Signatures of Natural SUSY

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- Introduction
- Signal I: two sources of SUSY breaking and third family of squarks
- Signal II: Photons from well-tempered neutralinos
- Conclusions

Worked based on:
AD and M. Quirós PRD 85 (2012) 015001
J. de Blas, AD and B. Ostdiek PRD 87 (2013) 115026
J. Bramante, AD, F. Elahi, A. Martin and B. Ostdiek arXiv:1408.6530

Introduction

- With the discovery of the Higgs the SM is now a complete description for particle physics (forgetting DM).
- On the other hand that same discovery by itself makes the theory fine-tuned.
- The lack of any other experimental evidence makes us believe that either the SM is the only theory above the Fermi scale or....

- We need to explain why the EW scale is still natural without any new particle at the EW scale.

- One possibility that I will follow in this talk is that, in fact, in the MSSM, the mass of the Higgs points to a heavy stop spectrum.

$$m_h^2 \simeq m_z^2 \cos^2 2\beta + \frac{3y_t^2 m_t^2}{4\pi^2} \log\left(\frac{m_S^2}{m_t^2}\right) + \dots$$

- Therefore since the stops have to be heavy one can allow the first and second generations of sparticles to be much heavier than the third one since their contribution to the fine-tuning is small. This will explain why we have not seen them.
- On the other hand the stops cannot be arbitrarily heavy because of the Higgs mass.

- This kind of scenarios in where the first two generations are heavy are known as natural susy scenarios.

- They have different phenomenology since there are much less cascade decays.

- Can these scenarios be realized on a top-down approach?

- In the first part of the talk I will answer Yes (if not I won't be giving this talk)
- In general one needs, at least, two different sources of susy breaking:
  - One for the heavy sfermions
  - Another one for the third family (plus gauginos)

- In the second part of the talk I will study an alternative signal to discover electroweakinos in compressed spectra.

- These scenarios are a possibility in order to explain the observed DM relic density through a non-trivial mixing among the different neutralinos, since a pure Bino tends to overclose the universe and a pure Higgsino or Wino will co-annihilate to fast.

Arkani-Hamed,AD, Giudice

The Model

- Supersymmetry is broken in a hidden sector
- And communicated via two mechanisms:
  - Gauge mediation (flavorful) to the first two generations
  - Gravity mediation to the third one and gauginos

$$X = M_* + \theta^2 F$$

- This scenario has the following key features:
  - No flavor problem in the first two families since gauge mediation is flavor blind.
  - Possibility of using the Giudice-Masiero mechanism to generate μ and B, for this to happen the Higgses should not get masses from gauge mediation.
  - Generation of A-terms for the third family.

- The realization is as follows:
  - There is a new gauge group U(1) under which the first two families are charged with opposite charges.
  - The third family and the Higgses are uncharged under this new group.

	ψ_1	ψ_2	ψ_3	$H_{u,d}$	φ_1	φ_2	S
Q'	$+1$	-1	0	0	$+1$	-1	0

- $\psi_{1,2}$ represent the first and second generation ψ_3 the third generation, $\varphi_{1,2}$ and S are needed to break the extra U(1)

- Assuming the usual superpotential with some messengers charged under the U(1):

$$W = \Phi_2 X \Phi_1$$

- One generates the following mass for all the first two generation scalars (plus the extra gaugino):

$$m^2 = \frac{g^2}{128\pi^4} \frac{F^2}{M_*^2}$$

- The existence of the extra U(1) forbids some Yukawa couplings for the first and second generations but they can be generated via non-renormalizable operators.

$$\frac{1}{M_*^2}\left(y_{11}\varphi_2^2\,\psi_1 H\psi_1^c + y_{22}\varphi_1^2\,\psi_2 H\psi_2^c\right) + \frac{1}{M_*}\left(y_{13}\varphi_2\,\psi_1 H\psi_3^c + y_{23}\varphi_1\,\psi_2 H\psi_3^c\right)$$

- To reproduce the CKM one needs to break the U(1) and:

$$v/M_* \sim 10^{-2}$$

- One can break the extra U(1) group via the following superpotential:

$$W = \lambda S(\varphi_1\varphi_2 - v^2)$$

- Once the gauge group is broken all extra fields (φ, S, gauge bosons and its superparners) get a mass of order v.

- The gravitino will get a mass (from the cancelation of the cosmological constant).

$$m_{3/2} \simeq \frac{F}{\sqrt{3}M_P}$$

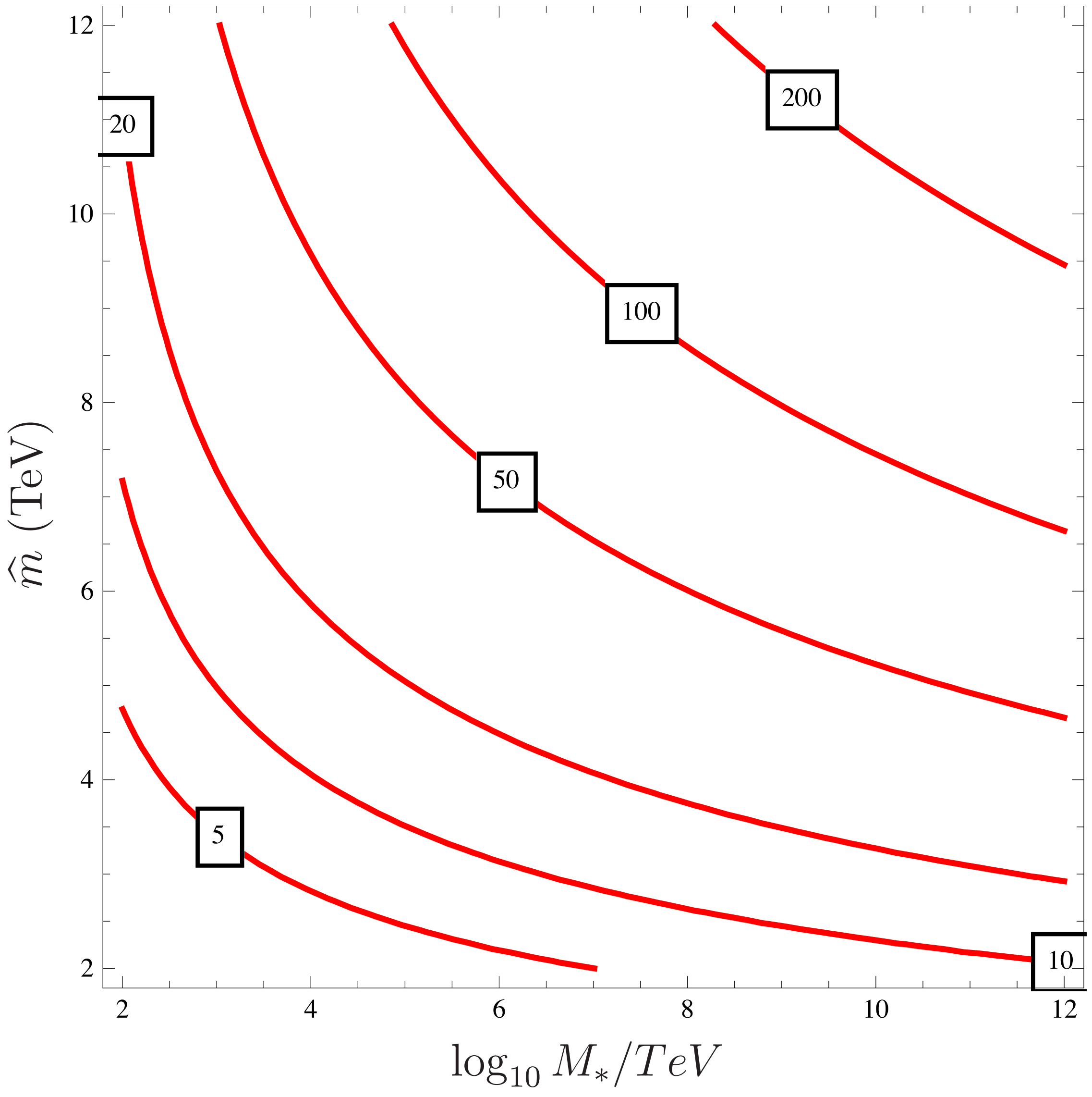
- It will be comunicated to the third family via the operators:

$$\frac{1}{M_P^2}\int d^4\theta X X^\dagger Q_i^\dagger Q_j, \quad \frac{1}{M_P}\int d^2\theta X Q_i H_2 U_j^c, \quad \frac{1}{M_P}\int d^2\theta X W^A W^A \quad \int d^4\theta X^\dagger H_1 H_2, \quad \int d^4 X^\dagger X (H_1 H_2 + h.c.)$$

$$m_0 = M_{1/2} = A_0 = \mu = B = O(m_{3/2})$$

How to fix the overall scale?

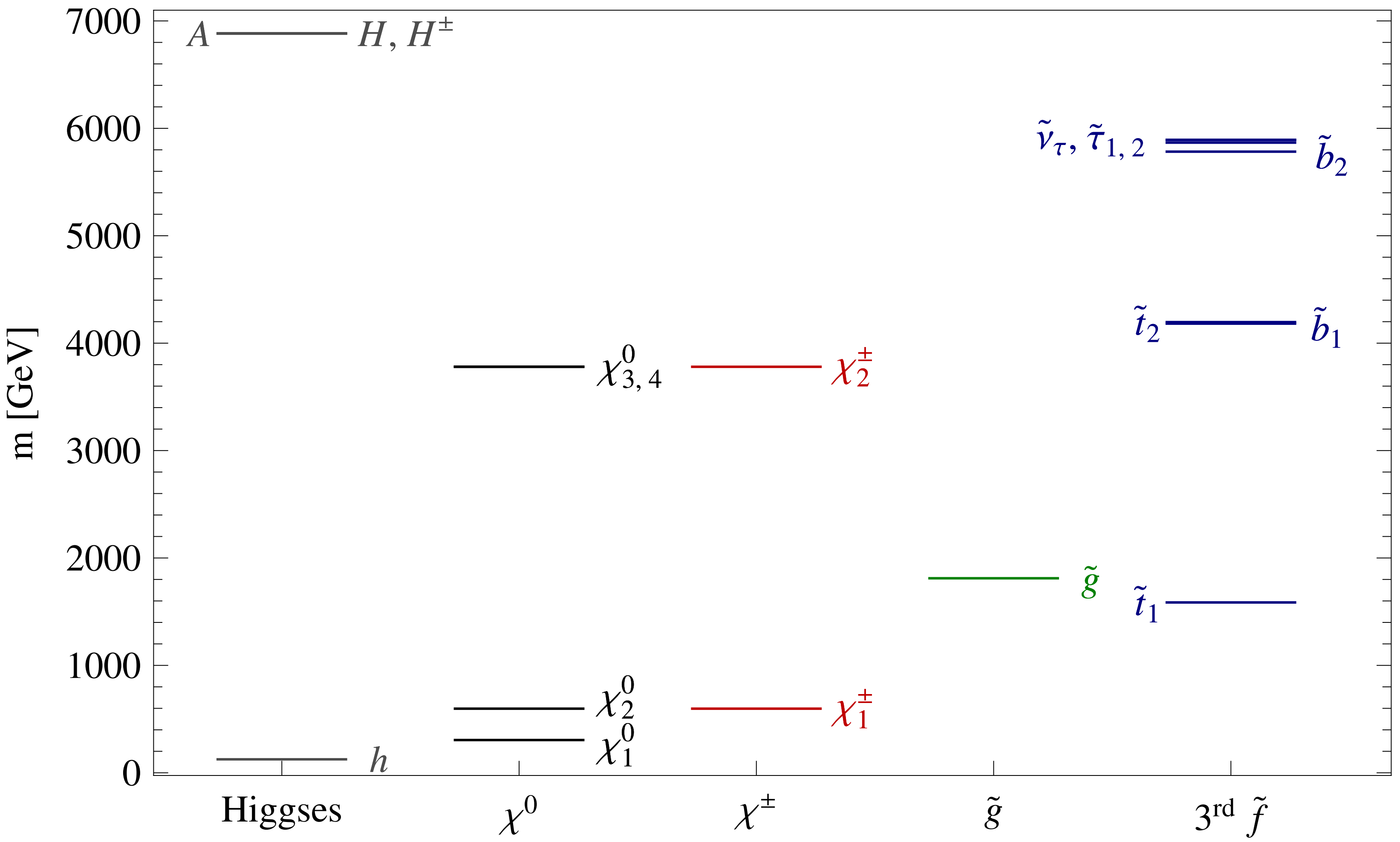
$$\Delta_{\widehat{m}^2} = \left| \frac{\widehat{m}^2}{m_Z^2} \frac{\partial m_Z^2}{\partial \widehat{m}^2} \right|$$



- To fix the scale of the first two families, a fine-tuning less than .5% is imposed.

- This fixes all the scales:
  - $M_*=10^{15}$ GeV
  - $v=10^{13}$ GeV
  - $F=(10^{10})^2$ GeV
  - $m_{1,2}=O(10\ \mathrm{TeV})$
  - $m_3, M_{1/2}=O(1\ \mathrm{TeV})$

- In order to study the phenomenology of the model:
  - EW breaking is imposed
  - The Higgs mass is imposed to be 125 GeV
  - All experimental constrains are satisfied
  - $m_{1,2}$>10 TeV



tan β=10

- This is scenario A, scenario B is similar but with the mass of the gluino of 2.25 TeV

Phenomenology of the LSSM

- Not having the first of second generation makes most of the cascade decays unavailable
- For EWinos we have the following processes:

$$\chi' \to \begin{cases} \chi \; W/Z \\ \chi \; h \\ f\tilde{f} \; (f = \tau, t, b) \end{cases}$$

- But the cross-section is too low:

$$\sigma(pp \to \chi + X) = 0.7 \text{ ab}$$

- We are left with either direct production of stops or production of gluinos which then decay into stops (sbottoms are heavier)

- But:

$$\sigma(pp \to \tilde{g}\tilde{g}) = 1.612 \text{ fb}, \ \sigma(pp \to \tilde{t}\tilde{t}) = 0.1 \text{ fb}$$

- Therefore the signal we will look for is:

$$pp \to \tilde{g}\tilde{g}, \ \tilde{g} \to t\tilde{t} \to b\bar{b}W^+W^-\chi$$

- The signal is calculated with Feynrules and Madgraph5, Pythia6 for hadronization and PGS for detector simulation

- The main backgrounds are:

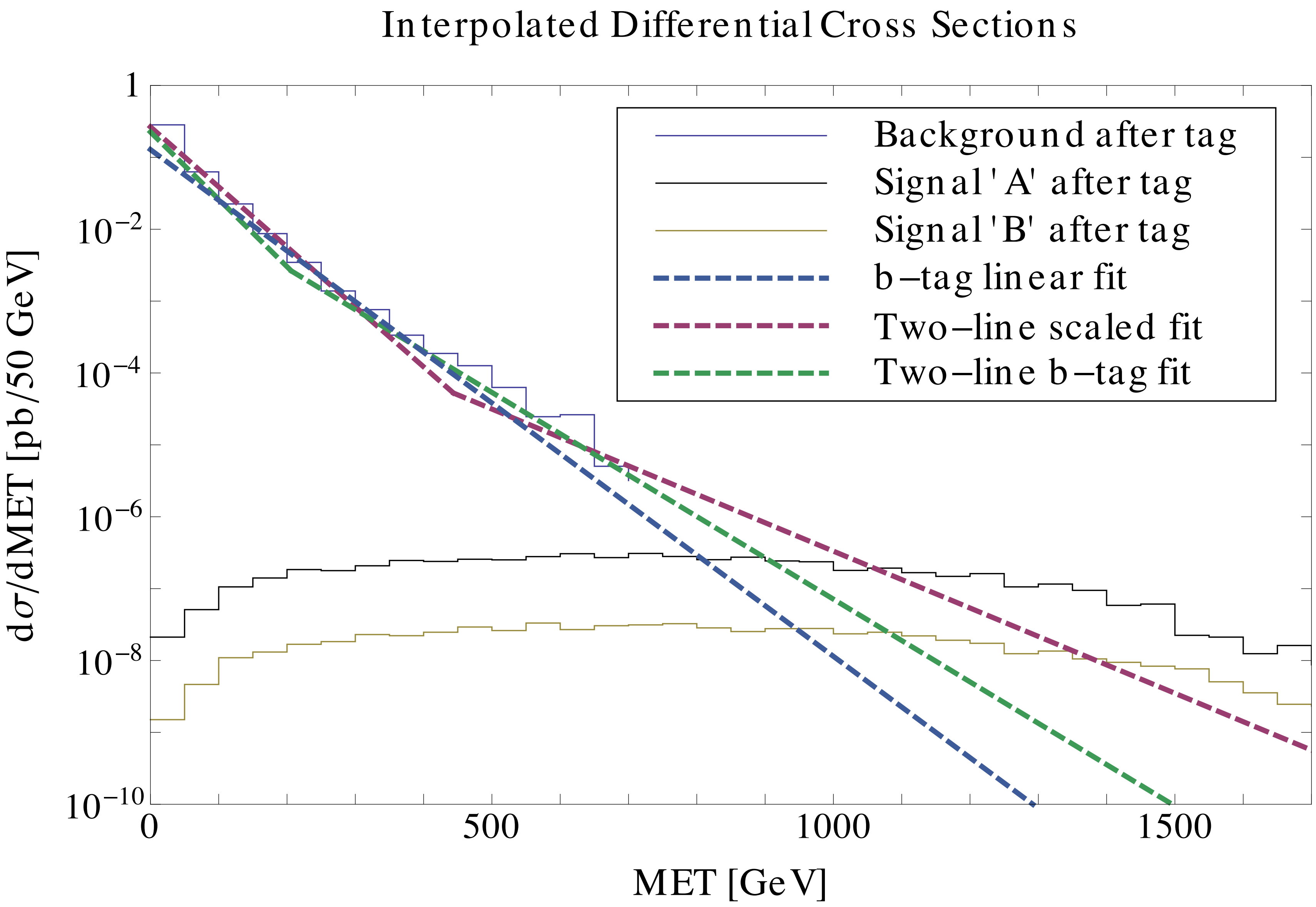
  - tops+jets: calculated with ALPGEN

  - tops+W/Z+jets: calculated with Madgraph

	Before b-tag	After b-tag
Signal Point A	1.612 fb	0.286 fb
Signal Point B	0.170 fb	0.032 fb
Background	1477 pb	19.18 pb

A: m_g=1.75 TeV
B: m_g=2.25 TeV

- We will demand three loose b-tags.
- We will demand four other jets and no photons in the final state.



- Due to lack of computing power we had to extrapolate the background

Estimation Method	$\not{E}_T^{\text{Cut}}$ [GeV]	$\sigma_{\text{B}}^{\text{Estimated}}$ [ab]	σ_{S} [ab]	S	B	$\text{S}/\sqrt{\text{B}}$
				$\mathcal{L} = 200\ \text{fb}^{-1}$ $(1000\ \text{fb}^{-1})$		
Linear	850 (950)	17.1 (3.73)	106.6 (10.8)	21 (11)	3 (4)	11.5 (5.6)
Two-Line	950 (1100)	10.4 (1.43)	80.7 (7.01)	16 (7)	2 (1)	11.2 (5.9)
Two-Line (Scaled)	1100 (1400)	14.7 (0.96)	50.3 (2.26)	10 (2)	3 (1)	5.9 (2.3)

- Whereas a gluino of 1.75 TeV (A) seems feasible in LHC14, a 2.25 (B) seems more doubtful in this conservative analysis.

Photons from well-tempered neutrinos

- DM relic abundance can be accommodated within the MSSM in the following cases:
    - Bino very light with mass $m_Z/2$ or $m_h/2$
    - Higgsino around 1 TeV
    - Wino around 2 TeV
    - Non-trivial admixture of Bino-Higgsino or Bino-Wino

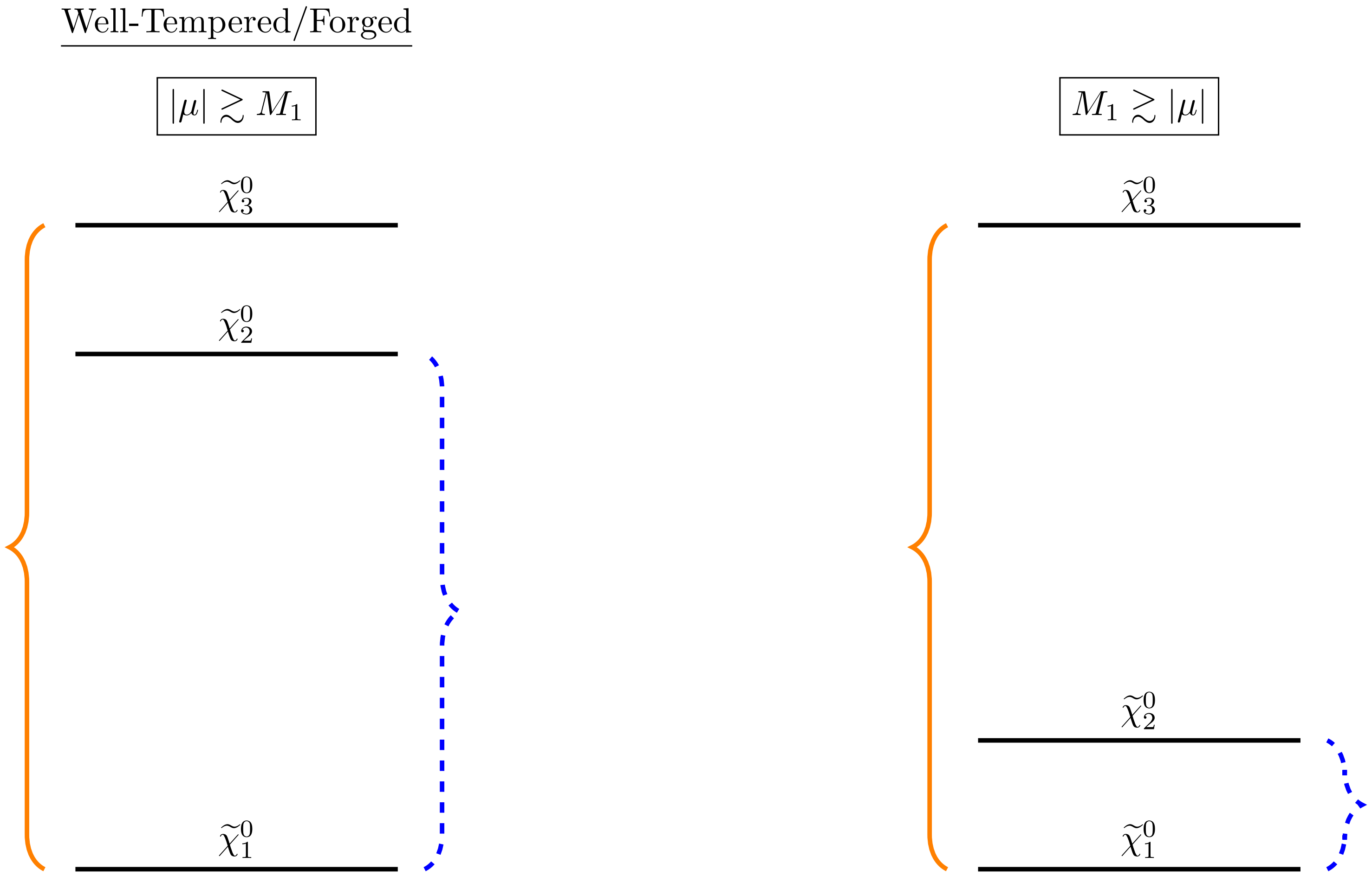
- The non-trivial Bino-Higgsino admixture could have implications for the LHC

- It can also be obtained in models of minimal sugra using the focus point scenario.

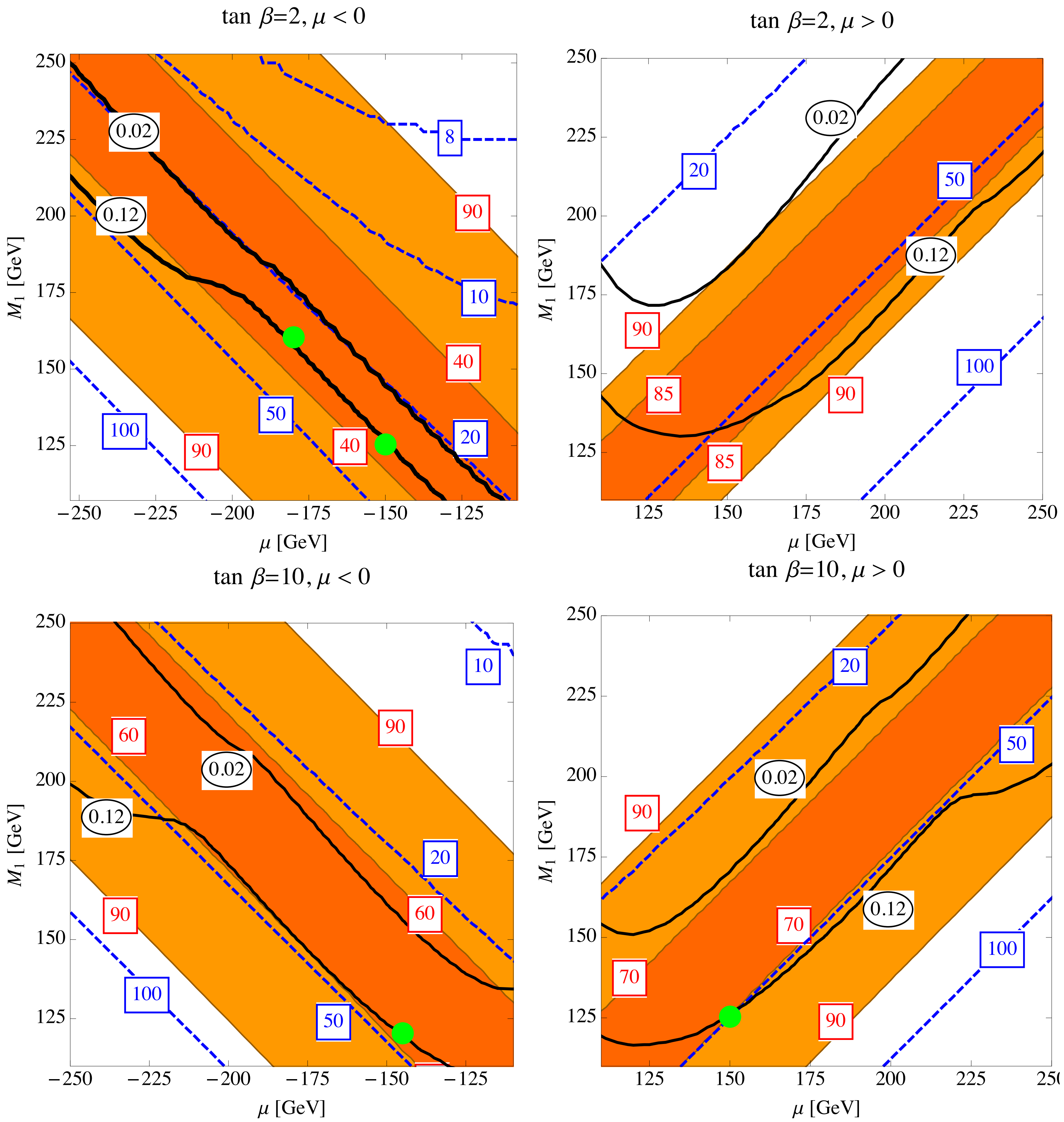
- μ is small due to the cancellation of the soft mass of the Higgs and M_1 is small due to the running.

- Another possible natural SUSY scenario.

- Standard trilepton searches for electrowikinos can be problematic for compressed spectra. These scenarios are motivated by DM.



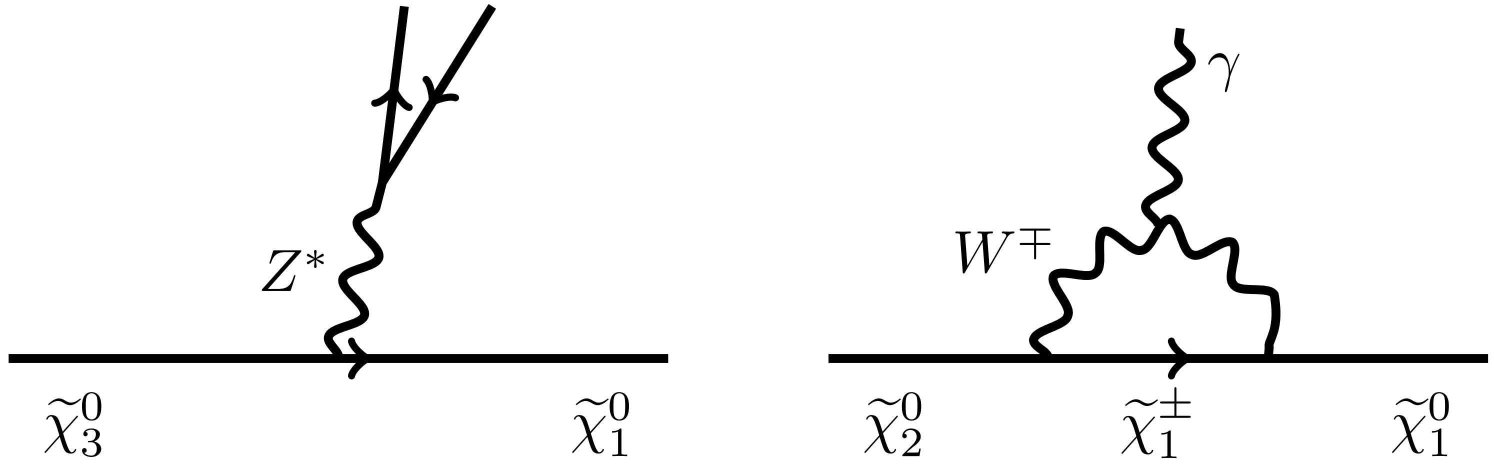
splittings of ~40 GeV

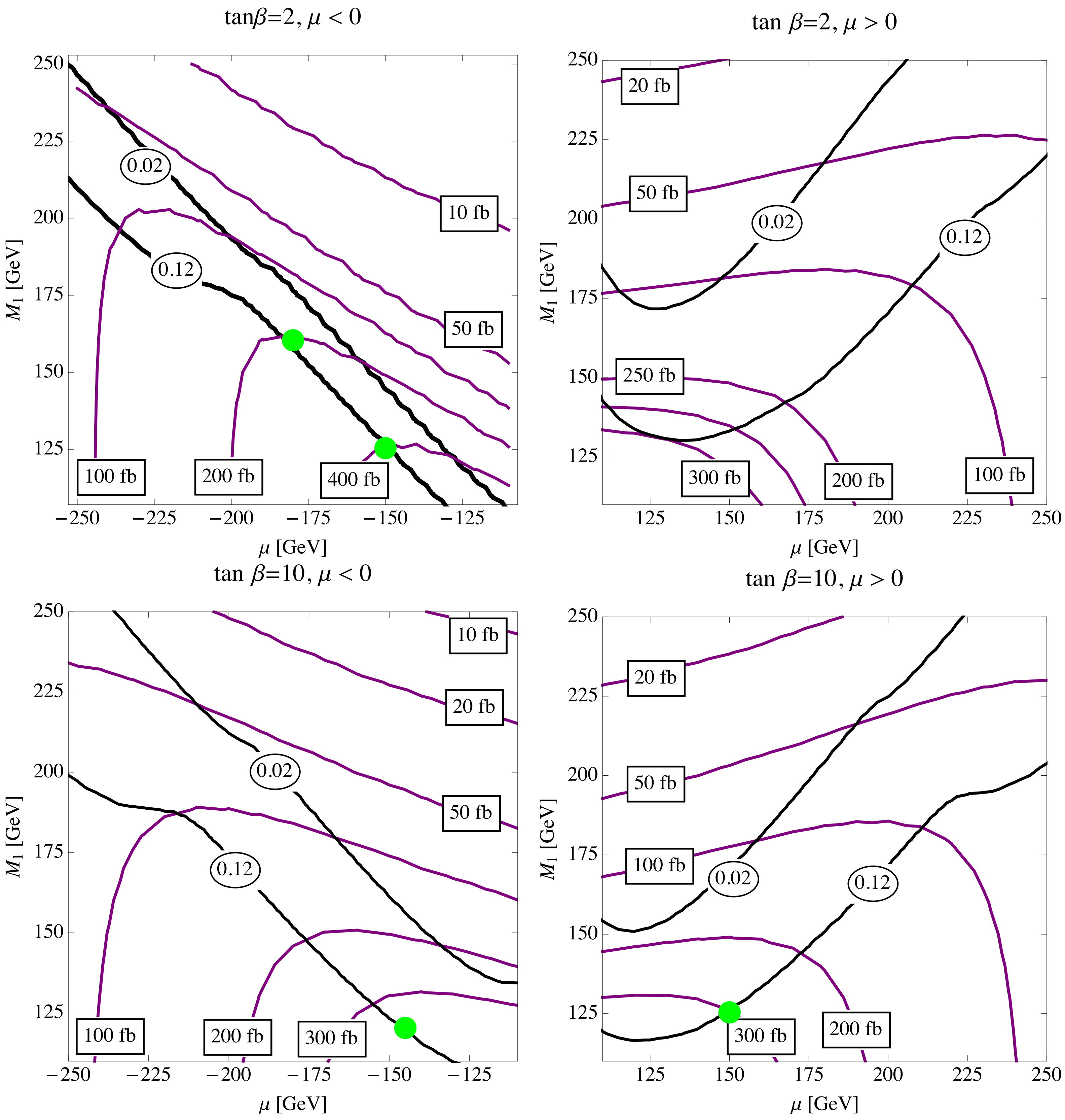


Masses, splitting and Ωh^2

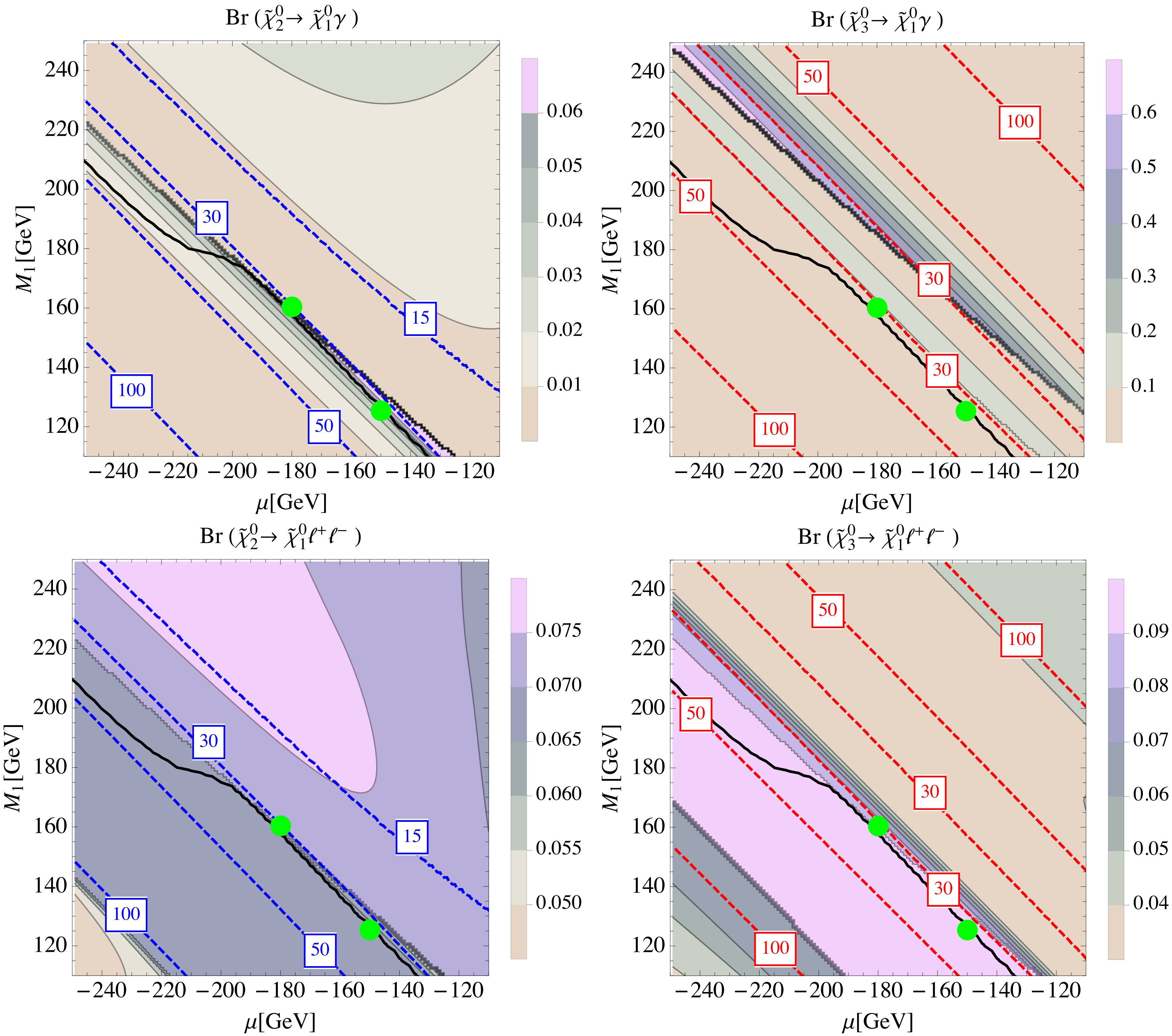
- Since the splittings are quite small I am going to propose a different way of discovering this kind of spectra:

$$pp \to \chi_2\chi_3 \to \ell^+\ell^-\gamma + \chi_1\chi_1$$





Total cross-section of $pp \to \chi_2\chi_3$



Splittings and BR's

- The following benchmark points are going to be simulated with SuSpect, SUSY-HIT, MG5@NCLO and Pythia and we trigger on the leptons:

Benchmark points	Point A	Point B	Point C	Point D
μ	-150 GeV	-180 GeV	-145 GeV	150 GeV
M_1	125 GeV	160 GeV	120 GeV	125 GeV
$\tan\beta$	2	2	10	10
$m_{\tilde{\chi}_1^0}$	124.0 GeV	157 GeV	105 GeV	103 GeV
$m_{\tilde{\chi}_2^0}$	156.9 GeV	186 GeV	150 GeV	153 GeV
$m_{\tilde{\chi}_3^0}$	157.4 GeV	188 GeV	163 GeV	173 GeV
$\sigma(pp \to \tilde{\chi}_2^0 \tilde{\chi}_3^0)$	394 fb	200 fb	345 fb	287 fb
$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma)$	0.0441	0.0028	0.0017	0.0014
$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-)$	0.0671	0.0712	0.0702	0.0700
$BR(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 \gamma)$	0.0024	0.0767	0.0115	0.0102
$BR(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-)$	0.0714	0.0613	0.0447	0.0304
$\sigma(pp \to \tilde{\chi}_2^0 \tilde{\chi}_3^0 \to \gamma \ell^+ \ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0)$	1.297 fb	1.125 fb	0.279 fb	0.205 fb

- Main backgrounds:

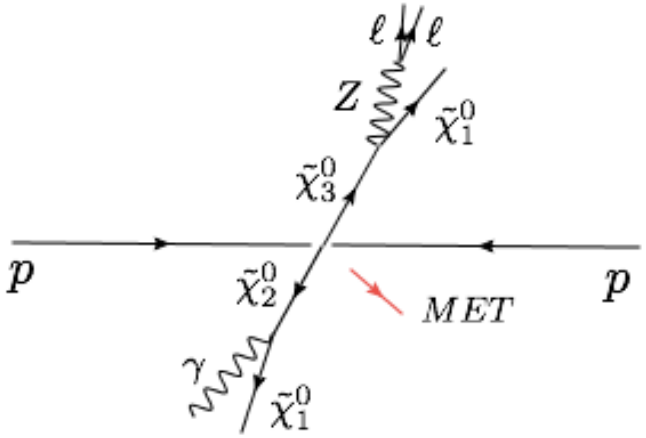
$$pp \to t\bar{t}\;\gamma\big|_{\text{dilepton decay}}$$

$$pp \to \gamma^*/Z(\tau^+\tau^-)\;\gamma\big|_{\text{dilepton decay}}$$

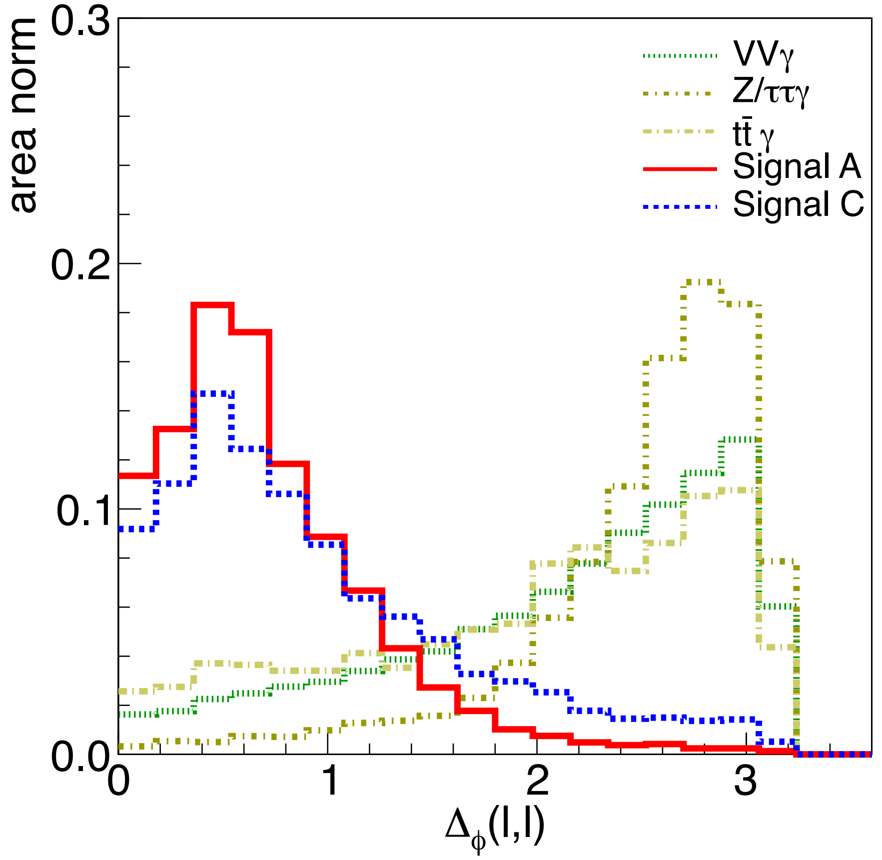
$$pp \to VV\;\gamma\big|_{\text{dilepton decay}}$$

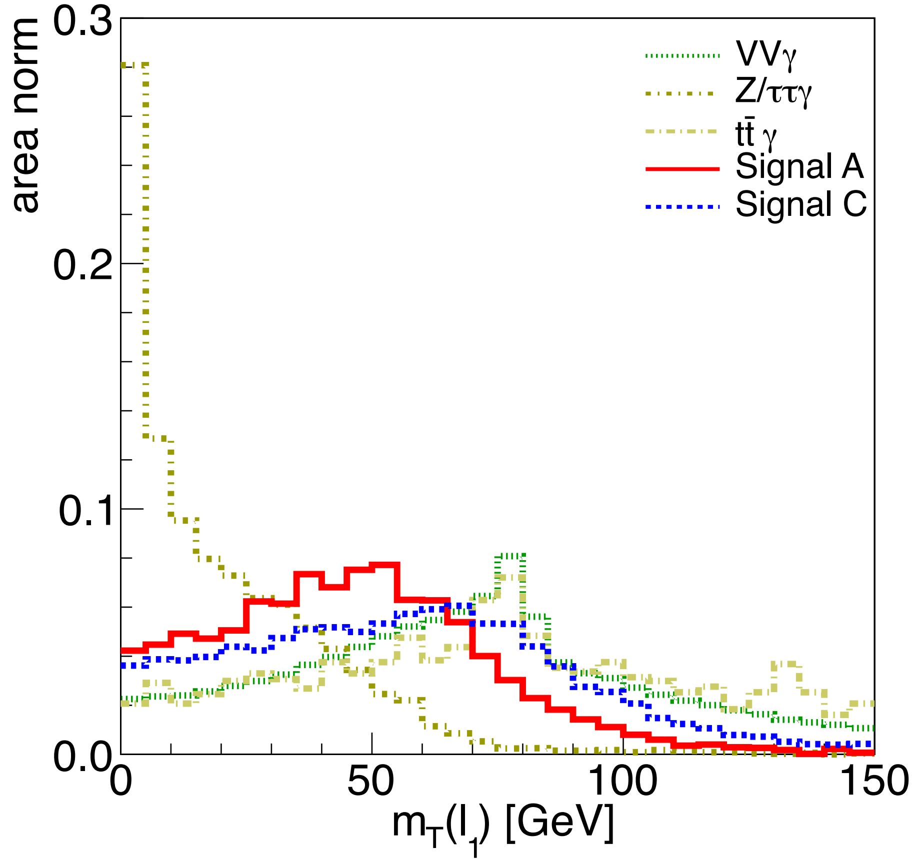
- Fakes coming from jets faking a lepton are under control assuming the following rate:

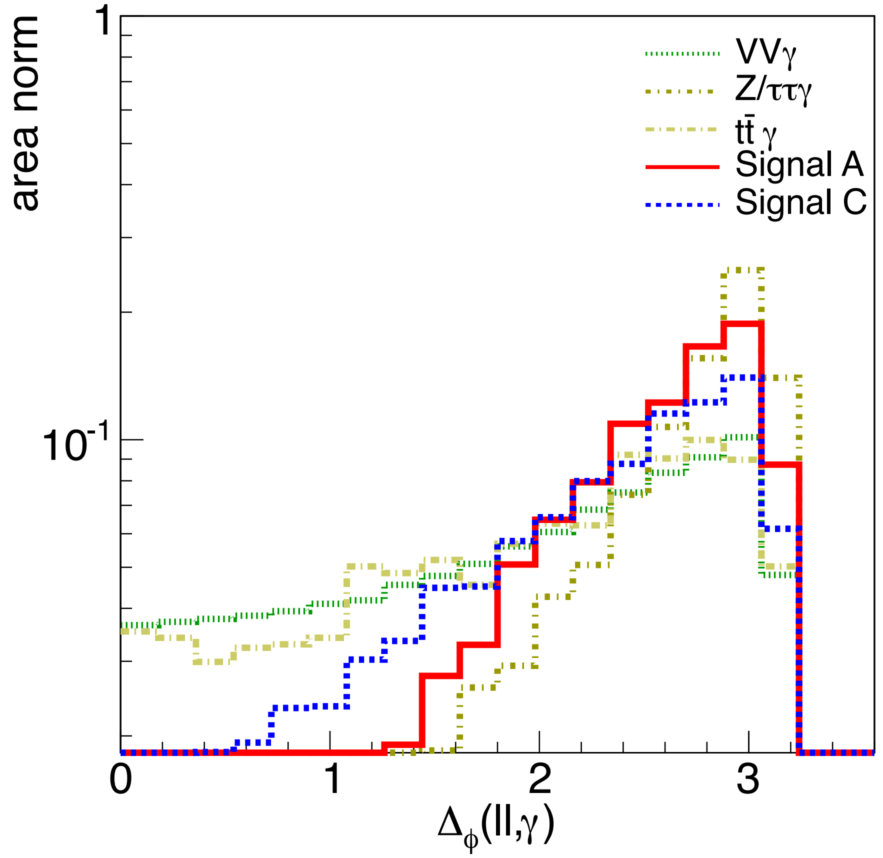
$$\epsilon_{j\to\ell} = 0.01\%$$



- p_t cuts: $p_{T,\ell_1} > 20\ \text{GeV}$ $p_{T,\ell_2} > 8\ \text{GeV}$ $p_{T,\gamma} > 20\ \text{GeV}$
- Jet-veto
- Azimutal angle between leptons <π/2
- 10 GeV <M_T(leptons)<m_W
- Azimutal angle between lepton pair and γ
- m_{ll}<<m_W


area norm
0.0
0.1
0.2
0.3
VVγ
Z/ττγ
tt̄ γ
Signal A
Signal C
0
1
2
3
$\Delta_\phi(l,l)$


area norm
0.0
0.1
0.2
0.3
VVγ
Z/ττγ
tt̄ γ
Signal A
Signal C
0
50
100
150
$m_T(l_1)$ [GeV]


area norm
1
10^{-1}
VVγ
Z/ττγ
tt̄ γ
Signal A
Signal C
0
1
2
3
$\Delta_\phi(ll,\gamma)$

‘small mass splitting’ cuts	Cross section [ab]					Significance
Cut	Signal A	Signal B	$VV\gamma$	$t\bar{t}\gamma$	$Z/\tau\tau\gamma$	S/B
0) Basic Selection	281	169	5830	18900	24500	5.7×10^{-3} (3.4×10^{-3})
1) $N_{jets} = 0$	181	108	4820	1220	21400	6.6×10^{-3} (3.9×10^{-3})
2) $\lvert\Delta\phi_{\ell_1,\ell_2}\rvert < 1.0$	118	79.5	580	201	567	8.8×10^{-2} (5.9×10^{-2})
3) $\left.\begin{array}{c} 15\text{ GeV} < m_T(\ell_2) < 50\text{ GeV} \\ m_T(\ell_1) < 60\text{ GeV} \end{array}\right\}$	52.4	38.2	93.3	32.8	92.2	0.24 (0.17)
4) $\lvert\Delta\phi_{\ell\ell-\gamma}\rvert > 1.45$	49.9	37.0	65.2	25.0	67.8	0.32 (0.23)
5) $30\text{ GeV} < p_{T,\gamma} < 100\text{ GeV}$	36.9	28.2	36.6	17.2	19.0	0.51 (0.39)
6) $\not{E}_T$ cuts	26.8	20.2	24.6	3.90	0.00	0.94 (0.71)
7) $m_{\ell\ell} < 24$ GeV	23.3	19.3	9.29	0.00	0.00	2.5 (2.1)

Luminosity needed: A 430 fb^{-1} B 620 fb^{-1}
C 4300 fb^{-1} D 1900 fb^{-1}

‘large mass splitting’ cuts	Cross section [ab]					Significance
Cut	Signal C	Signal D	$VV\gamma$	$t\bar{t}\gamma$	$Z/\tau\tau\gamma$	S/B
0) Basic Selection	256	411	5830	18900	24500	5.2×10^{-3} (8.3×10^{-3})
1) $N_{jets} = 0$	157	227	4820	1220	21400	5.7×10^{-3} (8.3×10^{-3})
2) $\lvert\Delta\phi_{\ell_1,\ell_2}\rvert < 1.05$	68.3	109	618	208	608	4.8×10^{-2} (7.6×10^{-2})
3) $\left.\begin{array}{c} 10\text{ GeV} < m_T(\ell_1) < 100\text{ GeV} \\ 10\text{ GeV} < m_T(\ell_2) < 95\text{ GeV} \end{array}\right\}$	47.9	72.2	389	127	117	7.5×10^{-2} (0.11)
4) $8\text{ GeV} < \not{E}_T < 95\text{ GeV}$	45.8	69.4	375	116	84.1	7.9×10^{-2} (0.12)
5) $m_{\ell\ell} < 39$ GeV	42.8	64.0	228	35.9	51.5	0.14 (0.20)

- In general the bigger the splitting the more difficult to use this signal
- Also the bigger the splitting the bigger chance not to lose one of the leptons in the usual tri-lepton searches
- Other photons signals with charginos were analyzed but the significance was smaller.

Conclusions

- In this talk I have analyzed two different channels to discover natural susy.
- First I introduced a realization for 'natural susy' based on two sources of susy breaking
  - Gauge mediation for the first two families
  - Gravity mediation for the third family, gauginos and Higgses
- In this top-down approach I have shown the prospects for discovery at the LHC producing gluinos that decays to stops. The reach seems to be for masses around 2 TeV.

- In the second part of my talk I have studied the possibility of an alternative way of discovering eletroweakinos with compressed spectrum motivated by DM
- Production of two heavier neutralinos with a subsequent decay into two leptons and a photon may provide the handle for mass differences around 40 GeV.
- This kind of studies may be very important for a future hadron collider.