LHC Constraints

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Perspectives on LHC Data, ICTP, June 2013

After Run 1: Why SUSY?

Stabilise electroweak hierarchy (naturalness...)

Unification of gauge couplings.

Radiative electroweak symmetry breaking.

(Cold) Dark Matter

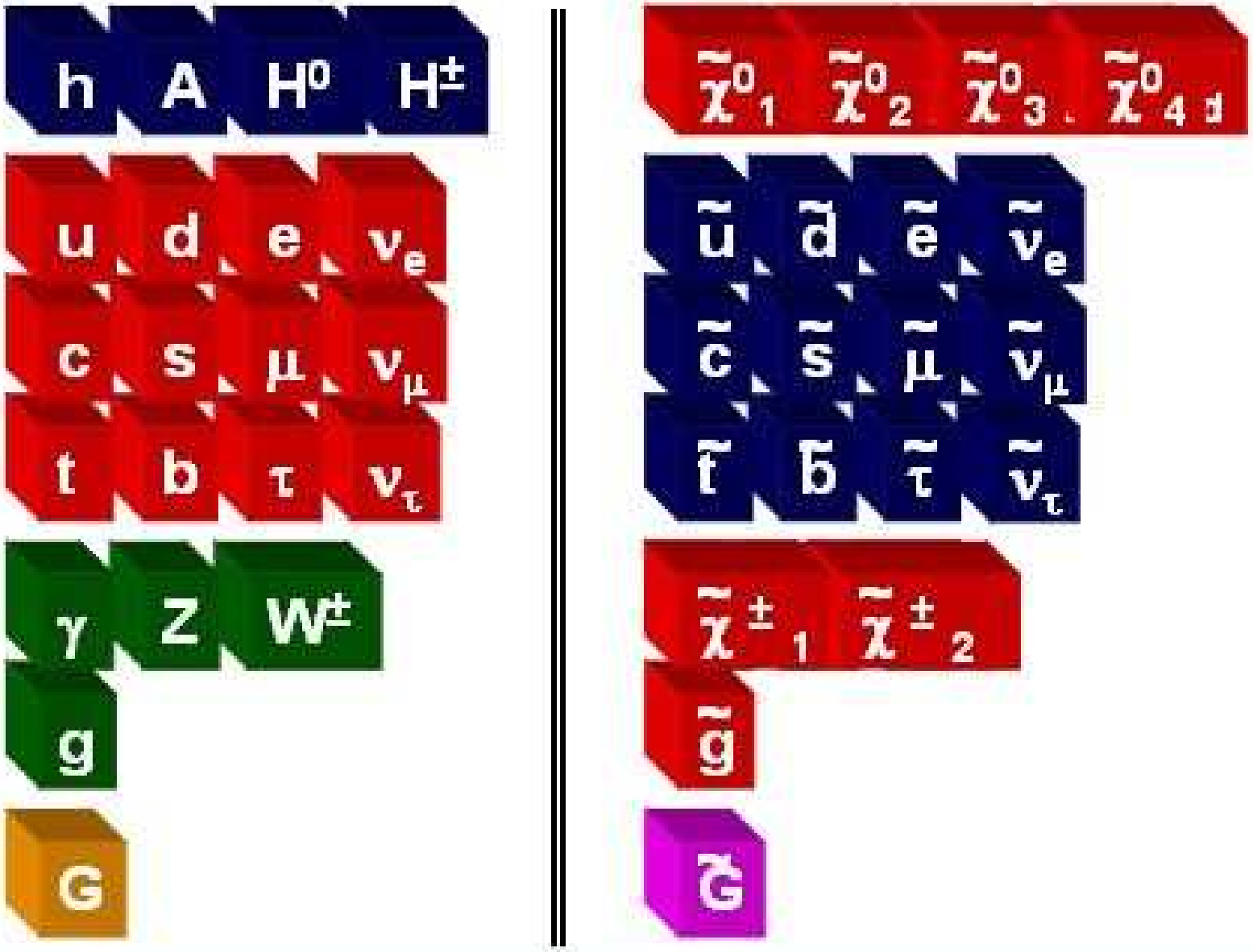
Minimal SUSY: The MSSM

- SM fields $\rightarrow$ superfields. Adds superpartners differing by $s = 1/2$.
- SUSY partners "should have" masses $\sim$ 0.1–1 TeV.

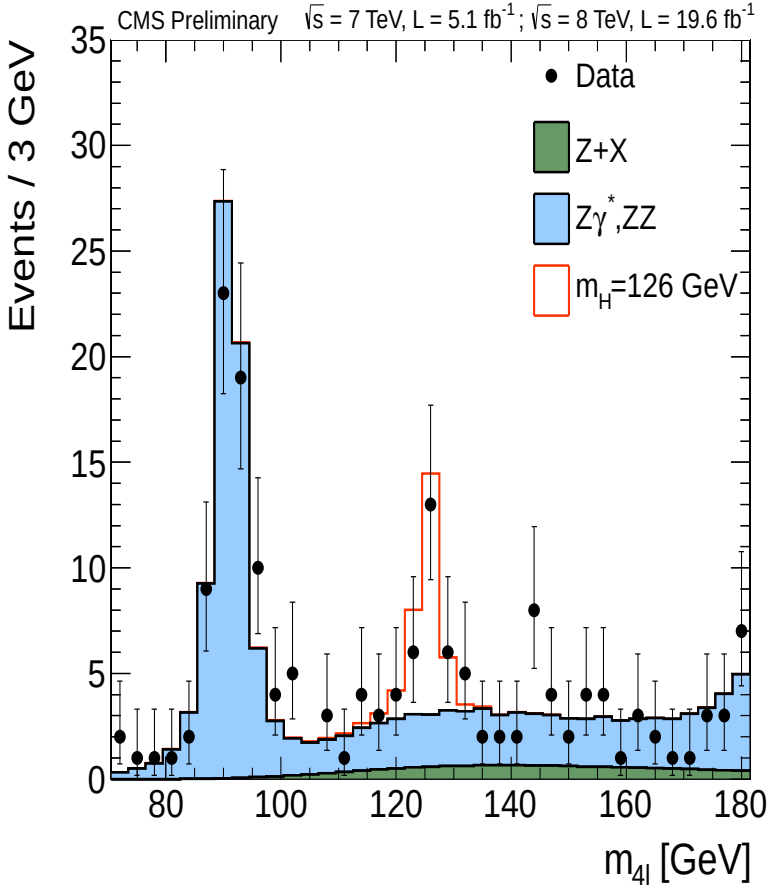
The Higgs Sector

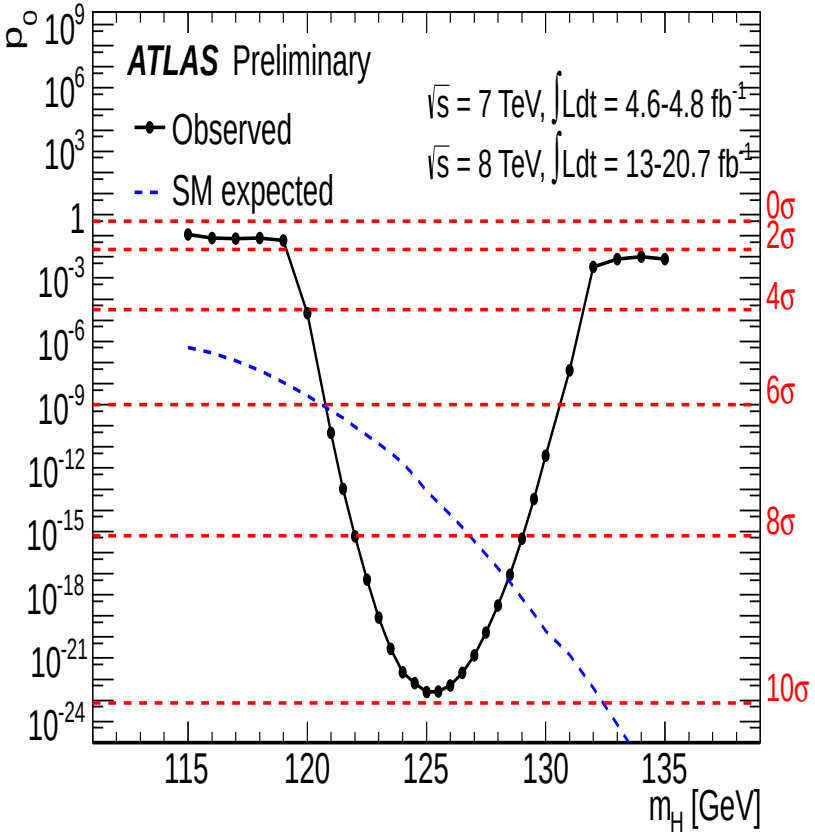
- Superpartner of Higgs boson is a fermion $\rightarrow$ anomalies.
- Solution: Add extra Higgs doublet.
- Physical states: $h^0, H^0, A, H^\pm$ and Goldstone bosons: G^0, $G^\pm$
- $\tan\beta = v_2/v_1$

The Minimal Supersymmetric Standard Model



Constraint: Higgs mass





The MSSM Higgs

Tree-level

- 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: 3rd family dominance, decoupling limit

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

Implications of 125 GeV

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

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

- (Minimal) SUSY predicts a light Higgs.
- 125 GeV: Light enough for SUSY to remain interesting.
- Heavy enough to put some specific models in trouble (mGMSB,mAMSB).

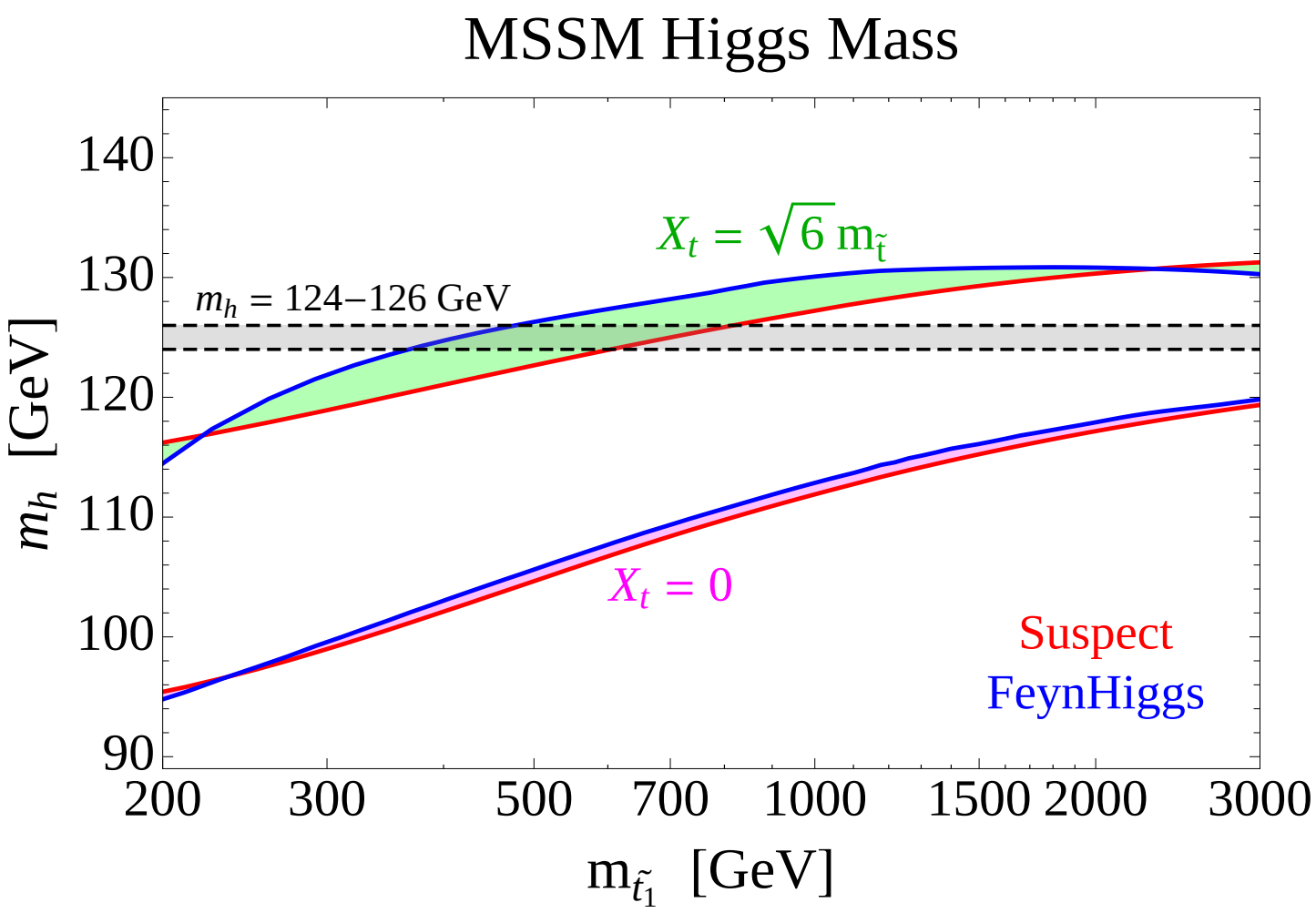
Implications

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

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

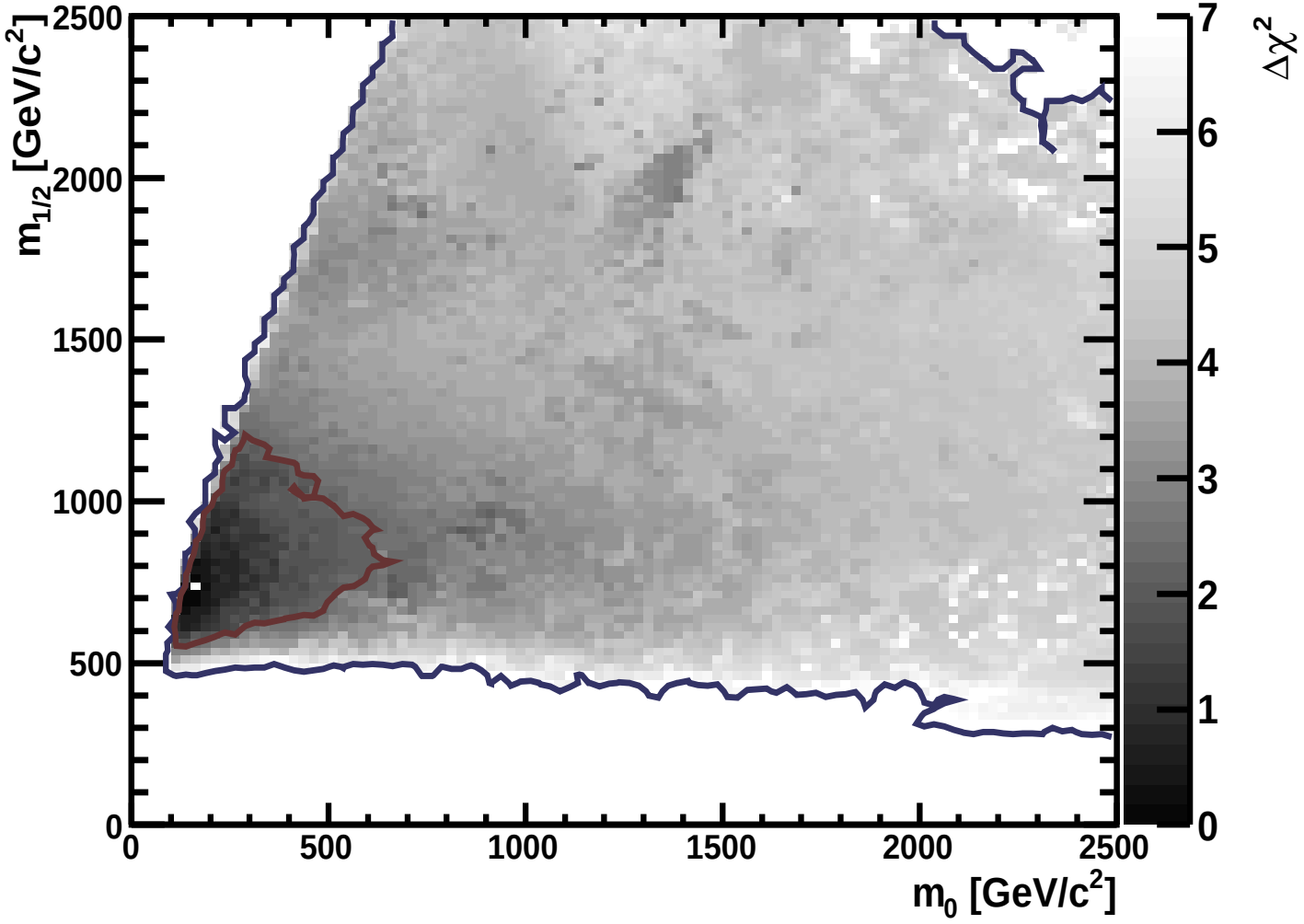
- Need heavy scalars: $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
- Or large LR stop mixing: $X_t = A_t - \mu \cot\beta$
- Maximised for $X_t = \sqrt{6} M_S$

Stop mass versus Higgs[1]



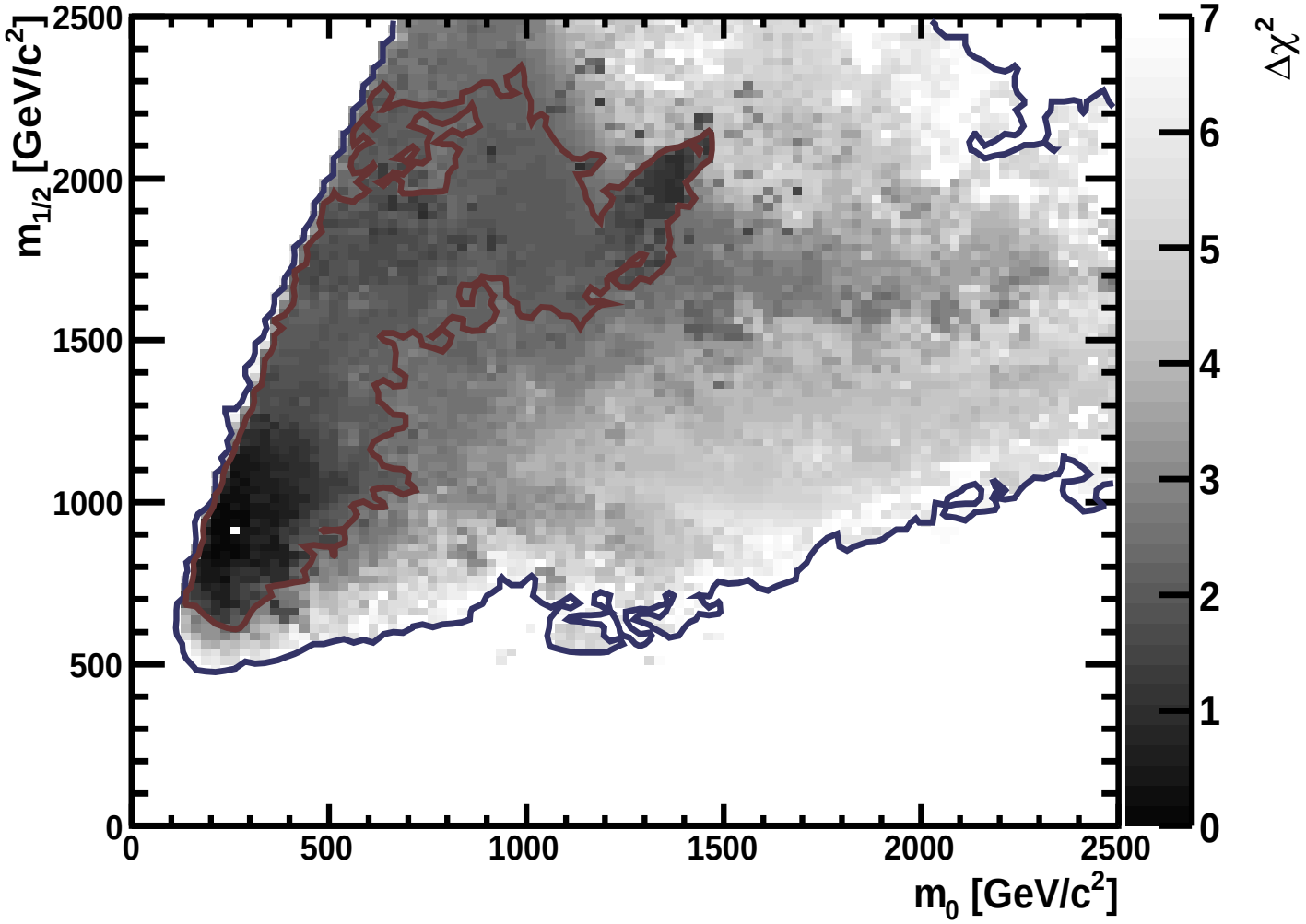
[1] from 1112.2703

MasterCode NUHM1 fit: pre-Higgs[2]

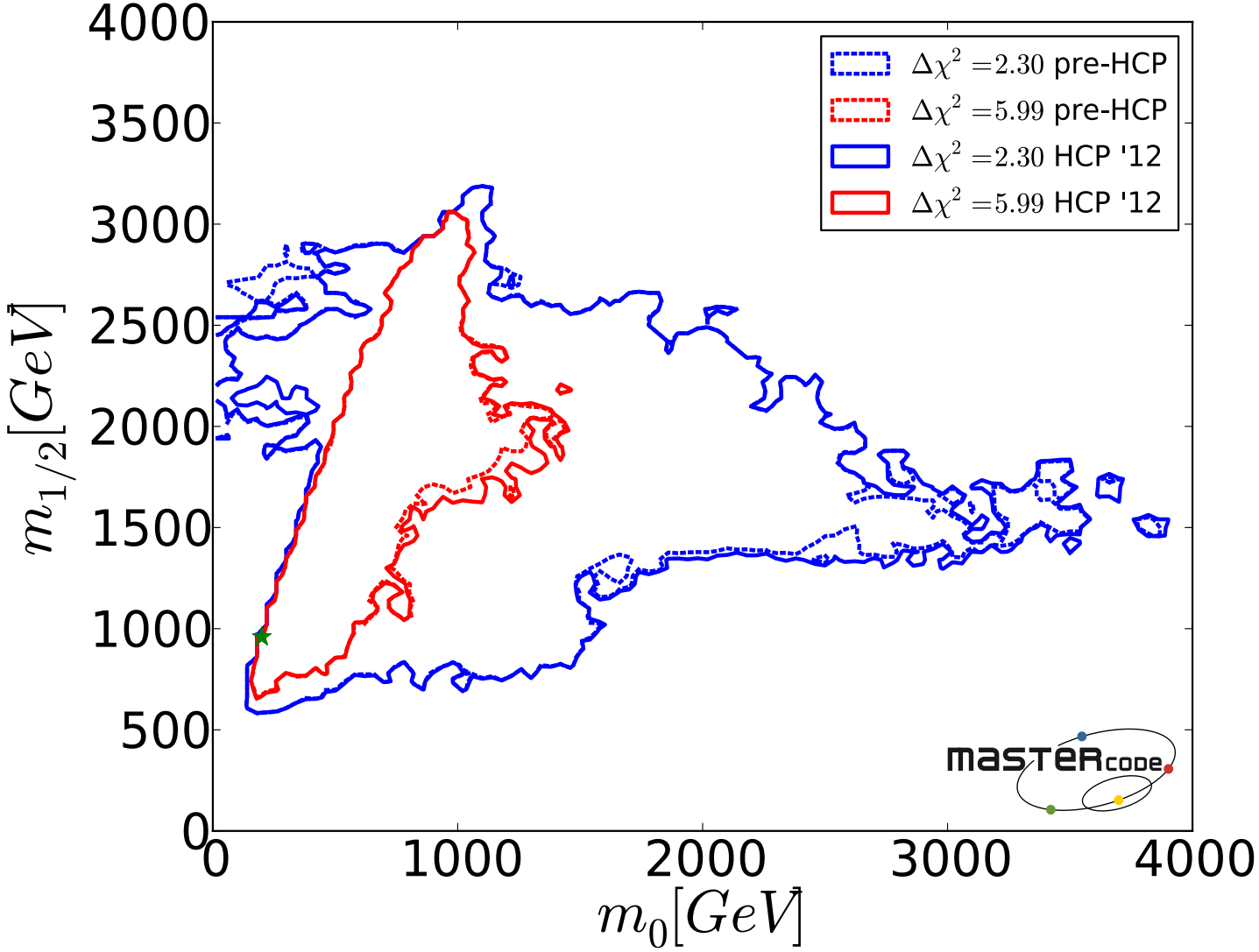


[2] 1112.3564

MasterCode NUHM1 fit: post-Higgs: Dec 2011

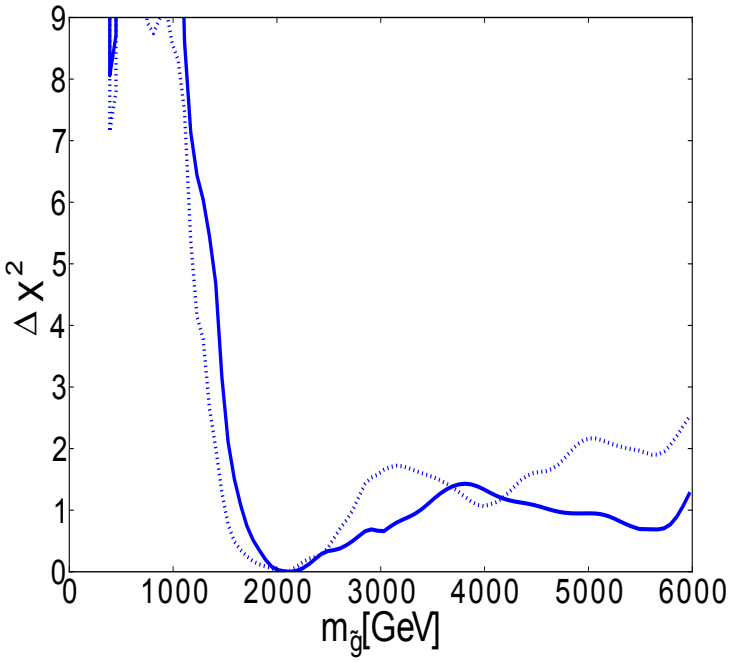


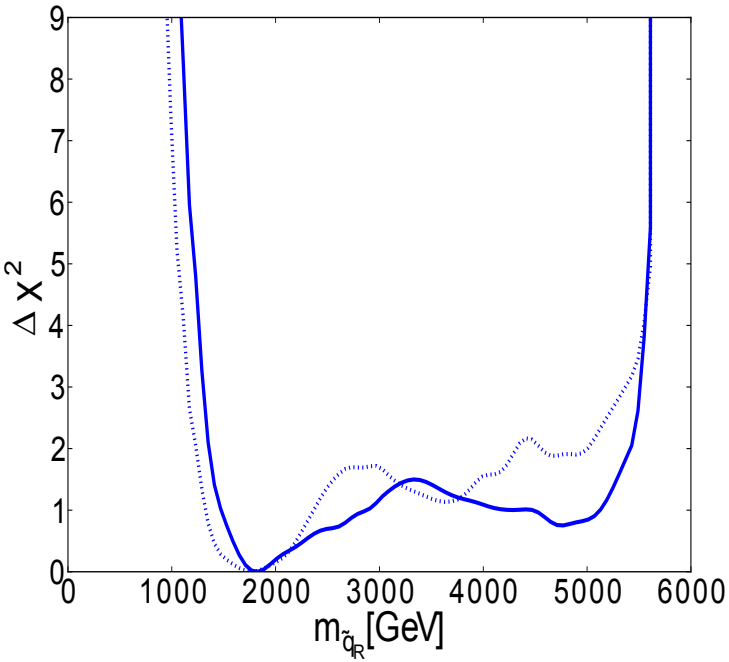
MasterCode NUHM1 fit[3]:



MasterCode NUHM1 fit[4]:

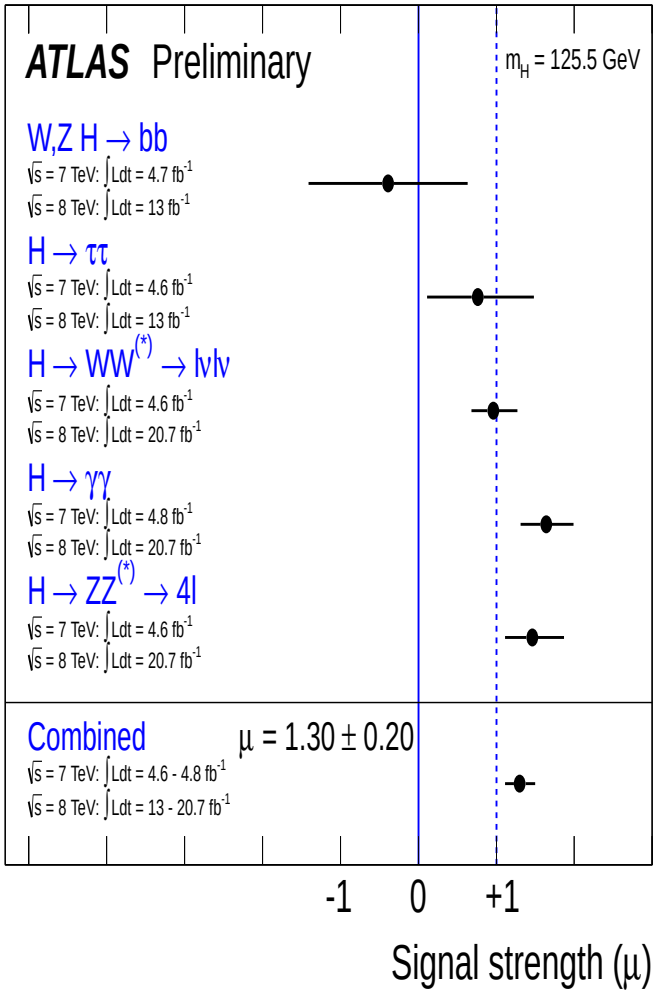
- Gluino and squark mass likelihoods

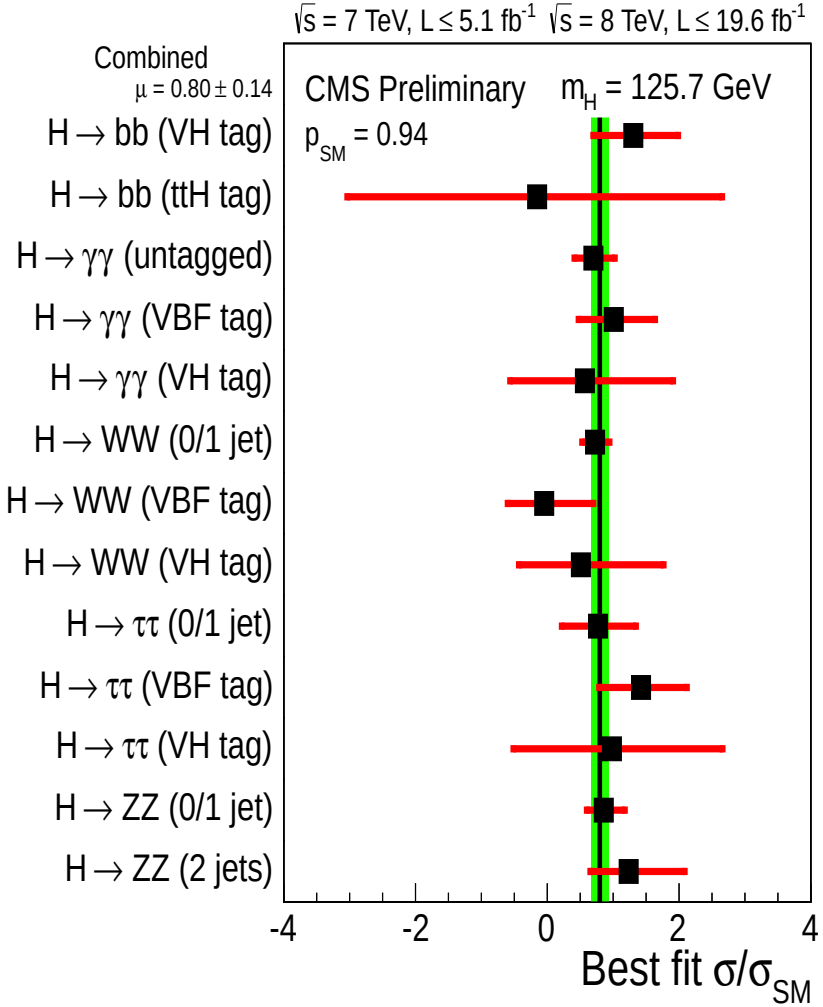




[4] 1207.7315

Constraint 2: Higgs Couplings





How SM-like is the MSSM Higgs?

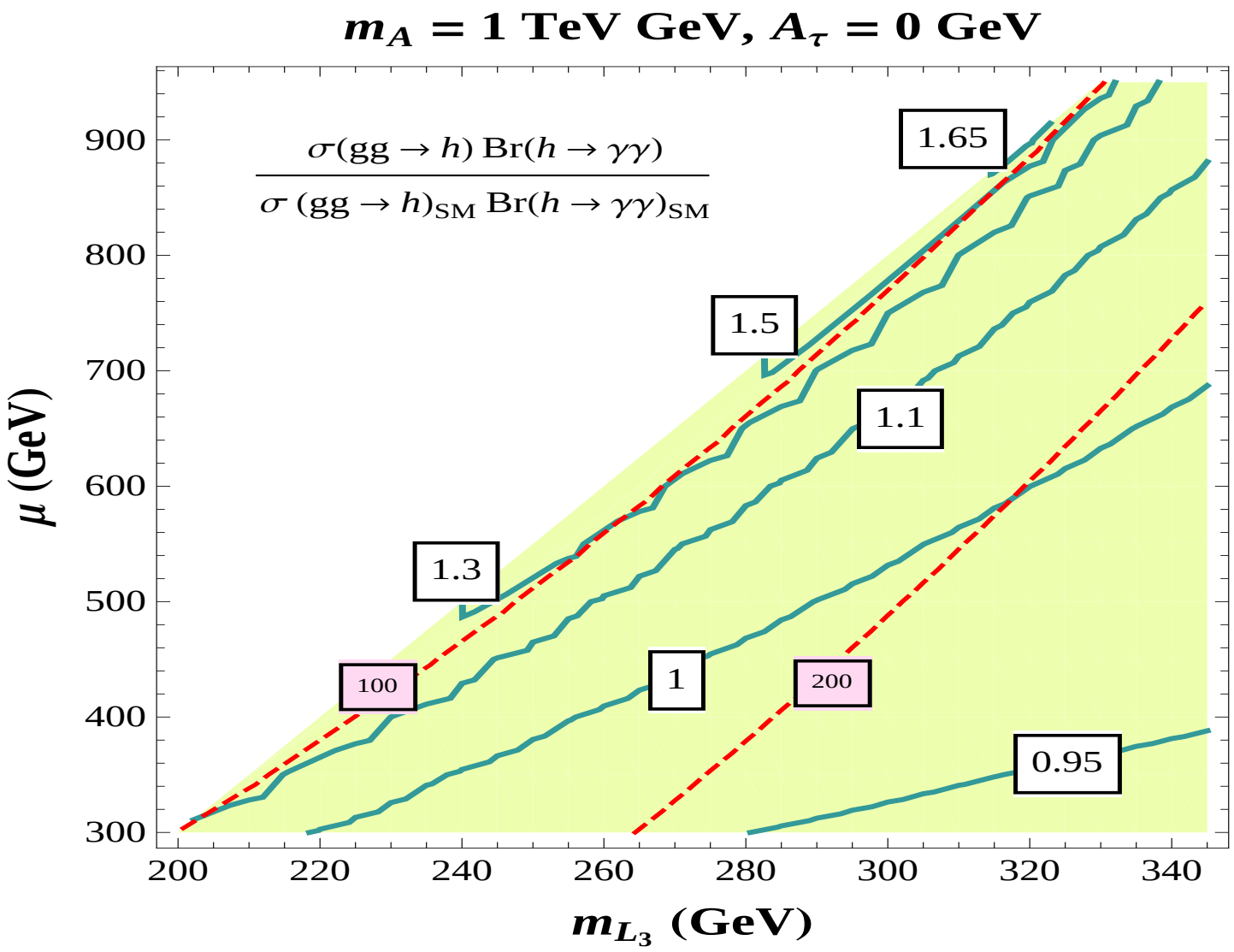
- In decoupling limit $m_{A,H,H^\pm} > m_h$ get SM like behaviour.
- Can still have $m_H \approx 125$, $m_h \approx 100$ GeV[5]
- $X125 = h$: $\chi^2/$ d.o.f 33.4/48.
- $X125 = H$: χ^2 d.o.f 47.4/48.

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 $h\gamma\gamma$ up to 2 $\times$BR$_{SM}$ [7]

[5] 1305.1933
[6] 0701235
[7] 1205.5842,1303.4414

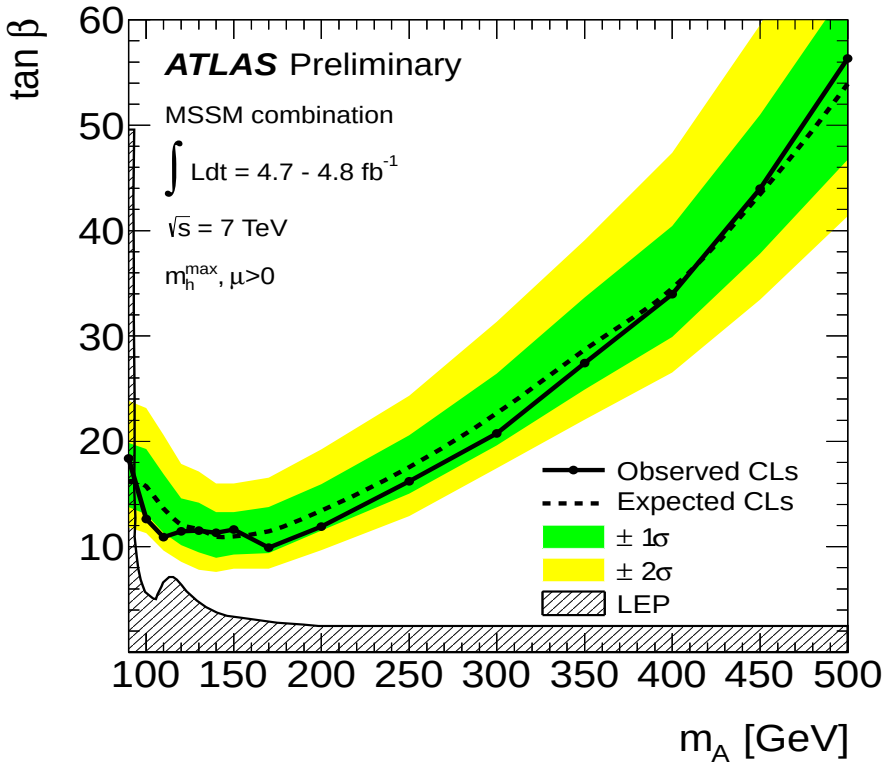
Light staus[8]



[8] 1205.5842

Other Higgs Constraints

- Searches for pseudoscalar A and charged H^+ pose constraints at low masses.



Other Higgs Constraints

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Exotic Higgs Decays

- Can still have invisible branching ratio $\sim \mathcal{O}(50\%)$
- Still possible to have $BR(h \to \tau\mu) \sim 10\%$[9].
- More exotic possibilities, 3-4 body decays?

[9] 1209.1397

Natural SUSY

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

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

- 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
- MSSM Naturalness $\rightarrow$ light higgsinos.

Radiative Corrections to $m_{H_u}^2$

One-loop

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

- Want light stops.
- Hierarchical stops with large A_t not good for naturalness.
- Tension with m_h?

Radiative Corrections to $m_{H_u}^2$

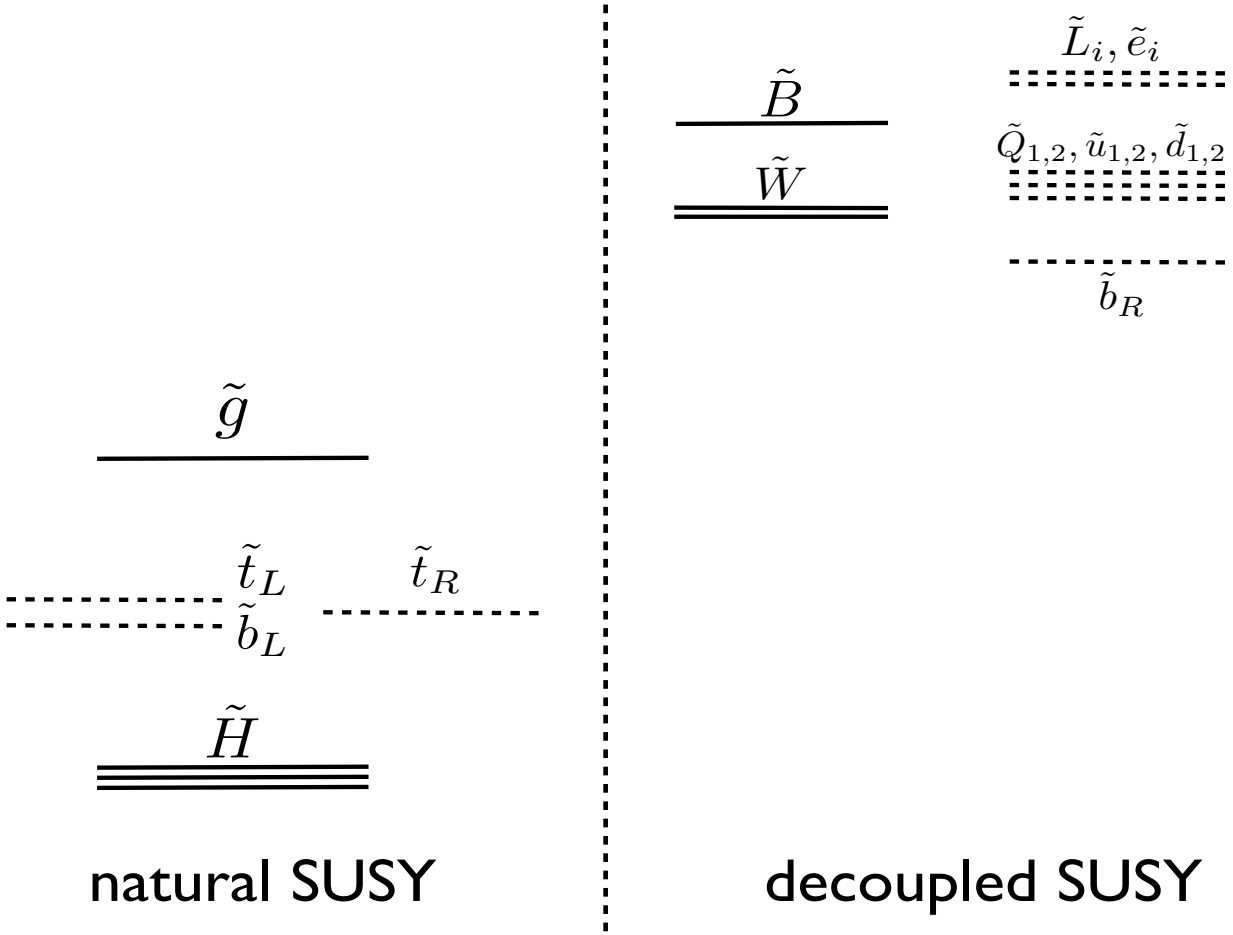
Two-loops

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

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

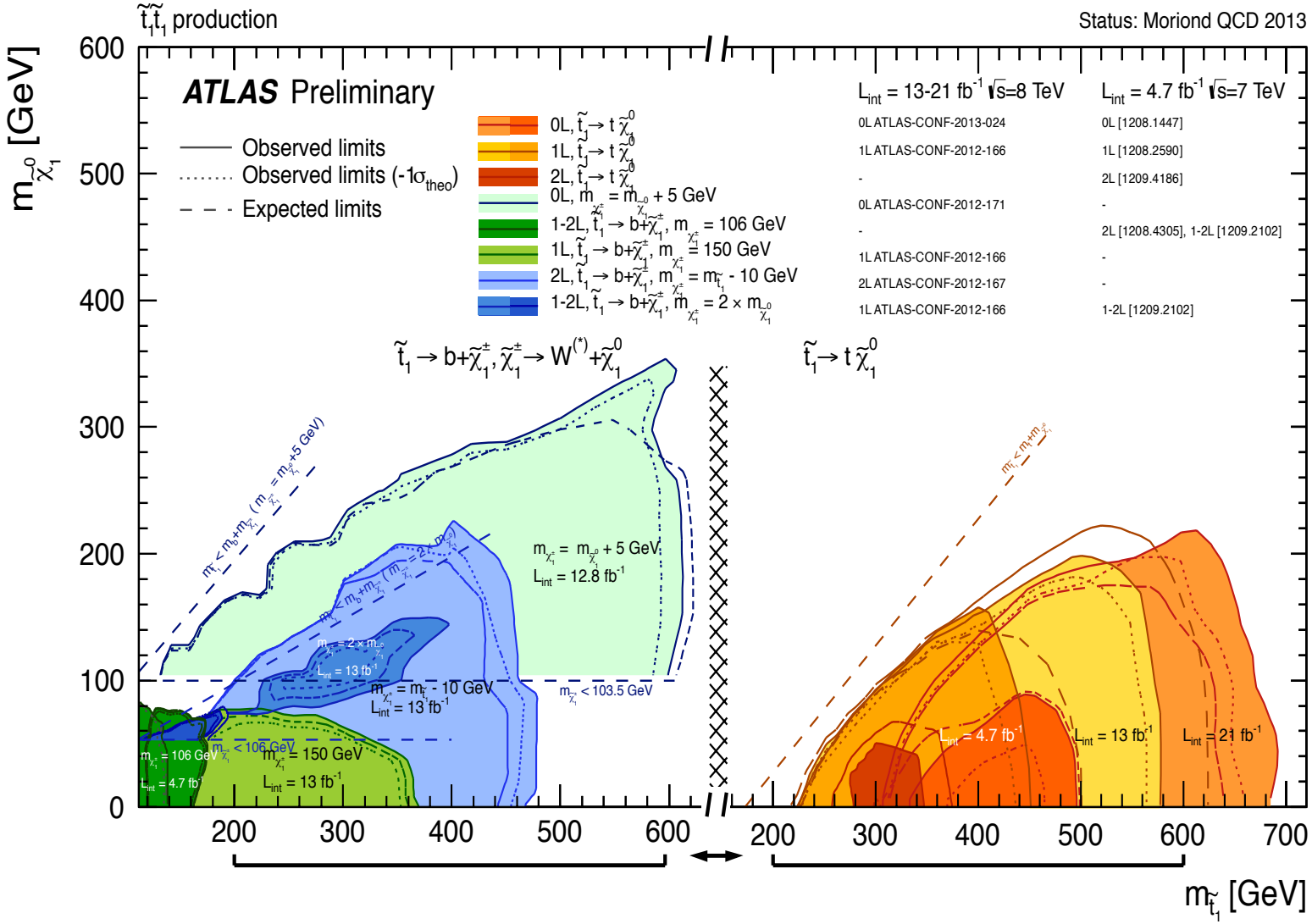
- Want light stops and gluino
- Tension with m_h and searches?

Natural SUSY Spectrum[10]



[10] from 1110.6926

ATLAS stop searches



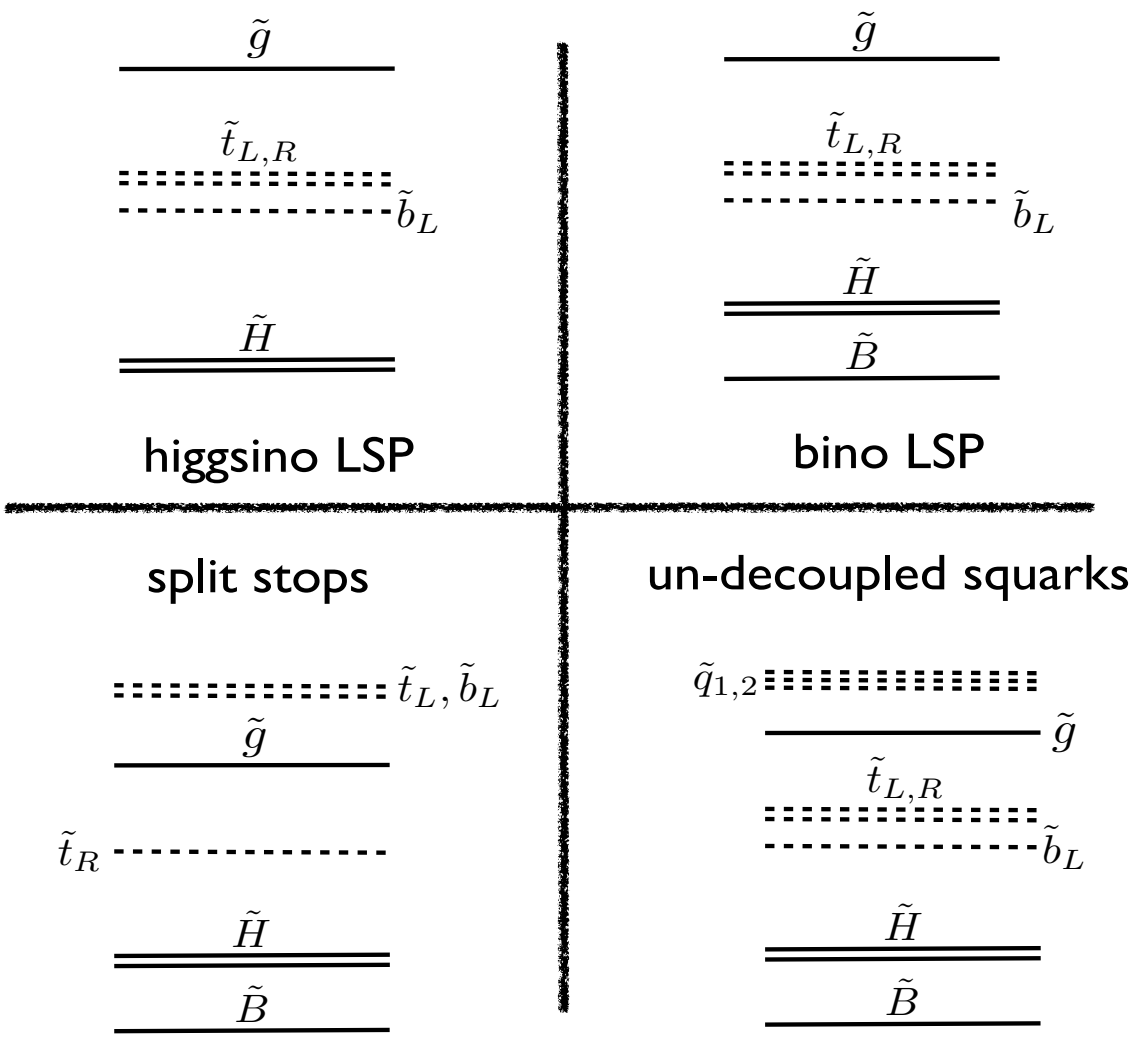
The Relic Density in Natural SUSY

- Assumption (RPC): LSP is a higgsino-like neutralino
- Pure higgsino 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

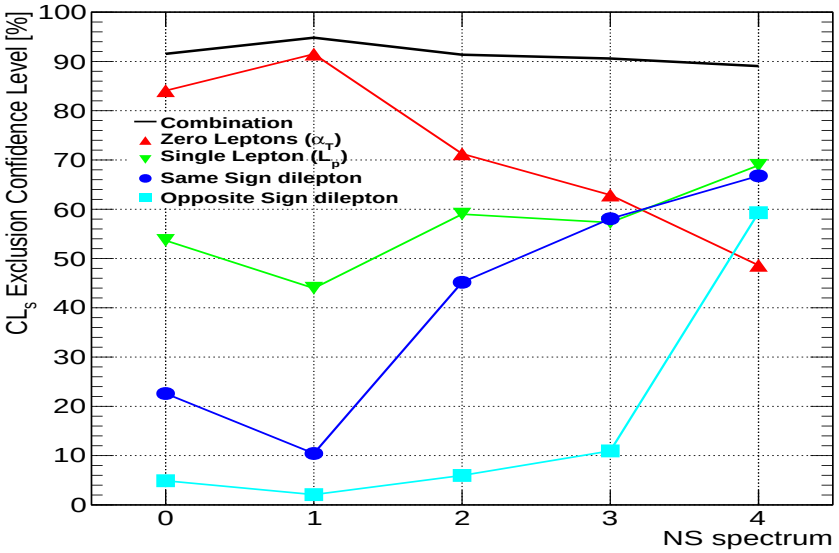
Natural SUSY Spectrum[11]



[11] from 1110.6926

What happens for more complicated spectra?[12]

- Fix $m_{\chi_1^0} = 100$, $m_{\tilde{g}} = 1000$, $m_{\tilde{t}} = 400$ GeV.
- Add in $\tilde{b}_{1,2}$, χ_2^0, $\chi_1^\pm$, sleptons.
- What happens to exclusion confidence limit?



[12] 1304.2185

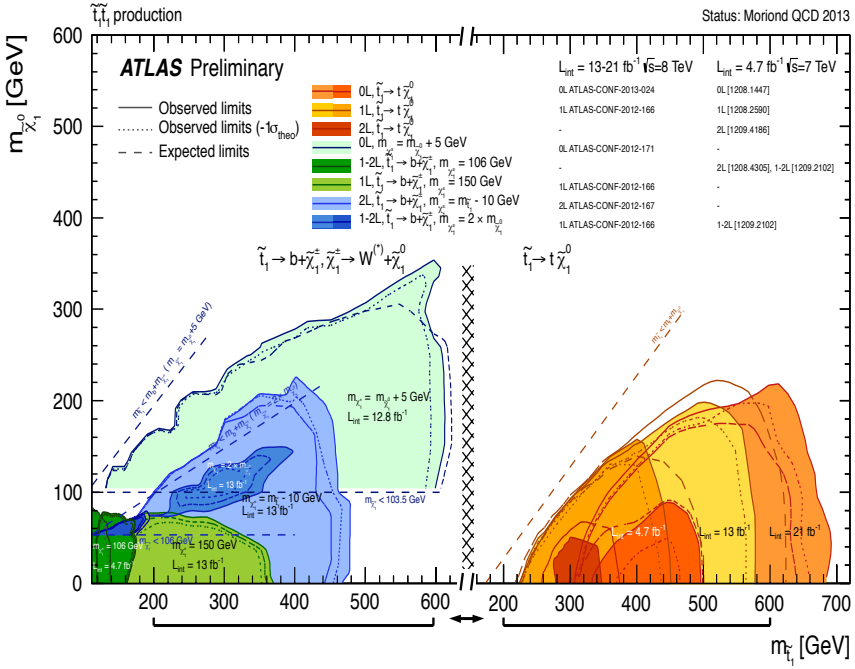
"Universal limits"[13]

	m_g for (m_{LSP})	$m_{3\tilde{G}}$ for (m_{LSP})	$m_g(m_{3\tilde{G}})$ for (m_{LSP})	$m_{3\tilde{G}}(m_g)$ for (m_{LSP})
	2011 final			
strongest limit	$\approx$ 900 GeV ($\leq$ 100 GeV)	$\approx$ 475 GeV ($\leq$ 100 GeV)	$\approx$ 1250 GeV ($\leq$ 100 GeV)	$\approx$675 GeV ($\leq$100 GeV)
weakest limit	$\approx$ 550 GeV ($\approx$ 450 GeV)	$\approx$ 400 GeV $\approx$ (300 GeV)	$\approx$ 600 GeV ($\approx$ 500 GeV)	$\approx$550 GeV ($\approx$450 GeV)
	2012 prediction			
strongest limit	$\approx$ 1150 GeV ($\leq$ 100 GeV)	$\approx$ 675 GeV ($\leq$ 100 GeV)	$\approx$ 1450 GeV ($\leq$ 100 GeV)	$\approx$800 GeV ($\leq$100 GeV)
weakest limit	$\approx$ 650 GeV ($\approx$ 550 GeV)	$\approx$ 500 GeV $\approx$ (400 GeV)	$\approx$ 750 GeV ($\approx$ 650 GeV)	$\approx$650 GeV ($\approx$550 GeV)

[13] 1304.2185

Room for light stops

- Still room for $m_{\tilde{t}} \sim m_t$, and for compressed natural spectra
- Searches like $c\bar{c} + MET$, $tb + MET$, $tW + MET$

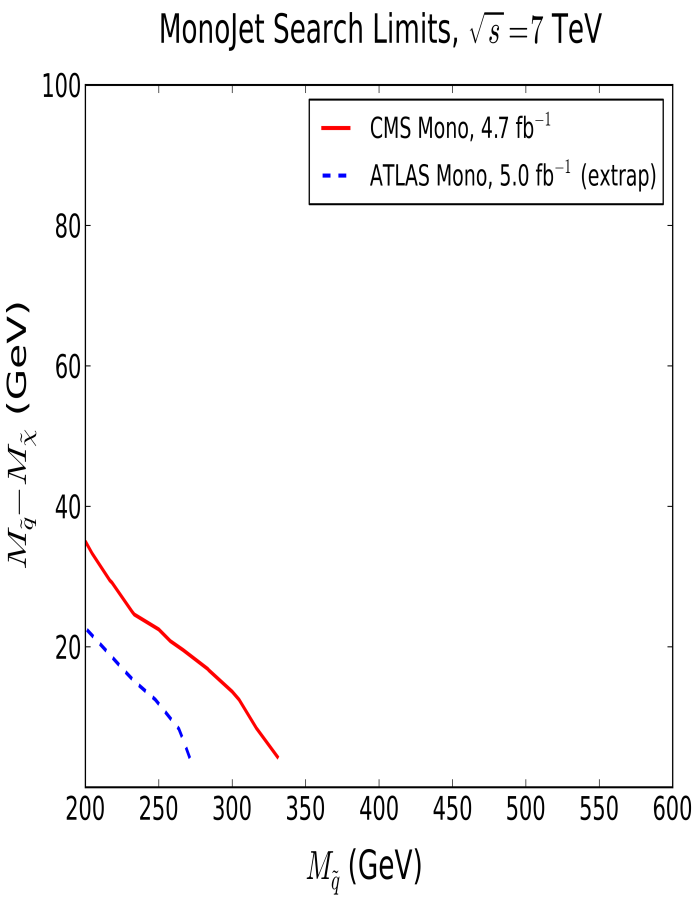


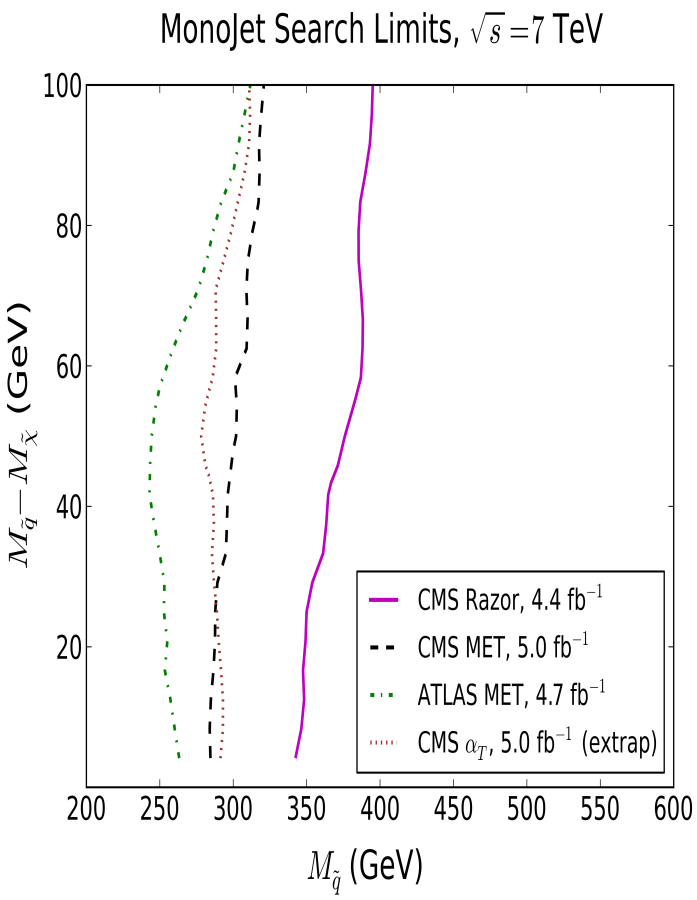
Crouching Theorist, Hidden SUSY

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

- How to increase Higgs mass without naturalness penalty?

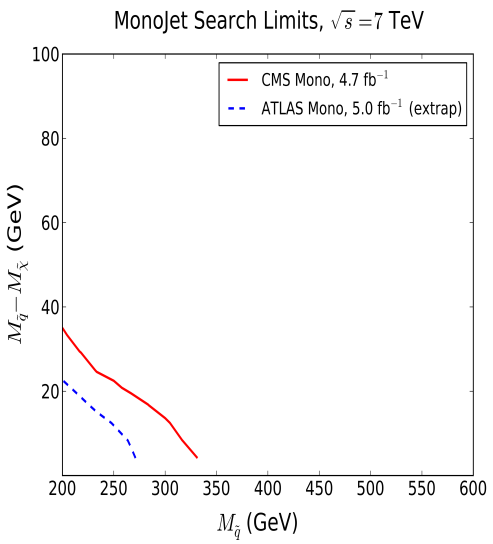
Constraints: Compressed spectra[14]

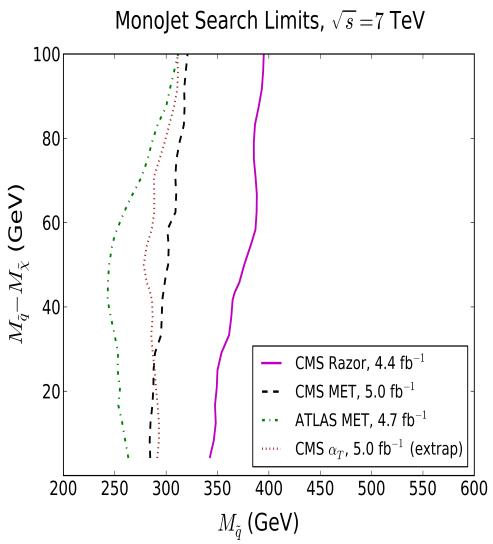




[14] 1207.1613,1211.4981

Constraints: Compressed spectra[15]





- What kind of models out there which give this?
- What does such a spectrum look like at the high scale?

[15] 1207.1613,1211.4981

Hiding SUSY: RPV

The usual suspects

$$W_{MSSM} = \bar{u}\mathbf{y}_u Q H_u + \bar{d}\mathbf{y}_d Q H_d + \bar{e}\mathbf{y}_e L H_d + \mu H_u H_d$$

Not-so-usual-suspects

$$W_{\Delta L=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu'^i L_i H_u$$

$$W_{\Delta B=1} = \frac{1}{2}\lambda''^{ijk} \bar{u}_i \bar{u}_j \bar{d}_k$$

Why not RPV?

$$\Gamma_{p\to e^+\pi^0} \sim m_p^5 \sum_{i=2,3} |\lambda'^{11i}\lambda''^{11i}|^2/m^4_{\tilde{d}_i}$$

- Dark Matter? Gravitino lifetime:

$$\tau_{3/2} = 10^{26}\ \mathrm{s}\left(\frac{\lambda}{10^{-7}}\right)^{-2}\left(\frac{m_{3/2}}{10\ \mathrm{GeV}}\right)^{-3}$$

Collider implications

- Sparticles not always pair produced
- Absence of missing energy signatures
- Presence of 'unusual signals': displaced vertices...

Constraints: RPV Searches

LLE

- LFV: the lowest-hanging RPV fruit. Example: e-μ resonance

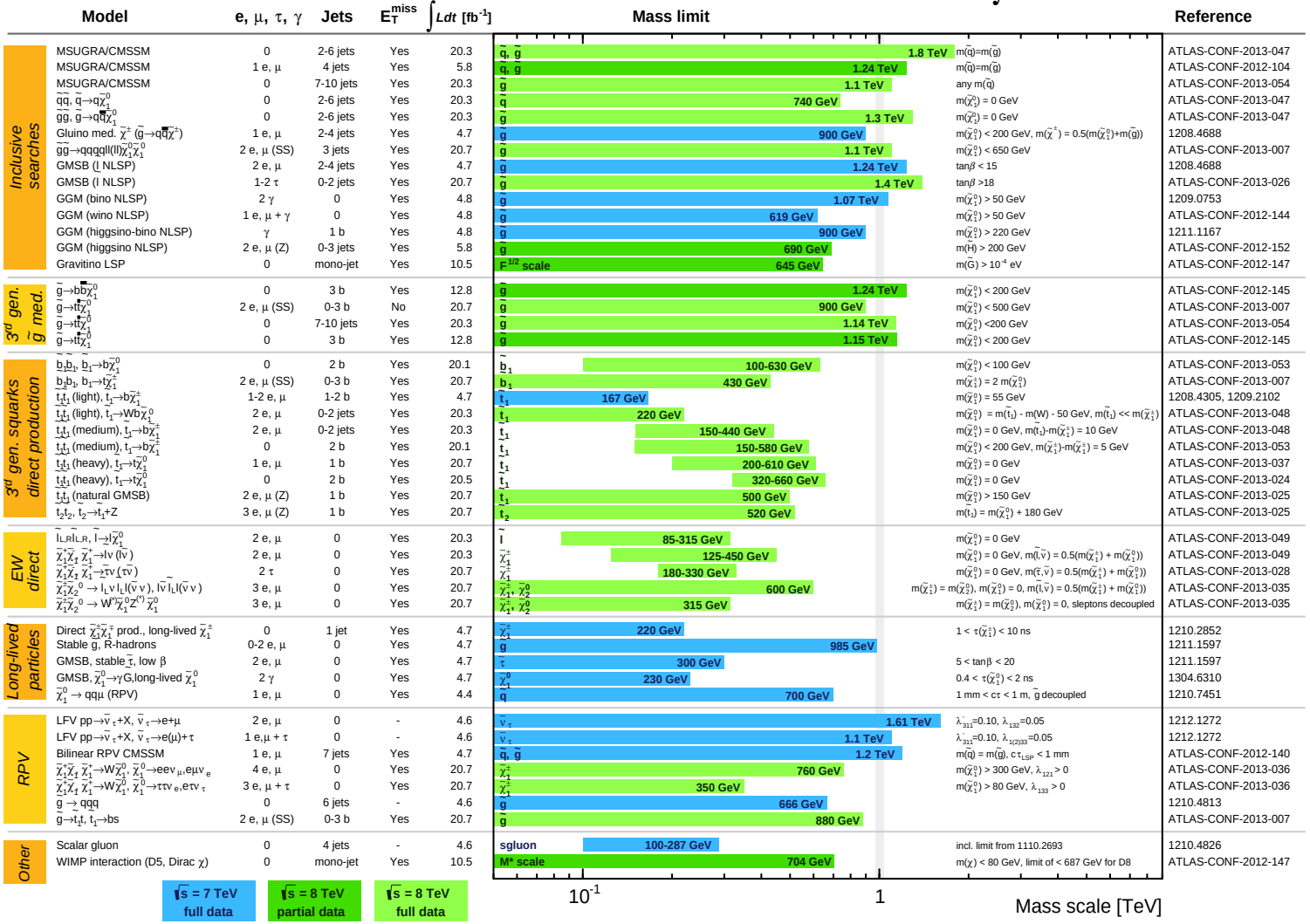
QLD

- Similar to leptoquarks. Harder with 3rd family.

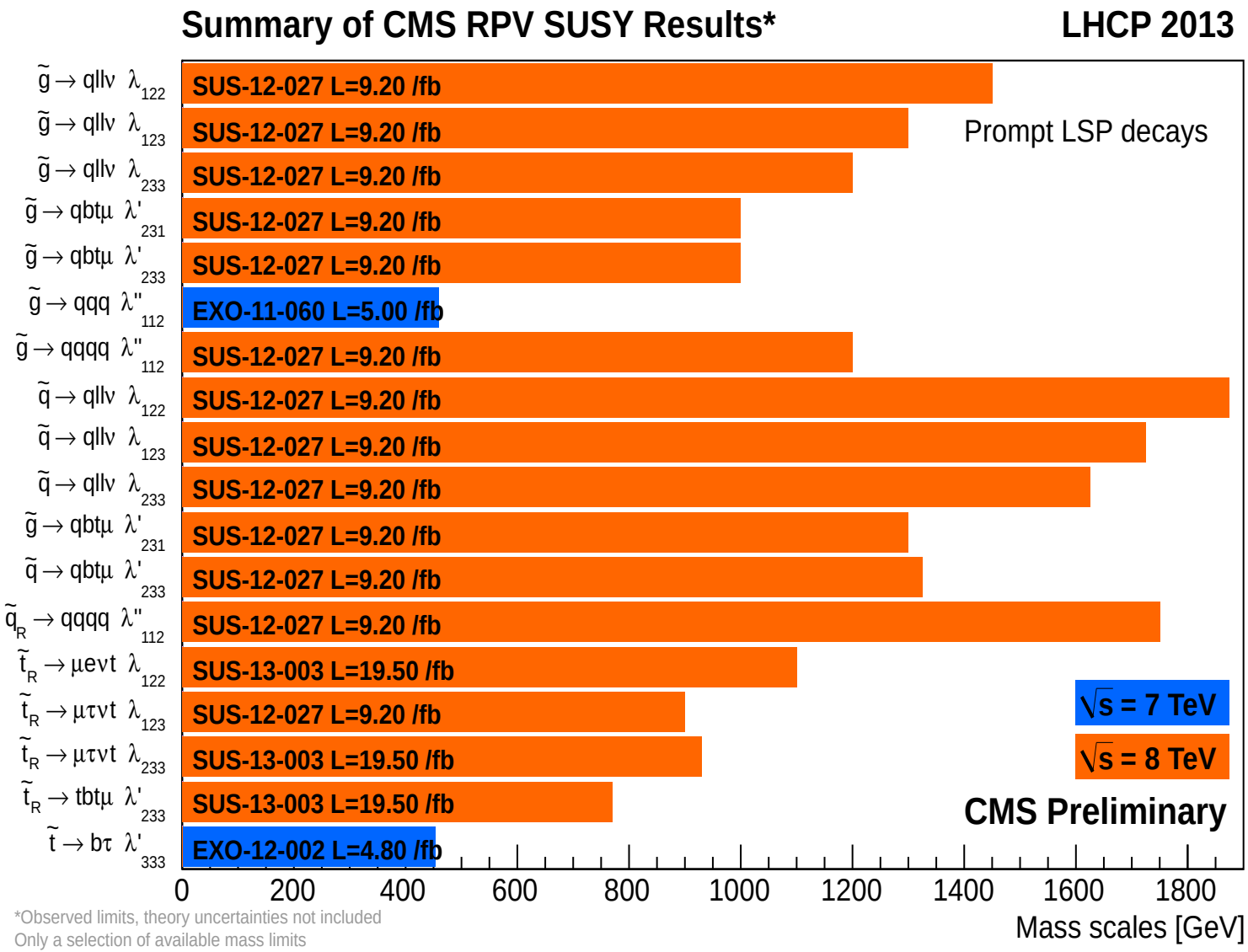
UDD

- Fully hadronic, no MET. Ex: three-jet resonance

ATLAS SUSY Searches



CMS RPV Searches



*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

Abandoning Naturalness

Minisplit

- Scalars at few TeV.
- SUSY solves 'most of' the hierarchy problem
- Only gauginos within reach.

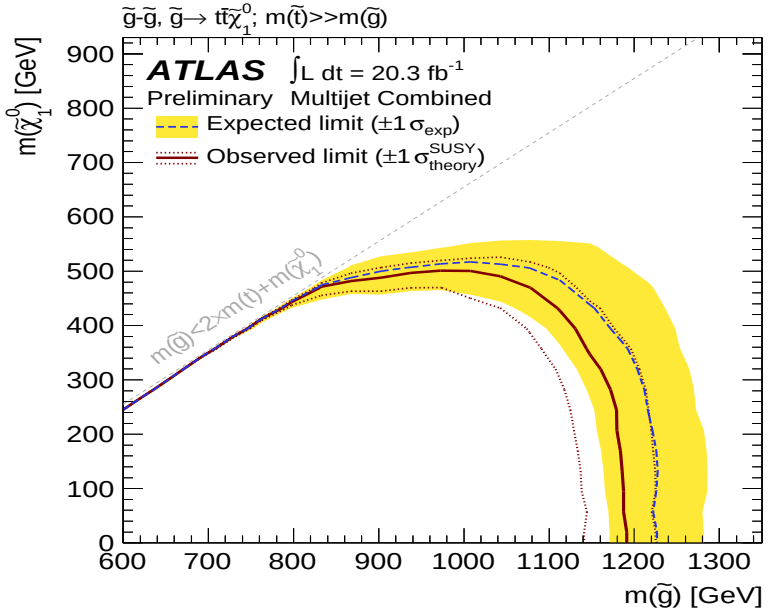
Tuning

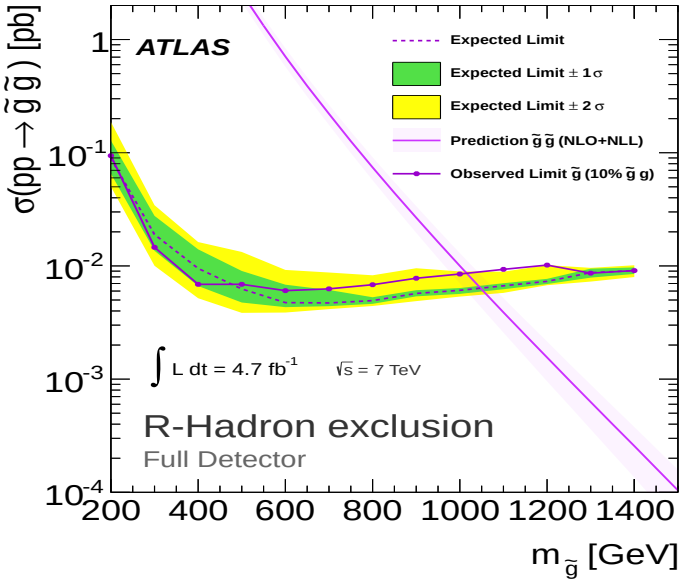
- Fine-tuning $\mathcal{O}(10^{3-4})$.
- How much fine-tuning are we willing to take?
- Why not go less minimal?

Constraints: Unnatural SUSY

Gaugino searches: Gluinos

- Decay via off-shell squark: $\tilde{g} \to q\bar{q}\chi$ ($t\bar{t}\chi$)
- Prompt: Jets+MET.
- Non-prompt: R-Hadron





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

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

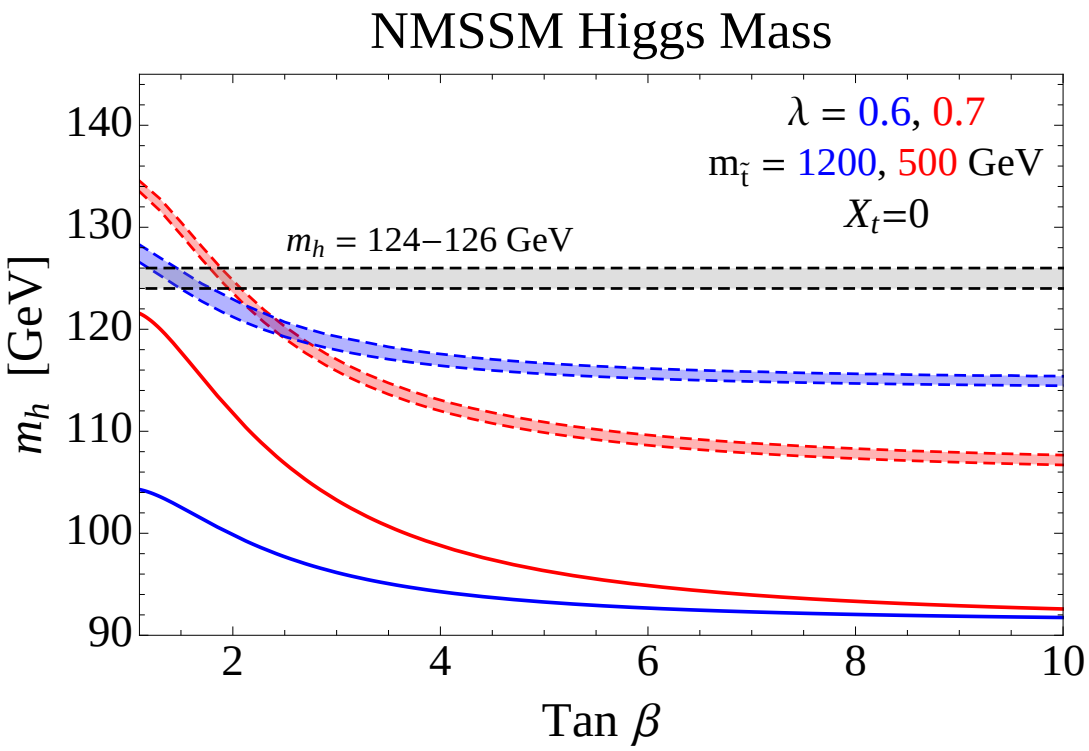
- 3 CP-even, 2CP-odd and charged Higgs states
- Lower fine-tuning possible for a given Higgs mass.

New features

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

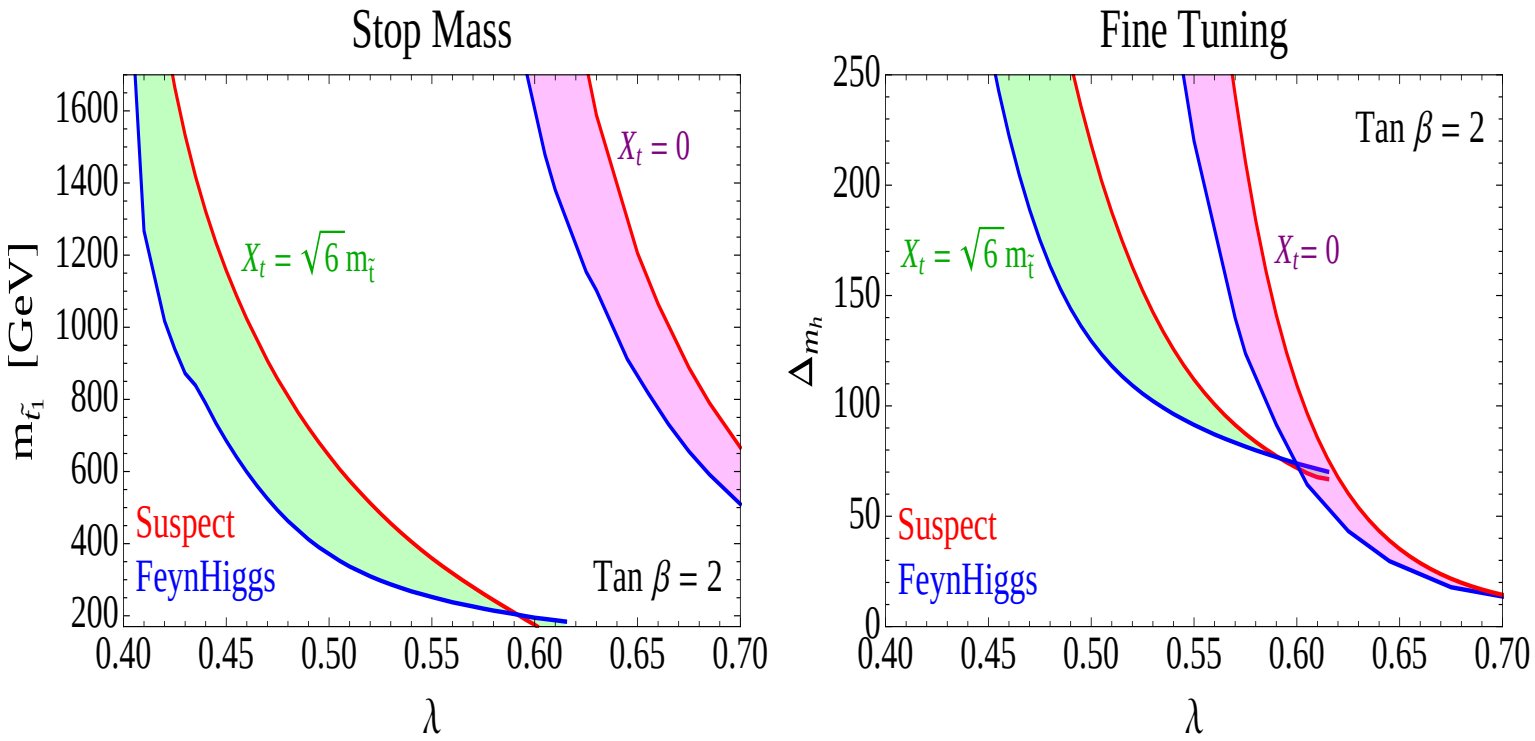
Higgs mass in the NMSSM

- Maximised for small tan β



Fine-tuning

- Low stop masses, fine-tuning



Conclusions

- “Vanilla” SUSY constrained
- MSSM Naturalness: being probed
- RPV: Interesting territory.
- More complicated theories alleviate naturalness
- Lots to do for 13 TeV!