Effects of Strong Moduli Stabilization on Low Energy Phenomenology

Which Supersymmetric Model?

- MSSM with R-Parity (still more than 100 parameters)

SUSY Superpotential + Soft terms

$$\begin{aligned} W &= h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1 \\ \mathcal{L}_{\rm soft} &= -\frac{1}{2} M_\alpha \lambda^\alpha \lambda^\alpha - m_{ij}^2 \phi^{i*} \phi^j \\ & -A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B\mu H_2 H_1 + h.c. \end{aligned}$$

$$\langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \qquad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

R-parity conservation assumed

Which Supersymmetric Model?

- MSSM with R-Parity (still more than 100 parameters)
- Gaugino mass Unification
- A-term Unification
- Scalar mass unification

CMSSM or mSUGRA

The CMSSM

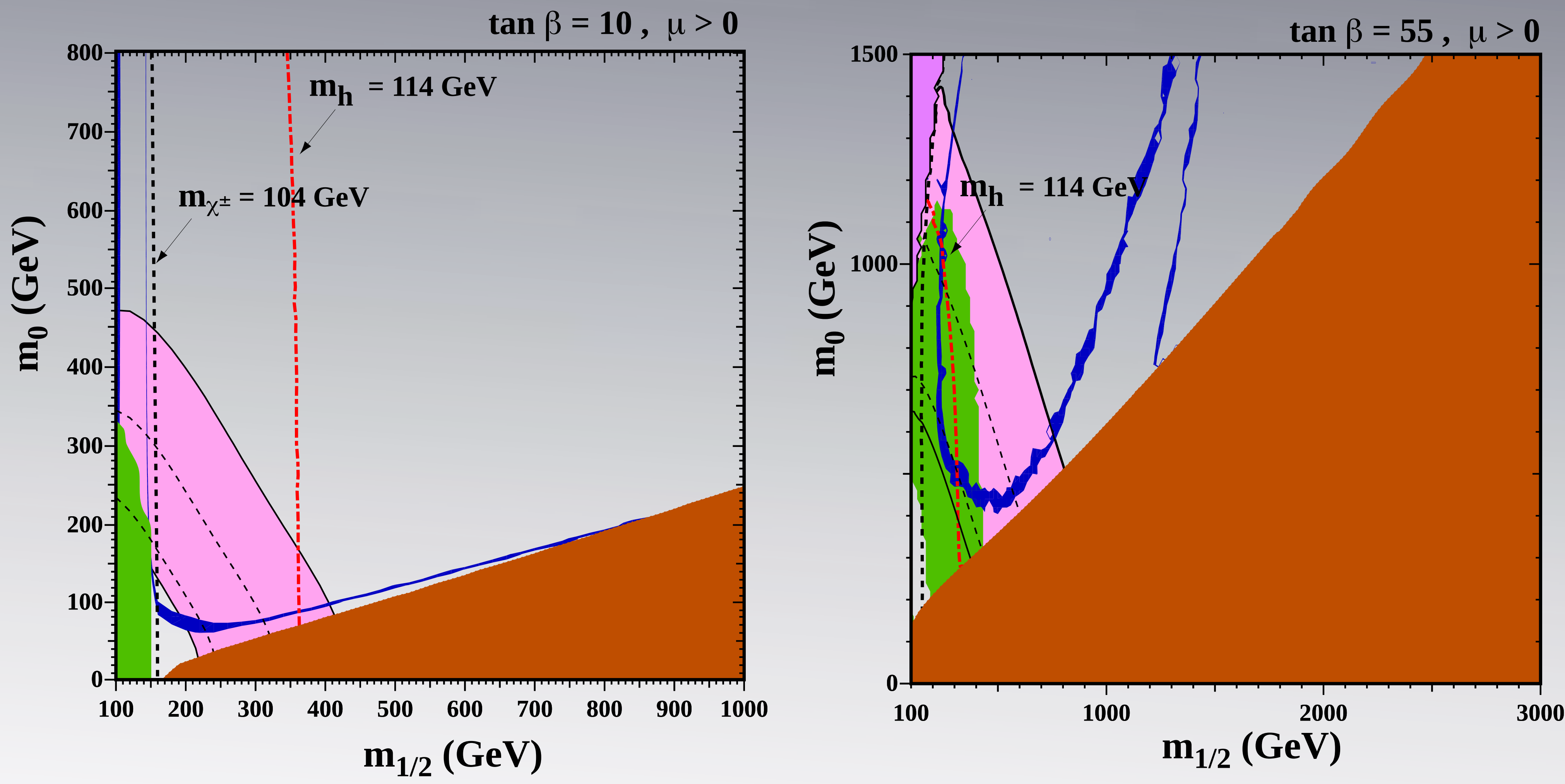
Parameters: $m_{1/2}$, m_0, A_0, $\tan\beta$, $\mathrm{sgn}(\mu)$ $\{m_{3/2}\}$

Electroweak Symmetry Breaking conditions:

$$\mu^2 = \frac{m_1^2 - m_2^2 \tan^2\beta + \frac{1}{2} M_Z^2 (1 - \tan^2\beta) + \Delta_\mu^{(1)}}{\tan^2\beta - 1 + \Delta_\mu^{(2)}}$$

$$B\mu = -\frac{1}{2}(m_1^2 + m_2^2 + 2\mu^2)\sin 2\beta + \Delta_B$$

$m_{1/2}$ - m_0 planes

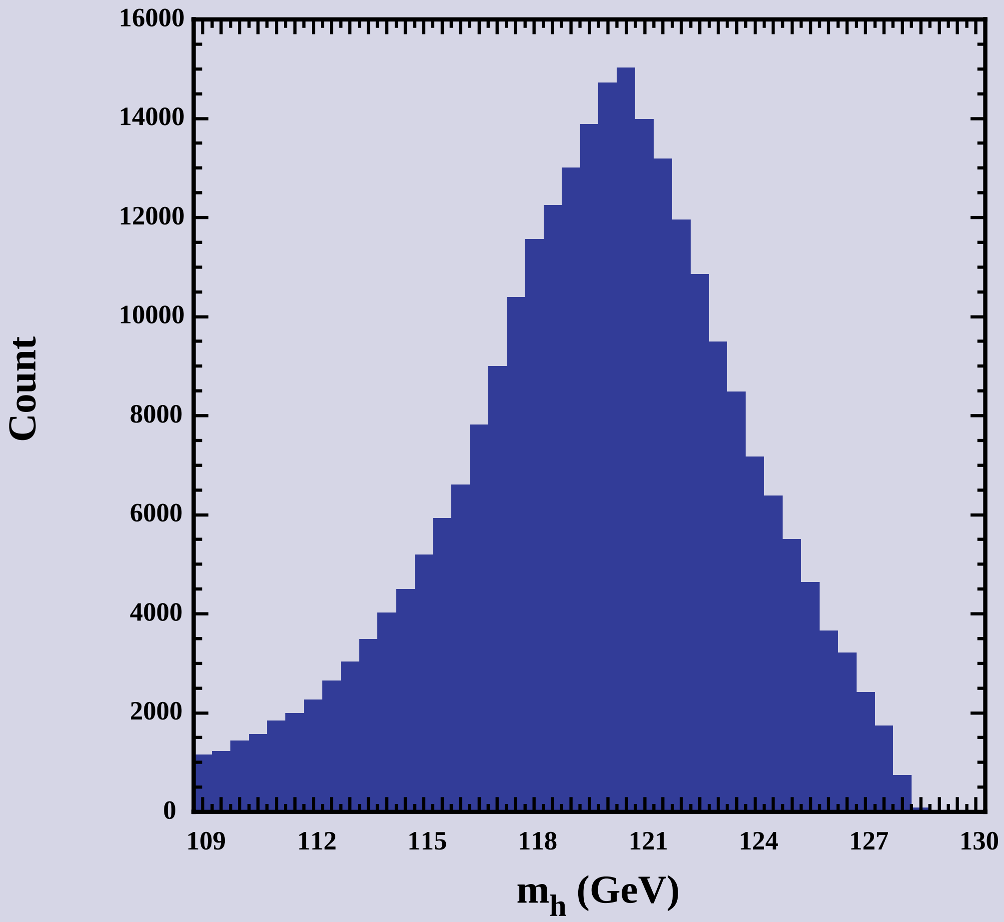


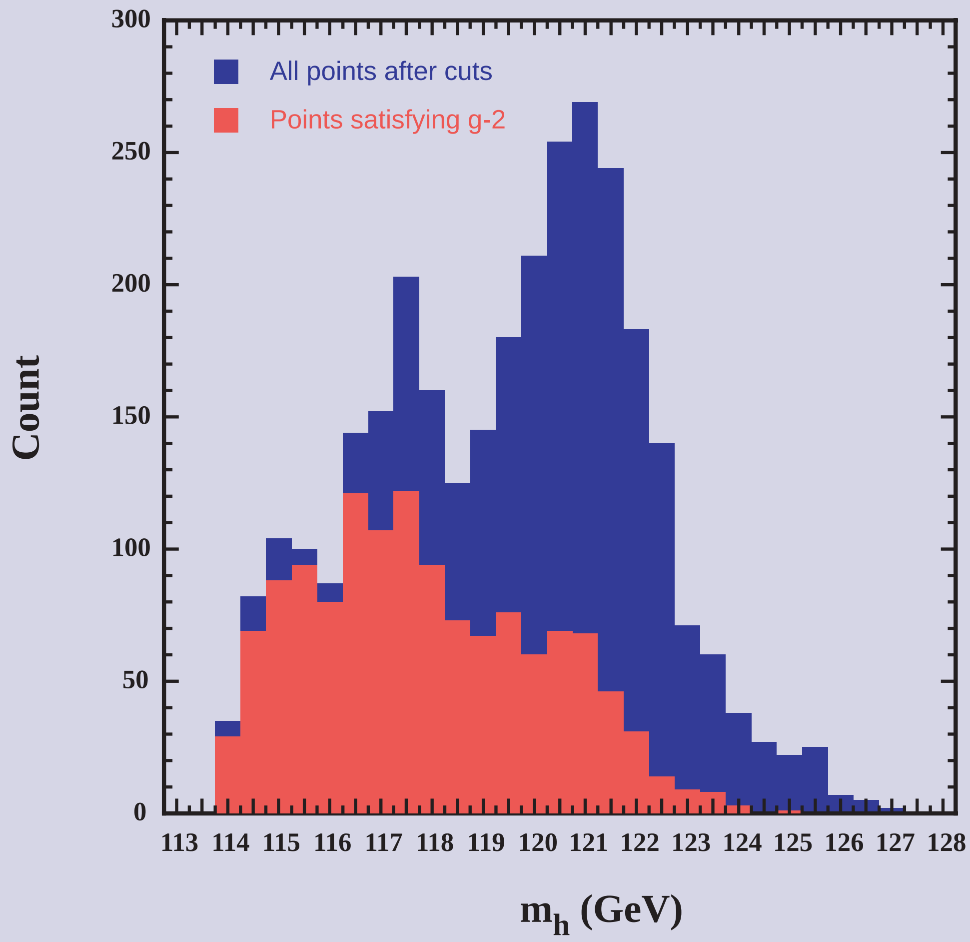
- CMSSM

Ellis, Olive, Santoso, Spanos

Friday, January 25, 13

The Higgs mass in the CMSSM





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mSUGRA models

e.g. Barbieri, Ferrara, Savoy

$G = \varphi\,\varphi* + z\,z^* + \ln|W|^2; \quad W = f(z) + g(\varphi)$

Scalar Potential (N=1):

$$V = e^{(|z|^2+|\varphi|^2)}\left[\left|\frac{\partial f}{\partial z} + z^*\left(f(z)+g(\varphi)\right)\right|^2 + \left|\frac{\partial g}{\partial \varphi} + \varphi^*\left(f(z)+g(\varphi)\right)\right|^2 - 3\left|f(z)+g(\varphi)\right|^2\right]$$

In the low energy limit ($M_P \to \infty$),

$$V = \left|\frac{\partial g}{\partial \phi^i}\right|^2 + \left(A_0 g^{(3)} + B_0 g^{(2)} + h.c.\right) + m_{3/2}^2 \phi^i \phi_i^*$$

where

$$A_0 g^{(3)} = \left(\phi^i \frac{\partial g^{(3)}}{\partial \phi^i} - 3g^{(3)}\right) m_{3/2} + z^*(z f^* + \frac{\partial f^*}{\partial z^*})$$

For <f> = m_0, <df/dz> = a m_0, and <z> = b with $(a+b)^2 = 3$

$A_0 = (ab + b^2)\, m_0$; $B_0 = A_0 - m_0$

e.g. Nilles, Srednicki, Wyler

For example,

Polonyi: $f(z) = m_0\,(z + \beta)$;

With <z> = b = $\sqrt{3} - 1$ for $\beta = 2 - \sqrt{3}$ (a = 1)

and $m_{3/2} = m_0$

$\longrightarrow$ $m_0 = m_{3/2}$; $A_0 = (3 - \sqrt{3})\, m_0$; $B_0 = A_0 - m_0$

mSUGRA

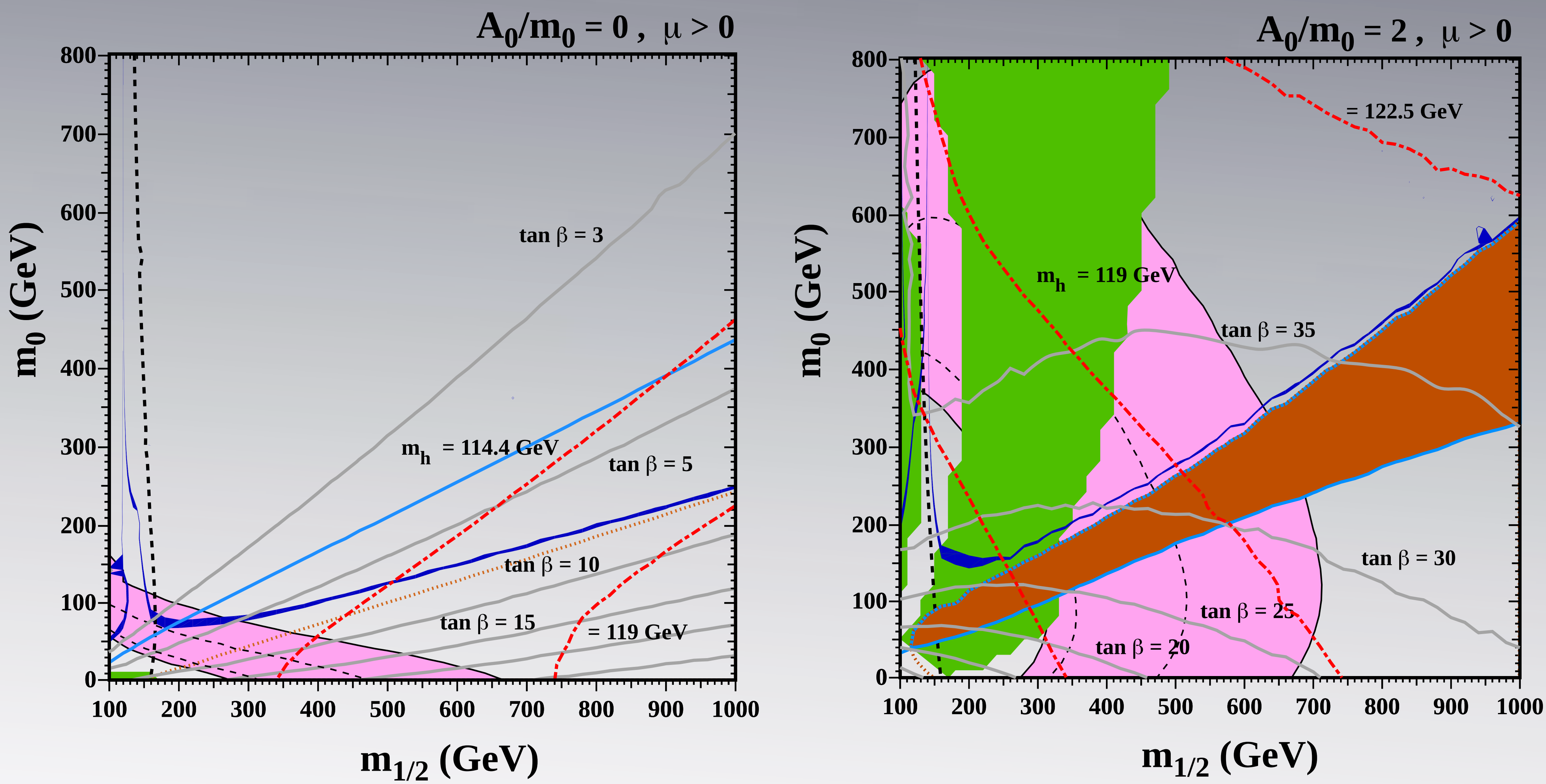
Parameters: $m_{1/2}$, $m_{3/2}$, A_0, sgn(μ)

Electroweak Symmetry Breaking conditions used to solve for tanβ:

$$\mu^2 = \frac{m_1^2 - m_2^2 \tan^2\beta + \frac{1}{2} M_Z^2 (1 - \tan^2\beta) + \Delta_\mu^{(1)}}{\tan^2\beta - 1 + \Delta_\mu^{(2)}}$$

$$B\mu = -\frac{1}{2}(m_1^2 + m_2^2 + 2\mu^2)\sin 2\beta + \Delta_B$$

mSUGRA planes



Ellis, Olive, Santoso, Spanos
Dudas,Mambrini,Mustafayev,Olive

Relating the CMSSM to mSUGRA through Giudici-Masiero

Dudas, Mambrini, Mustafayev, Olive

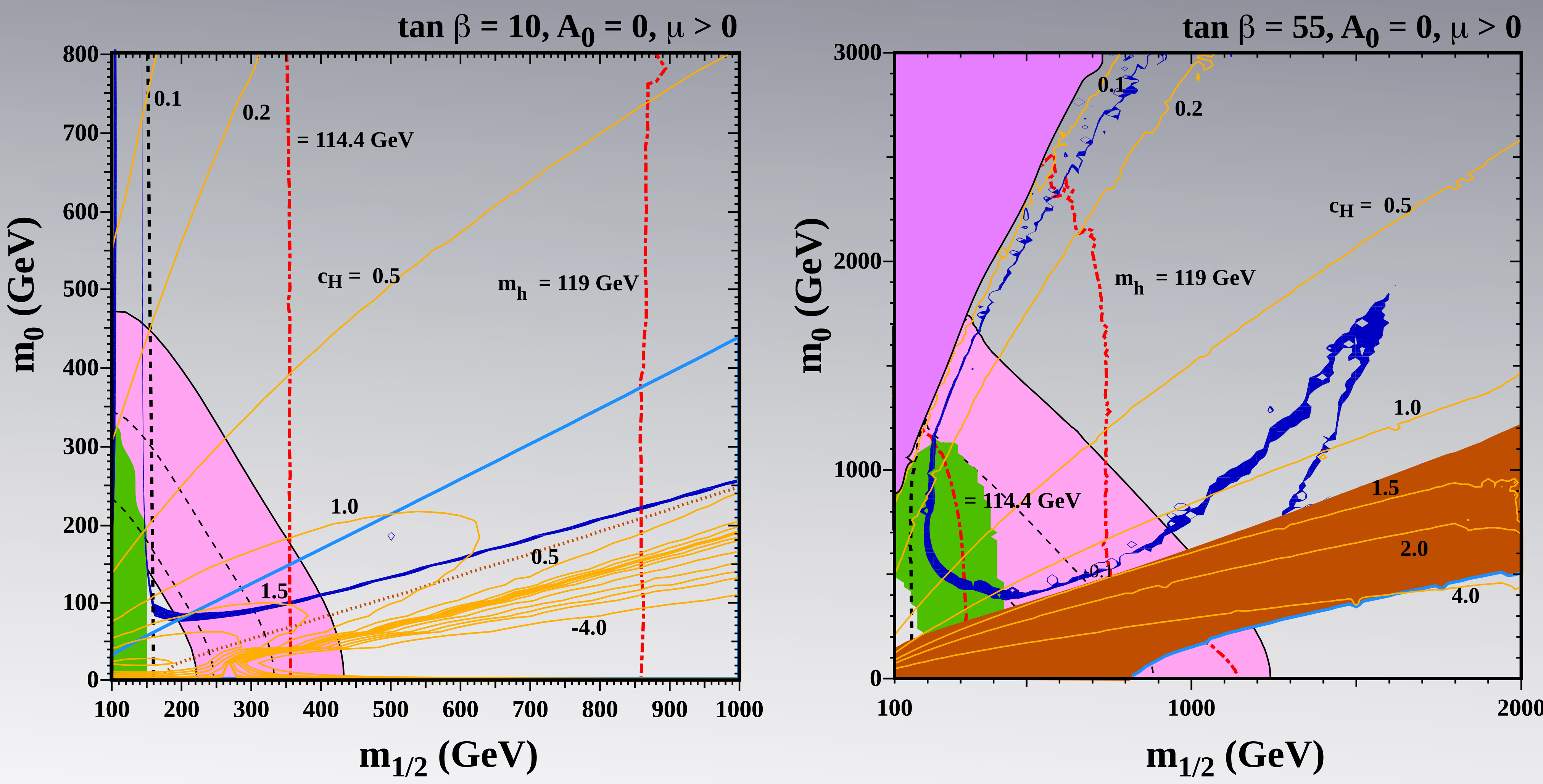
add non-minimal Kähler correction

$$\Delta K = c_H H_1 H_2 + h.c.$$

produces shifts

$$\mu = \mu_0 + c_H m_0 \,,$$
$$B_0 = A_0 - m_0 + 2 c_H m_0^2/\mu_0 \,.$$

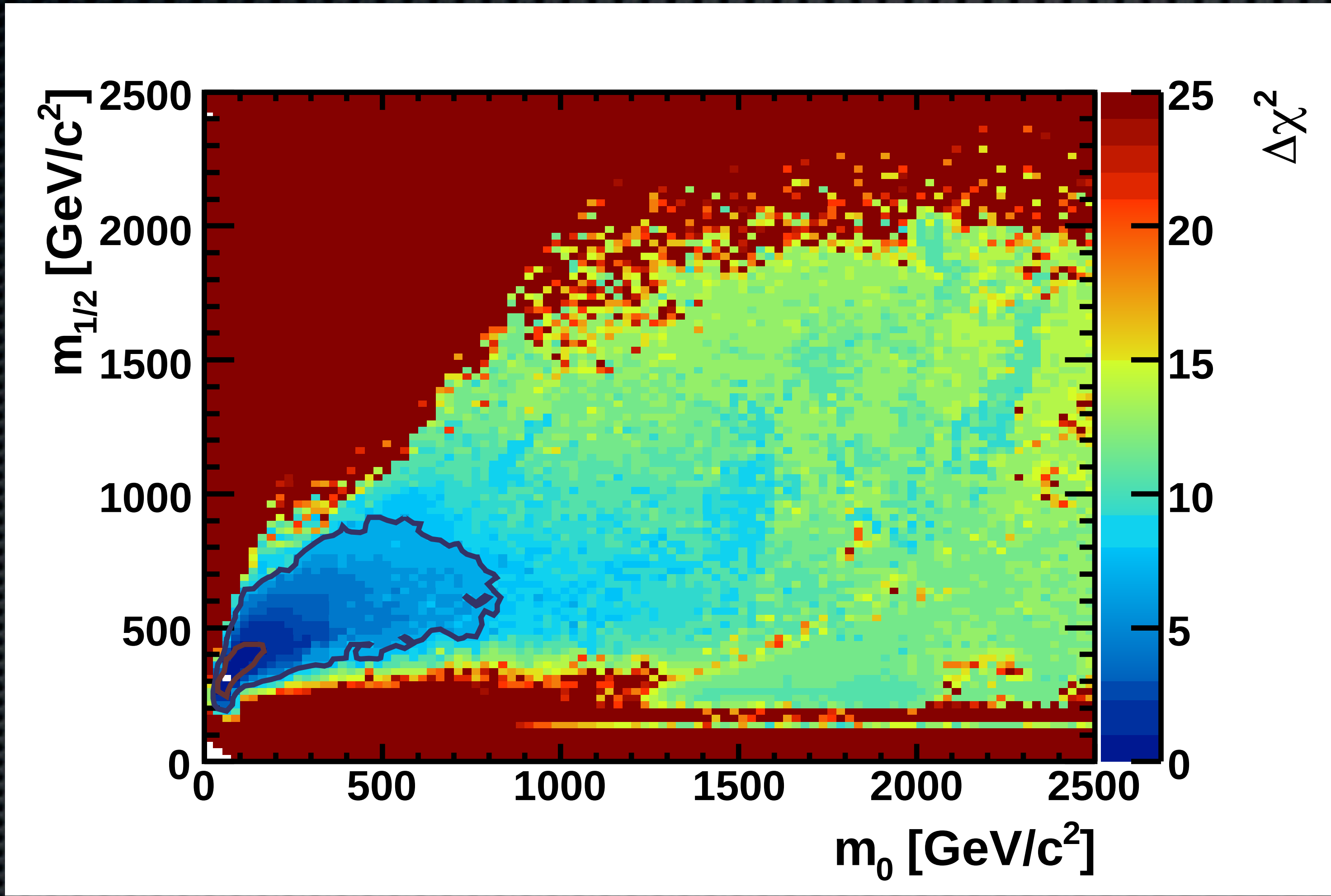
GM SUGRA planes



Dudas,Mambrini,Mustafayev,Olive

$\Delta\chi^2$ map of m_0 - $m_{1/2}$ plane

Mastercode

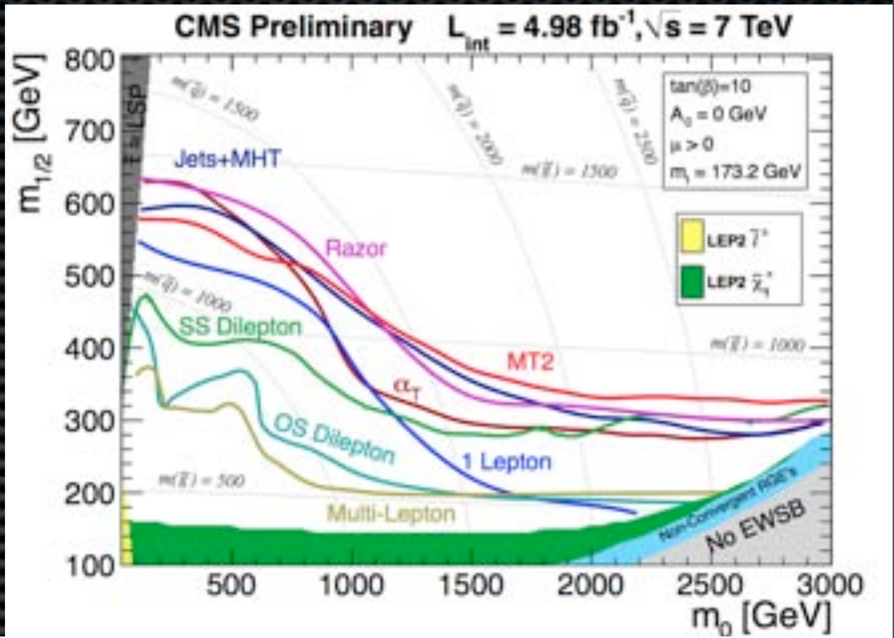


- CMSSM

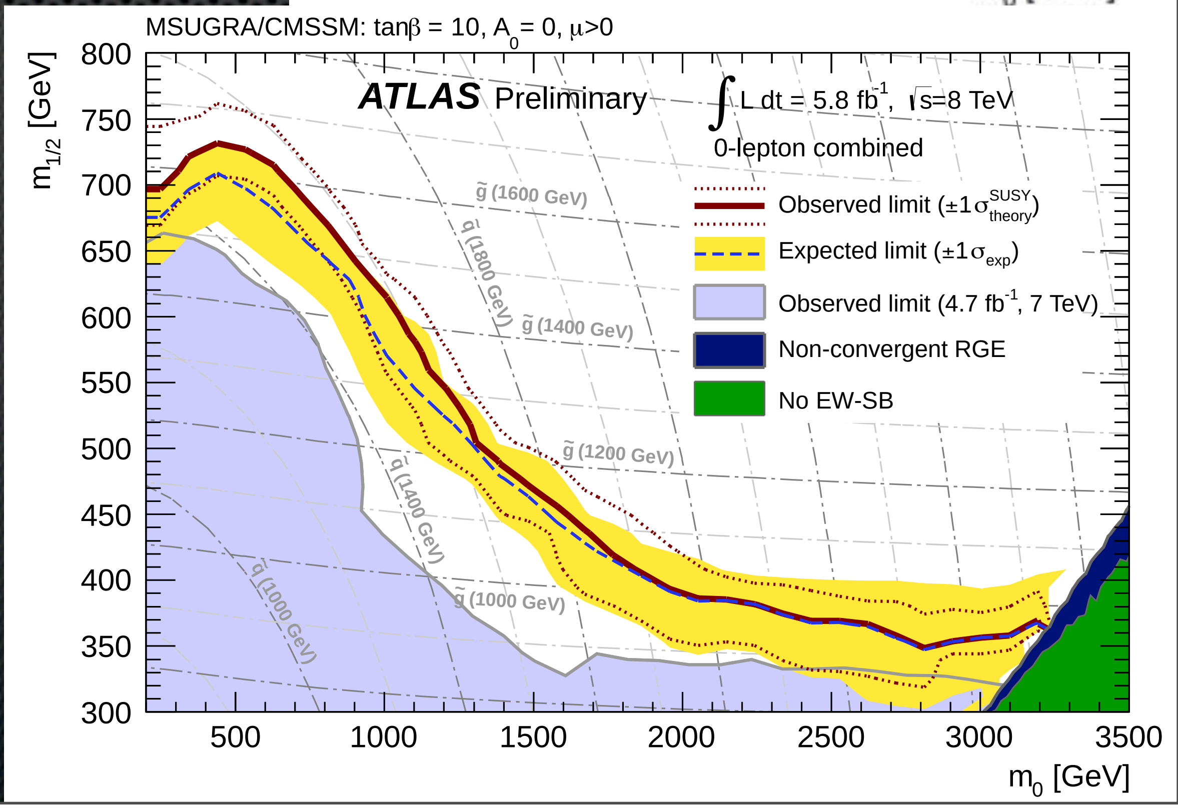
Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein

Effect of Results from LHC

~5fb^{-1} @ 7 TeV

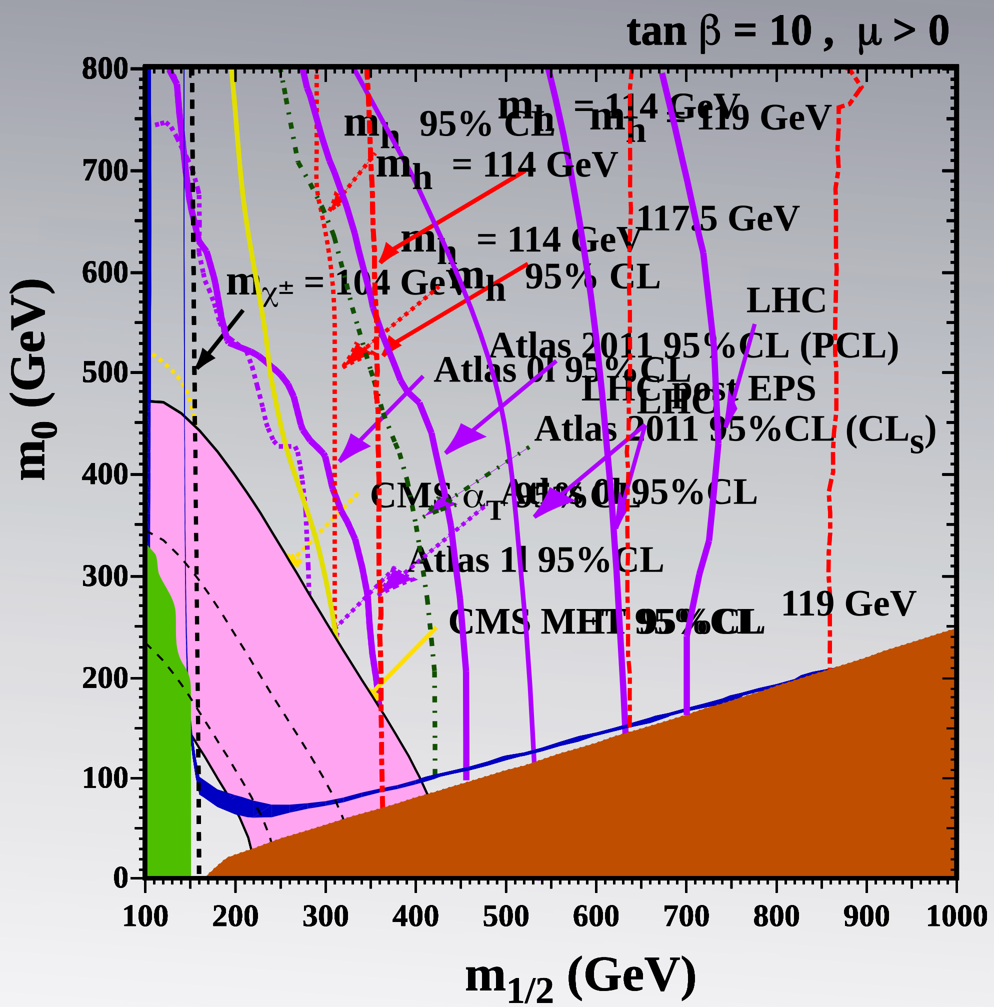


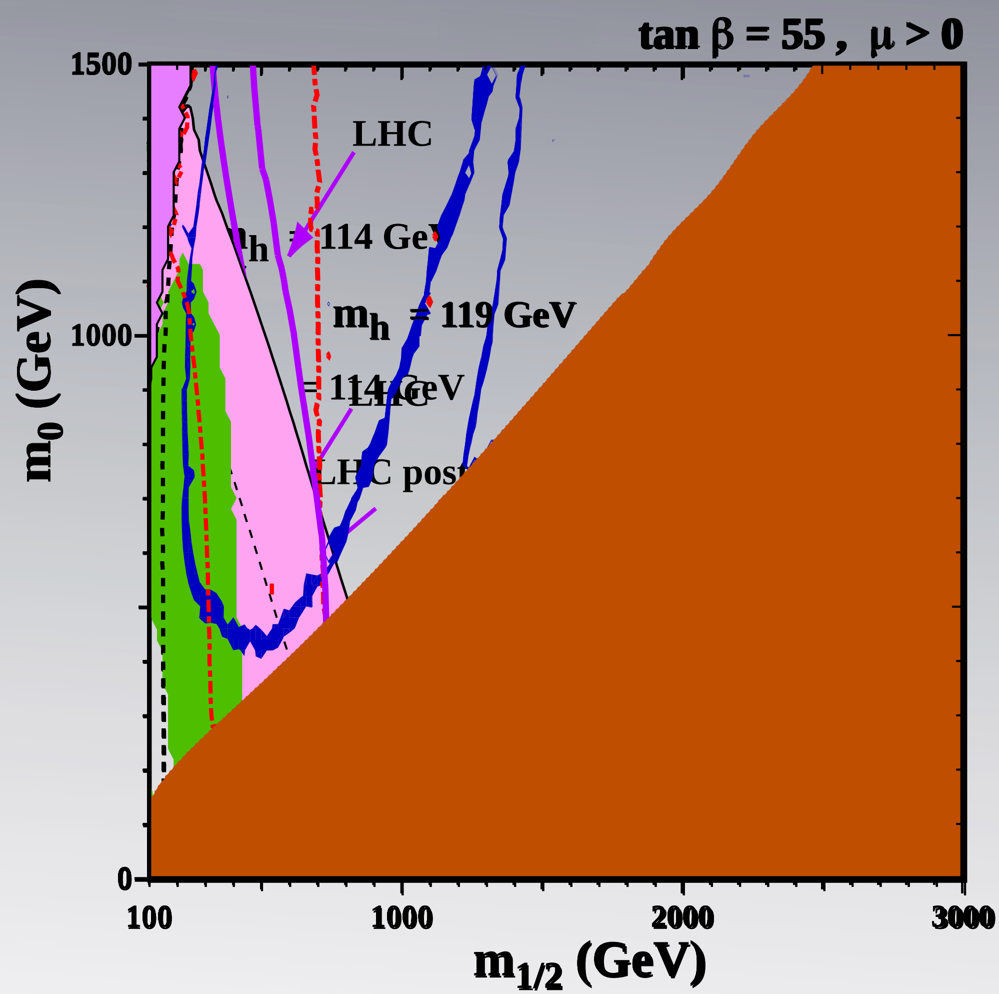
- jets + missing E_T with/ without leptons
- Heavy Higgs to ττ
- B to μμ



~6fb^{-1} @ 8 TeV

$m_{1/2}$ - m_0 planes incl. LHC





- CMSSM

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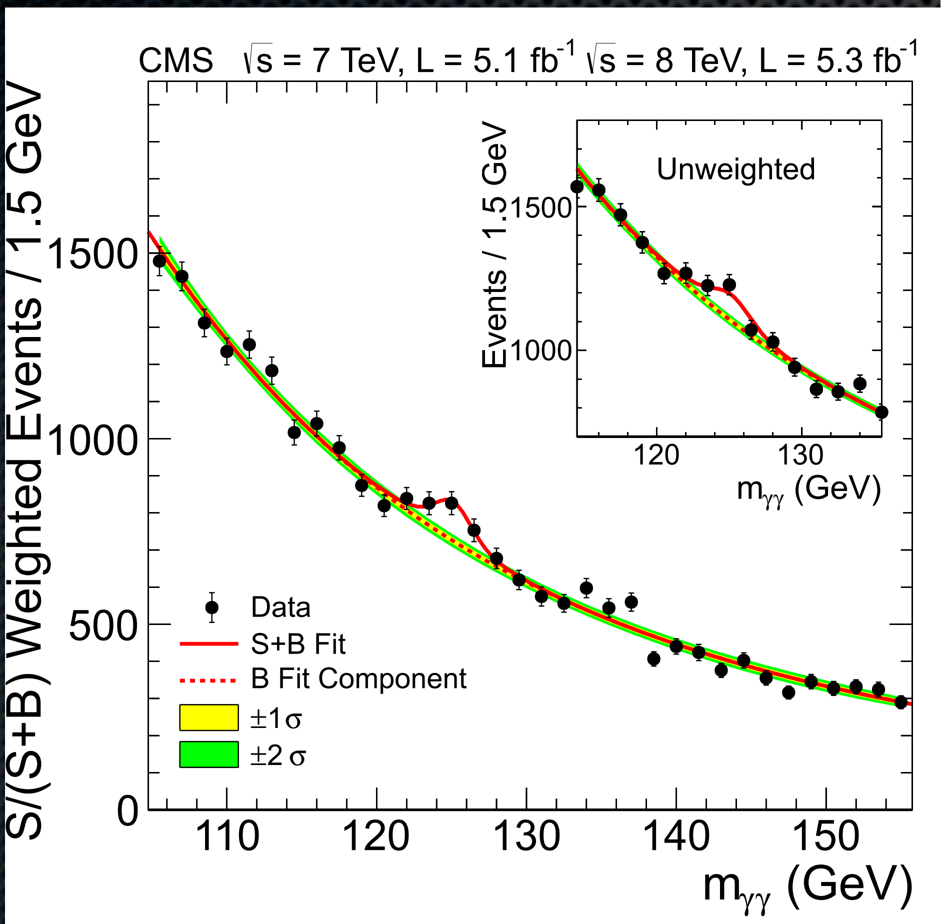
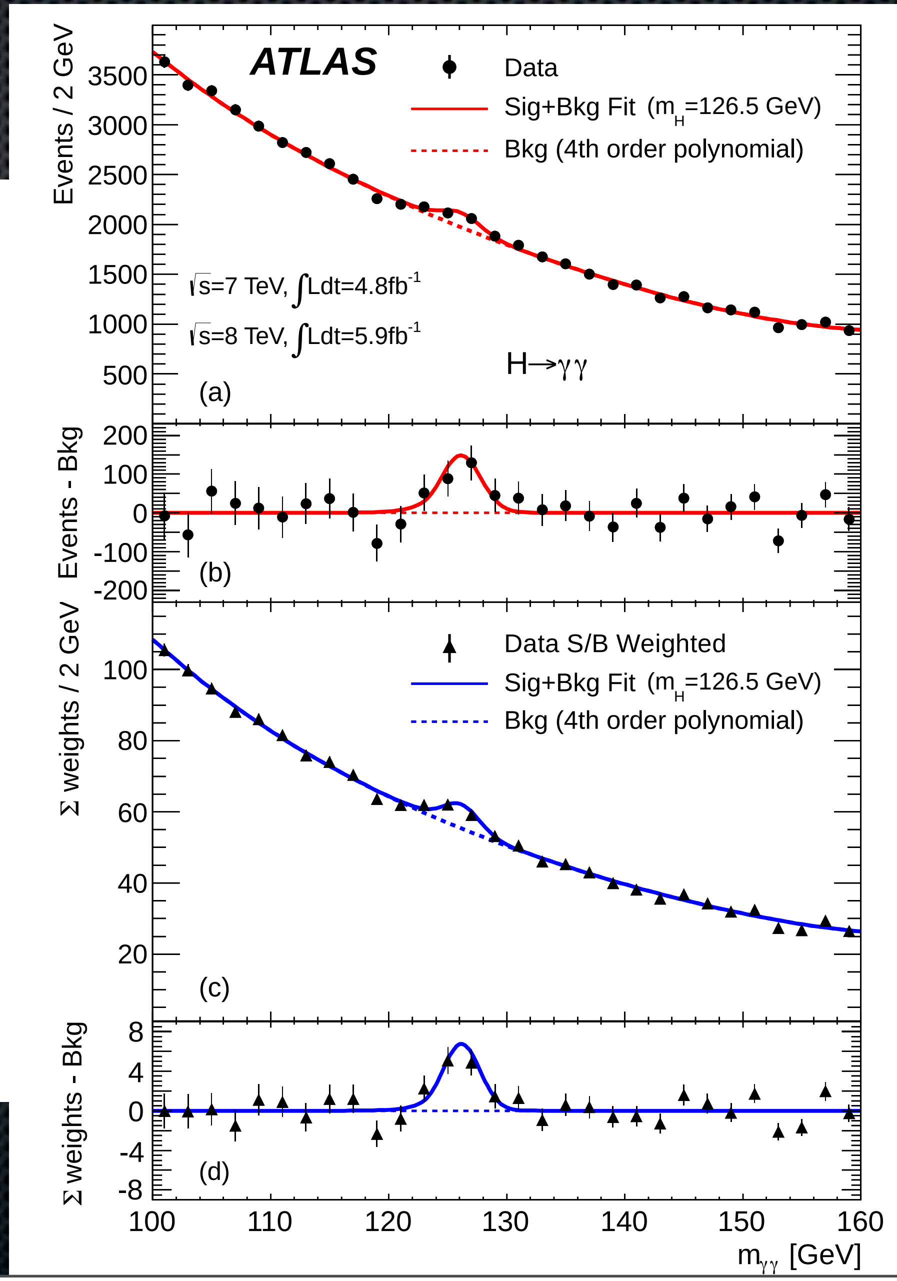
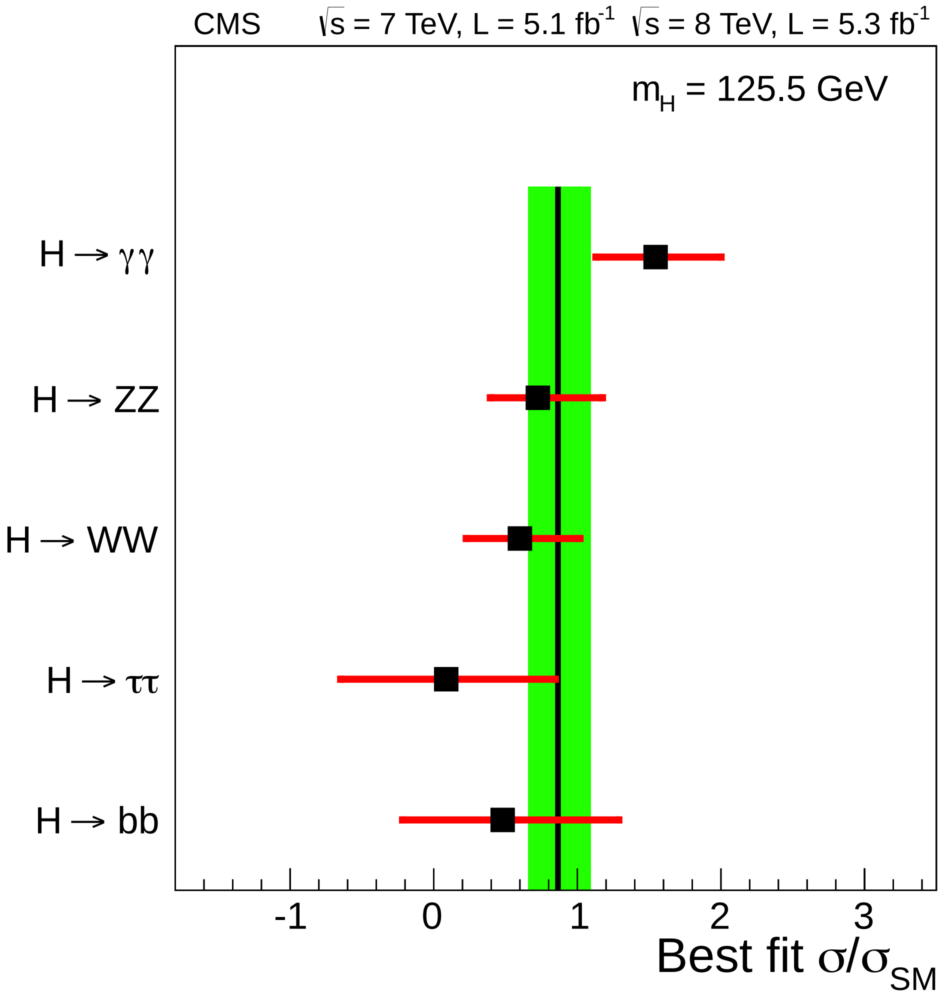
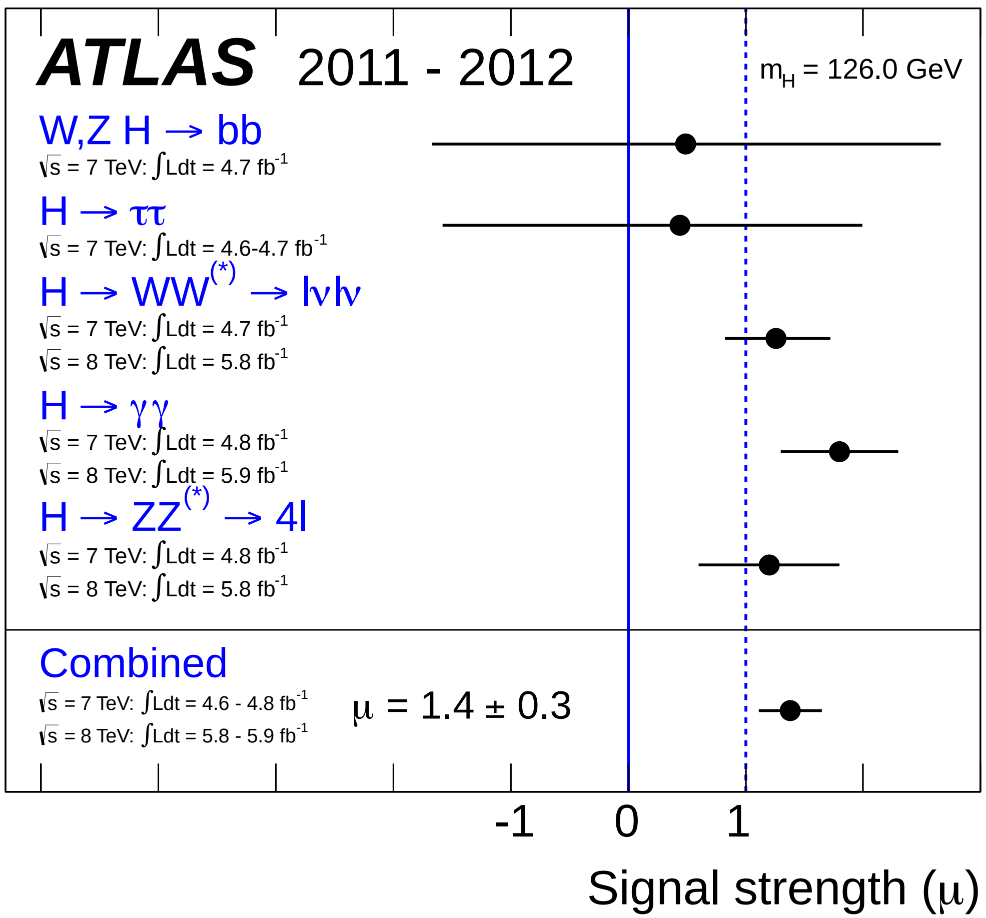
Back to the Higgs Search
The LHC @ ~5/fb





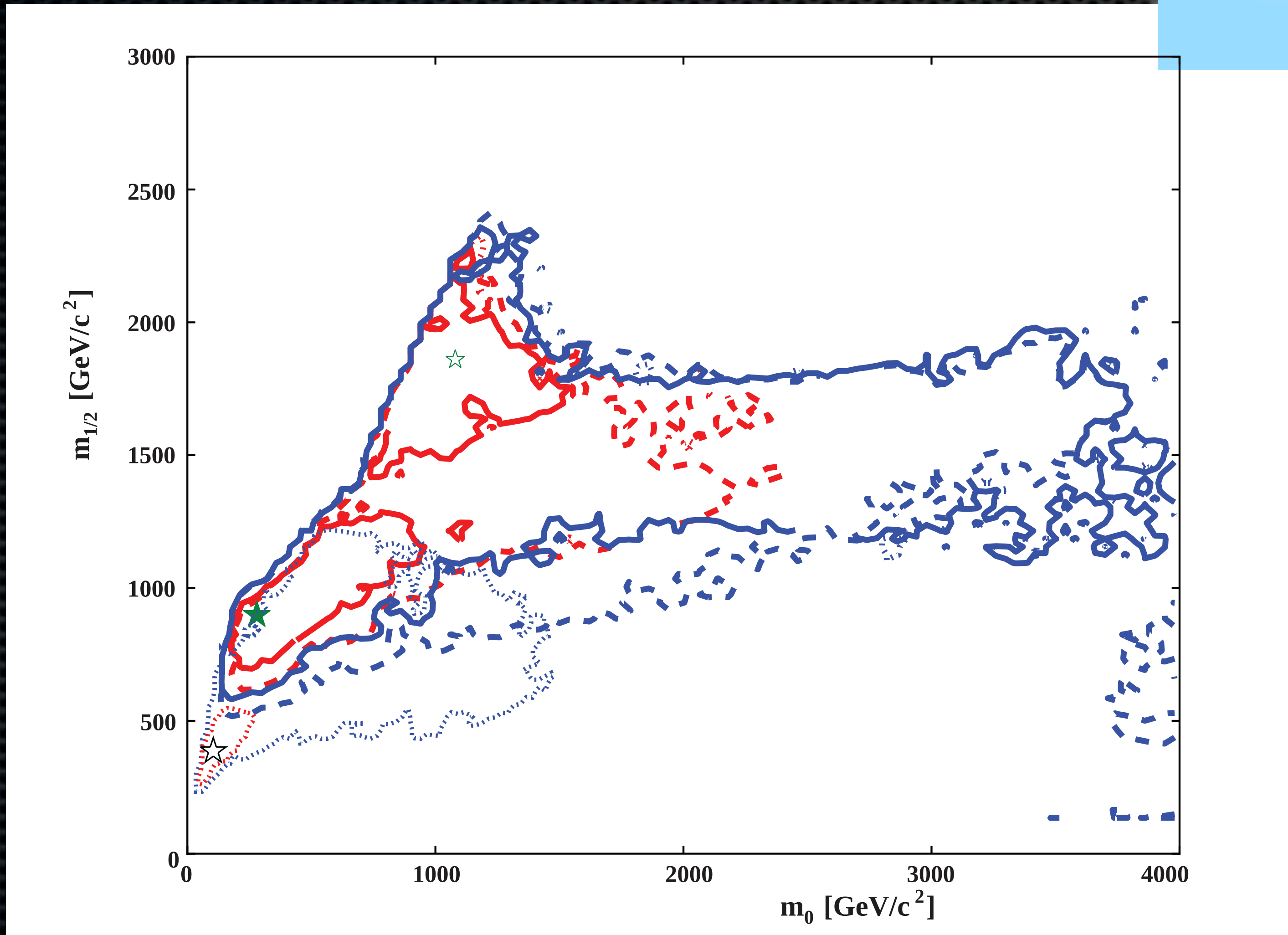
The Higgs Search
The LHC @ ~5/fb





$\Delta\chi^2$ map of m_0 - $m_{1/2}$ plane

Limits at ~5 fb^{-1}



Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Marrouche, Martinez Santos, Nakach, Olive, Rogerson, Ronga, de Vries, Weiglein

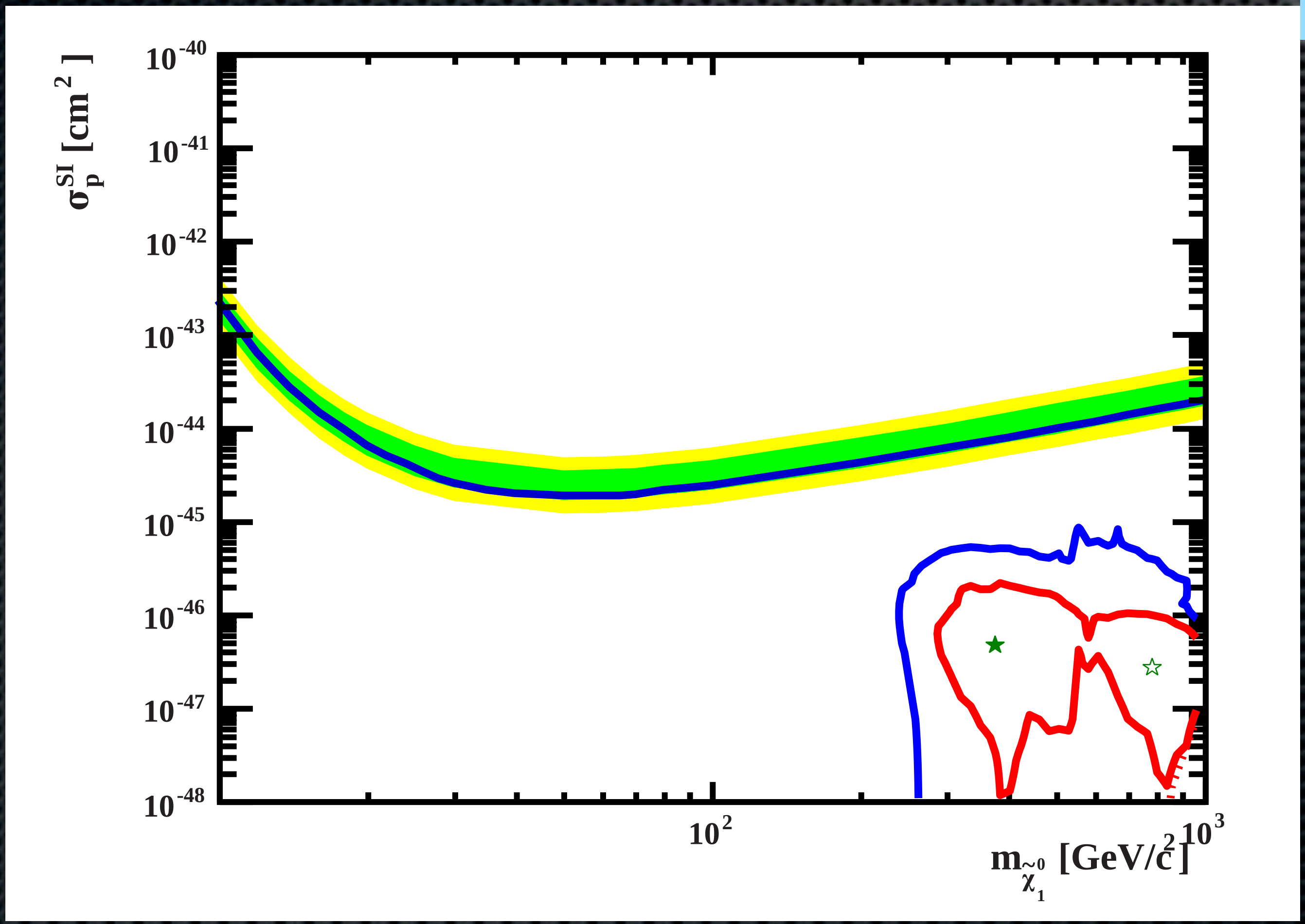
Comparison of best fit points pre and post LHC

Model	Data set	Minimum χ^2/d.o.f.	Prob- ability	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$
CMSSM	pre-LHC	21.5/20	37 %	90	360	-400	15
	$\mathrm{LHC}_{1/\mathrm{fb}}$	31.0/23	12%	1120	1870	1220	46
	$\mathrm{ATLAS}_{5/\mathrm{fb}}$ (low)	32.8/23	8.5%	300	910	1320	16
	$\mathrm{ATLAS}_{5/\mathrm{fb}}$ (high)	33.0/23	8.0%	1070	1890	1020	45
NUHM1	pre-LHC	20.8/18	29 %	110	340	520	13
	$\mathrm{LHC}_{1/\mathrm{fb}}$	28.9/22	15%	270	920	1730	27
	$\mathrm{ATLAS}_{5/\mathrm{fb}}$ (low)	31.3/22	9.1%	240	970	1860	16
	$\mathrm{ATLAS}_{5/\mathrm{fb}}$ (high)	31.8/22	8.1%	1010	2810	2080	39

p-value of SM = 9% (32.7/23) - but note: does not include dark matter

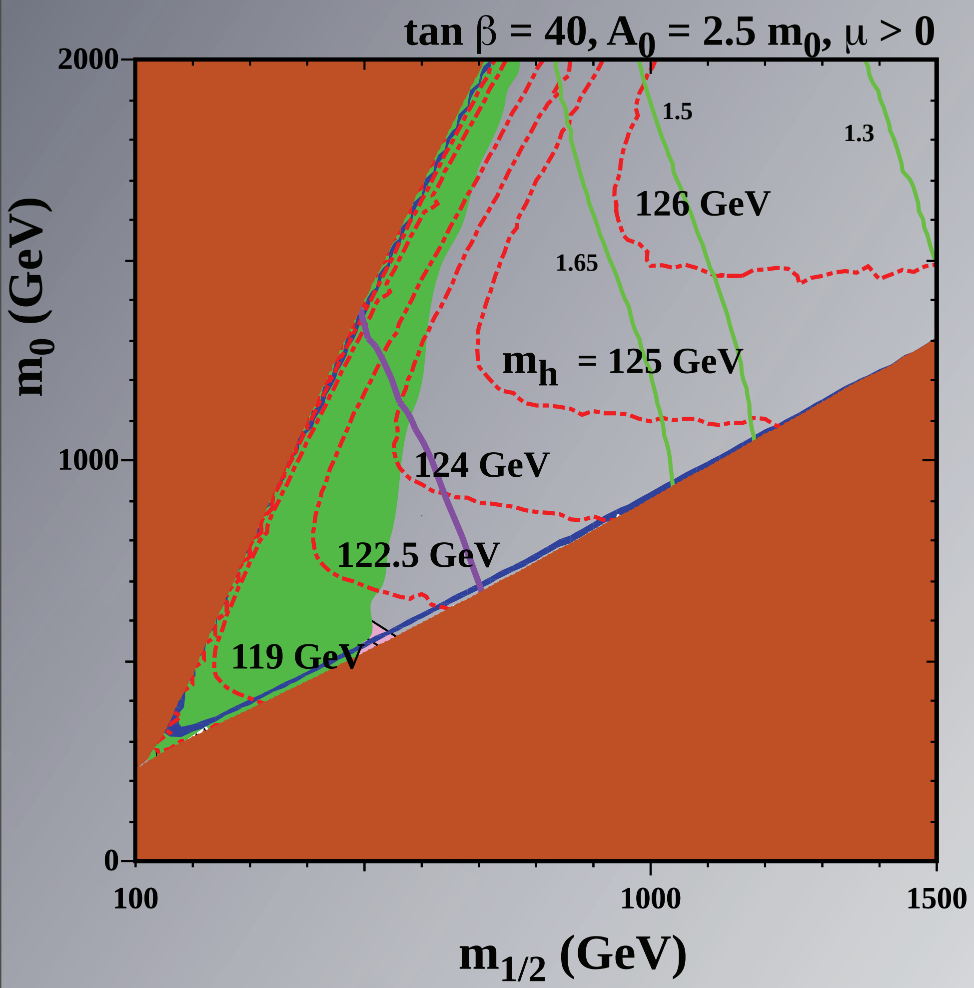
Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Marrouche, Martinez Santos, Nakach, Olive, Rogerson, Ronga, de Vries, Weiglein

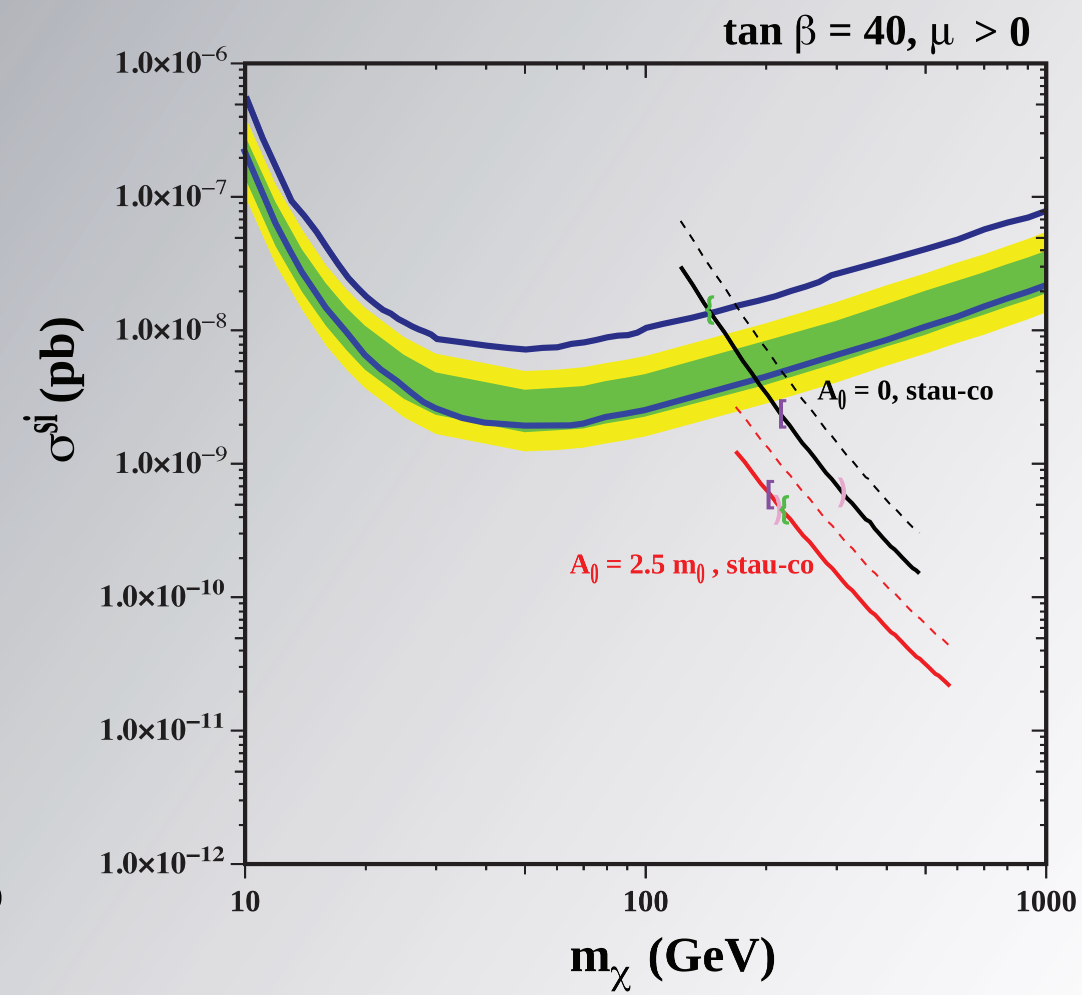
Elastic cross sections



Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Marrouche, Martinez Santos, Nakach, Olive, Rogerson, Ronga, de Vries, Weiglein

Higgs masses vs elastic cross sections



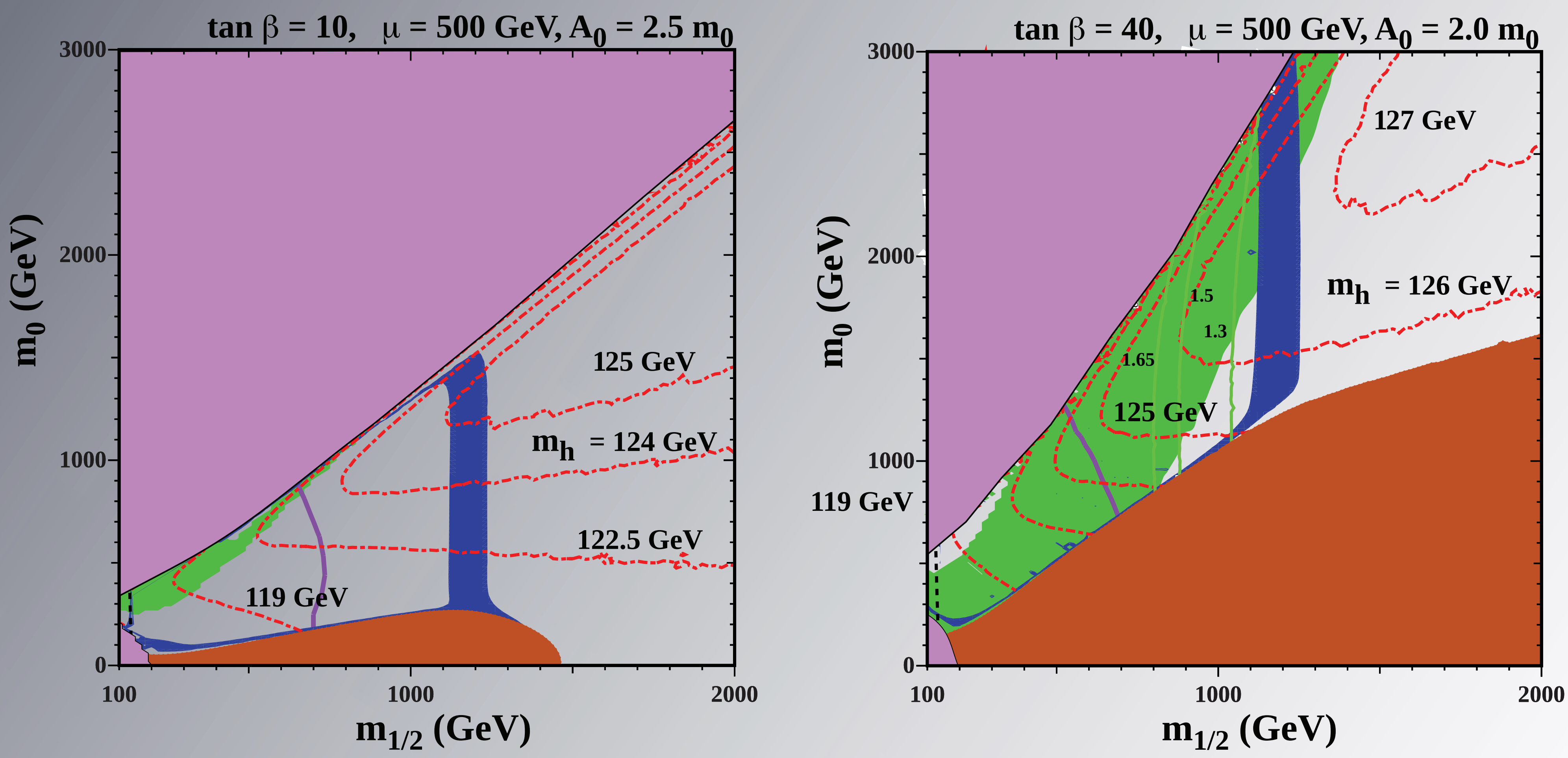


May require more general models
which are concordant with LHC MET;
Higgs; and $B_s \to \mu^+\mu^-$; and Dark Matter

Other Possibilities

- NUHM1,2: $m_1^2 = m_2^2 \neq m_0^2$, $m_1^2 \neq m_2^2 \neq m_0^2$
  - μ and/or m_A free
- subGUT models: $M_{in} < M_{GUT}$
  - with or without mSUGRA

NUHM1 models with μ free



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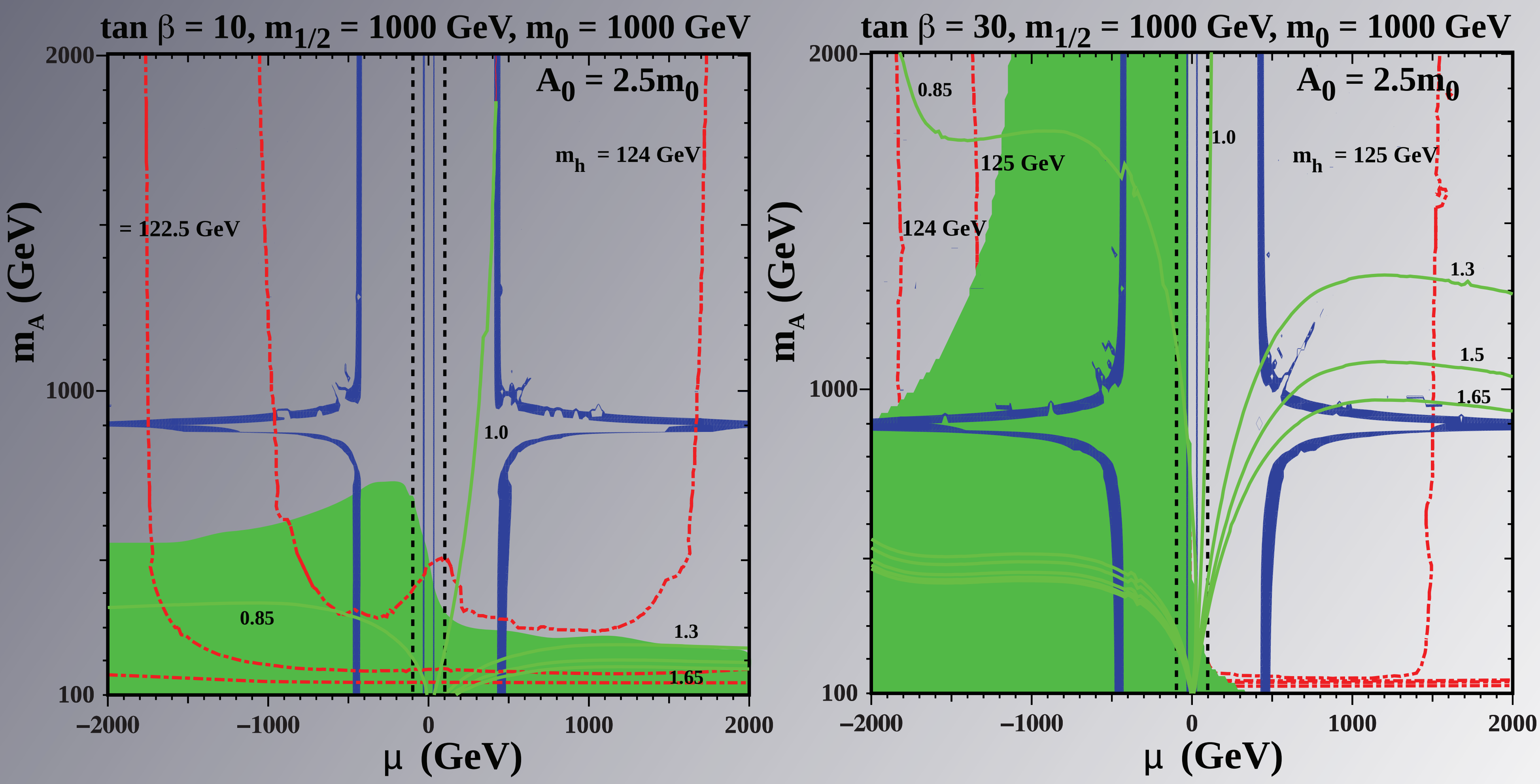
NUHM2 models with μ and m_A free



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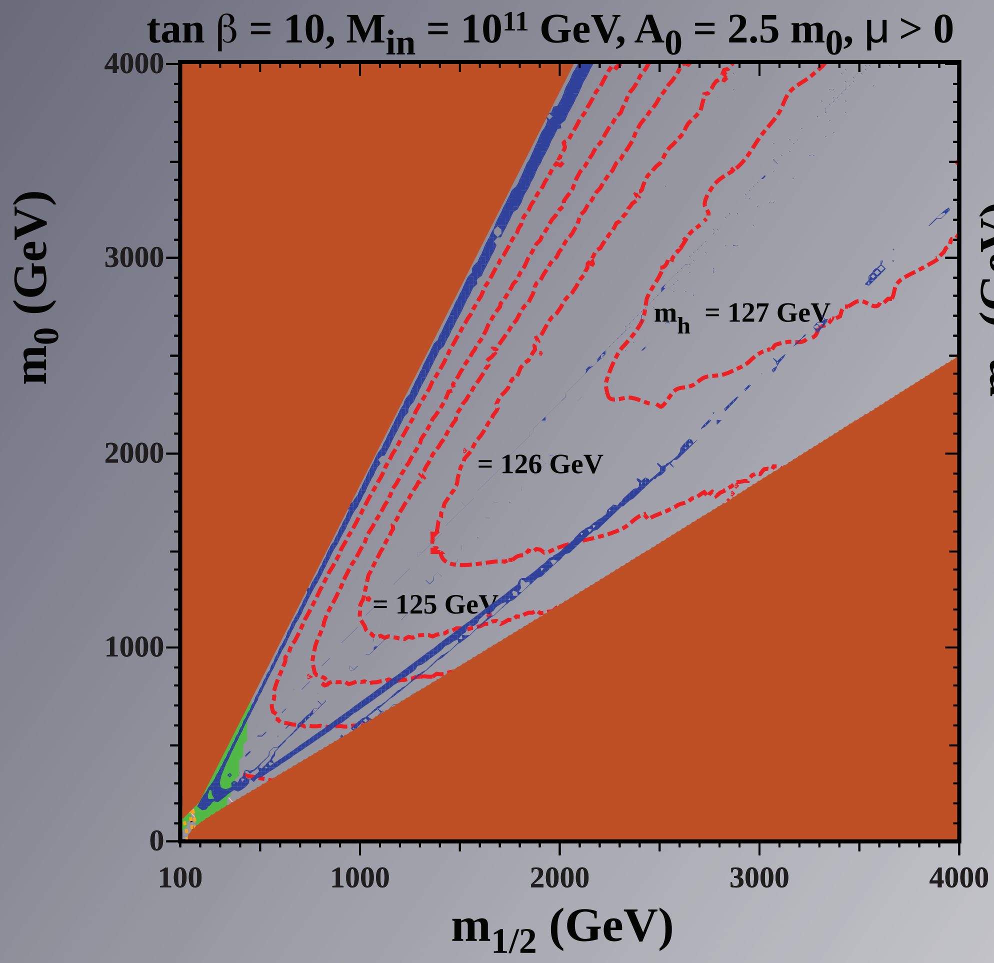
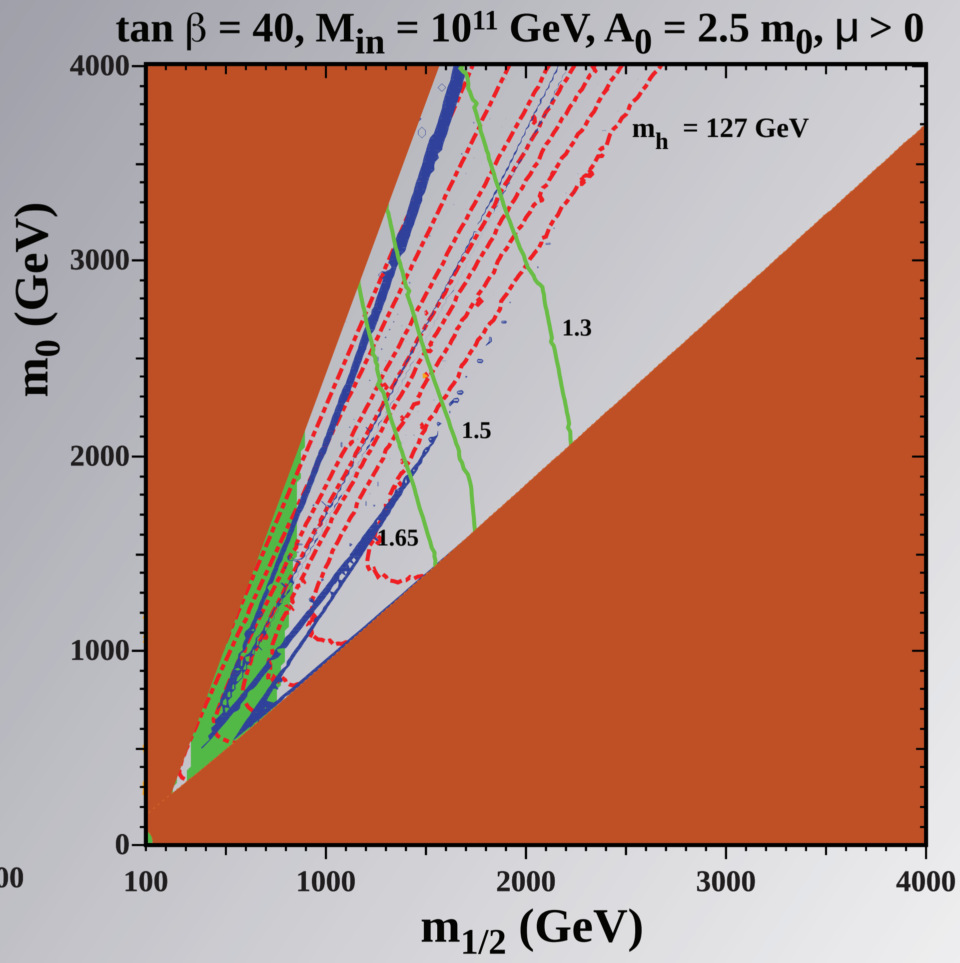
subGUT model with $M_{in} = 10^{11}$ GeV





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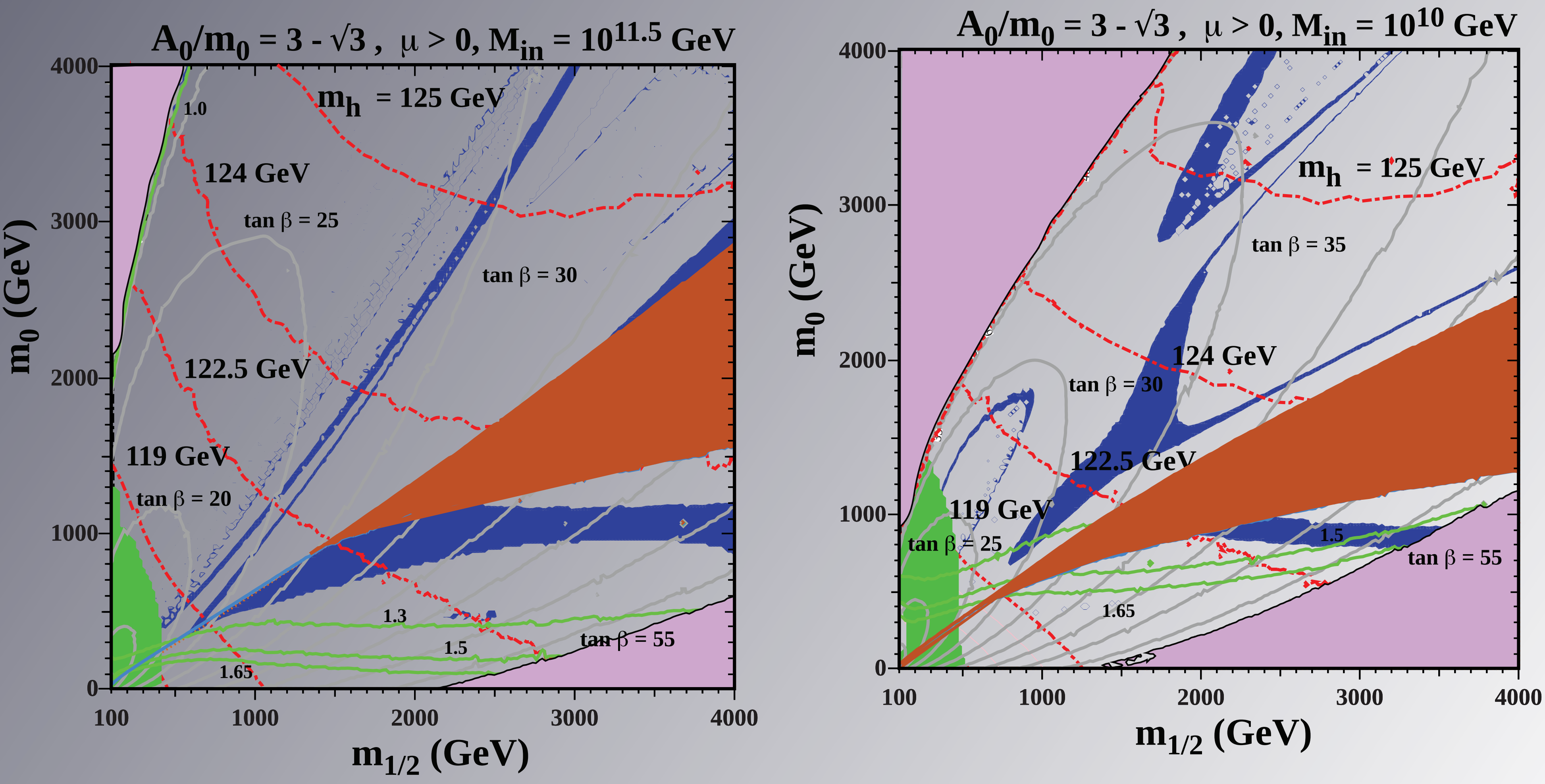
subGUT mSUGRA models



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Lots of possibilities still exist!

Moduli

- Usually ignored in phenomenological studies of the MSSM
- In general, many moduli:
- Volume Modulus: destabilization
- Polonyi-like fields: cosmological entropy production; gravitino production; LSP production....

Volume modulus (ρ) - Stabilization - KKLT

$$K = -3\log(\rho + \bar{\rho}) + y\bar{y}$$

y - matter fields

with

$$W = W(\rho) + W_{SM}(y)$$

and

$$W_{KKLT} = W_0 + Ae^{-a\rho}$$

Volume modulus - KKLT

In this construction, there is a susy ADS minimum at $\rho=\sigma_0$; with

$$W(\sigma_0) = -\frac{2a\sigma_0}{3} A e^{-a\sigma_0} \qquad W_\rho(\sigma_0) = -aAe^{-a\sigma_0},$$

and

$$V_{\mathrm{AdS}} = V(\sigma_0) = -\frac{a^2 A^2 e^{-2a\sigma_0}}{6\sigma_0}.$$

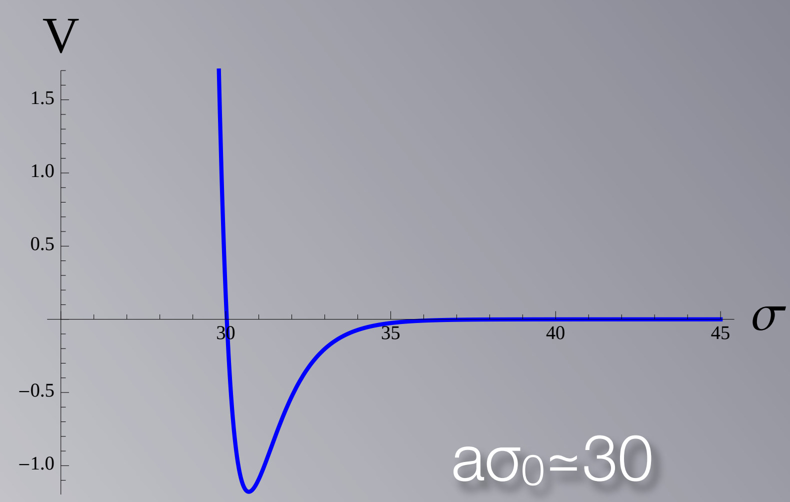
$\Rightarrow D_\rho W \equiv \partial_\rho W + K_\rho W = 0$

Obtain

$$m_{3/2} = \frac{W_0}{(2\sigma_0)^{3/2}}$$

and

$$m_\sigma = \frac{\sqrt{2\sigma_0}}{3} W_{\rho,\rho} = 2a\sigma_0\, m_{3/2}$$

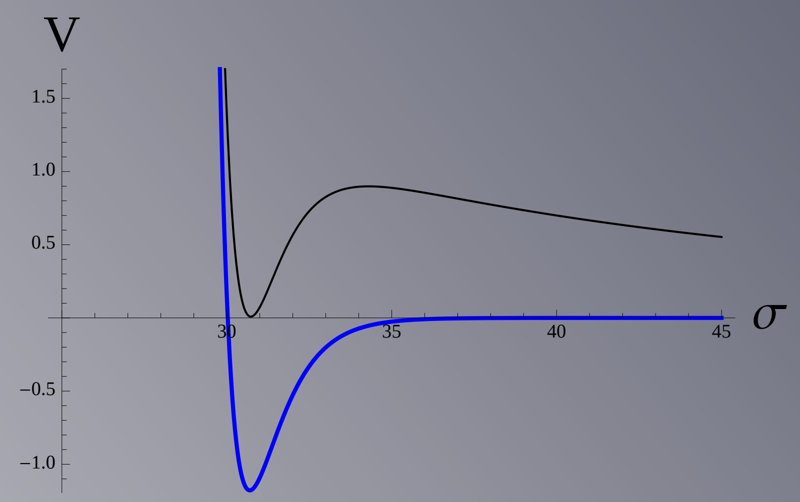


Volume modulus - KKLT

Requires uplifting

$$\Delta V \approx |V_{\rm AdS}|\ \frac{\sigma_0^n}{\sigma^n}$$

$$\frac{\Delta\sigma}{\sigma_0} = (a\sigma_0)^{-2} \ll 1.$$

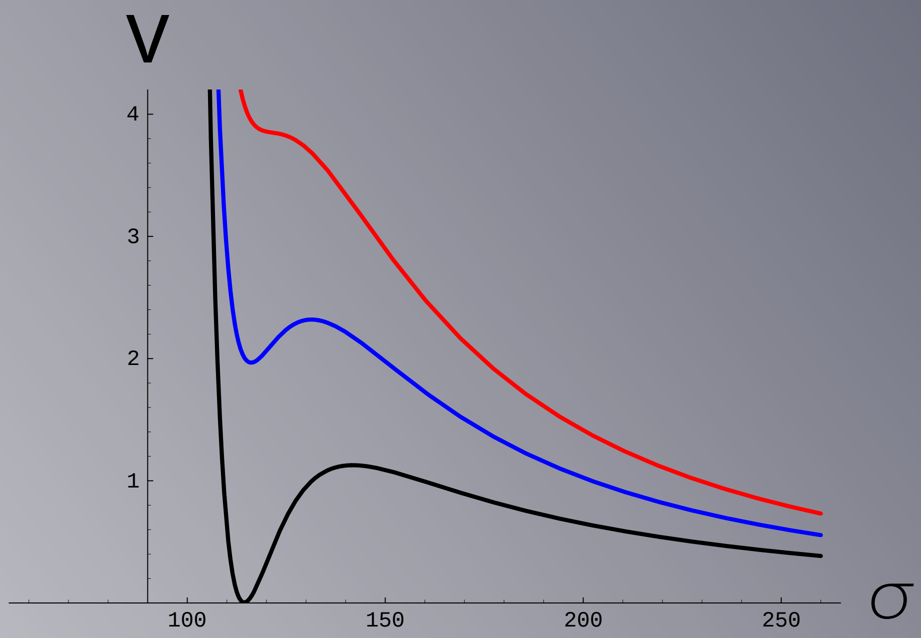


and gravitino mass essentially unchanged, but now

$$D_\rho W = (D_\rho W)_\sigma \Delta\sigma \simeq W_{\rho,\rho}\Delta\sigma = \frac{3\sqrt{2}}{a\sqrt{\sigma_0}}\, m_{3/2}$$

Volume modulus - KKLT

All quantities (W, W_ρ, $D_\rho W$, m_σ) are determined by $m_{3/2}$



Leads to the destabilization of the compactification if $H_I > m_{3/2}$

Kallosh-Linde

Volume modulus - KL

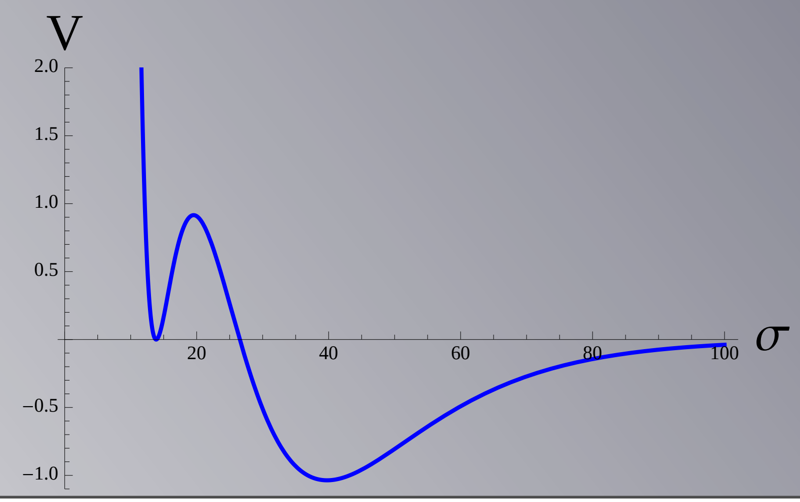
In the KL construction, there is a susy Minkowski minimum at $\rho=\sigma_0$; with

$$W_{\mathrm{KL}} = W_0 + Ae^{-a\rho} - Be^{-b\rho}$$

and now obtain with $D_\rho W = W = V = 0$ at the minimum.

$$m_{3/2} = 0$$

$$m_\sigma^2 = \frac{2}{9} W^2_{\rho,\rho}\sigma_0 = \frac{2}{9} a\, A\, b\, B\, (a-b) \left(\frac{aA}{bB}\right)^{-\frac{a+b}{a-b}} \ln\left(\frac{aA}{bB}\right)$$

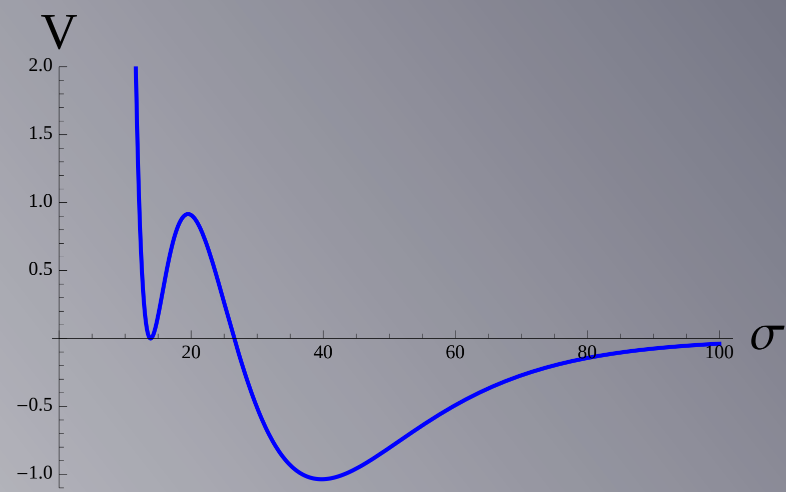


Volume modulus - KL

Next, add a constant Δ to W which will break susy and shift the minimum down slightly which requires uplifting as before.

But now,

$$m_{3/2}^2 = \frac{\Delta^2}{8\sigma_0^3}$$



and

$$\mathbf{m_{3/2} \ll m_\sigma}$$

$$D_\rho W = (D_\rho W)_\sigma \Delta\sigma \simeq W_{\rho,\rho}\Delta\sigma = 6\sqrt{2\sigma_0}\,\frac{m_{3/2}}{m_\sigma}\, m_{3/2}.$$

Thus, W = Δ and $D_\rho W \ll \Delta, m_{3/2}$

Impact on Phenomenology

Linde, Mambrini, Olive

Soft scalar masses
$$m_0^2 = \frac{1}{8\sigma^3}|W(\rho)|^2 \equiv m_{3/2}^2, \quad *$$

A terms
$$A_0 W_{SM} = (yW_y - 3W(y))m_{3/2} - \frac{1}{\sqrt{2\sigma}}\bar{D}_{\bar{\rho}}\bar{W}(\bar{\rho})W_{SM}.$$

$$A_0 = -\frac{1}{\sqrt{2\sigma}}\bar{D}_{\bar{\rho}}\bar{W}(\bar{\rho})$$

gaugino masses
$$m_{1/2} = \frac{\sqrt{2\sigma}}{6}D_\rho W(\rho)\ln(\mathrm{Re}\, h^*)_\rho$$

$$D_\rho W(\rho) = \frac{3\sqrt{2}}{a\sqrt{\sigma_0}}\ m_{3/2} \qquad \text{KKLT}$$

$$D_\rho W(\rho) = 6\sqrt{2\sigma_0}\,\frac{m_{3/2}}{m_\sigma}\ m_{3/2} \qquad \text{KL}$$

Impact on Phenomenology

* Scalar masses require F-term uplift
  or pure anomaly mediation

So add a Polonyi-like field

$$K = -3\log(\rho+\bar{\rho})+h_i^j(\rho,\bar{\rho})\phi^i\bar{\phi}_j+K(S^i,\bar{S}_i)+\Delta K(\phi^i,\bar{\phi}_i)+\cdots$$

$$K(S,\bar{S}) = S\bar{S} - \frac{(S\bar{S})^2}{\Lambda^2}$$

$$W = W(\rho) + W_F(S^i) + g(\phi^i,\rho)$$

Kitano

$$W_F(S) = M^2 S$$

(constant already in W(ρ))

The Polonyi Sector

For Δ « 1, S will also be strongly stabilized

Uplifting to Minkowski with

$$M^4 = 3\Delta^2 = 24\sigma_0^3 m_{3/2}^2$$

$$W_F(S) = M^2 S$$

and

$$\langle S \rangle = \frac{\sqrt{3}\Lambda^2}{6}$$

$$K(S,\bar{S}) = S\bar{S} - \frac{(S\bar{S})^2}{\Lambda^2}$$

$$m_S^2 = \frac{3\Delta^2}{2\sigma_0^3\Lambda^2} = \frac{12 m_{3/2}^2}{\Lambda^2} \gg m_{3/2}^2$$

Back to Phenomenology

Dudas, Linde, Mambrini, Mustafayev, Olive

Soft scalar masses $$m_0^2 = m_{3/2}^2$$

$$m_{3/2}^2 = \frac{1}{8\sigma_0^3}|W(\rho) + W_F(S)|^2 = \frac{1}{8\sigma_0^3}|\Delta + \frac{\Delta\Lambda^2}{2}|^2 \approx \frac{1}{8\sigma_0^3}|\Delta|^2$$

A terms $$(Ay)_{ijk} = e^K \left[K^{\rho\bar{\rho}}\overline{D_\rho W}(K_\rho + \nabla_\rho) + K^{S\bar{S}}\overline{D_S W} K_S \right] W_{ijk}$$

$$\Rightarrow \qquad A_0 \simeq \frac{1}{2} m_{3/2}\Lambda^2$$

Back to Phenomenology

Dudas, Linde, Mambrini, Mustafayev, Olive

μ and B terms

$$\mu = m_{3/2} G_{12} = e^{K/2} W_{12} + m_{3/2} K_{12} = \mu_0 + m_{3/2} K_{12}$$

$$B\mu = (A_0 - m_{3/2})\mu_0 + 2m_{3/2}^2 K_{12}$$

gaugino masses

$$m_{1/2} = \frac{\sqrt{2\sigma}}{6} D_\rho W(\rho) \ln(\mathrm{Re}\, h^*)_\rho$$

as before

Massive scalar sector as in split susy, with anomaly mediation for A-terms and gaugino masses

Problems constructing a phenomenologically viable theory

1. No guarantee that there are solutions for $\tan\beta$, while requiring $B_0 = A_0 - m_0$. Solutions exist in limited domains of $m_{1/2}$, m_0, A_0.
2. No guarantee that solutions exist with $\mu^2 > 0$ when m_0 is very large (past the focus point) - particularly when A_0 is small.

Possible resolutions

1. Add GM term $\Delta K = c_H H_1 H_2 + h.c.$

Now boundary condition on μ becomes,

$$\mu_0 B_0 + c_H m_0$$

don’t care

More importantly, boundary condition on μB becomes

$$\mu_0 B_0 + 2 c_H m_0^2$$

Possible resolutions

2. a) Take $M_{in} > M_{GUT}$

   Extra running between M_{in} and M_{GUT} allows EWSB solutions with very large m_0

   b) Add source of non-universality to Higgs masses

Constructions

$$W_5 \quad = \quad \mu_\Sigma Tr\hat{\Sigma}^2 + \frac{1}{6}\lambda' Tr\hat{\Sigma}^3 + \mu_H \hat{\mathcal{H}}_1 \hat{\mathcal{H}}_2 + \lambda \hat{\mathcal{H}}_1 \hat{\Sigma} \hat{\mathcal{H}}_2$$
$$+(\mathbf{h_{10}})_{ij} \hat{\psi}_i \hat{\psi}_j \hat{\mathcal{H}}_2 + (\mathbf{h_{\bar{5}}})_{ij} \hat{\psi}_i \hat{\phi}_j \hat{\mathcal{H}}_1 \ ,$$

$$\varDelta K = c_H \mathcal{H}_1 \mathcal{H}_2 + \frac{1}{2} c_\varSigma \, \mathrm{Tr}\, \varSigma^2 + h.c.$$

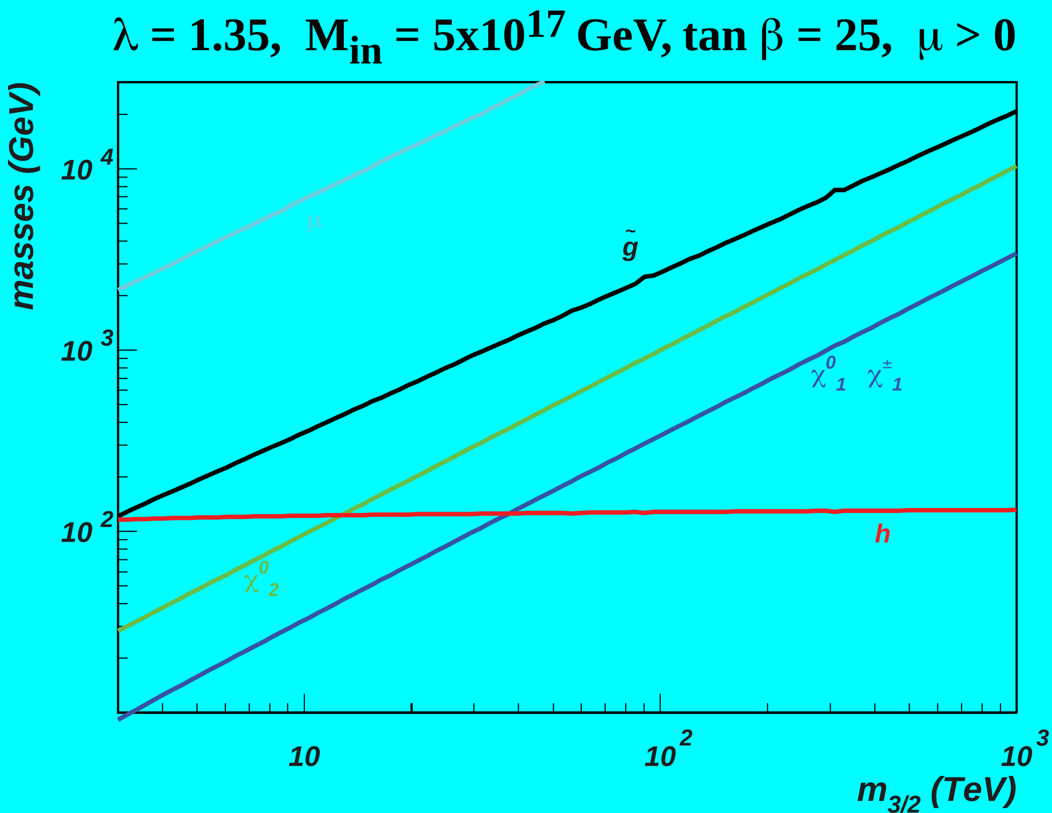
Boundary conditions now set at M_{in}, with $m_0 = m_{3/2}$ and A_0 and $m_{1/2}$ set by anomalies

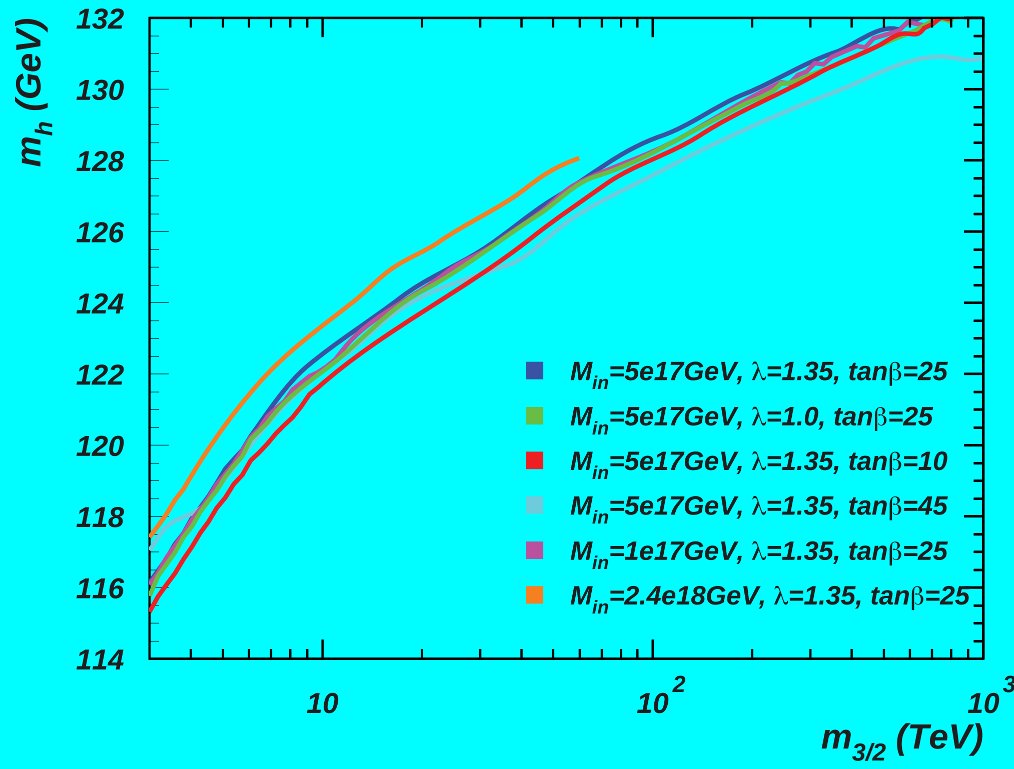
Canonical example,

$$m_0 = m_{3/2} = 32 \text{ TeV}$$
$$\tan\beta = 25$$
$$M_{in} = 5 \times 10^{17} \text{ GeV}$$
$$\lambda = 1.35$$
$$\lambda' = 0.1 \qquad \text{almost arbitrary}$$
$$c_\Sigma = -.85 \qquad \text{set to get}$$
$$c_H = 0$$

$$m_{\tilde{f}_{1,2}} \simeq 32 \text{ TeV}$$
$$m_{\tilde{\tau}_1} \simeq 29.6 \text{ TeV}$$
$$m_{\tilde{t}_1} \simeq 24.2 \text{ TeV}$$
$$m_{\tilde{b}_1} \simeq 26.9 \text{ TeV}$$
$$\mu \simeq 20.4 \text{ TeV}$$
$$\text{Higgsinos, and}$$
$$\text{heavy Higgs} \simeq 22 \text{ TeV}$$
$$m_{\tilde{g}} \simeq 1 \text{ TeV}$$
$$m_{\tilde{B}} \simeq 314 \text{ GeV}$$
$$m_{\tilde{W}} \simeq 107 \text{ GeV}$$
$$m_h \simeq 125 \text{ GeV}$$

Light masses and Higgs mass





$$m_{\chi^+} > 104 \text{ GeV} \to m_{3/2} > 31 \text{ TeV} \to m_h > 125.3 \text{ GeV}$$

Other Phenomenological Aspects

1. Gluinos $m_{\tilde{g}} \ll m_{\tilde{q}}$

$\tilde{g} \longrightarrow \tilde{q} q$ forbidden

3 body $\tilde{g} \rightarrow \tilde{q}^* q \rightarrow q q \chi$

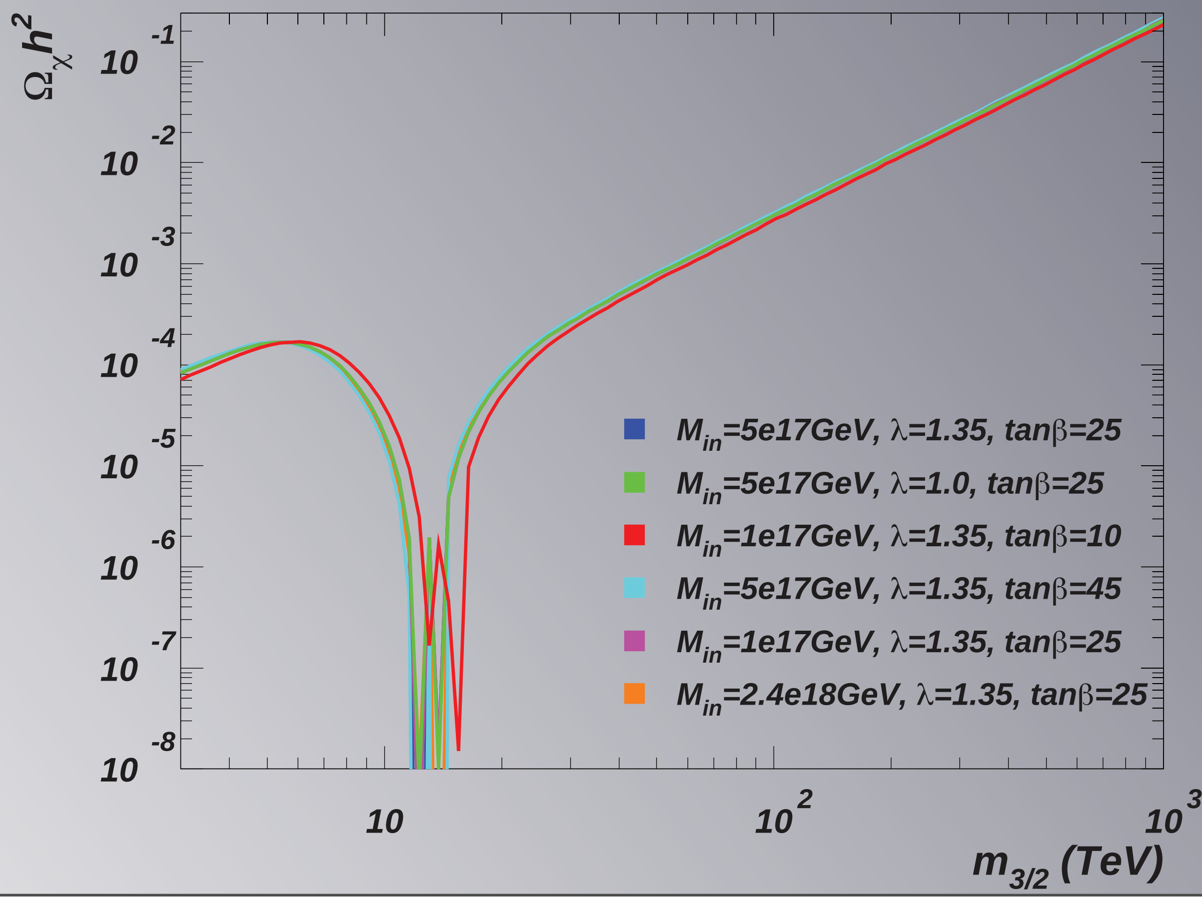
or 2 body through loops $\tilde{g} \rightarrow q \chi$

2. Charginos $m_{\chi^+} \approx m_{\chi}$

Slow decay

Other Phenomenological Aspects

3. Dark Matter
   (a) LSP is a wino
   (b) $\Omega h^2 = 2.8 \times 10^{-4}$ @ $m_{3/2} = 32$ TeV



More on Dark Matter

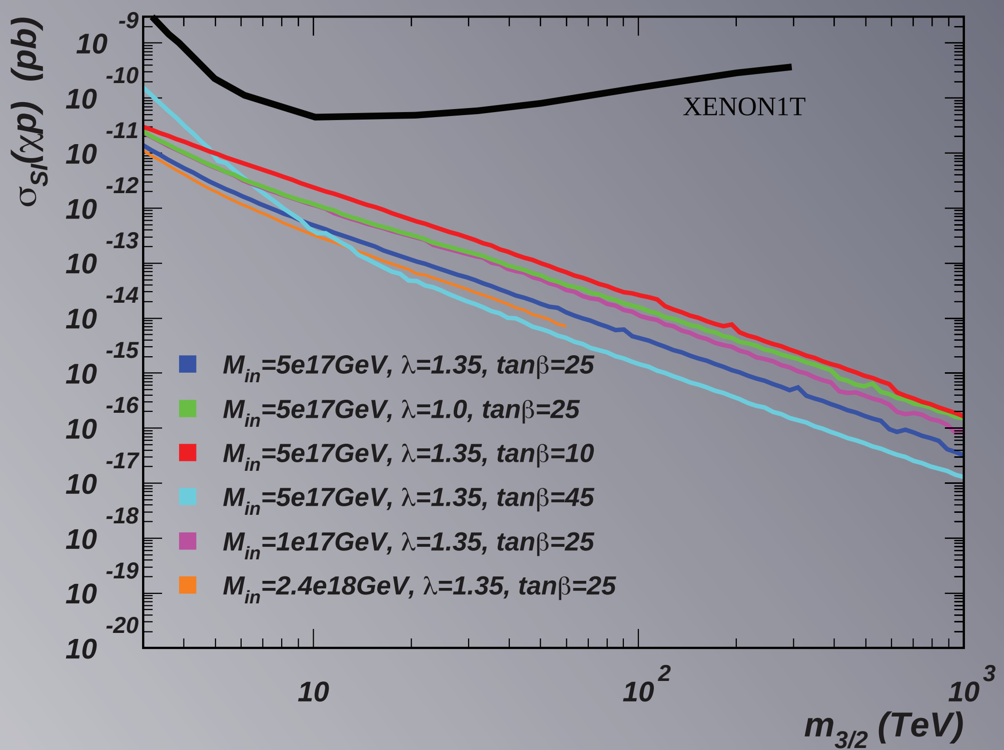
- Dark matter is something else (axion)
- LSPs from gravitino or moduli (S) decay*
- $m_{3/2}$ ~ 650 TeV, and Ωh^2 ~ 0.11

$$\Omega_\chi h^2 = \frac{m_\chi}{m_{3/2}} \Omega_{3/2} h^2 = 0.4 (\frac{m_\chi}{\mathrm{TeV}})(\frac{T_R}{10^{10}\mathrm{GeV}})$$

*Strong moduli stabilization is expected to limit the role of moduli in this context

Direct and Indirect detection

(a) Elastic cross sections for direct detction low



(b) cross section to gamma rays large: constraint from Fermi could be significant.

Summary

- LHC susy and Higgs searchs have pushed CMSSM-like models to “corners”
- Though many phenomenological solutions are viable, they typically ignore the role of moduli
- Models with strong moduli stabilization:
  - easier for inflation,
  - no cosmological problems
  - interesting phenomenology
- Heavy scalar spectrum with anomaly mediated gaugino masses
- Challenge lies in detection strategies