Here Be Dragons:

The Unexplored Continents of the CMSSM

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(SLAC)

with Jay Wacker

arXiv:13XX.soon

MCTP Light Dark Matter Workshop
April 17, 2013

Disclaimer

This is not a talk on light dark matter,

but

dark matter phenomenology plays a central role.

Outline

I) Motivation
II) CMSSM Cartography
III) Circumnavigating the CMSSM
IV) Conclusions

MOTIVATION

The MSSM in the Era of Higgs Discovery

- A SM-like Higgs has been discovered at 125 GeV.

  ATLAS [arXiv:1207.7214]
  CMS [arXiv:1207.7235]

- This measurement is "consistent" with the MSSM (and its extensions).
  - Stops can lie from O(100) GeV to O(100) TeV.

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- This measurement is "consistent" with the MSSM (and its extensions).
  - Stops can lie from O(100) GeV to O(100) TeV.
- The motivation for weak-scale superpartners still stands:
  - Solves the hierarchy problem;
  - Explains the dark matter;
  - Predicts gauge coupling unification.

The MSSM in the Era of Higgs Discovery

- The parameter space of the MSSM is enormous.
  - The soft supersymmetry breaking Lagrangian includes more than 120 new dimensionful terms.
- How can we map out all possible signatures?
  - Simplified models: isolate particles responsible for the signature of interest. The parameter space becomes tractable; there are typically only a few masses and branching ratios to specify.
    Alwall, Le, Listanti, Wacker [arXiv:0809.3264]; Alwall, Schuster, Toro [arXiv:0810.3921]; LHC New Physics Working Group [arXiv:1105.2838]
  - pMSSM: phenomenologically motivated reduction to 19 parameters.
    Berger, Gainer, Hewett, Rizzo [arXiv:0812.0980]
  - CMSSM/mSUGRA: 4 parameters.
    Chamseddine, Arnowitt, Nath [PRL 49 (1982)]; Barbieri, Ferrara, Savoy [PLB (1982)]; Hall, Lykken, Weinberg [PRD (1983)]
- 4 parameters is potentially tractable.
- Can we understand all predictions of the CMSSM ansatz?

A simple ansatz - a wide range of dynamics

- The CMSSM is a four dimensional subspace of the *R*-parity conserving MSSM.
- It is defined at the GUT scale by the following (real) inputs:
  - The unified scalar soft mass, M_0 .
  - The unified gaugino mass: $M_{1/2}$.
  - The unified *A*-term: A_0 .
  - The ratio of the Higgs vevs: $\tan\beta$ (traded for the B_μ term).

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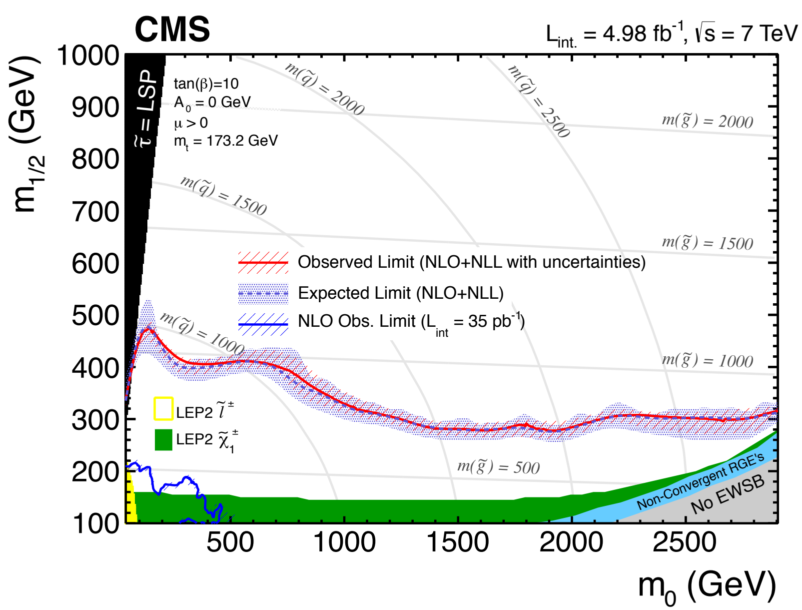
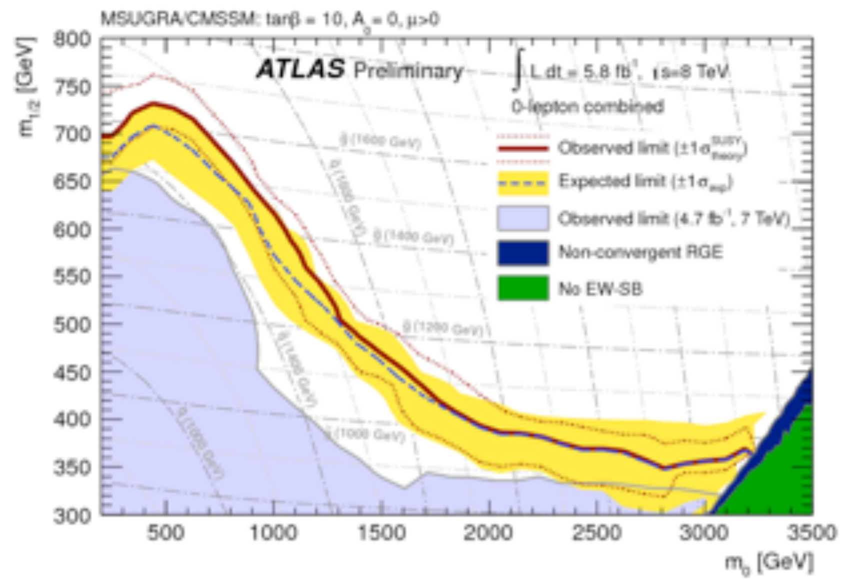
  - The ratio of the Higgs vevs: $\tan\beta$ (traded for the B_μ term).
- These parameters are evolved to the weak scale using the renormalization group equations (RGEs).
- The μ-term is determined by requiring that the *Z*-boson mass match the measured value.
- Since the RGEs are integrated over 14 orders of magnitude, the relation between the low energy parameters and the inputs is highly non-linear.

The state of the art

- Both ATLAS and CMS put limits on the CMSSM:



CMS [arXiv:1205.6615]



ATLAS-CONF-2012-109

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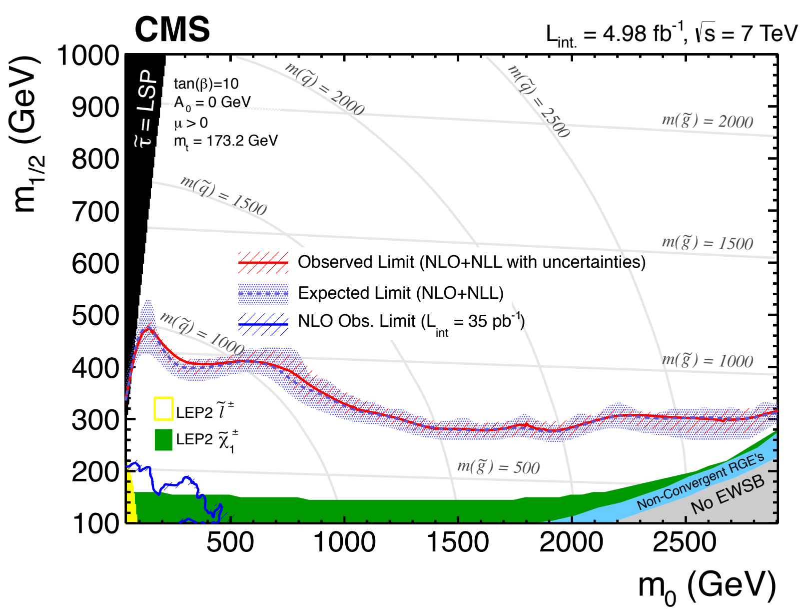

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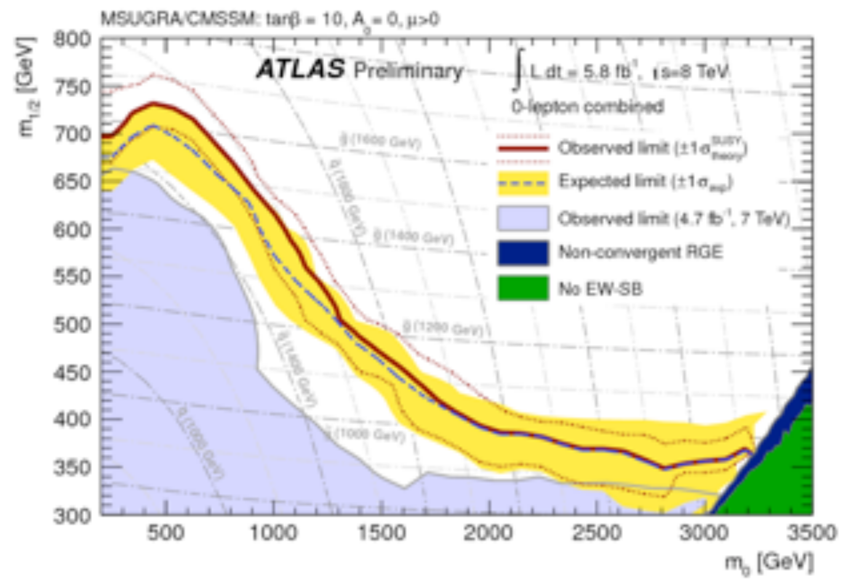

ATLAS-CONF-2012-109

- They exclude a region of the $M_{1/2}$ versus M_0 plane for a fixed choice of A_0 and $\tan\beta$.
- What is the Higgs mass?
- Does the neutralino overclose the Universe?

Our approach to the CMSSM

- We will require that the Higgs mass is ~125 GeV and the neutralino comprises all of the dark matter.

- "Quadrants" are defined by the $\mathrm{sign}(A_0)$ and the $\mathrm{sign}(\mu)$.

- Schematically, the RGEs for *A* and *B* terms are given by

$$16\,\pi^2 \frac{d}{dt} A \;=\; A\,\left(|y|^2 - g^2\right) + y\, g^2\, M,$$
$$16\,\pi^2 \frac{d}{dt} B \;=\; B\,\left(|y|^2 - g^2\right) + \mu\,\left(A\, y^\dagger + g^2\, M\,\right),$$

- The low energy behavior can be very different depending on these signs.

Classification

- What process determines the relic abundance?
  - "light $\widetilde{\chi}^0$": annihilation is dominated by the Z^0 and *h* poles.
  - "well-tempered": annihilation via Higgsino/Bino mixing to $W^+ W^-$.
  - "A^0 pole": annihilation is dominated by an *s*-channel A^0 resonance.
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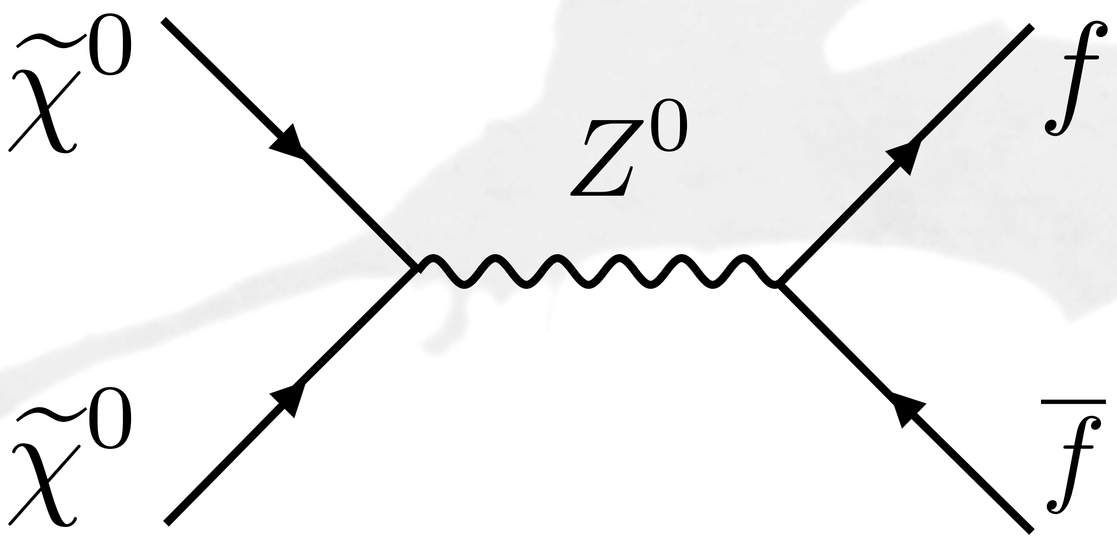

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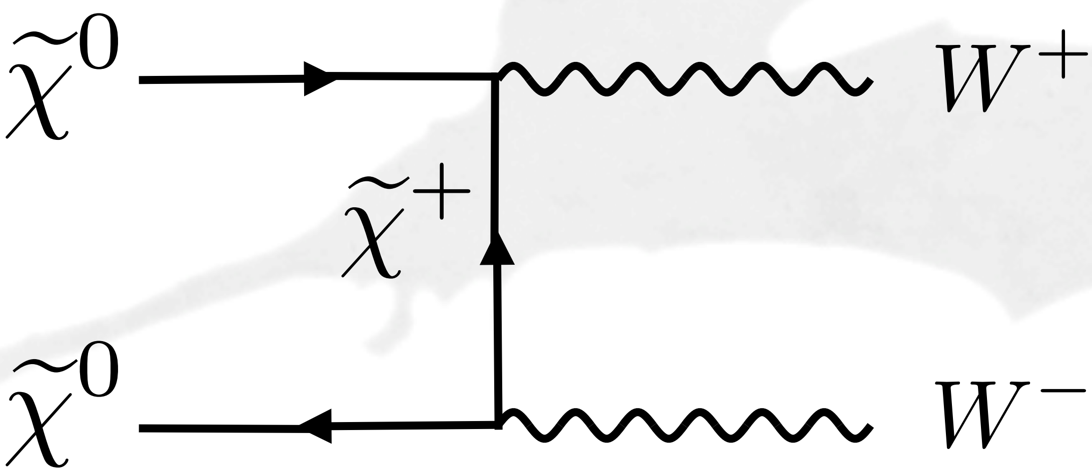

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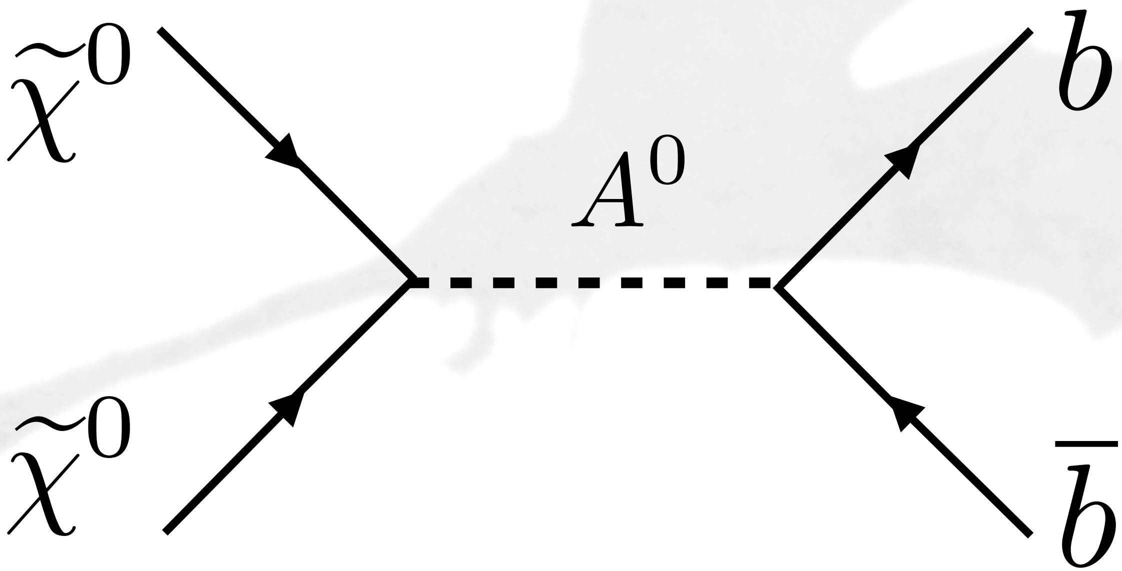

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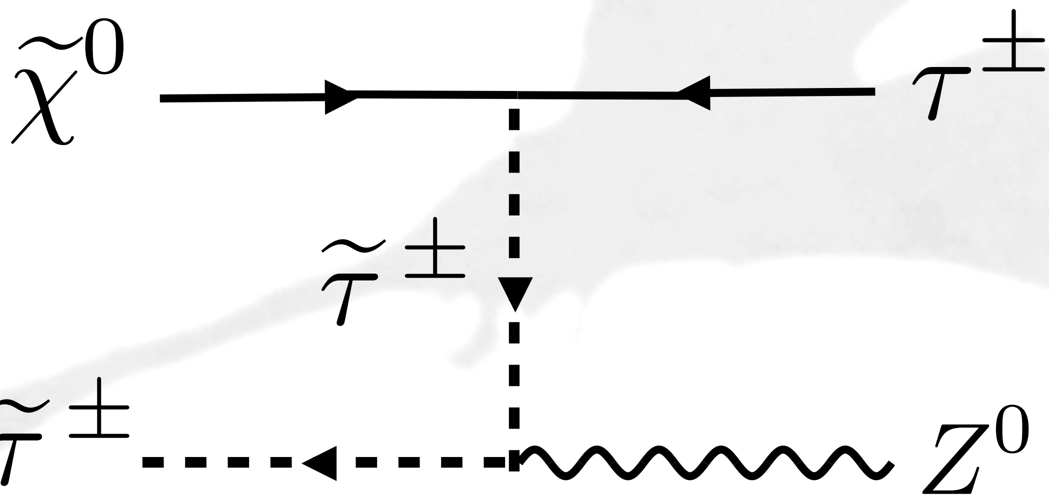

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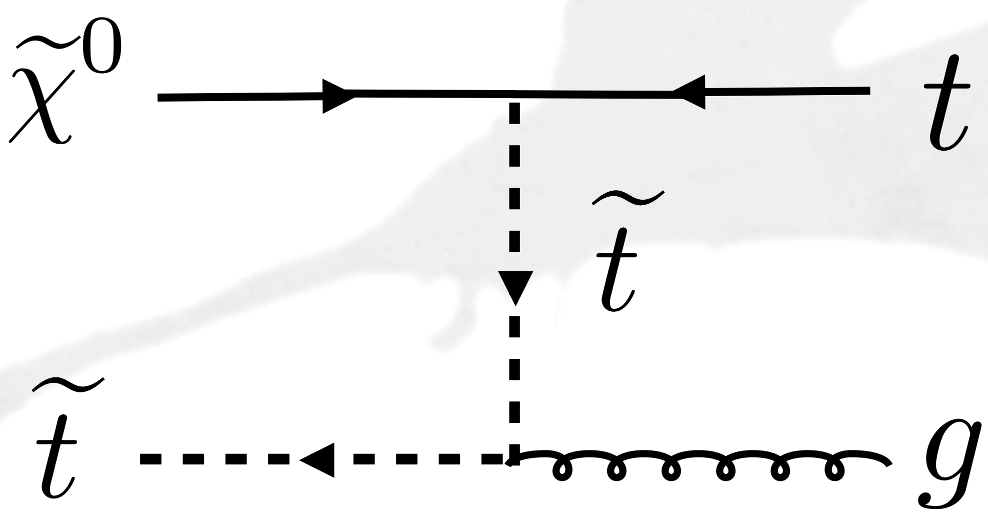

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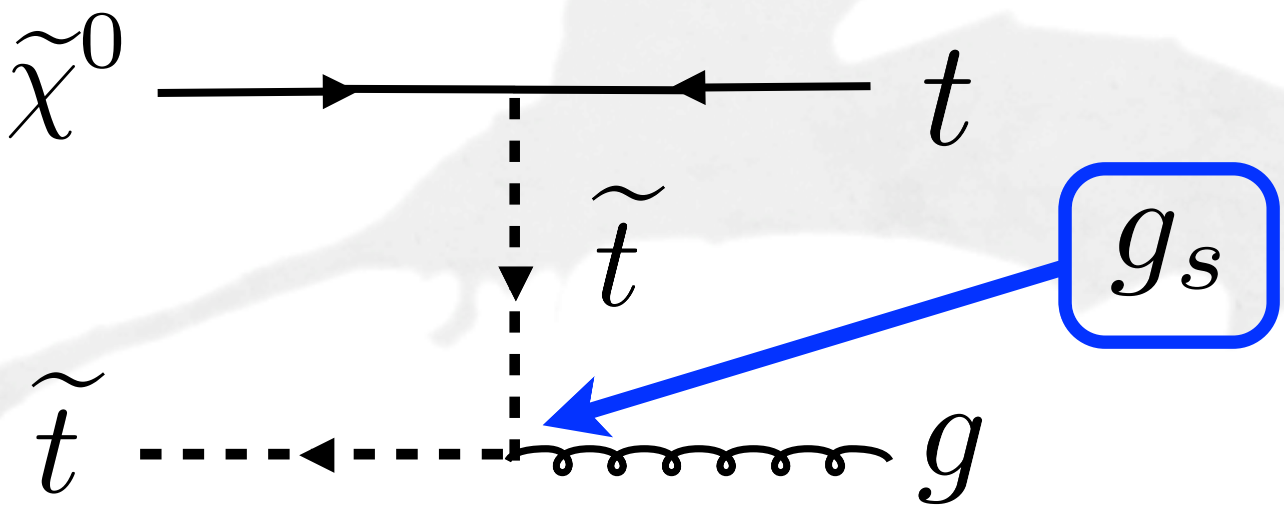


The CMSSM should be compact

- Requiring a 125 GeV Higgs boson implies that one can not take M_0 to be arbitrarily large.
- Relic density
  - The pure Bino limit bounds $M_{1/2}$.
    - The lightest gaugino is the Bino.
    - As one decouples the scalars, the Bino becomes inert.
    - Its early Universe annihilation cross section goes to zero.
    - It freezes out with too large a relic density.
  - The pure Higgsino limit bounds M_0.
    - As one decouples the gauginos, the LSP becomes Higgsino like.
    - If the mass of a pseudo-Dirac Higgsino is greater than ~1 TeV, it freezes out with too large a relic density.
- Requiring the lifetime of our vacuum be longer than the age of the Universe bounds A_0.
- Perturbativity of the bottom Yukawa coupling bounds $\tan\beta$.

CMSSM Cartography

Tools

- SoftSUSY v3.3.7 computes the low energy spectrum from the CMSSM inputs. Allanach [arXiv:hep-ph/0104145]
  - The two loop MSSM RGEs are included (leading log decoupling is accounted for by the inclusion of all 1-loop finite terms).
  - The two loop contributions to the Higgs potential are included.
- DarkSUSY v5.1.1 computes the relic density and direct detection cross sections.
  - All 2-2 scattering processes are included.

  Gondolo, Edsjo, Ullio, Bergstrom, Schelke [arXiv:astro-ph/0406204]
- SUSY-HIT v1.3 computes the decay tables.

  Djouadi, Muhlleitner, Spira [arXiv:hep-ph/0609292]
- We have had 186+ cores running for roughly 4 continuous months.

Constraints

- We take a 3 GeV error for the theoretical prediction for the Higgs mass:

$$122 \text{ GeV} < m_h < 128 \text{ GeV}$$

Allanach, Djuadi, Kneur, Porod, Slavich [arXiv:hep-ph/0406166]

- We require the relic density be in the range:

$$0.08 < \Omega\, h^2 < 0.14$$

- We require that the lifetime for the vacuum to decay to a charge/color breaking minimum be longer than the age of the Universe:

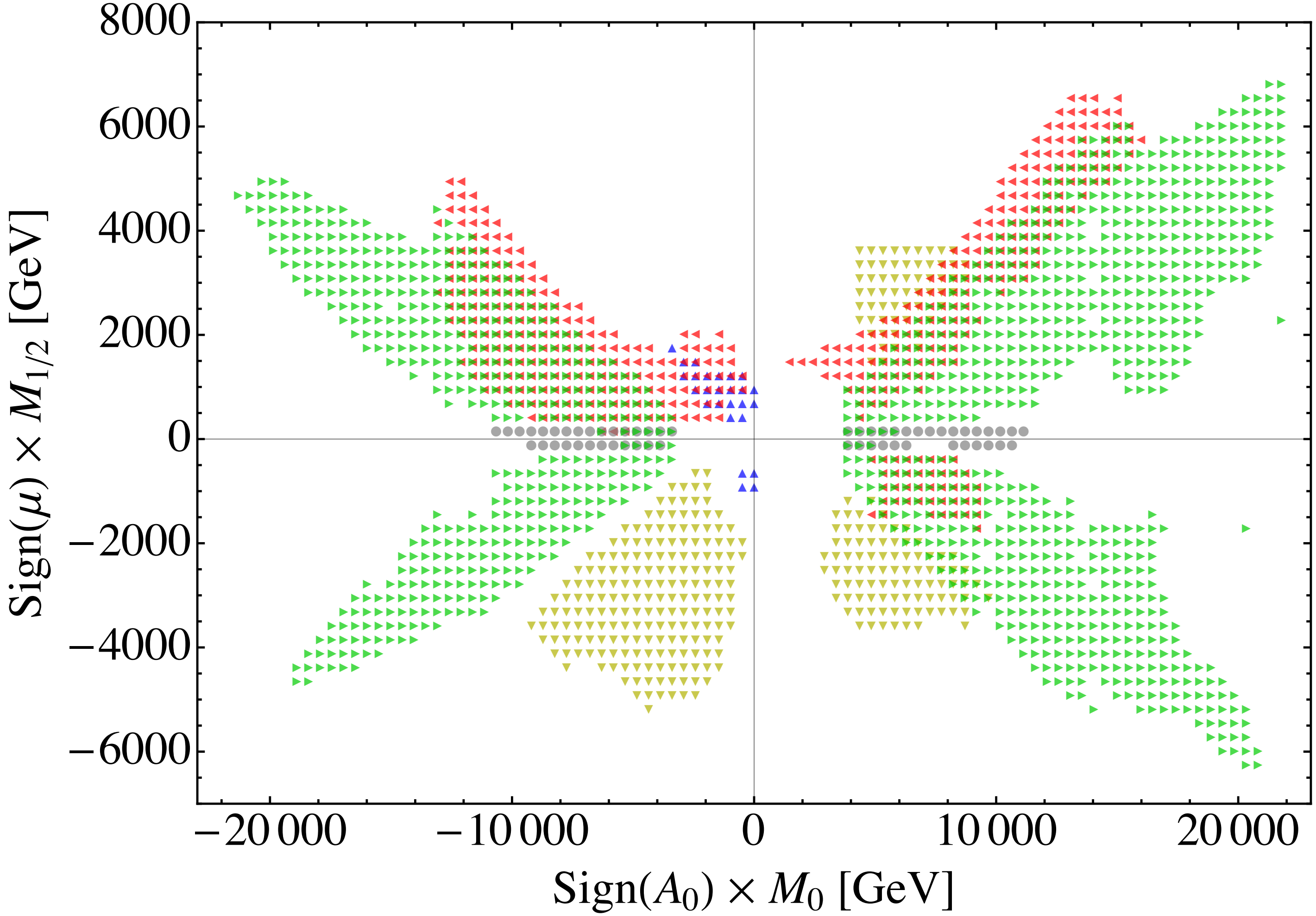
$$|a_t|^2 < (7.5\, m_{q_3}^2 + 7.5\, m_{u_3^c}^2 + 3\,(m_{H_u}^2 + |\mu|^2))$$

  - with a similar condition for staus. Kusenko, Langacker, Segre [arXiv:hep-ph/9602414]

- We require that the chargino mass satisfy a naive LEP bound:

$$\widetilde{m}_{\chi^+} > 100 \text{ GeV}$$

Charting the CMSSM



- light $\widetilde{\chi}^0$
- Well-tempered
- A^0 pole
- stau coann
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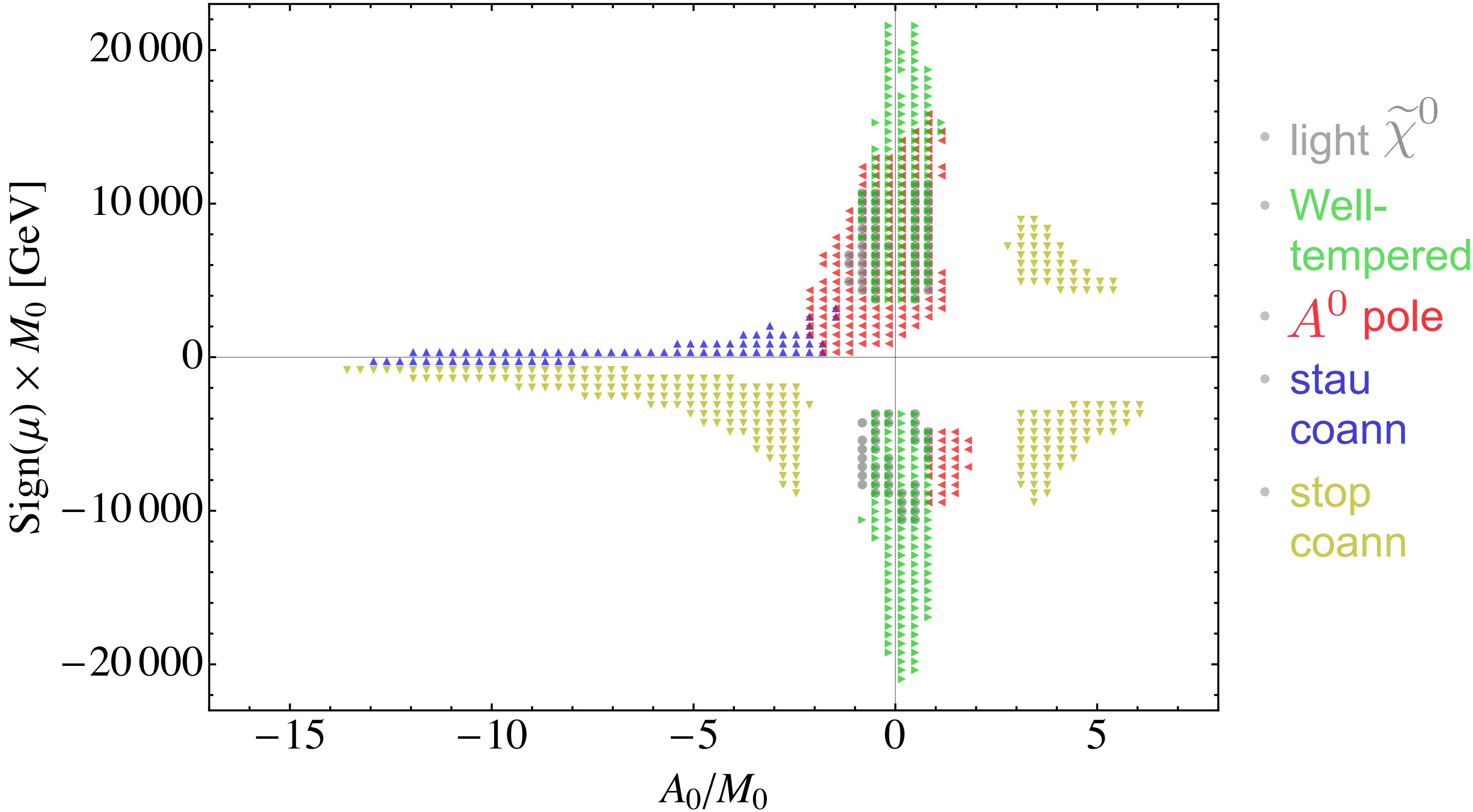

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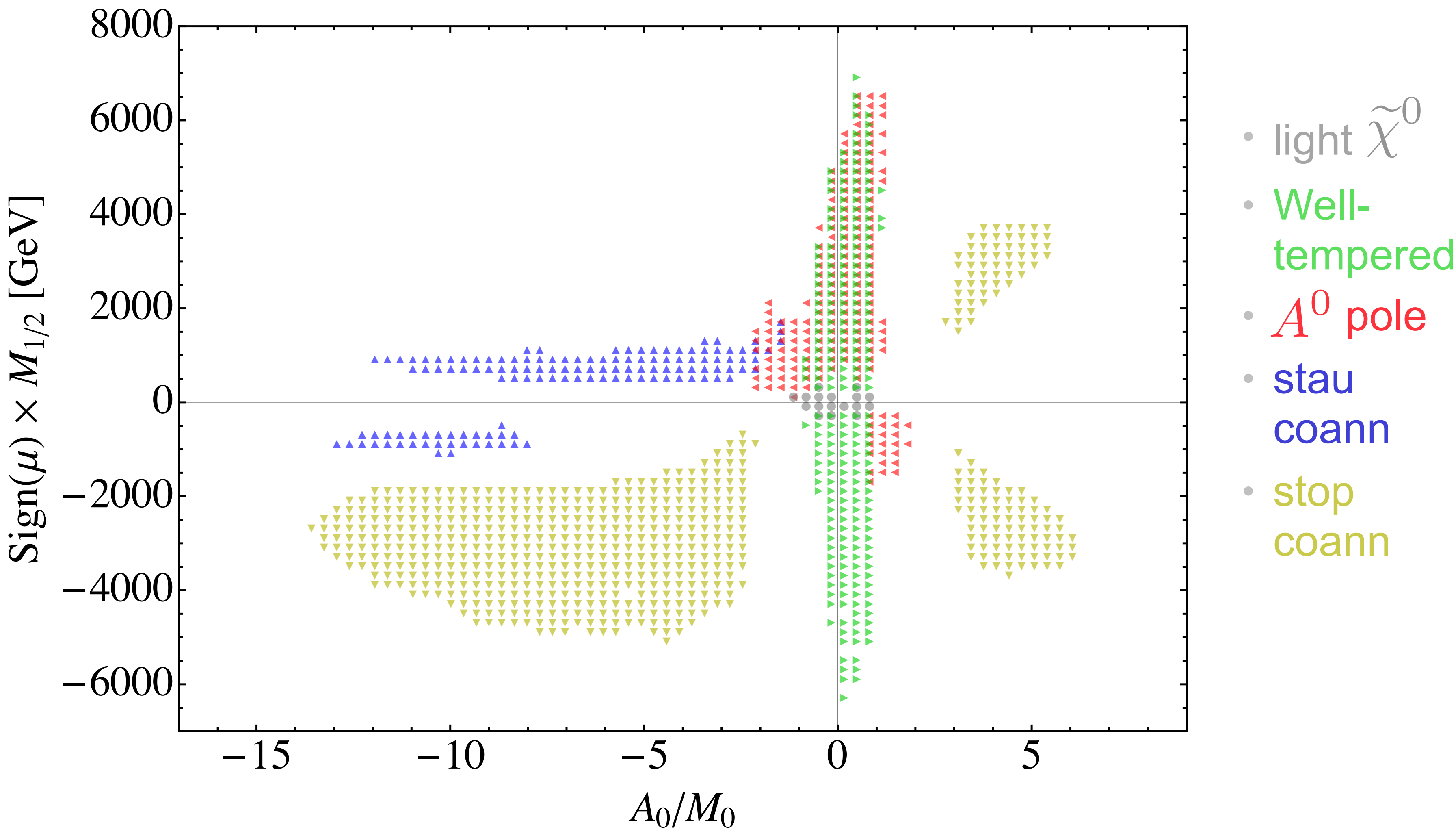

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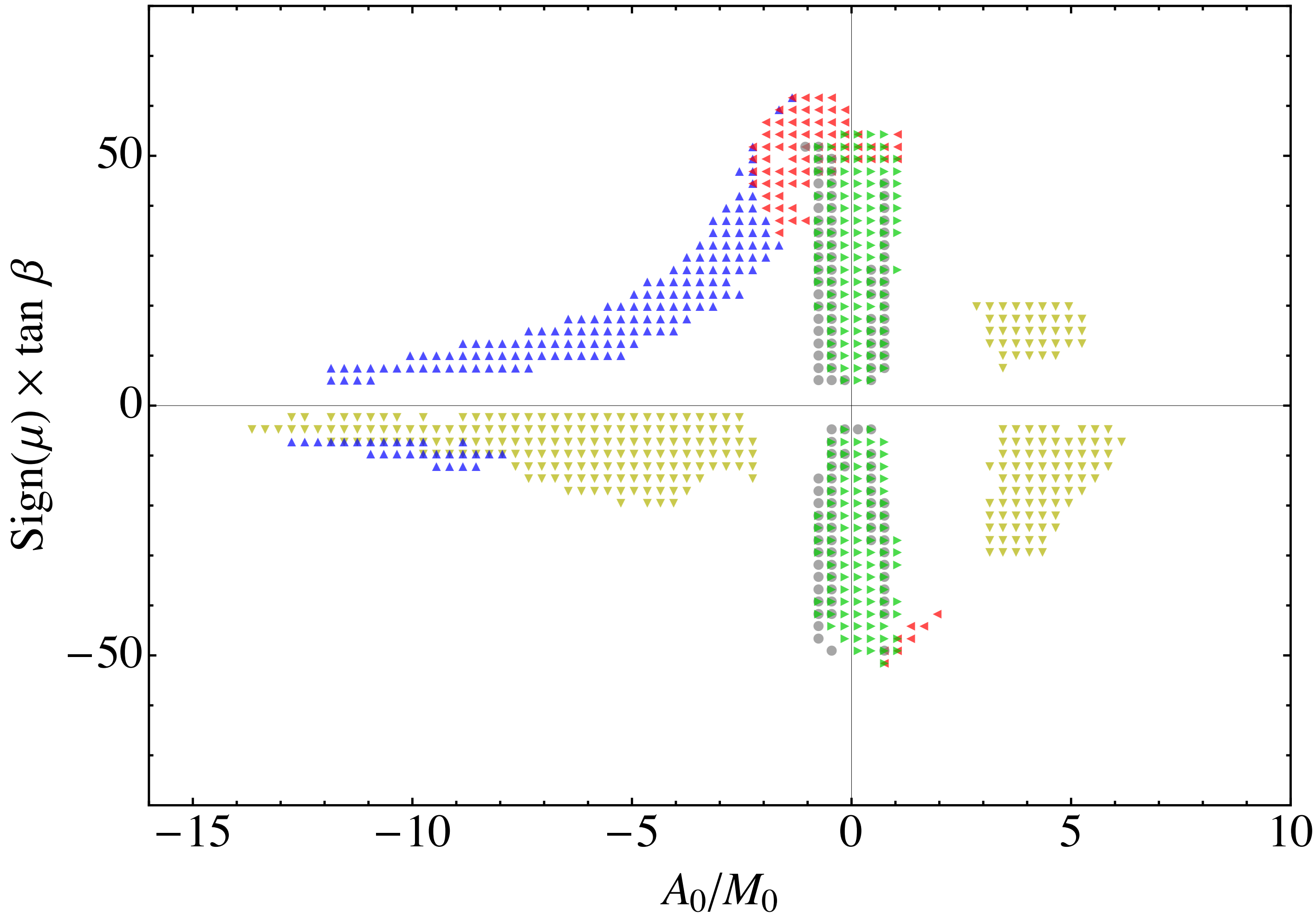

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Lessons

- The CMSSM is compact.

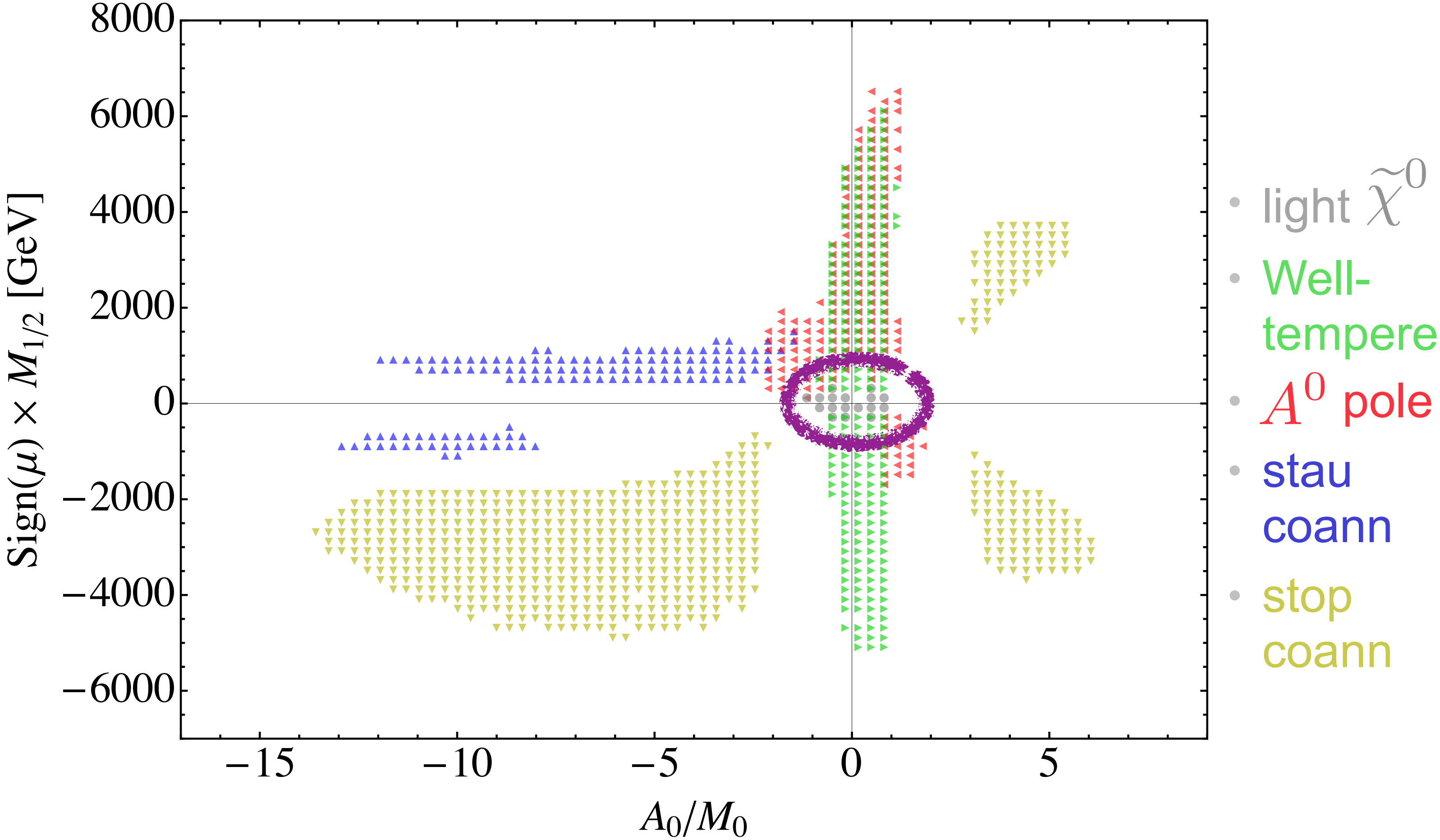
- The size of the allowed parameter space is huge!
- Our classification scheme is a useful way to organize the CMSSM.

- There is a range of possible low energy signatures.
- The rest of this talk will be devoted to exploring them.

Circumnavigating the CMSSM

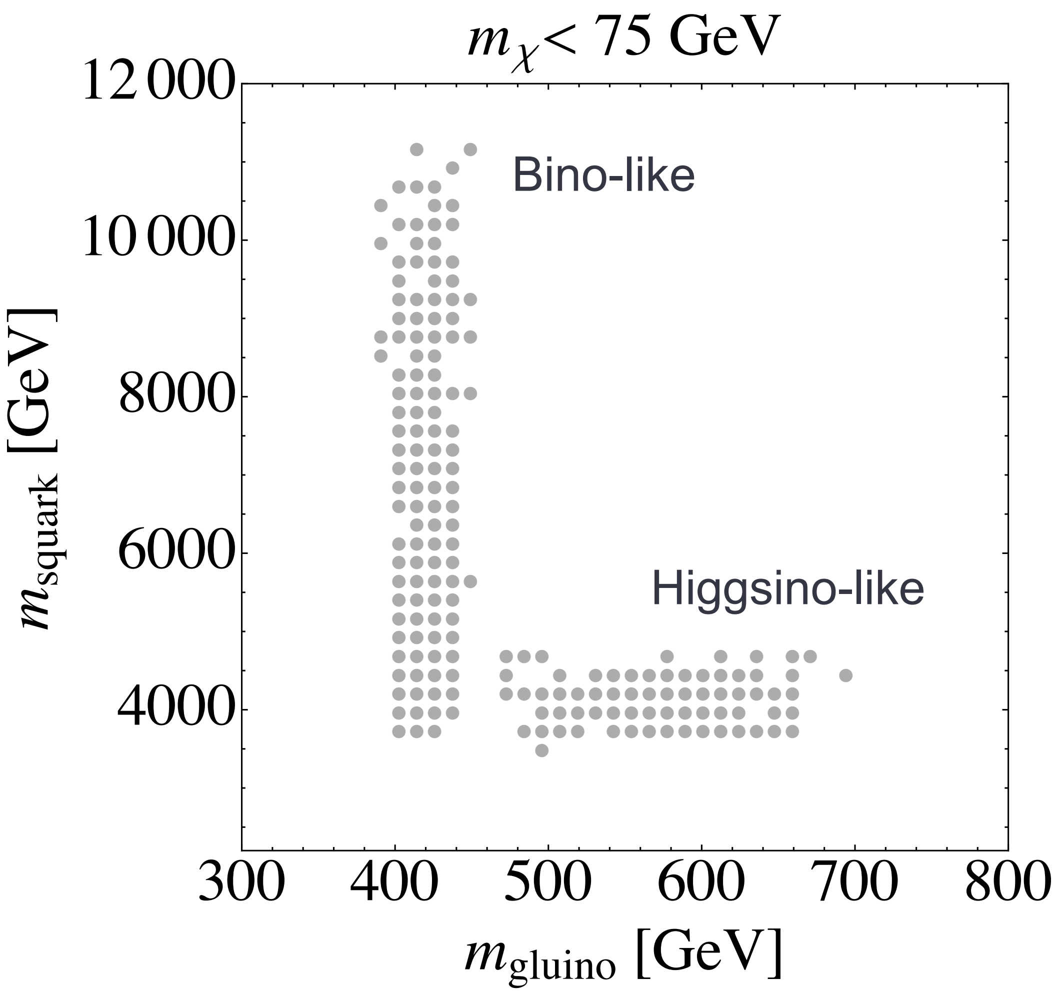
Light $\widetilde{\chi}^0$

Setting sail for light $\widetilde{\chi}^0 \Longleftrightarrow \tilde{m}_{\chi^0} < 75$ GeV



- $2 \text{ TeV} \lesssim M_0 \lesssim 12 \text{ TeV}$
- $5 \lesssim \tan\beta \lesssim 50$

Light $\tilde{\chi}^0$ implies light gluinos



Has the LHC excluded this region?

- Take as a benchmark:

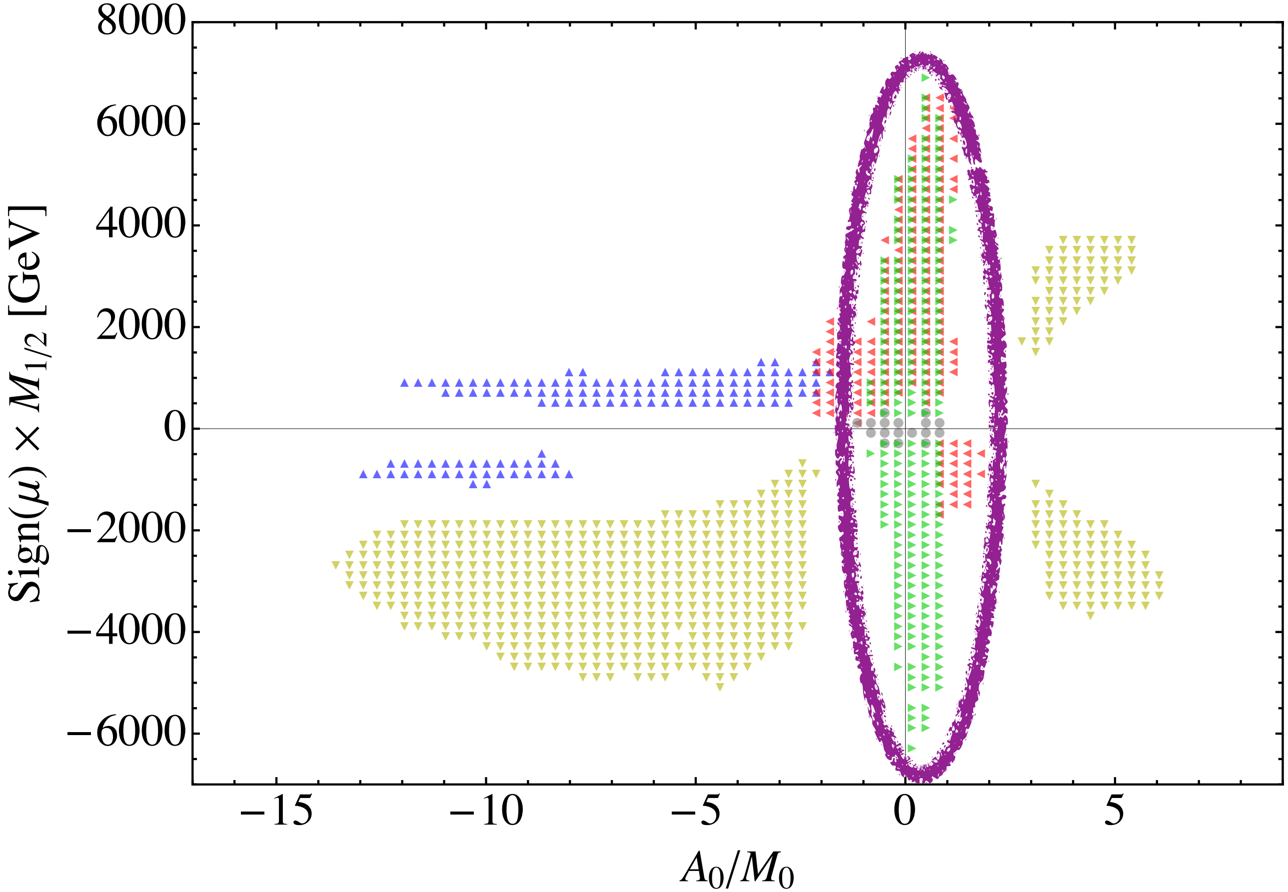
M_0	$M_{1/2}$	A_0	$\tan\beta$	sign(μ)	$\lvert\mu\rvert$	B_μ
5455.8	132.315	-3480.24	15.5977	1	301.773	2.01762×10^8

  - Squarks and sleptons are heavier than 5 TeV.
  - The gluino is 409 GeV and the LSP is 57 GeV.
- $\widetilde{g} \to q + \overline{q} + Z^0 + \widetilde{\chi}_0$
  - The 7 TeV CMS search yields $\sigma \times \text{BR} \lesssim 1$. CMS [arXiv:1204.3774]
  - The 7 TeV prediction is $\sigma \times \text{BR} \simeq 1.0 \text{ pb}$.
- $\widetilde{g} \to q + \overline{q} + \widetilde{\chi}^0$
  - The 7 TeV CMS Razor search does not exclude this channel. CMS [CMS-PAS-SUS-12-005]
- $\widetilde{g} \to q + \overline{q}' + W^\pm + \widetilde{\chi}_0$
  - The 7 TeV ATLAS search for (requiring same sign $W^\pm$) does not exclude this channel. ATLAS [arXiv:1208.0949]
- So the exclusion is borderline at 7 TeV without performing any combinations.
- Likely excluded at 8 TeV (unless efficiency drops for low masses; no detailed efficiency plots are public yet).

CIRCUMNAVIGATING THE CMSSM

Well-tempered

Setting sail for well-tempered



- light $\widetilde{\chi}^0$
- Well-tempered
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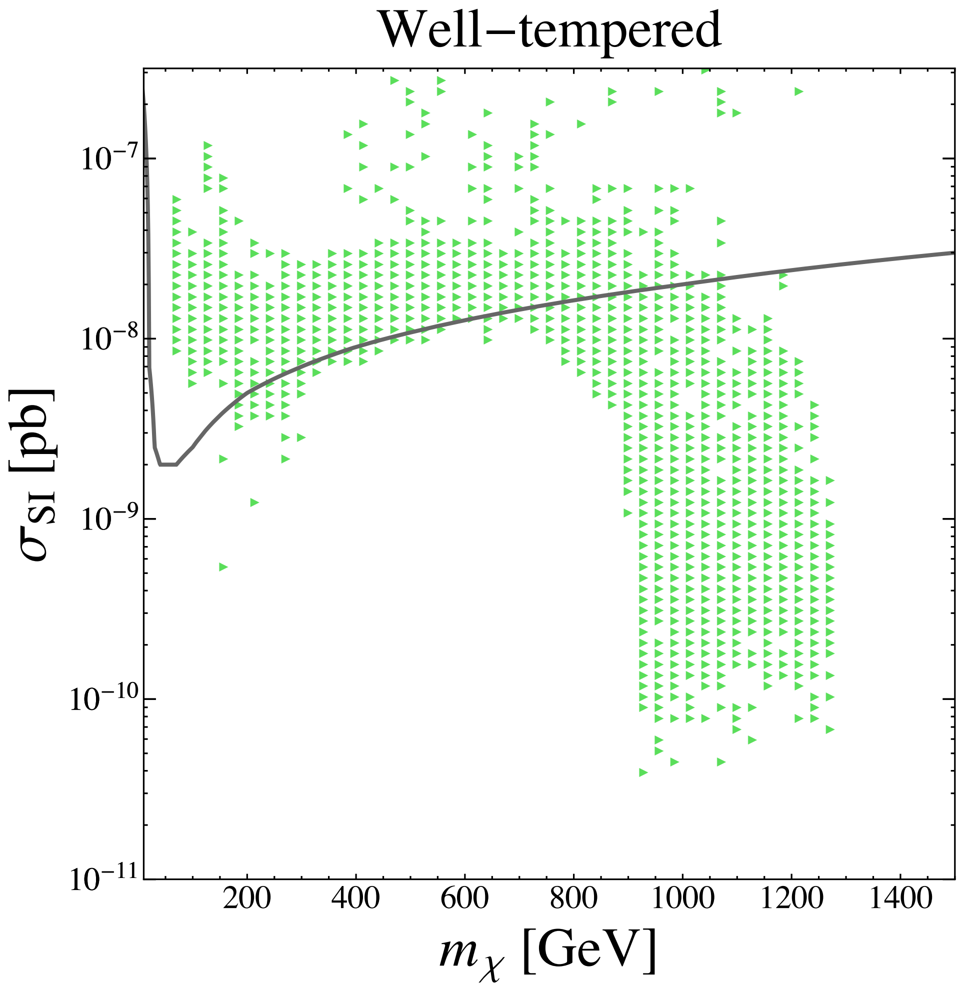
- $4 \text{ TeV} \lesssim M_0 \lesssim 20 \text{ TeV}$
- $5 \lesssim \tan\beta \lesssim 50$

Will direct detection exclude this region?



- A 1-ton Xenon experiment can reach spin-independent cross sections of 5×10^{-12} pb at 300 GeV.

Dark matter limit plotter [http://dmtools.brown.edu/]

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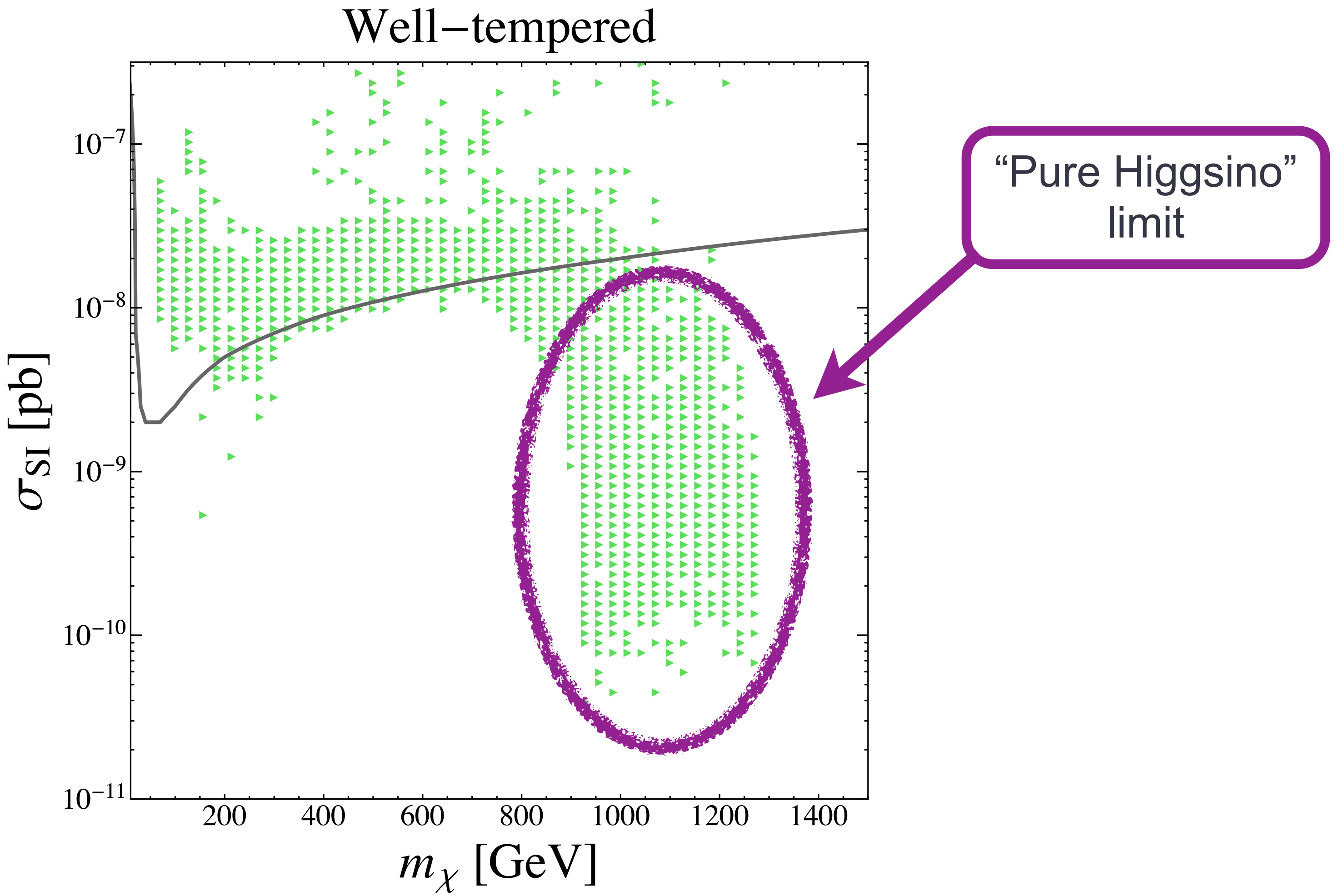

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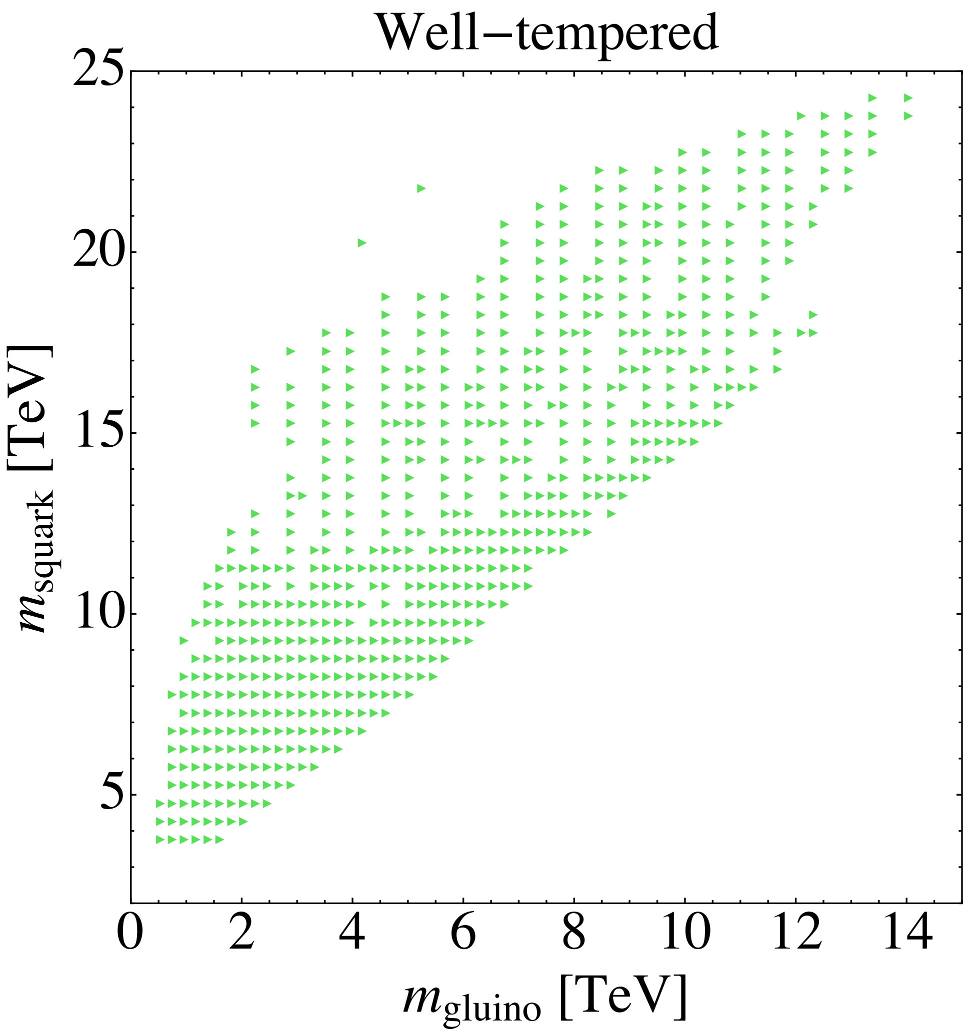
What about the LHC?



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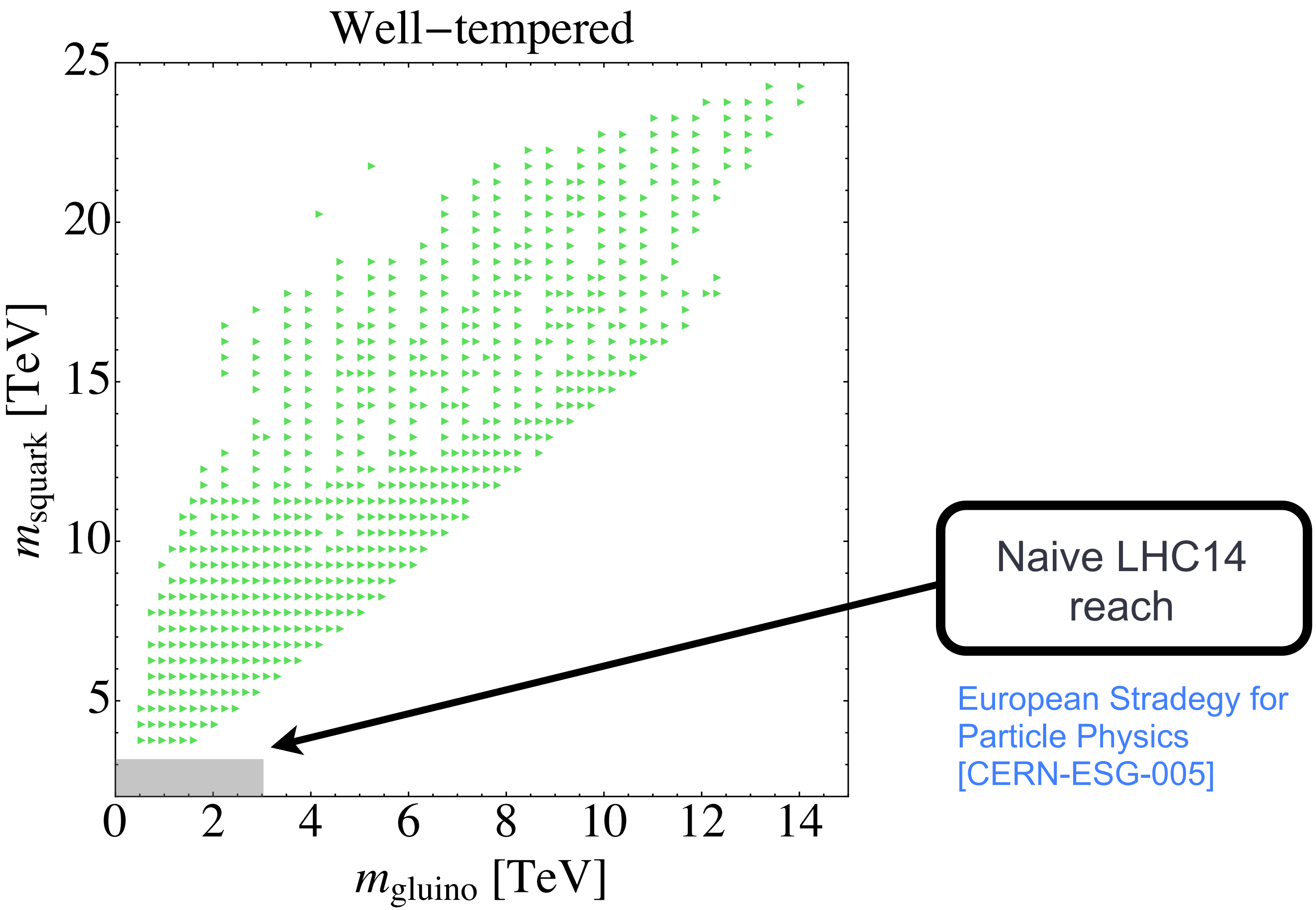


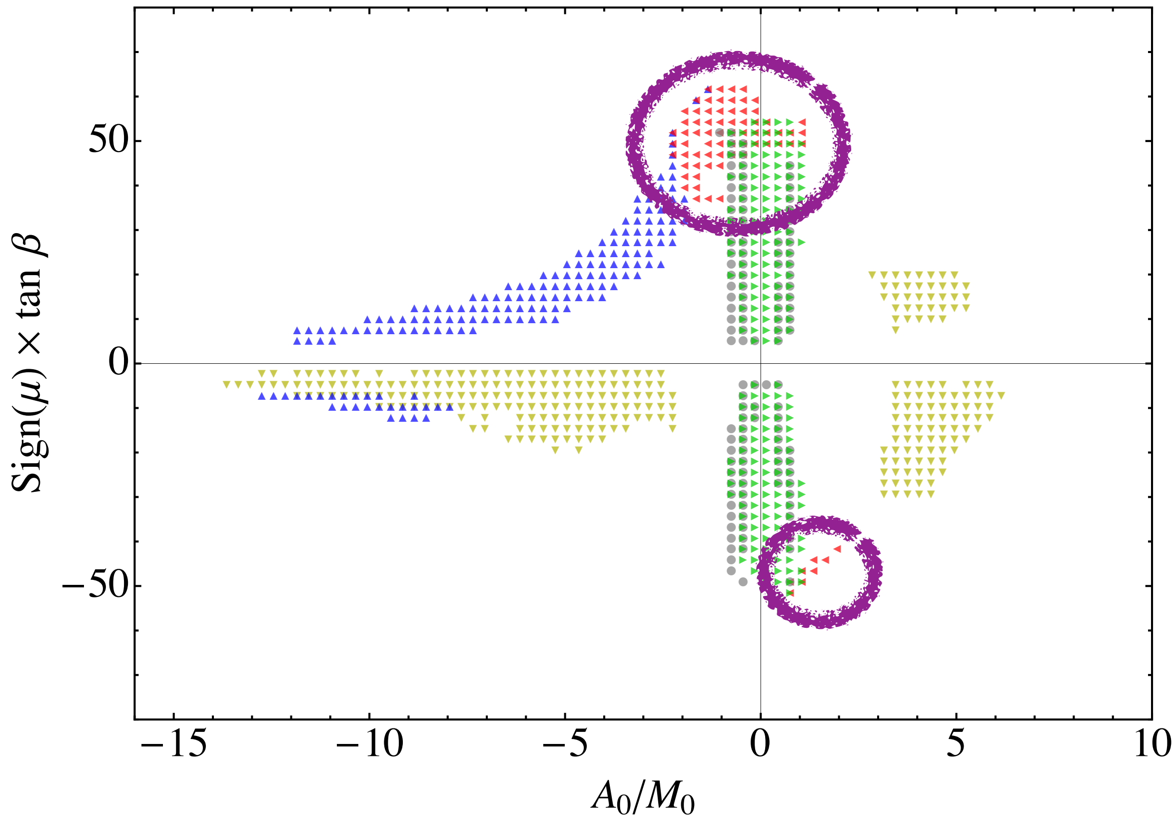
European Stradegy for Particle Physics [CERN-ESG-005]

- The LHC will have little impact on the well-tempered spectra.

Circumnavigating the CMSSM

A^0 pole annihilation

Setting sail for A^0 pole annihilation



- light $\tilde{\chi}^0$
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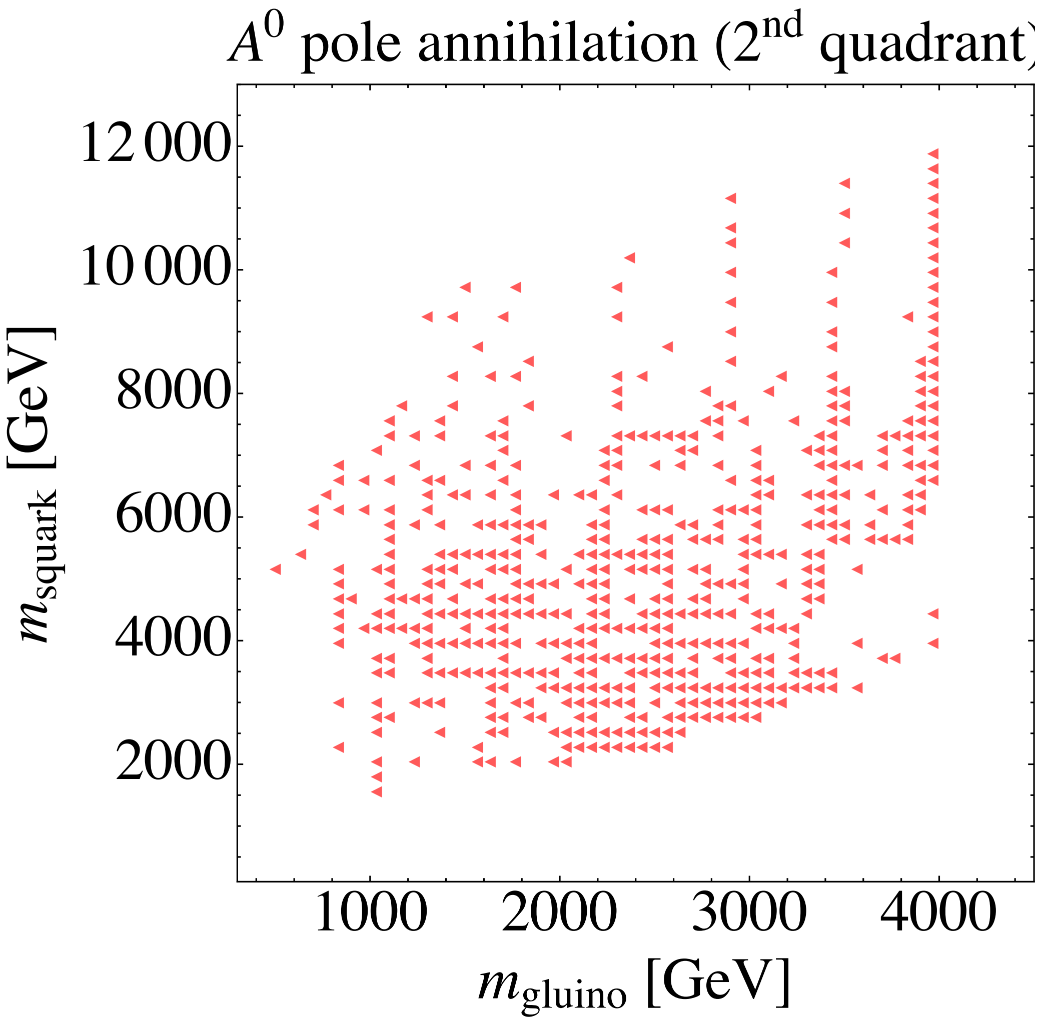
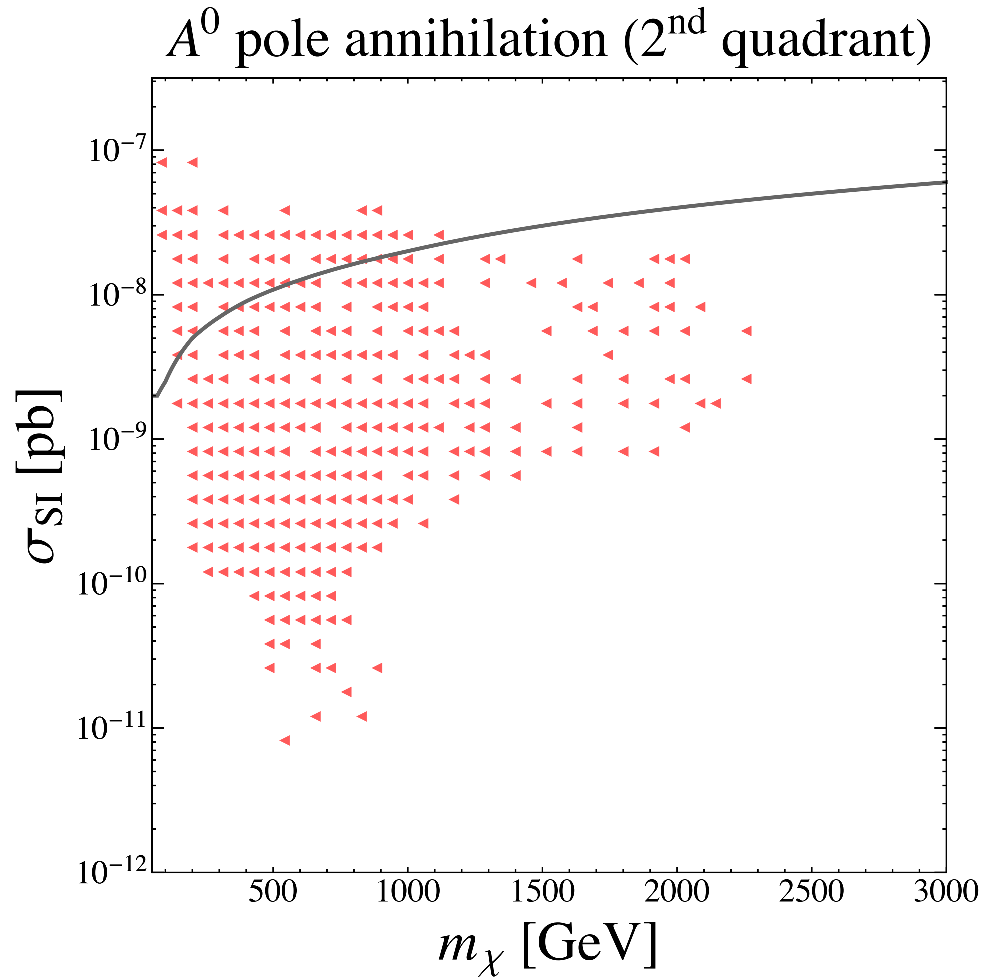
- $500 \text{ GeV} \lesssim M_0 \lesssim 16 \text{ TeV} \quad [\mu > 0]$
  $200 \text{ GeV} \lesssim M_{1/2} \lesssim 7 \text{ TeV} \quad [\mu > 0]$
- $5 \text{ TeV} \lesssim M_0 \lesssim 10 \text{ TeV} \quad [\mu < 0]$
  $300 \text{ GeV} \lesssim M_{1/2} \lesssim 2 \text{ TeV} \quad [\mu < 0]$

The squark-gluino plane



- 1^{st} quadrant is similar.

Direct detection

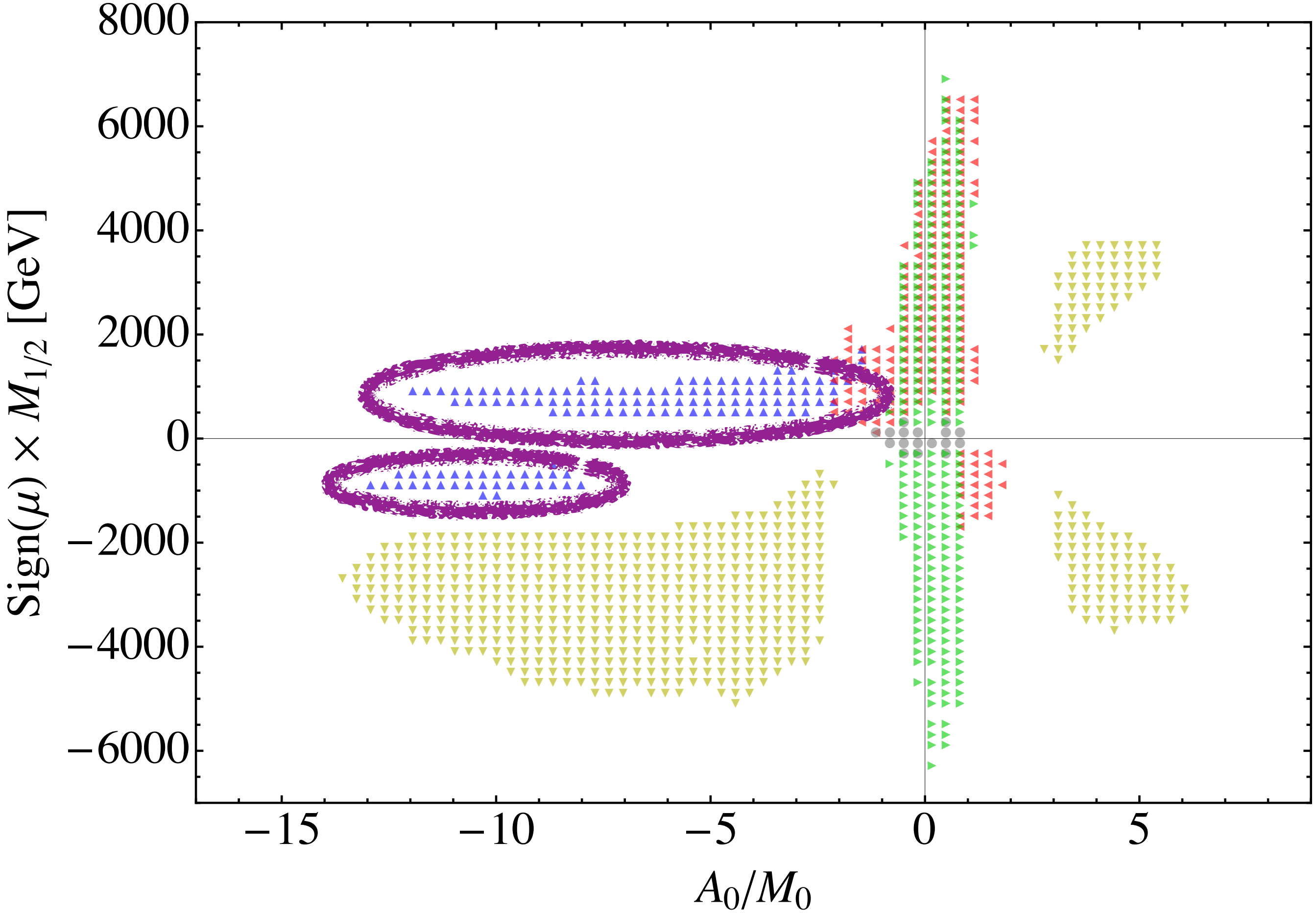


- 1^{st} quadrant is similar but 4^{th} quadrant extends below 10^{-14} pb .

Circumnavigating the CMSSM

Stau coannihilation

Setting sail for stau coannihilation



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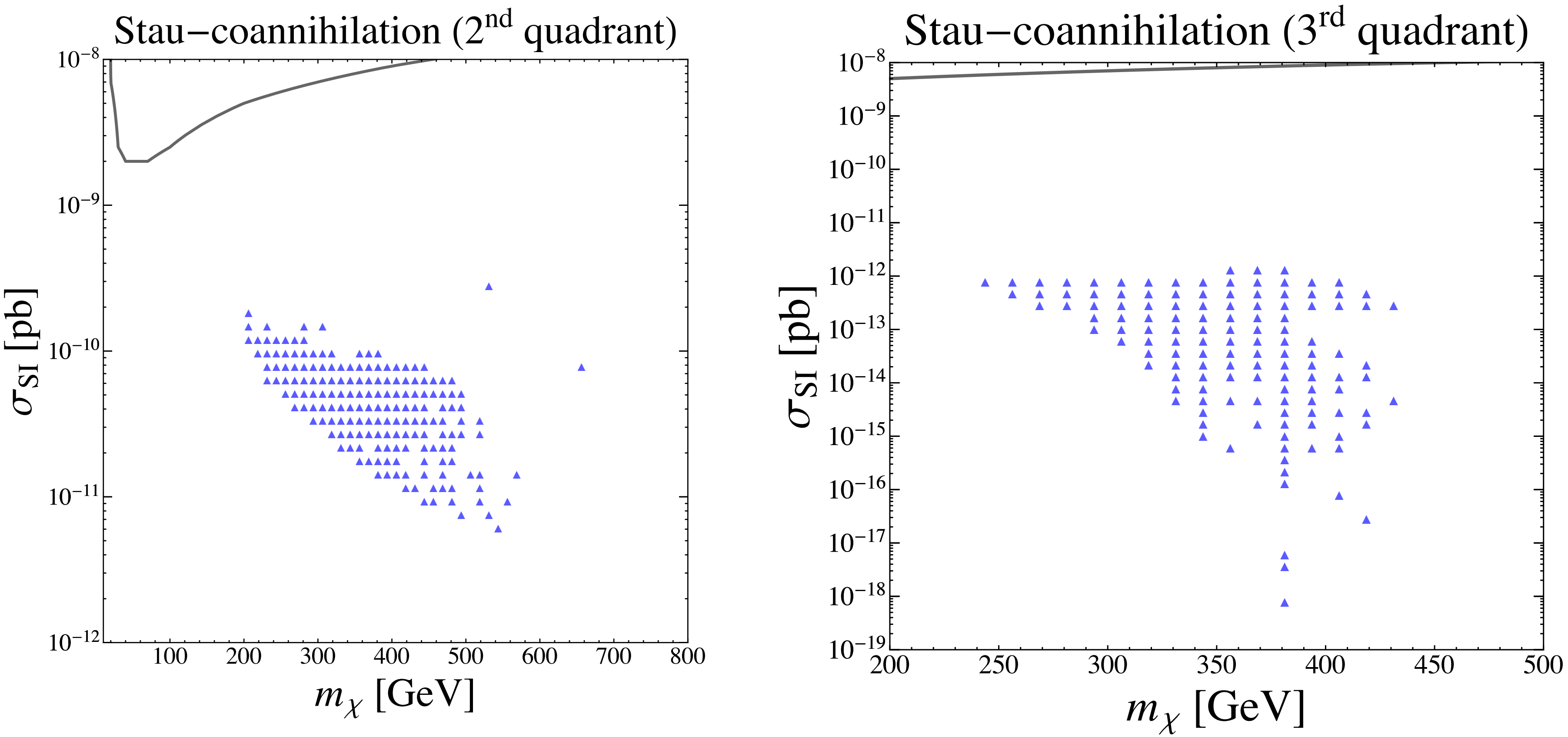
- $200 \text{ GeV} \lesssim M_0 \lesssim 3 \text{ TeV}$
- $5 \lesssim \tan\beta \lesssim 60$

Stau-coann: direct detection



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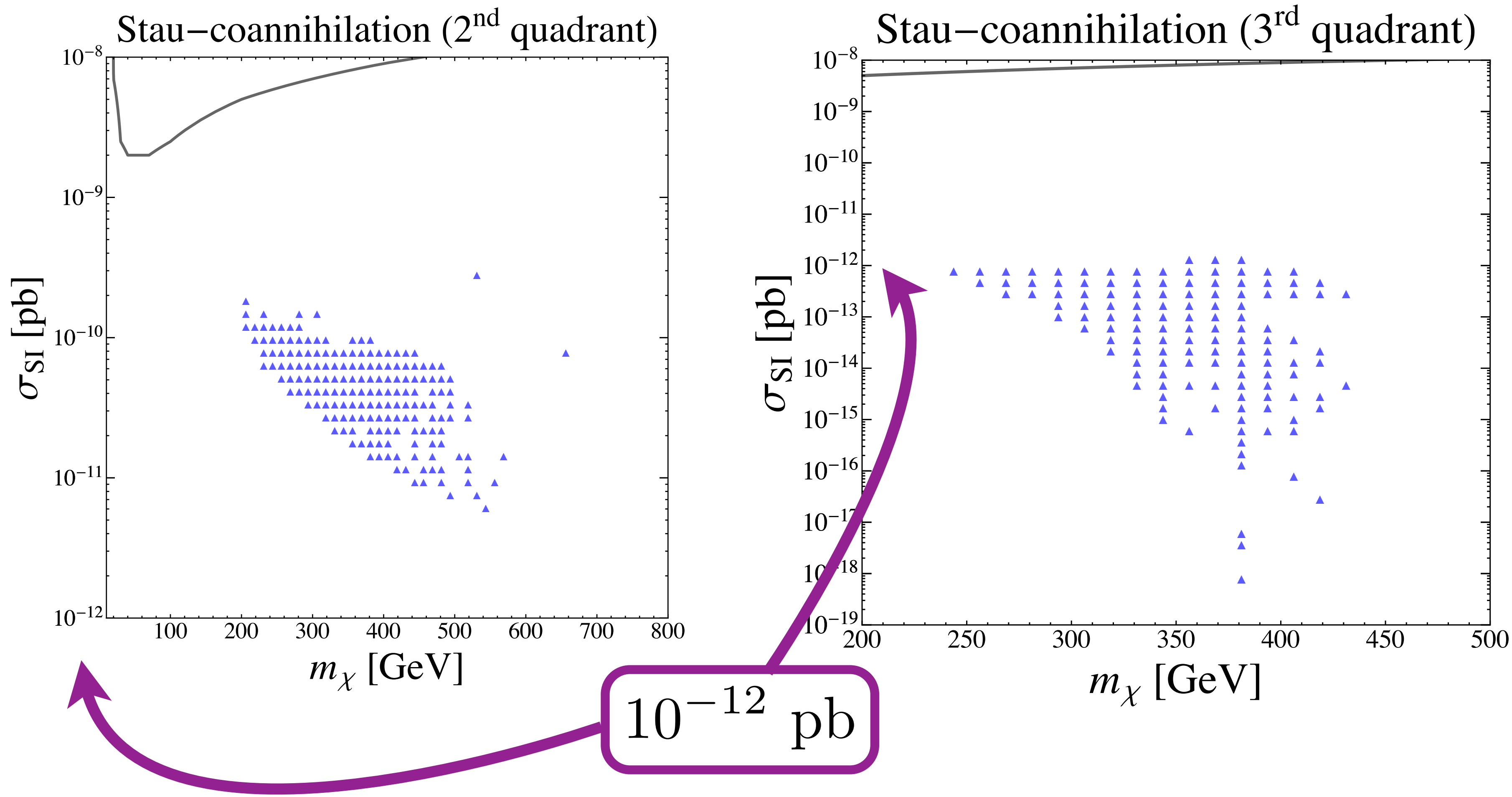
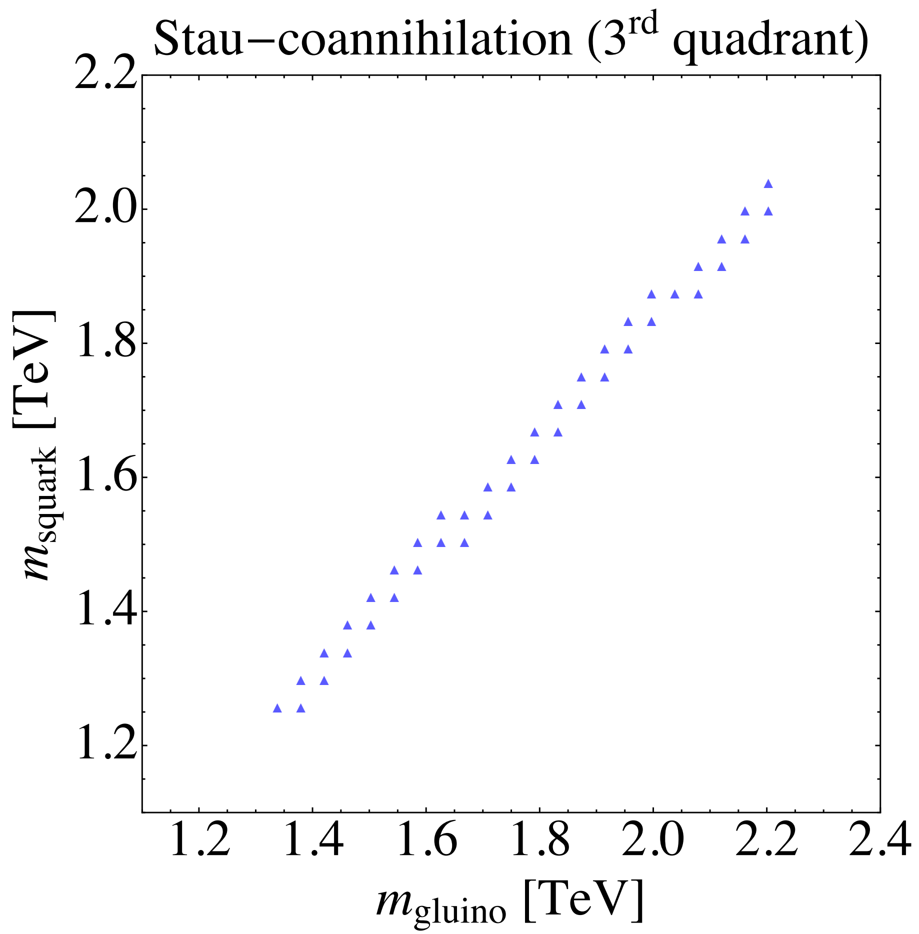
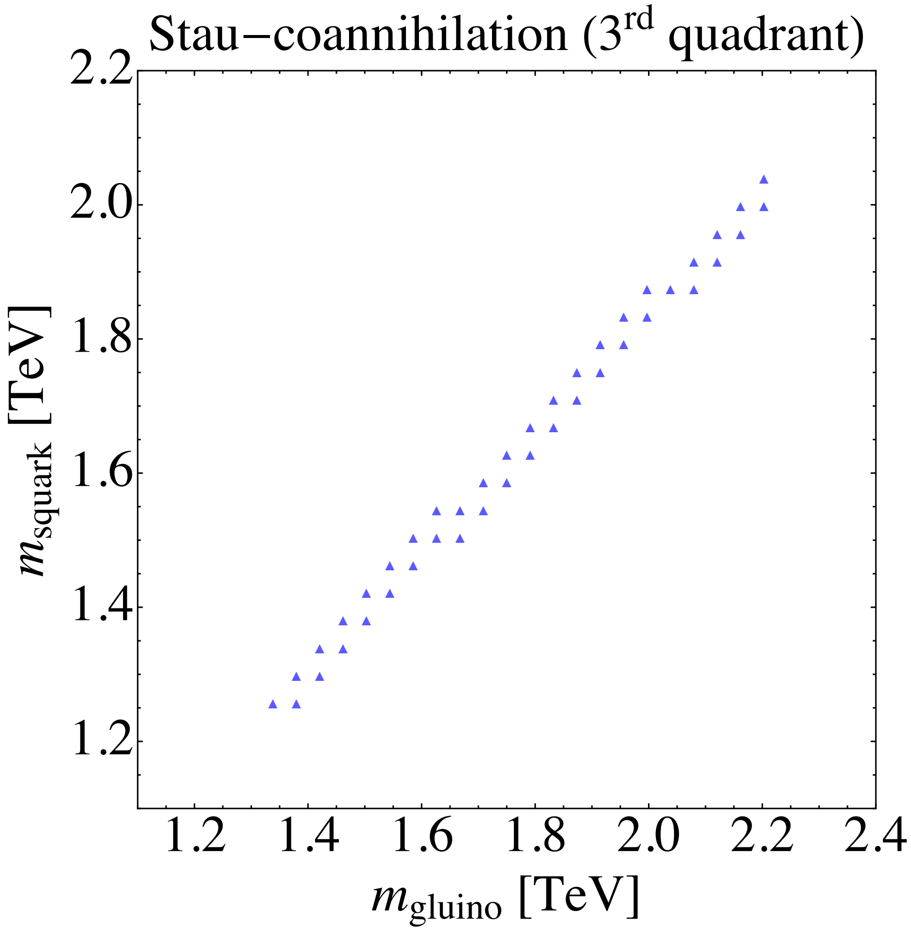


- A 1-ton Xenon experiment can reach spin-independent cross sections of 5×10^{-12} pb at 300 GeV. Dark matter limit plotter [http://dmtools.brown.edu/]
- Direct detection can probe all of the 2nd quadrant.

Stau-coann: squark-gluino plane



Stau-coann: squark-gluino plane



Are these spectra discoverable at the 14 TeV LHC?

A stau-coann benchmark (3rd quad)

Input parameters						
M_0	$M_{1/2}$	A_0	$\tan\beta$	$\text{sign}(\mu)$	$\lvert\mu\rvert$	B_μ
259.515	900.862	-2296.71	9.23077	-1	-1555.68	7.574×10^7

- The LSP is 383.52 GeV; the lighter stau is 383.8 GeV.
  - The stau lifetime is $O\left(10^{-2}\ \text{s}\right)$. Probed via long-lived stau searches?

Citron, Ellis, Luo, Marrouche, Olive, Vries [arXiv:1212.2886]

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- The gluino is 1980 GeV.
- The squark masses are

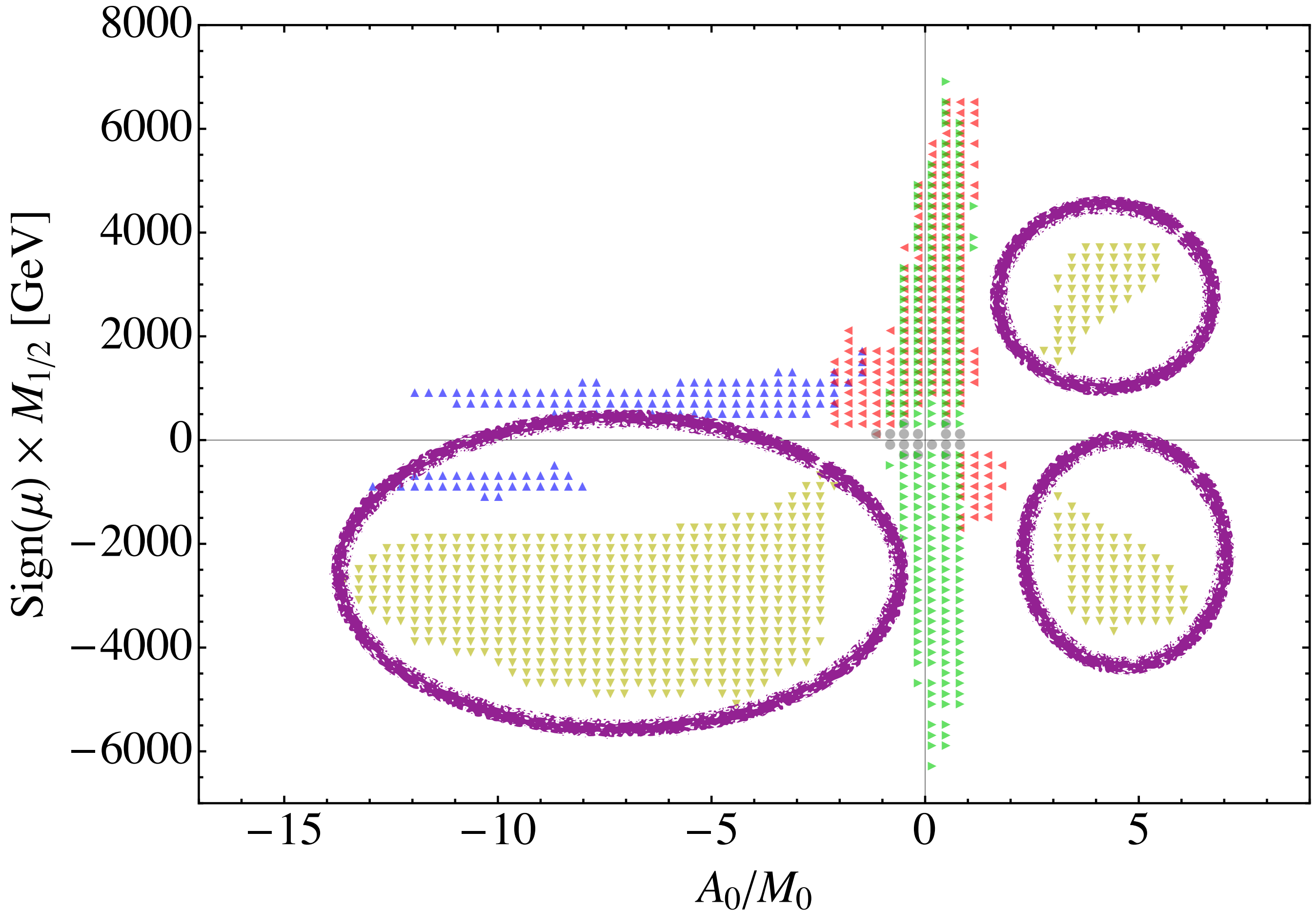
	$\widetilde{q}$	$\widetilde{b}_1$	$\widetilde{b}_2$	$\widetilde{t}_1$	$\widetilde{t}_2$
m [GeV]	1780.8	1529.9	1715.3	1067.2	1562.9

- The gluino branching ratios are
  - $\widetilde{g} \to \widetilde{t}_{1,2} + \overline{t}$ [52%]
  - $\widetilde{g} \to \widetilde{b}_{1,2} + \overline{b}$ [20%]
  - $\widetilde{g} \to \widetilde{q} + \overline{q}$ [28%]
- Probed via gluino pair production?

Circumnavigating the CMSSM

Stop coannihilation

Setting sail for stop coannihilation



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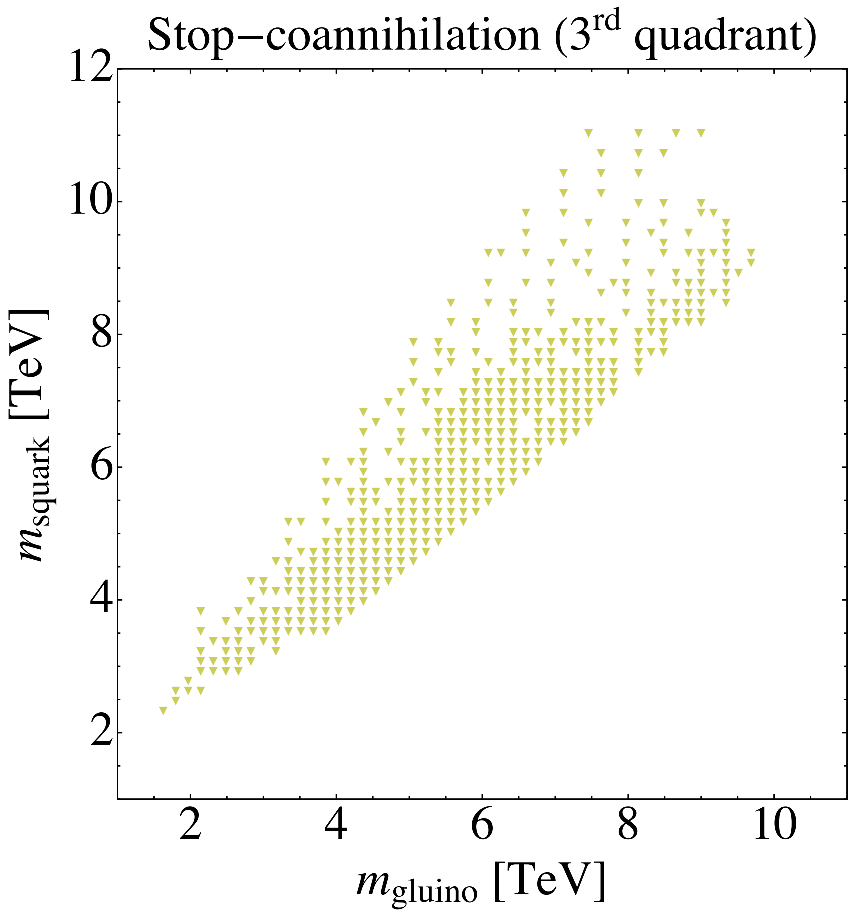
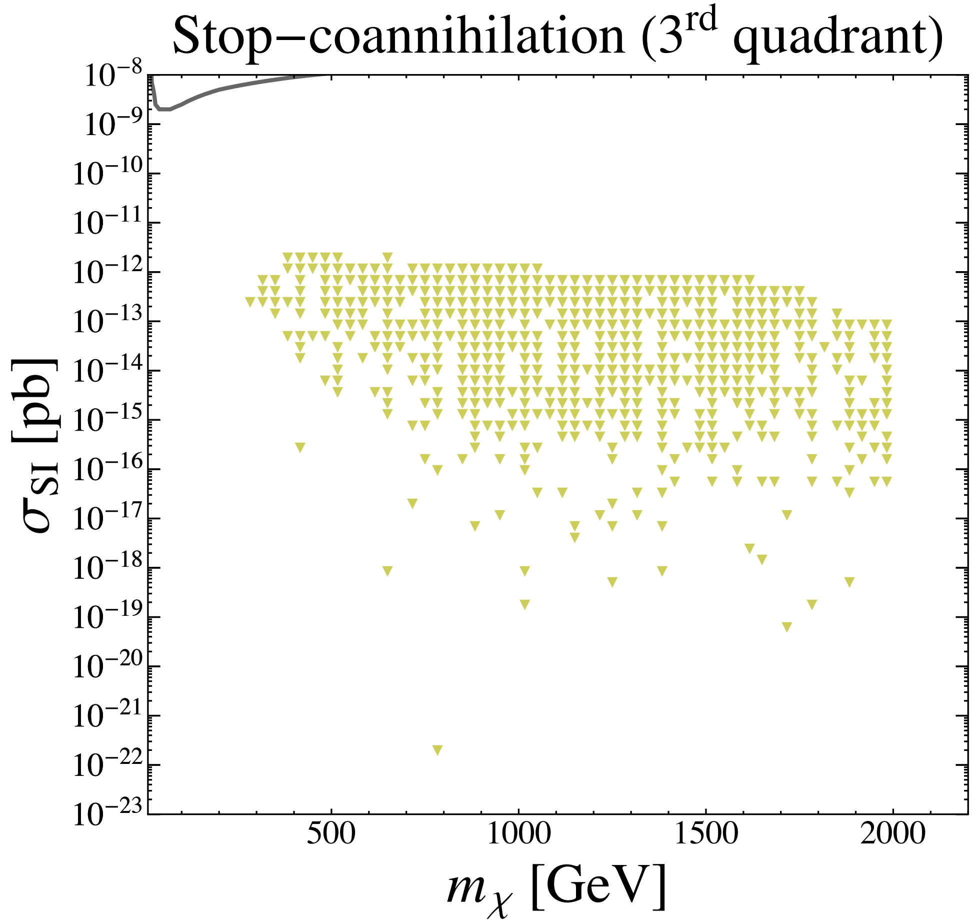
Stop-coannihilation phenomenology





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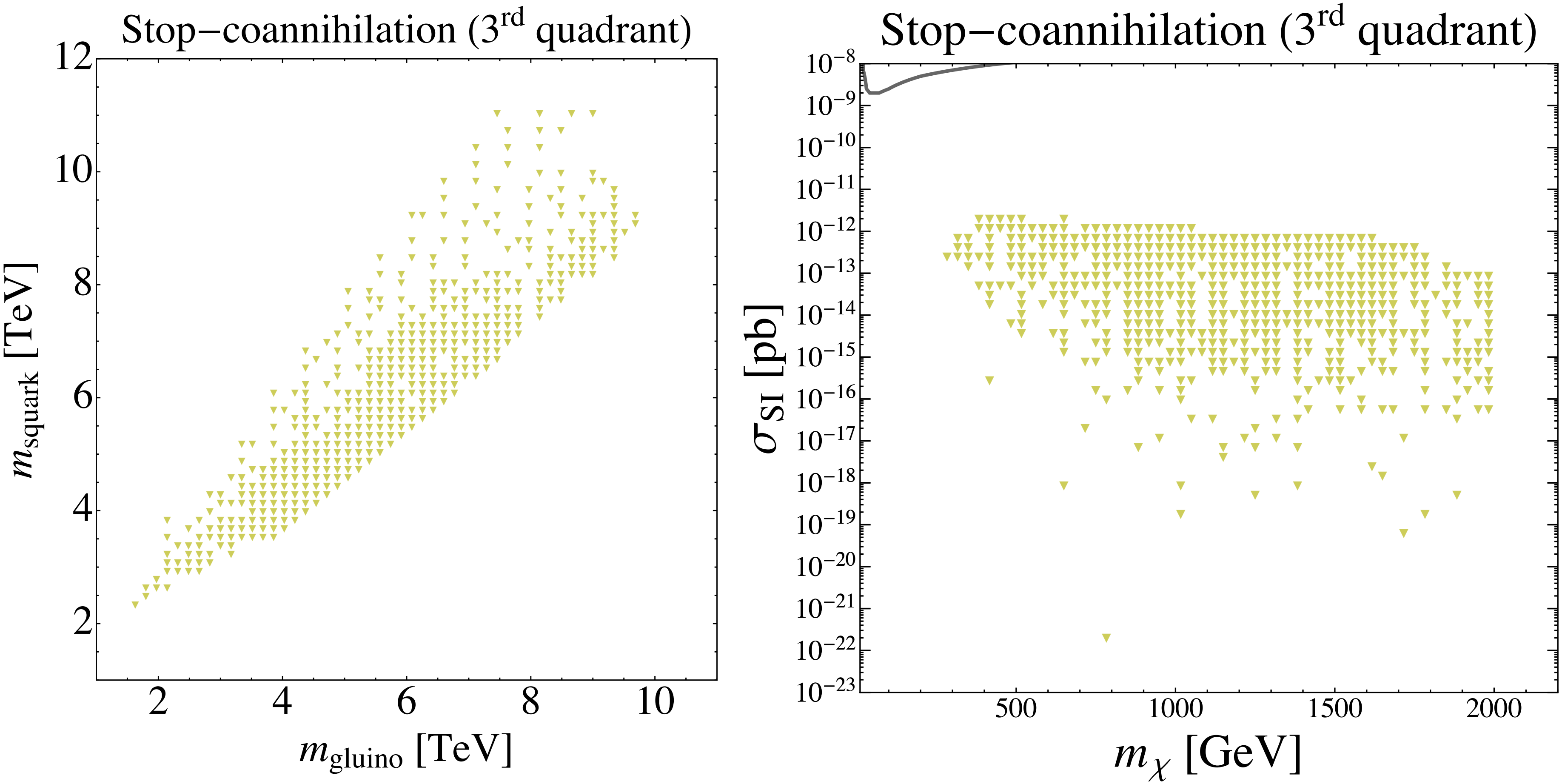

A large portion of these spectra will require a machine beyond the 14 TeV LHC.

Almost Home

Conclusions

Conclusions

- The CMSSM provides a simple ansatz which allows one to explore the phenomenology of the full parameter space.
- We provide a map of the CMSSM which is consistent with a Higgs at 125 GeV and thermal dark matter comprised of neutralinos.
- We demonstrate that the parameter space is compact.
- What regions will remain unconstrained after LHC14 and 1 Ton scale spin-independent direct detection?
  - The 4th quadrant of A^0-pole annihilation;
  - Large portions of the stop coannihilation regions.
- Note we need LHC results to be presented as generally as possible so it is easy to interpret bound for non-trivial models.