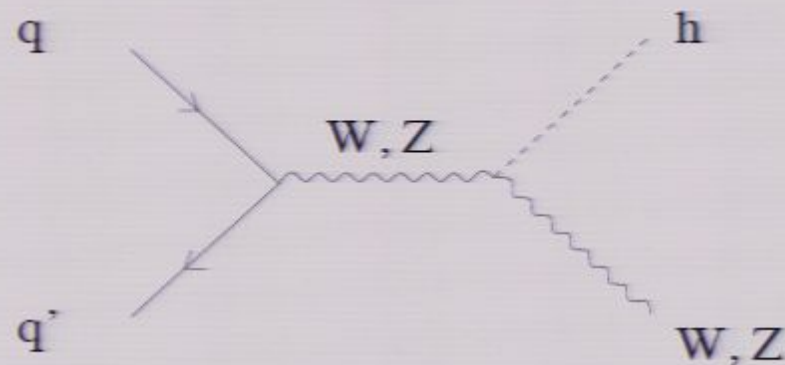
- Requiring $60 \text{ GeV} < m_{\gamma\gamma} < 90 \text{ GeV}$ gives

$$S/\sqrt{B} = 1.1 \text{ with } 1 \text{ fb}^{-1}$$

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

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

-



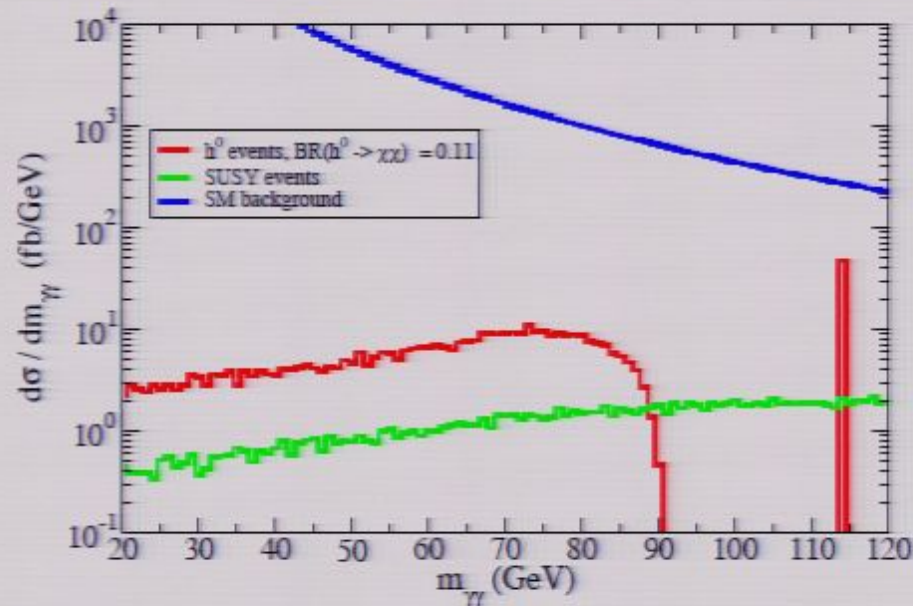
- Requiring a lepton from the W/Z makes this channel clean.
- CMS Search: $p_T^\gamma = 35, 20 \text{ GeV}$, $|\eta| < 2.5$, $N_\ell \geq 1, \dots$
- With $20 \text{ GeV} < m_{\gamma\gamma} < 90 \text{ GeV}$ we find (after cuts)

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

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

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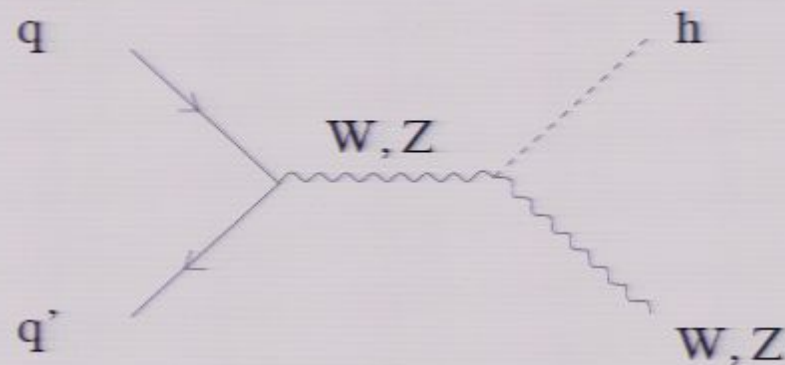
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Some Philosophy

- $h^0 \rightarrow \chi_1^0 \chi_1^0 \rightarrow \gamma\gamma \cancel{E}_T$ is not a generic SUSY signal, but it is not so crazy either.
- Planned $D\cancel{\theta}$ searches for GMSB and ATLAS searches for $(W/Z) h^0 \rightarrow \gamma\gamma$ are potentially sensitive to this mode.
- CDF GMSB searches use a cut $H_T = \sum_i p_T^i + \cancel{E}_T > 200 \text{ GeV}$ which eliminates this signal.
- CMS non-inclusive $h^0 \rightarrow \gamma\gamma$ searches apply $p_T^{\gamma 1} \gtrsim 50 \text{ GeV}$ which removes most of this signal.
- It is important to search broadly in LHC data!

Summary

- $h^0 \rightarrow \chi_1^0 \chi_1^0$ with $\chi_1^0 \rightarrow \gamma \tilde{g}$ 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 $\chi_1^0 \rightarrow \gamma \tilde{g}$ decays.
 - NMSSM #1: larger $BR(h^0 \rightarrow \chi_1^0 \chi_1^0)$ with smaller $\tan \beta$.
 - NMSSM #2: $h^0 \rightarrow \chi_1^0 \chi_1^0$ with $\chi_1^0 \rightarrow a^0 \tilde{g}$ and $a^0 \rightarrow b\bar{b}, \tau\bar{\tau}$.
 - NMSSM #3: $h^0 \rightarrow \chi_2^0 \chi_2^0$ with $\chi_2^0 \rightarrow \chi_1^0 X$ and $\chi_1^0 \rightarrow \gamma \tilde{g}$.