Supersymmetric Dark Matter post run I at the LHC

Which Supersymmetric Model?

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

- CMSSM
- mSUGRA
- NUHM
- (mini) Split SUSY

The CMSSM

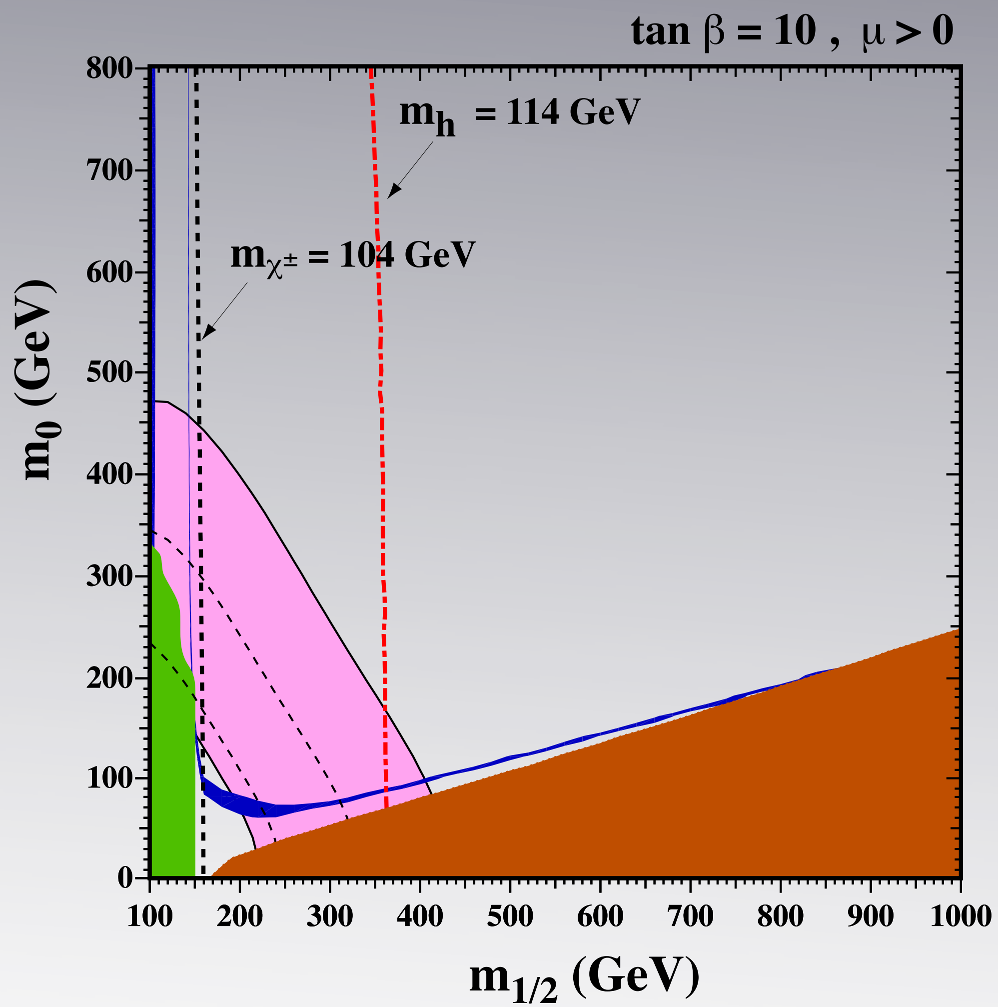
Parameters: $m_{1/2}$, m_0, A_0, $\tan\beta$, sgn(μ)　　　{$m_{3/2}$}

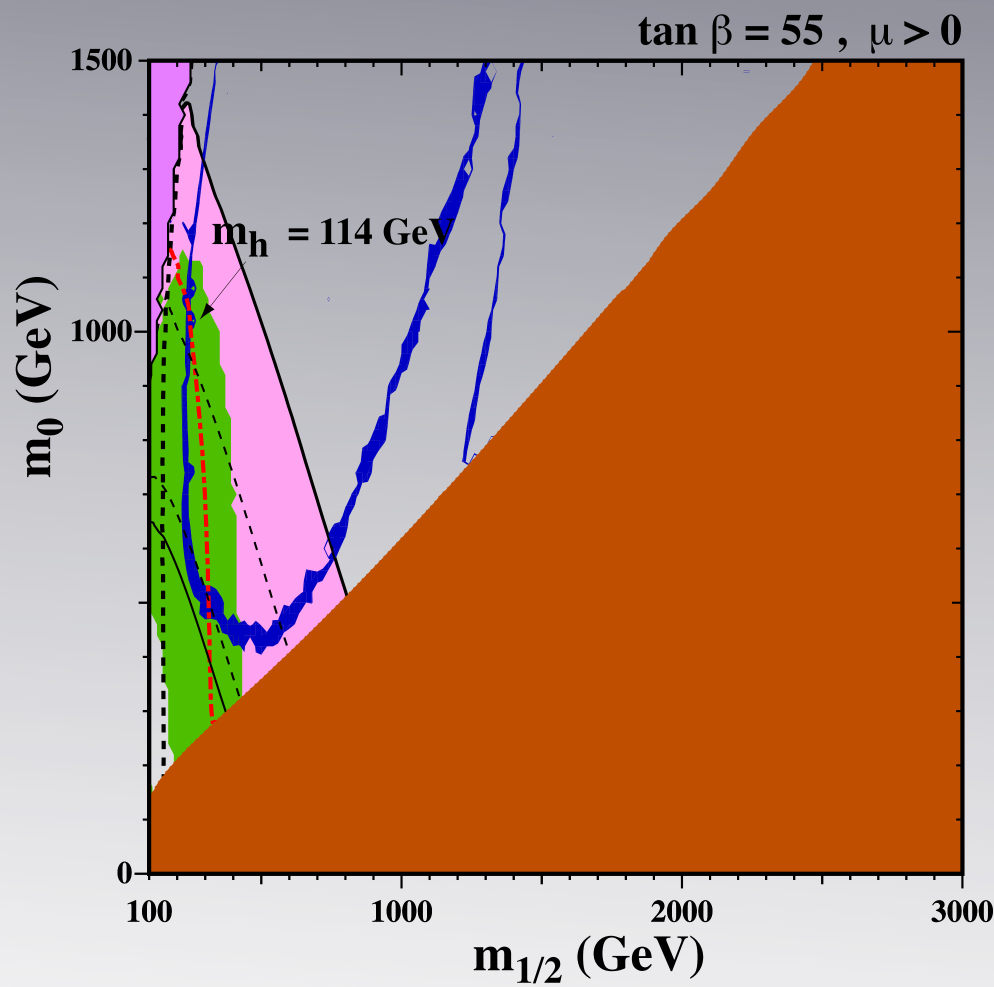
Electroweak Symmetry Breaking conditions:

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

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

$m_{1/2}$ - m_0 planes

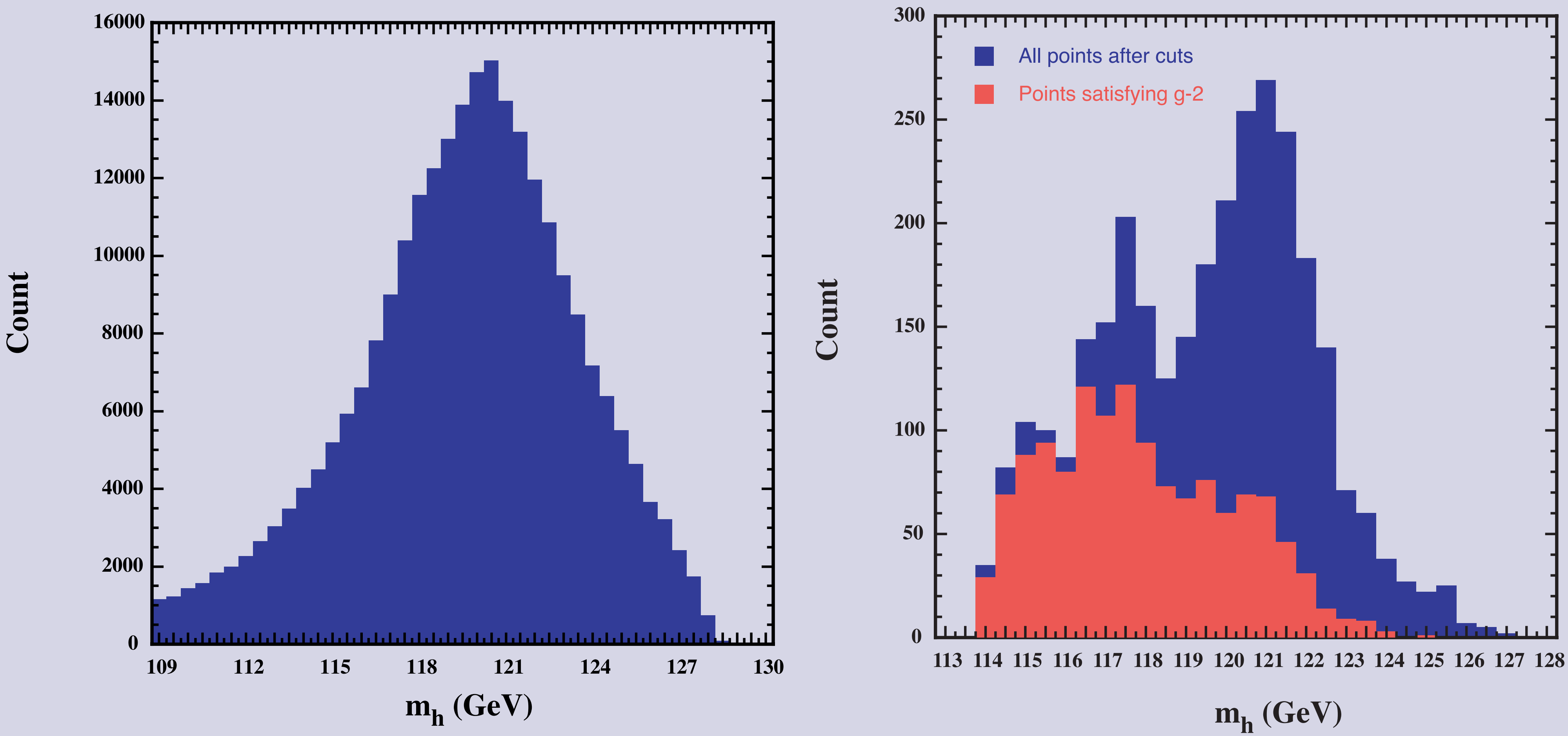




- CMSSM

Ellis, Olive, Santoso, Spanos

The Higgs mass in the CMSSM



Ellis, Nanopoulos, Olive, Santoso

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):

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

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

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

For example,

Polonyi: f(z) = **m_0** (z + β) ;

With <z> = √3 - 1 for β = 2 - √3

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

mSUGRA

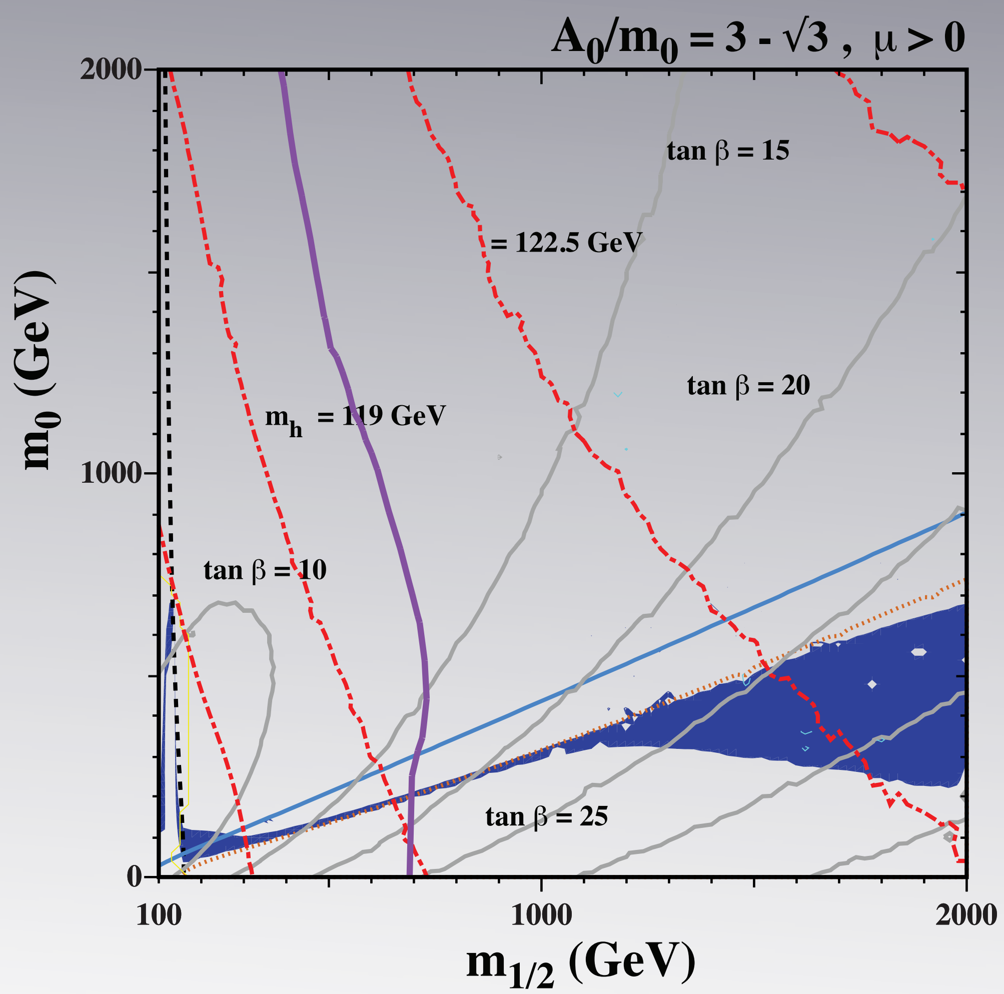
Parameters: $m_{1/2}$, $m_{3/2}$, A_0, sgn(μ)

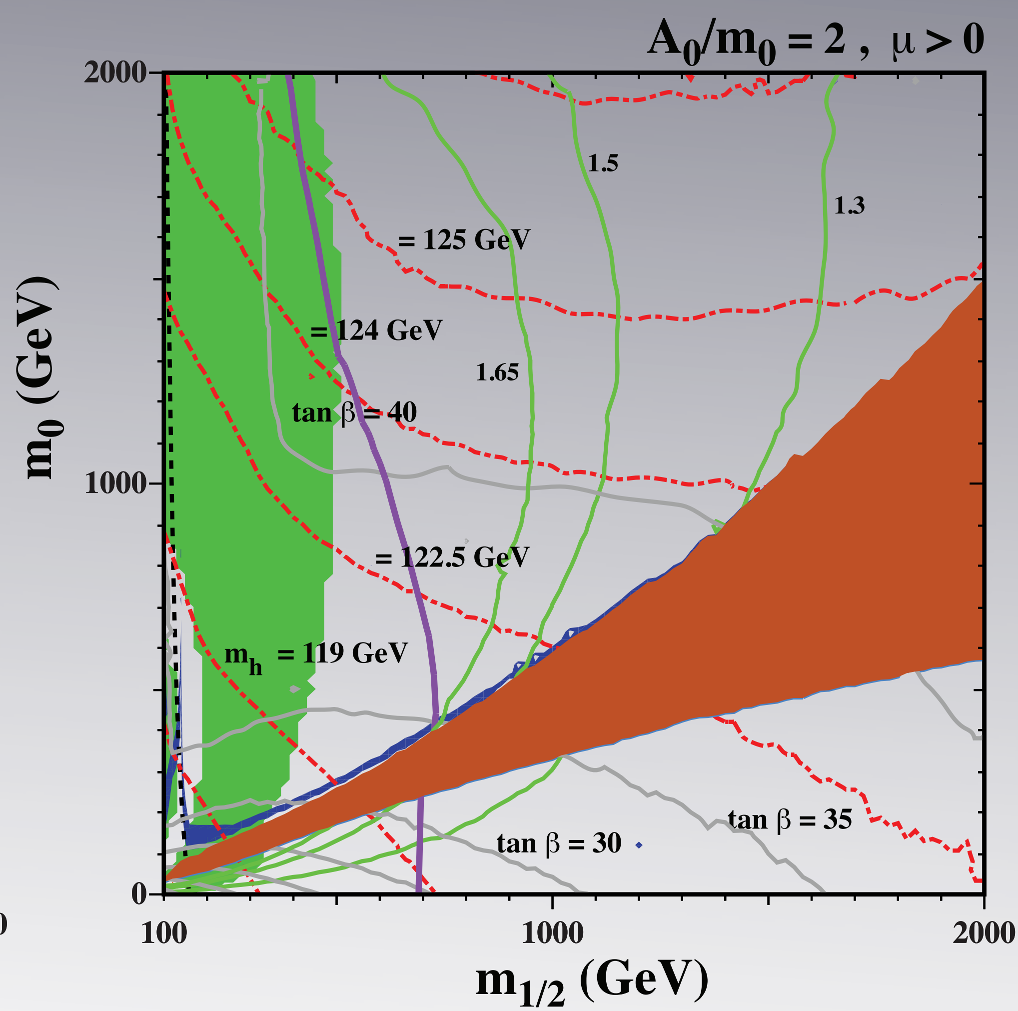
Electroweak Symmetry Breaking conditions used to solve for tanβ:

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

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

mSUGRA planes

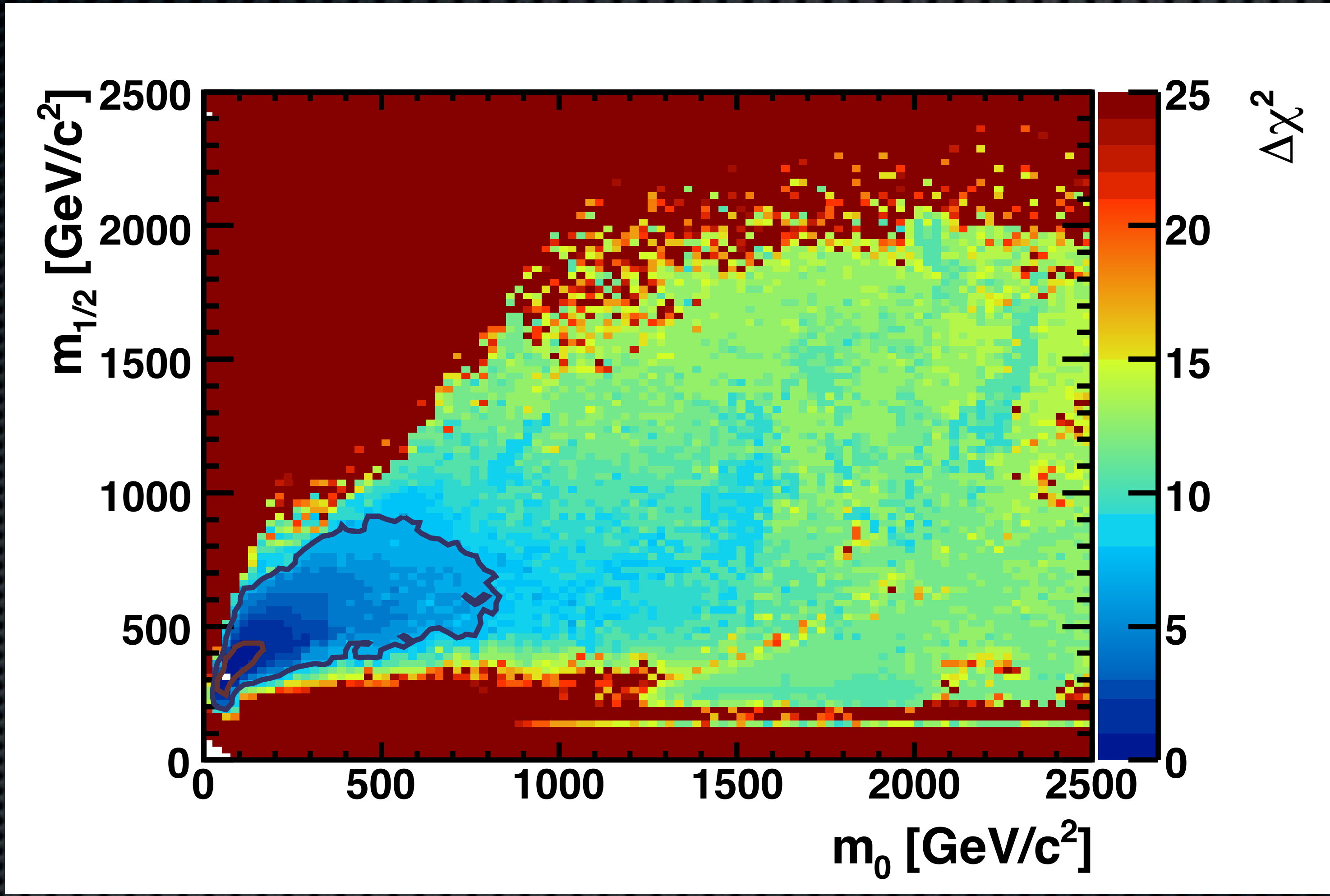




Ellis, Luo, Olive, Sandick

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

Mastercode



2009

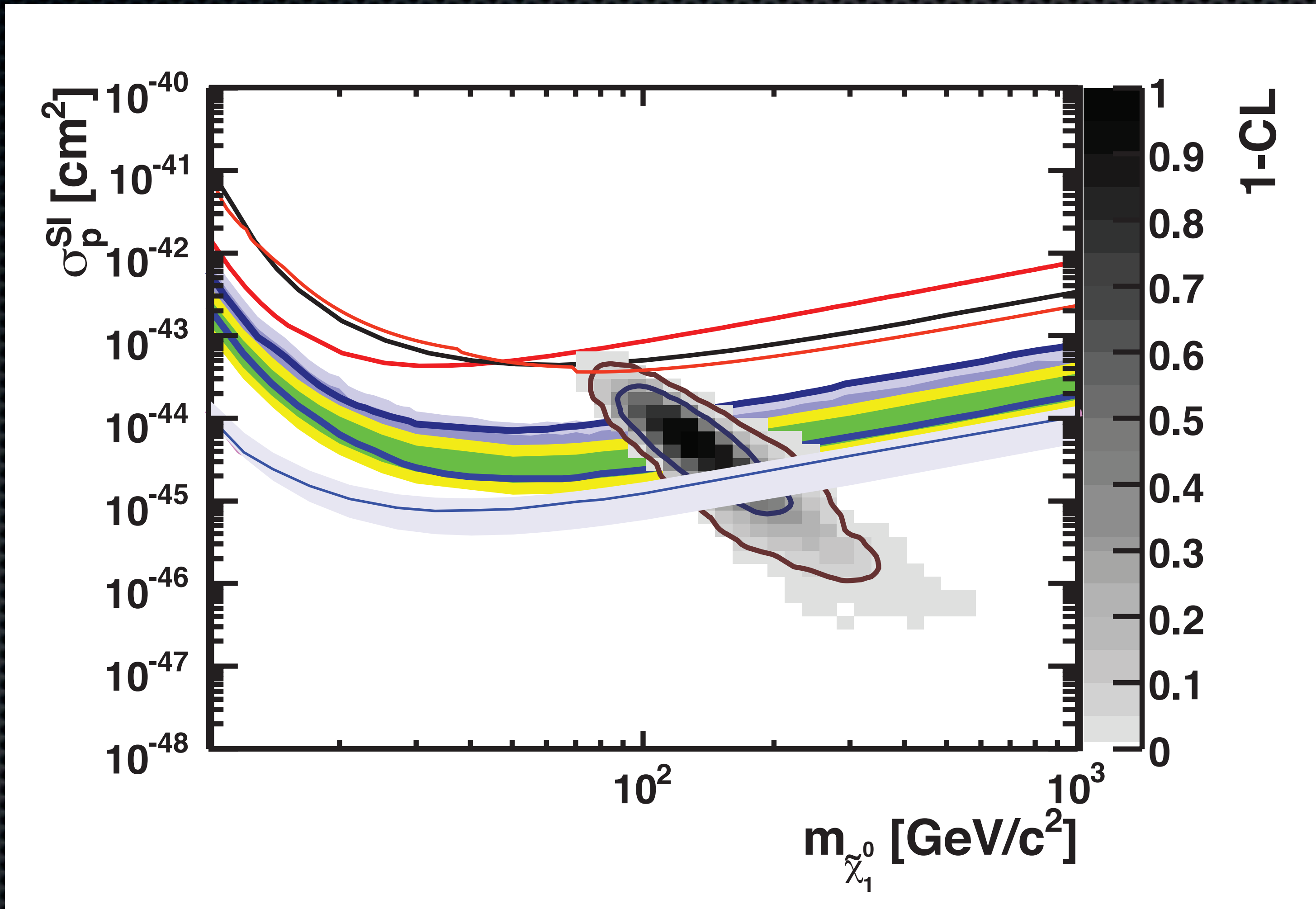
- CMSSM

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

Elastic scaterring cross-section

Mastercode

2009



Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer
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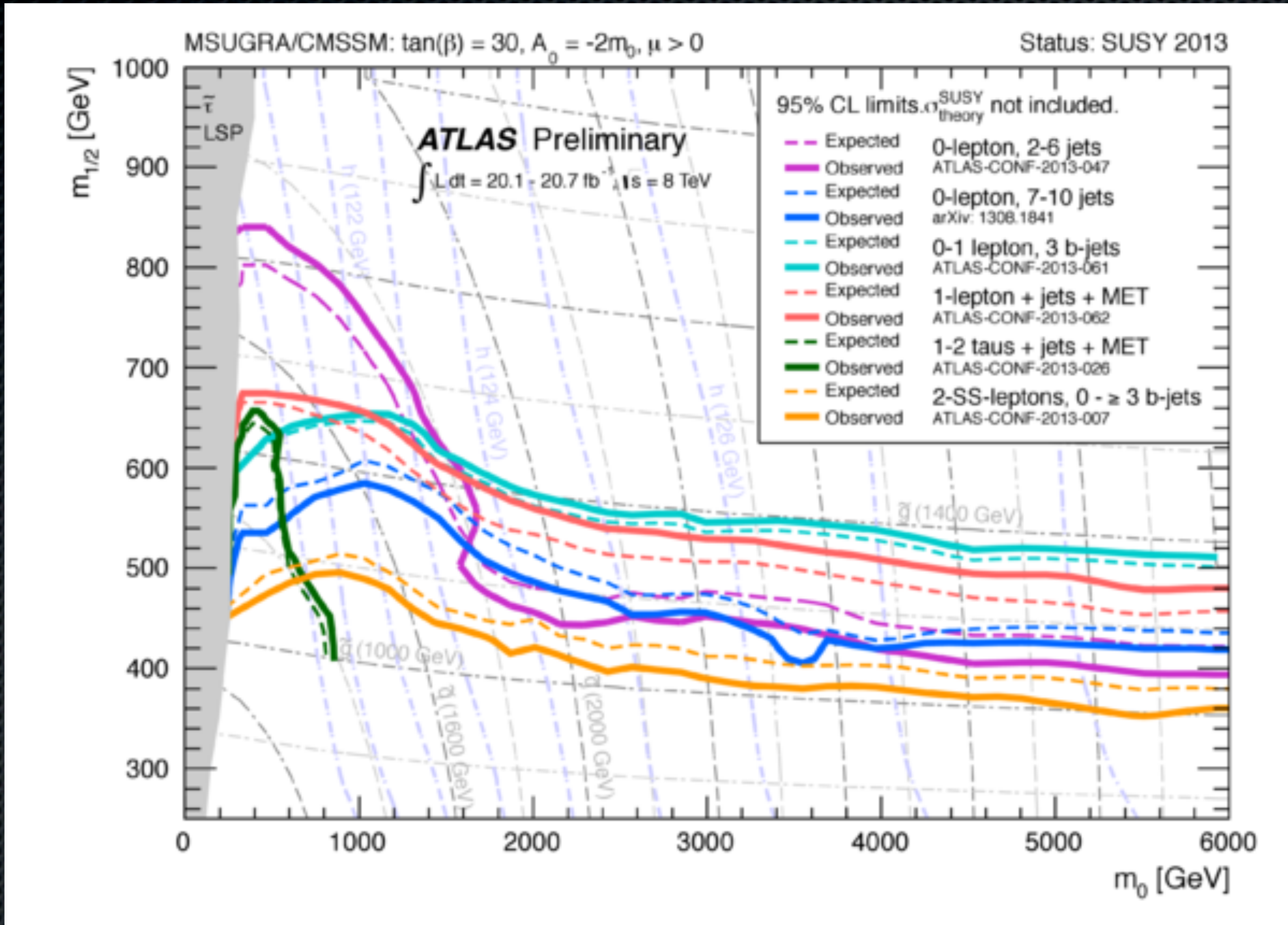
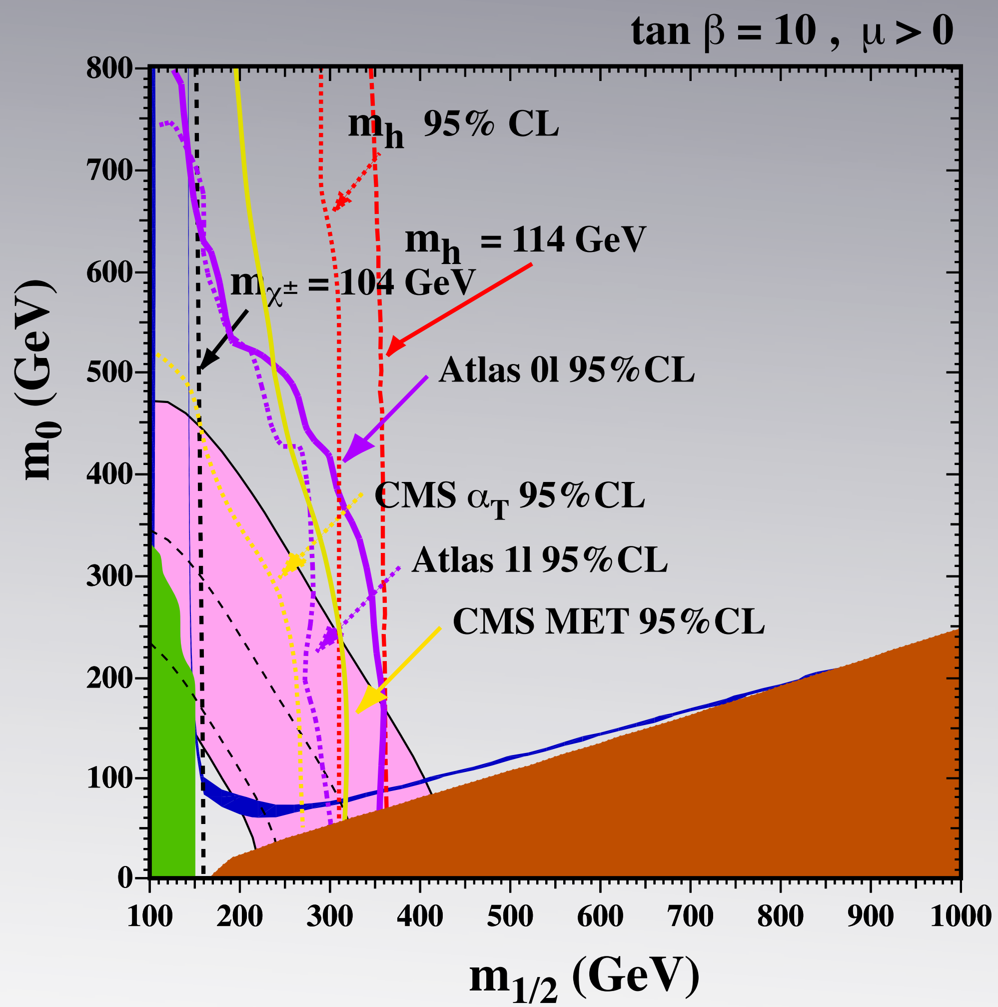
- CMSSM

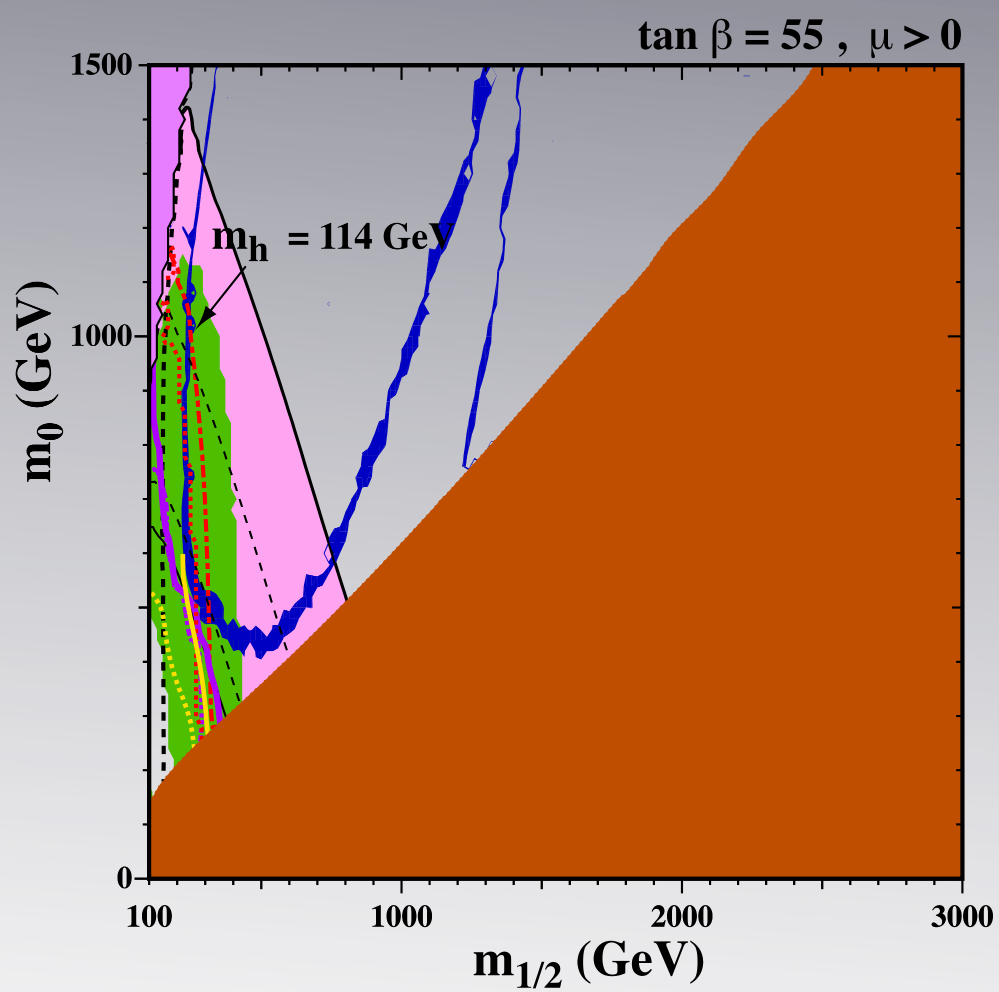
ATLAS Results from run I



~20.7fb^{-1} @ 8 TeV

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

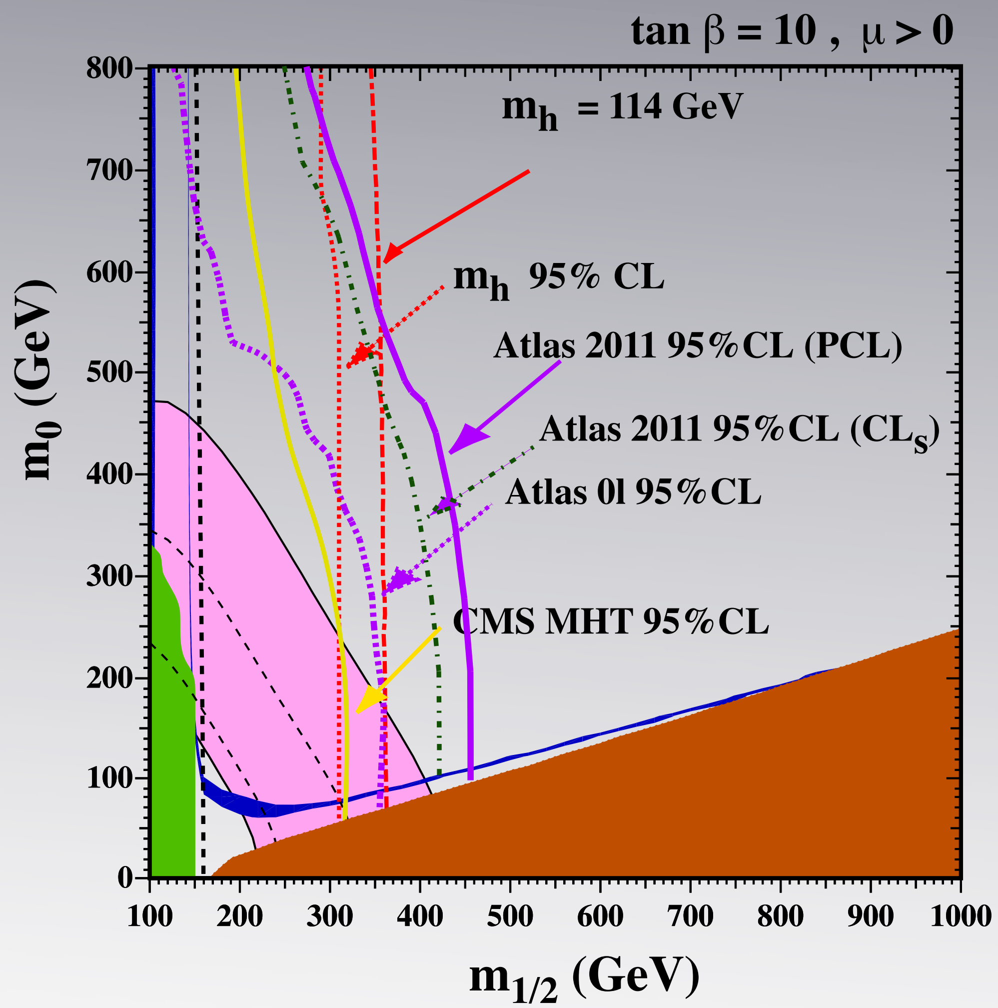


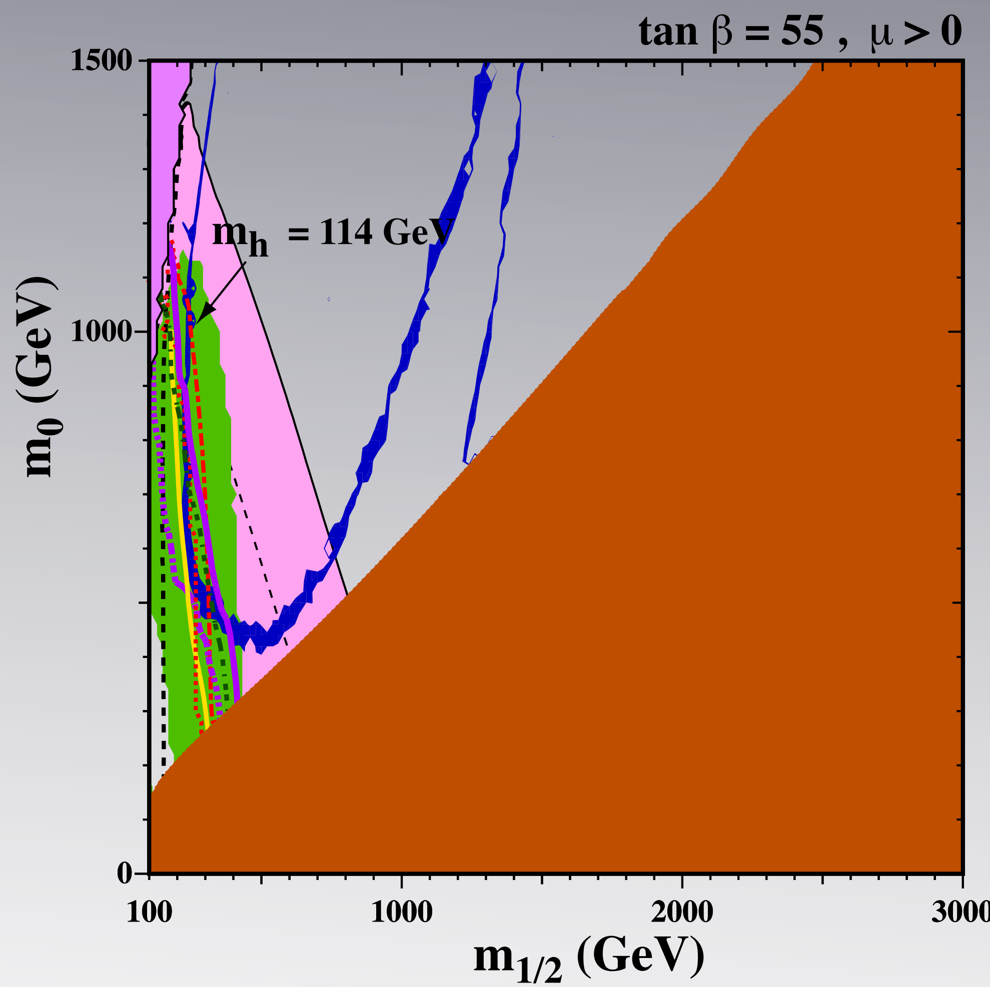


- CMSSM

Ellis, Olive, Santoso, Spanos

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





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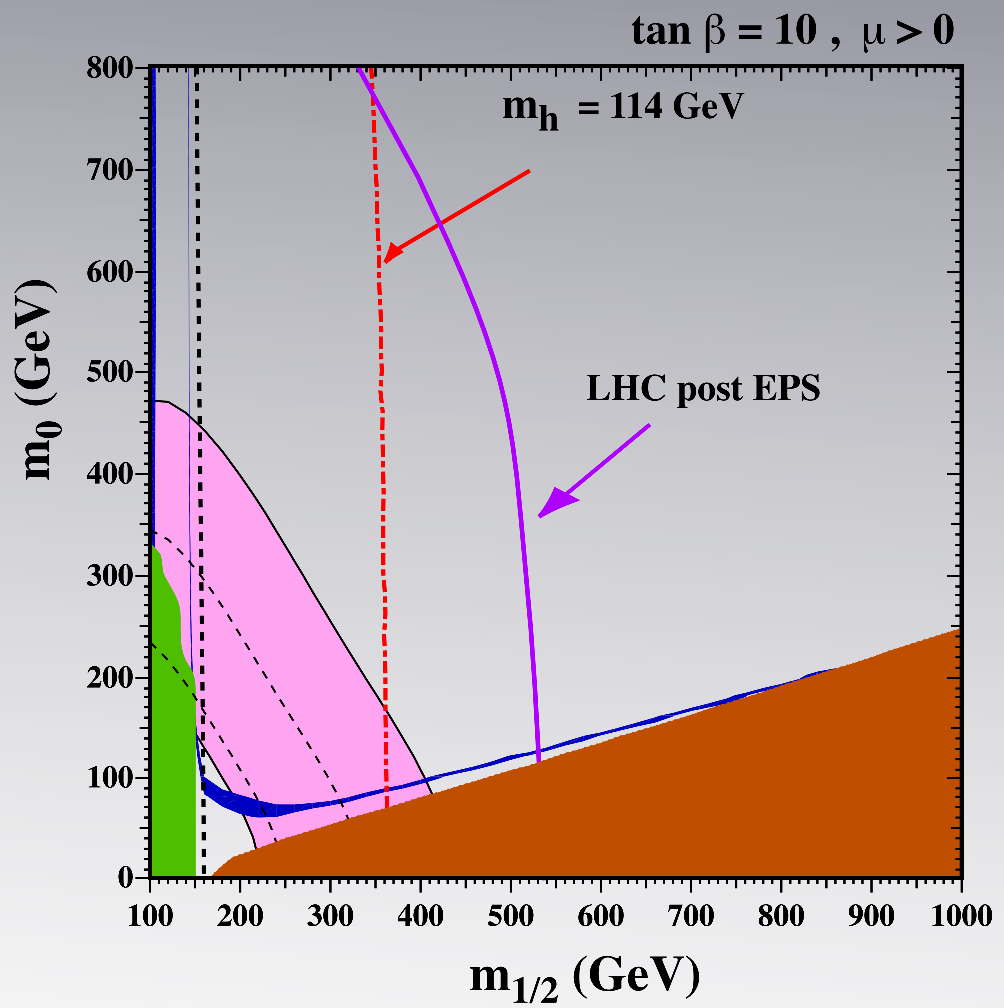

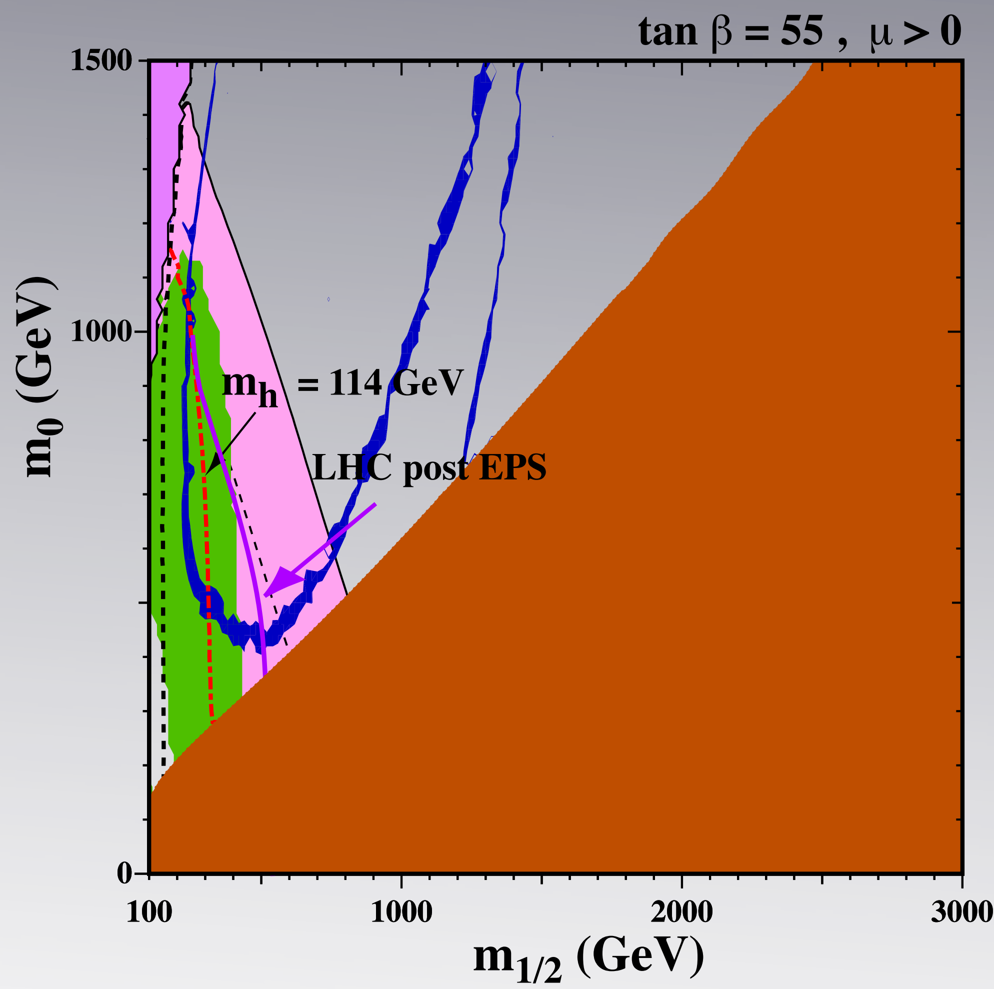

- CMSSM

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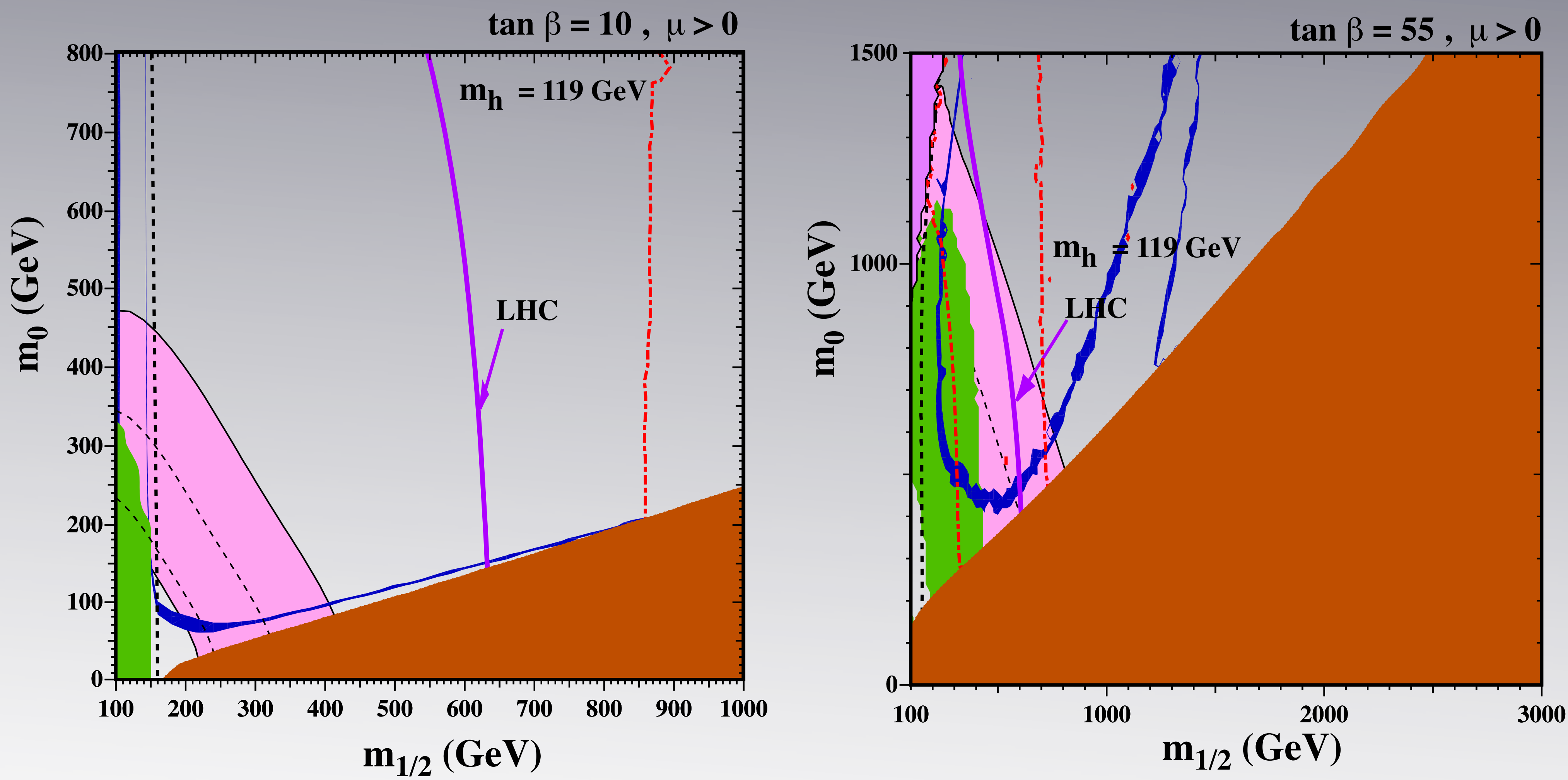
$m_{1/2}$ - m_0 planes incl. LHC



- CMSSM

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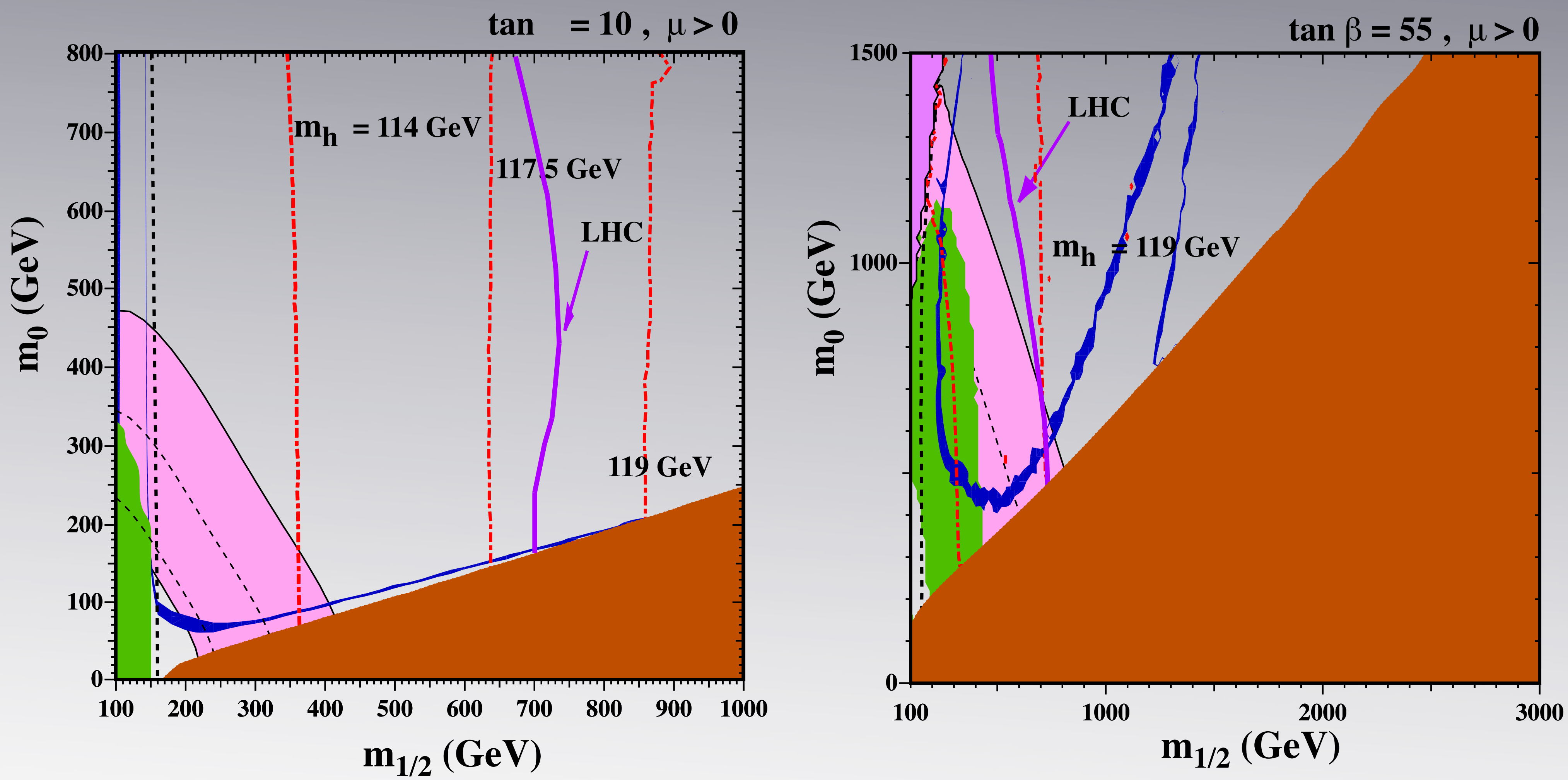
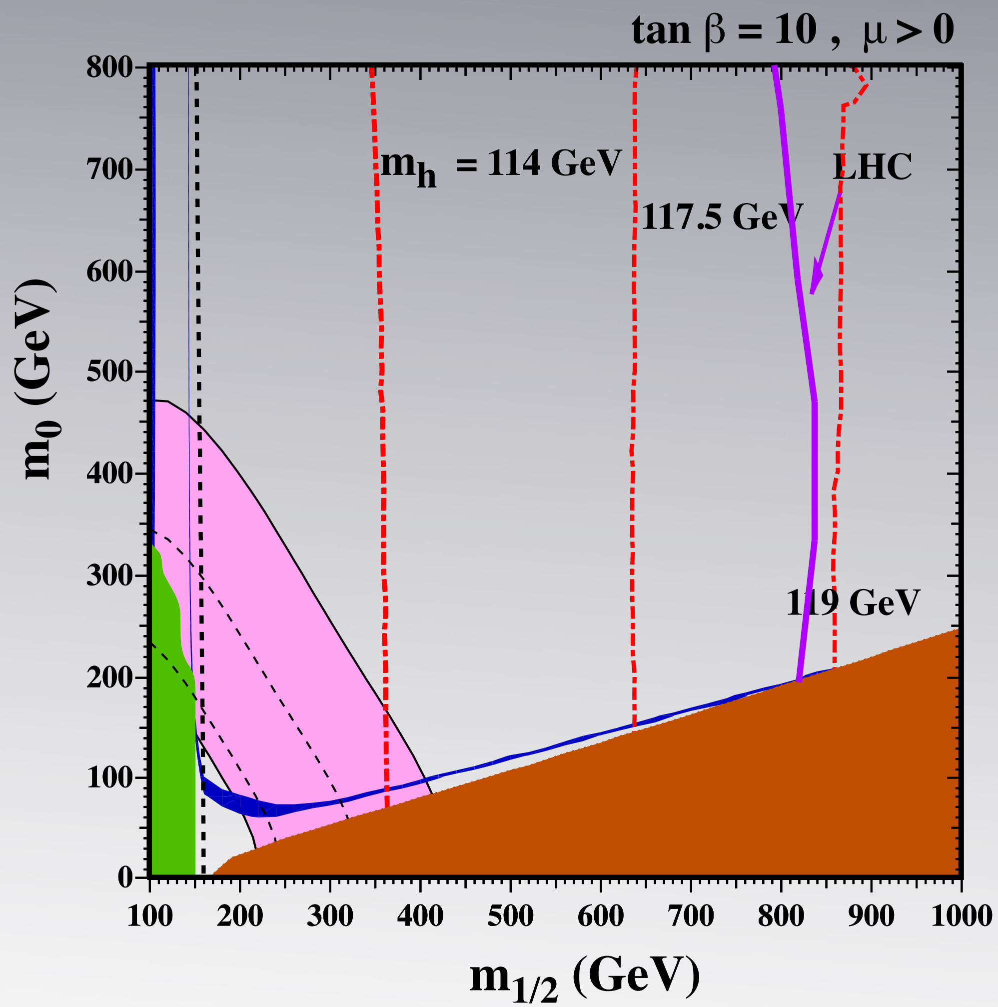


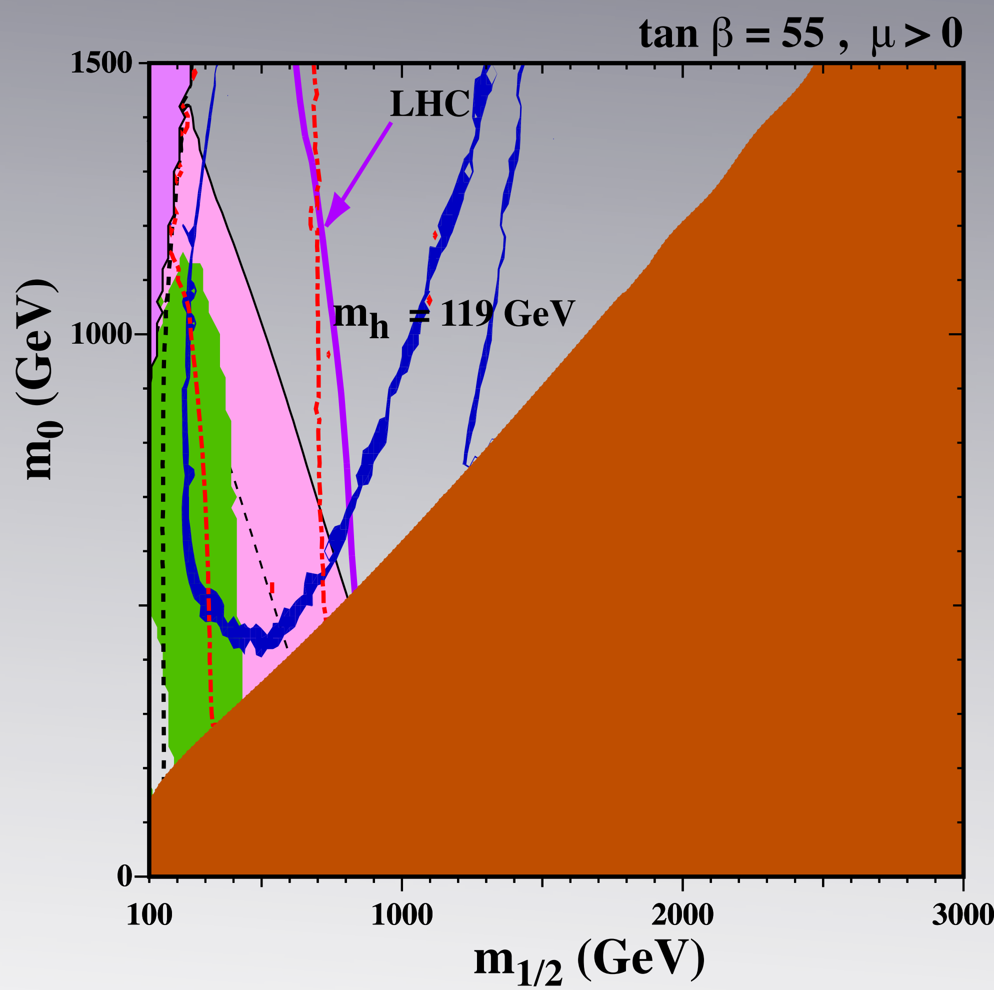
- CMSSM

Ellis, Olive, Santoso, Spanos

Monday, November 11, 13

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

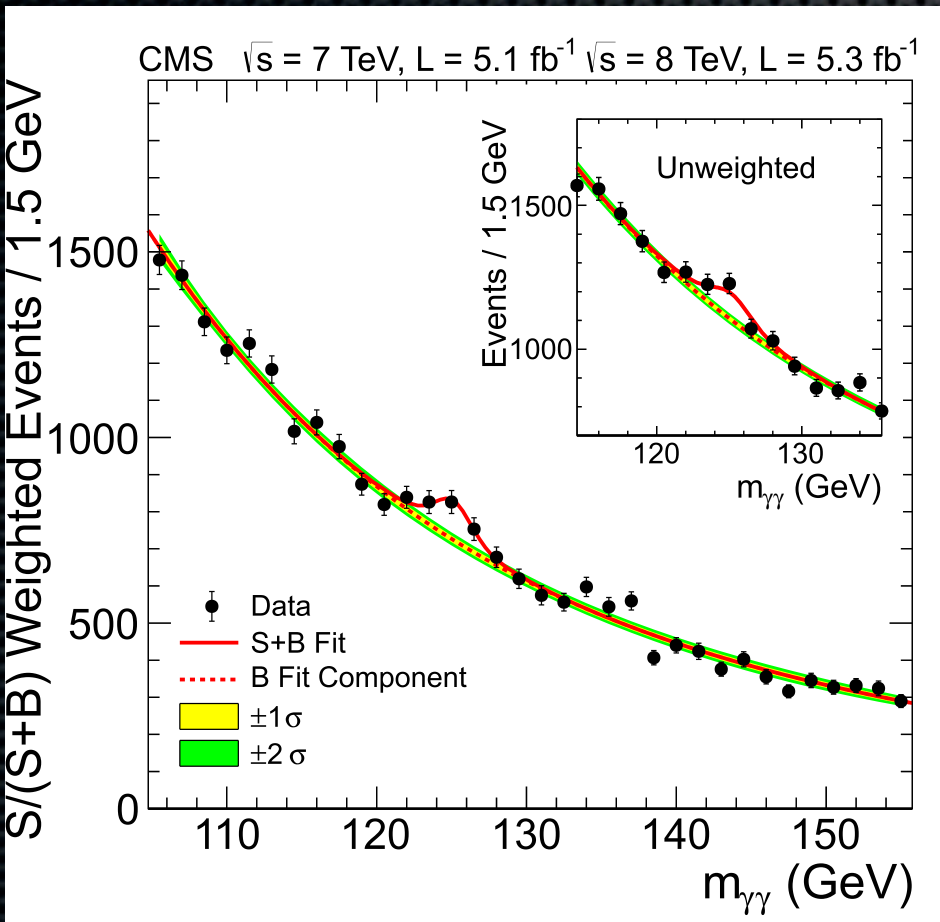


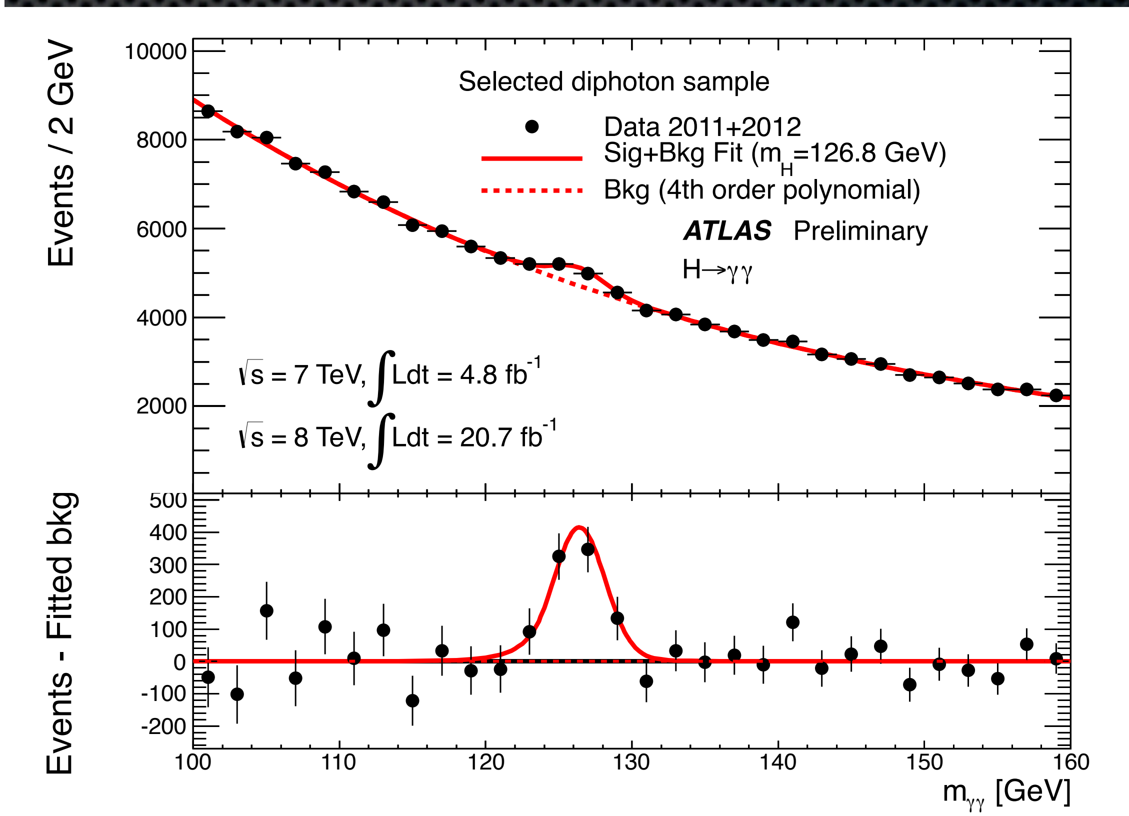


- CMSSM

Ellis, Olive, Santoso, Spanos

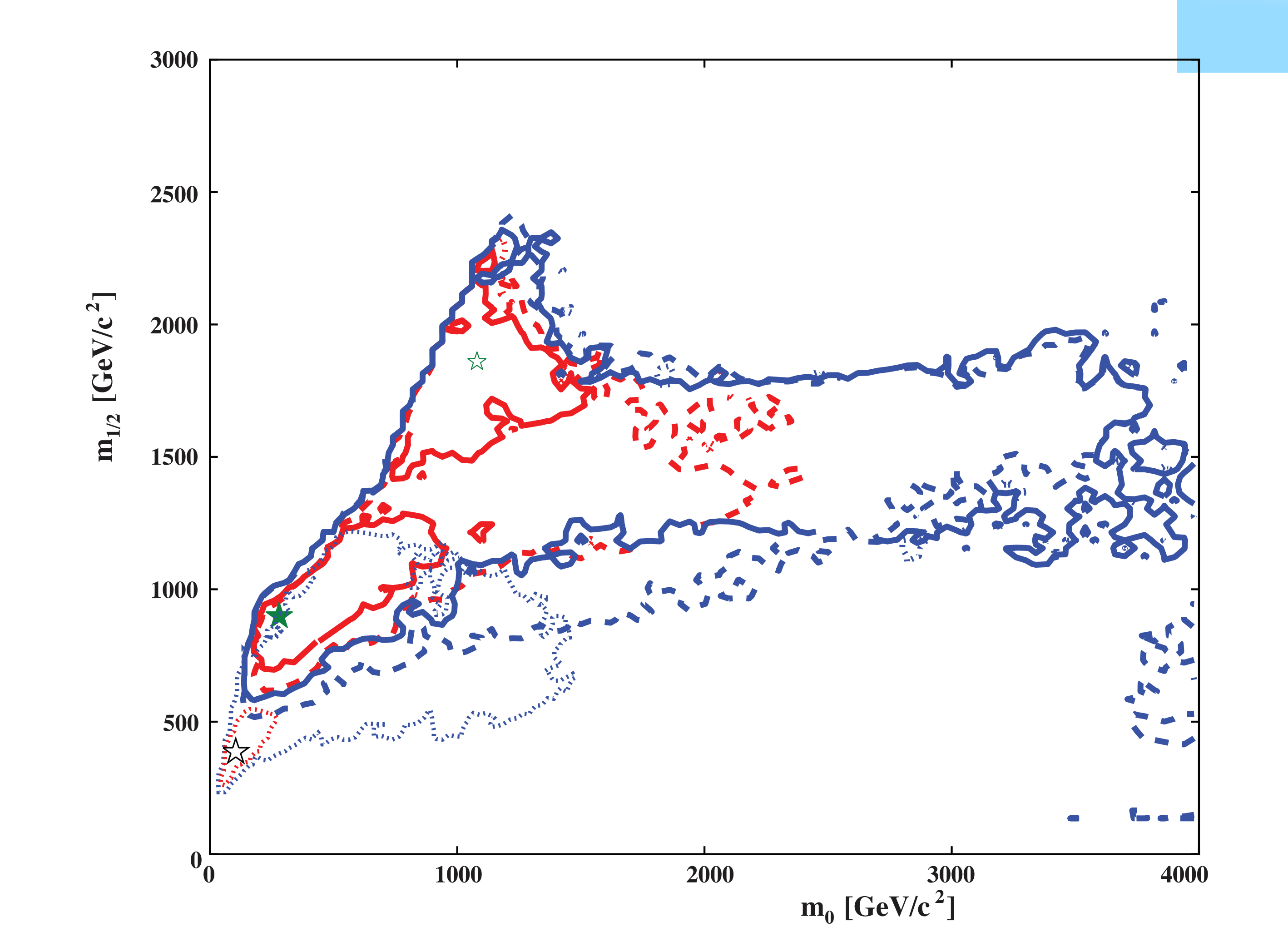
The Higgs Search
The LHC @ ~20.7/fb





$\Delta\chi^2$ 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

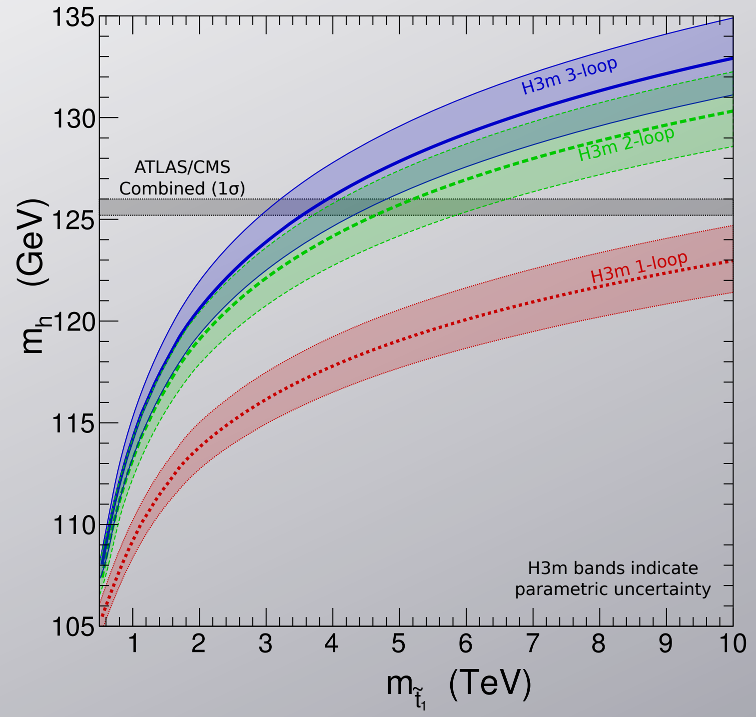
Comparison of best fit points pre and post LHC

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
	$LHC_{1/fb}$	31.0/23	12%	1120	1870	1220	46
	$ATLAS_{5/fb}$ (low)	32.8/23	8.5%	300	910	1320	16
	$ATLAS_{5/fb}$ (high)	33.0/23	8.0%	1070	1890	1020	45
NUHM1	pre-LHC	20.8/18	29 %	110	340	520	13
	$LHC_{1/fb}$	28.9/22	15%	270	920	1730	27
	$ATLAS_{5/fb}$ (low)	31.3/22	9.1%	240	970	1860	16
	$ATLAS_{5/fb}$ (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

New Higgs Mass Calculations



Feng, Kant, Profumo, Sanford

Includes dominant $O(\alpha_t \alpha_s^2)$ corrections

FeynHiggs 2.10.0

to include next-to-leading logs $Log(m_{\tilde{t}}/m_t)$ to all orders

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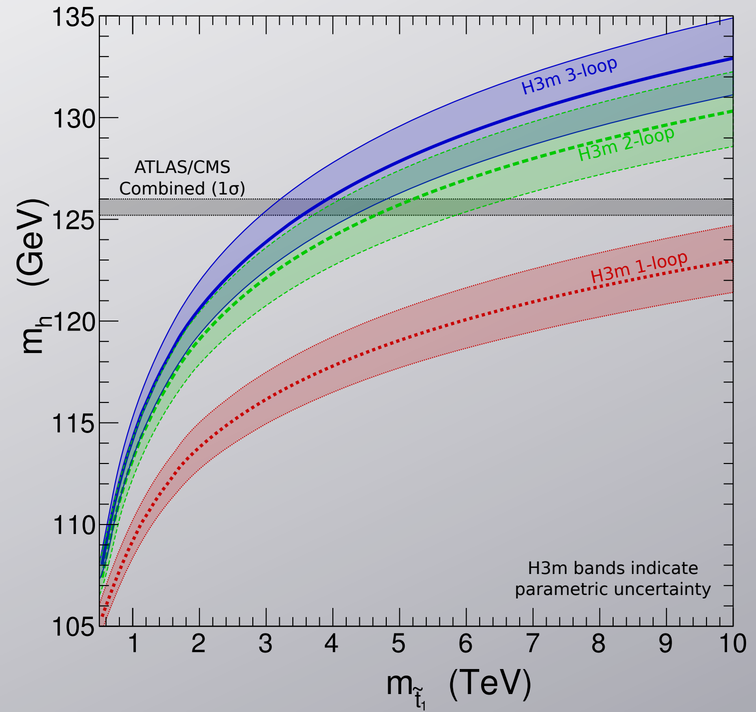


Feng, Kant, Profumo, Sanford

Includes dominant $O(\alpha_t \alpha_s^2)$ corrections

FeynHiggs 2.10.0

to include next-to-leading logs $\mathrm{Log}(m_{\tilde{t}}/m_t)$ to all orders

B →μμ

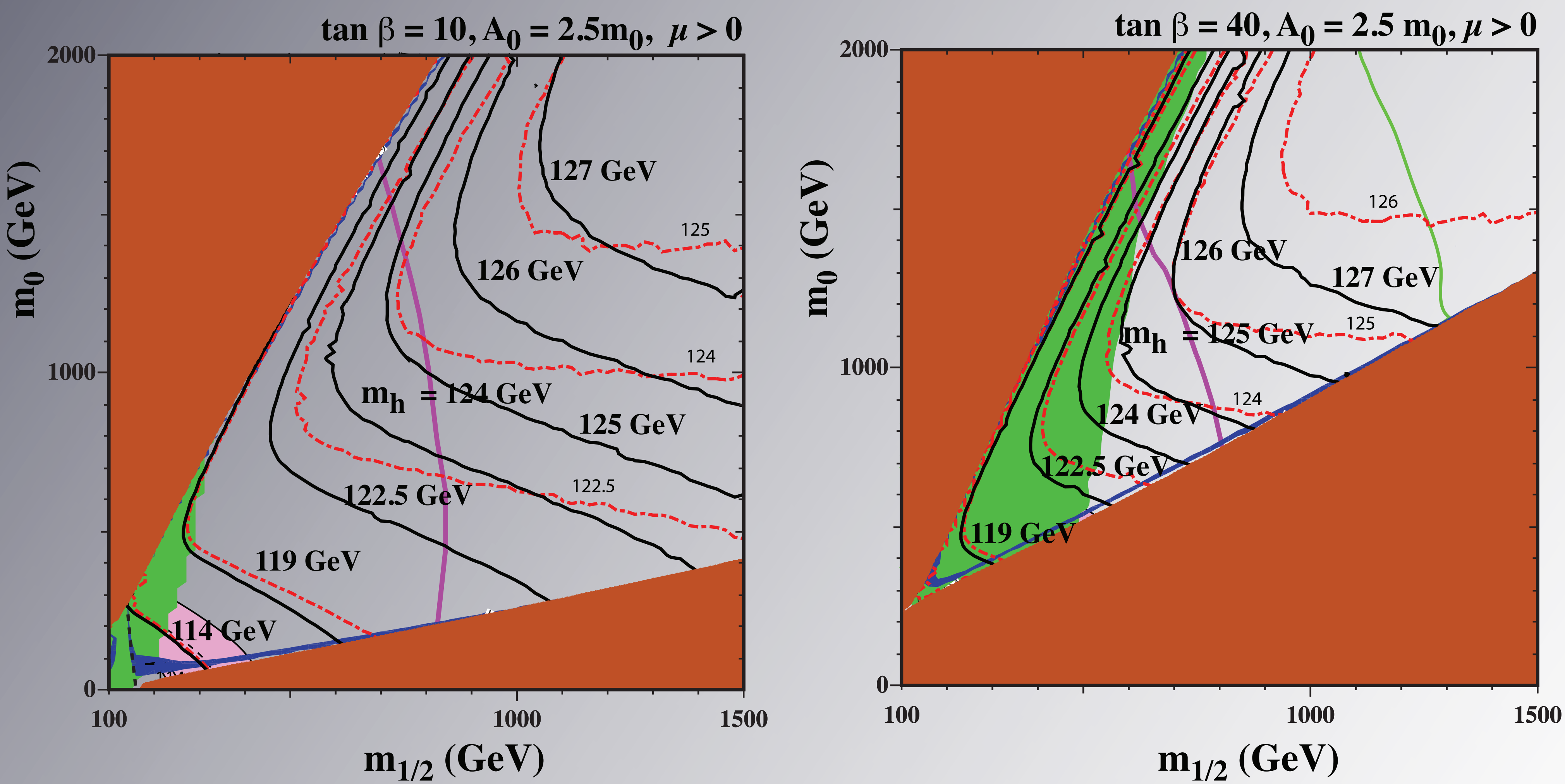
CMS: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}\,,$

LHCb: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}\,,$

Combined: $$\left(\frac{\mathrm{BR}(B_{s,d} \to \mu^+\mu^-)_{EXP}}{\mathrm{BR}(B_{s,d} \to \mu^+\mu^-)_{SM}}\right)_{TA} = 0.94^{+0.22}_{-0.21}\,.$$

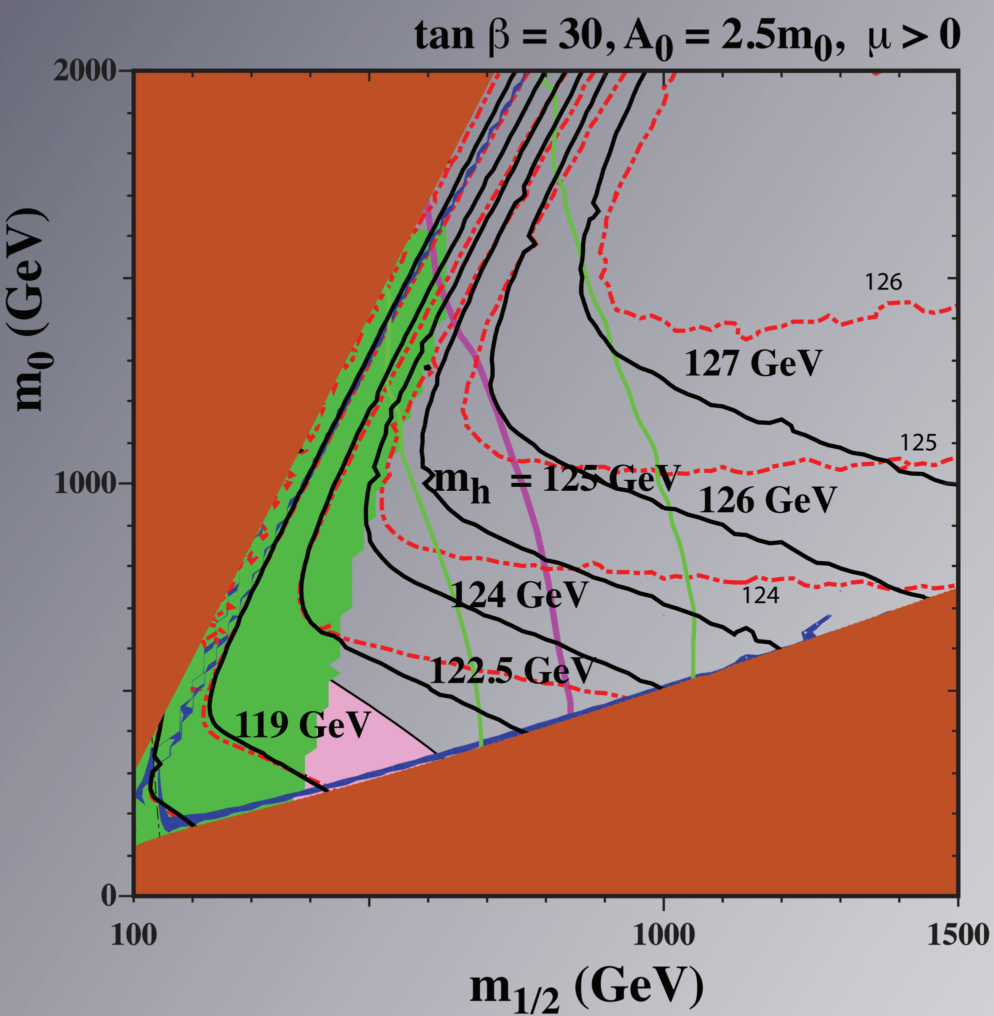
Buchmuller et al.

High and low tan β gone!

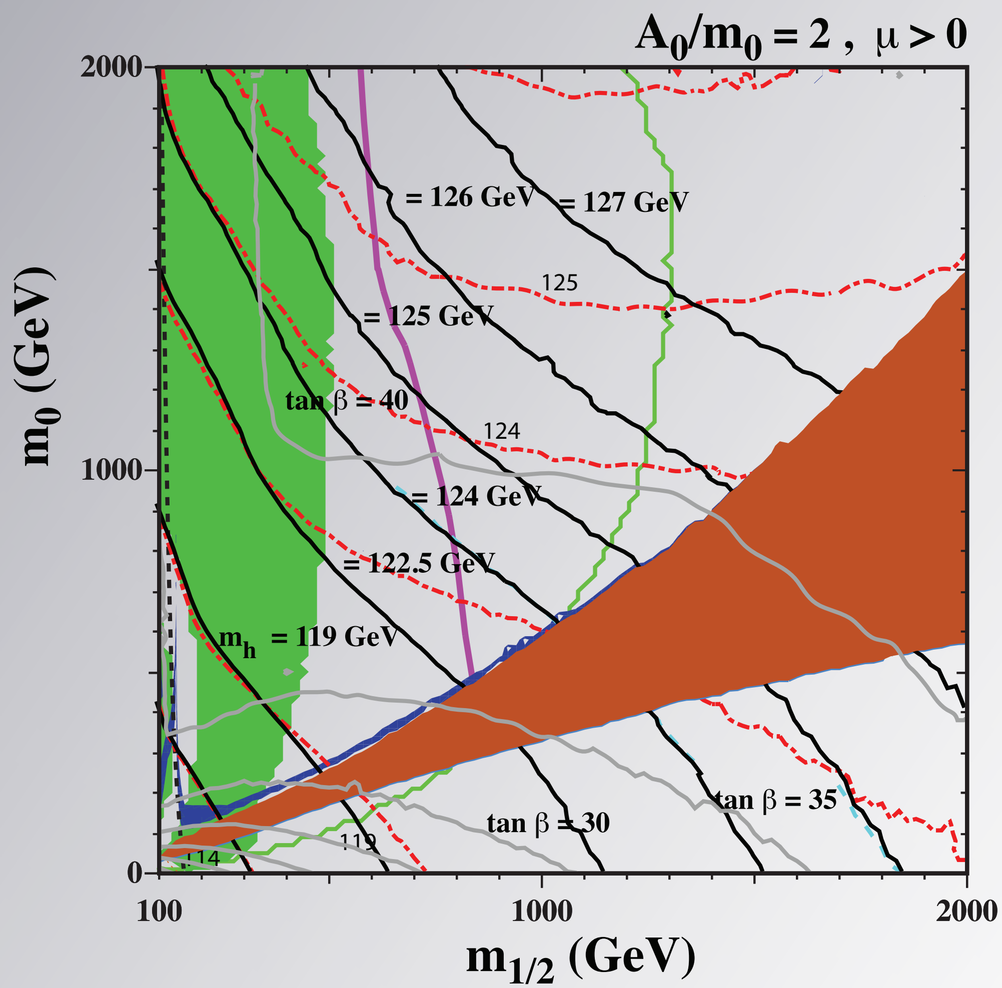


Buchmueller, Dolan, Ellis, Flacher, Hahn, Heinemeyer, Marrouche, Olive, de Vries, Weiglein

Something left?



CMSSM

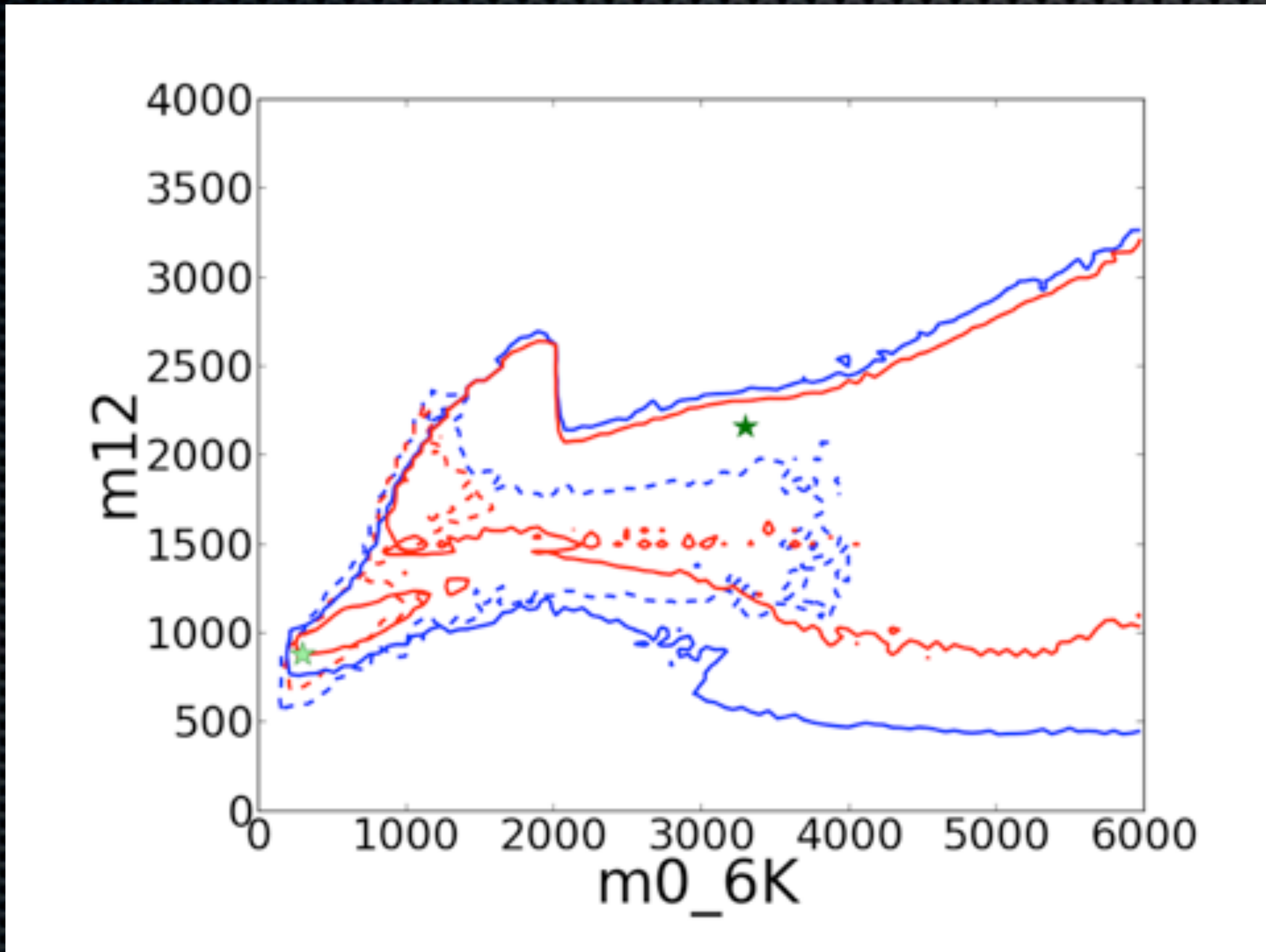


mSUGRA

Buchmueller, Dolan, Ellis, Flacher, Hahn, Heinemeyer, Marrouche, Olive, de Vries, Weiglein

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

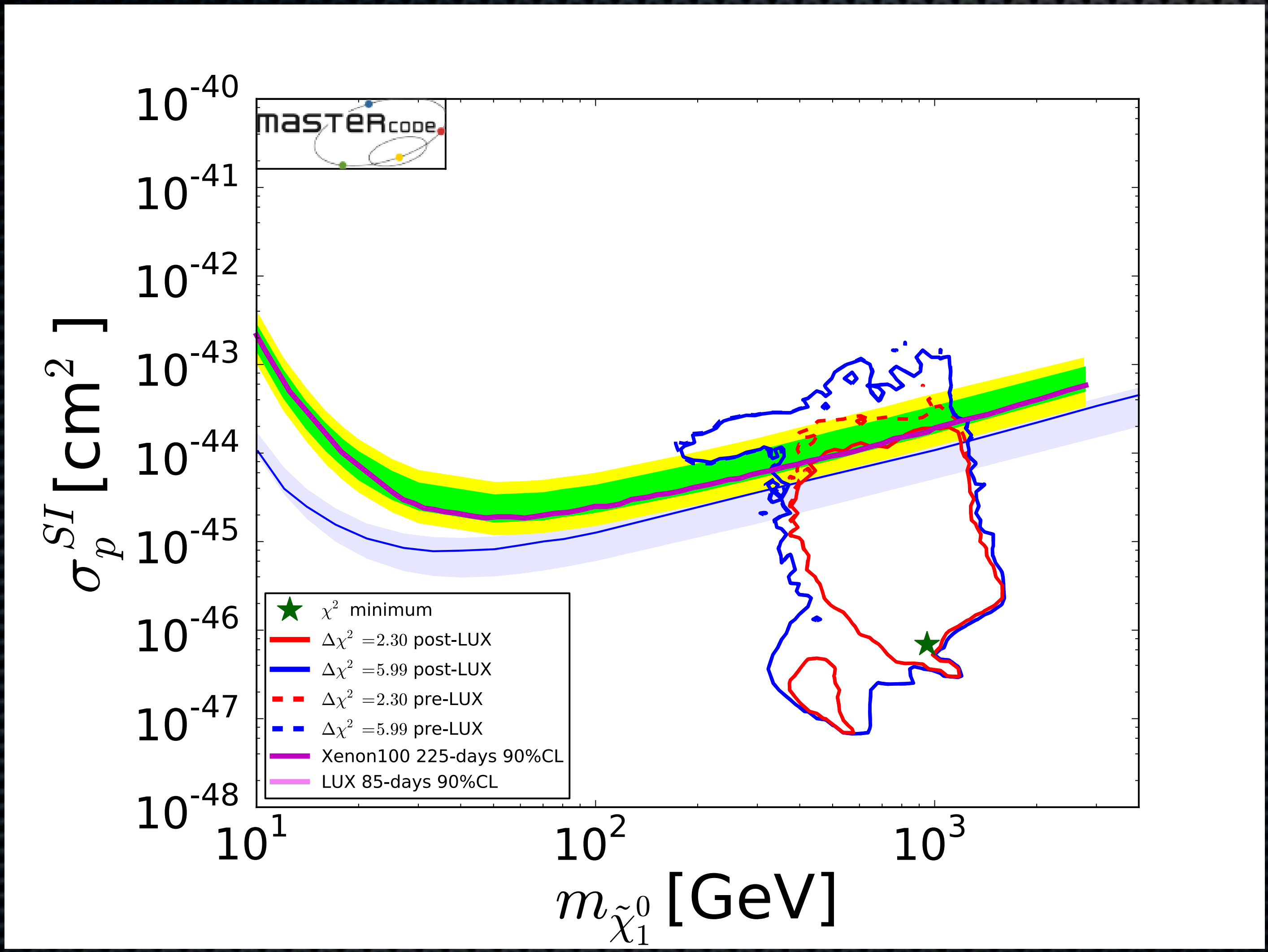
Final run I



Preliminary

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

Elastic cross sections



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

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

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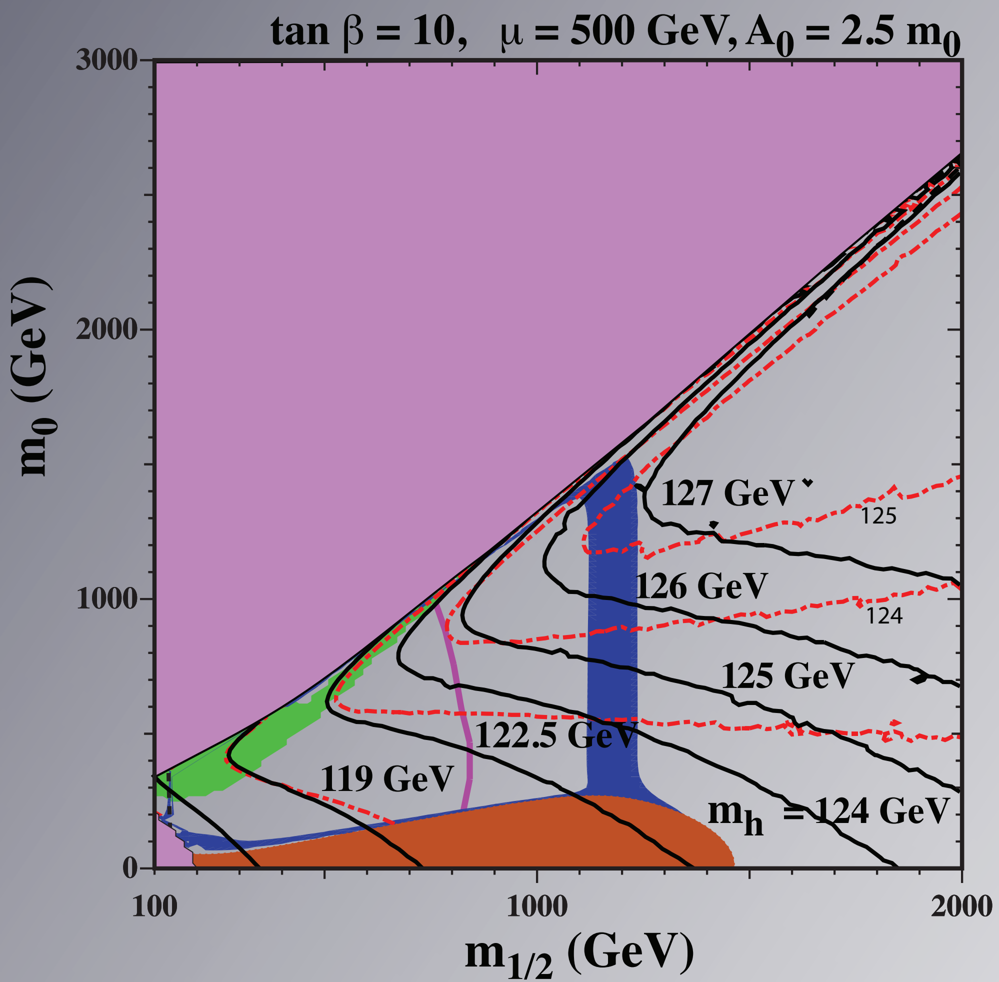
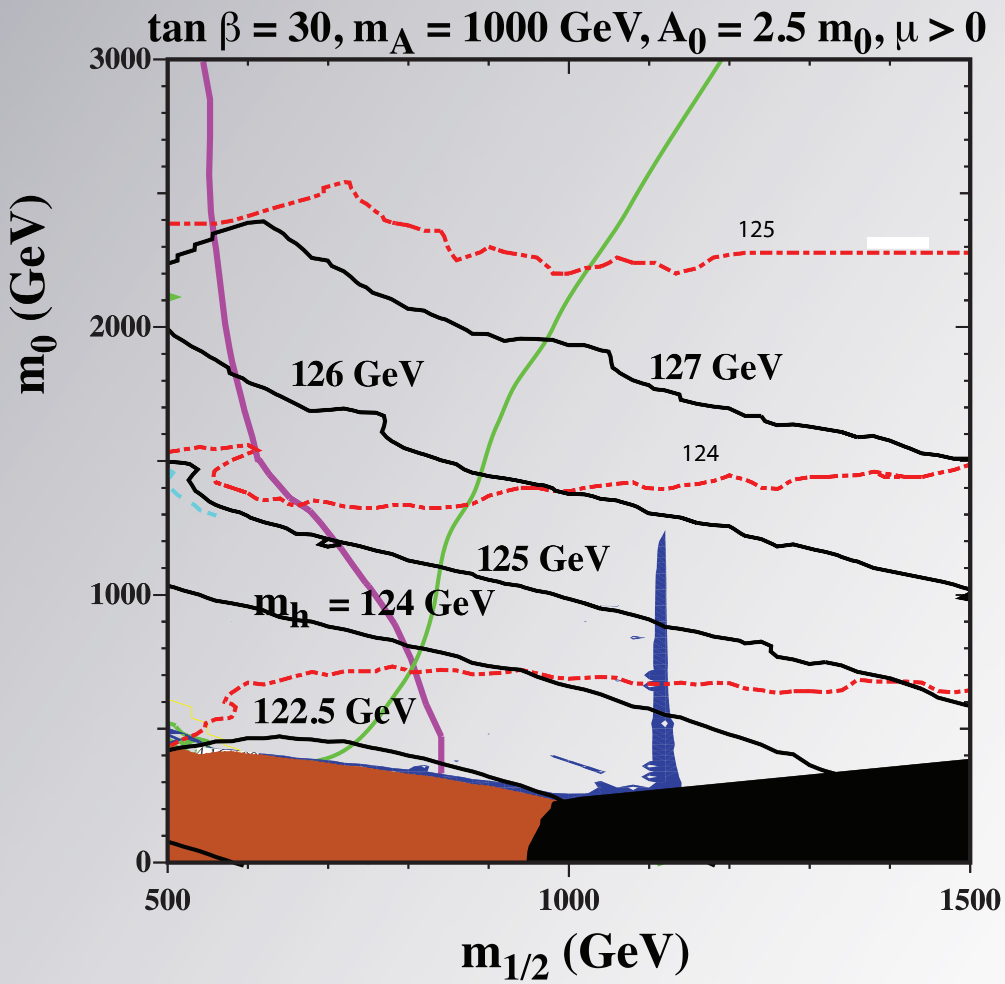
Other Possibilities

- 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 or m_A free





Ellis, Luo, Olive, Sandick

Moving beyond the CMSSM-like models

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Models with Strongly Stabilized Moduli; Pure Gravity Mediation (PGM)

Moving beyond the CMSSM-like models

Models with Strongly Stabilized Moduli; Pure Gravity Mediation (PGM)

- 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....

Consider a Polonyi-like modulus but with a non-minimal kinetic term

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

Dine et al, Kitano

and Polonyi superpotential

$$W = \mu^2(Z + \nu)$$

$$\langle z \rangle_{\rm Min} \simeq \frac{\Lambda^2}{\sqrt{6}} \ , \quad \langle \chi \rangle = 0 \ , \quad \nu \simeq \frac{1}{\sqrt{3}}$$

where $Z = \frac{1}{\sqrt{2}}(z + i\chi)$

Impact on Phenomenology

$$m_{3/2} = \langle e^{K/2} W \rangle \simeq \mu^2/\sqrt{3}$$

$$m^2_{z,\chi} \simeq \frac{12\, m^2_{3/2}}{\Lambda^2} \gg m^2_{3/2}$$

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

A terms $A_0 \simeq \frac{1}{2} m_{3/2} \Lambda^2$ + anomalies

gaugino masses anomalies

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gaugino masses anomalies

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

Pure Gravity Mediation

- Two parameter model!
  - $m_0 = m_{3/2}$; $\tan\beta$
  - gaugino masses (and A-terms) generated through loops

$$
\begin{aligned}
M_1 &= \frac{33}{5}\frac{g_1^2}{16\pi^2}m_{3/2}\ , \\
M_2 &= \frac{g_2^2}{16\pi^2}m_{3/2}\ , \\
M_3 &= -3\frac{g_3^2}{16\pi^2}m_{3/2}\ .
\end{aligned}
$$

- $\Rightarrow$ Push towards very large masses

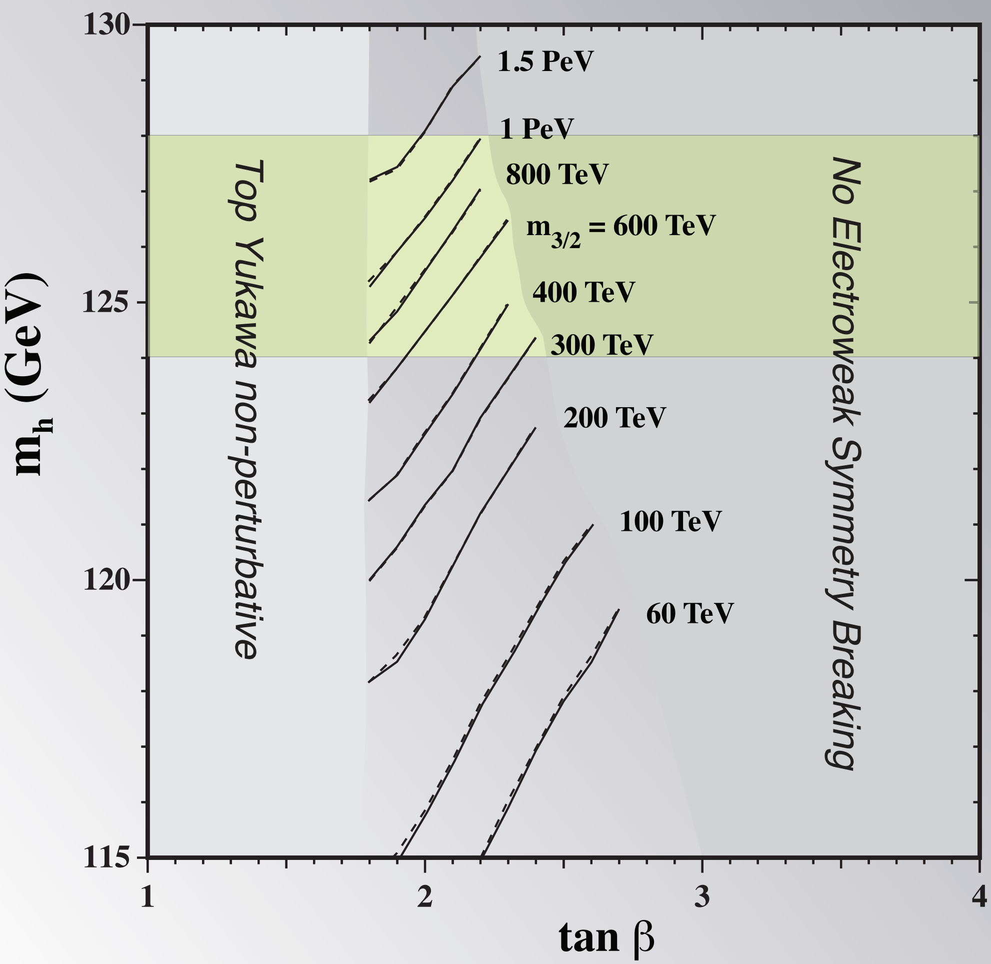
Evans, Ibe, Olive, Yanagida

Pure Gravity Mediation

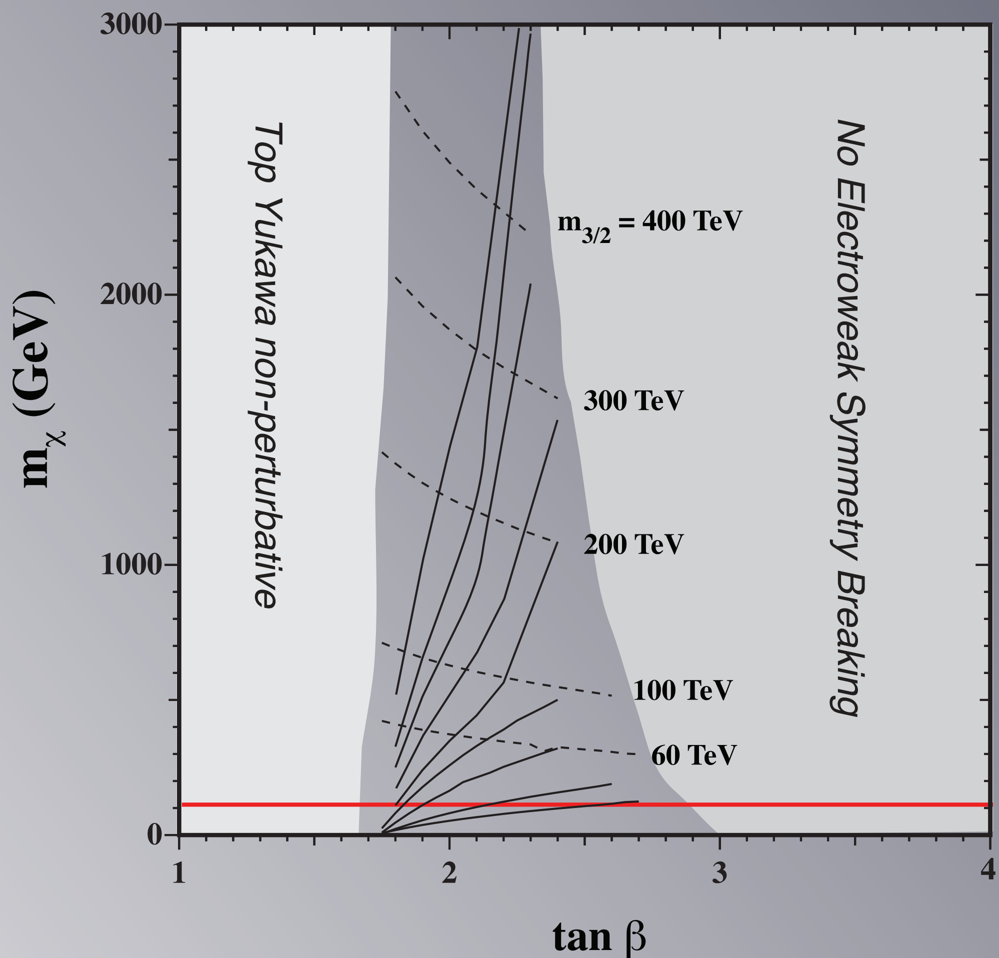
- The sfermion and gravitino have masses O(100) TeV.
- The higgsino and the heavier Higgs boson also have masses O(100) TeV.
- The gaugino masses are in the range of hundreds to thousands of GeV.
- The LSP is the neutral wino which is nearly degenerate with the charged wino.
- The lightest Higgs boson mass is consistent with the observed Higgs-like boson, i.e. $m_h \sim 125 - 126$ GeV.

Phenomenological Aspects

Higgs Mass

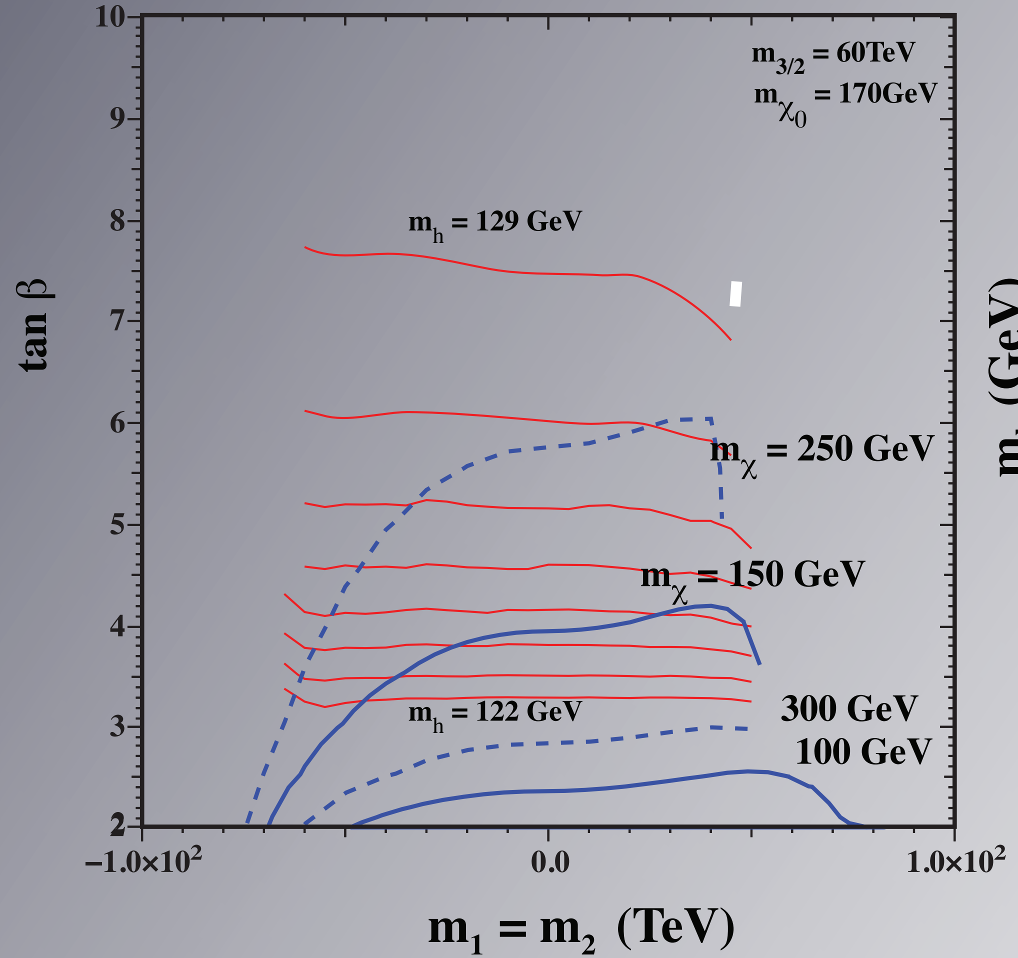


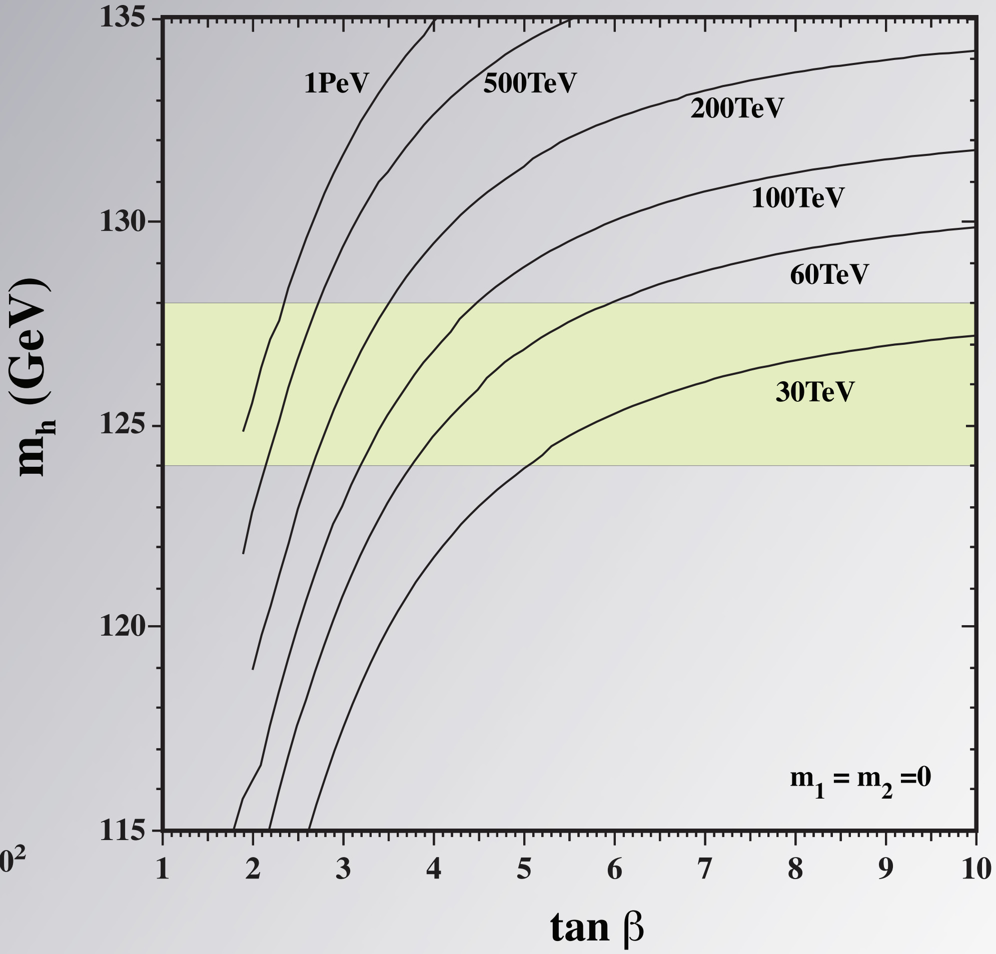
Neutralino mass



Evans, Ibe, Olive, Yanagida

Somewhat more freedom with non-universal Higgs masses

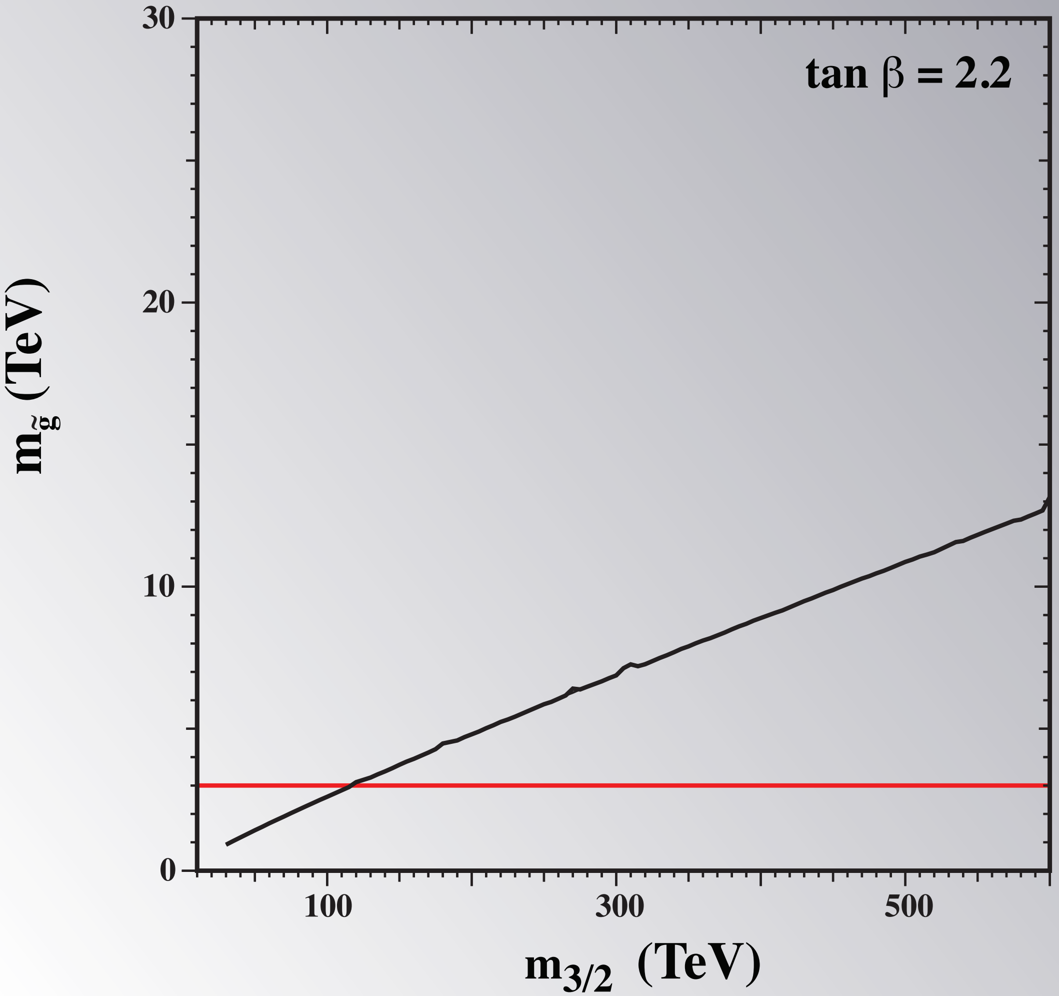




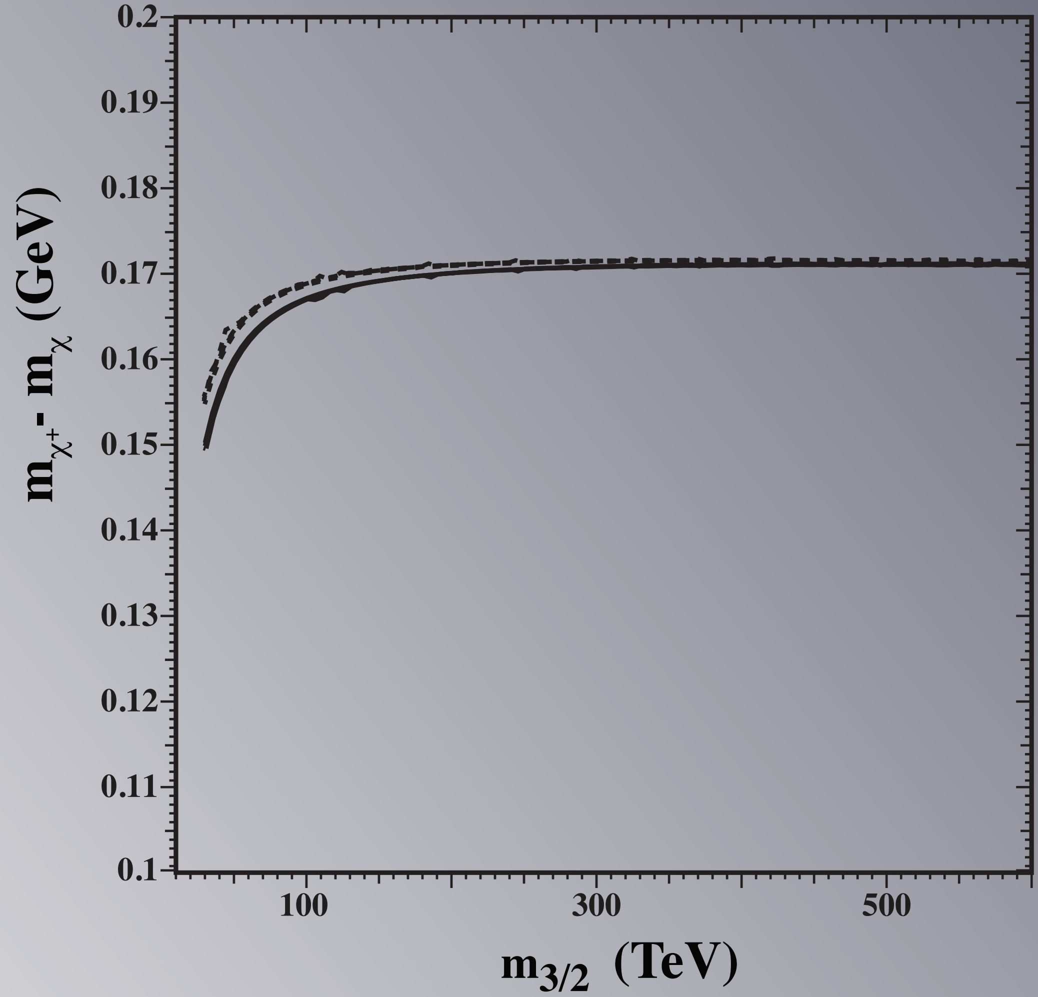
Evans, Ibe, Olive, Yanagida

Phenomenological Aspects

gluino Mass



chargino mass



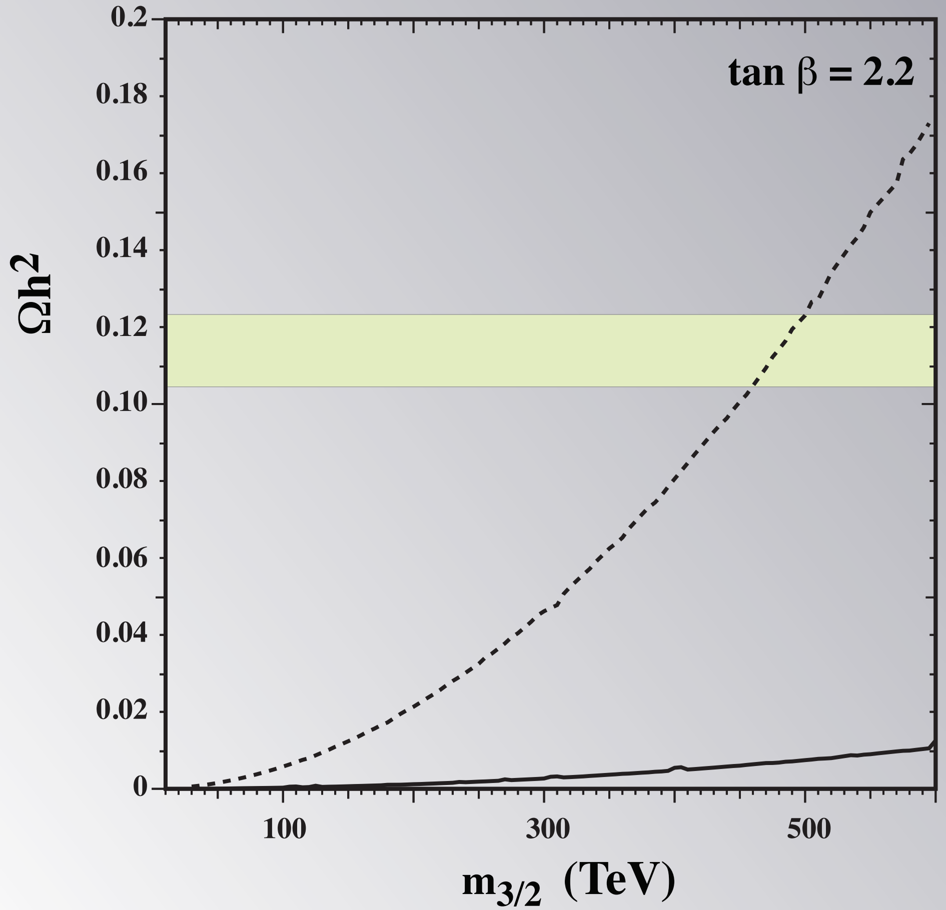
Dark Matter

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

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

Other Phenomenological Aspects

Dark Matter:
LSP is a wino



Potential problem for wino dark matter from Fermi/HESS
(Fan + Reese;
Cohen, Lianti, Pierce, Slatyer)

Summary

- LHC susy and Higgs searchs have pushed CMSSM-like models to “corners”
- Though many phenomenological solutions are still viable
- 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