Here Be Dragons:

The Unexplored Continents of the CMSSM

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arXiv:1305.soon

SLAC ATLAS Jamboree
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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).

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

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

$$m_{h'} - m_h \simeq \frac{3\,g^2\,m_t^4}{16\,\pi^2\,m_h\,m_W^2}\log\frac{\widetilde{m}_{t'_1}\,\widetilde{m}_{t'_2}}{\widetilde{m}_{t_1}\,\widetilde{m}_{t_2}} \quad \Longrightarrow \quad \widetilde{m}_{t'_1}\,\widetilde{m}_{t'_2} \simeq \widetilde{m}_{t_1}\,\widetilde{m}_{t_2}\,2^{\frac{\Delta m_h}{5.6\ \mathrm{GeV}}}$$

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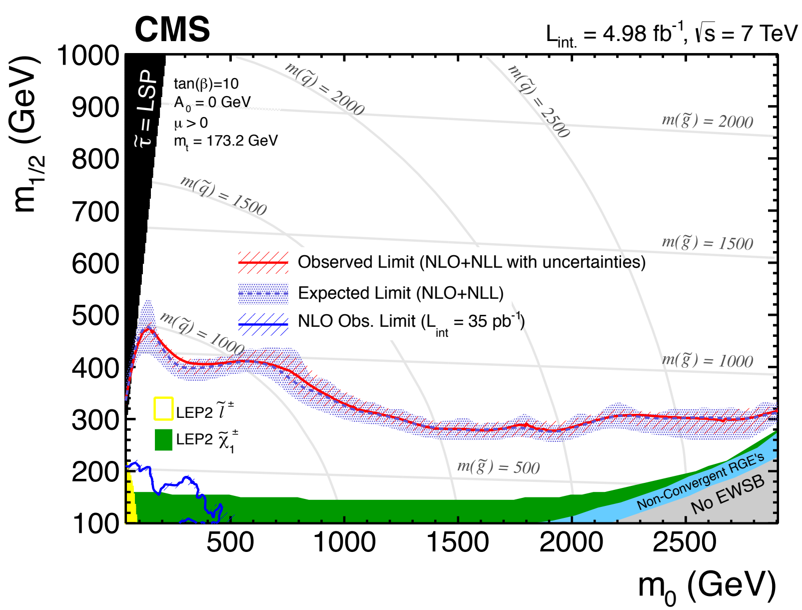
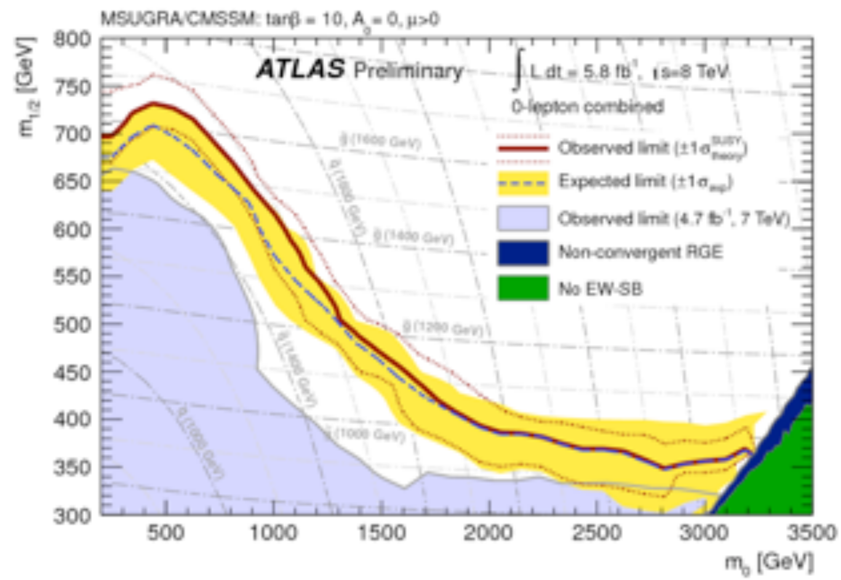
  - The ratio of the Higgs vevs: $\tan\beta$ (traded for the B_μ term).
- Parameters are evolved to weak scale using RGEs.
- μ-term is determined by requiring $m_Z = 91\ \mathrm{GeV}$.
- 19 coupled RGEs integrated over 32 e-folds: relation between the inputs & low energy parameters is highly non-linear.

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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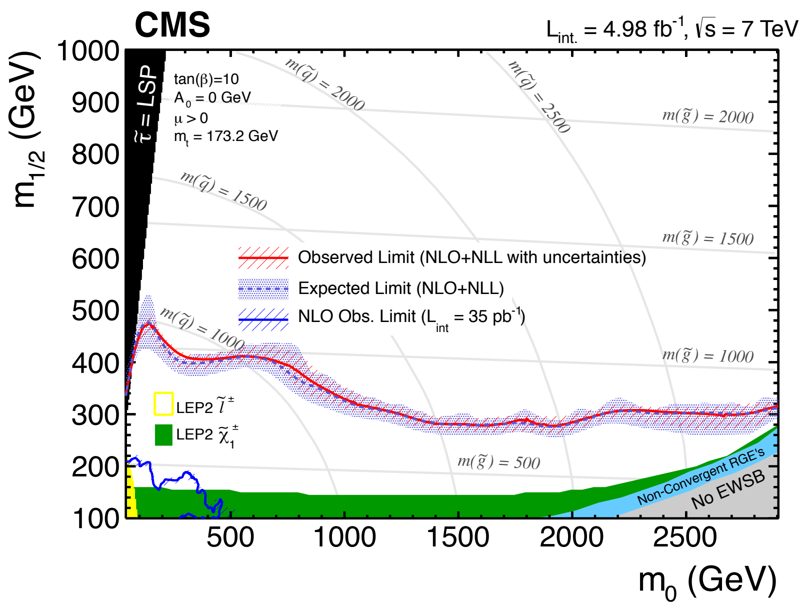

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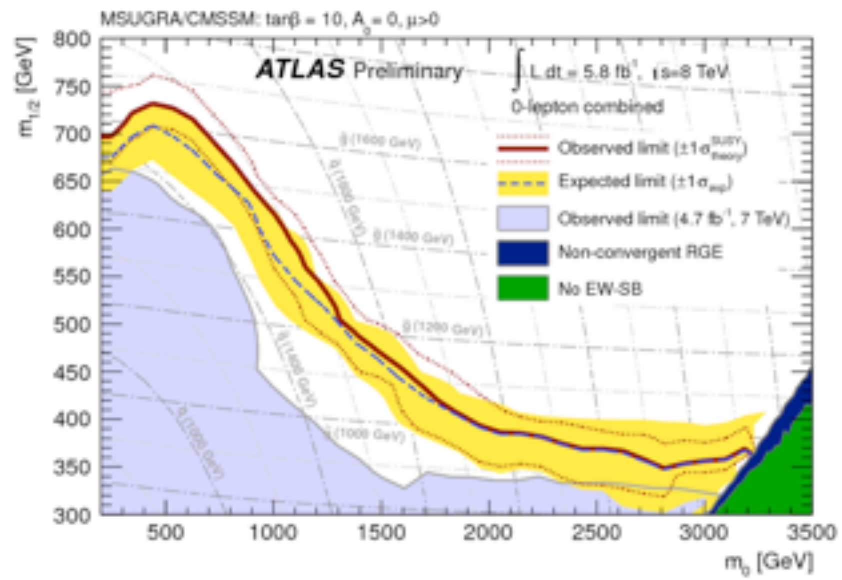

ATLAS-CONF-2012-109

- 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?

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.
  - "stau coannihilation"
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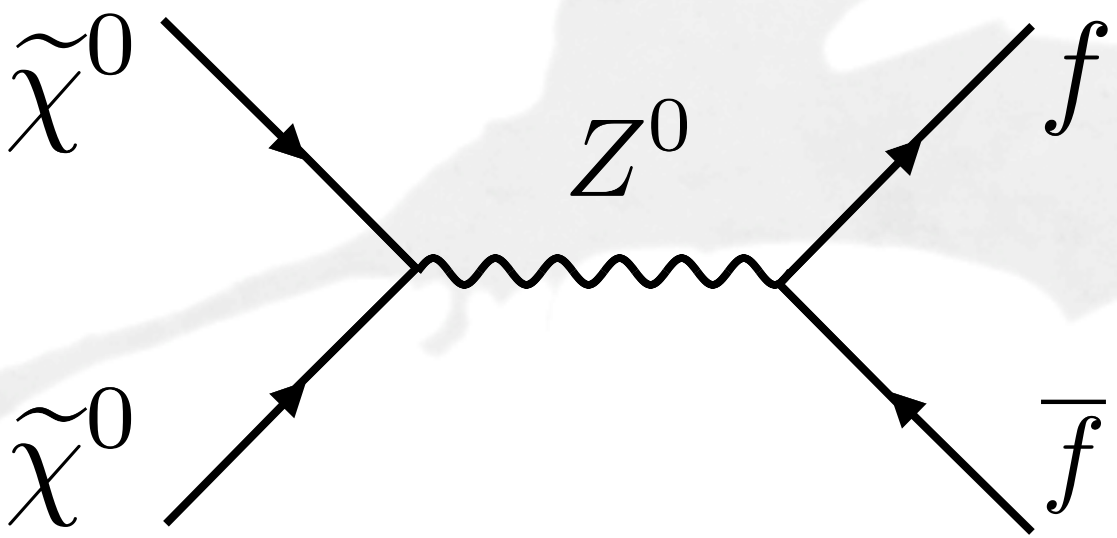

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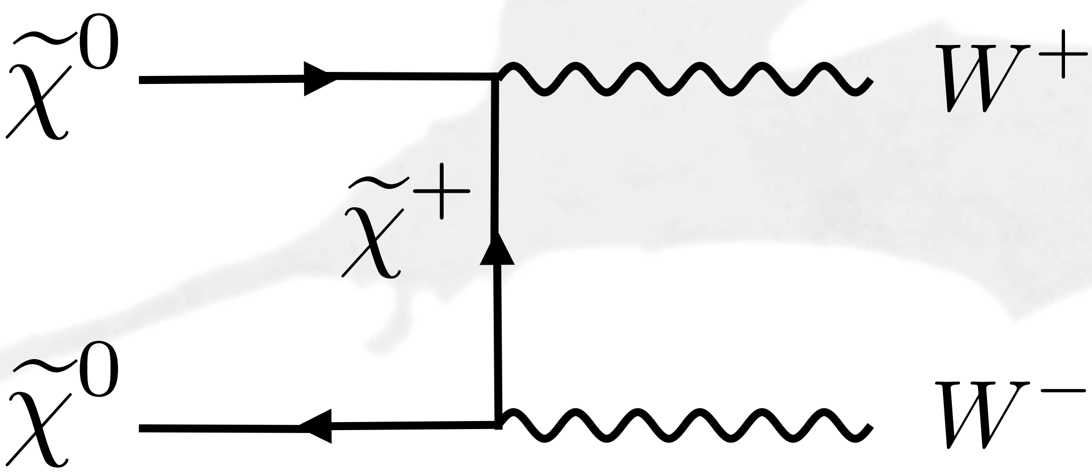

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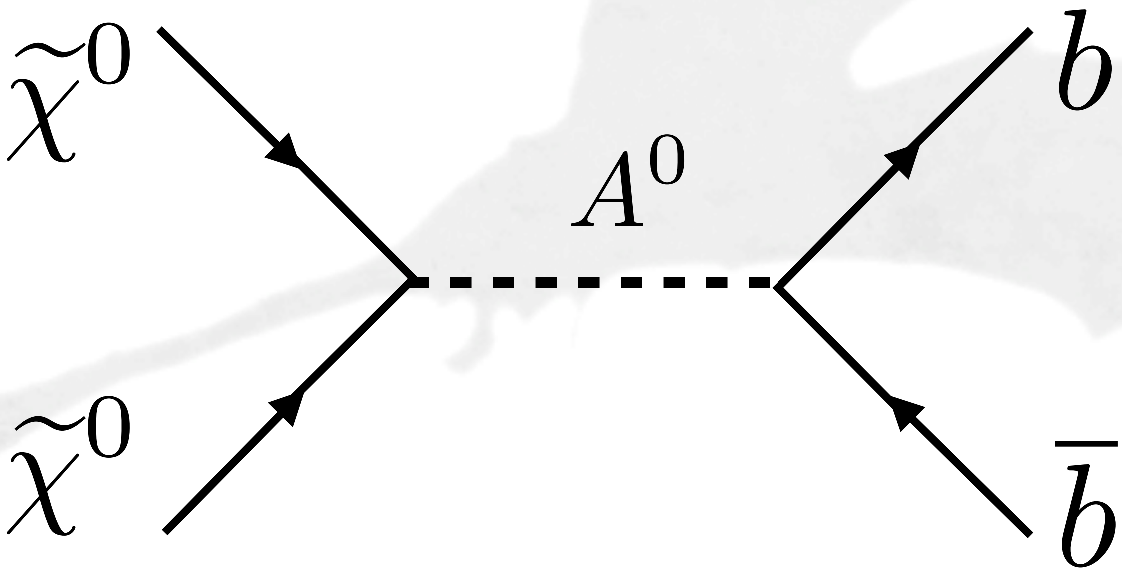

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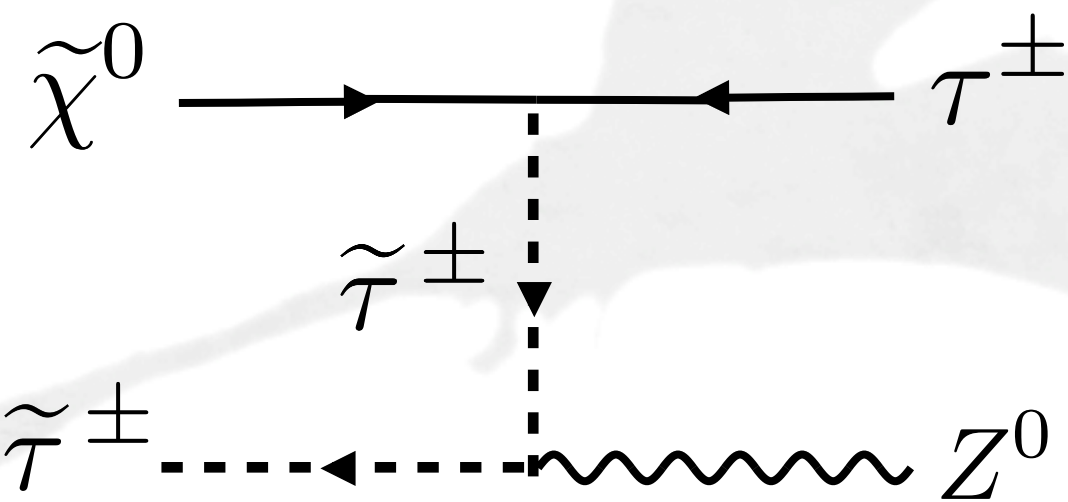

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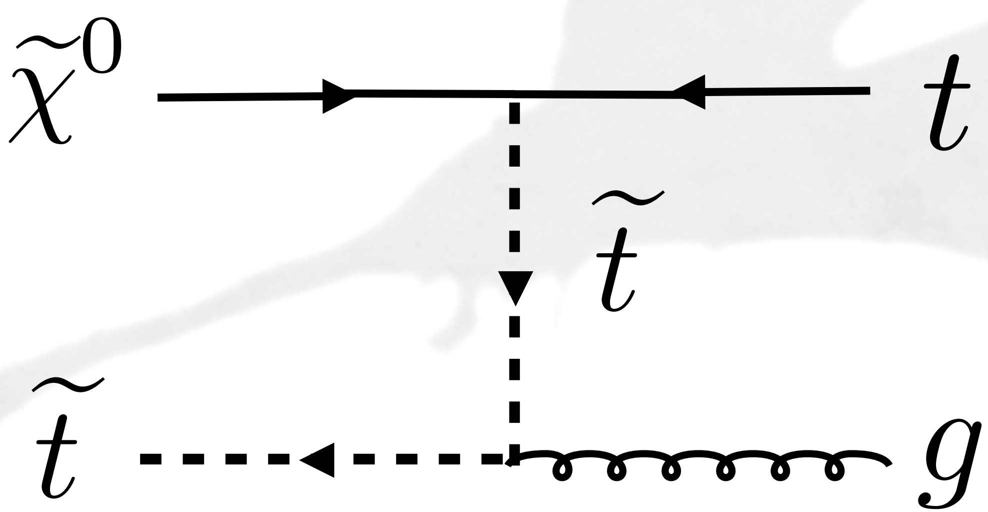

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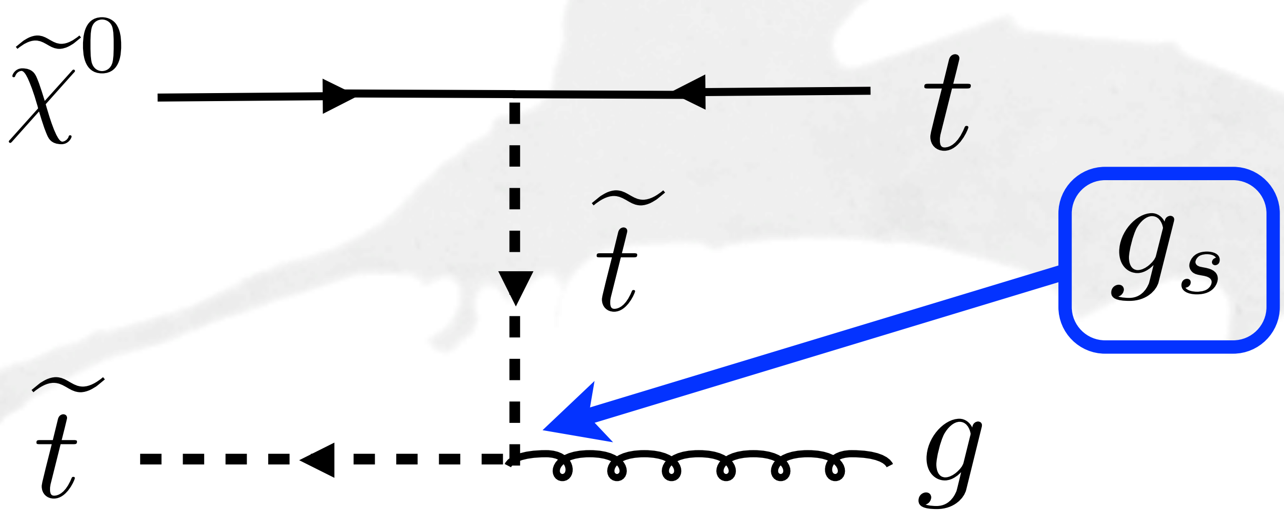

CMSSM Cartography

The CMSSM is Compact

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

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:

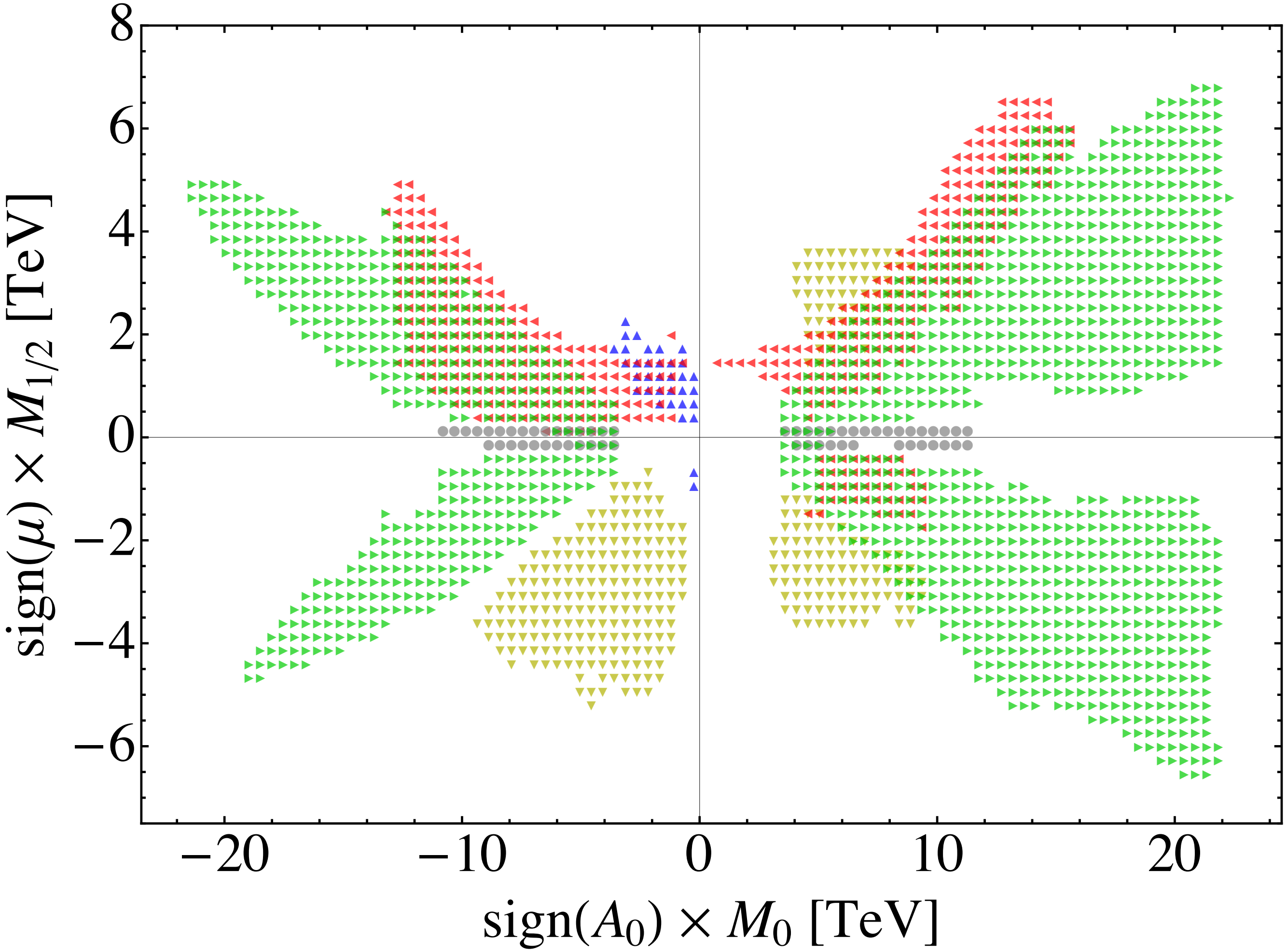
$$|a_t|^2 < (7.5\, m_{q_3}^2 + 7.5\, m_{u_3^c}^2 + 3\,(m_{H_u}^2 + |\mu|^2))$$

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

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

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

Charting the CMSSM



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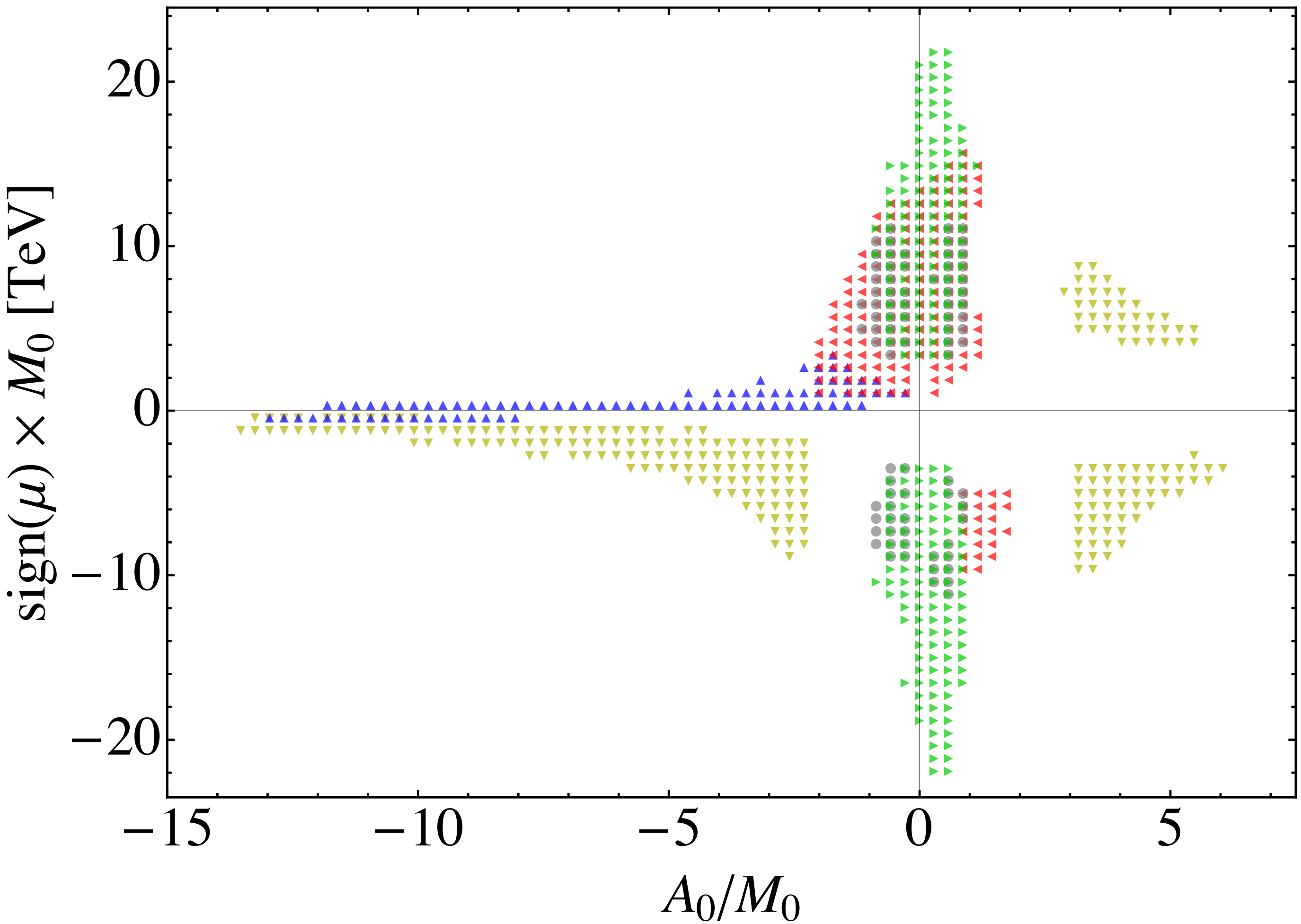

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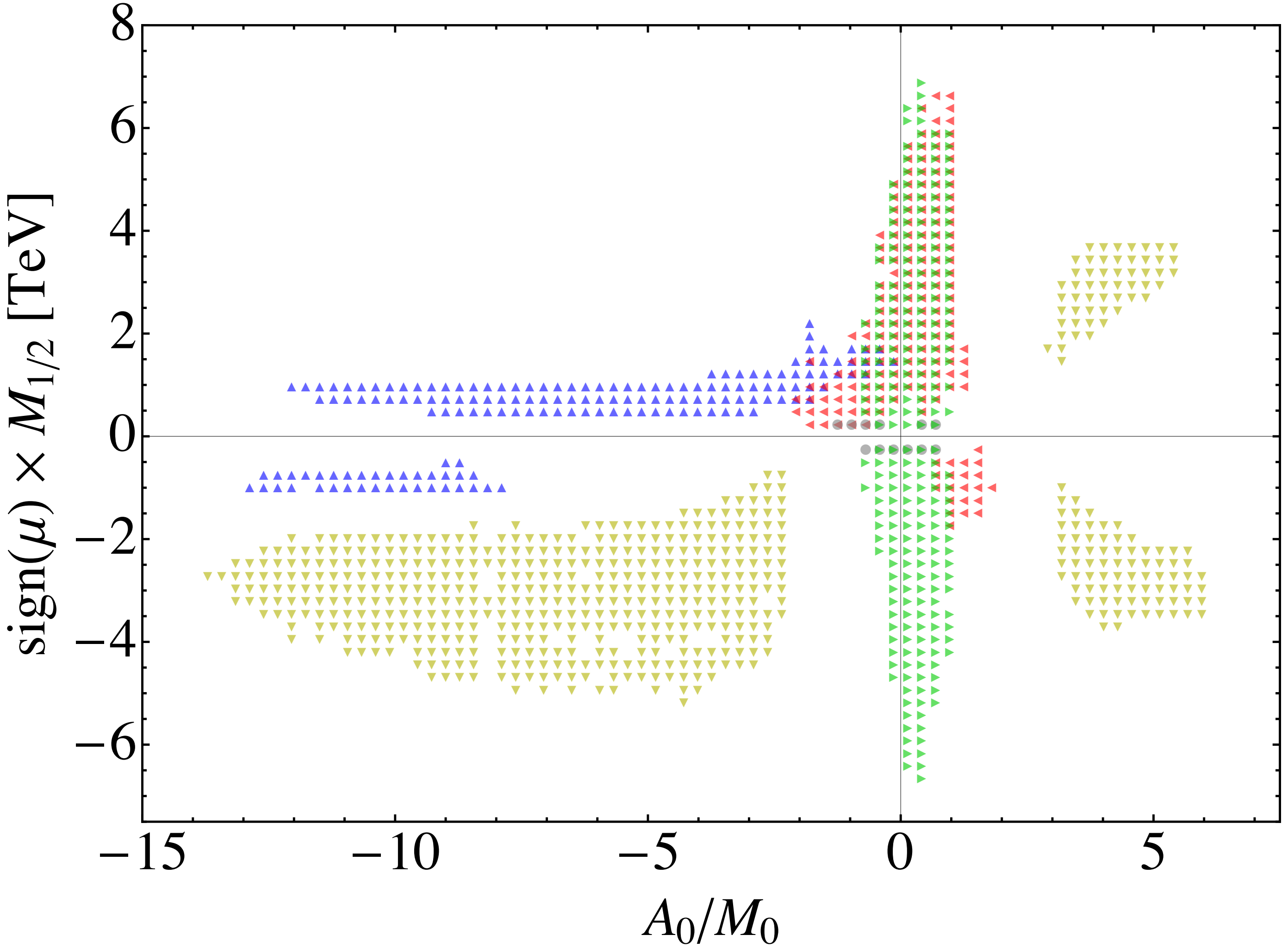

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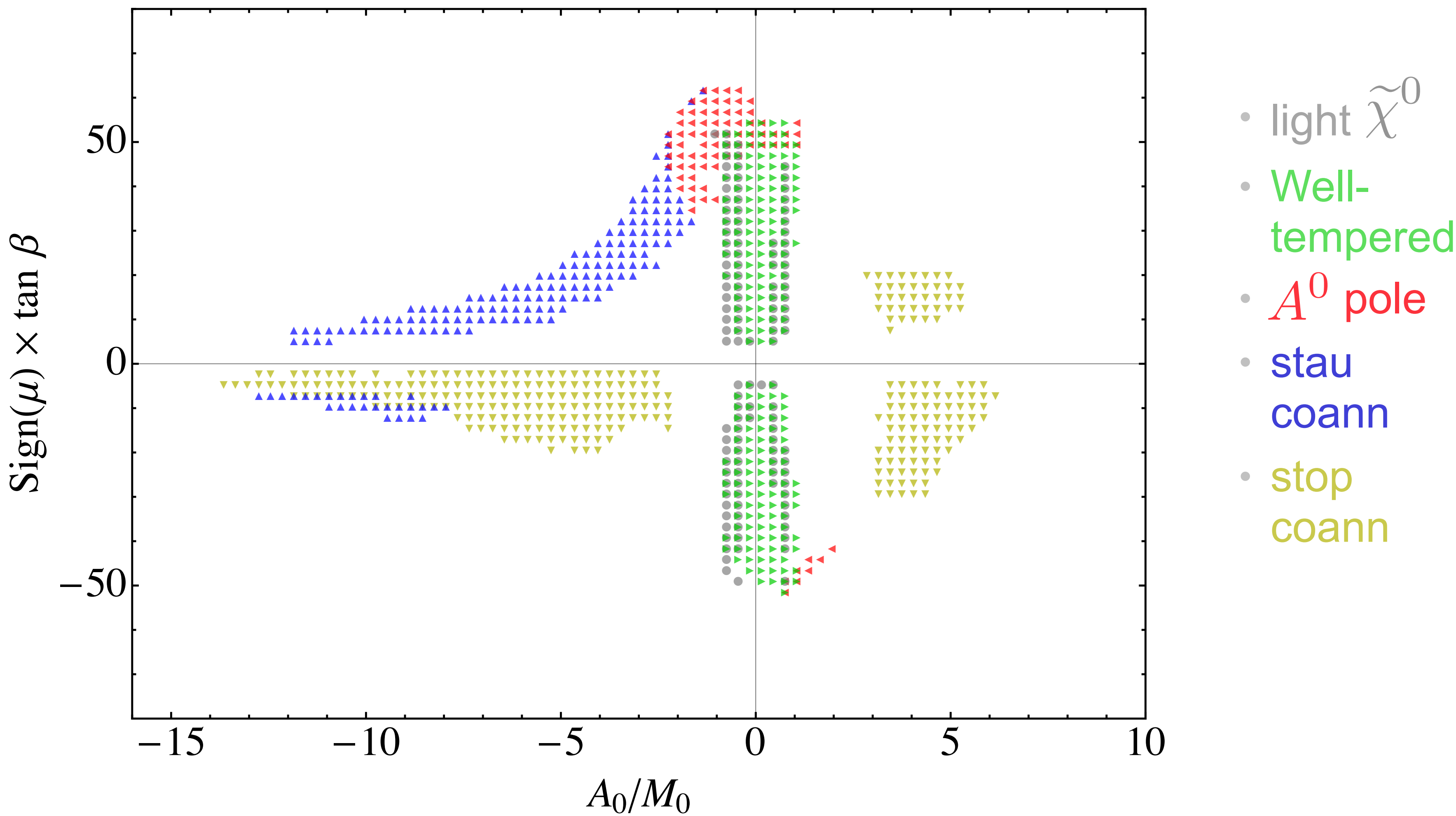
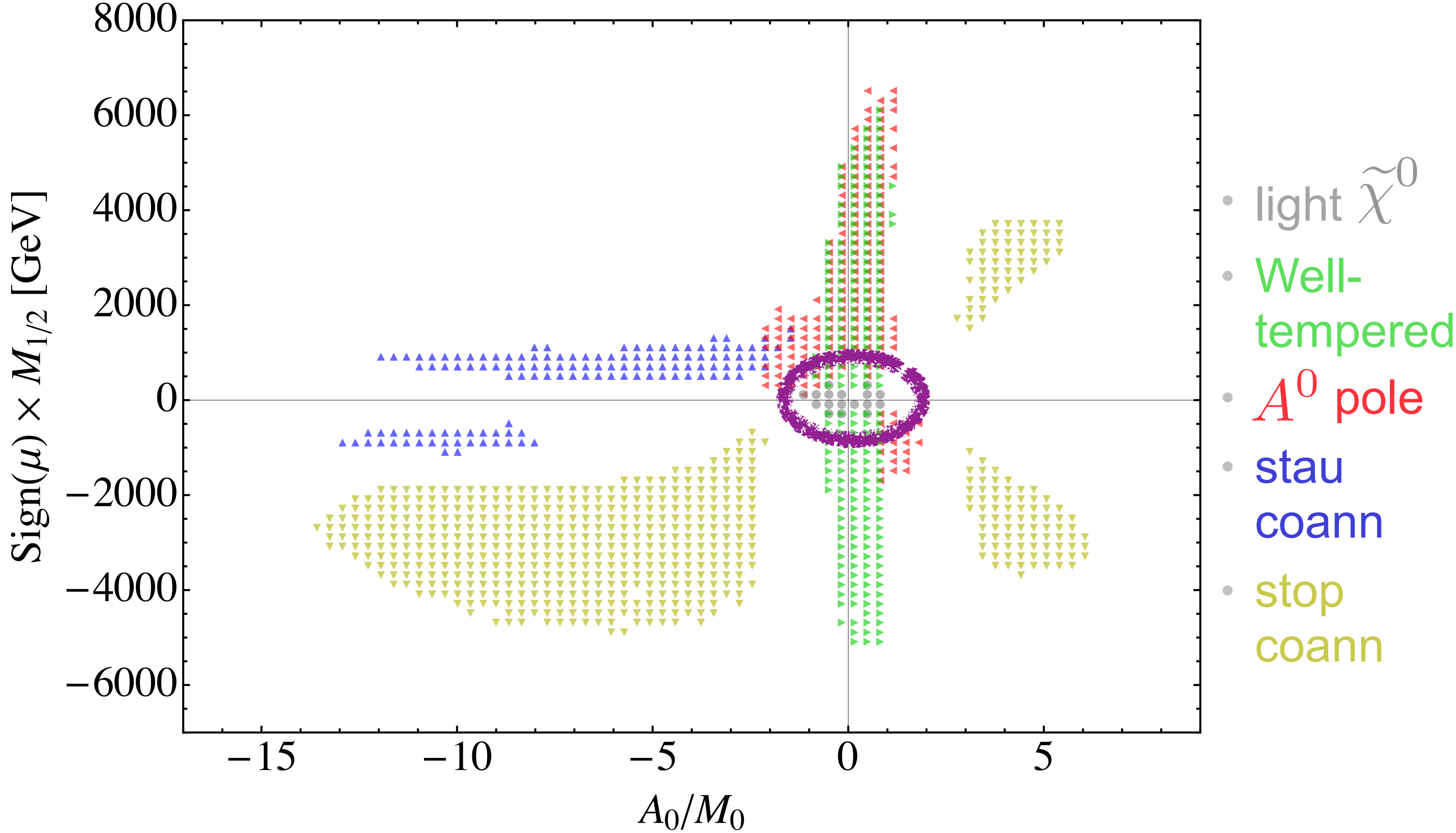


Circumnavigating the CMSSM

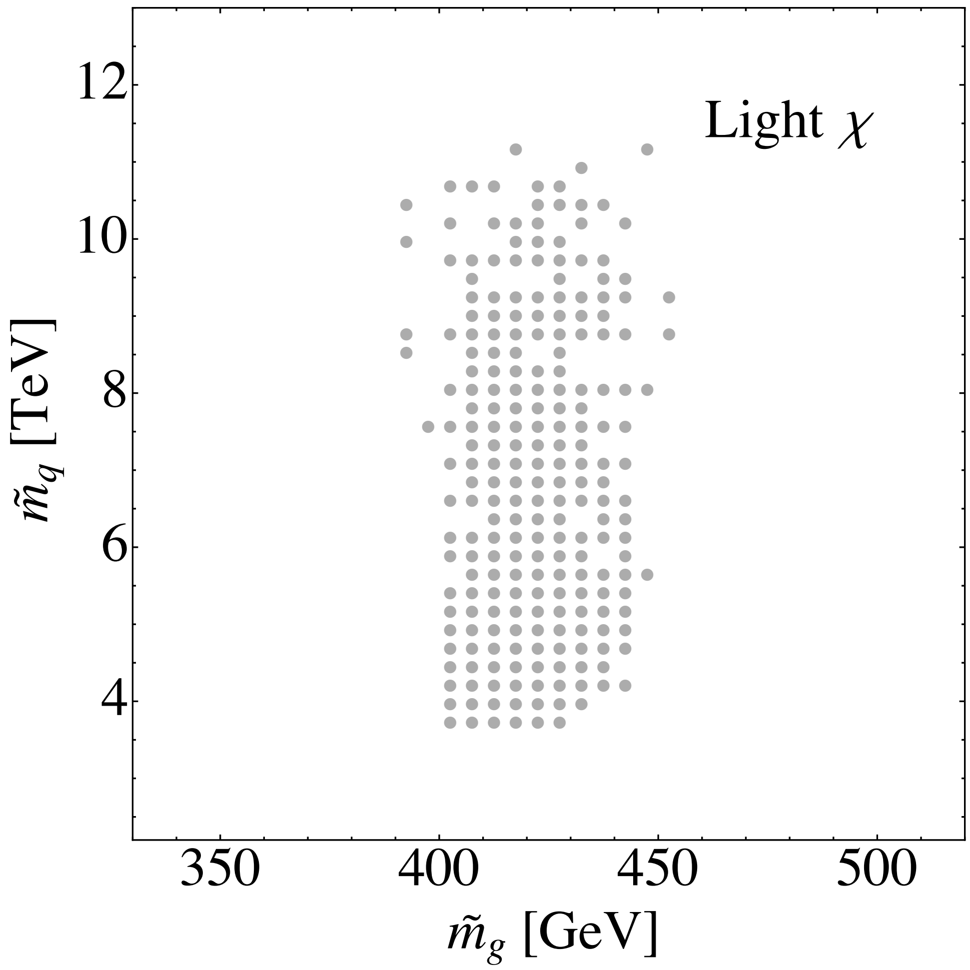
Light $\widetilde{\chi}^0$

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	$\tan\beta$	$\text{sign}(\mu)$	$\lvert\mu\rvert$	B_μ
5455.8	132.315	-3480.24	15.5977	1	301.773	2.01762×10^8

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

$$\widetilde{g} \to \begin{cases} \widetilde{B}\, q\, \bar{q} & 1.9\% \\ \widetilde{\chi}_1^{\pm}\, q\, \bar{q} \to \widetilde{B}\, W^{\pm}\, q\, \bar{q}' & 45\% \quad [r = 0.181] \\ \widetilde{\chi}_2^{0}\, q\, \bar{q} \to \widetilde{B}\, Z^{0}\, q\, \bar{q} & 34\% \quad [r = 0.181] \end{cases}$$

- ATLAS recast of jets + MET + no leptons for

ATLAS [arXiv:1208.0949]

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

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

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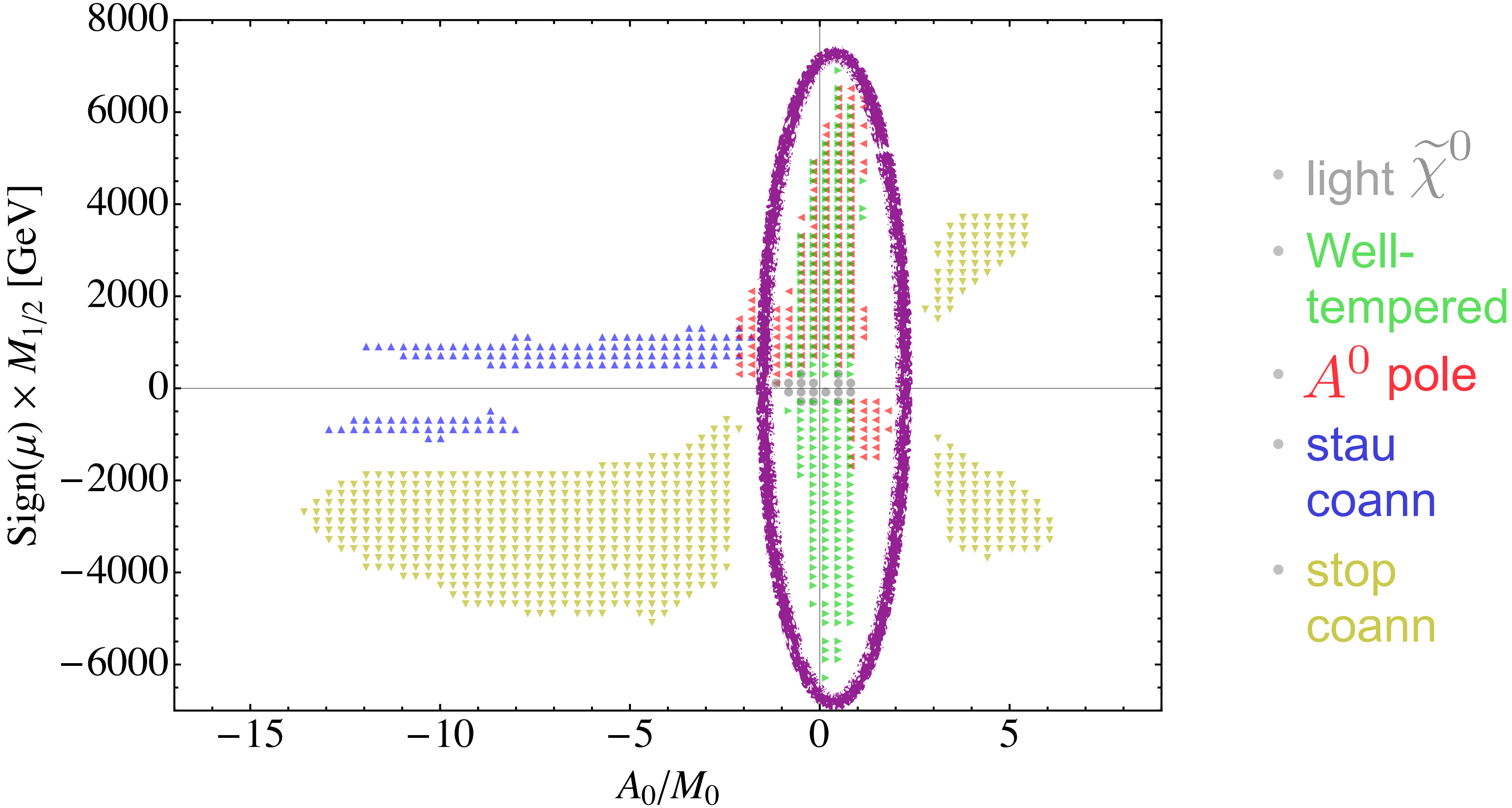
Excluded!

Circumnavigating the CMSSM

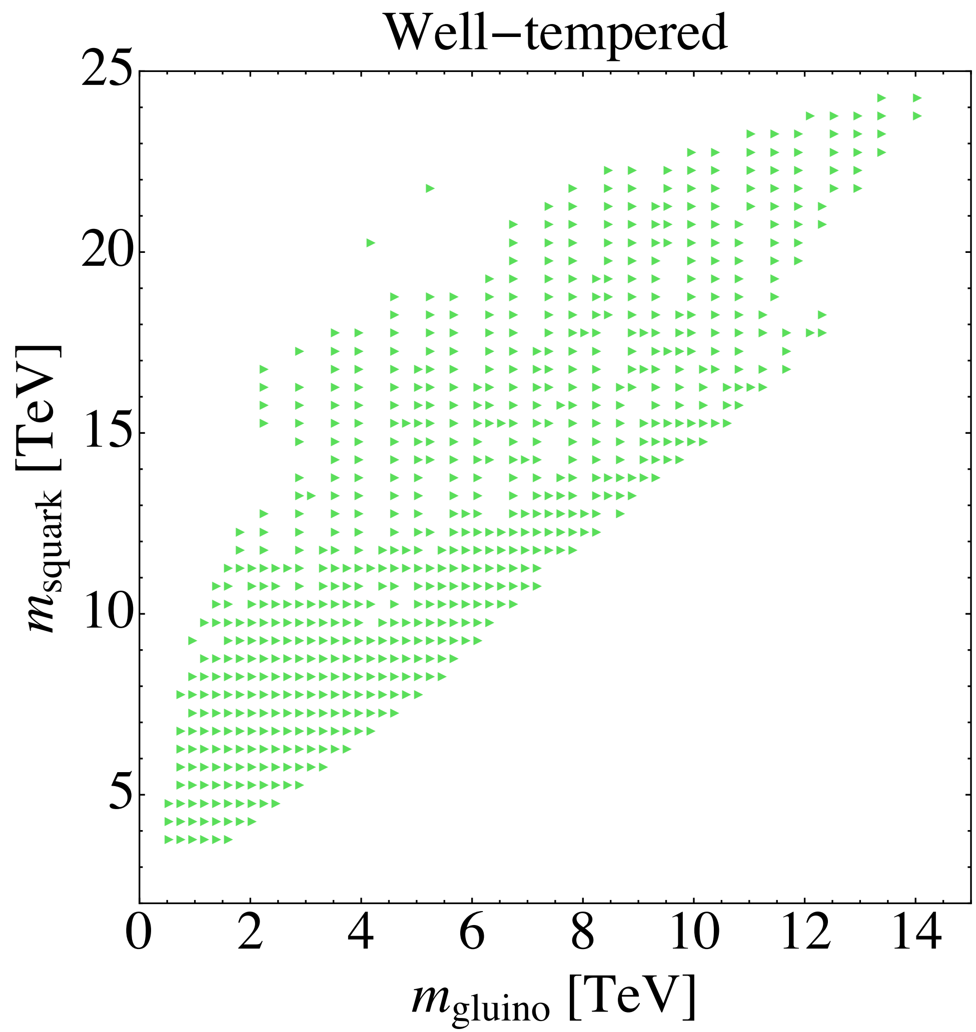
Well-tempered

Setting sail for well-tempered



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

What about the LHC?



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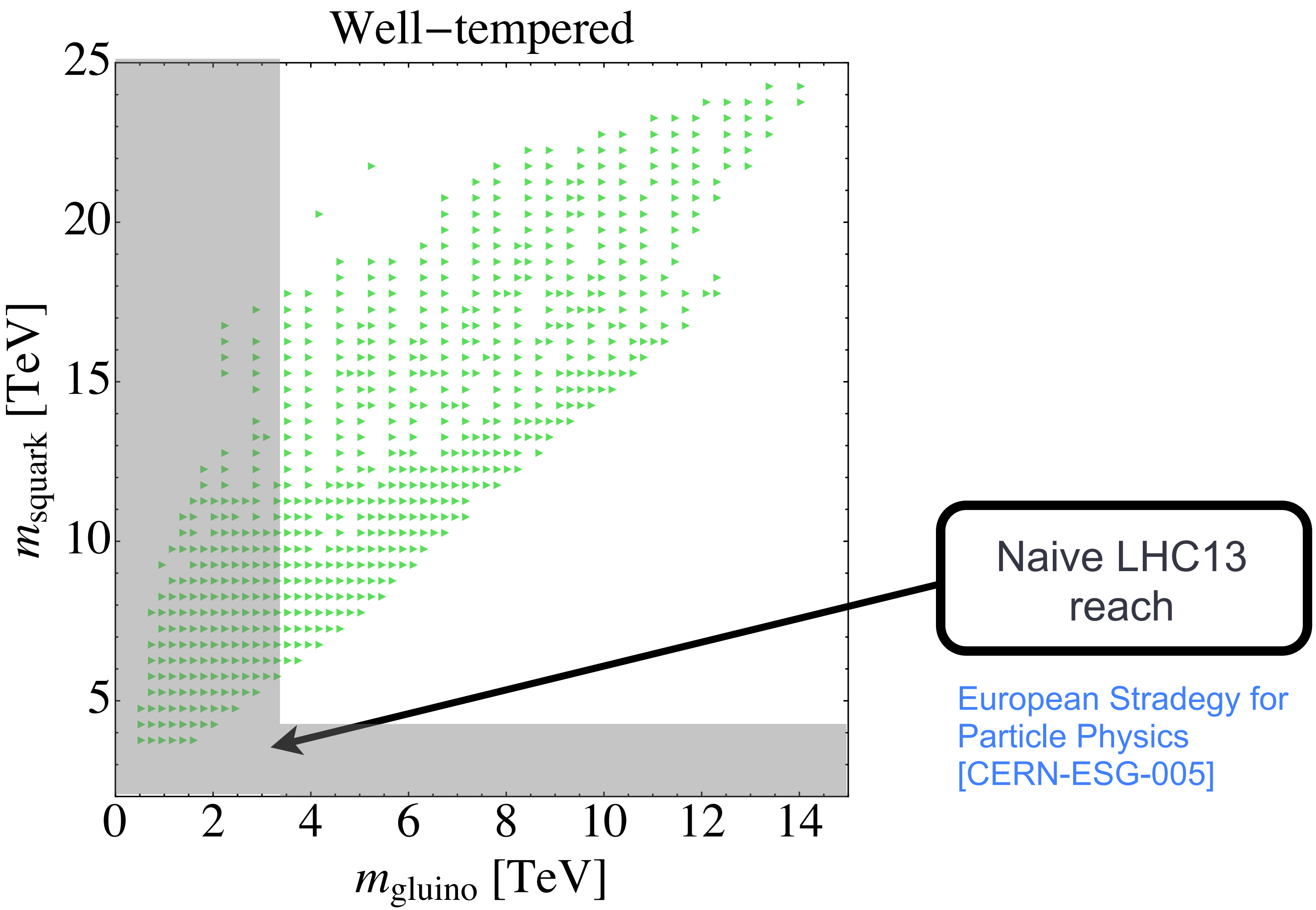
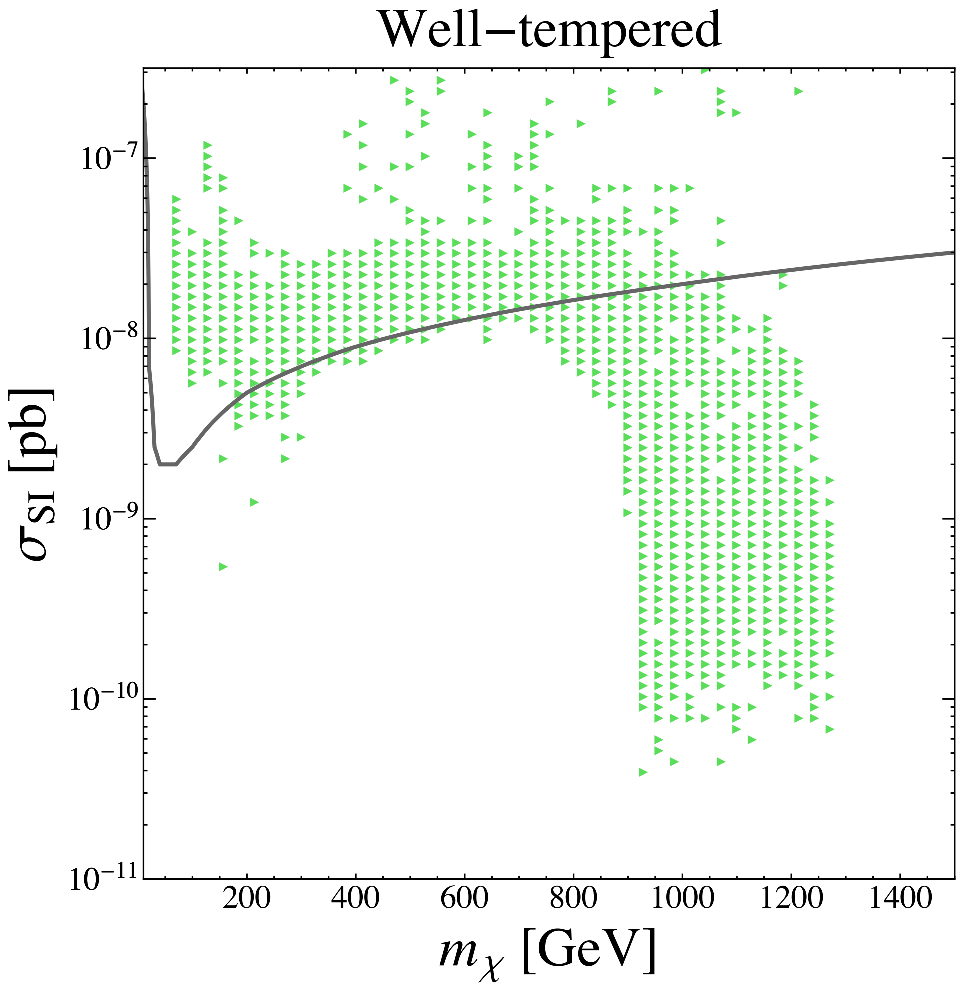


European Stradegy for Particle Physics [CERN-ESG-005]

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

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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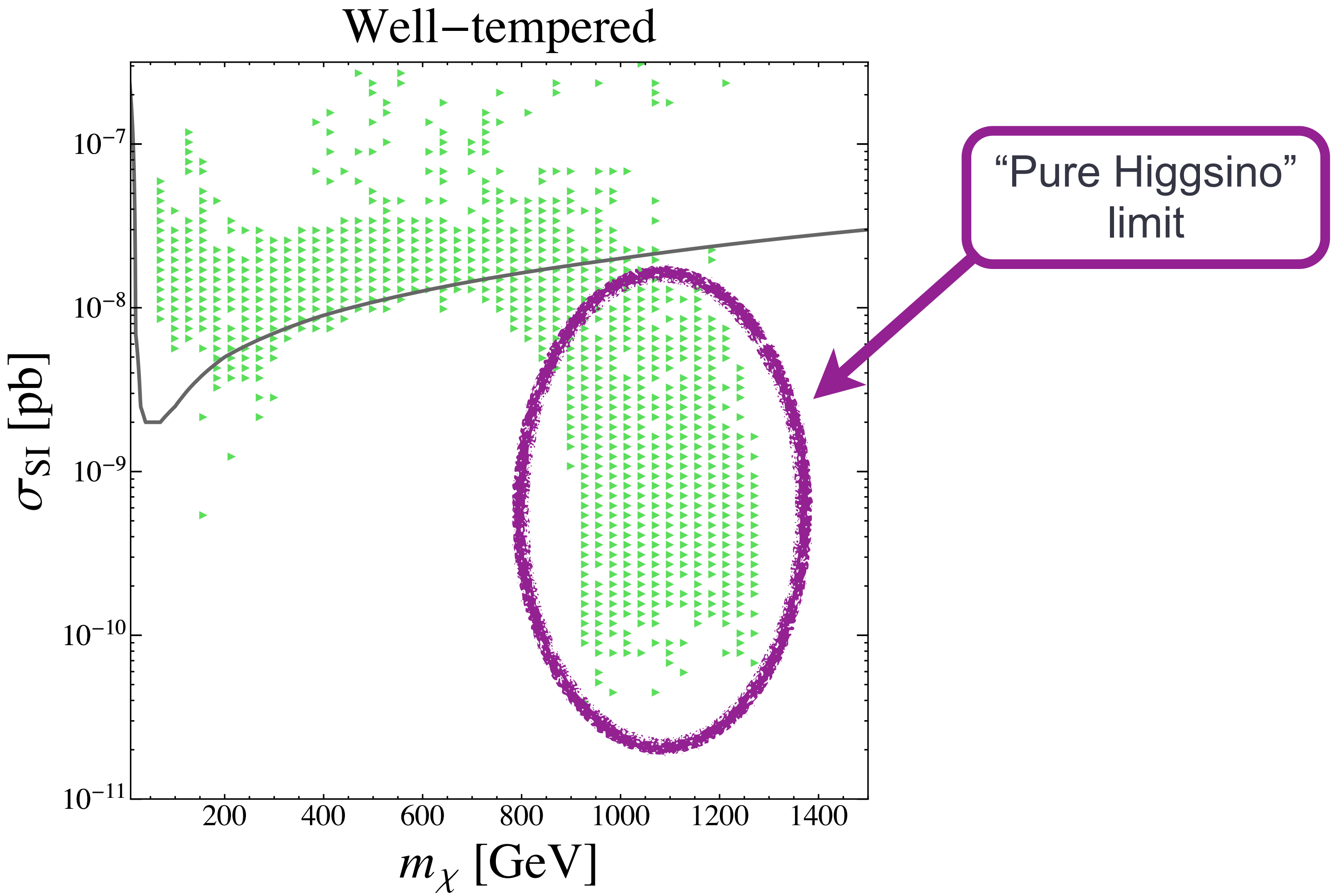

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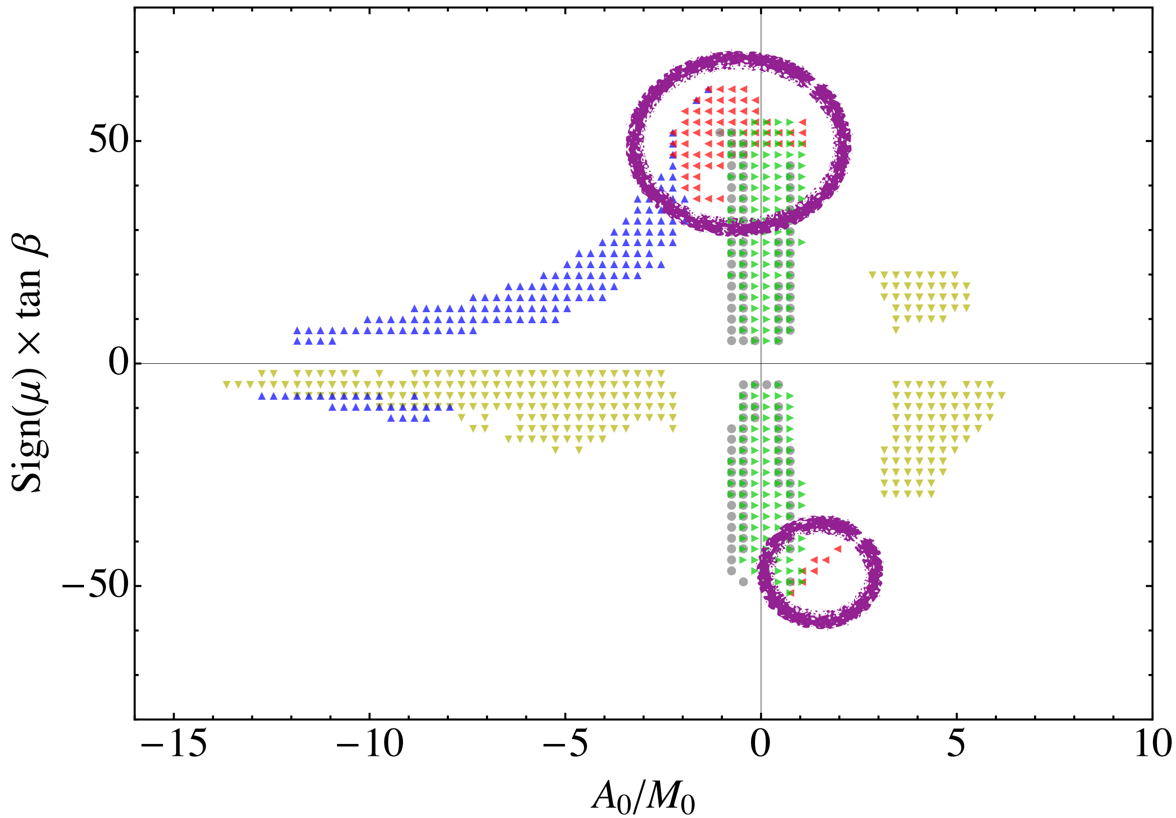
Circumnavigating the CMSSM

A^0 pole annihilation

Setting sail for A^0 pole annihilation



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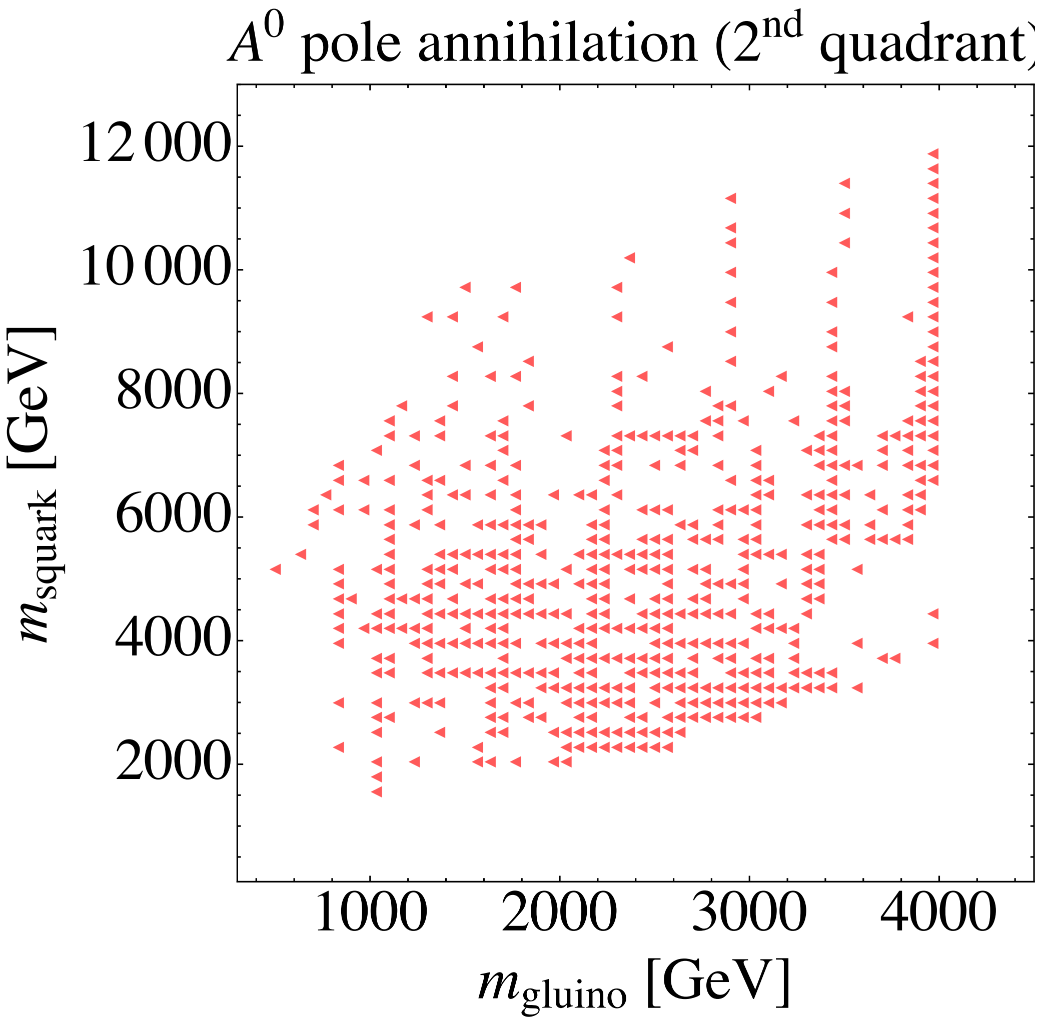
- $500\ \text{GeV} \lesssim M_0 \lesssim 16\ \text{TeV} \qquad [\mu > 0]$
  $200\ \text{GeV} \lesssim M_{1/2} \lesssim 7\ \text{TeV} \qquad [\mu > 0]$
- $5\ \text{TeV} \lesssim M_0 \lesssim 10\ \text{TeV} \qquad [\mu < 0]$
  $300\ \text{GeV} \lesssim M_{1/2} \lesssim 2\ \text{TeV} \qquad [\mu < 0]$

The squark-gluino plane



- 1st quadrant is similar.

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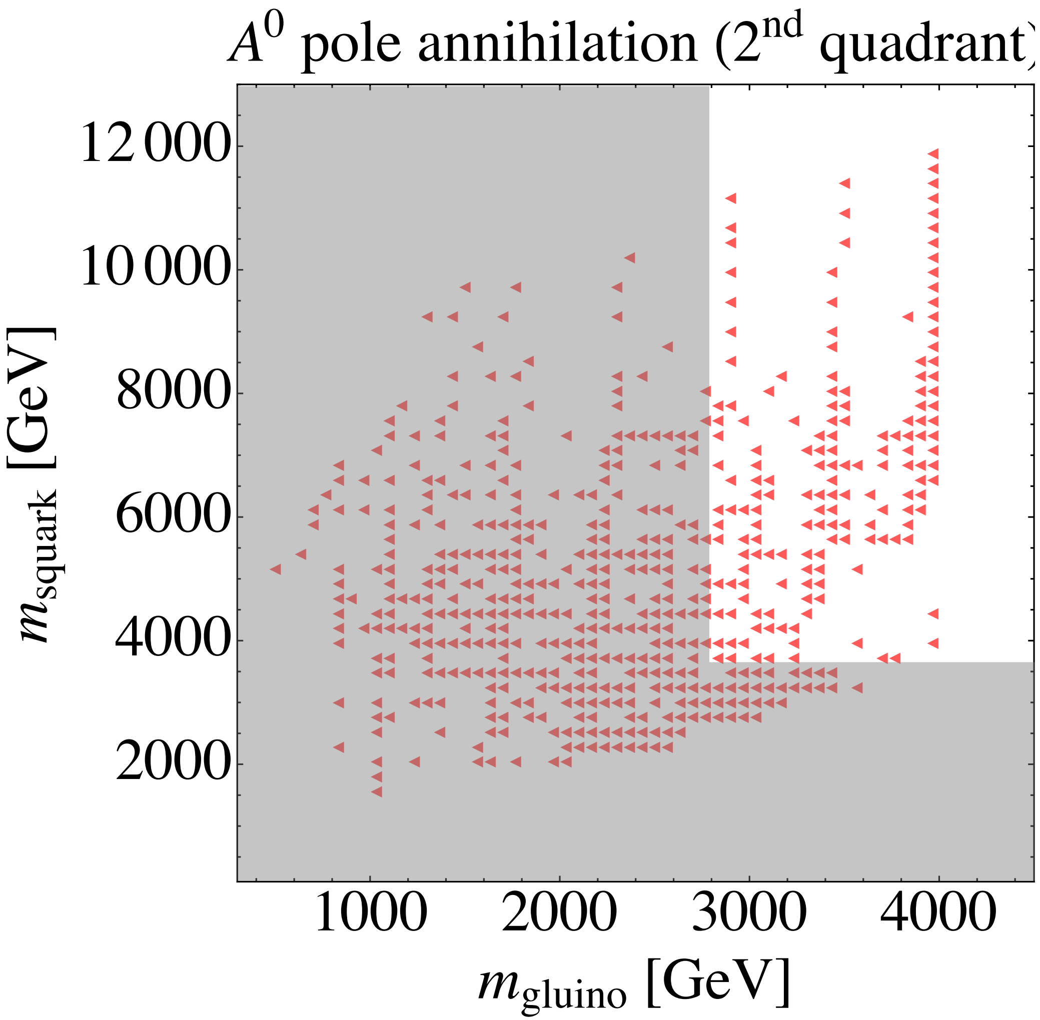
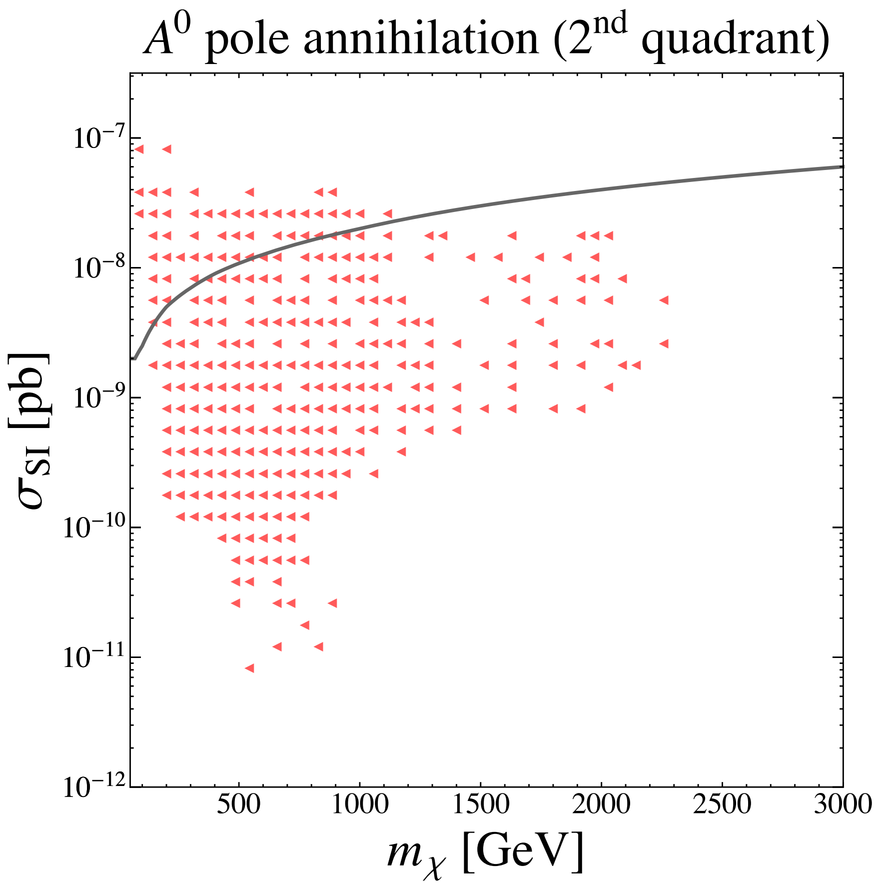
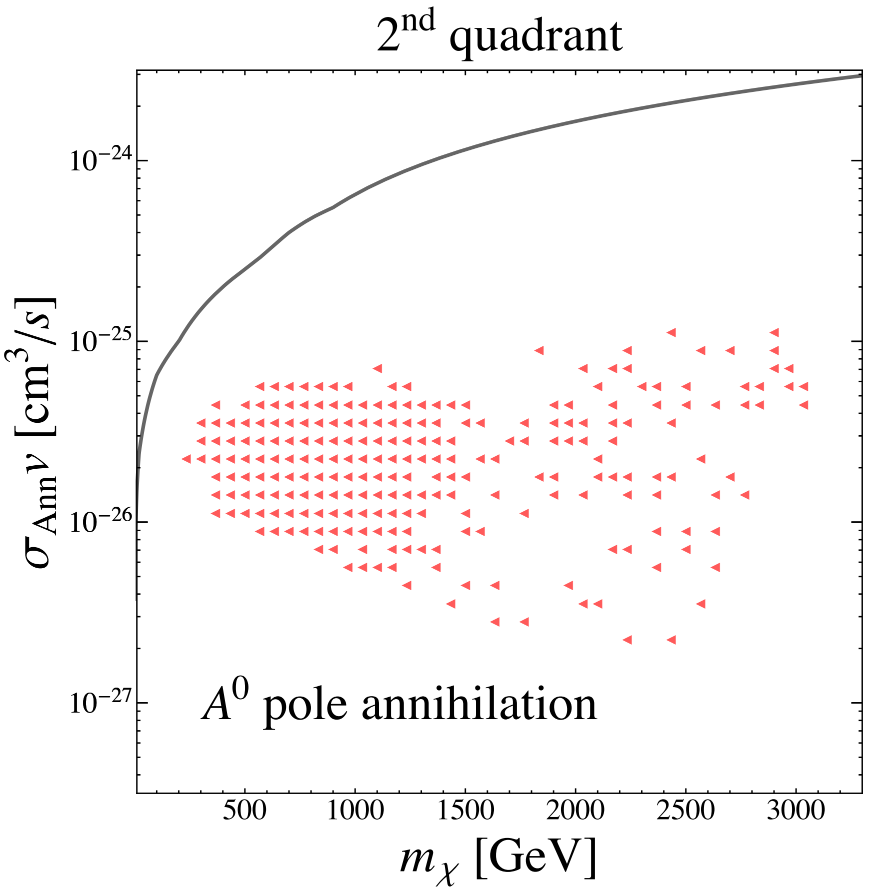


- 1^{st} quadrant is similar.

Direct & Indirect Detection



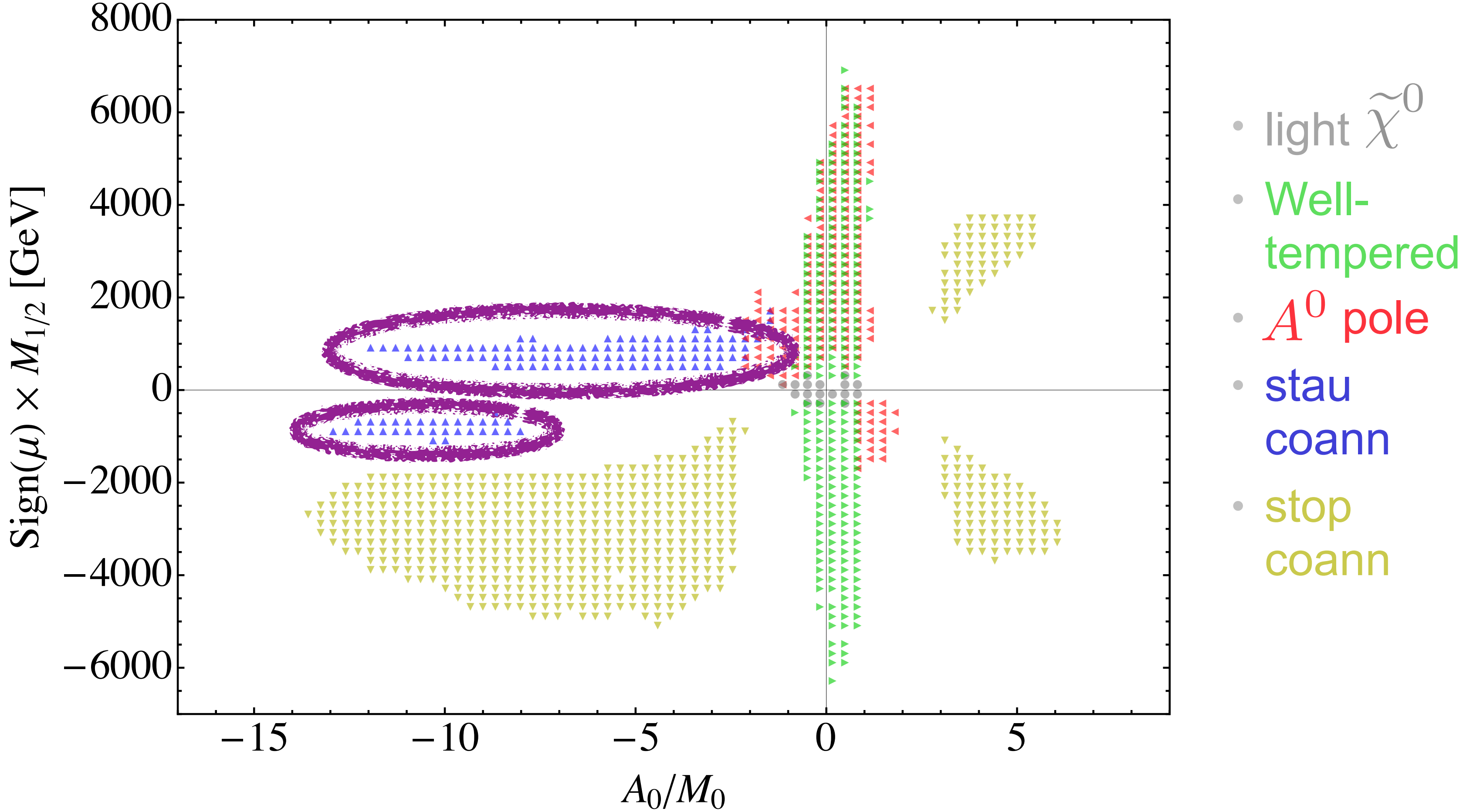


- 1st quadrant is similar but 4th quadrant extends below 10^{-14} pb .

CIRCUMNAVIGATING THE CMSSM

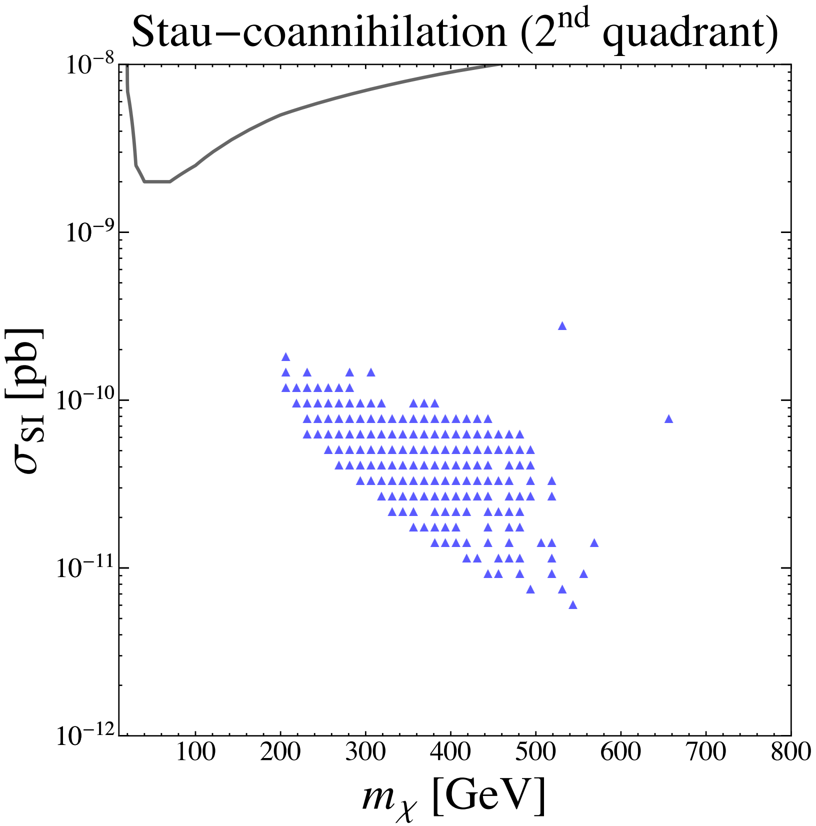
Stau coannihilation

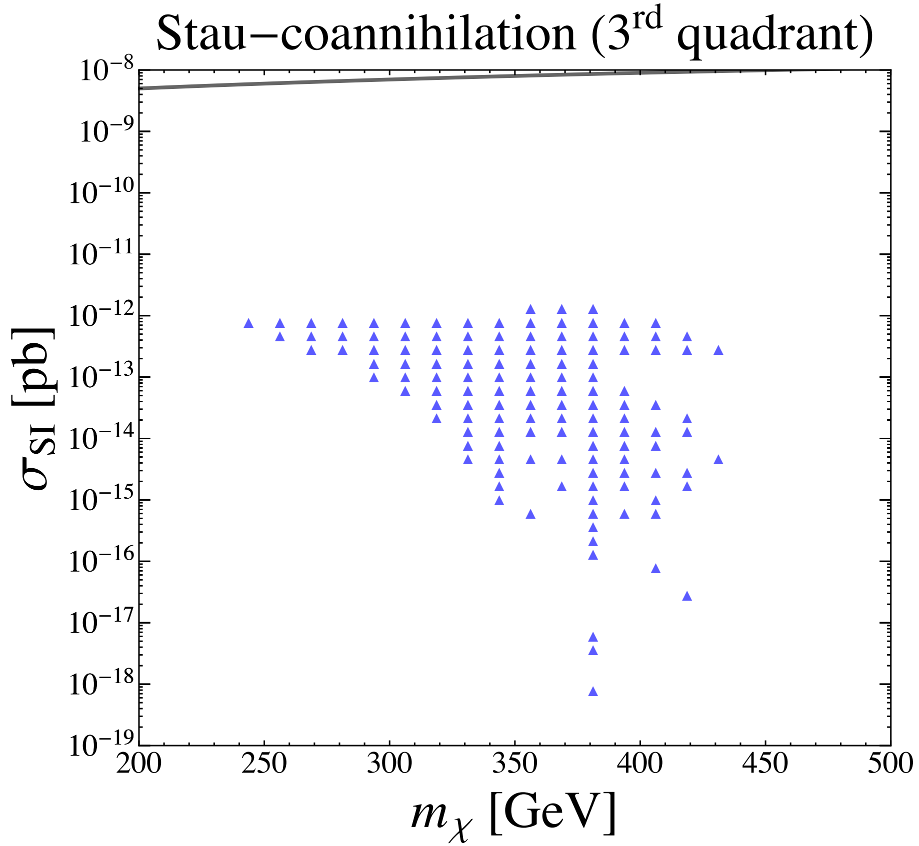
Setting sail for stau coannihilation



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

Stau-coann: direct detection





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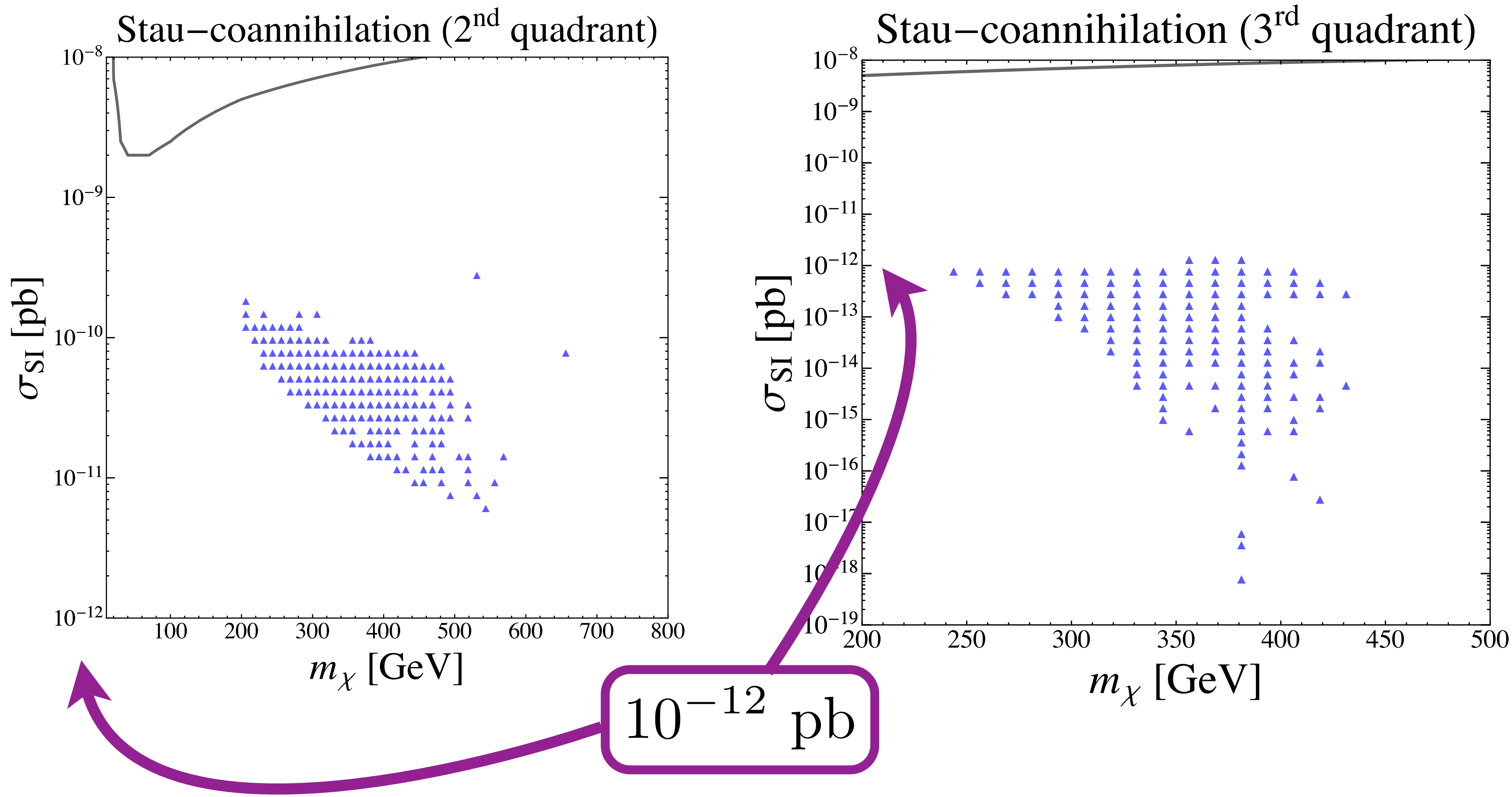
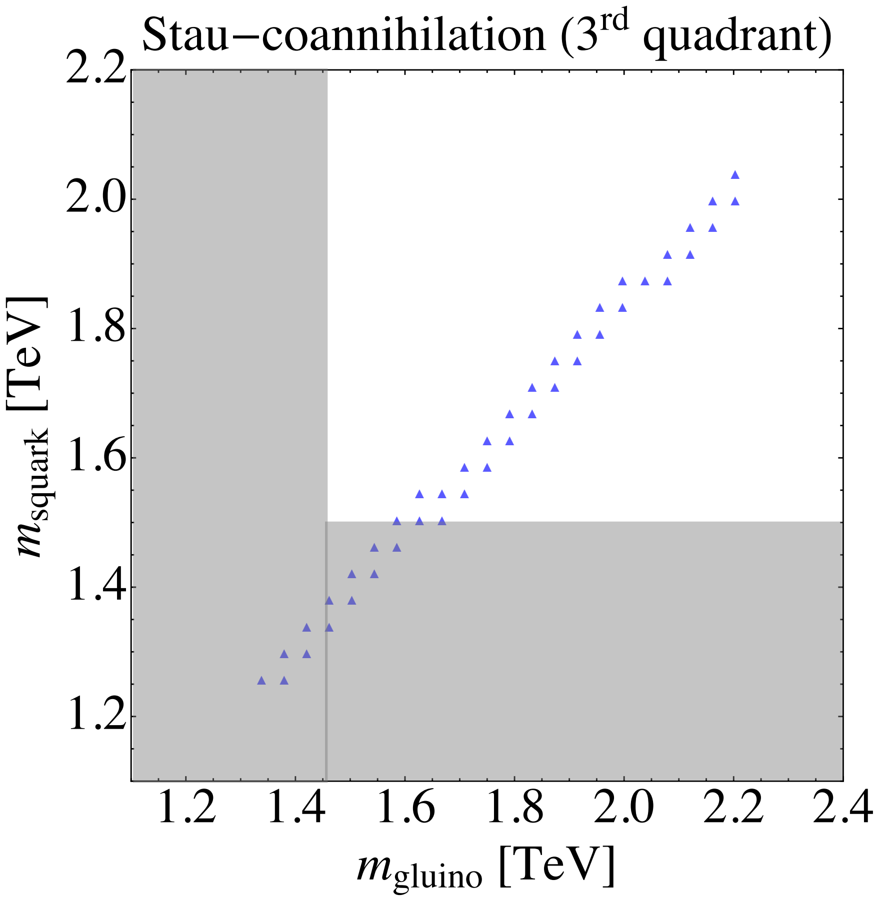
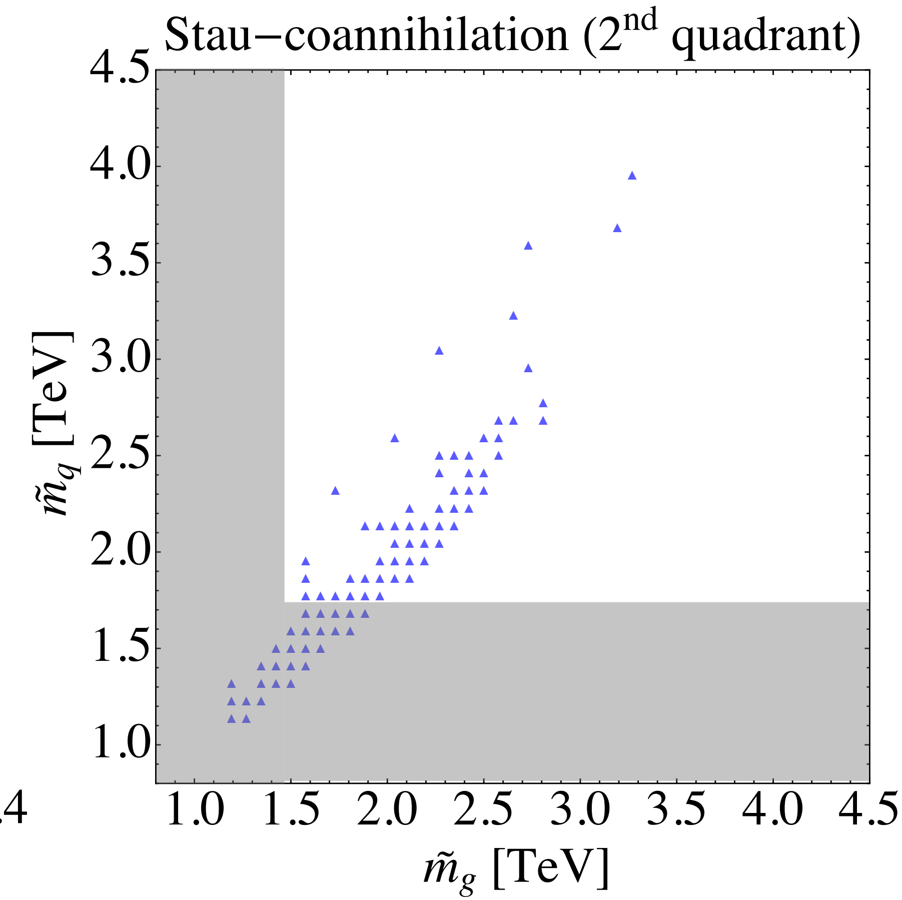


- A 1-ton Xenon experiment can reach spin-independent cross sections of 5×10^{-12} pb at 300 GeV. Dark matter limit plotter [http://dmtools.brown.edu/]
- Direct detection can probe all of the 2nd quadrant.

Stau-coann: squark-gluino plane





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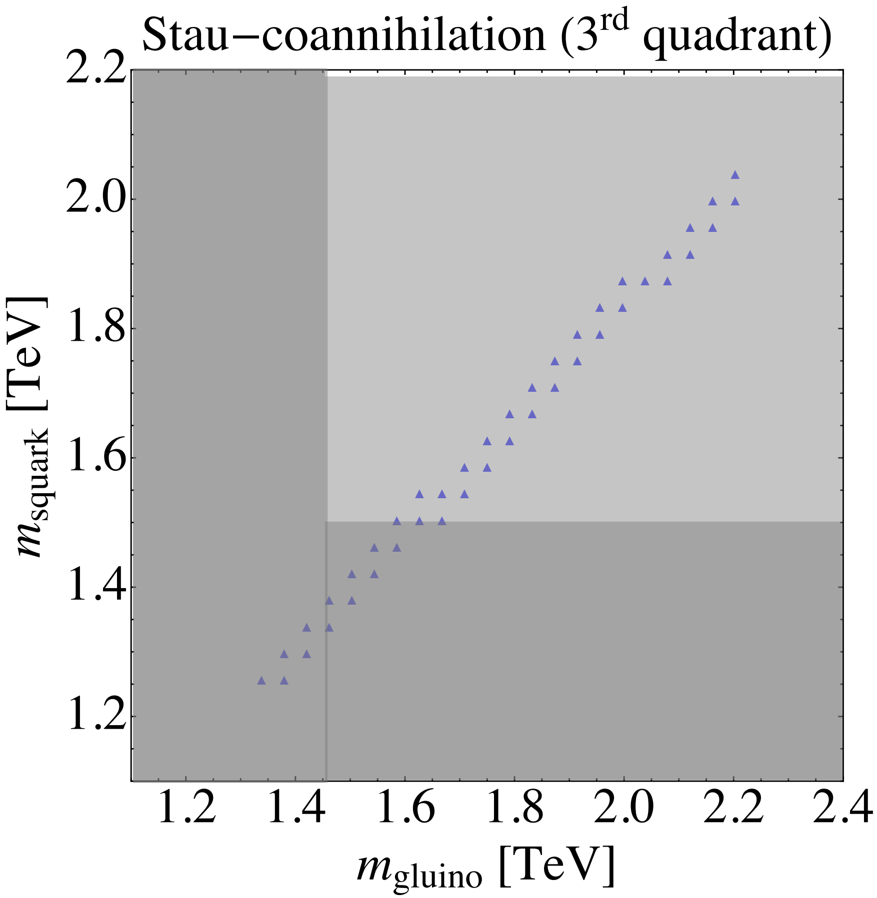

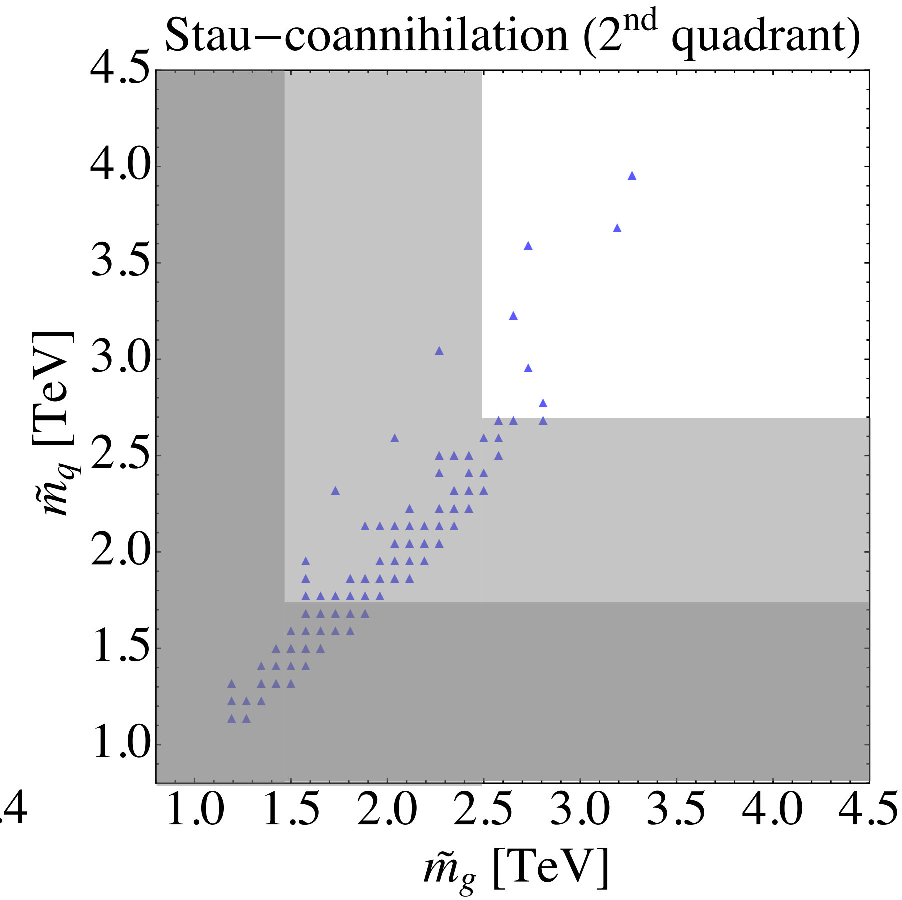

Are these spectra discoverable at the 13 TeV LHC?

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

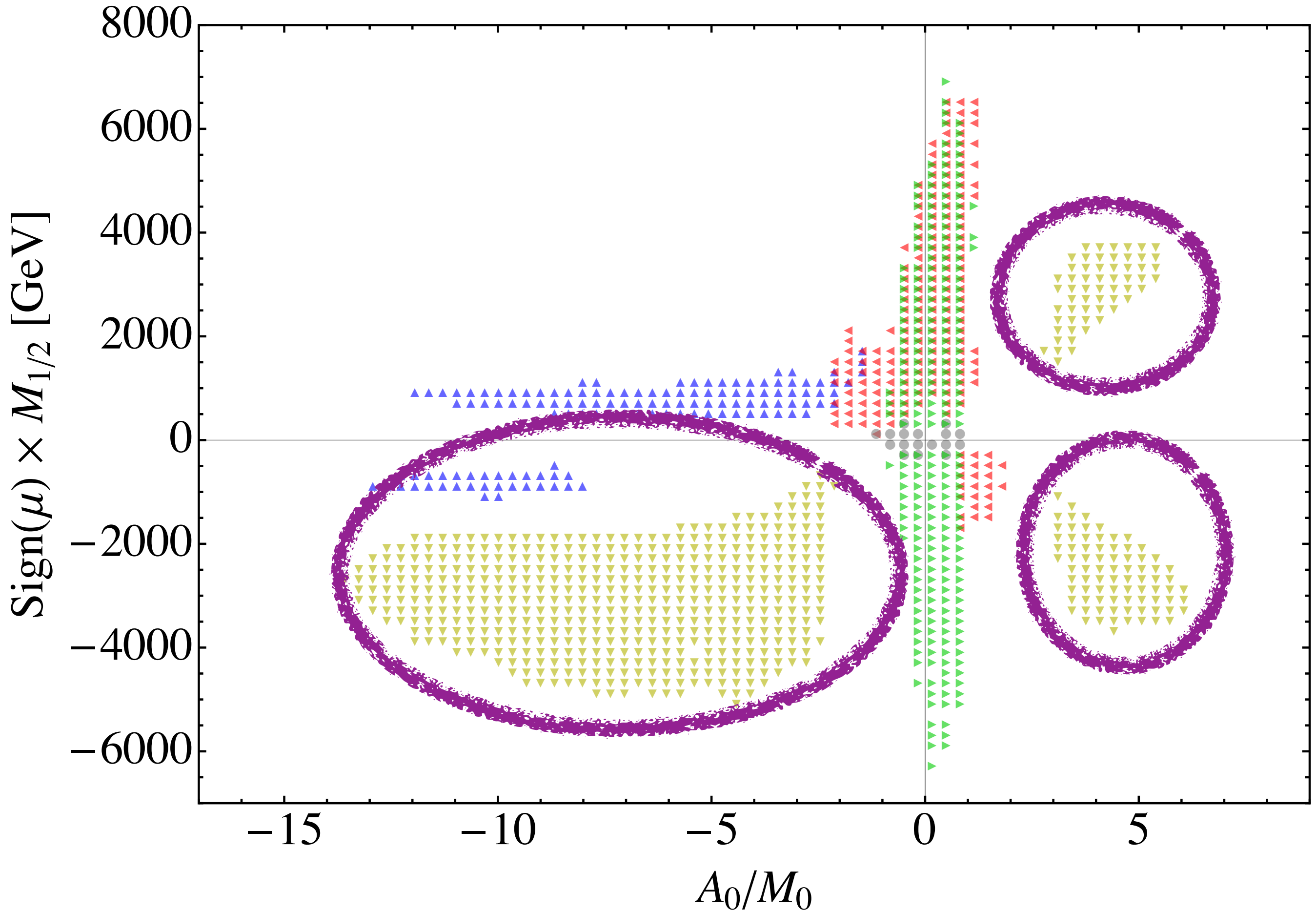
	$\tilde{q}$	$\tilde{b}_1$	$\tilde{b}_2$	$\tilde{t}_1$	$\tilde{t}_2$
m [GeV]	1780.8	1529.9	1715.3	1067.2	1562.9

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

CIRCUMNAVIGATING THE CMSSM

Stop coannihilation

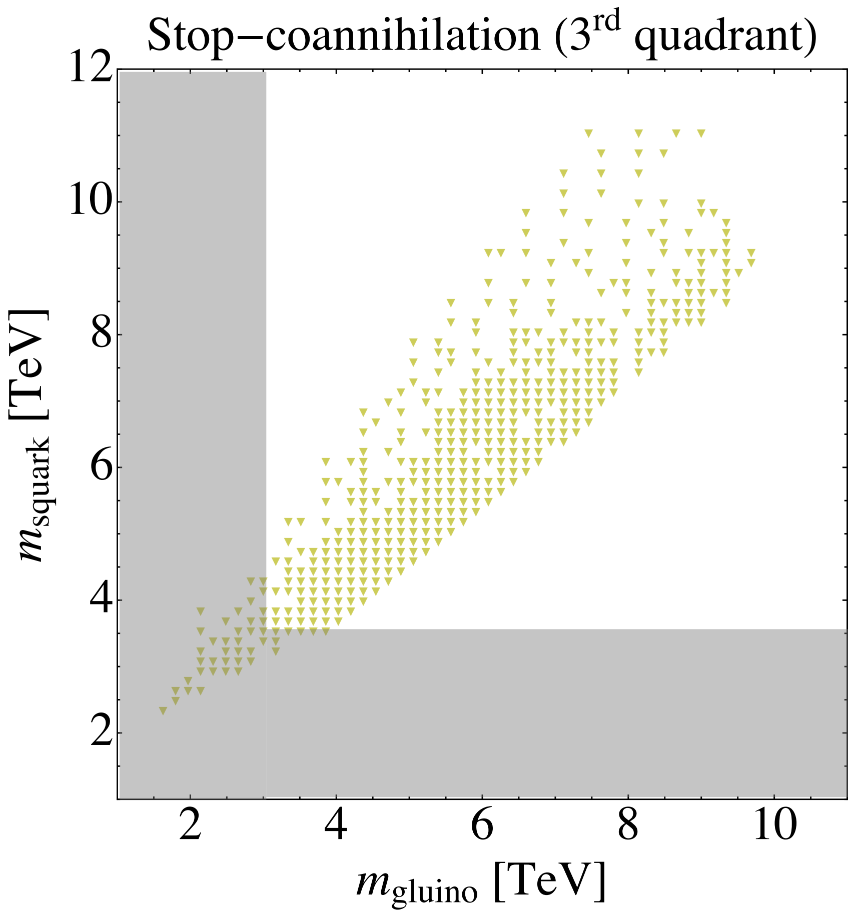
Setting sail for stop coannihilation

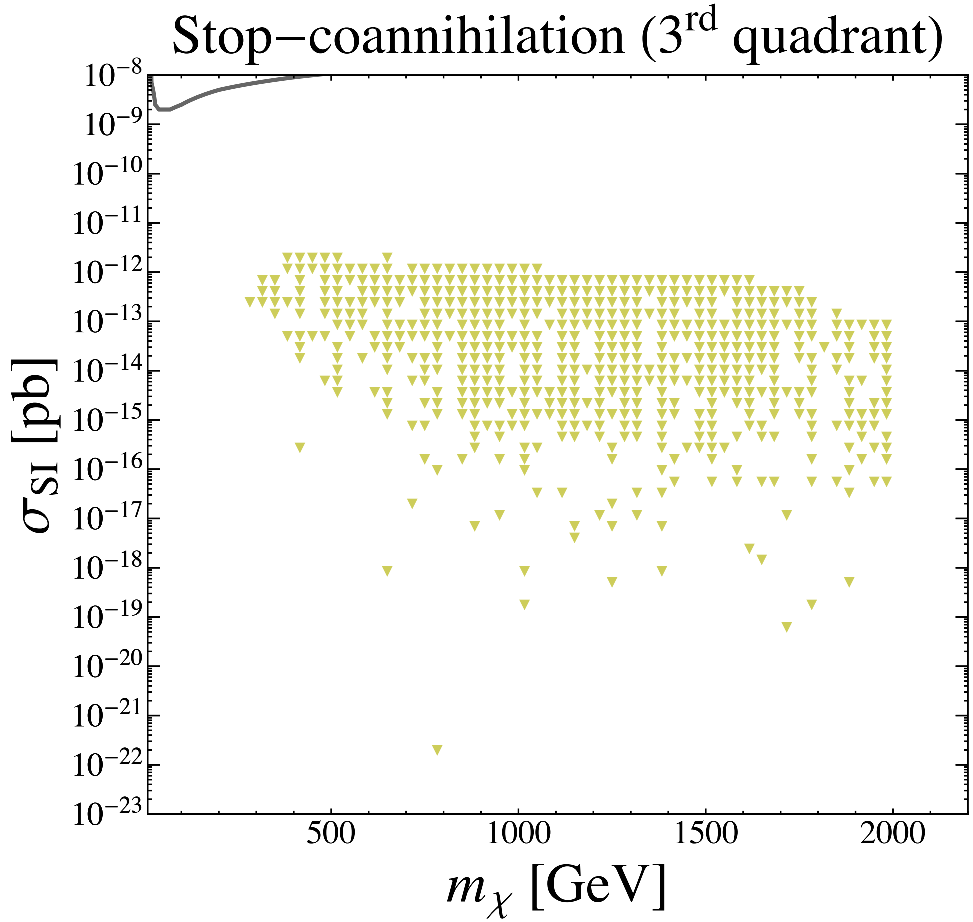


- light $\widetilde{\chi}^0$
- Well-tempered
- A^0 pole
- stau coann
- stop coann

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

Stop-coannihilation phenomenology





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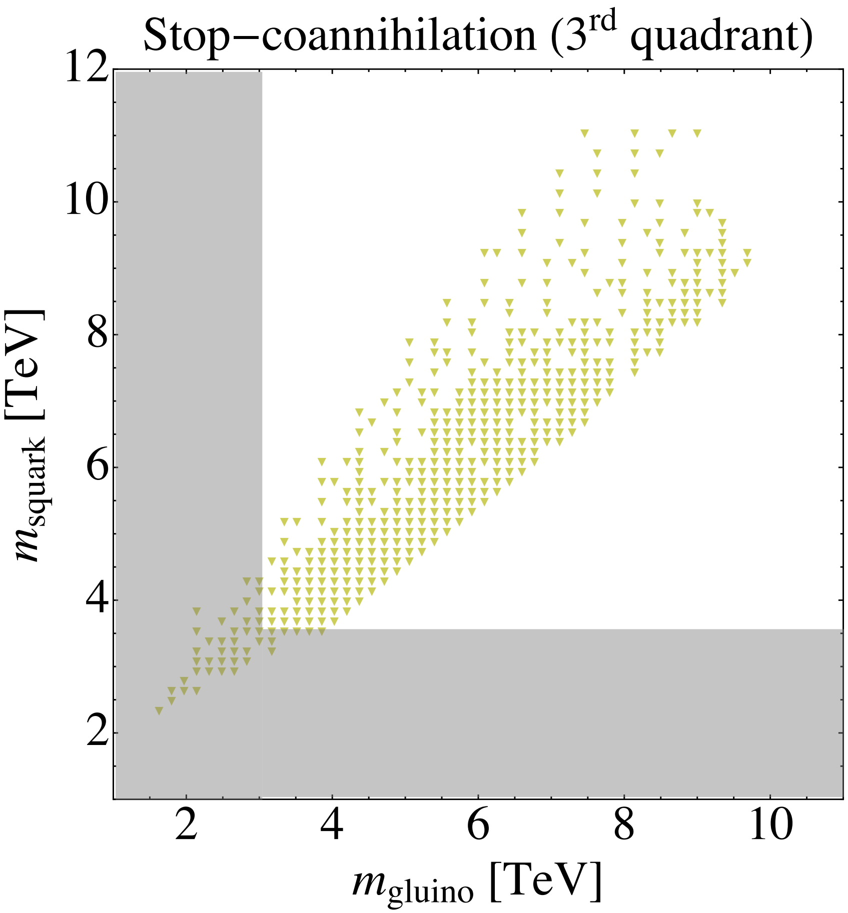

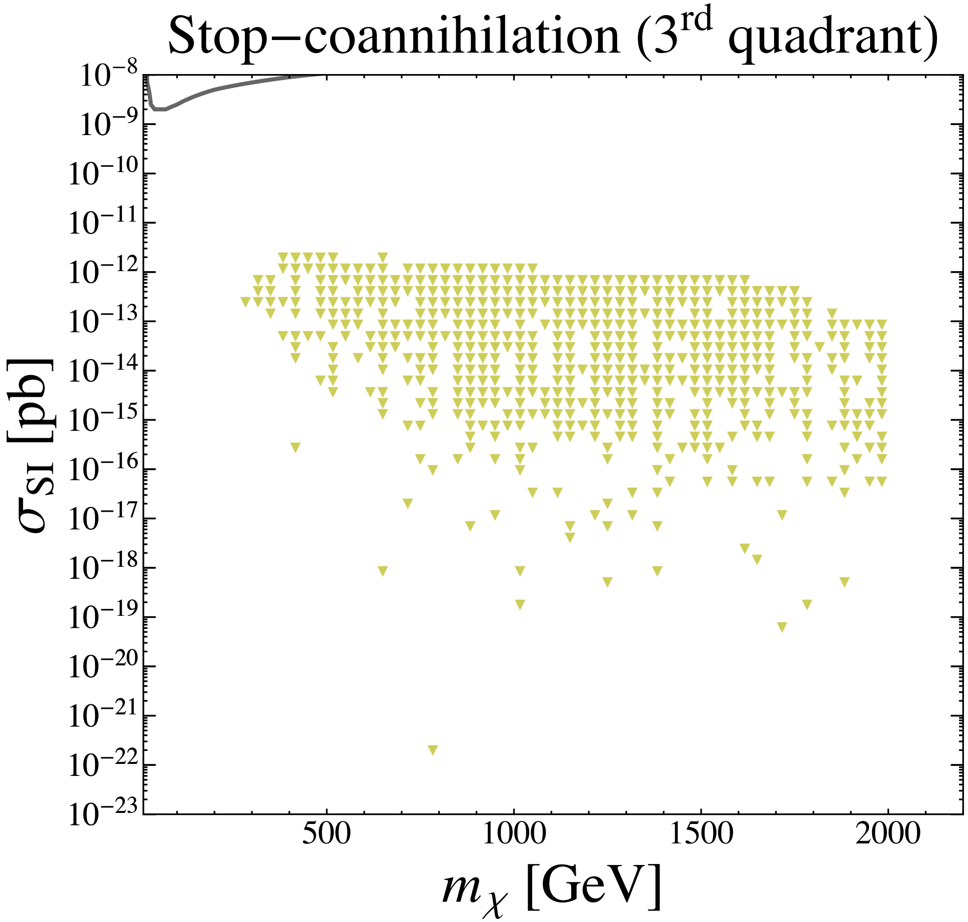

A large portion of these spectra will require a machine beyond the 13 TeV LHC.

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

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

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

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

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

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

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

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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 LHC13 and Ton scale spin-independent direct detection?
    - A^0-pole annihilation
    - Stop coannihilation
- 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.