Here Be Dragons:

The Unexplored Continents of the CMSSM

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(SLAC)

with Tim Cohen

arXiv:13XX.soon

PCTS After the Higgs Workshop
April 25, 2013

Disclaimer

This is not a talk on the Higgs boson,

but

the Higgs boson mass plays a central role.

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The 8 TeV LHC just began to exploring
CMSSM
Need 13 TeV (and beyond)

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.
  - Profound implications for spectrum

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

$$m_{h^0}^2 \simeq m_{Z^0}^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_{W^\pm}^2}\left(\log\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right)$$

$$m_{h^{0\prime}} - m_{h^0} \simeq \frac{3g^2 m_t^4}{16\pi^2 m_{W^\pm}^2 m_{h^0}} \log\frac{m_{\tilde{t}_1'} m_{\tilde{t}_2'}}{m_{\tilde{t}_1} m_{\tilde{t}_2}} \quad\Longrightarrow\quad m_{\tilde{t}_1'} m_{\tilde{t}_2'} \simeq m_{\tilde{t}_1} m_{\tilde{t}_2}\; 2^{\frac{\Delta m_h}{5.6\ \mathrm{GeV}}}$$

- This measurement is “consistent” with MSSM.
  - Stops 500 GeV to 100 TeV - 4x heavier than pre-Higgs

- The motivation for weak-scale superpartners remains:
  - Solves the hierarchy problem;
  - Explains the dark matter;
  - Predicts gauge coupling unification.

The MSSM in the Era of Higgs Discovery

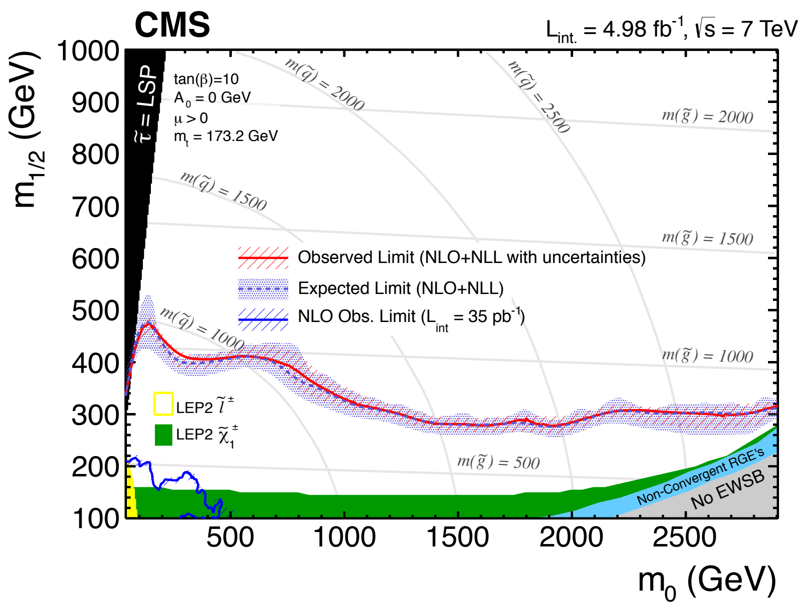
- The parameter space of the MSSM is enormous.
  - The soft supersymmetry breaking Lagrangian includes more than 120 new parameters.
- How can we map out all possible signatures?
  - Simplified models: isolate particles for specific signature. Parameter space is tractable; only a few masses and branching ratios to specify.
  - 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 this ansatz?

A Simple Ansatz - a wide range of dynamics

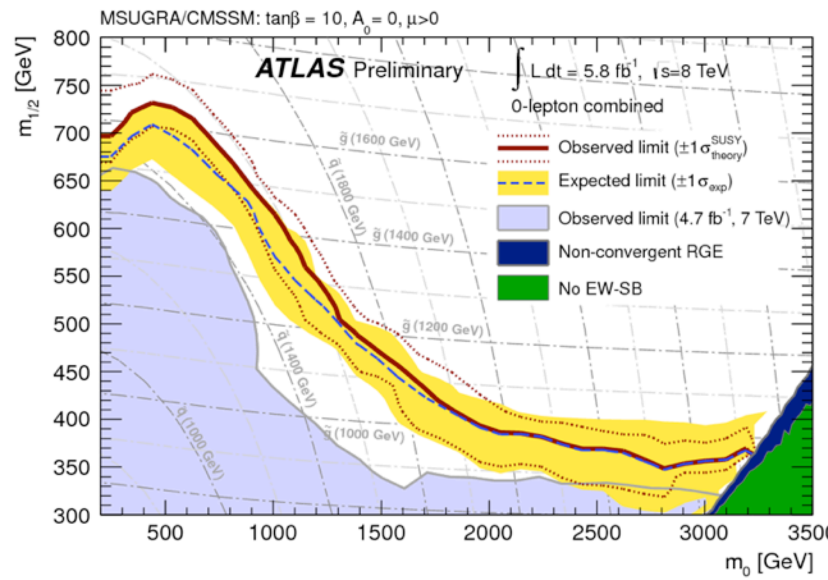
- CMSSM is 4-dimensional subspace of the *R*-parity conserving MSSM.
- Defined at the GUT scale by the following (real) inputs:
  - The unified scalar soft mass M_0
  - The unified gaugino mass $M_{1/2}$
  - The unified *A*-term A_0
  - The ratio of the Higgs vevs tan β (traded for B_μ term).
- Parameters are evolved to M_W using the RGEs.
- μ-term determined by requiring m_Z
- 19 coupled RGEs integrated over 32 e-folds ⇒ relation between input parameters & low energy spectrum is non-linear.

The State of the Art

- Both ATLAS and CMS put limits on the CMSSM:



CMS [arXiv:1205.6615]



ATLAS-CONF-2012-109

- Exclusions are regions of the $M_{1/2}$ versus M_0 plane at fixed A_0 & tan β .
- What is the Higgs mass?
- Does the neutralino overclose the Universe?

Classification

- “Quadrants” defined by sign A_0 & sign μ with $M_{1/2}$ >0.
  - Schematically RGEs for *A* and *B* terms are

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

  - Low energy spectrum is different depending quadrant.

- What process determines the relic abundance?

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.
  - "stau coannihilation"
  - "stop coannihilation"

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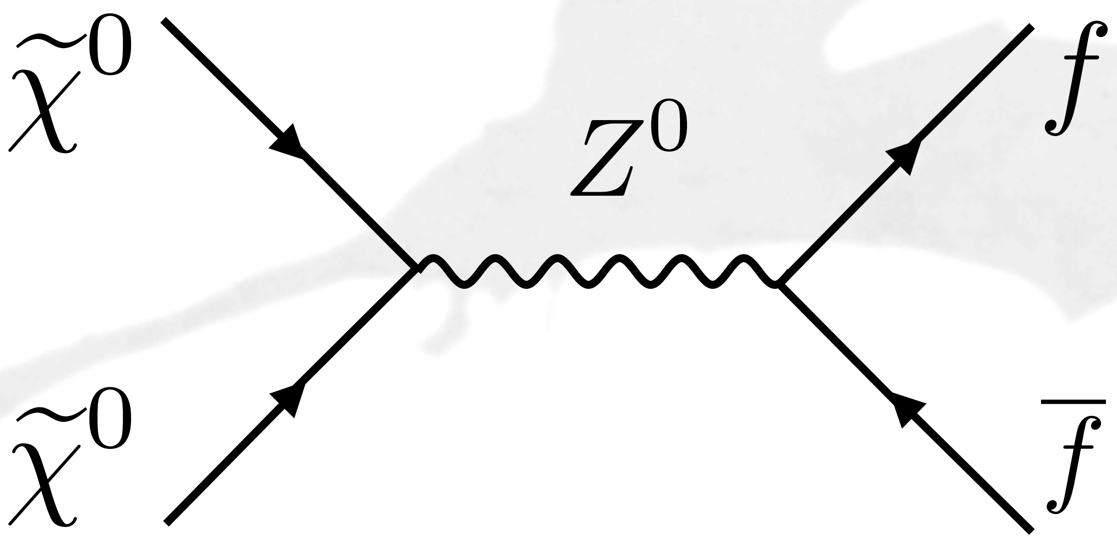

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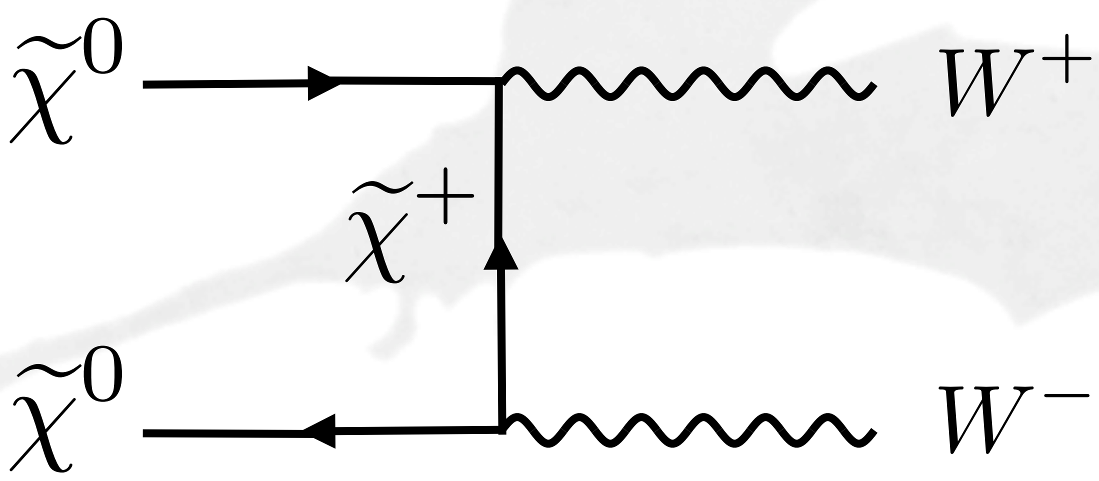

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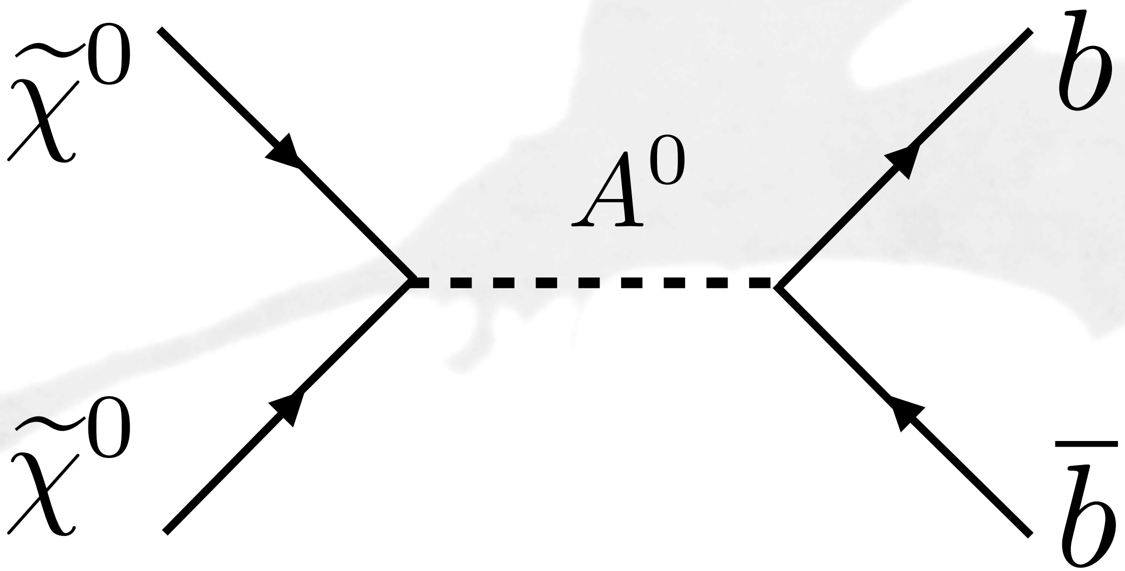

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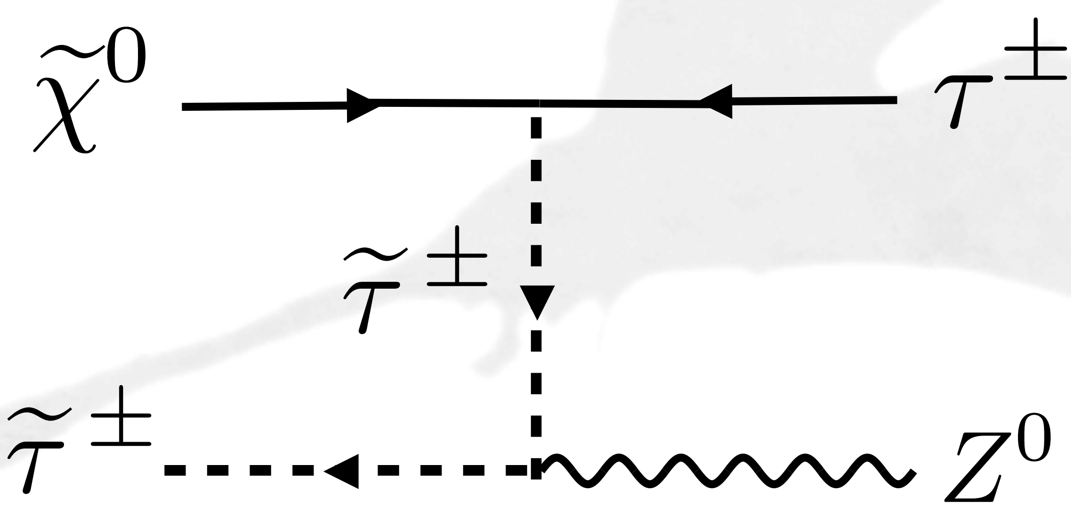

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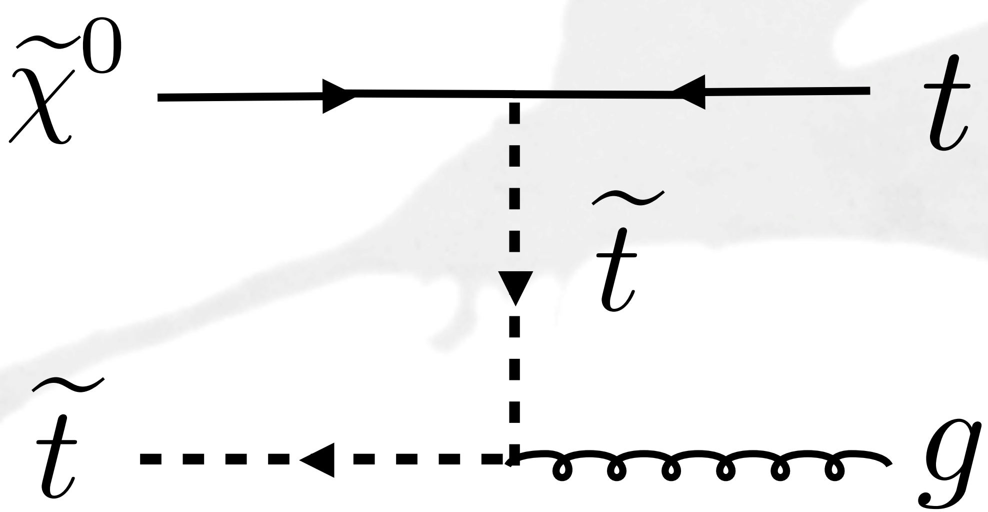

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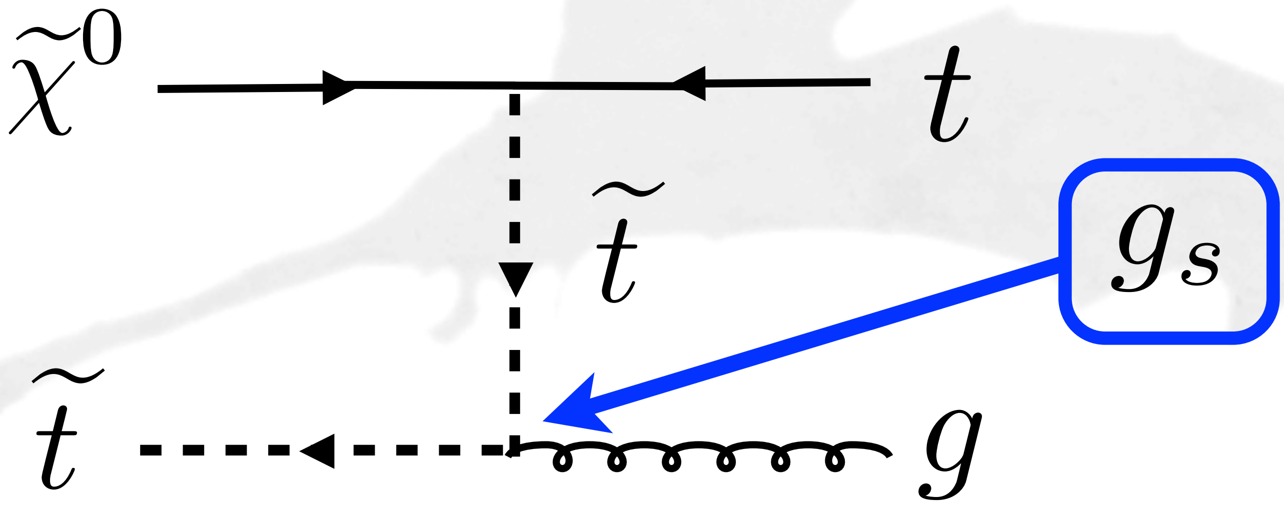
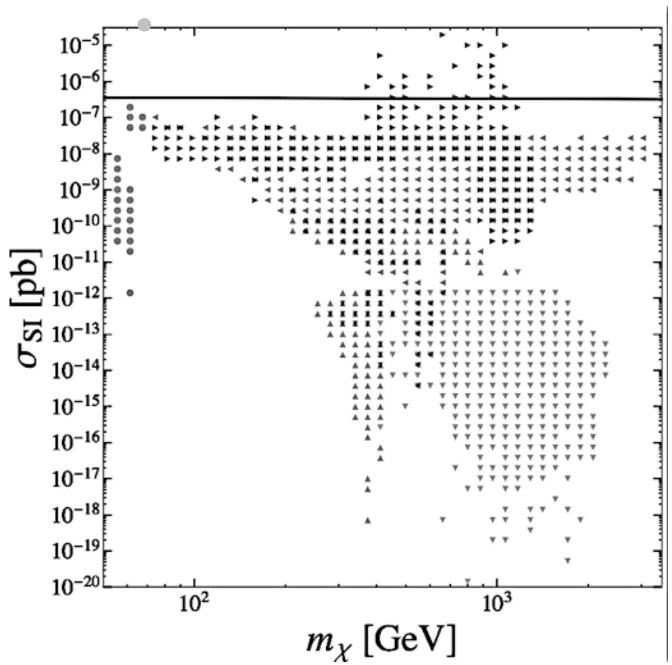
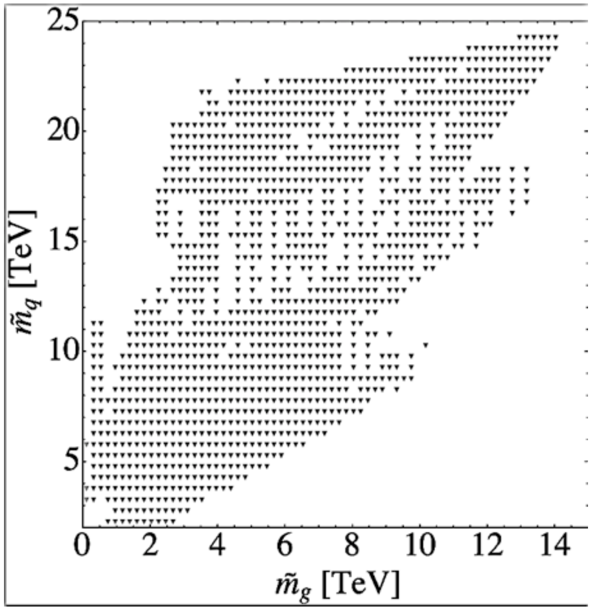


Grading The Post-h^0 Discovery CMSSM Literature

- Light χ^0
- Well Tempered
- A^0-pole
- Stau Coannihilation
- Stop Coannihilation

- A (Excluded by LHC gluinos)
- B- ("will be excluded by DD soon")
- D (nothing said recently)
- B ("will be excluded by LHC soon")
- F (Last paper in 2001)





CMSSM Cartography

The CMSSM is compact

- 125 GeV Higgs mass means M_0 not arbitrarily large.
- Relic density: not overclosing
    - Bounds $M_{1/2}$ from being too large
- Lifetime of vacuum being longer than 14Gyr bounds A_0.
- Perturbativity of bottom Yukawa coupling bounds tan β.

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<u>Consequence</u>

Every MSSM particle discoverable by a human-buildable accelerator

Tools

- SoftSUSY v3.3.7 computes low energy spectrum from CMSSM inputs. Allanach [arXiv:hep-ph/0104145]
  - Two loop MSSM RGEs (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]

Constraints

- 3 GeV error for the theoretical prediction for the Higgs mass:

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

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

- Require the relic density be in the range:

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

- Require that the lifetime of vacuum decay to a charge/color breaking minimum be longer than 14Gyr:

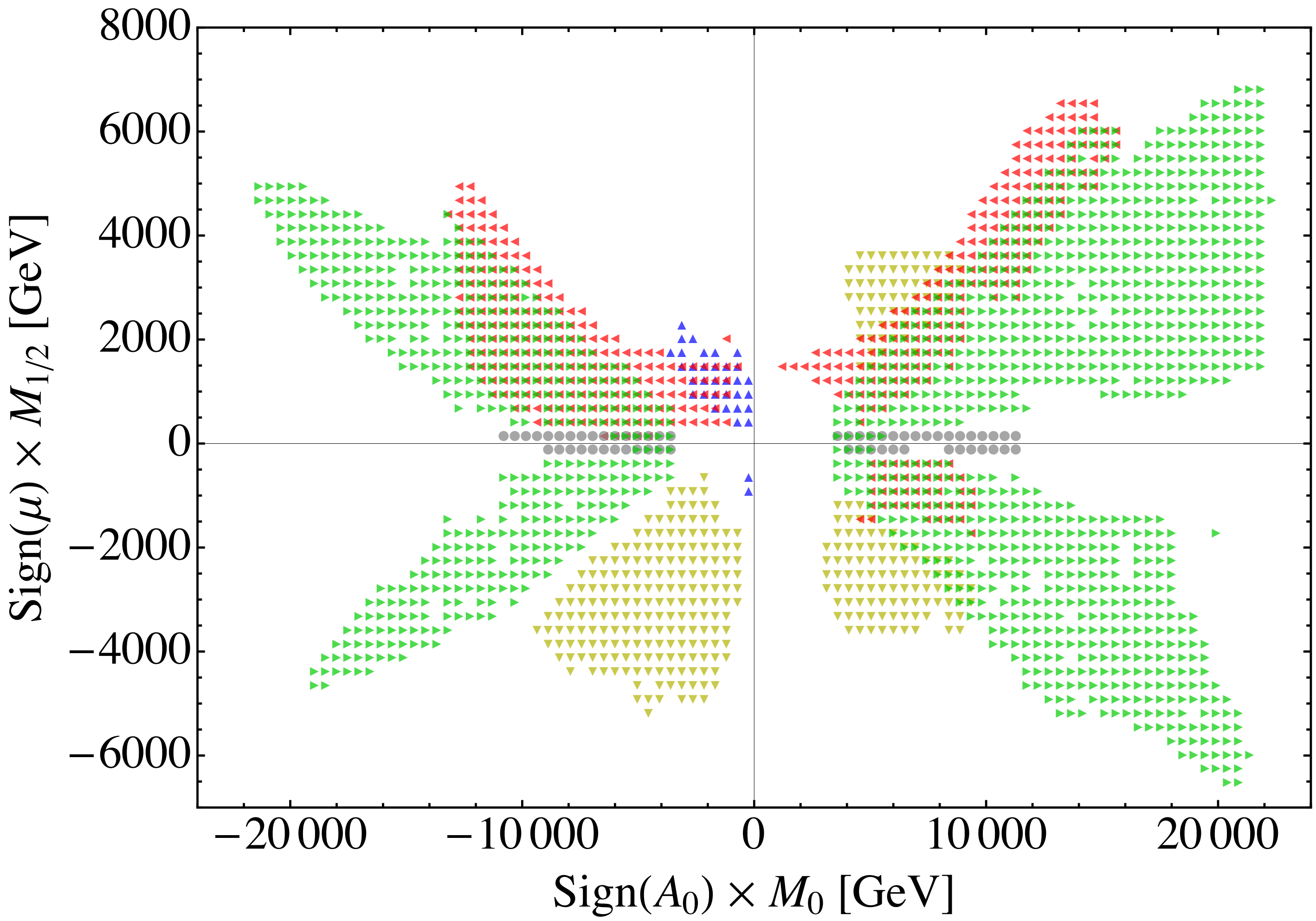
$$|a_t|^2 < (7.5\, m_{q3}^2 + 7.5\, m_{u_3^c}^2 + 3\,(m_{H_u}^2 + |\mu|^2))$$

Kusenko, Langacker, Segre [arXiv:hep-ph/9602414]

- Require that the chargino mass satisfy LEP bound:

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

Charting the CMSSM



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

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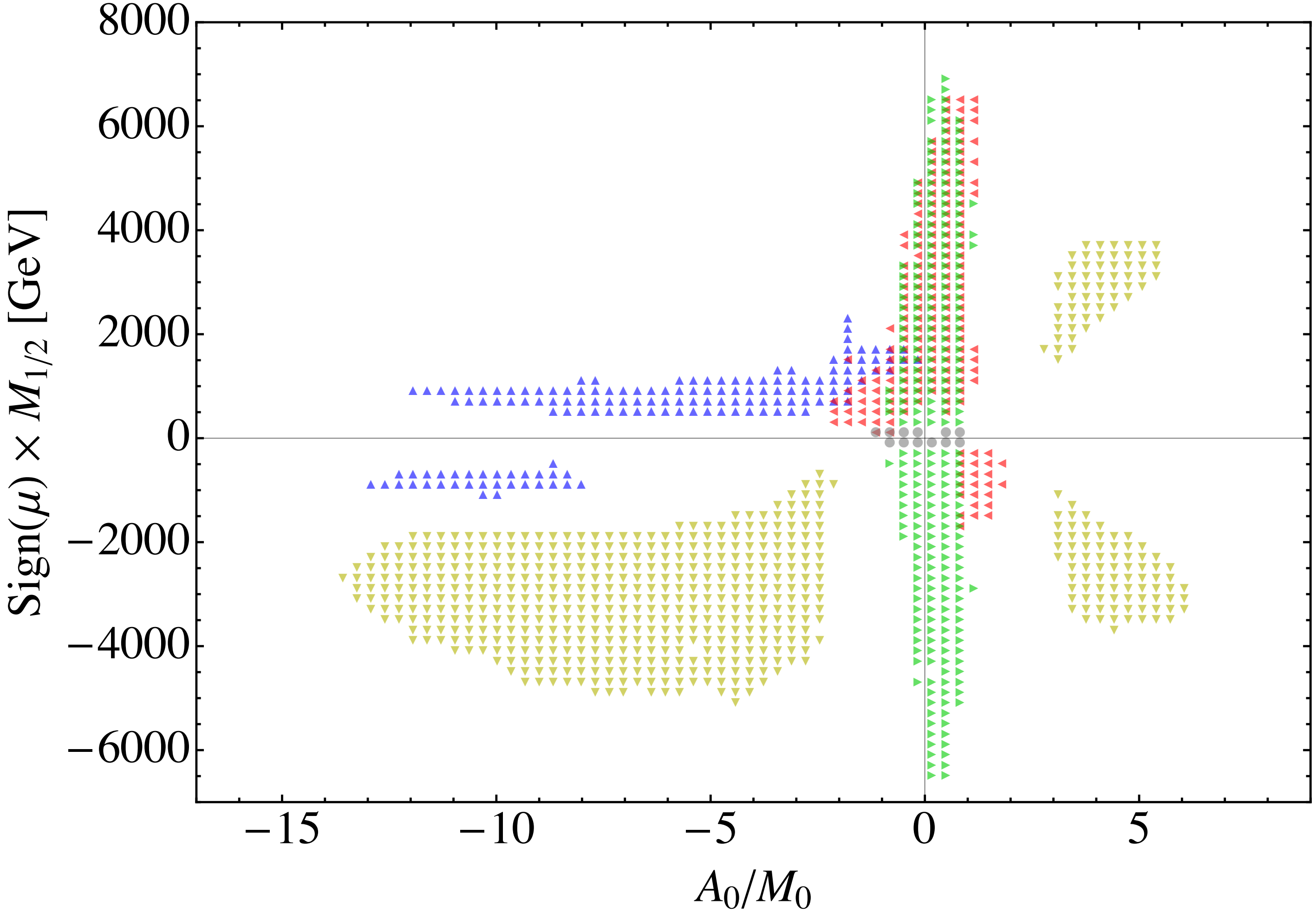

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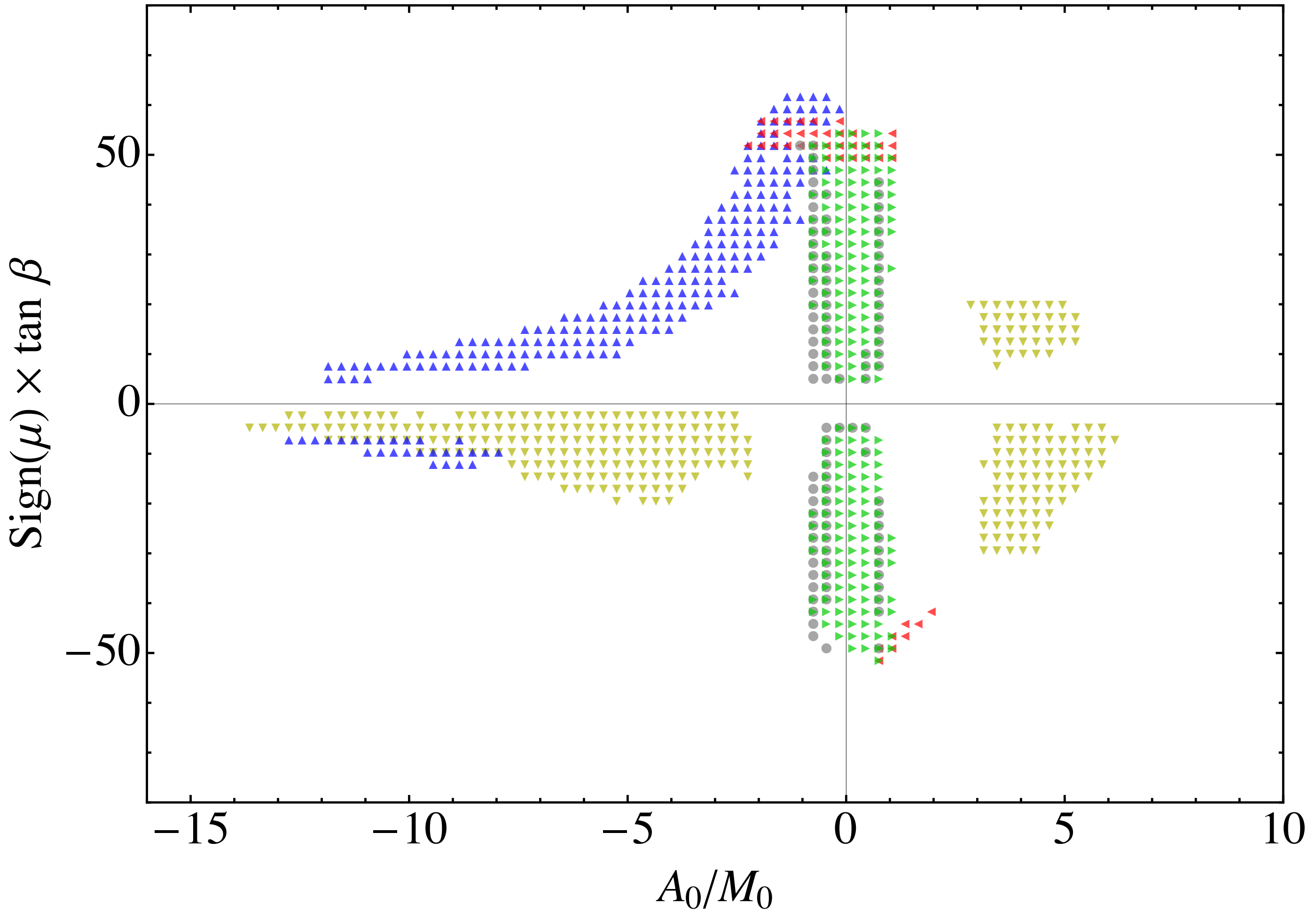

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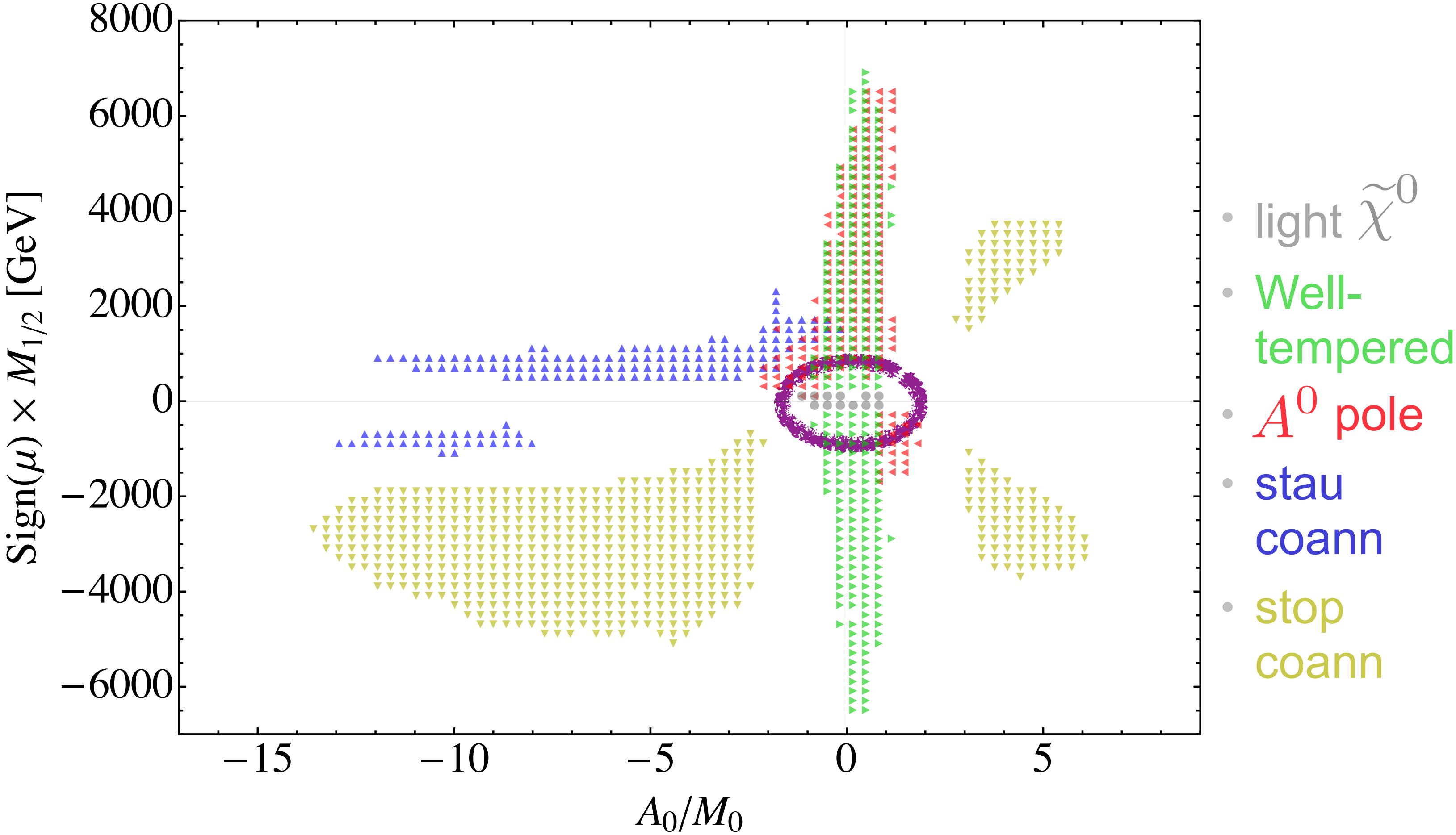
CIRCUMNAVIGATING THE CMSSM

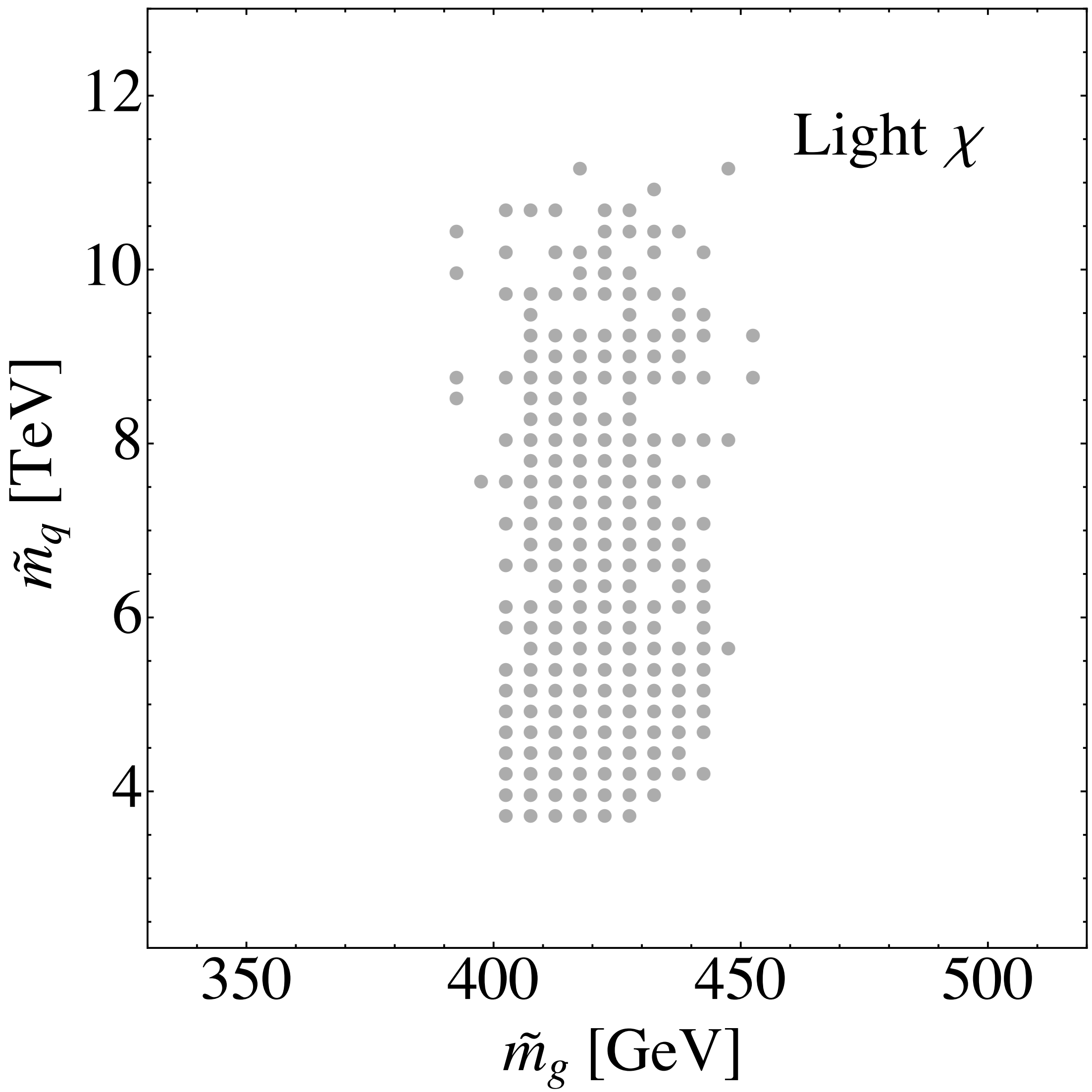
Light $\widetilde{\chi}^0$

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



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

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



$\widetilde{m}_g$	$\widetilde{m}_q$	$\widetilde{m}_{t_1}$	$\widetilde{m}_{\tau_1}$	m_χ	$m_{\chi_1^\pm}$	m_h	m_{A^0}
409.28	5393.5	3098.7	5327.3	57.139	111.1	124.14	5214.8

Probably Excluded

$\widetilde{g} \to \widetilde{B}\, q\, \bar{q}$ 1.9%

$\widetilde{g} \to \widetilde{W}^{\pm}\, q\, \bar{q} \to \widetilde{B}\, W^{\pm}\, q\, \bar{q}$ 46%

$\widetilde{g} \to \widetilde{W}^{0}\, q\, \bar{q} \to \widetilde{B}\, Z^{0}\, q\, \bar{q}$ 34%

Have separate searches for

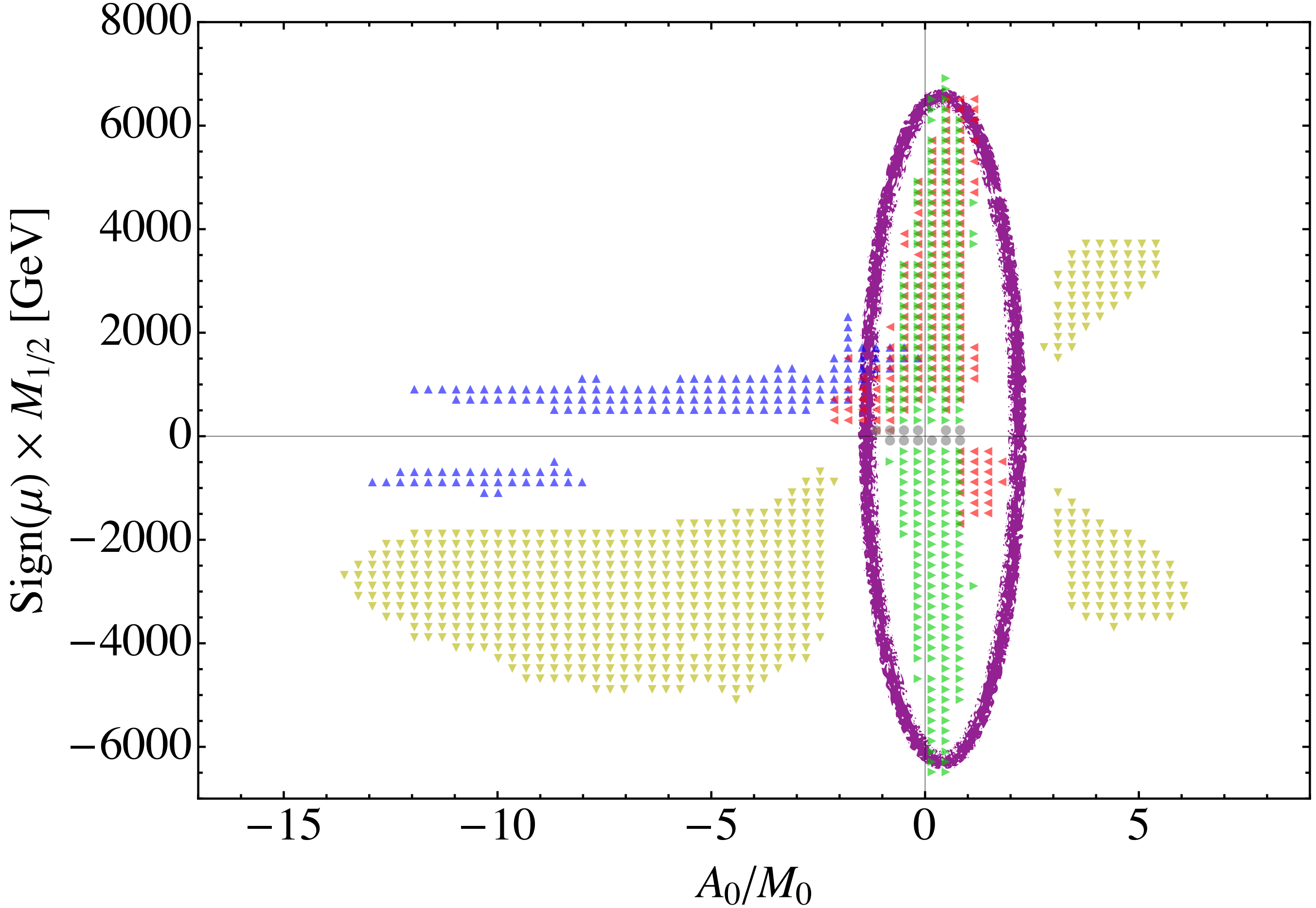
$$\widetilde{g}\,\widetilde{g} \to W^{\pm}\, W^{\pm}\, q\, \bar{q}\, q\, \bar{q}\, \chi\, \chi$$
$$\widetilde{g}\,\widetilde{g} \to Z^{0}\, Z^{0}\, q\, \bar{q}\, q\, \bar{q}\, \chi\, \chi$$
$$\widetilde{g}\,\widetilde{g} \to q\, \bar{q}\, q\, \bar{q}\, \chi\, \chi$$

Don’t provide efficiencies of alternate simplified models

CIRCUMNAVIGATING THE CMSSM

Well-tempered

Setting sail for well-tempered



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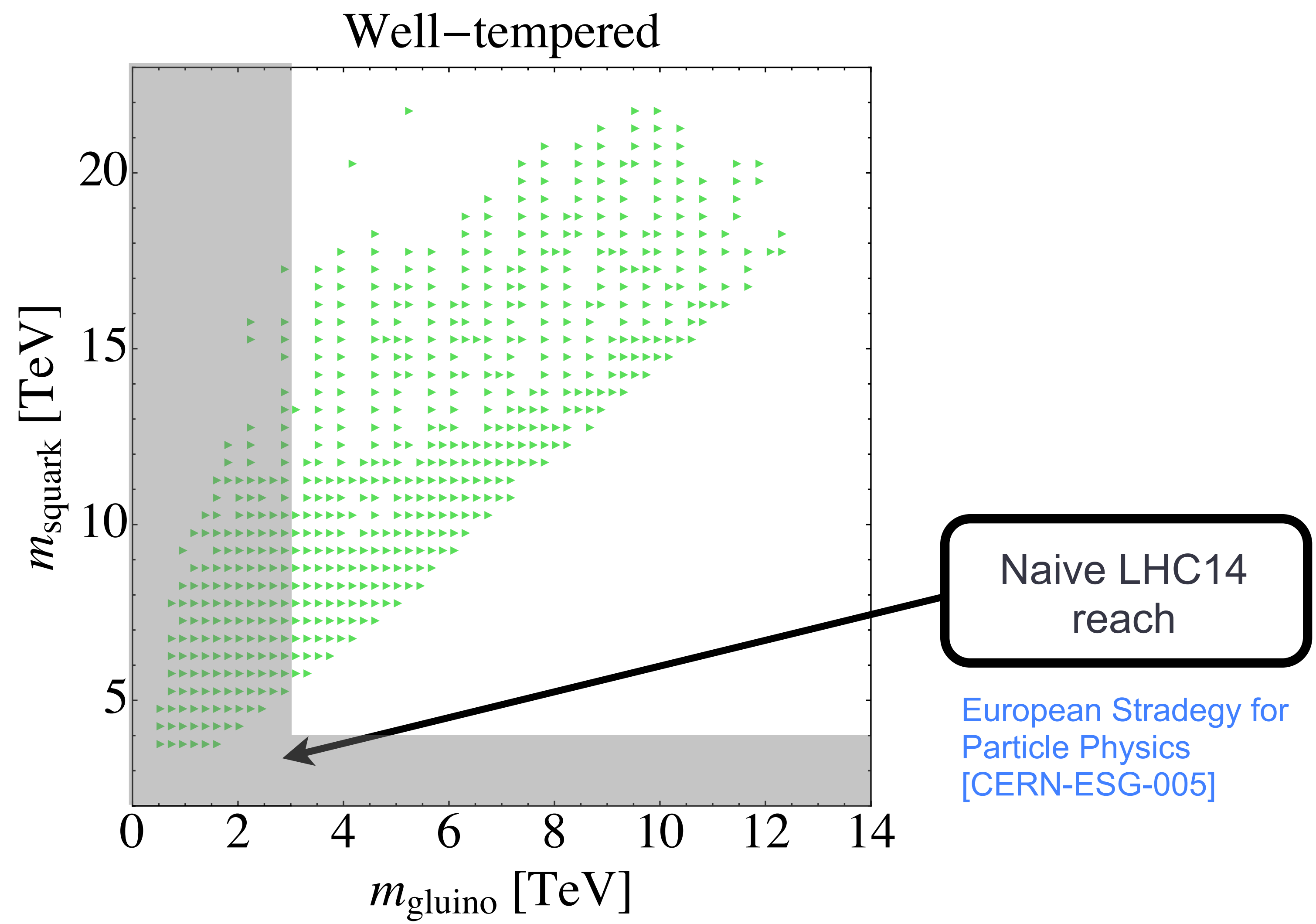
- $4 \text{ TeV} \lesssim M_0 \lesssim 20 \text{ TeV}$
- $5 \lesssim \tan\beta \lesssim 50$

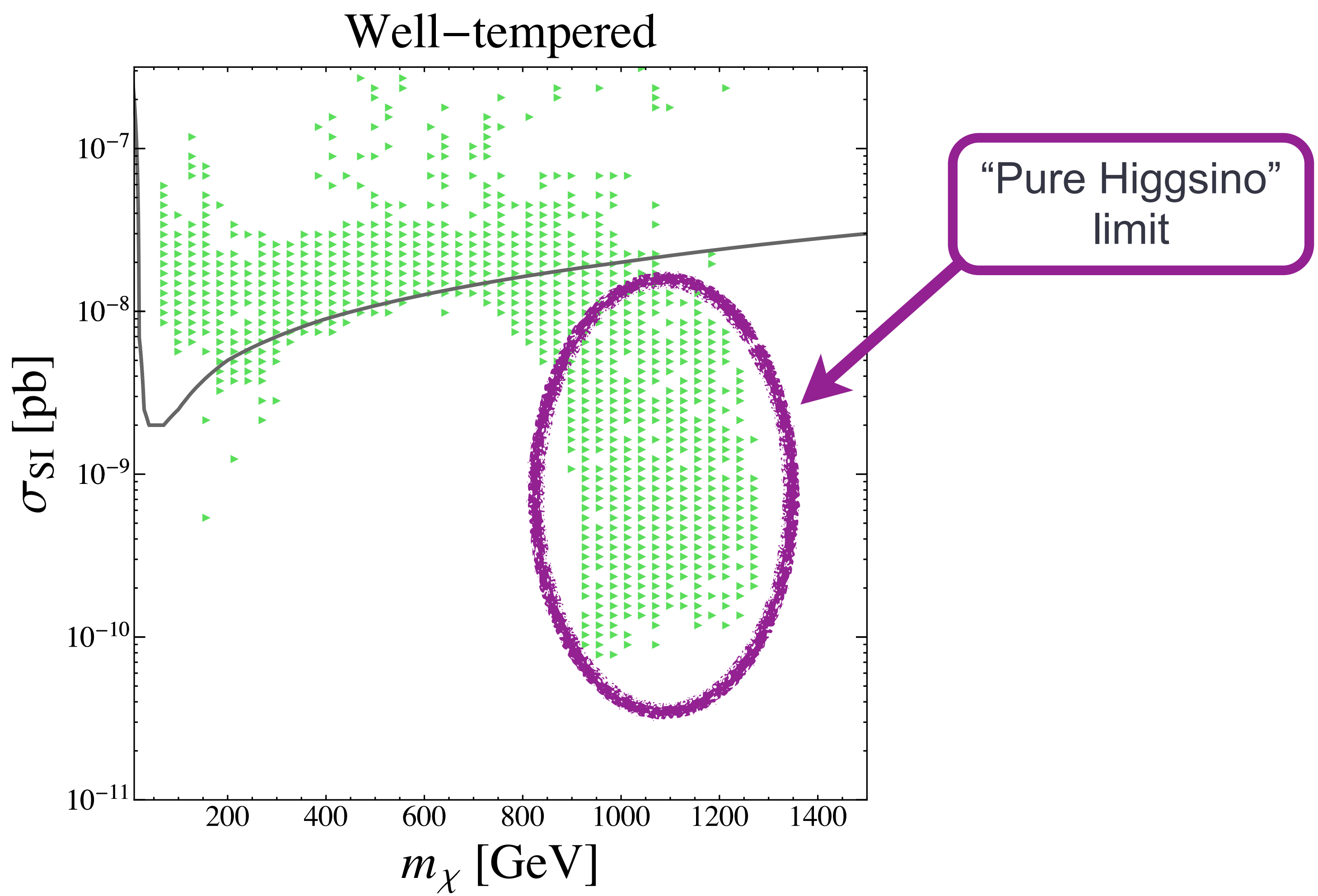
What about the LHC?



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

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

Will direct detection exclude this region?



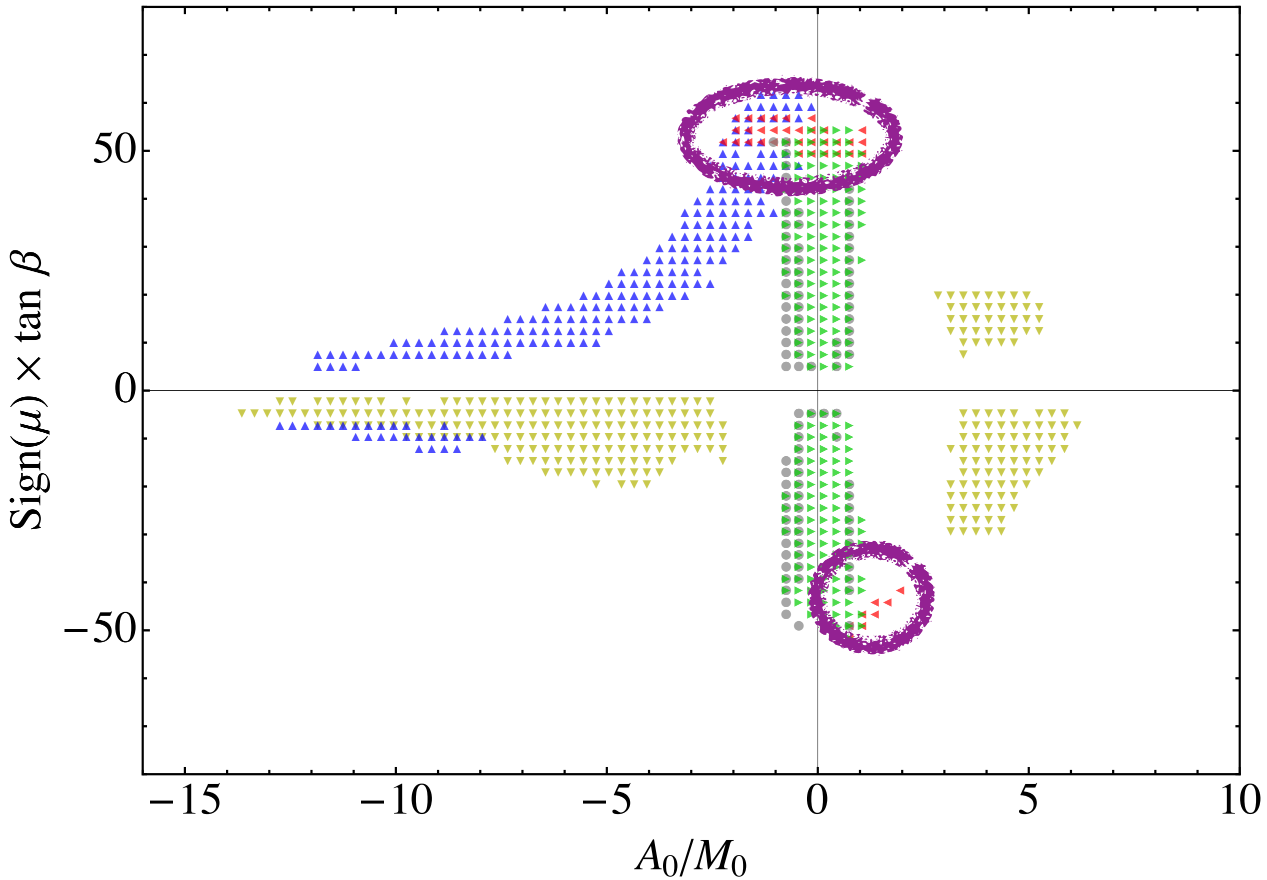
- A 1-ton Xenon experiment can reach spin-independent cross sections of 5×10^{-12} pb at 300 GeV.

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

CIRCUMNAVIGATING THE CMSSM

A^0 pole annihilation

Setting sail for A^0 pole annihilation



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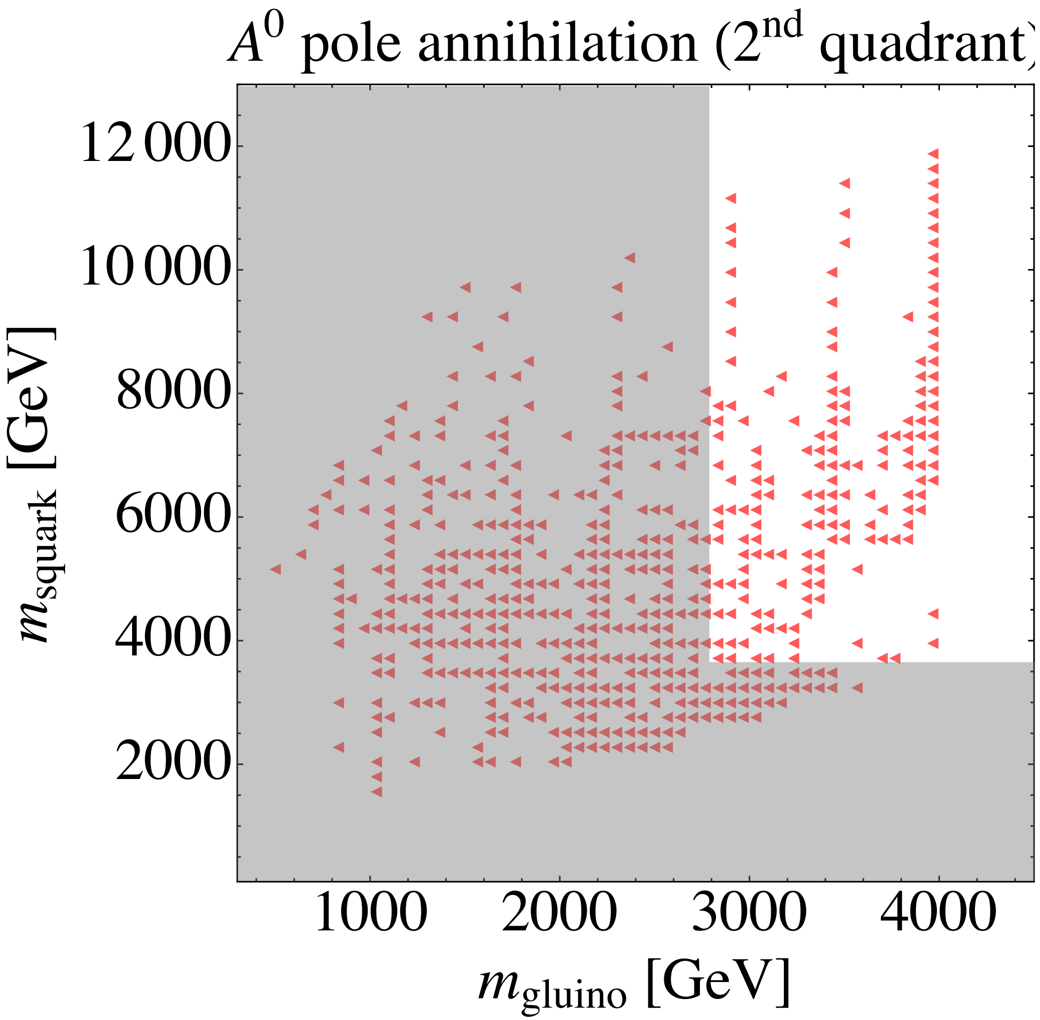
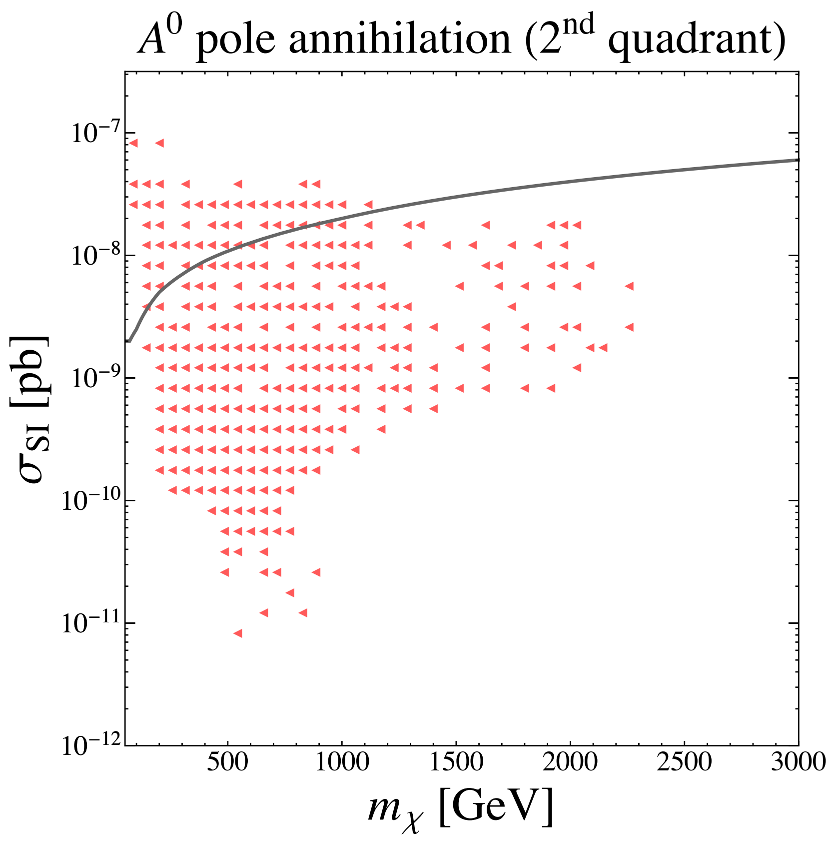
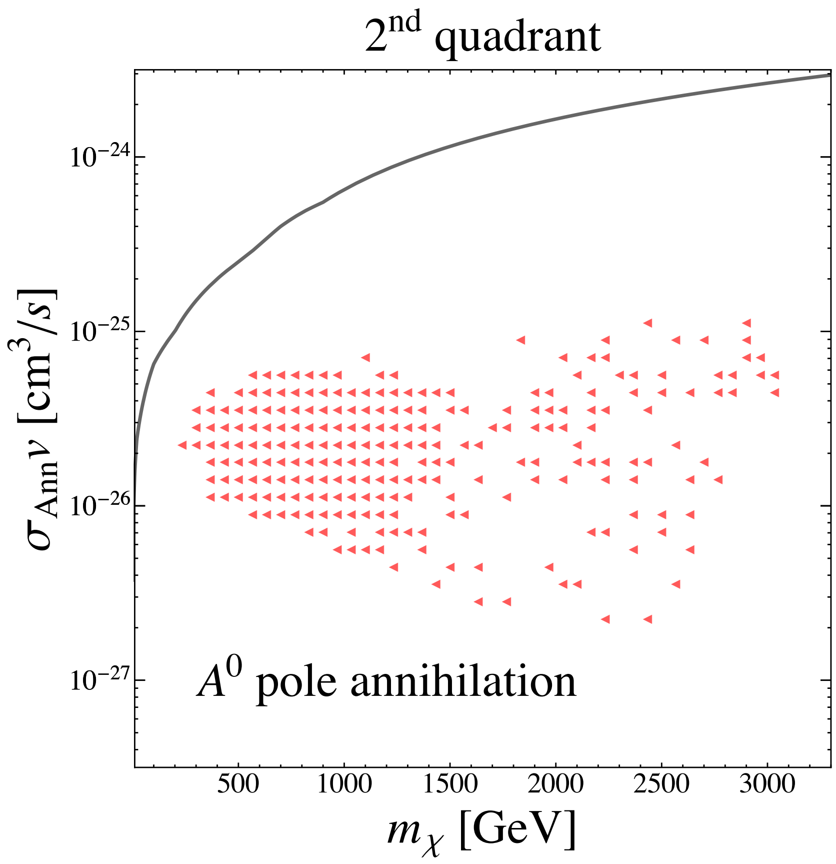
The squark-gluino plane



- 1st quadrant is similar.

Direct & Indirect Detection

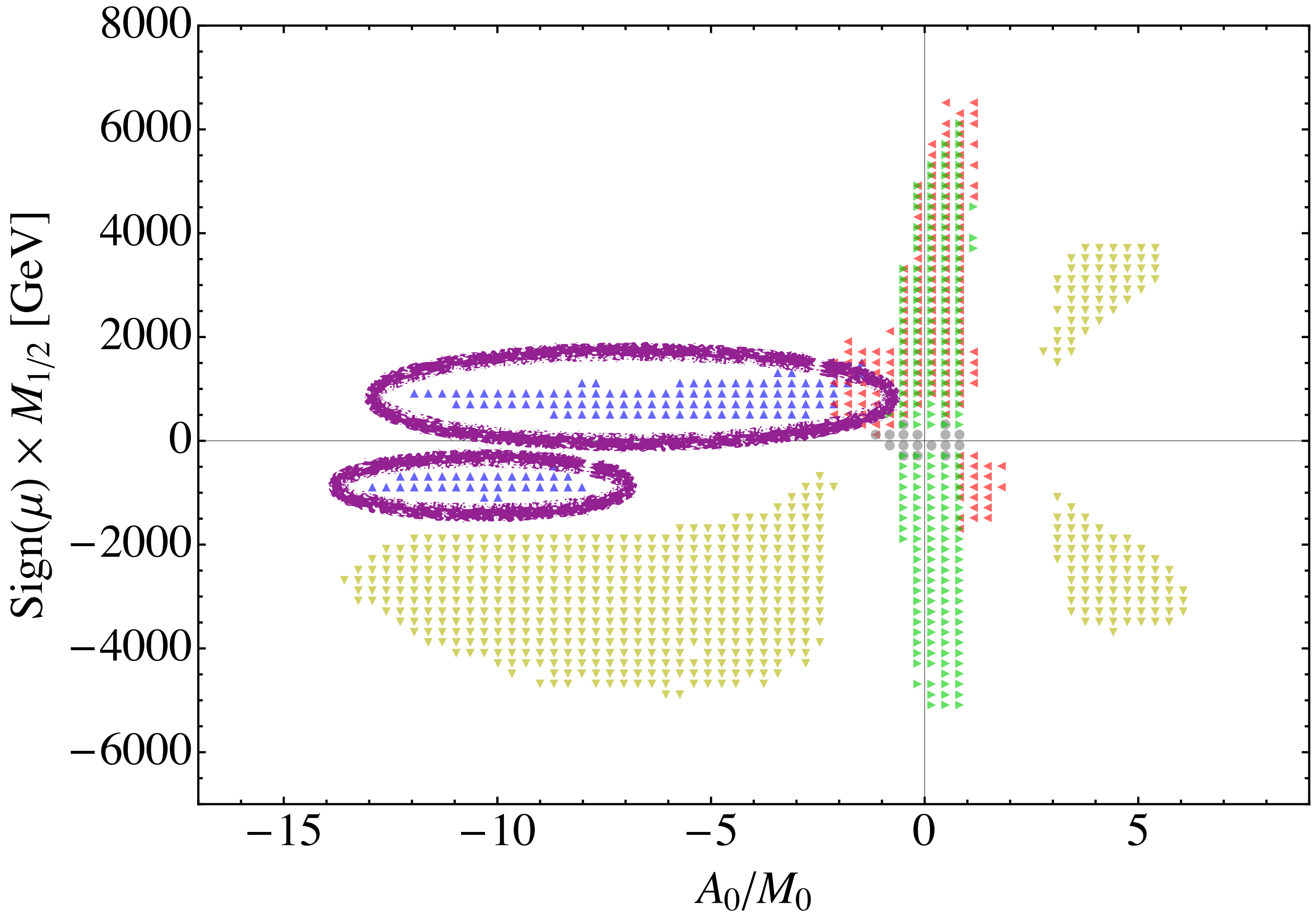




Circumnavigating the CMSSM

Stau coannihilation

Setting sail for stau coannihilation



- light $\widetilde{\chi}^0$
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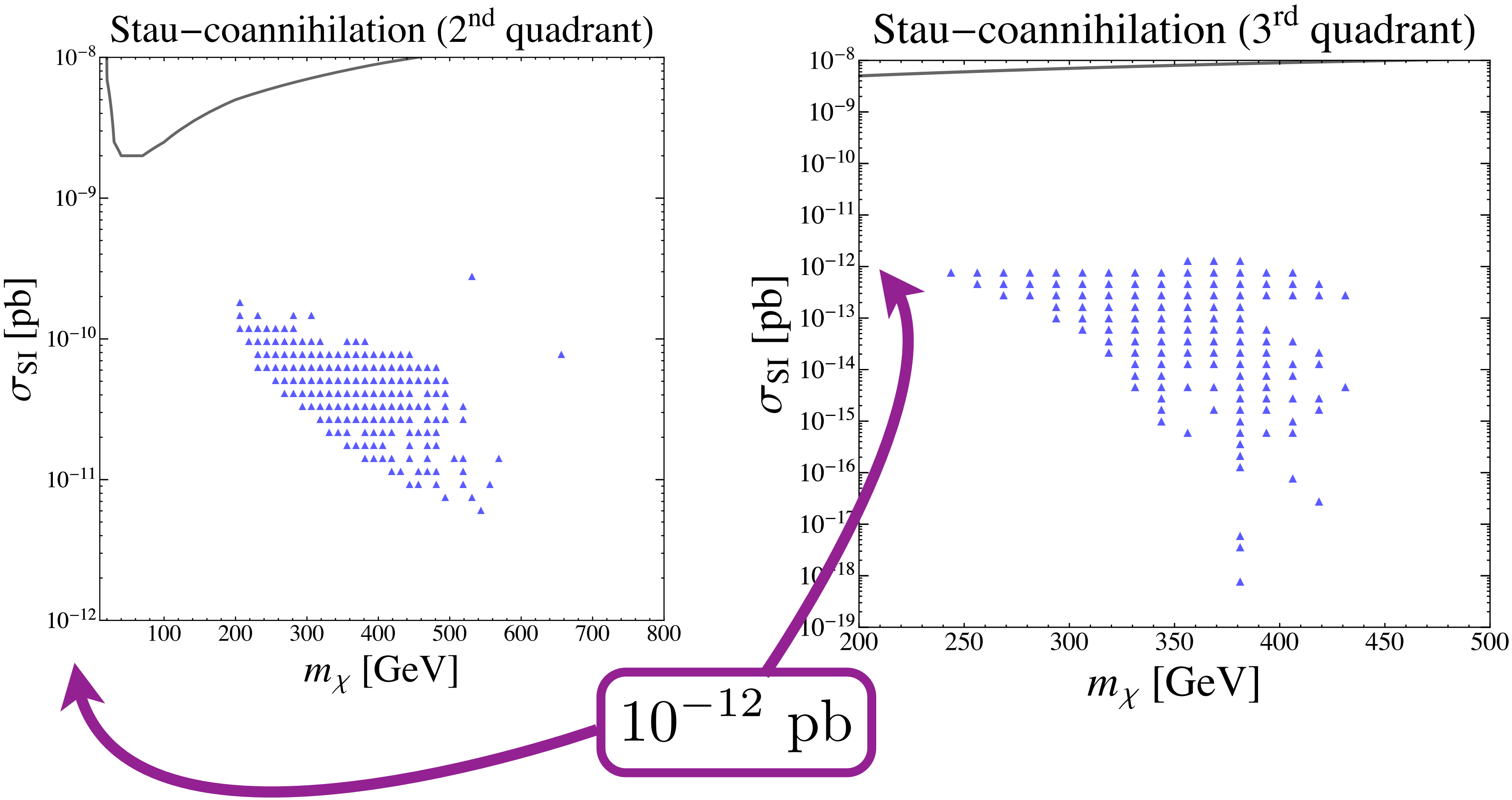
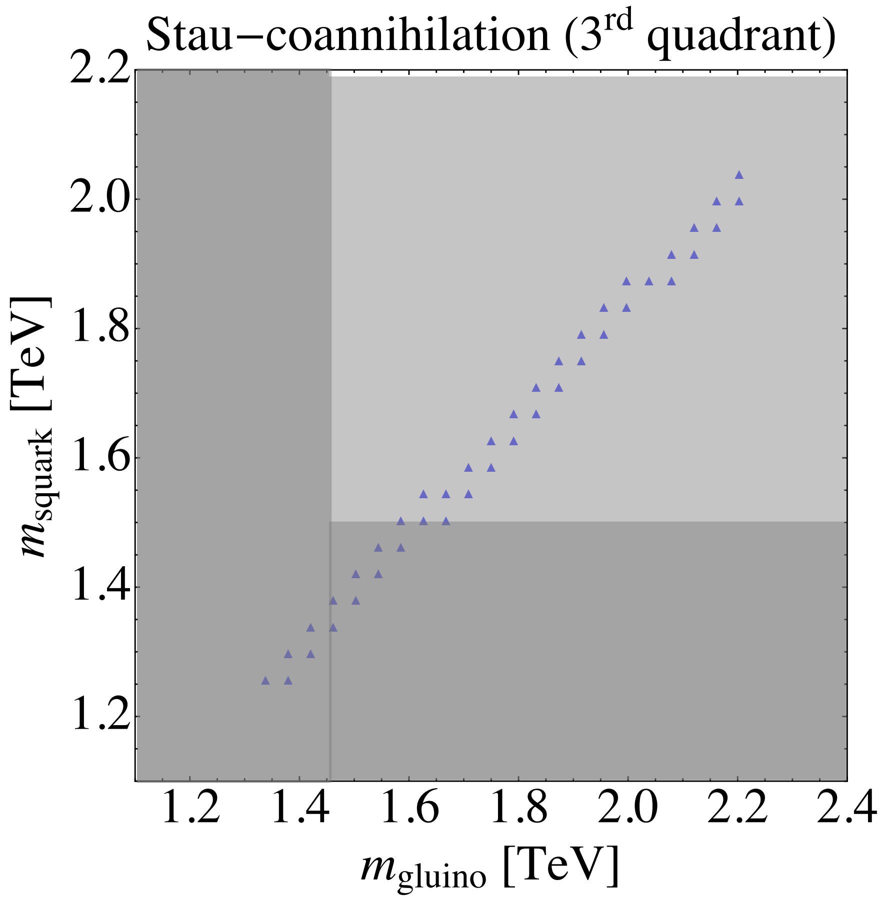
- $200 \text{ GeV} \lesssim M_0 \lesssim 3 \text{ TeV}$
- $5 \lesssim \tan\beta \lesssim 60$

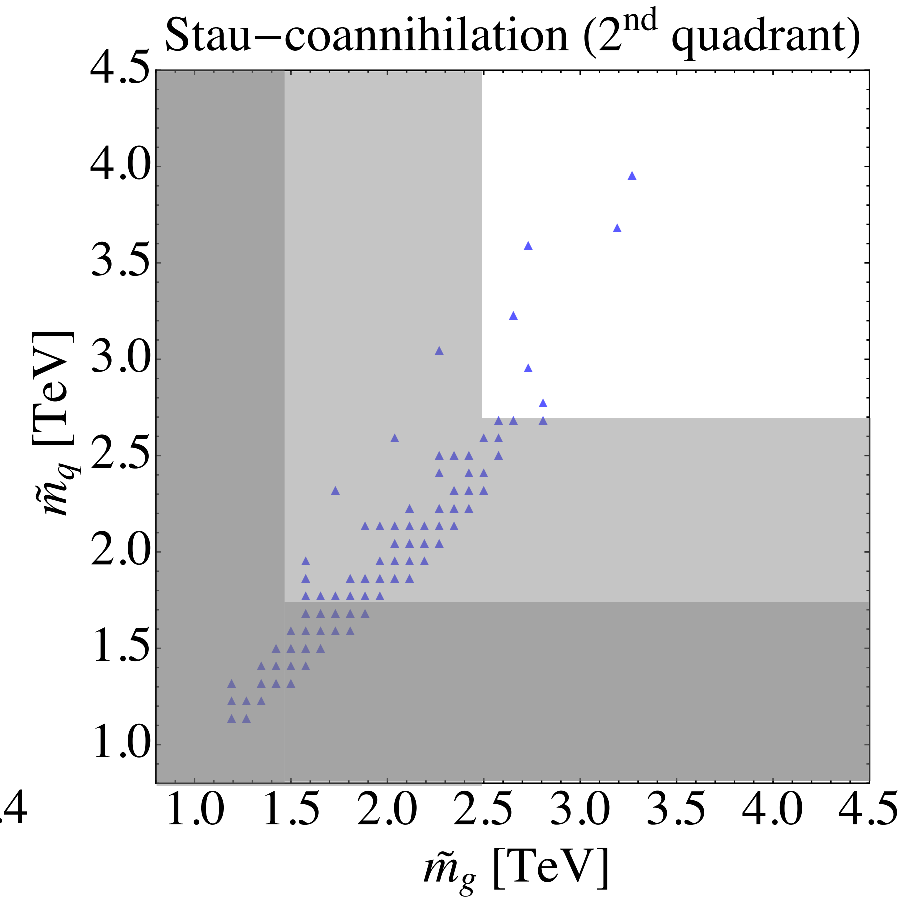
Stau-coann: direct detection



- 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





- Are these spectra discoverable at the LHC?

A stau-coann benchmark (3rd quad)

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

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

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

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

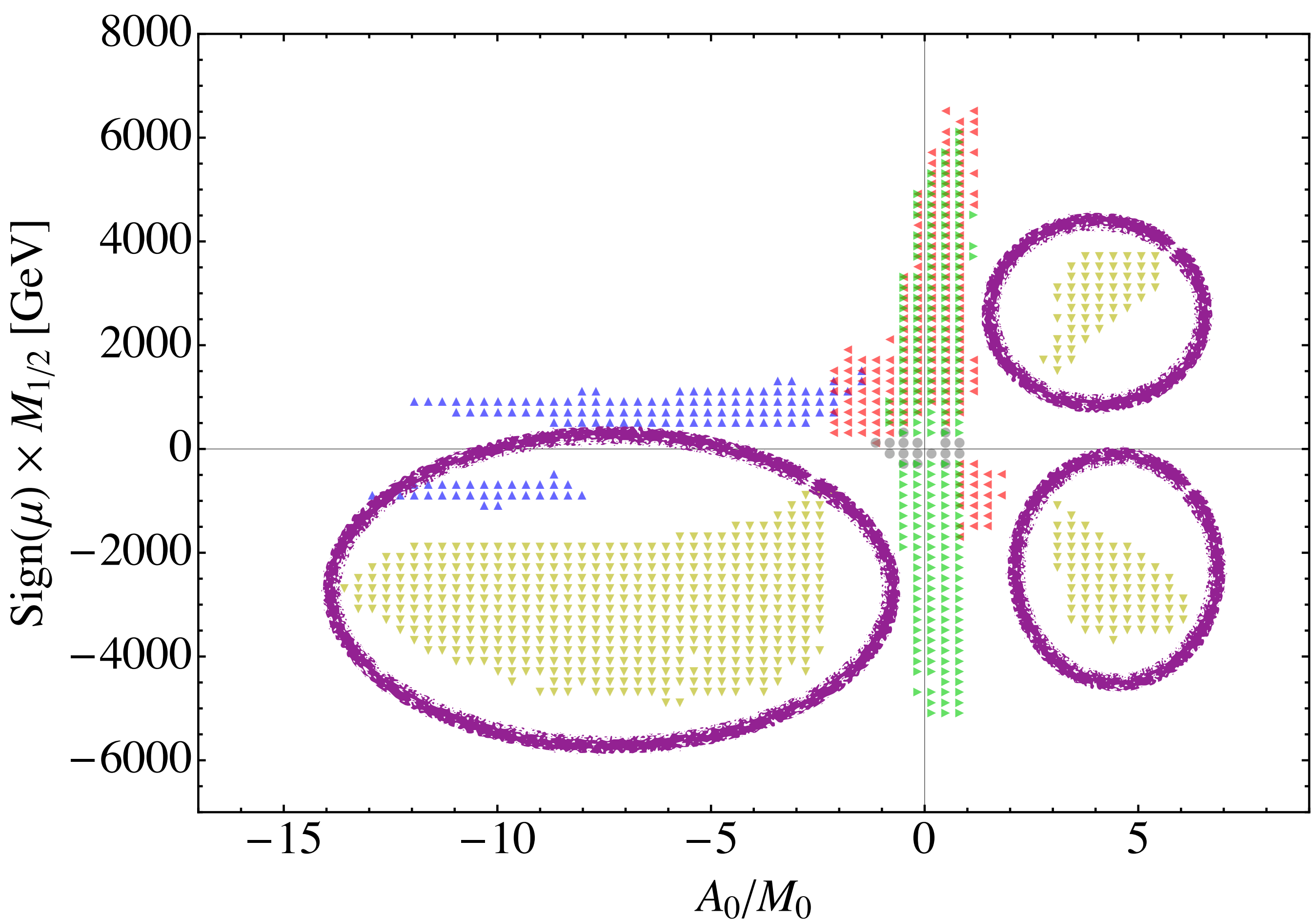
	$\widetilde{q}$	$\widetilde{b}_1$	$\widetilde{b}_2$	$\widetilde{t}_1$	$\widetilde{t}_2$
m [GeV]	1780.8	1529.9	1715.3	1067.2	1562.9

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

CIRCUMNAVIGATING THE CMSSM

Stop coannihilation

Setting sail for stop coannihilation



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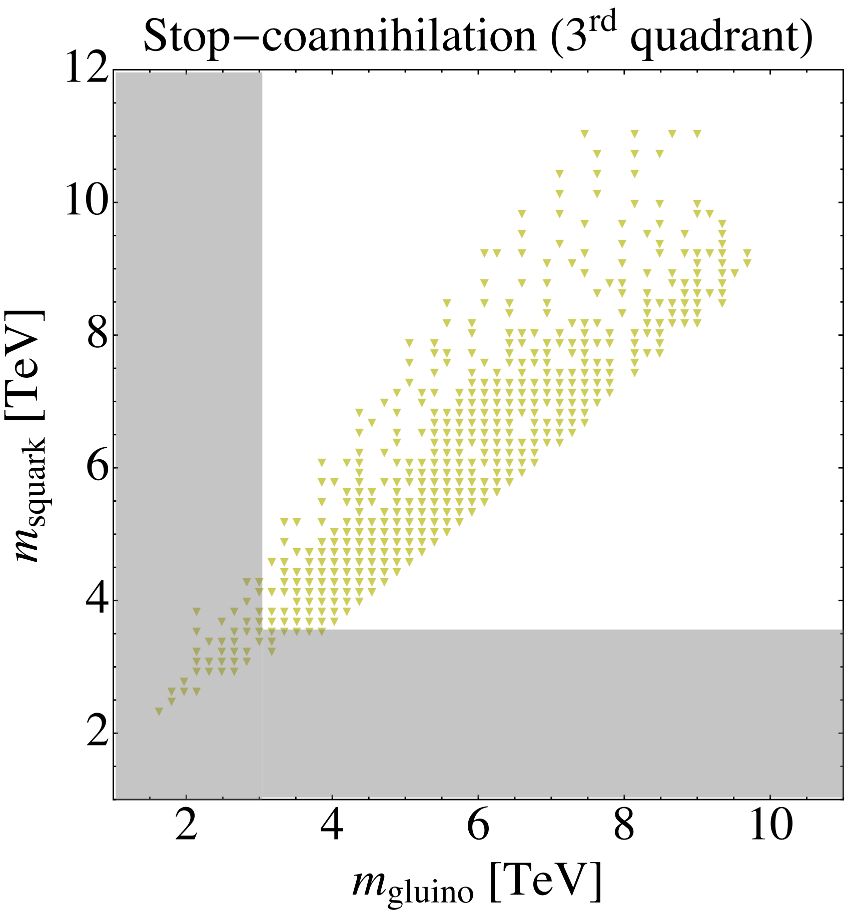
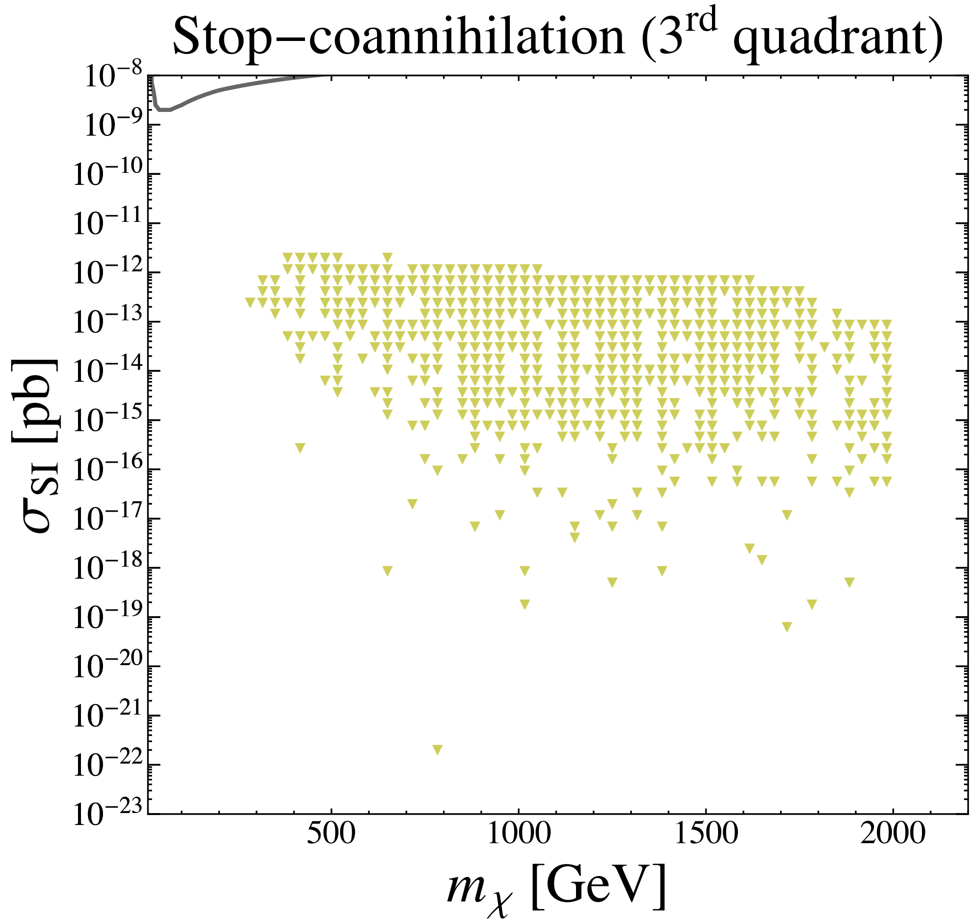
Stop-coannihilation phenomenology





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

A Missing Simplified Model

- A new simplified model appears in stop coannihilation

$\widetilde{m}_g$	$\widetilde{m}_q$	$\widetilde{m}_{t_1}$	$\widetilde{m}_{\tau_1}$	m_χ	$m_{\chi_1^\pm}$
2174.1	3200.3	445.51	2636.4	410.64	790.82

$$\widetilde{t}_1 \to \begin{cases} c\,\chi_1^0 & 69\% \\ b\,(W^+)^*\,\chi_1^0 & 31\% \end{cases}$$

$$\sigma(p\,p \to \widetilde{t}_1\,\widetilde{t}_1) = 1.21\ \text{pb.}$$

$$\widetilde{g} \to \bar{t}\,\widetilde{t}_1 + \text{c.c.} \qquad 100\%$$

$$\widetilde{q}_R \to q\,\widetilde{g} \qquad 100\%$$

$$\widetilde{q}_L \to \begin{cases} q\,\widetilde{g} & 88\% \\ q'\,\chi_1^+ & 8\% \\ q\,\chi_2^0 & 4\% \end{cases}$$

$$\sigma(p\,p \to \widetilde{g}\,\widetilde{g}) = 0.42\ \text{fb}$$

$$\sigma(p\,p \to \widetilde{g}\,\widetilde{q}) = 0.43\ \text{fb.}$$

$$\sigma(p\,p \to t\,t\,\not{E}_T\,X) = 0.41\ \text{fb}$$

$$\sigma(p\,p \to t\,\bar{t}\,\not{E}_T\,X) = 0.42\ \text{fb}$$

Same Sign Tops (boosted)

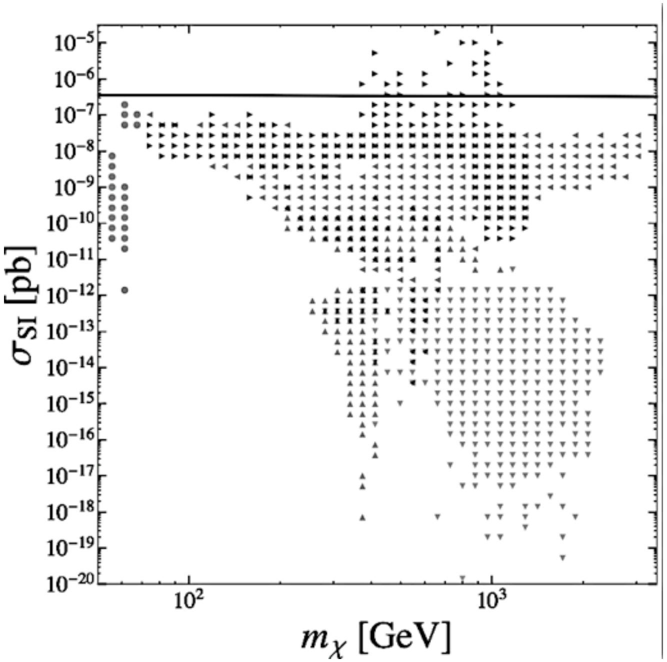
ALMOST HOME

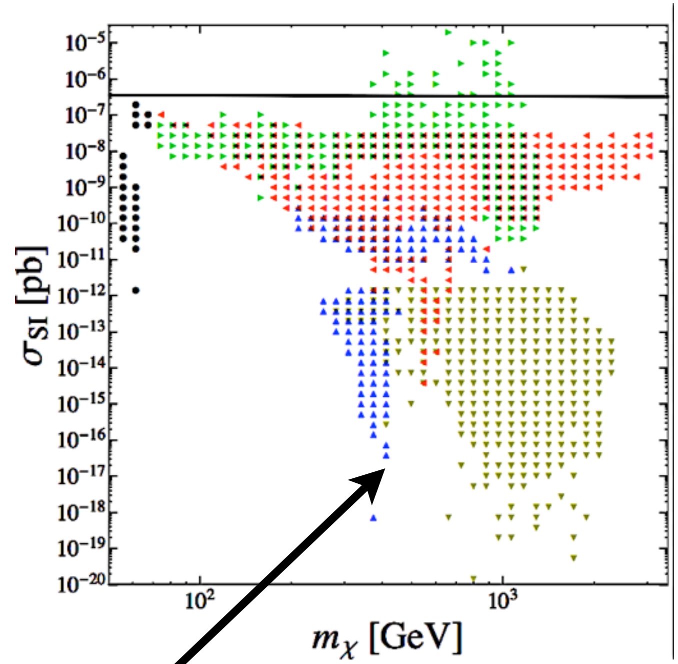
Conclusions

Conclusions

- CMSSM provides tractable ansatz & allows study of full parameter space.
- Provided a map of the CMSSM consistent with Higgs mass & thermal dark matter.
- Demonstrated that parameter space is compact.
- Regions will remain unconstrained after LHC14 and Ton scale spin-independent direct detection?
  - Large portions of the stop coannihilation regions.
- LHC results to be presented as generally as possible so it is easy to interpret bound for non-trivial models
  - More Simplified Model efficiency plots needed.

Colors in the CMSSM





HERE BE DRAGONS