Here Be Dragons:

The Unexplored Continents of the CMSSM

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(SLAC)

with Jay Wacker

arXiv:1305.2914

GGI workshop: Beyond the Standard Model after the first run of the LHC
July 5, 2013

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]

- “Consistent” with the MSSM (and its extensions).

$$m_h^2 \simeq m_Z^2 \cos^2 2\,\beta + \frac{3\,g^2\,m_t^4}{8\,\pi^2\,m_W^2}\left[\log\left(\frac{\widetilde{m}_{t_1}\,\widetilde{m}_{t_2}}{m_t^2}\right) + \frac{A_t^2}{\widetilde{m}_{t_1}\,\widetilde{m}_{t_2}}\left(1 - \frac{A_t^2}{12\,\widetilde{m}_{t_1}\,\widetilde{m}_{t_2}}\right)\right]$$

- Stops from O(100 GeV) to O(100 TeV) ⇨ 4x heavier than pre discovery:

$$m_{h'} - m_h \simeq \frac{3\,g^2\,m_t^4}{16\,\pi^2\,m_h\,m_W^2}\log\frac{\widetilde{m}_{t_1'}\,\widetilde{m}_{t_2'}}{\widetilde{m}_{t_1}\,\widetilde{m}_{t_2}} \quad \Longrightarrow \quad \widetilde{m}_{t_1'}\,\widetilde{m}_{t_2'} \simeq \widetilde{m}_{t_1}\,\widetilde{m}_{t_2}\,2^{\frac{\Delta m_h}{5.6\text{ GeV}}}$$

- 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 for specific signature. Parameter space is tractable; only a few masses and branching ratios.
    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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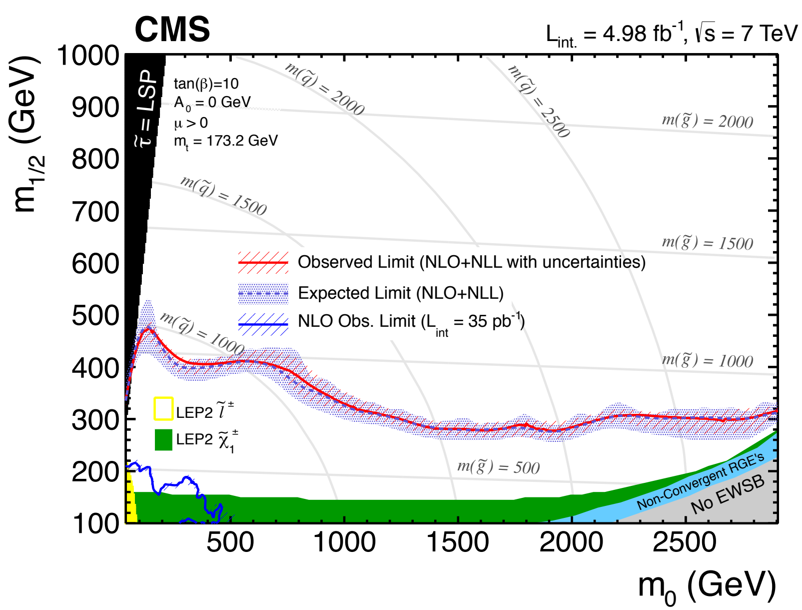
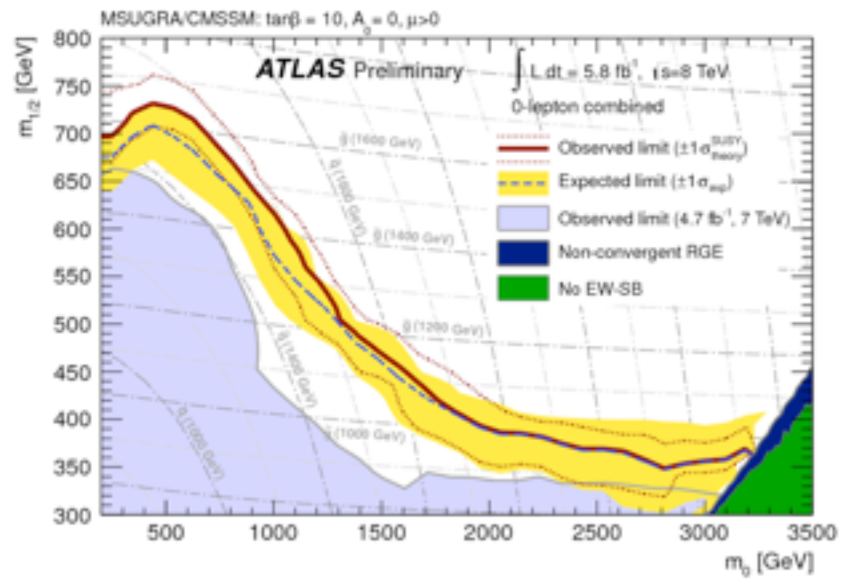
  - The ratio of the Higgs vevs: $\tan\beta$ (traded for the B_μ term).
- Parameters are evolved to weak scale using RGEs.
- μ-term is determined by requiring $m_Z = 91\ \mathrm{GeV}$.
- 19 coupled RGEs integrated over 32 e-folds: relation between the inputs & low energy parameters is highly non-linear.

State of the Art: The LHC

- Both ATLAS and CMS put limits on the CMSSM:



CMS [arXiv:1205.6615]



ATLAS-CONF-2012-109

- Exclusions for a region of the $M_{1/2}$ versus M_0 plane at a fixed A_0 and $\tan\beta$.

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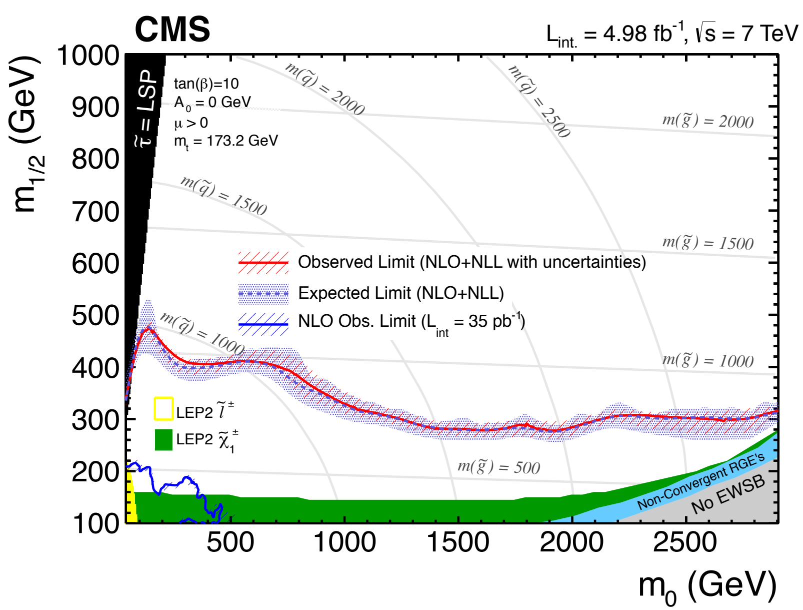

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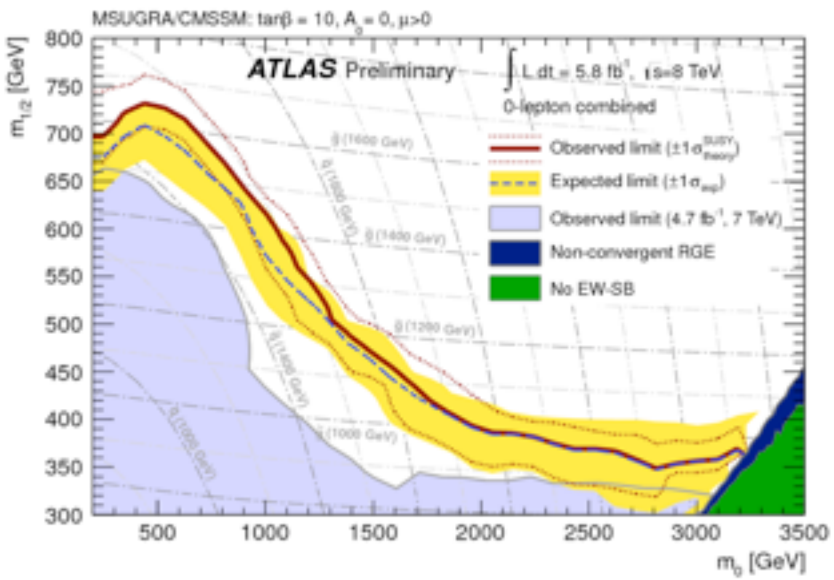

ATLAS-CONF-2012-109

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

State of the Art: Theory

- Many groups approach CMSSM (and other models) from statistical point of view.

  Baltz, Gondolo [arXiv:hep-ph/0407039]; Allanach, Lester [arXiv:hep-ph/0507283];
  de Austri, Trotta, Roszkowski [arXiv:hep-ph/0602028];
  Akrami, Scott, Edsjo, Conrad, Bergstrom [arXiv:0910.3950]; Buchmueller et. al [arXiv:0907.5568]

- Techniques are very powerful.
- Allow inclusion of many experimental inputs (with errors).
- Assign likelihood to all points in parameter space.
- Not obvious what drives boundaries.
  - For example: claims that stop coannihilation largely excluded.

    Allanach, Lester [arXiv:hep-ph/0507283]

Classification

- 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

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

- 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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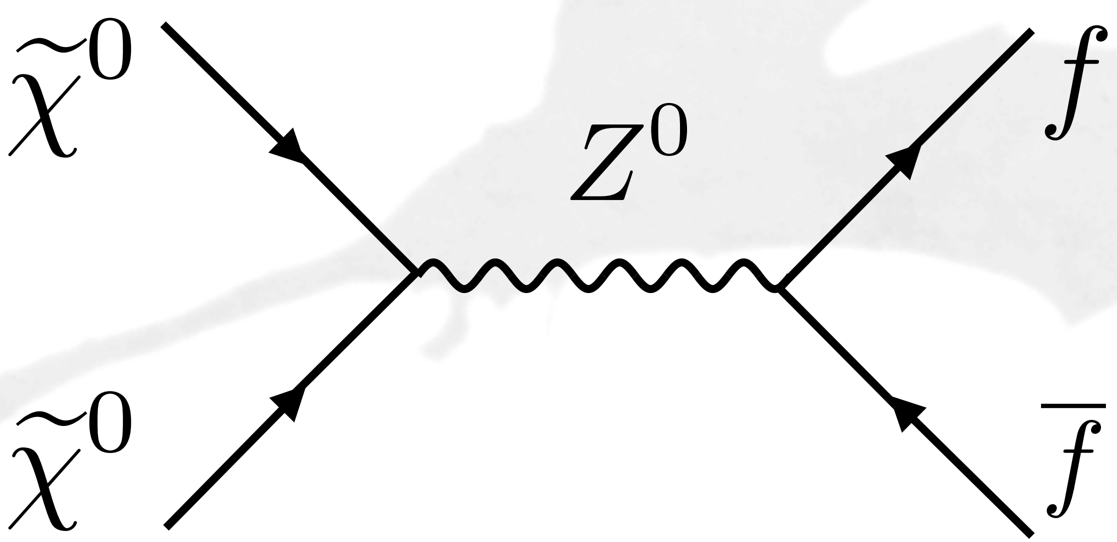

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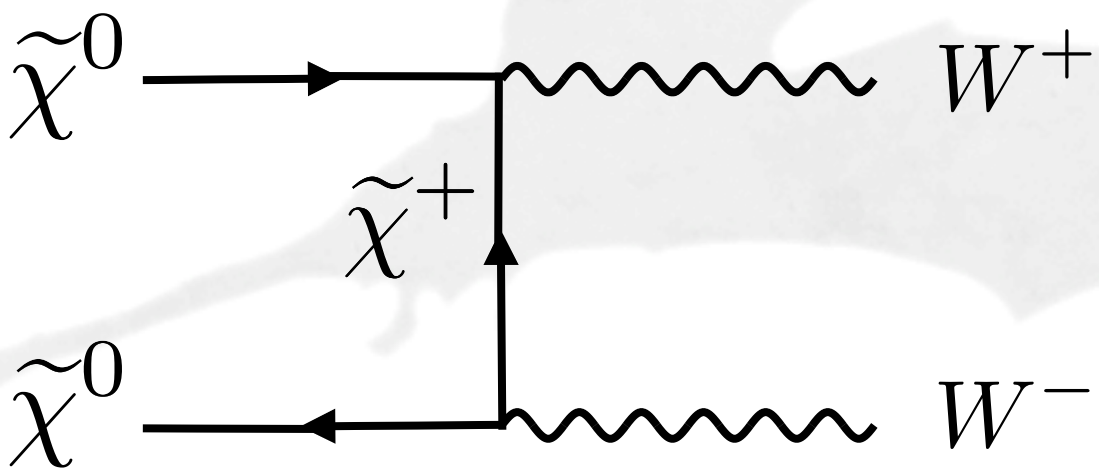

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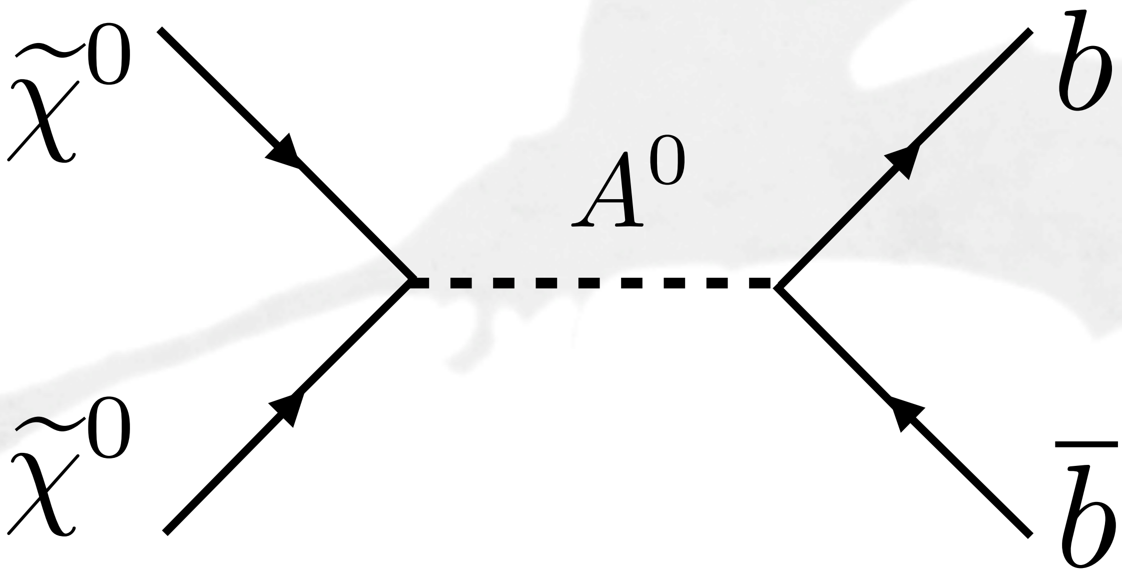

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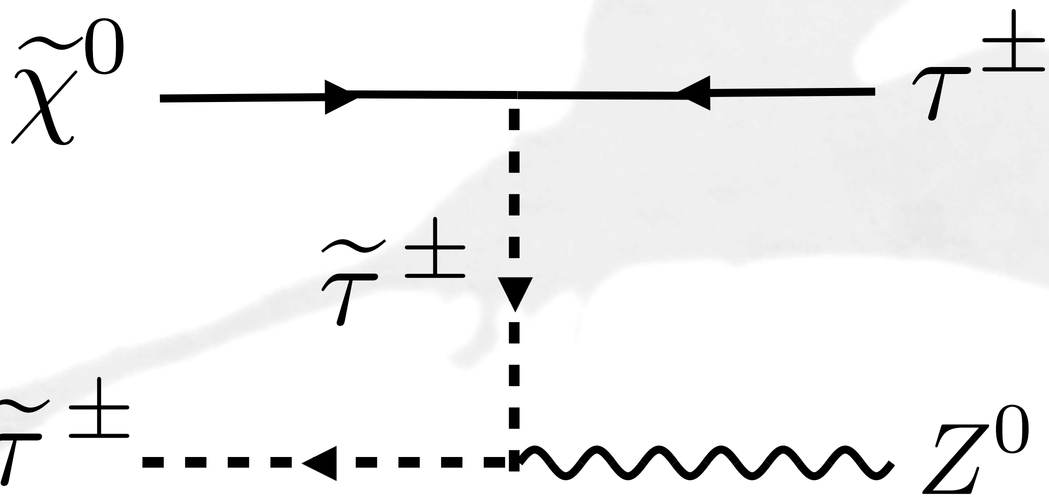

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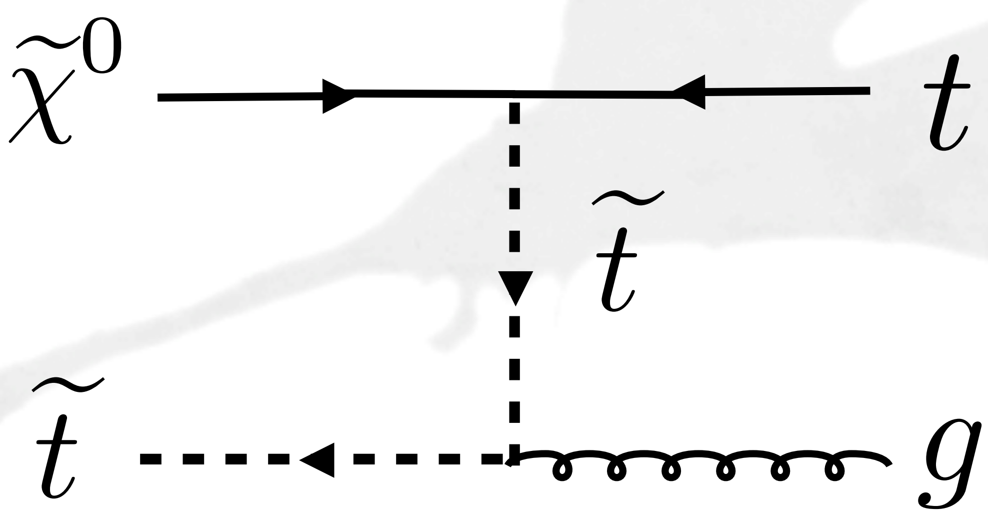

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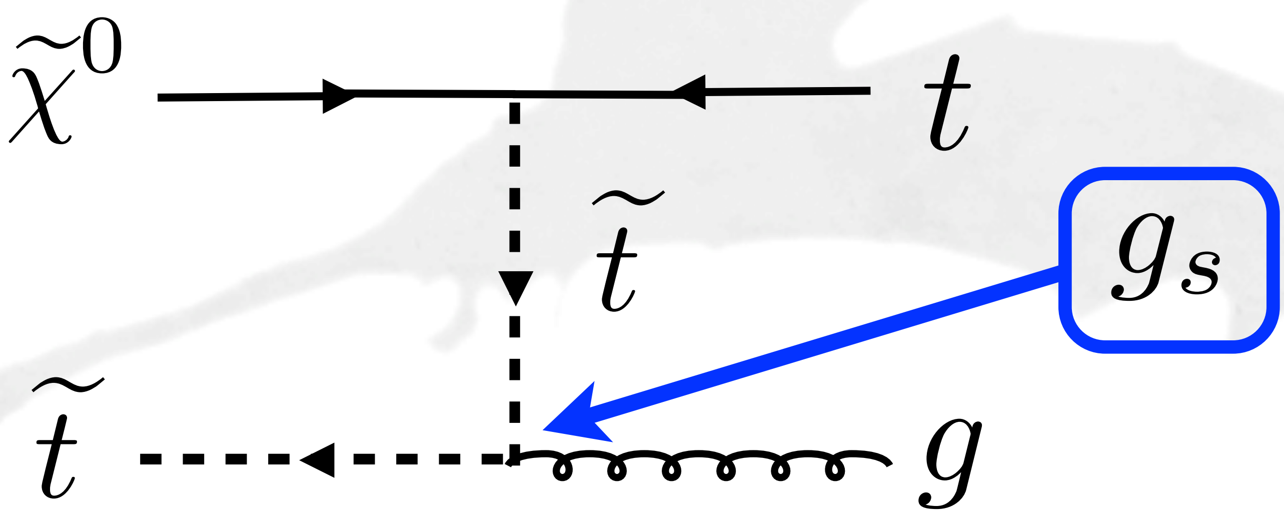

CMSSM Cartography

The CMSSM is Compact

- Higgs mass: $m_h = 125\ \mathrm{GeV} \implies M_0$ bounded.
- Relic density: not overclosing $\implies m_\chi$ bounded.
- Lifetime of our vacuum longer than 14 Gyr $\implies A_0$ bounded.
- Perturbativity of bottom Yukawa coupling $\implies \tan\beta$ bounded.

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Consequence

The *entire* CMSSM is discoverable by human-buildable experiments

Tools

- SoftSUSY v3.3.7 computes the low energy spectrum from the CMSSM inputs. Allanach [arXiv:hep-ph/0104145]
  - The 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.
- 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]
- Prospino v2.1 computes NLO cross sections.

  http://www.thphys.uni-heidelberg.de/~plehn/index.php?show=prospino&visible=tools

Constraints

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

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

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

- Require the relic density in the range:

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

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

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

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

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

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

Scan Strategy

- Start with seed random scan:

$$0 \leq M_0 \leq 10 \text{ TeV}; \quad 0 \leq M_{\frac{1}{2}} \leq 10 \text{ TeV};$$

$$-6 \leq A_0/m_0 \leq 6; \quad 1.5 \leq \tan\beta \leq 50; \quad \text{sign}(\mu) = \pm 1,$$

- Implies no island missed (with 95% confidence) larger than

$$\Delta M_0 \times \Delta M_{\frac{1}{2}} \times \Delta \frac{A_0}{M_0} \times \Delta \tan \quad \leq 0.036 \text{ TeV}^2.$$

- Fill in with targeted scans.

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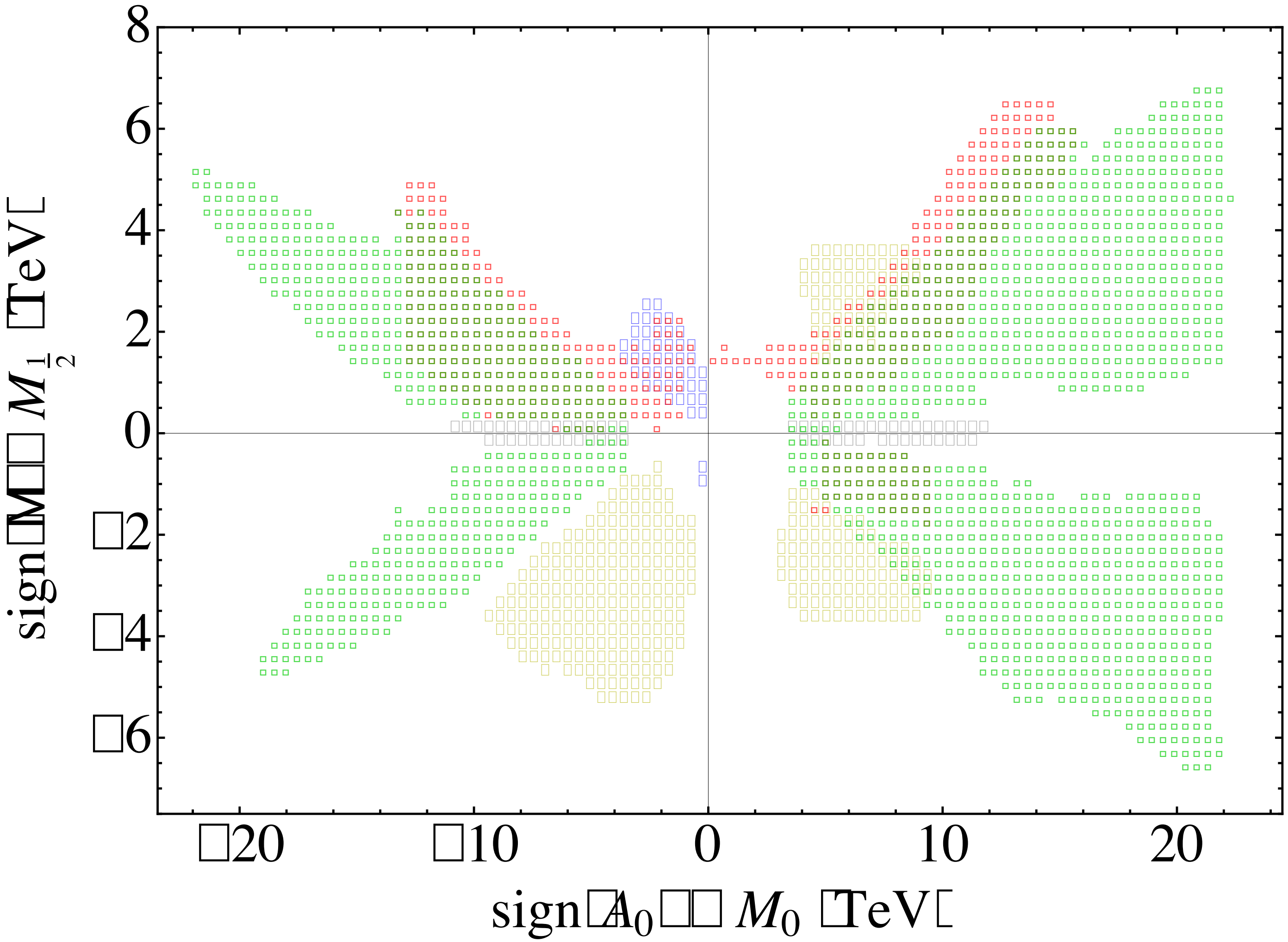
- Fill in with targeted scans.
- Given this seed data:
  - Choose a 2-d slice.
  - Make a grid.
  - Find any point on the grid that has > 1 filled neighbor.
  - Scan in the orthogonal directions using range determined by neighbors.

Charting the CMSSM



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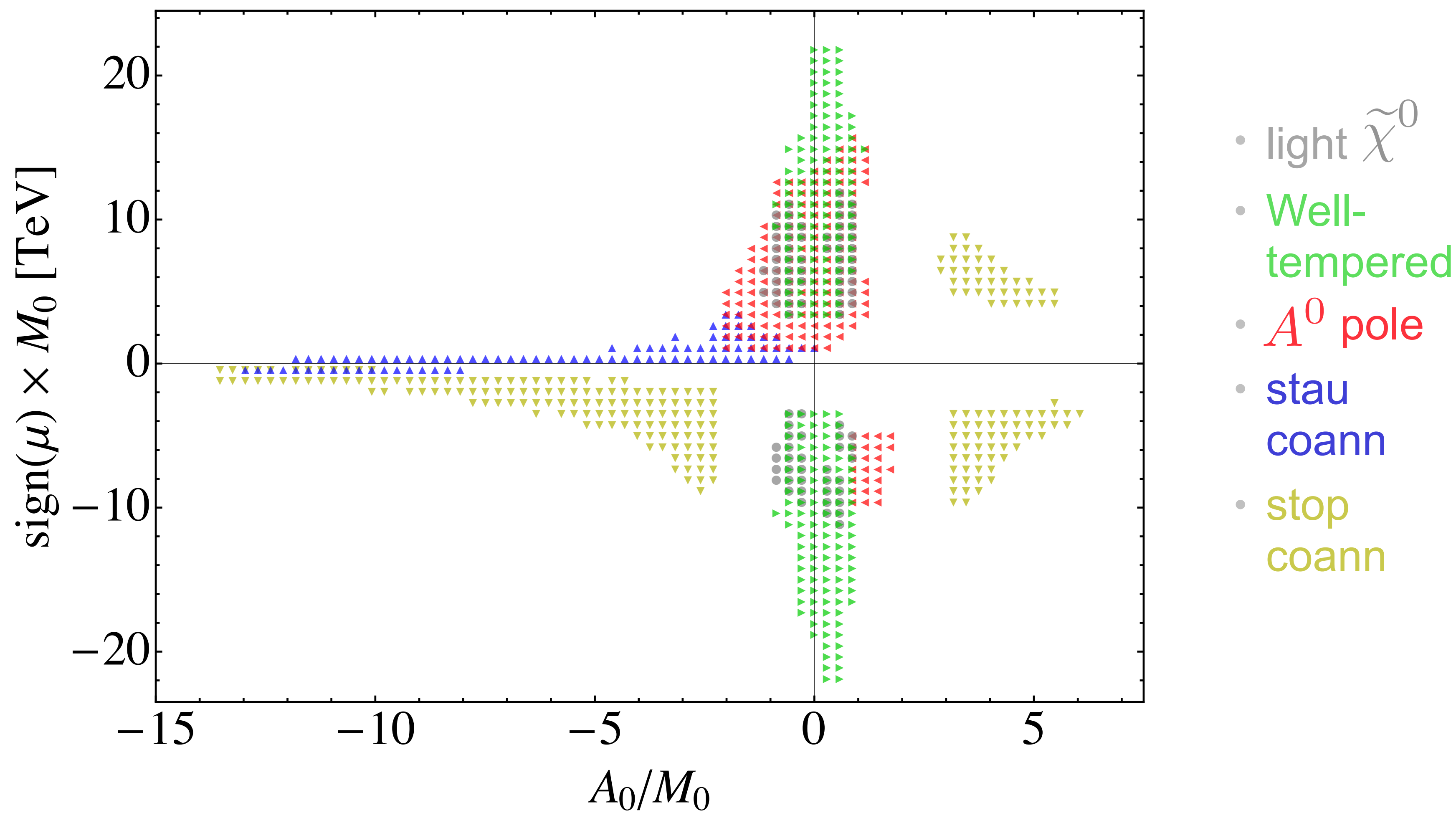

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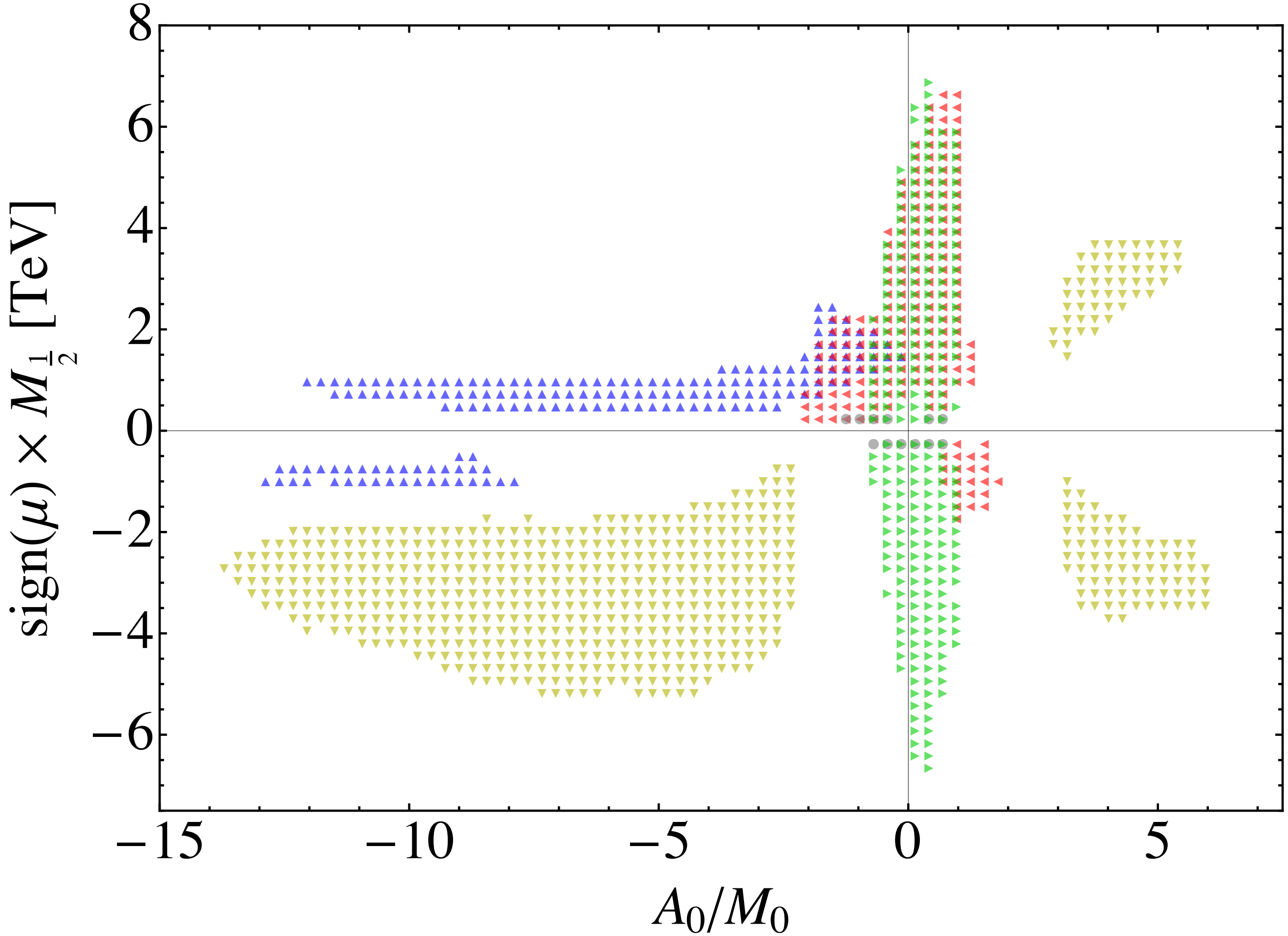

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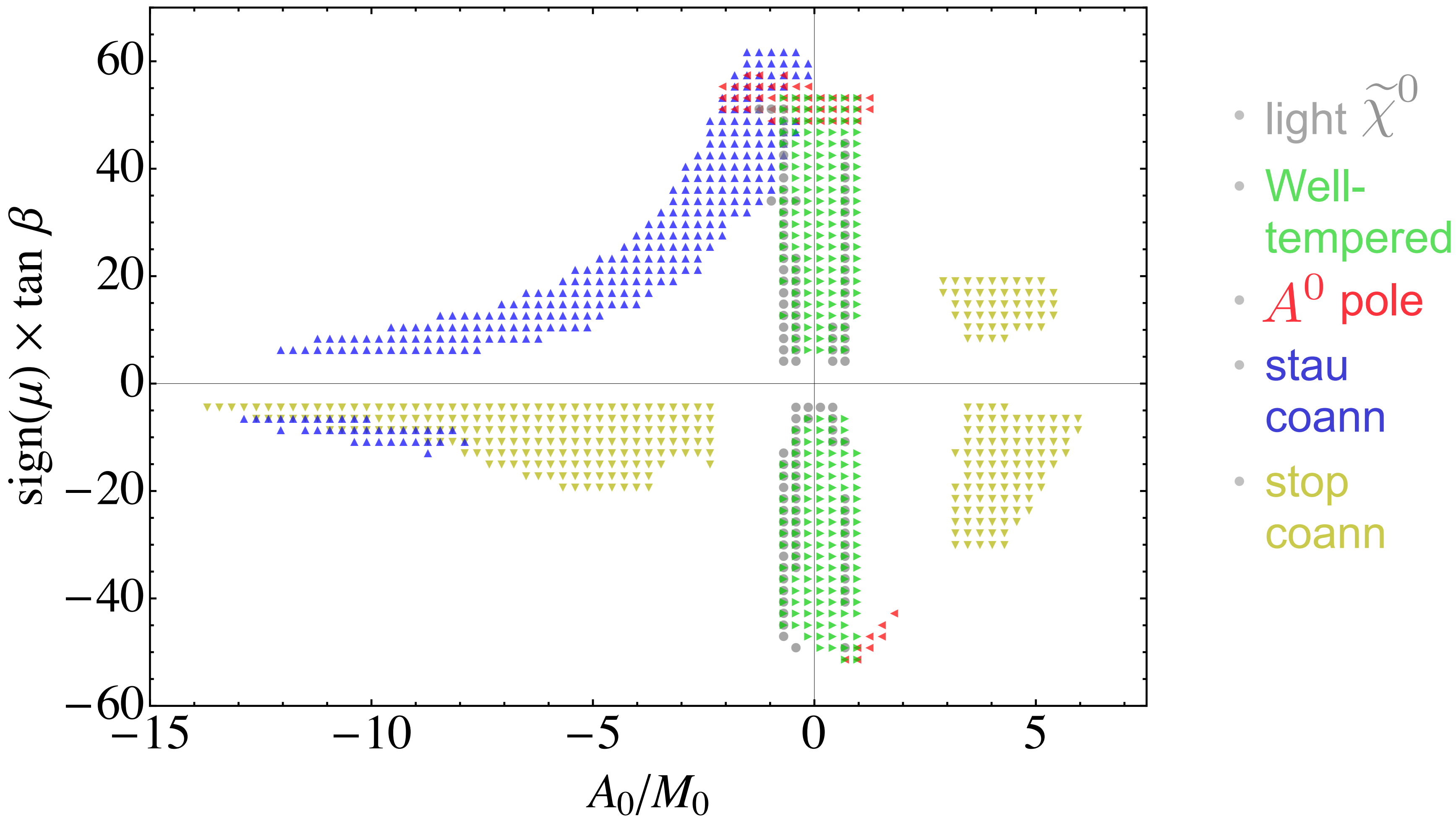


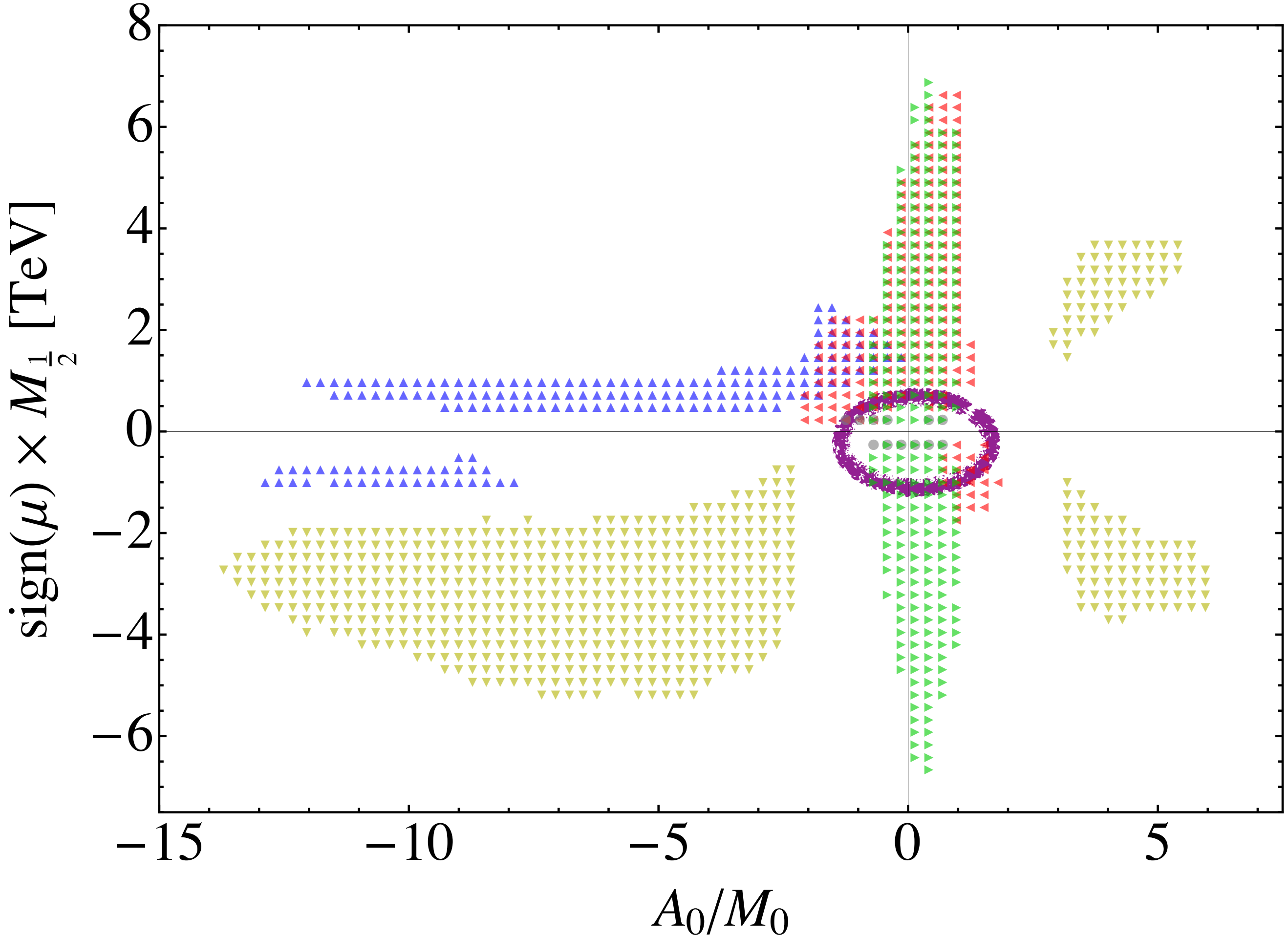
Lessons

- The CMSSM is compact.
- Size of the allowed parameter space is huge!
- Classification scheme useful for organizing the CMSSM.
- Range of possible low energy signatures.
- The rest of this talk devoted to exploring them.

CIRCUMNAVIGATING THE CMSSM

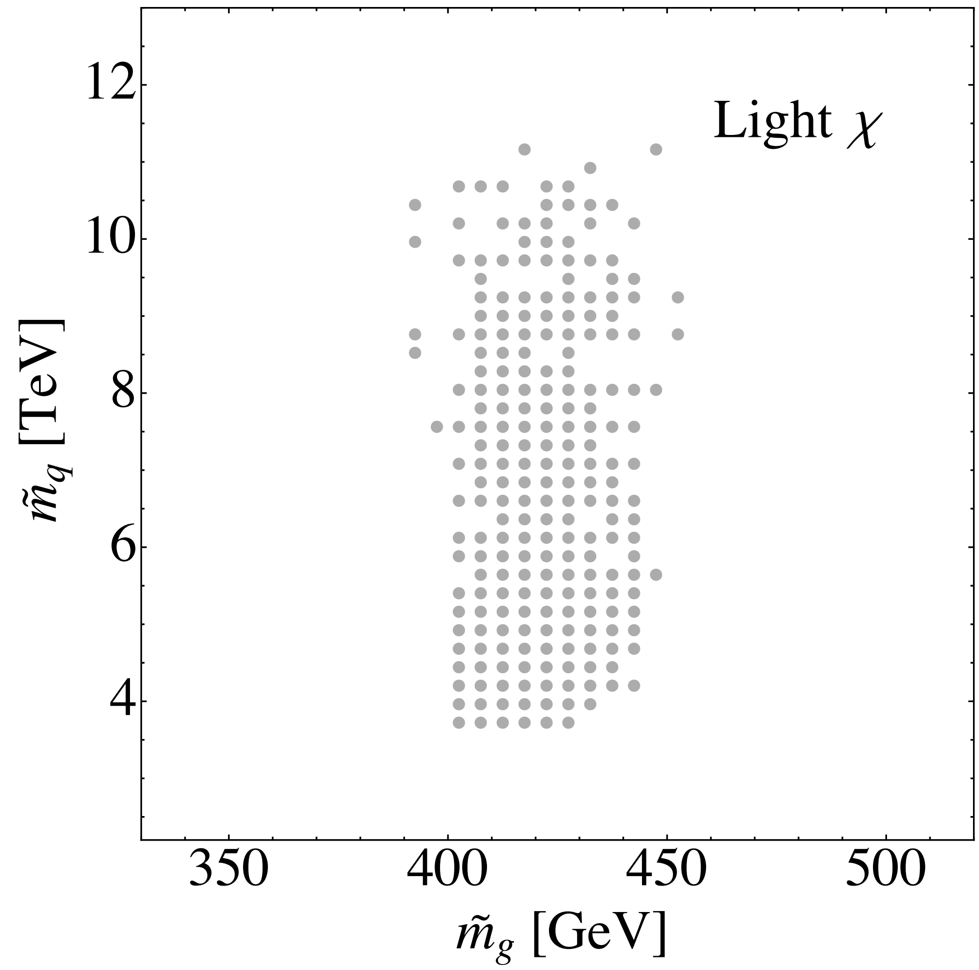
Light $\widetilde{\chi}^0$

Setting sail for light $\chi \Longleftrightarrow m_\chi < 70$ GeV



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

Light χ implies light gluinos



Has the LHC excluded this region?

- A benchmark:

M_0	$M_{1/2}$	A_0	β	μ	$\|\mu\|$	B_μ
						$. \quad \times \quad {}^{8}$

  - Squarks and sleptons heavier than 5 TeV.
  - Gluino is 409 GeV; LSP is 57 GeV.

$$\tilde{g} \to \begin{cases} \tilde{\ } \; q\,\bar{q} \\ \tilde{\chi}^{\pm}\, q\, q \to \tilde{\ } \; W^{\pm}\, q\, \bar{q}' \\ \tilde{\chi} \;\; q\,\bar{q} \to \tilde{\ } \quad q\,\bar{q} \end{cases}$$

- ATLAS recast of jets + MET + no leptons for

ATLAS [arXiv:1208.0949]

$$\tilde{g}\,\tilde{g} \to W^{\pm}\, W^{\pm}\, q\,\bar{q}\, q\,\bar{q}\, \chi\, \chi$$

  - Limit: $\sigma \times \mathrm{BR} \lesssim 1\ \mathrm{pb}$
  - Prediction: $\sigma \times \mathrm{BR} = 1.8\ \mathrm{pb}$

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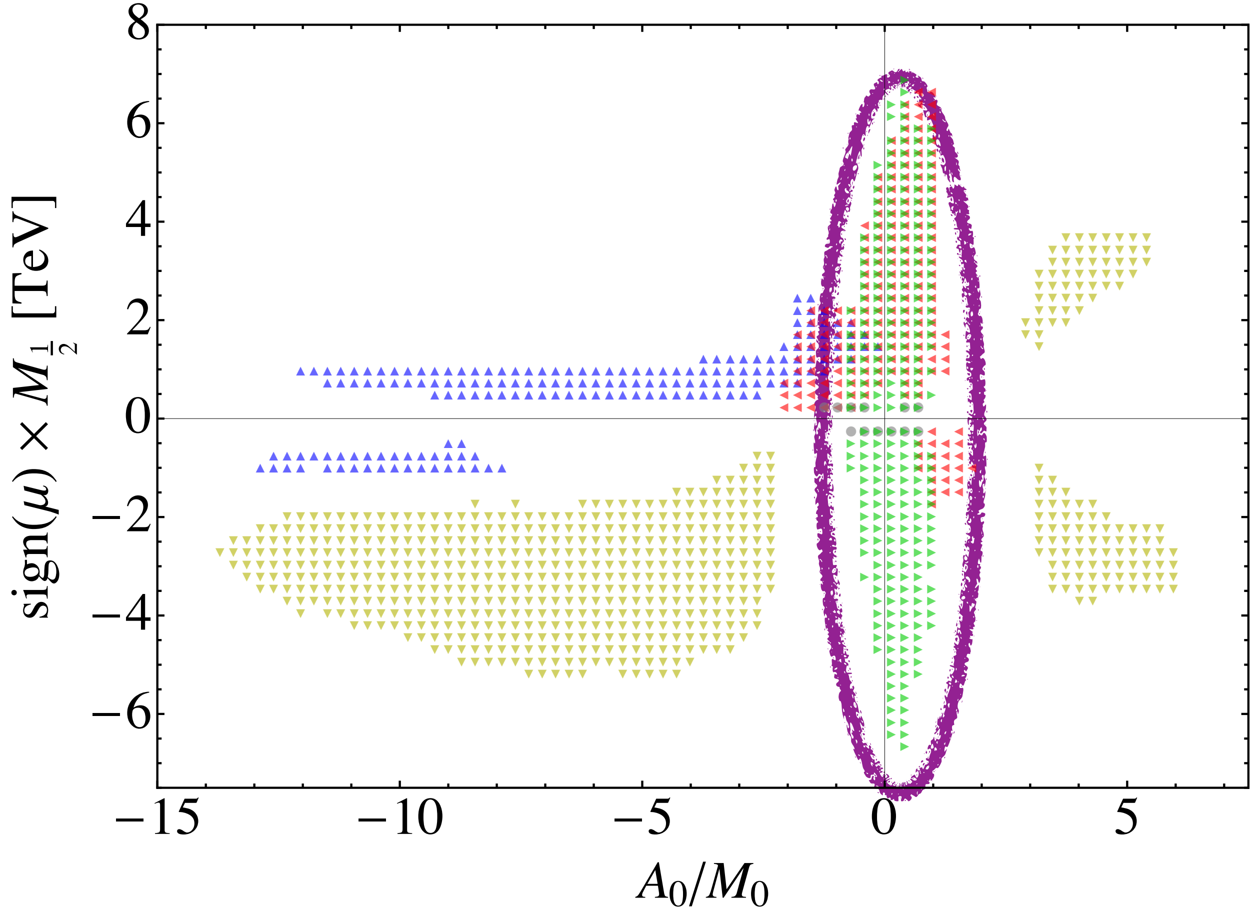
Excluded!

Circumnavigating the CMSSM

Well-tempered

Setting sail for well-tempered



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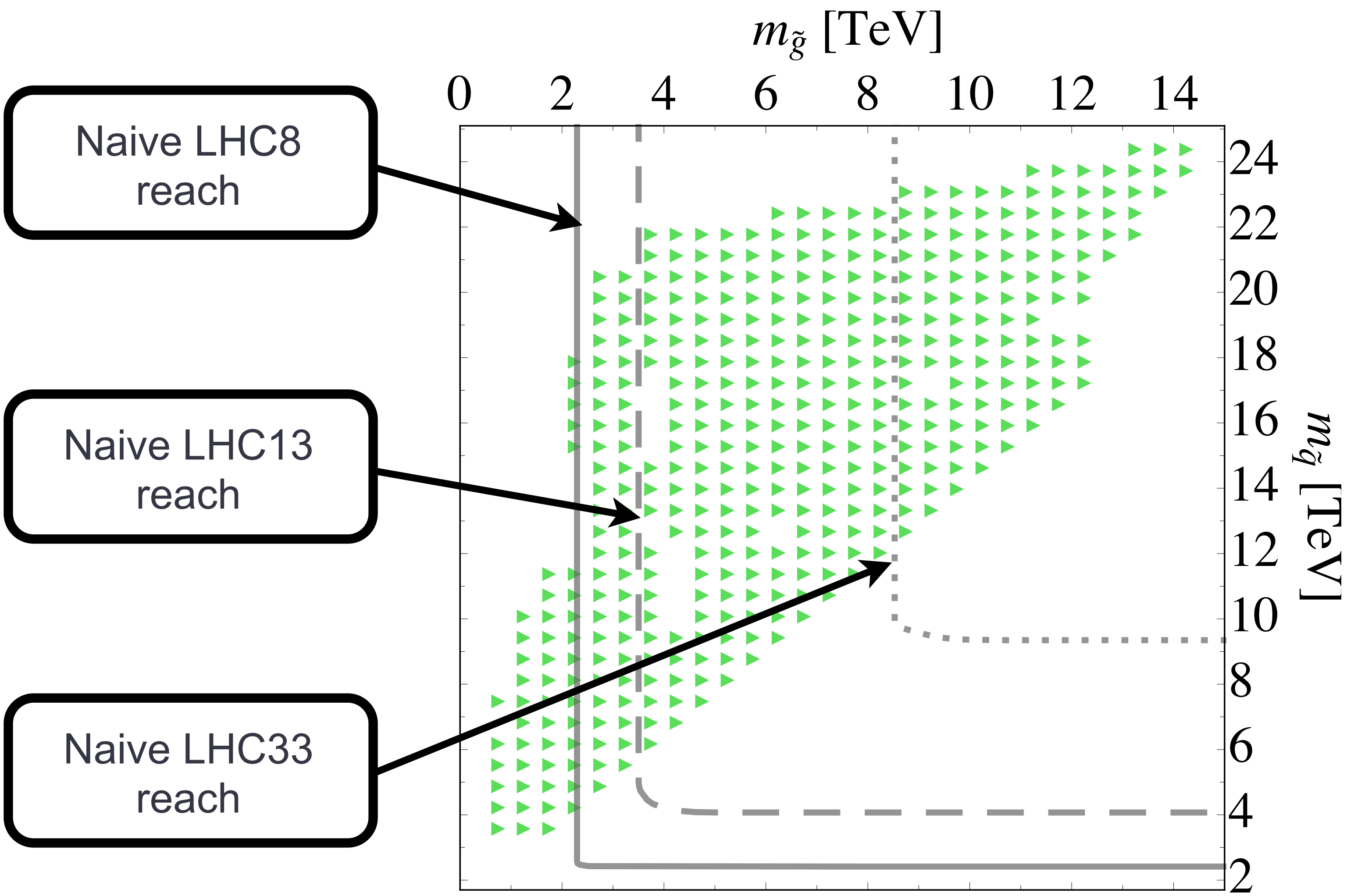
- $4 \text{ TeV} \lesssim M_0 \lesssim 20 \text{ TeV}$
- $5 \lesssim \tan\beta \lesssim 50$

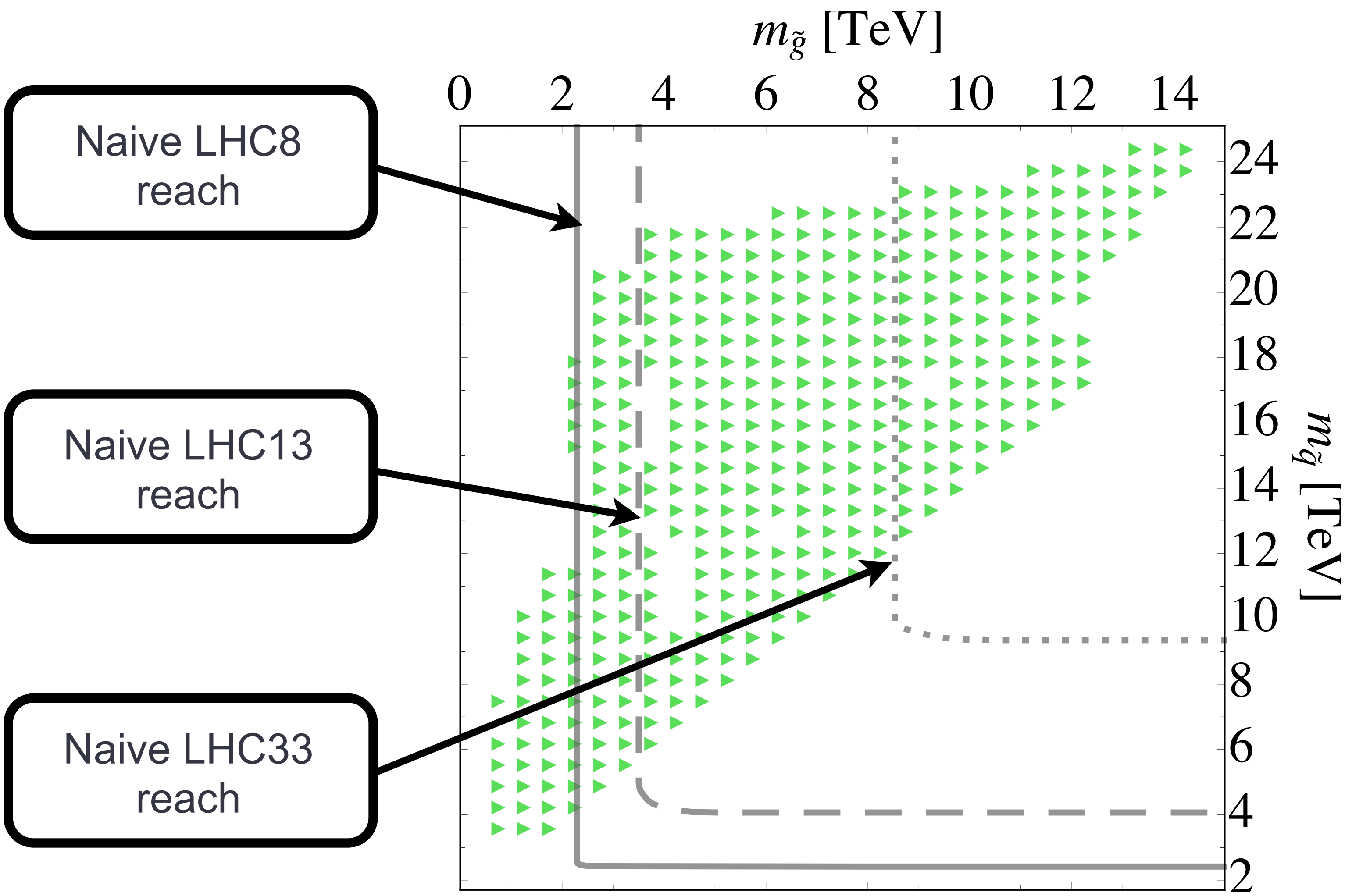
What about the LHC?

1st quadrant



What about the LHC?

1st quadrant



- LHC13 will have little impact on the well-tempered spectra.

Well-tempered LHC benchmark

Input parameters						
M_0	$M_{\frac{1}{2}}$	A_0	$\tan\beta$	sign(μ)	$\lvert\mu\rvert$	$\sqrt{B_\mu}$
4103.76	525.385	905.88	13.6663	-1	292.034	10805.

- Gluinos: $m_{\widetilde{g}} = 1.3 \text{ TeV} \Longrightarrow \sigma(p\,p \to \widetilde{g}\,\widetilde{g}) = 30 \text{ fb.}$
  - $\widetilde{g} \to q\,\bar{q}'\,X \quad 11.5\%$

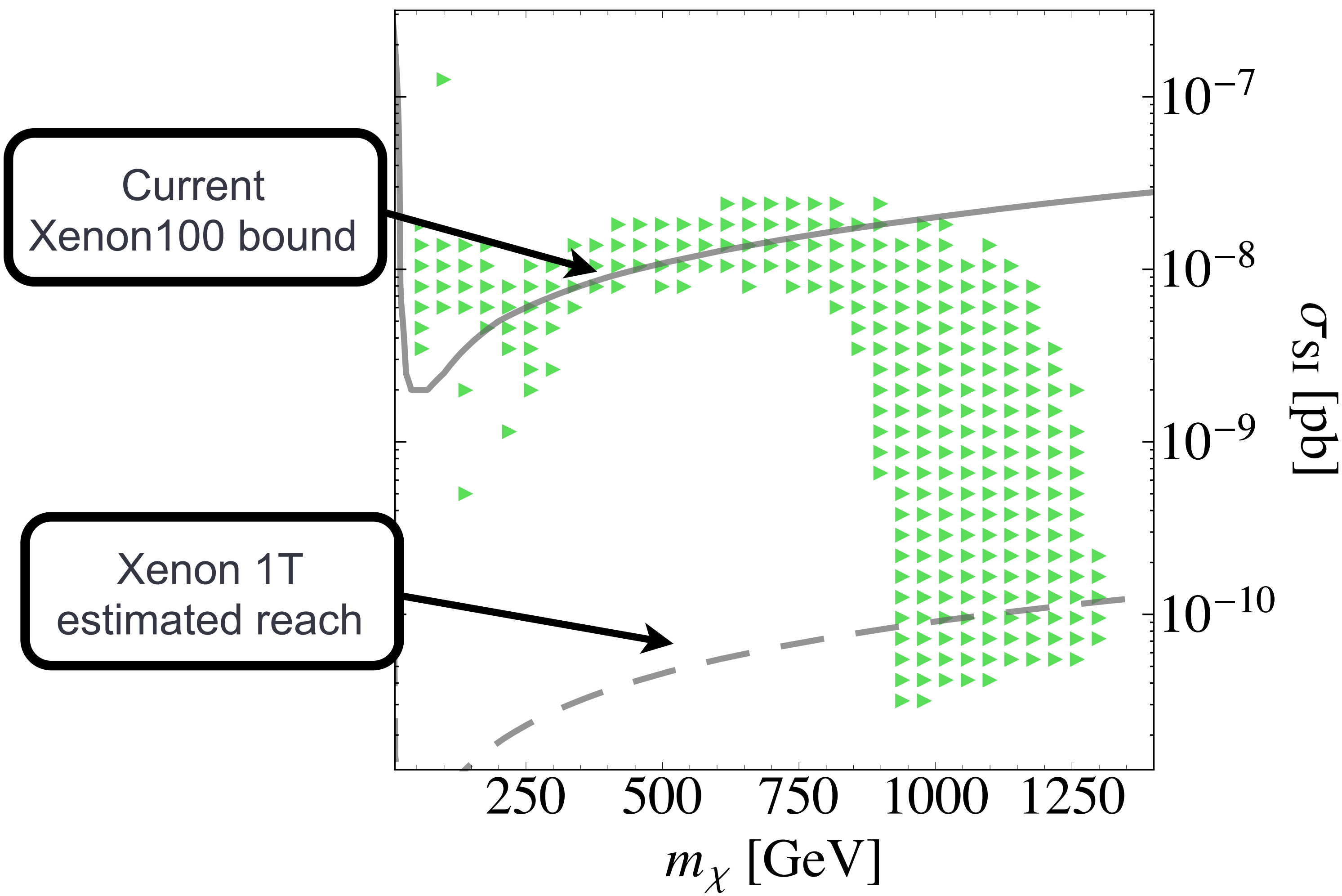
$$\widetilde{g} \to \begin{cases} t\,\bar{b}\,\chi_1^- + \text{c.c.} \;\to t\,\bar{b}\,(W^-)^*\,\chi_1^0 & 33\% \\ t\,\bar{t}\,\chi_2^0 \to t\,\bar{t}\,(Z^0)^*\,\chi_1^0 & 15\% \\ t\,\bar{t}\,\chi_3^0 \to t\,\bar{t}\,Z^0\,\chi_1^0 & 15\% \end{cases}$$

- Higgsinos: $\sigma(p\,p \to \chi_1^+\,\chi_2^0) = 73 \text{ fb}$

- Squarks:

	$\widetilde{q}$	$\widetilde{q}_3$	$\widetilde{d}_3^c$	$\widetilde{u}_3^c$
m [TeV]	4.2	3.4	4.1	2.5

Will direct detection exclude this region?



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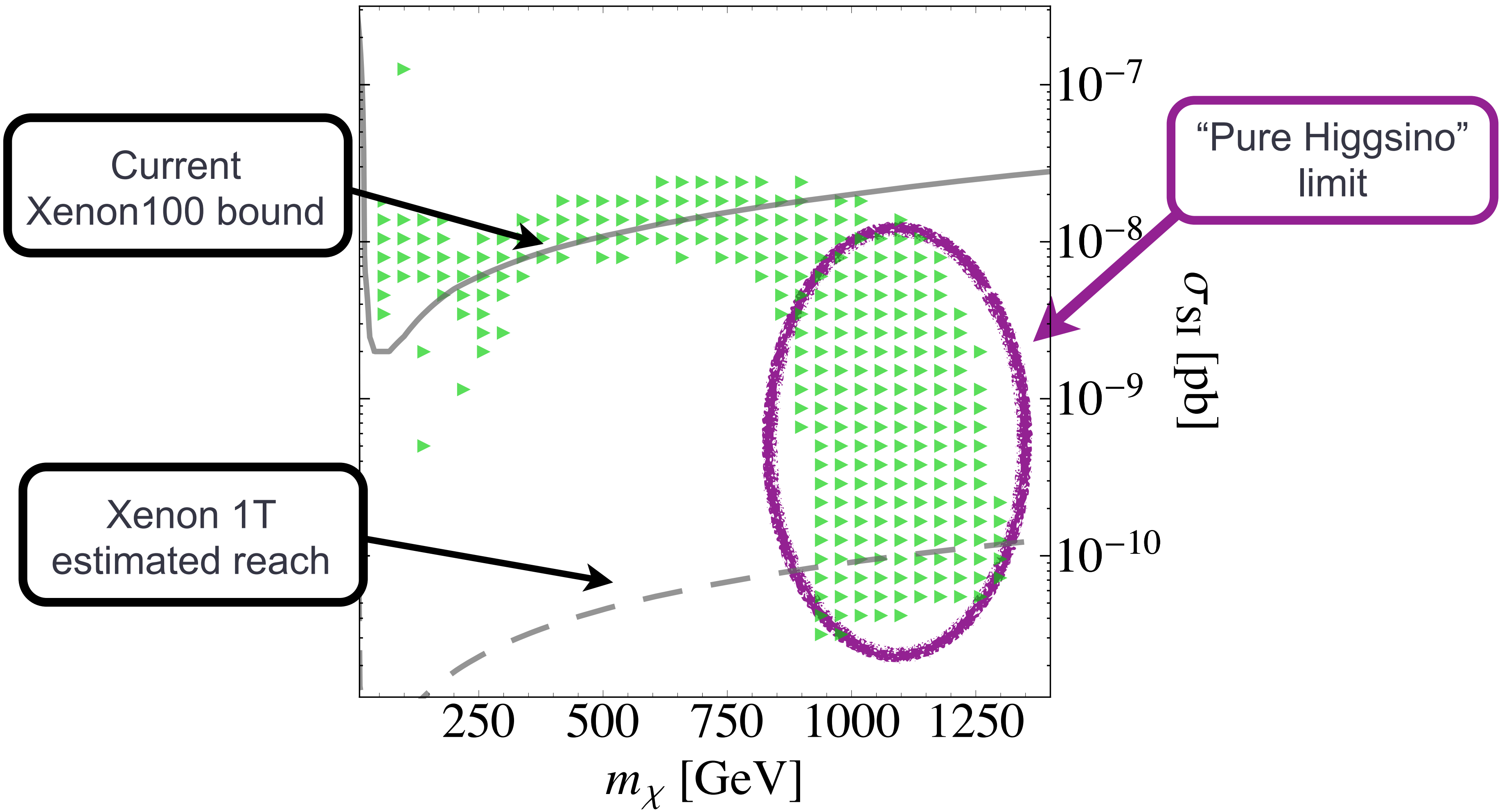
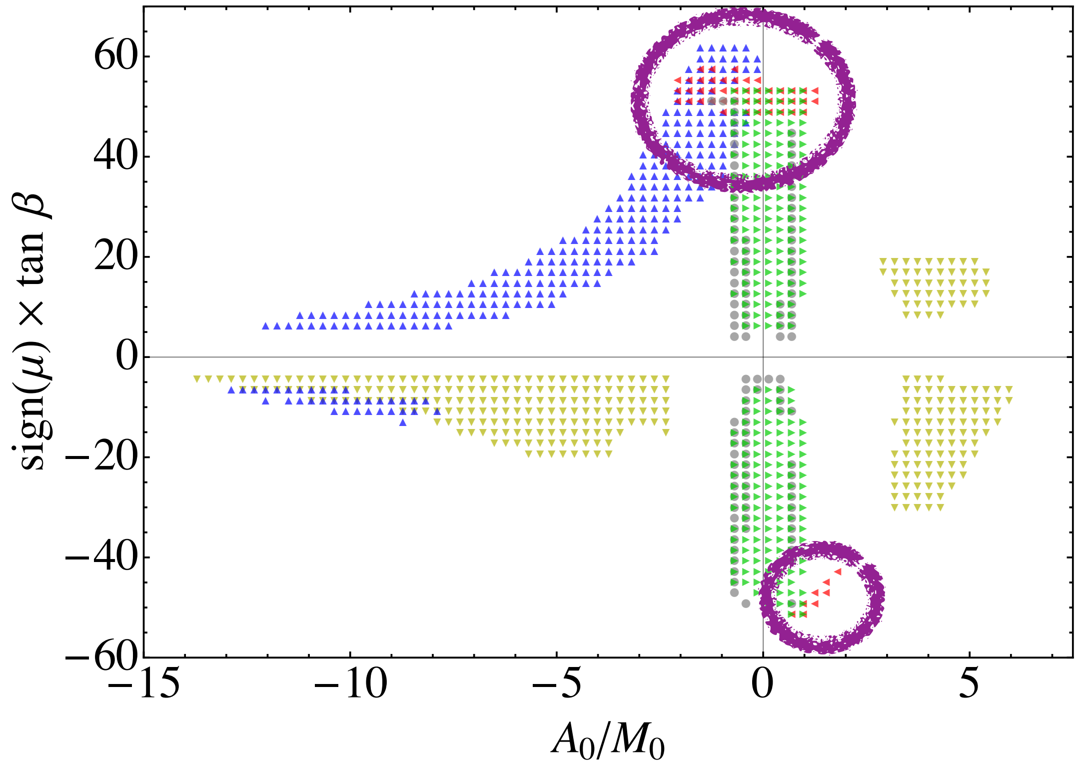


1st quadrant

Circumnavigating the CMSSM

A^0 pole annihilation

Setting sail for A^0 pole annihilation



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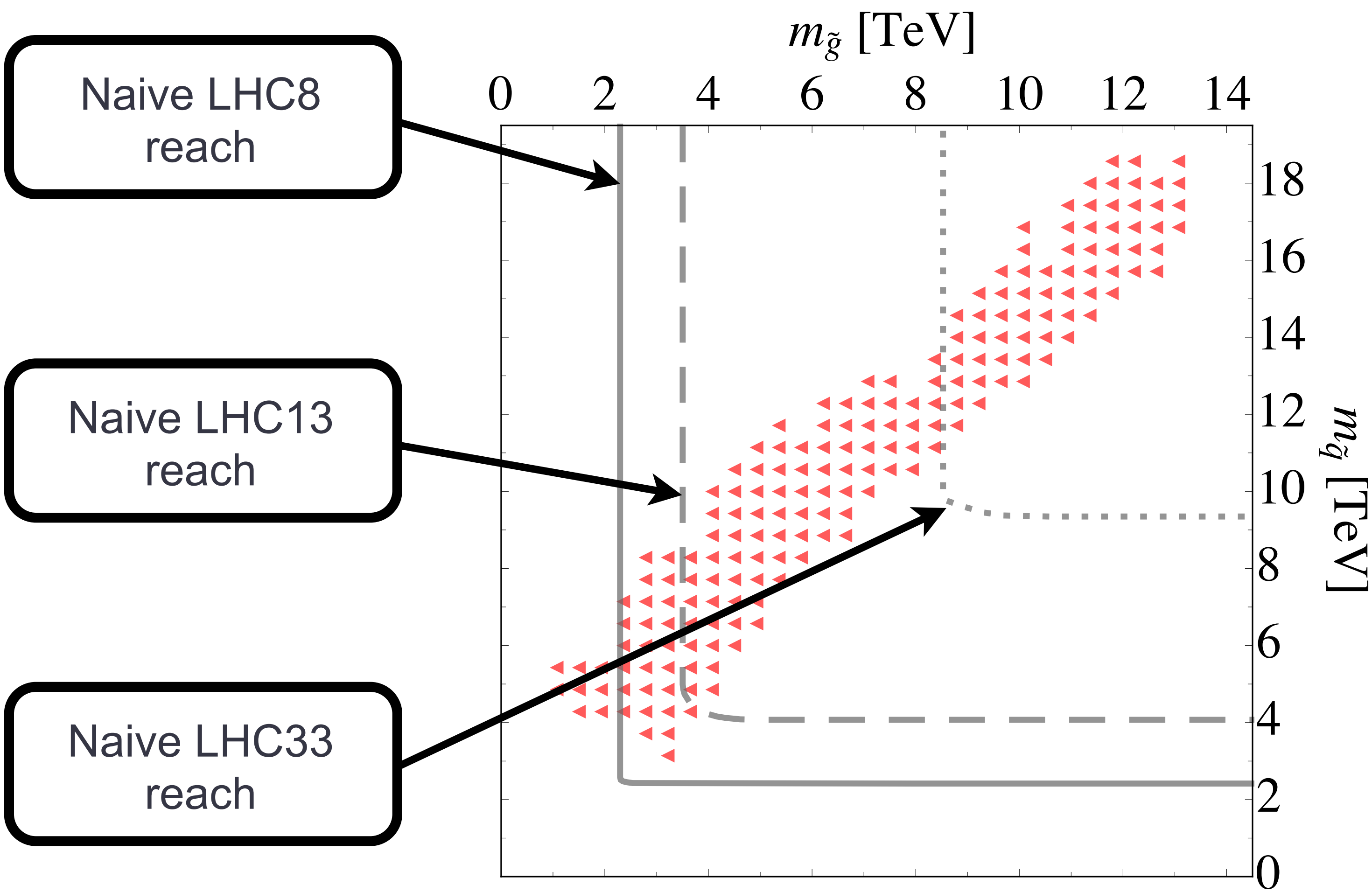
- $500 \text{ GeV} \lesssim M_0 \lesssim 16 \text{ TeV} \quad [\mu > 0]$
  $200 \text{ GeV} \lesssim M_{1/2} \lesssim 7 \text{ TeV} \quad [\mu > 0]$

- $5 \text{ TeV} \lesssim M_0 \lesssim 10 \text{ TeV} \quad [\mu < 0]$
  $300 \text{ GeV} \lesssim M_{1/2} \lesssim 2 \text{ TeV} \quad [\mu < 0]$

The squark-gluino plane

1st quadrant



- 2nd quadrant similar; 4th quadrant gluino mass < 4 TeV.

A^0 pole LHC benchmark

Large A-terms

Input parameters						
M_0	$M_{\frac{1}{2}}$	A_0	$\tan\beta$	sign(μ)	$\|\mu\|$	$\text{sign}(B_\mu)\sqrt{\|B_\mu\|}$
2311.11	666.667	-3021.77	55.8605	1	1708.6	−99290.9

- Squarks:

	$\widetilde{q}$	$\widetilde{d}^c_3$	$\widetilde{q}_3$	$\widetilde{u}^c_3$
m [TeV]	2.6	1.7	1.9	1.4

- Gluino: $m_{\widetilde{g}} = 1.6\ \text{TeV} \implies \sigma(p\,p \to \widetilde{g}\,\widetilde{g}) = 8.0\ \text{fb}$

$$\widetilde{g} \to \begin{cases} t\,\bar{t}\,\chi^0_1 & 18\% \\ t\,\bar{t}\,\chi^0_2 \to t\,\bar{t}\,h\,\chi^0_1 & 22.5\% \\ \bar{t}\,b\,\chi^+_1 + \text{c.c.} \;\; \to \bar{t}\,b\,W^+\,\chi^0_1 + \text{c.c.} & 53\% \end{cases}$$

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	$\widetilde{q}$	$\widetilde{d}_3^c$	$\widetilde{q}_3$	$\widetilde{u}_3^c$
m [TeV]	2.6	1.7	1.9	1.4

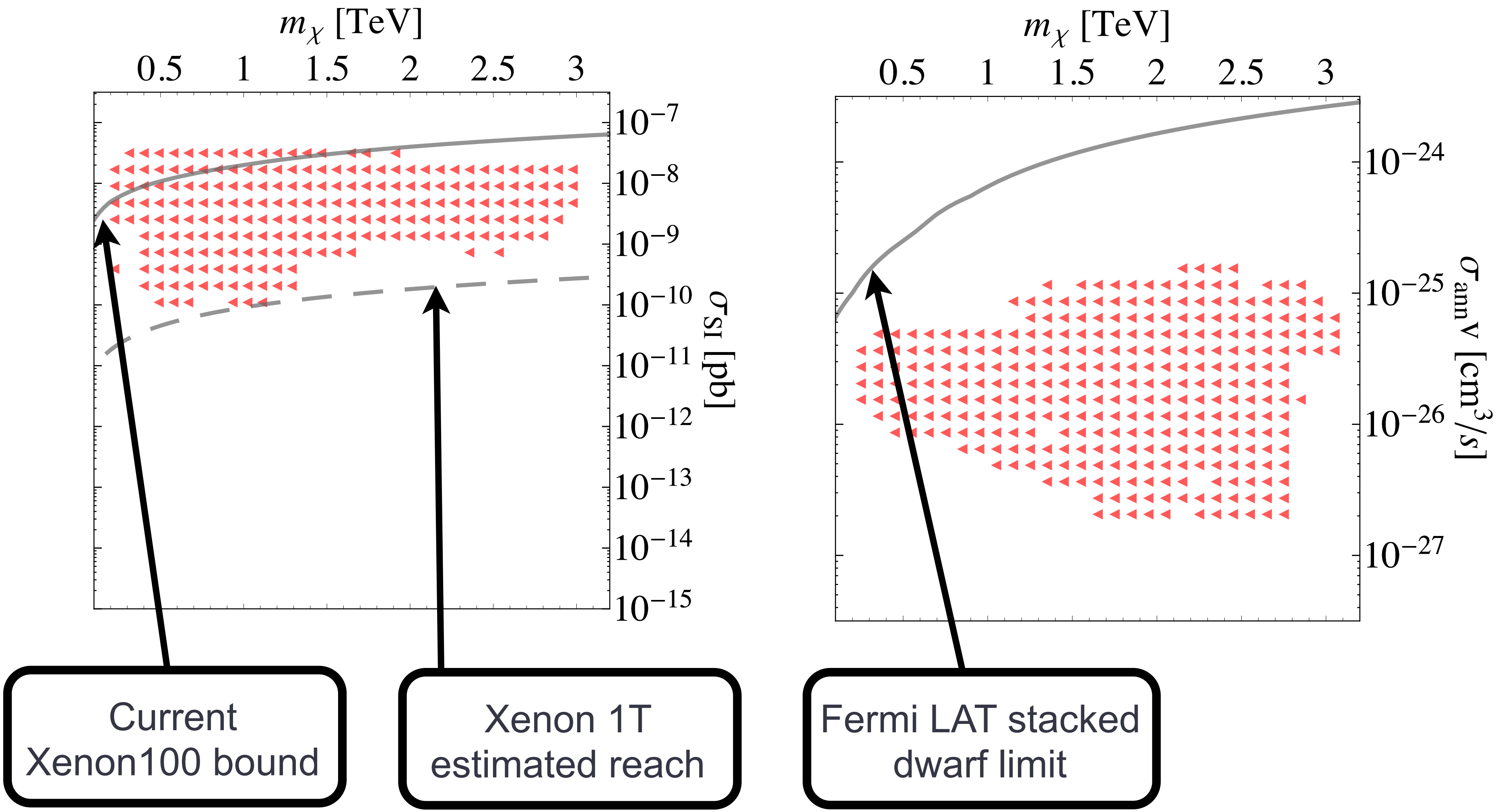
- Gluino: $m_{\widetilde{g}} = 1.6\ \text{TeV} \Longrightarrow \sigma(p\,p \to \widetilde{g}\,\widetilde{g}) = 8.0\ \text{fb}$

$$\widetilde{g} \to \begin{cases} t\,\bar{t}\,\chi_1^0 & 18\% \\ t\,\bar{t}\,\chi_2^0 \to t\,\bar{t}\,h\,\chi_1^0 & 22.5\% \\ \bar{t}\,b\,\chi_1^+ + \text{c.c.} \to \bar{t}\,b\,W^+\,\chi_1^0 + \text{c.c.} & 53\% \end{cases}$$

Tops, MET, and Higgses!

Direct & Indirect Detection

1st quadrant



- 2nd quadrant is similar but 4th quadrant extends below 10^{-14} pb .

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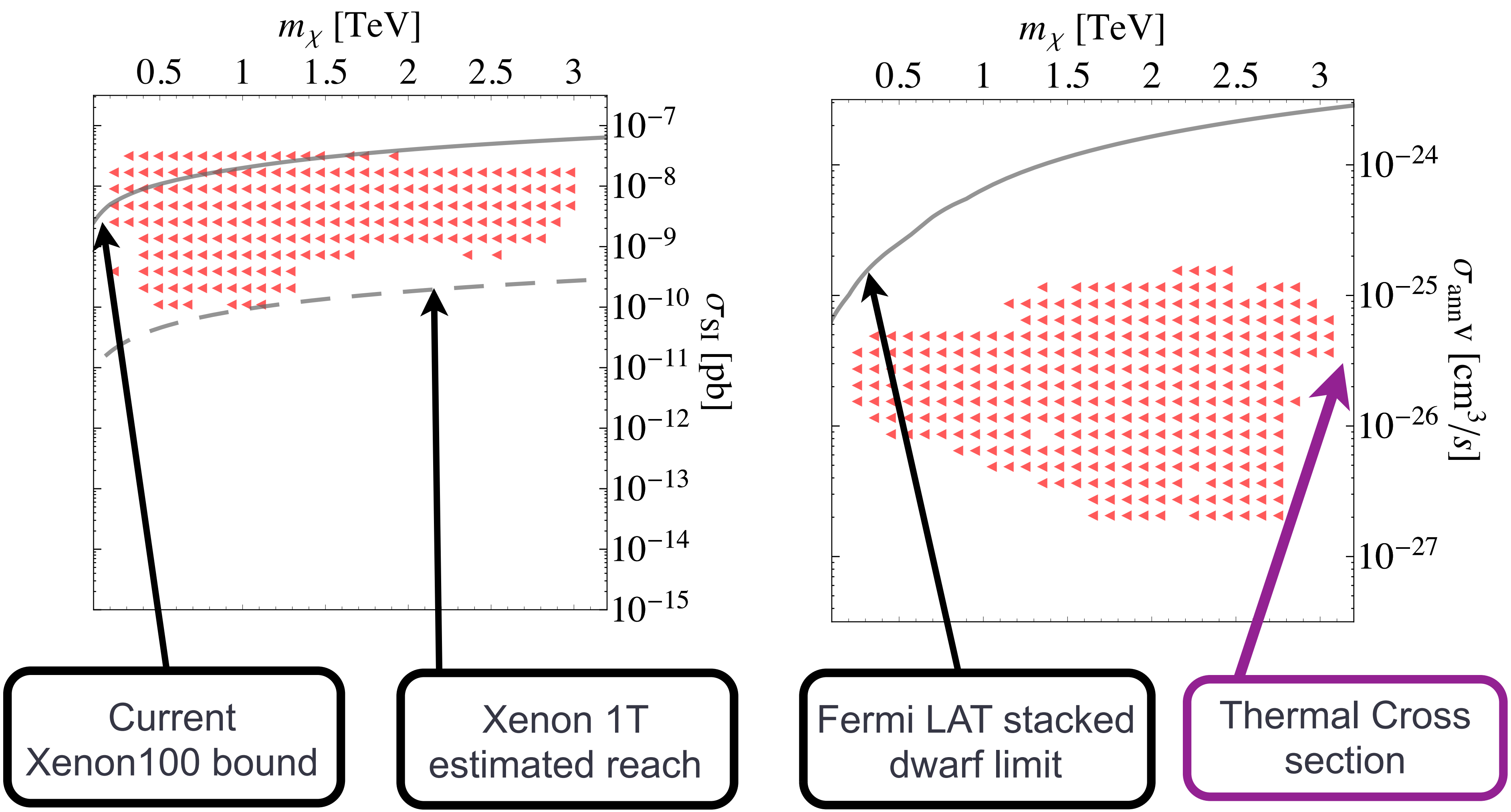

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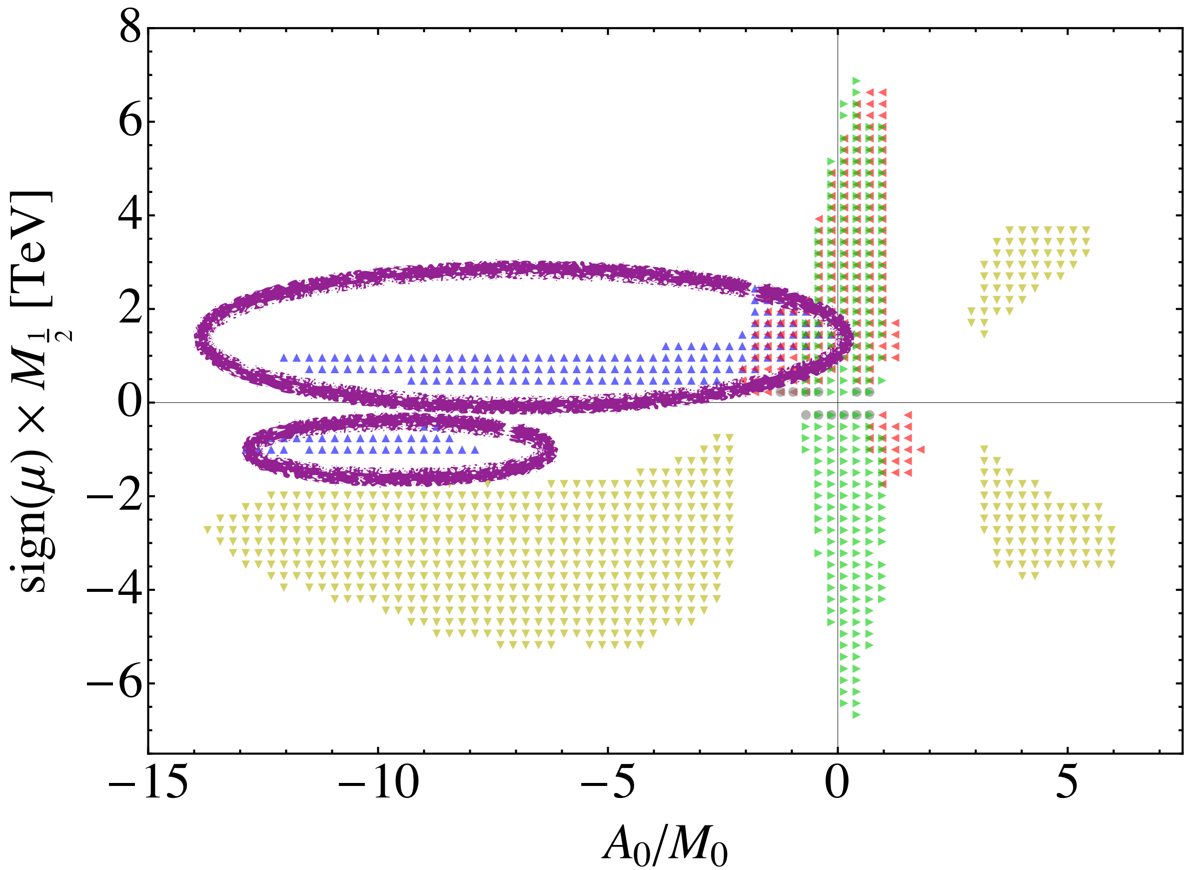
Circumnavigating the CMSSM

Stau coannihilation

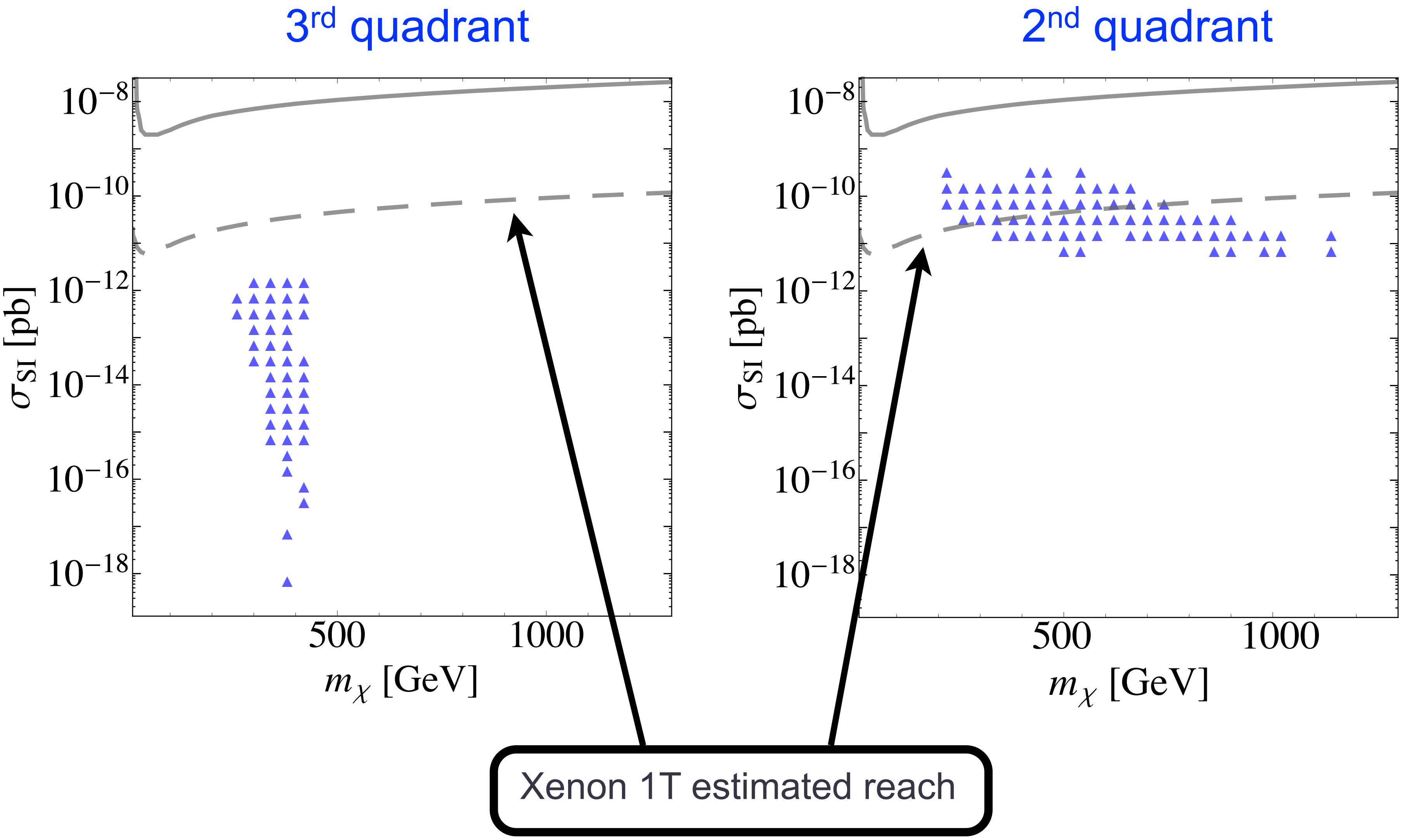
Setting sail for stau coannihilation



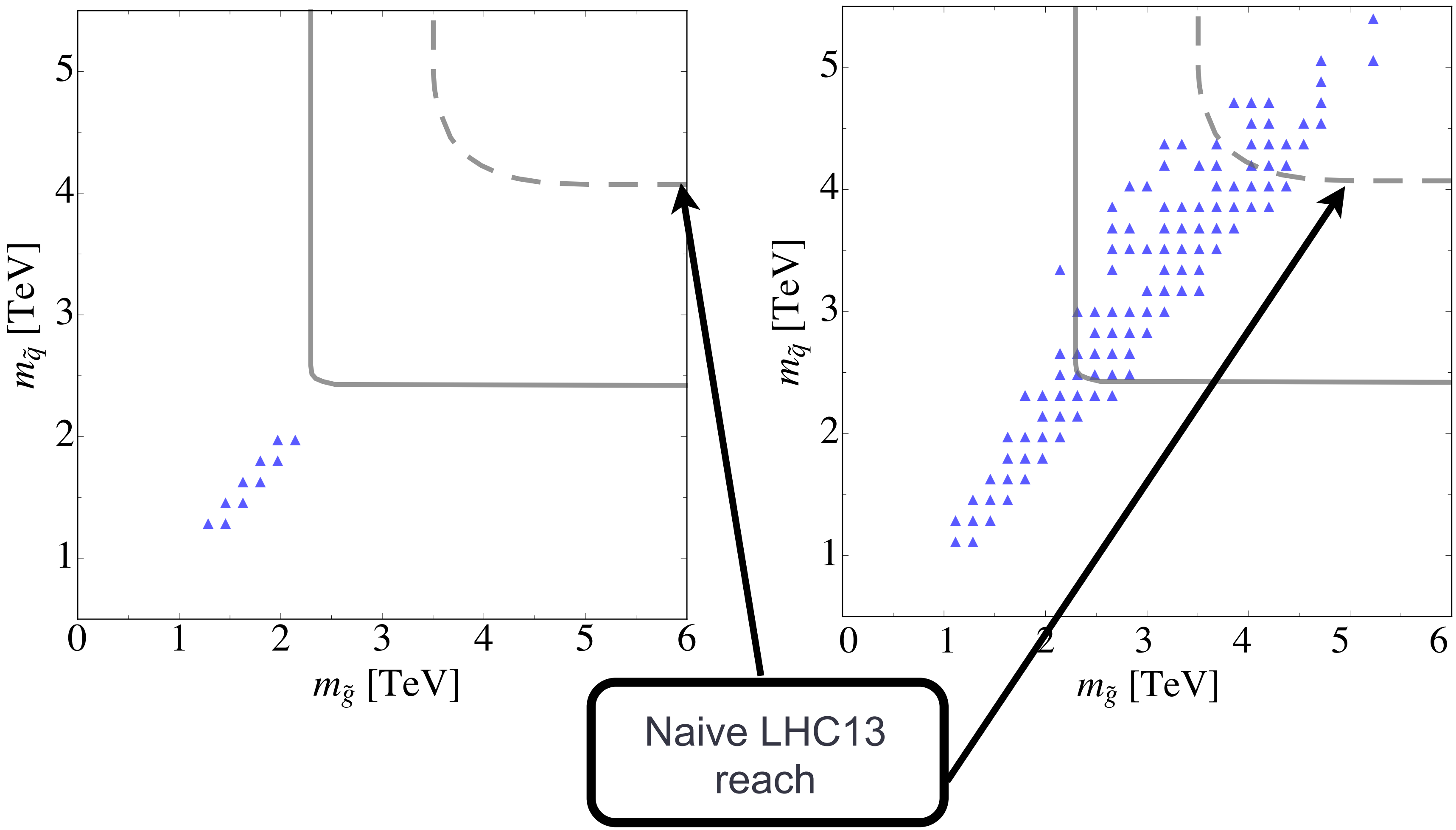
- light $\widetilde{\chi}^0$
- Well-tempered
- A^0 pole
- stau coann
- stop coann

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

Stau-coann: direct detection



Stau-coann: squark-gluino plane



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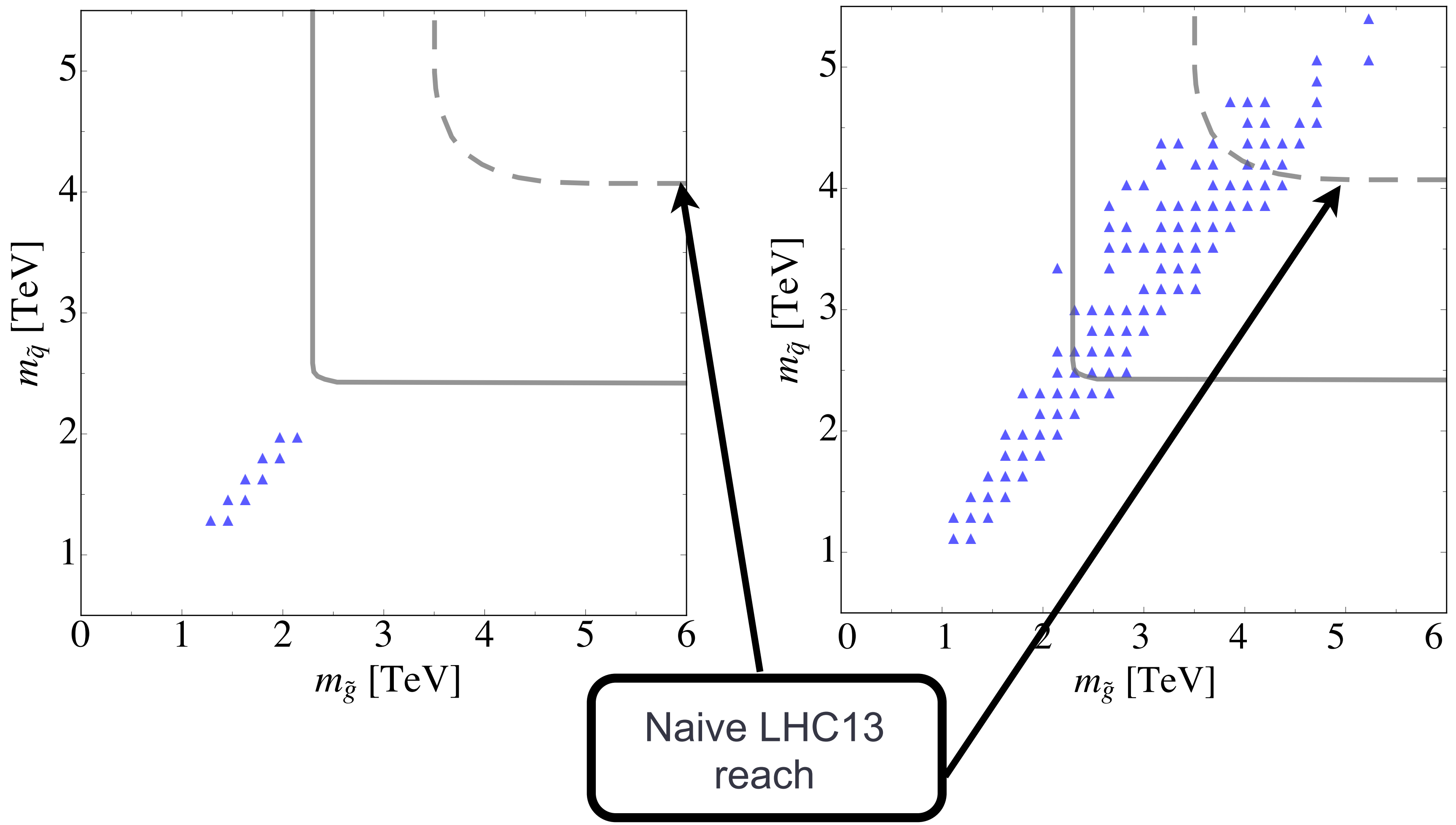

Most of these spectra are discoverable at the 13 TeV LHC.

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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- Gluino is 1980 GeV.
- Squarks:

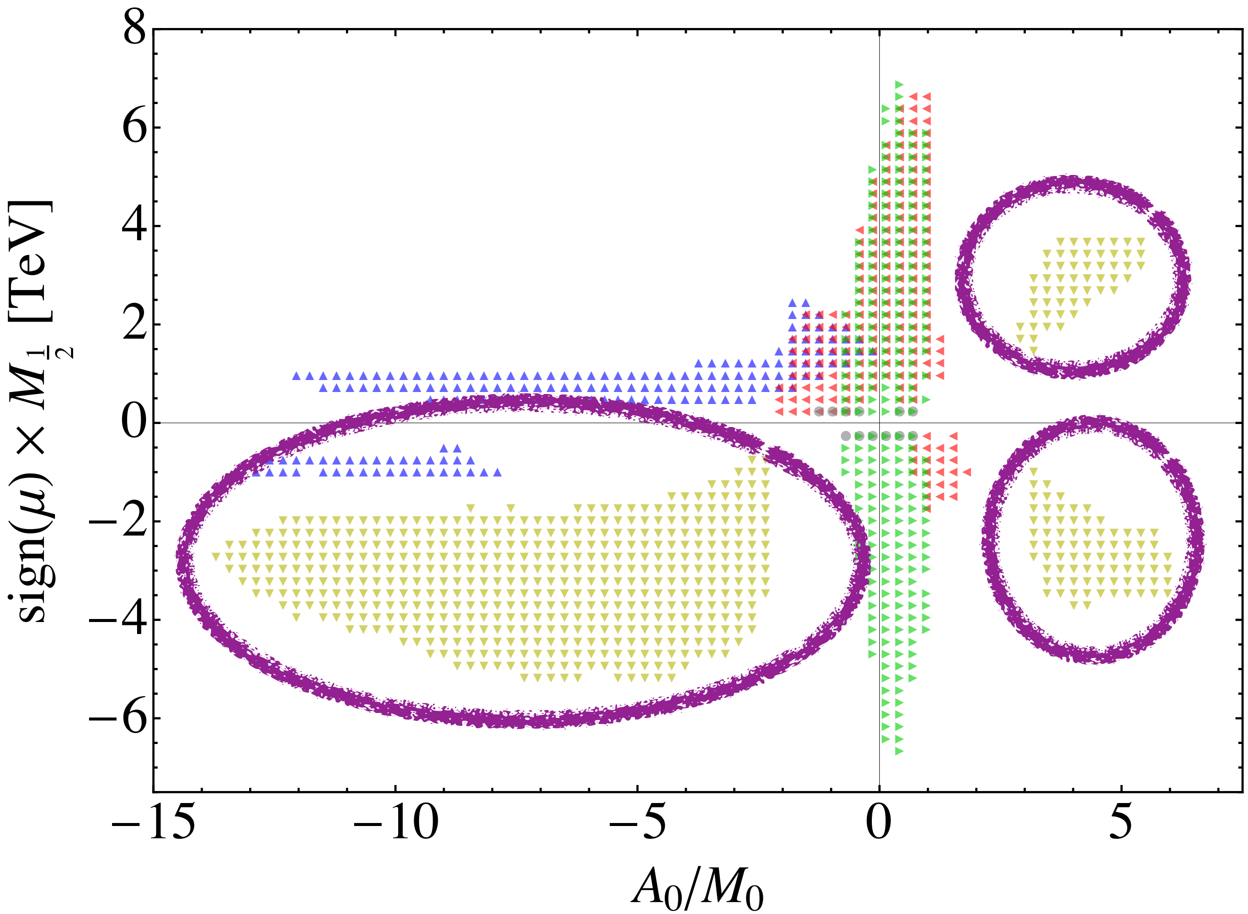
	$\widetilde{q}$	$\widetilde{b}_1$	$\widetilde{b}_2$	$\widetilde{t}_1$	$\widetilde{t}_2$
m [GeV]	1780.8	1529.9	1715.3	1067.2	1562.9

- 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



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

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

A Missing Simplified Model

Input parameters						
M_0	$M_{\frac{1}{2}}$	A_0	$\tan\beta$	sign(μ)	$\lvert\mu\rvert$	$\sqrt{B_\mu}$
2666.67	933.333	-6444.	8.52015	-1	2794.86	18094.8

- 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

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

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

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

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

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

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

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

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

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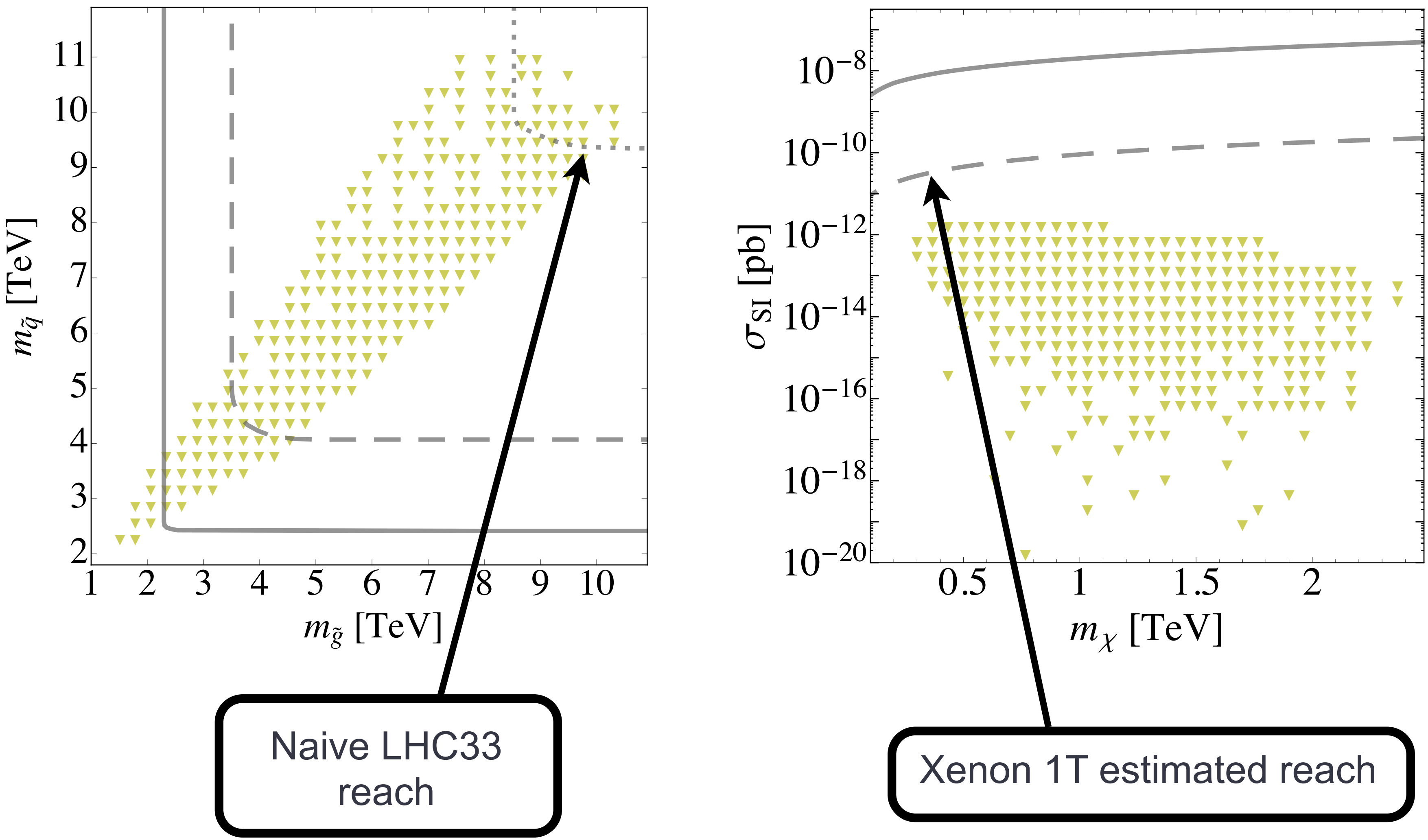
Same Sign Tops (boosted)

Stop-coannihilation phenomenology

3rd quadrant



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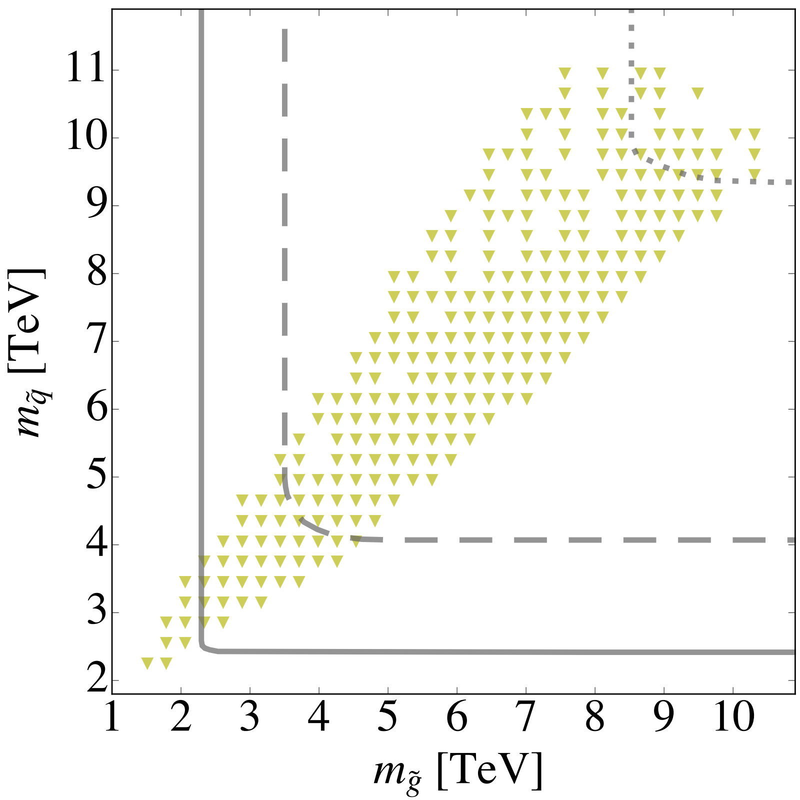
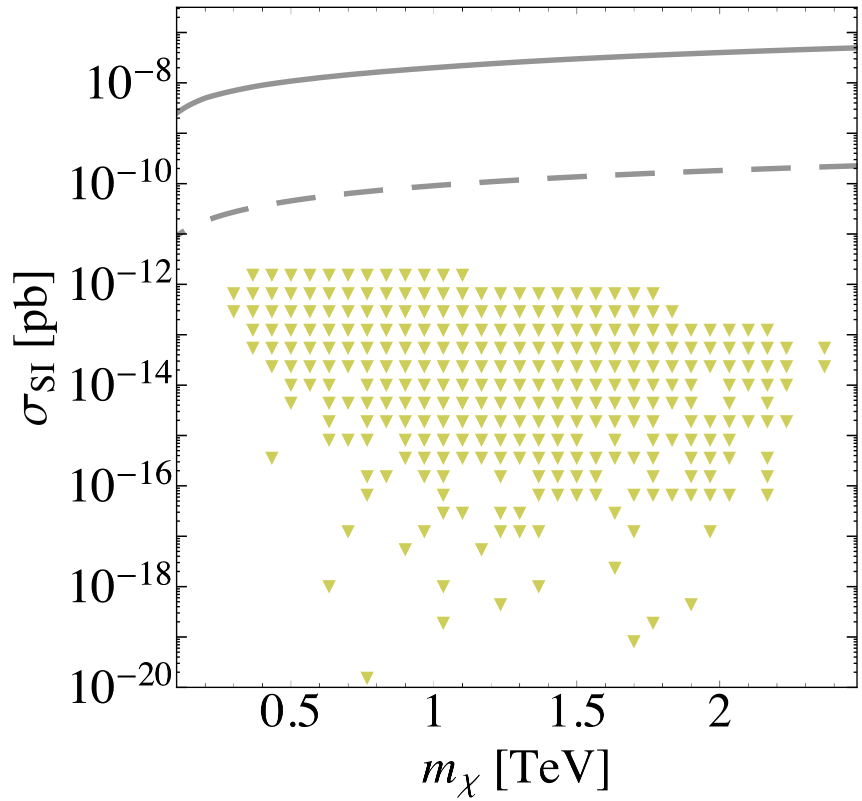
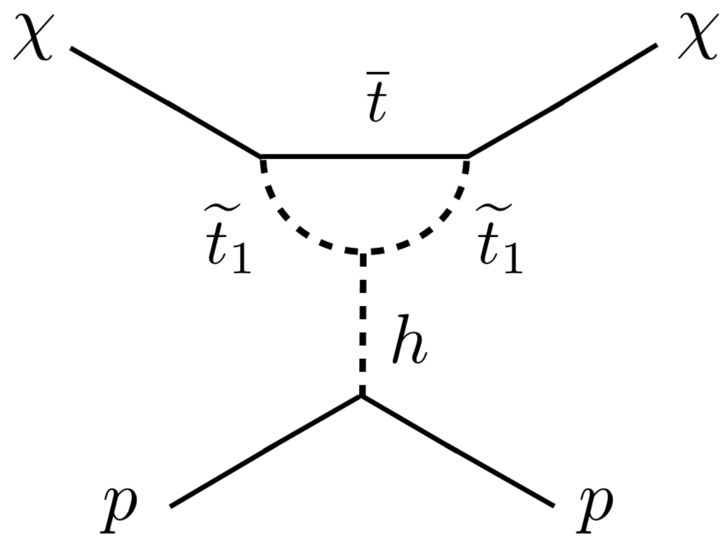




Some spectra will require beyond 33 TeV LHC.

Is direct detection hopeless?!?

New contribution at 1-loop



- Possibly observable for large *A* terms.

$$\sigma_{\rm SI}^{\rm 1-loop} \sim 3 \times 10^{-13}\ {\rm pb} \times \left(\frac{A_t}{m_{\tilde{t}_1}} \right)^2$$

- Range of *A* terms in the CMSSM from O(1-10).

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 LHC13 and Ton scale spin-independent direct detection?
    - A^0-pole annihilation
    - Stop coannihilation
- CMSSM predictions extend far beyond previous claims!