The Eternal Sunshine of the Supersymmetric Mind

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Eloisa to Abelard

How happy is the blameless theorist's lot!
The world forgetting, by the world forgot.
Eternal sunshine of the supersymmetric mind!
Each pray'r accepted, and each wish resign'd;

Since last Cosener's House Forum

From LHC

- Higgs discovery
- New/more searches
- $BR(B_s \to \mu^+\mu^-)$

Dark Matter

- Fermi γ-ray lines(?)

What's a SUSY?

Bosons $\Leftrightarrow$ Fermions

- $\mathcal{Q}|\text{Fermion}\rangle = |\text{Boson}\rangle$
  $\mathcal{Q}|\text{Boson}\rangle = |\text{Fermion}\rangle$
- $\mathcal{Q}|\text{top}, t\rangle = |\text{scalar top}, \tilde{t}\rangle$
  $\mathcal{Q}|\text{gluon}, g\rangle = |\text{gluino}, \tilde{g}\rangle$
- Doubles size of SM spectrum.

Breaking SUSY

- Unbroken SUSY: All particles in multiplet have same mass.
- Reality: $m_e \neq m_{\tilde{e}} \implies$ SUSY broken.

Why?

SUSY can

Stabilise electroweak hierarchy.

Unification of gauge couplings.

Radiative electroweak symmetry breaking.

Cold dark matter candidate: neutralino,gravitino...

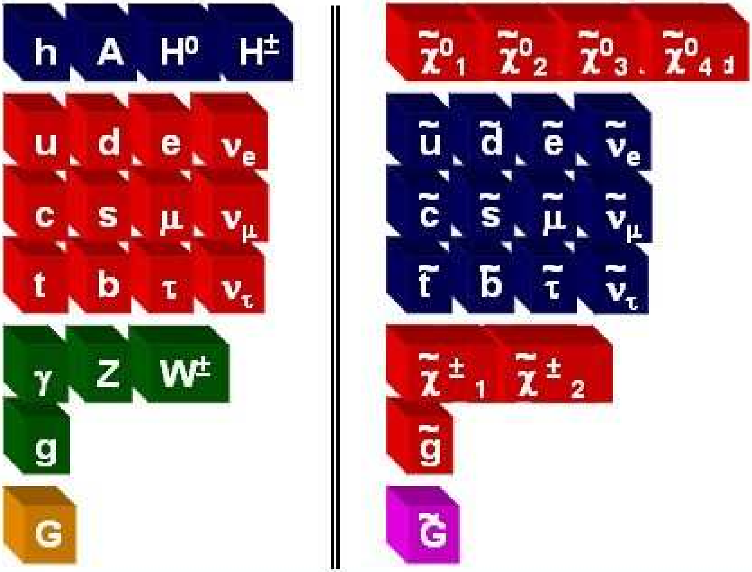
The MSSM

- Take the field content of the SM and promote all fields to superfields. Adds superpartners differing by $s = 1/2$.
- SUSY partners should have masses $\sim$ 0.1–1 TeV.

The Higgs Sector

- Superpartner of Higgs boson is a fermion $\implies$ anomalies don't cancel anymore.
- Solution: Add extra Higgs doublet.
- Physical states: $h^0, H^0, A, H^\pm$ and Goldstone bosons: G^0, $G^\pm$
- $\tan\beta = v_2/v_1$

The Minimal Supersymmetric Standard Model



Natural SUSY

- "SUSY partners should have masses $\sim$ 0.1–1 TeV".
- MSSM:

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

- In absence of large cancellations should have $\mu^2 \sim m_{H_u}^2 \sim \mathcal{O}(v^2)$

- Higgsino masses directly controlled by μ
- Want light higgsinos.

Radiative Corrections to $m_{H_u}^2$

One-loop

$$\delta m_{H_u}^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2 \right) \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

- Want light stops.
- Hierarchical stops with large A_t not necessarily good for naturalness.

Radiative Corrections to $m_{H_u}^2$

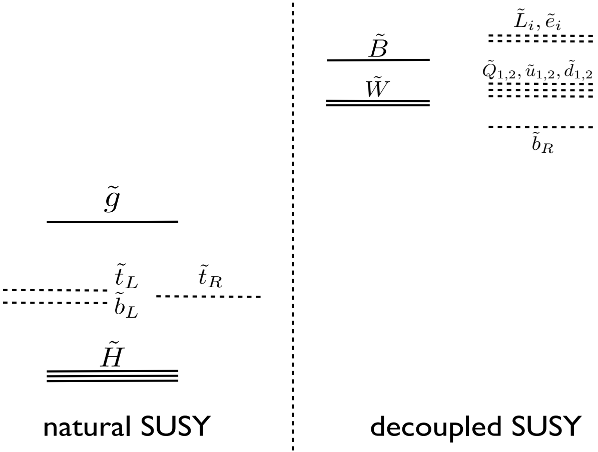
Two-loops

$$\delta m_{H_u}^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2 \right) \log \left(\frac{\Lambda}{\text{TeV}} \right)$$

$$\delta m_{H_u}^2|_{gluino} = -\frac{2}{\pi^2} y_t^2 (\frac{\alpha_s}{\pi}) |M_3|^2 \log^2 (\frac{\Lambda}{\text{TeV}})$$

- Want light stops and gluino

Natural SUSY Spectrum[1]



[1] from 1110.6926

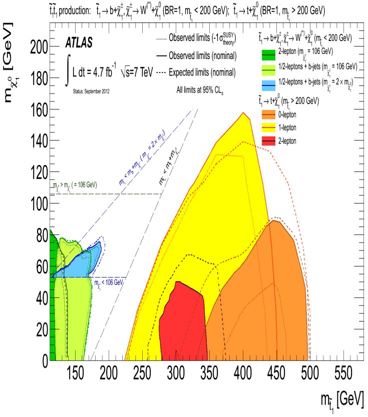
The Relic Density in Natural SUSY

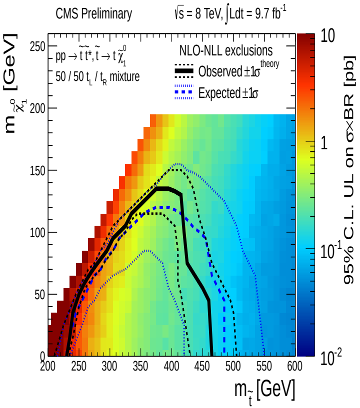
- Assumption (RPC): LSP is a higgsino-like neutralino
- Can calculate thermal relic density

$$\Omega h^2 \sim 0.1 \left(\frac{\mu}{1\,\mathrm{TeV}}\right)^2$$

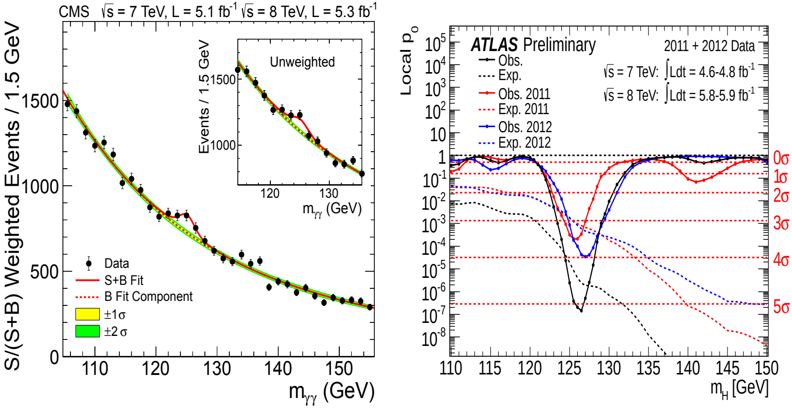
- Relic density might be non-thermally produced
- LSP could have a substantial bino-component
- Relic density could be 'topped-up' with something else

Searches for Natural SUSY





Habemus Higgs



The MSSM Higgs

- Higgs mass in MSSM is not a free parameter
- Tree level bound: $M_h^2 < M_Z^2 \cos^2 2\beta$
- Need large radiative corrections

1-loop corrections: 3^{rd} family dominance, decoupling limit

$$M_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 m_t^4}{2\pi^2 v^2} \left[\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12 M_S^2} \right) \right]$$

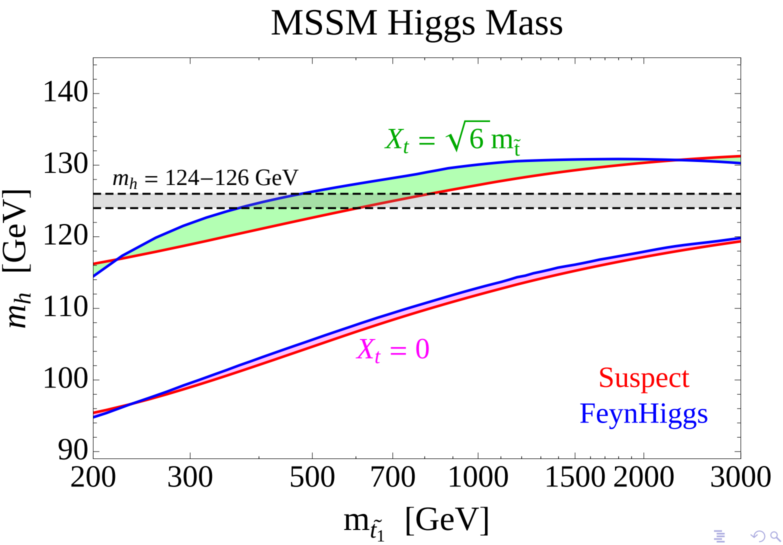
Implications

1-loop corrections: 3rd family dominance, decoupling limit

$$M_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

- Need heavy scalars: $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
- Or large mixing: $X_t = A_t - \mu \cot \beta$
- Maximised for $X_t = \sqrt{6} M_S$

Stop mass versus Higgs[2]

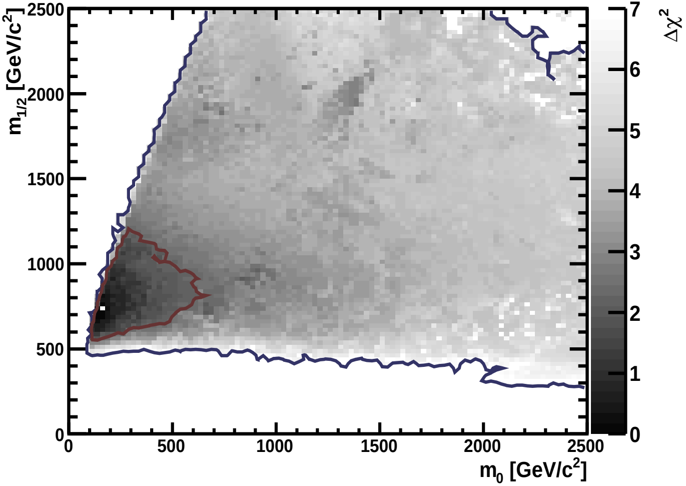


Comments

- Plenty of parameter space left to explore.
- Example: three-body stop decays.
- But constrained models have become...constrained.

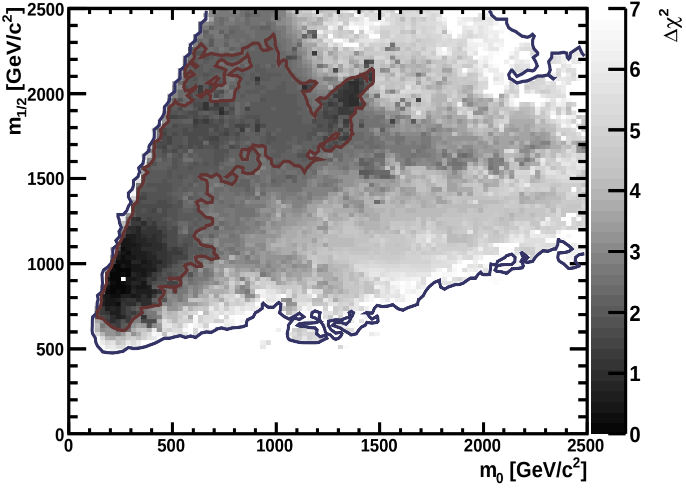
- Models with significant universality (universal scalars m_0, gauginos $M_{1/2}$)
- These models still provide an acceptable fit to data

MasterCode NUHM1 fit: pre-Higgs[3]

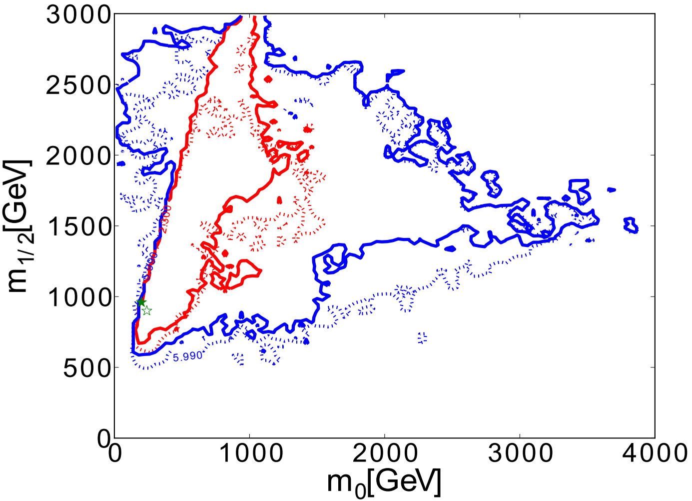


[3] 1112.3564

MasterCode NUHM1 fit: post-Higgs (inc. $A \to \tau\tau$)



MasterCode NUHM1 fit: everything pre-$BR(B_s \to \mu^+\mu^-)$[4]



[4] 1207.7315

How SM-like is the MSSM Higgs?

- In decoupling limit $m_{A,H,H^\pm} > m_h$ get SM like behaviour.
- Can still have $m_H \approx 125$, $m_h \approx 100$ GeV[5]
- $X125 = h$: $\chi^2/$ d.o.f 30.4/36. $p = 73\%$
- $X125 = H$: χ^2 d.o.f 42.4/36. $p = 21\%$

Enhancing rates

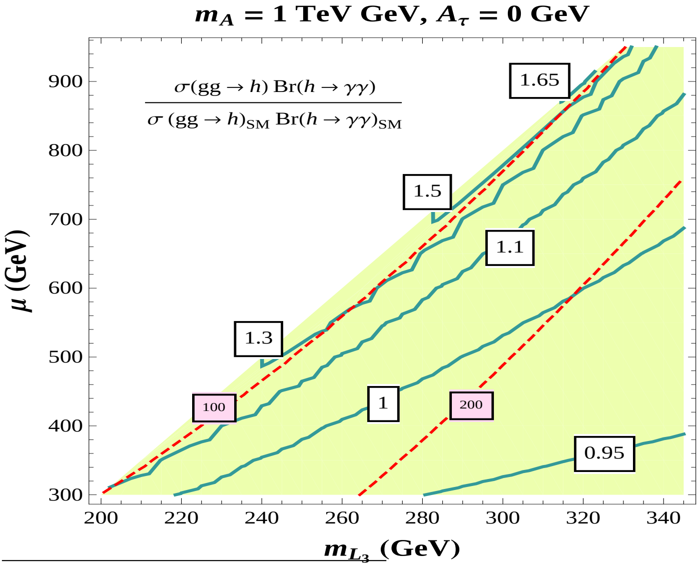
- $h\gamma\gamma/hgg$ loop suppressed $\rightarrow$ sensitive to NP
- Coloured states (stops) enhance $h\gamma\gamma$, suppress hgg[6].
- Light staus can enhance $h\gamma\gamma$: BR $\approx$1.5-2 $\times$BR$_{SM}$ [7]

[5] 1211.1955

[6] 0701235

[7] 1112.3336,1205.5842

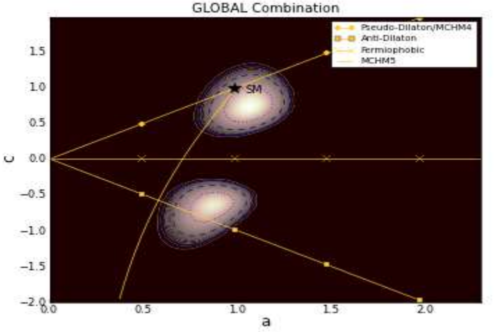
Light staus[8]



[8] 1205.5842

Wrong-sign hGG amplitudes[9]

- Recent Higgs fits allow/prefer $R_t \sim -1$
- New coloured particles in loop - stops?



[9] 1208.1765

Wrong-sign hGG

- Can get $R_t = -1$ with *very* large A_t

$$\frac{A(hGG)}{A_{SM}(hGG)} = 1 + \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1^2}} + \frac{m_t^2}{m_{\tilde{t}^2}} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1^2} m_{\tilde{t}_2^2}}\right)$$

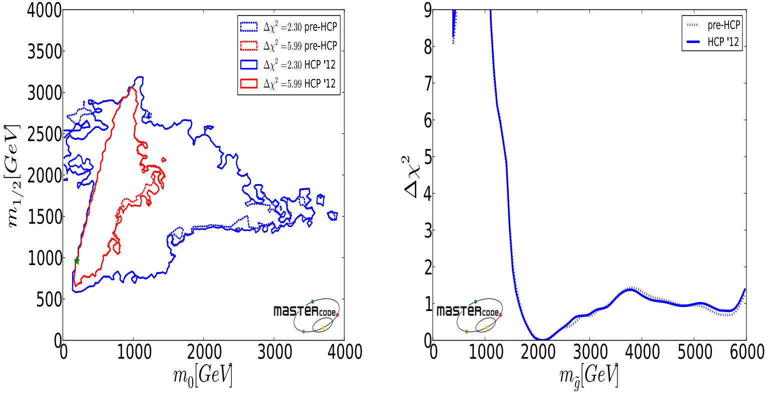
- Leads to violent changes in Higgs potential
- Generally get colour/charge-breaking minima

Recent results on $BR(B_s \to \mu^+\mu^-)$

- LHCb: $BR(B_s \to \mu^+\mu^-) = 3.2^{+1.5}_{-1.2} \times 10^{-9}$
- Combination: $BR(B_s \to \mu^+\mu^-) = 3.0^{+1.2}_{-1.1} \times 10^{-9}$
- SUSY contribution $\propto \tan^6\beta / M_A^4$

- If $\tan\beta$ not very large, ≤ 40,
- If $m_{H,A}$, $m_{\chi^\pm}$ not very light.
- Largest SUSY effects will mostly decouple

Effects of $BR(B_s \to \mu^+\mu^-)$ on global fits: NUHM1



Where does this leave us?

- Vanilla SUSY, naturalness paradigm being probed.
- Constraints start to bite some models
- But still plenty of room left.
- Fine-tuning issues with Higgs mass?

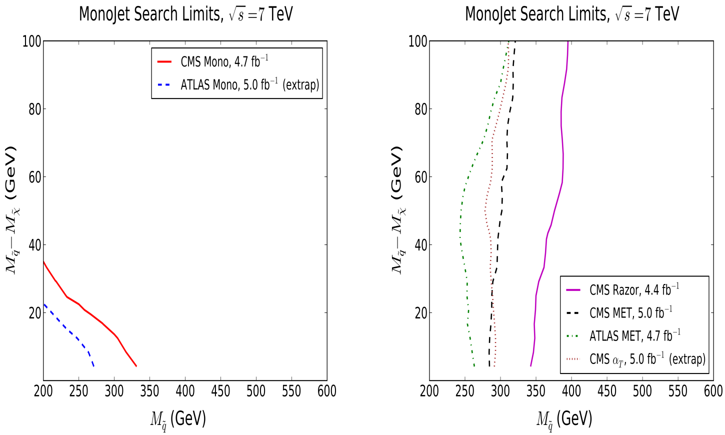
Evasive Manoeuvres

- Higgs not a fundamental scalar $\rightarrow$ Giacomo's talk.
- Evading searches
- Evading MSSM naturalness

Crouching Theorist, Hidden SUSY

- Theorists are good at hiding things.
- SUSY can hide by having soft p_T spectrum $\longrightarrow$ compressed mass spectrum.
- Low MET $\longrightarrow$ R-parity violation

How low can SUSY go?[10]



[10] 1207.1613, also 1211.4981

A final possibility

Minisplit

- Scalars at few TeV, outside LHC reach.
- SUSY solves 'most of' the hierarchy problem
- Fine-tuning $\mathcal{O}(10^{3-4})$.

Is this a suggestion towards something less minimal?

Beyond the MSSM : the NMSSM

Next-to-Minimal

- Add an extra SM singlet S, and $\lambda S H_u H_d \subset \mathcal{W}$
- Changes tree-level mass

$$m_h^2 < M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$

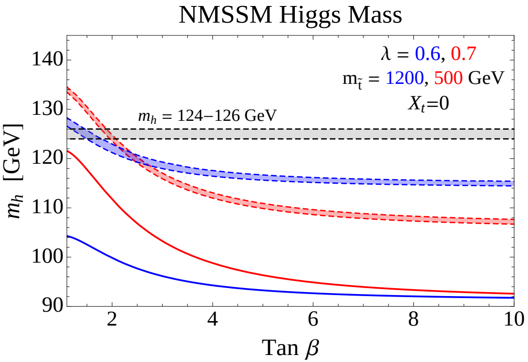
- 3 CP-even, 2CP-odd and charged Higgs states
- Lower fine-tuning possible for a given Higgs mass.

New features

- Doublet-singlet mixing
- Lighter Higgs state could have escaped LEP.
- Longer decay chains, softer decay products.

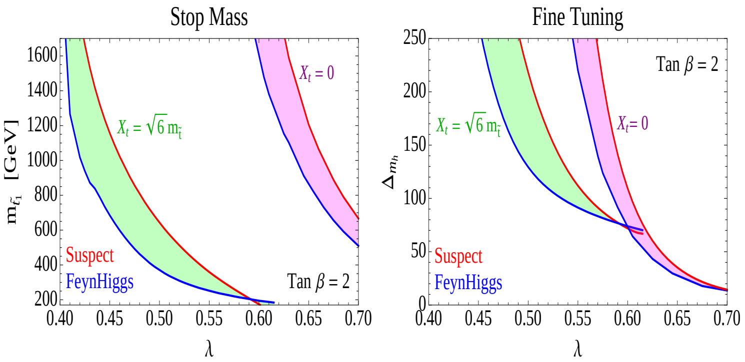
Higgs mass in the NMSSM

- Maximised for small tan β



Fine-tuning

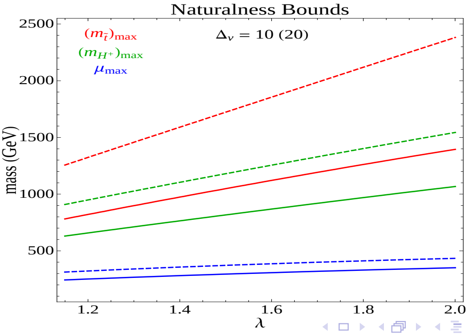
- Low stop masses, fine-tuning



λSUSY

Why stop at $\lambda = 0.7$?

- $\lambda \geq 0.7$: expect non-perturbativity before GUT scale
- What if only perturbative until ~ 10 TeV?
- Larger contribution to m_h, naturalness bounds relaxed



Something Completely Different

- Recent claims of 5σ observation[11] of line(s) in FERMI γ-ray spectrum
- Consistent with $m_\chi \sim 130$ GeV with $\chi\chi \to \gamma\gamma$

Neutralino?

- Doesn't work in the MSSM[12]
- Correct linestrength $\to$ ruled out by continuum γ constraints
- Correct relic density $\to$ linestrength too small.
- Need keep Ωh^2 , but boost $\langle \sigma v \rangle_{\gamma\gamma}$

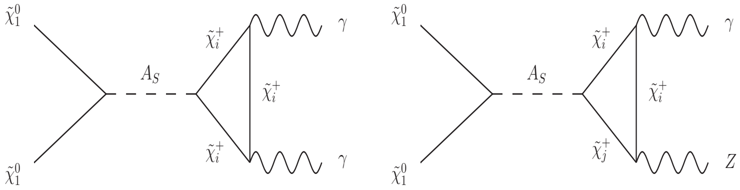
[11] 1204.2797,1205.1045,1206.1616

[12] 1206.7056,1207.0800

Add a new resonance [13]

Pseudoscalar decaying to $\gamma\gamma$

- Need to suppress decays to $f\bar{f}$ - singlet-like state.
- Have this in the NMSSM



[13] 1206.2639,1211.2835,1211.Monday

Boosting the Cross-Section

$$\langle \sigma v \rangle_{\gamma\gamma} \sim \frac{\alpha^2 \lambda^2}{4\pi^3} \frac{\left(\lambda N_{13} N_{14} - \kappa N_{15}^2\right)^2 m_{\tilde{\chi}_1^+}^2}{(4 m_{\tilde{\chi}_1^0}^2 - m_A^2)^2} \arctan^4 \left(\sqrt{\frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\chi}_1^+}^2 - m_{\tilde{\chi}_1^0}^2}} \right)$$

$$\sim 1.2 \times 10^{-27}\ \mathrm{cm}^2 \mathrm{s}^{-1} \left(\frac{\lambda}{0.7} \right)^2 \left(\frac{\lambda N_{13} N_{14} - \kappa N_{15}^2}{0.05} \right)^2 \left(\frac{1.5\ \mathrm{GeV}}{\delta_\chi} \right)^2 .$$

We want

- Large λ
- Large $N_{13},\ N_{14} \rightarrow$ light higgsinos
- $m_{\chi_1^\pm} - m_{LSP}$ small $\rightarrow$ compressed.

Summary

SUSY

- MSSM Naturalness: starting to be probed
- Higgs puts constraints on part of MSSM spectrum
- NMSSM alleviates problems with naturalness
- Rich Higgs phenomenology
- Can explain Fermi line