Supersymmetric Dark Matter post run I at the LHC

Which Supersymmetric Model?

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

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CMSSM

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CMSSM

add parameter for ratio of Higgs vevs: $\tan\beta$

Which Supersymmetric Model?

- CMSSM (4+ parameters)
- mSUGRA (3+ parameters)
- NUHM (5,6+ parameters)
- (mini) Split SUSY (2+ parameters)

The CMSSM

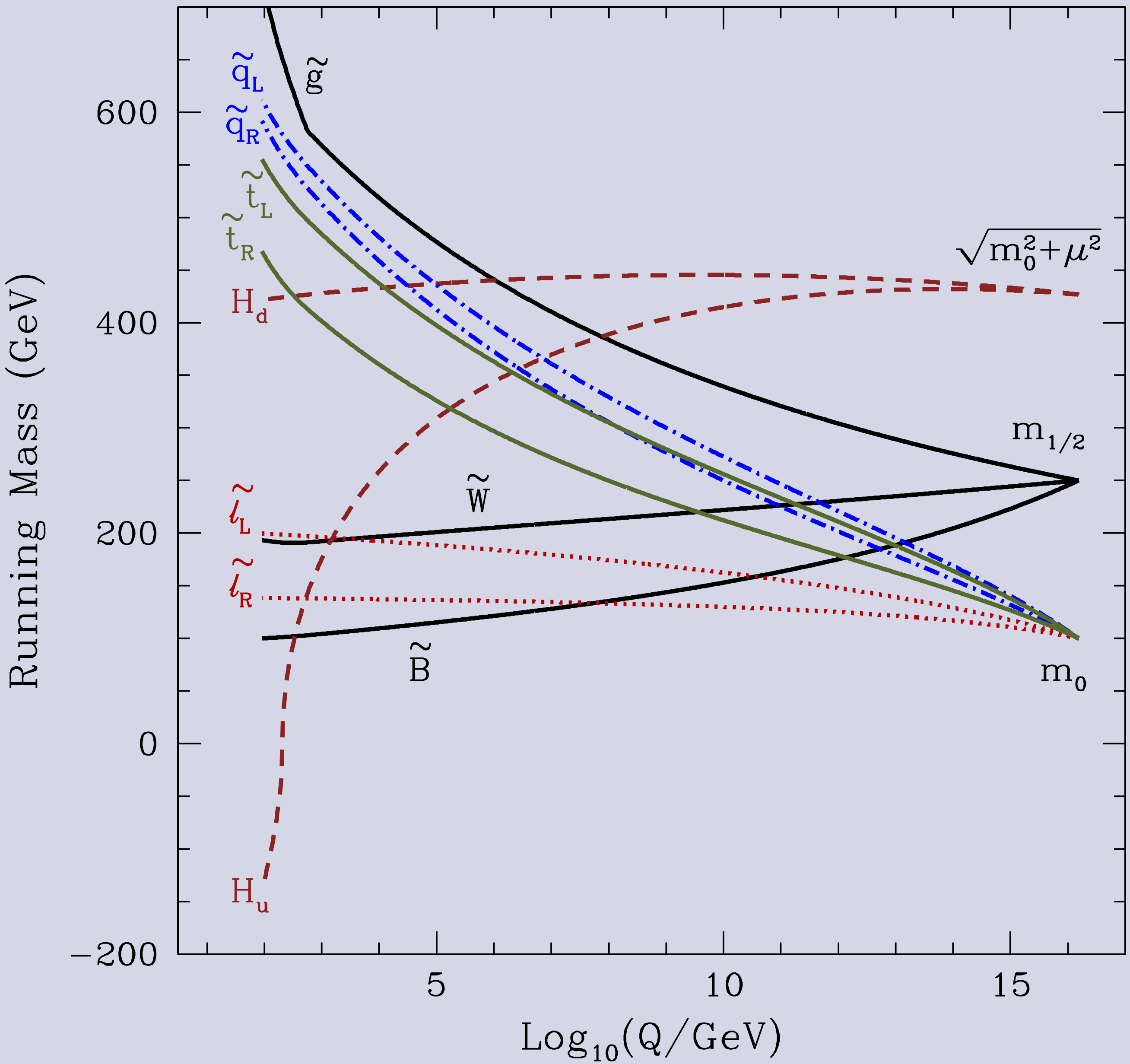
Parameters: $m_{1/2}$, m_0, A_0, tan β, sgn(μ) {$m_{3/2}$}

Electroweak Symmetry Breaking conditions:

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

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

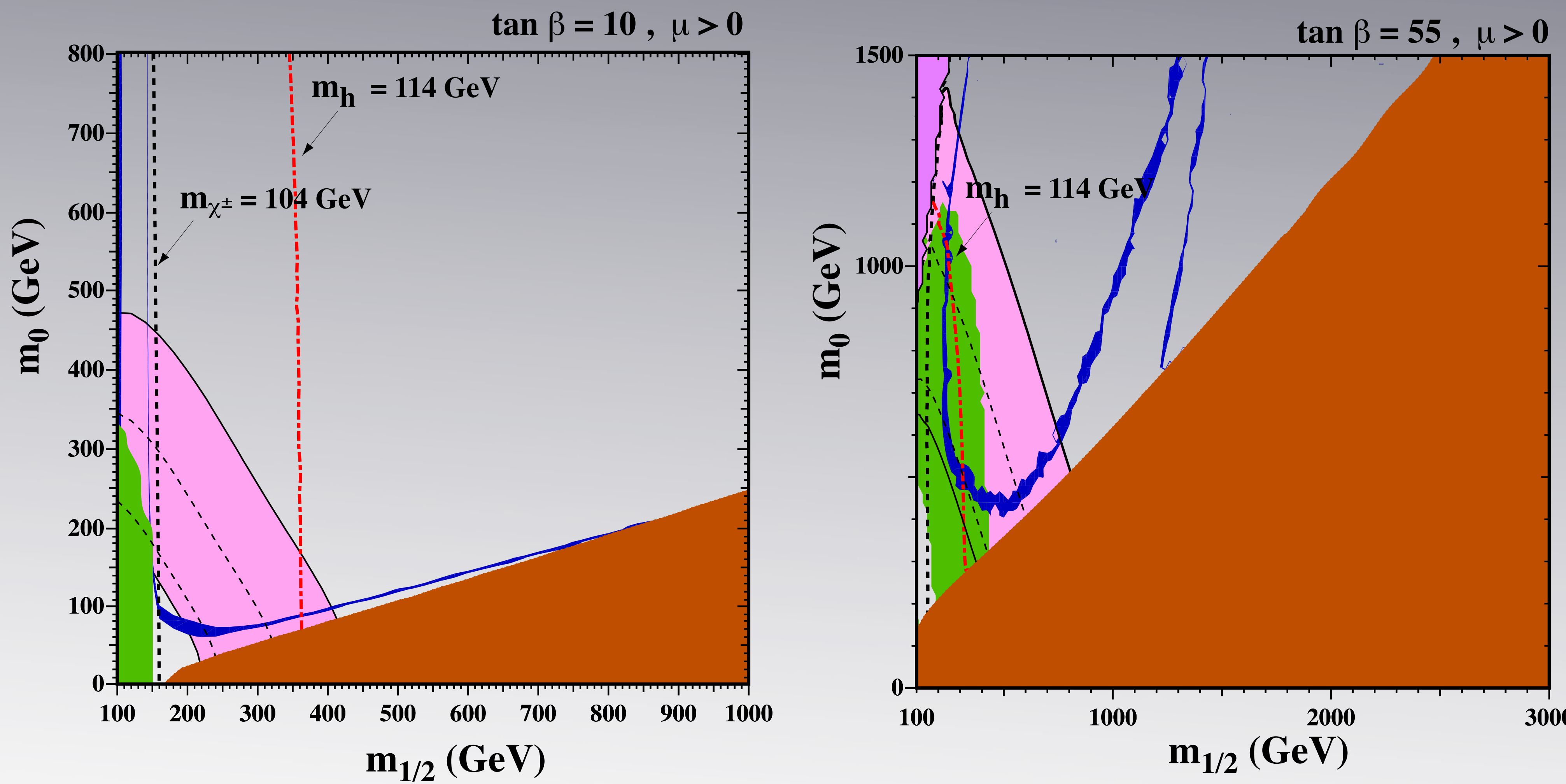
CMSSM Spectra



Unification to rich spectrum
+
EWSB

Falk

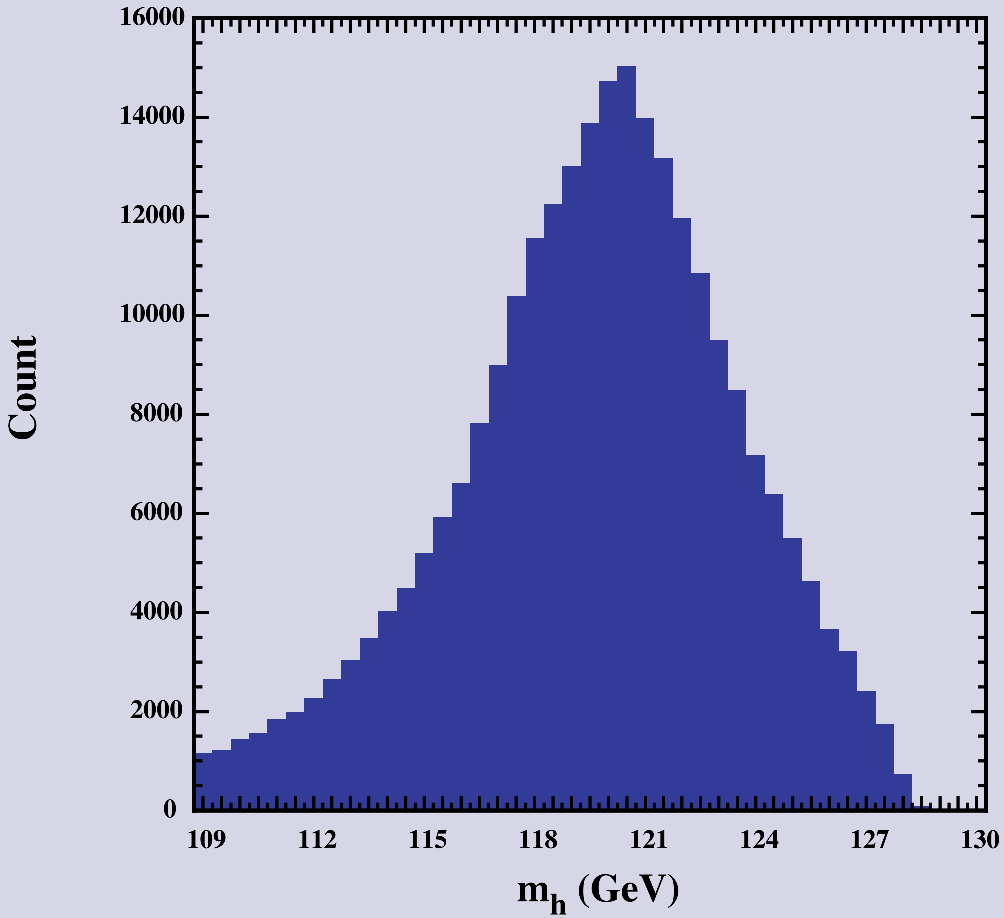
$m_{1/2}$ - m_0 planes

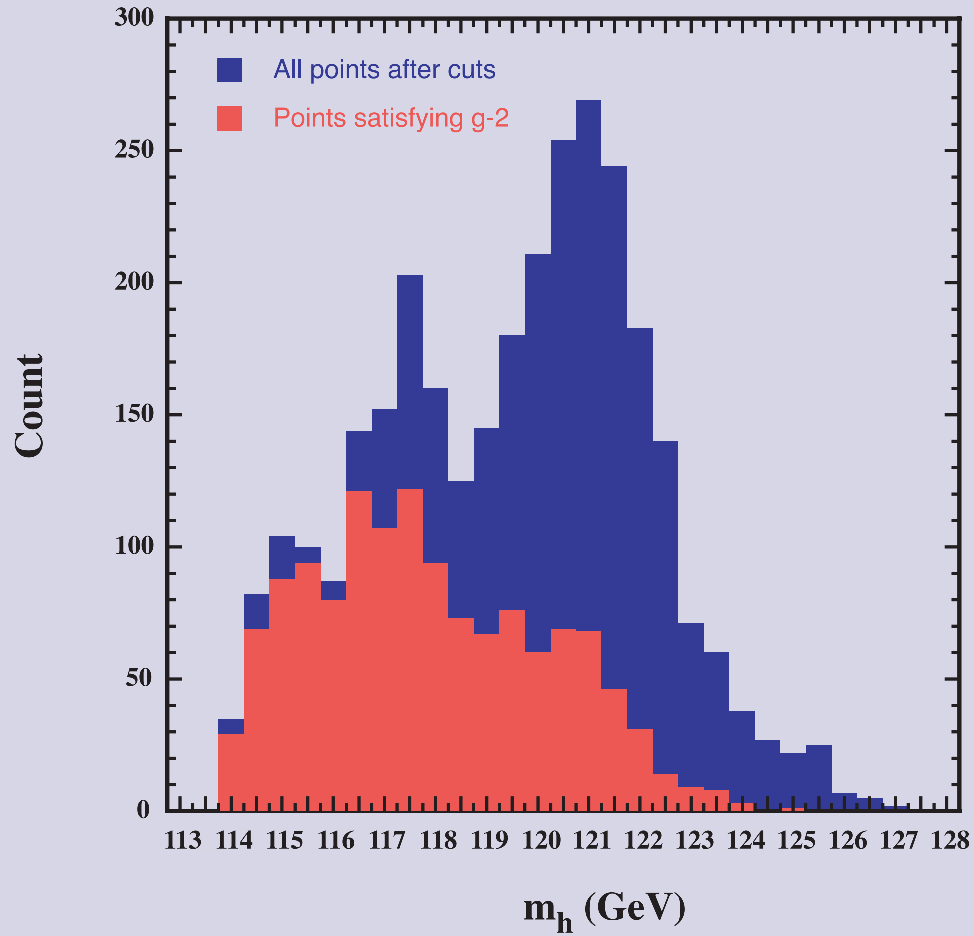


- CMSSM

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):

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

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

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

For example,

Polonyi: $f(z) = \mathbf{m_0} (z + \beta)$;

With $\langle z \rangle = \sqrt{3} - 1$ for $\beta = 2 - \sqrt{3}$

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

mSUGRA

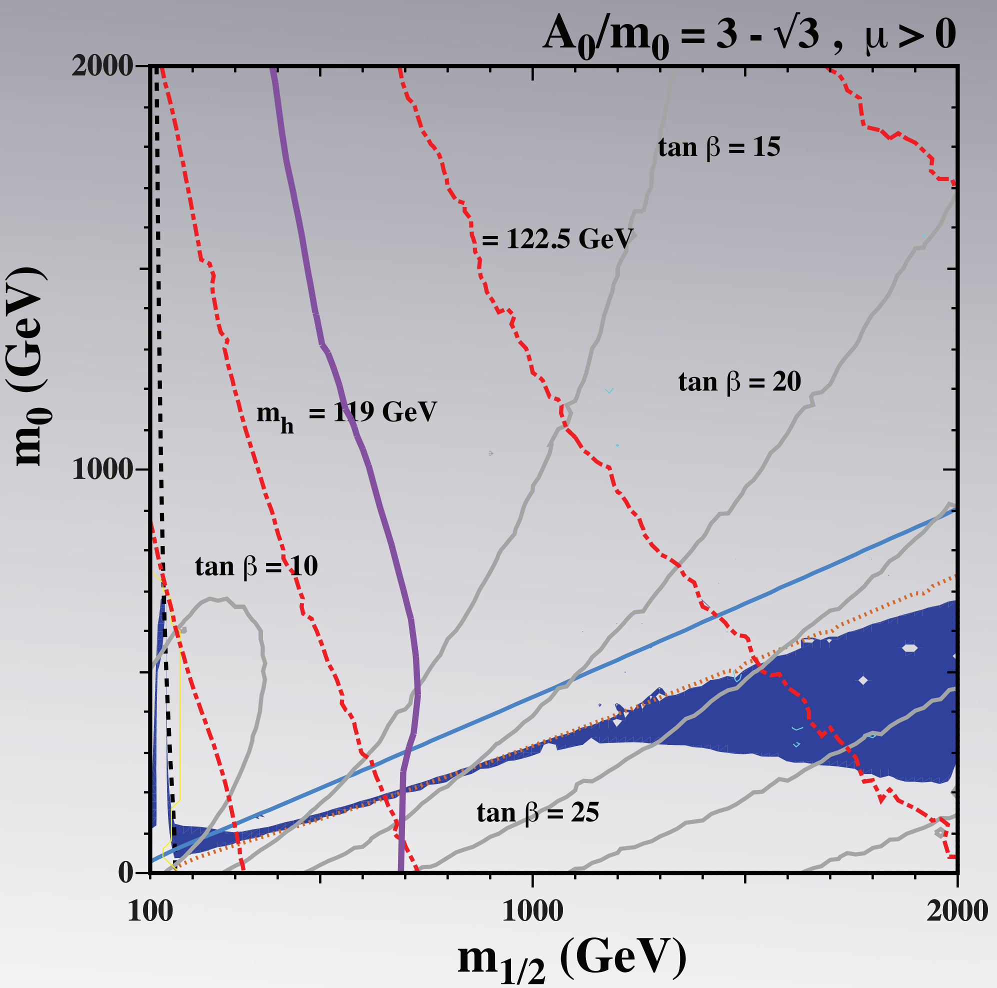
Parameters: $m_{1/2}$, $m_{3/2}$, A_0, sgn(μ)

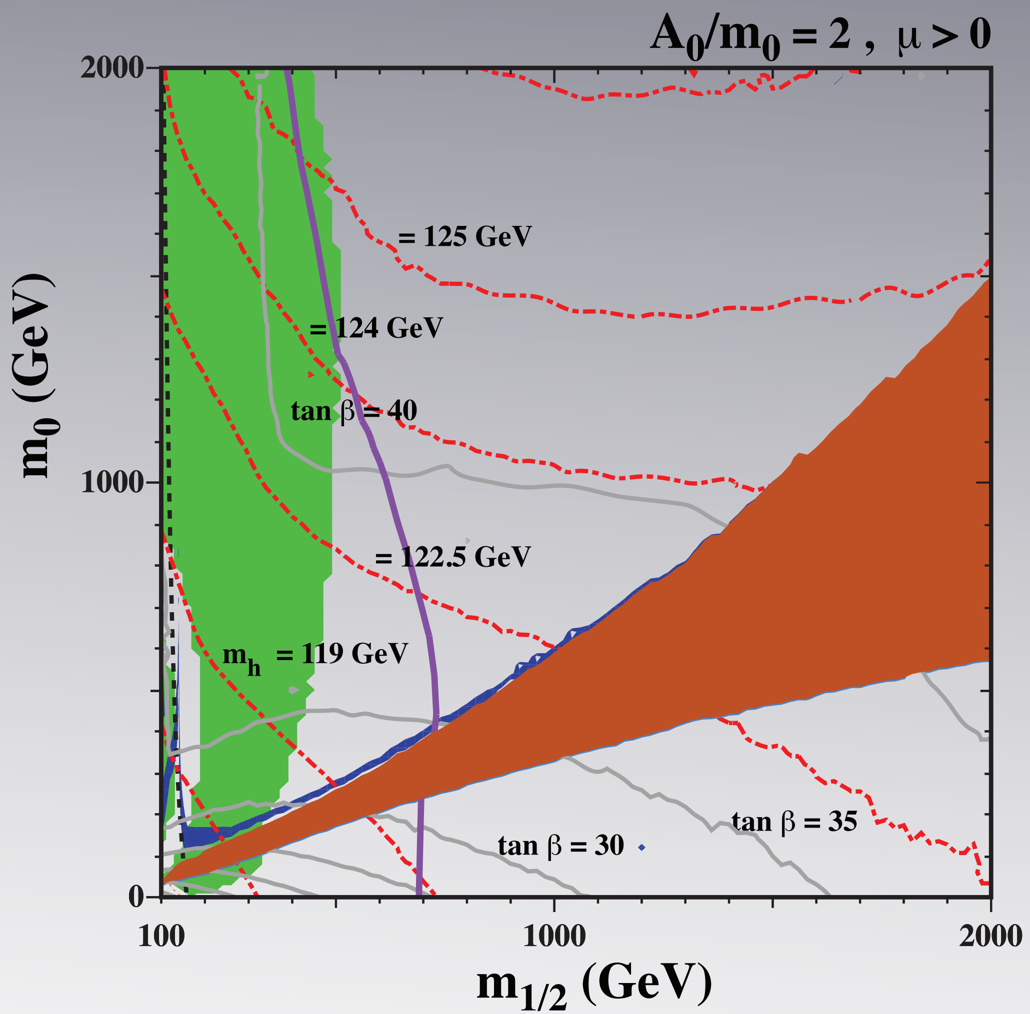
Electroweak Symmetry Breaking conditions used to solve for tanβ:

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

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

mSUGRA planes





Ellis, Luo, Olive, Sandick

Mastercode - MCMC

Long list of observables to constrain CMSSM parameter space

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2}$$
$$+ \chi^2(M_h) + \chi^2(\mathrm{BR}(B_s \to \mu\mu))$$
$$+ \chi^2(\text{SUSY search limits})$$
$$+ \sum_i^M \frac{(f^{\mathrm{obs}}_{\mathrm{SM}_i} - f^{\mathrm{fit}}_{\mathrm{SM}_i})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

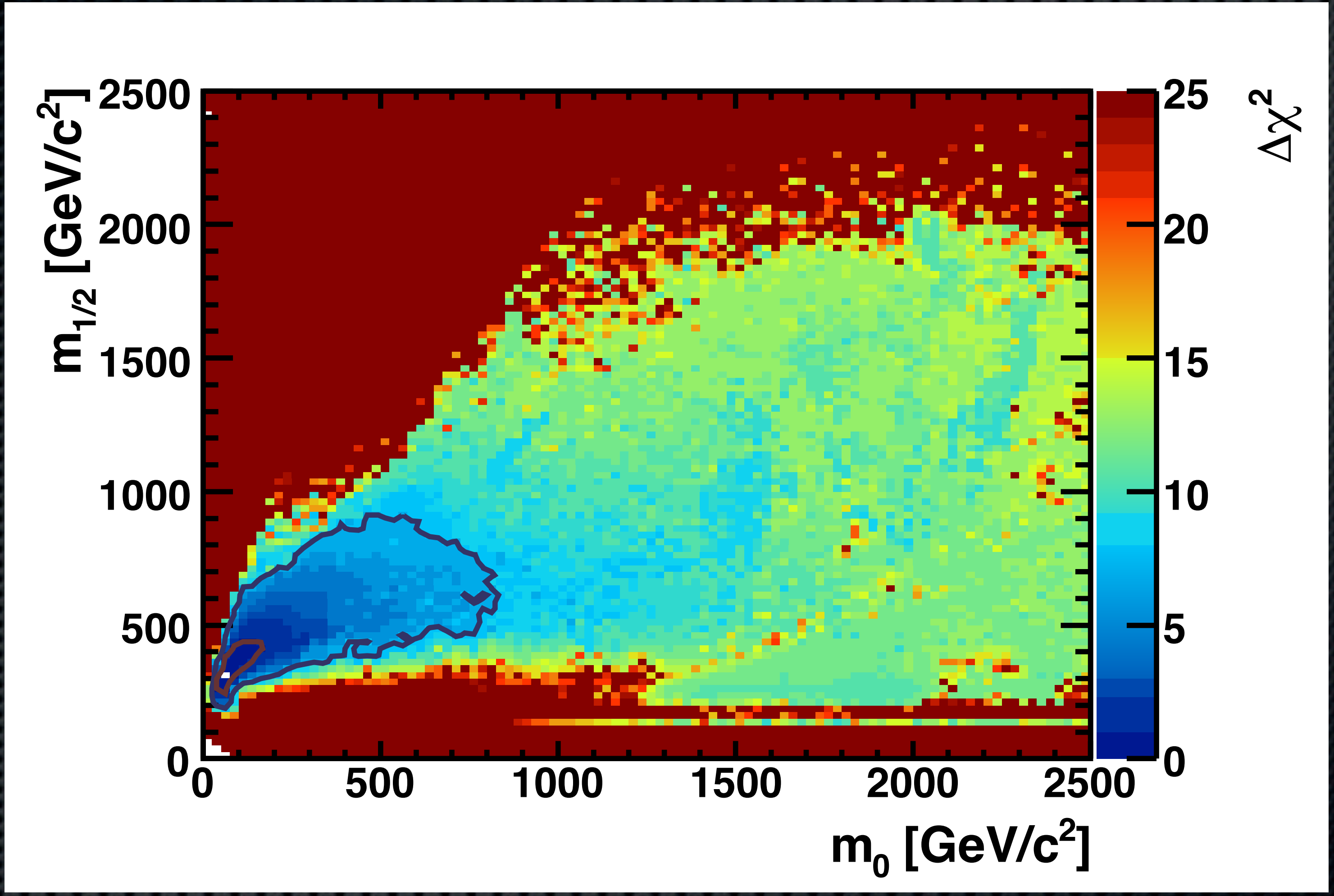
- MCMC technique to sample efficiently the SUSY parameter space, and thereby construct the χ^2 probability function
- Combines SoftSusy, FeynHiggs, SuperFla, SuperIso, MicrOmegas, and SSARD
- Purely frequentist approach (no priors) and relies only on the value of χ^2 at the point sampled and not on the distribution of sampled points.
- 70 million points sampled (CMSSM)

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

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

Mastercode

2009

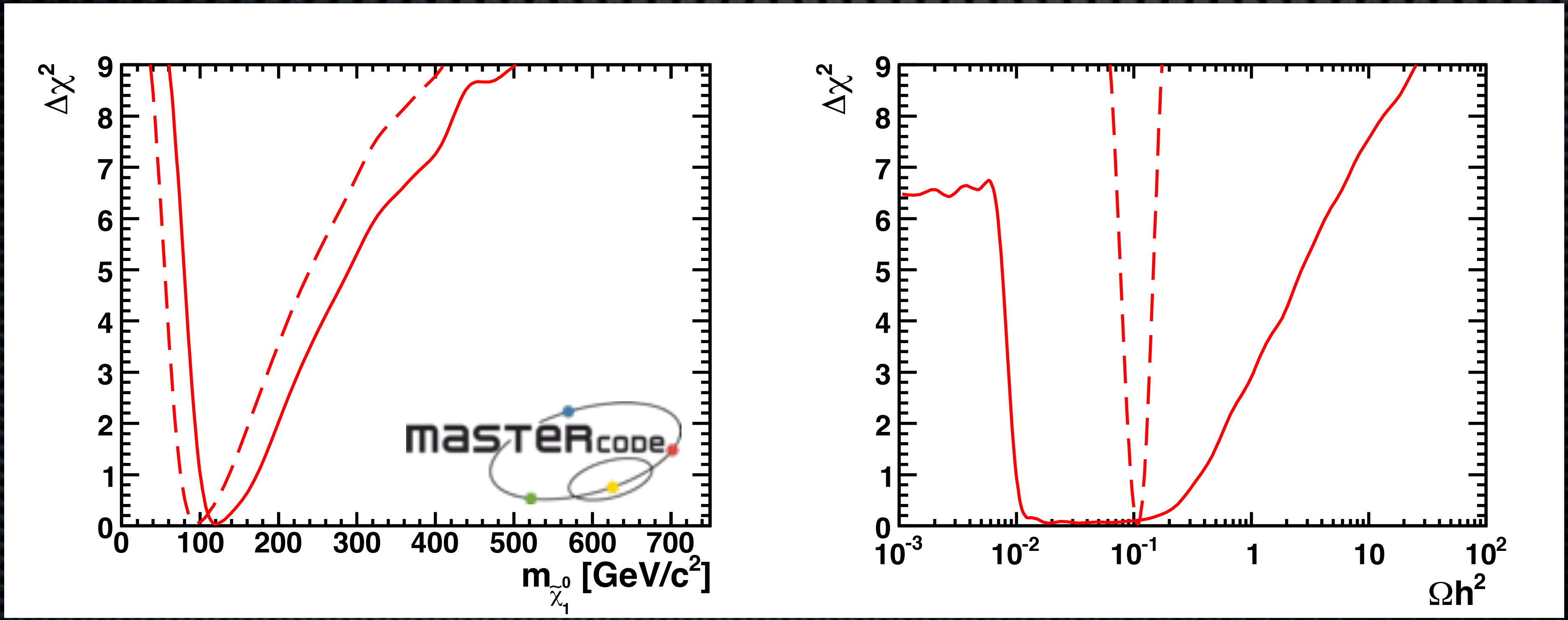


- CMSSM

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

Neutralino mass and Relic Density from MCMC analysis

Mastercode 2009

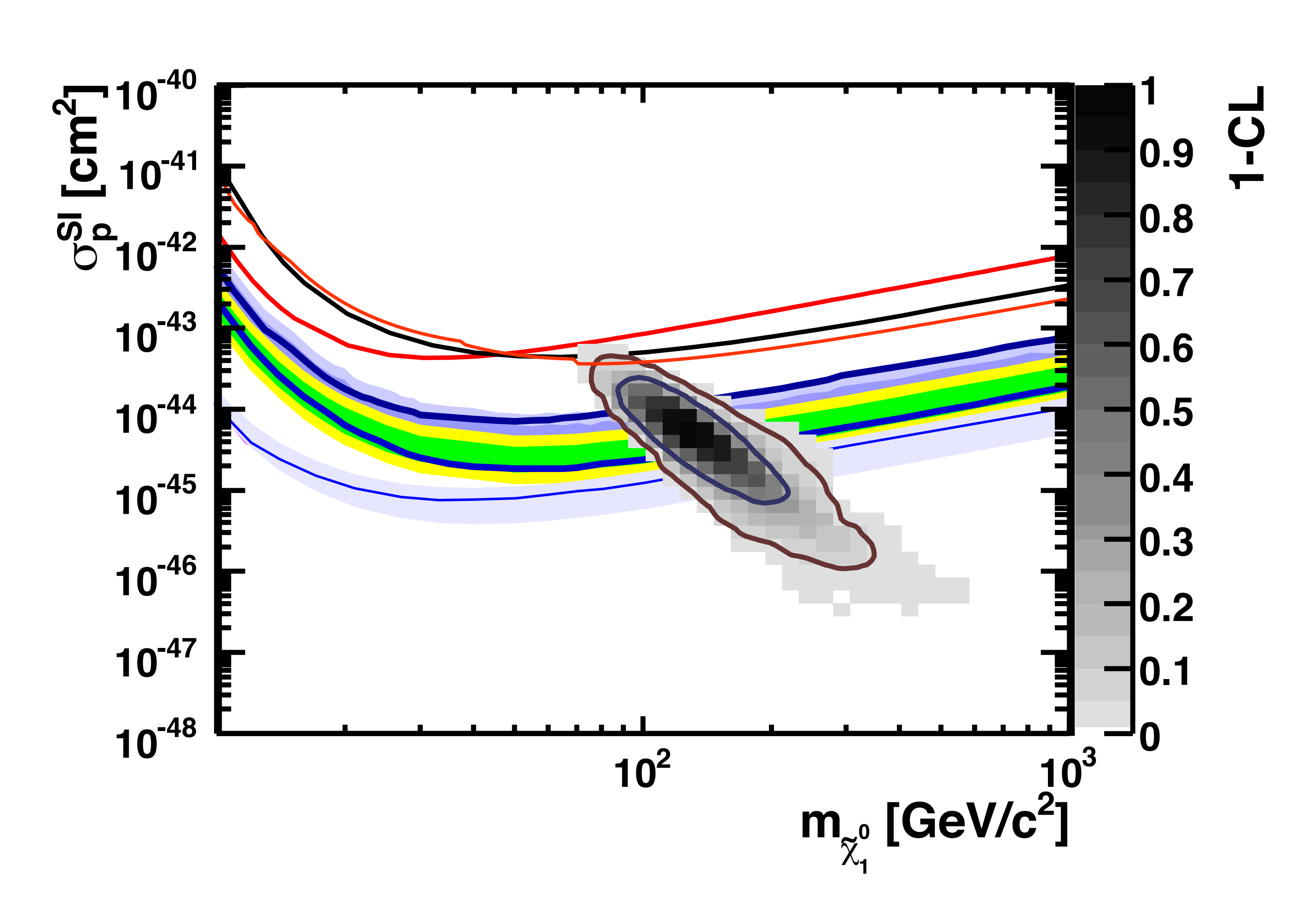


Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein

Elastic scaterring cross-section

Mastercode

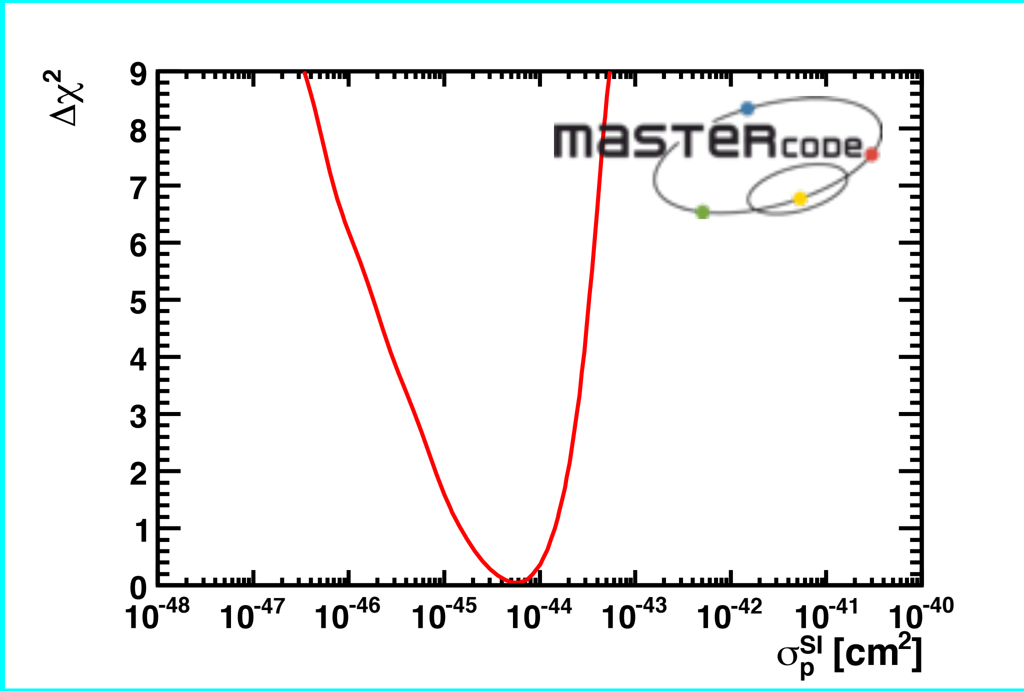
2009

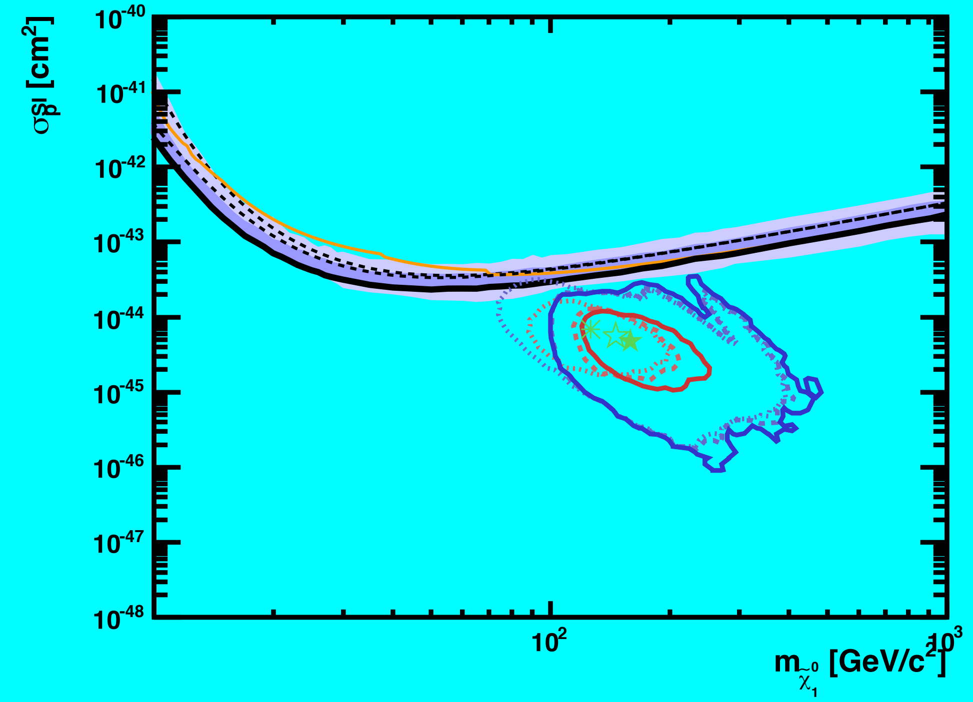


- CMSSM

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

Elastic cross section from MCMC analysis





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

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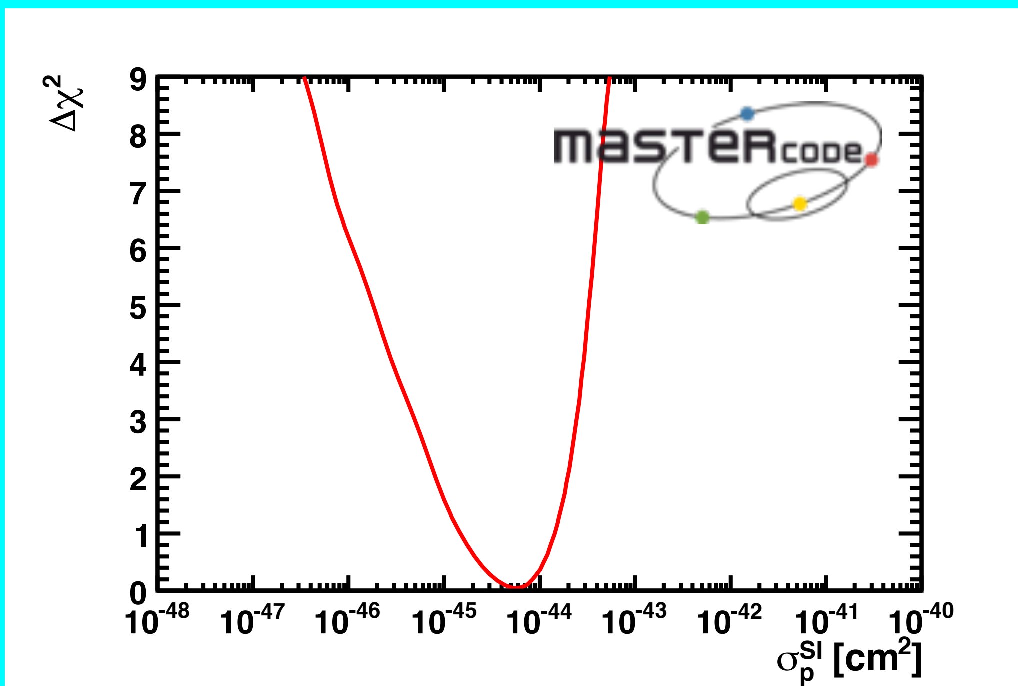
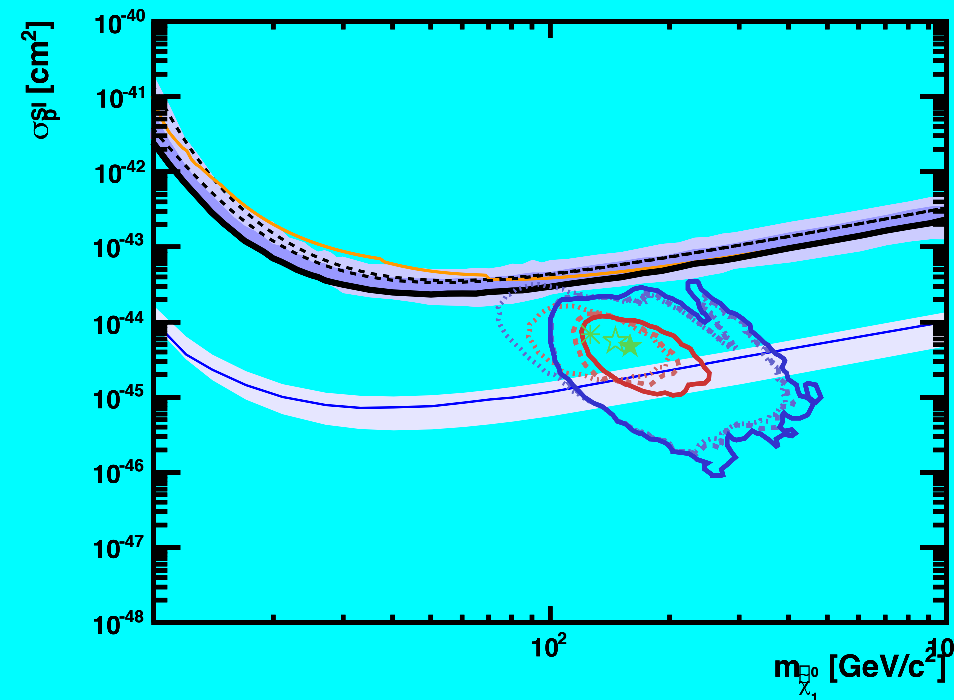
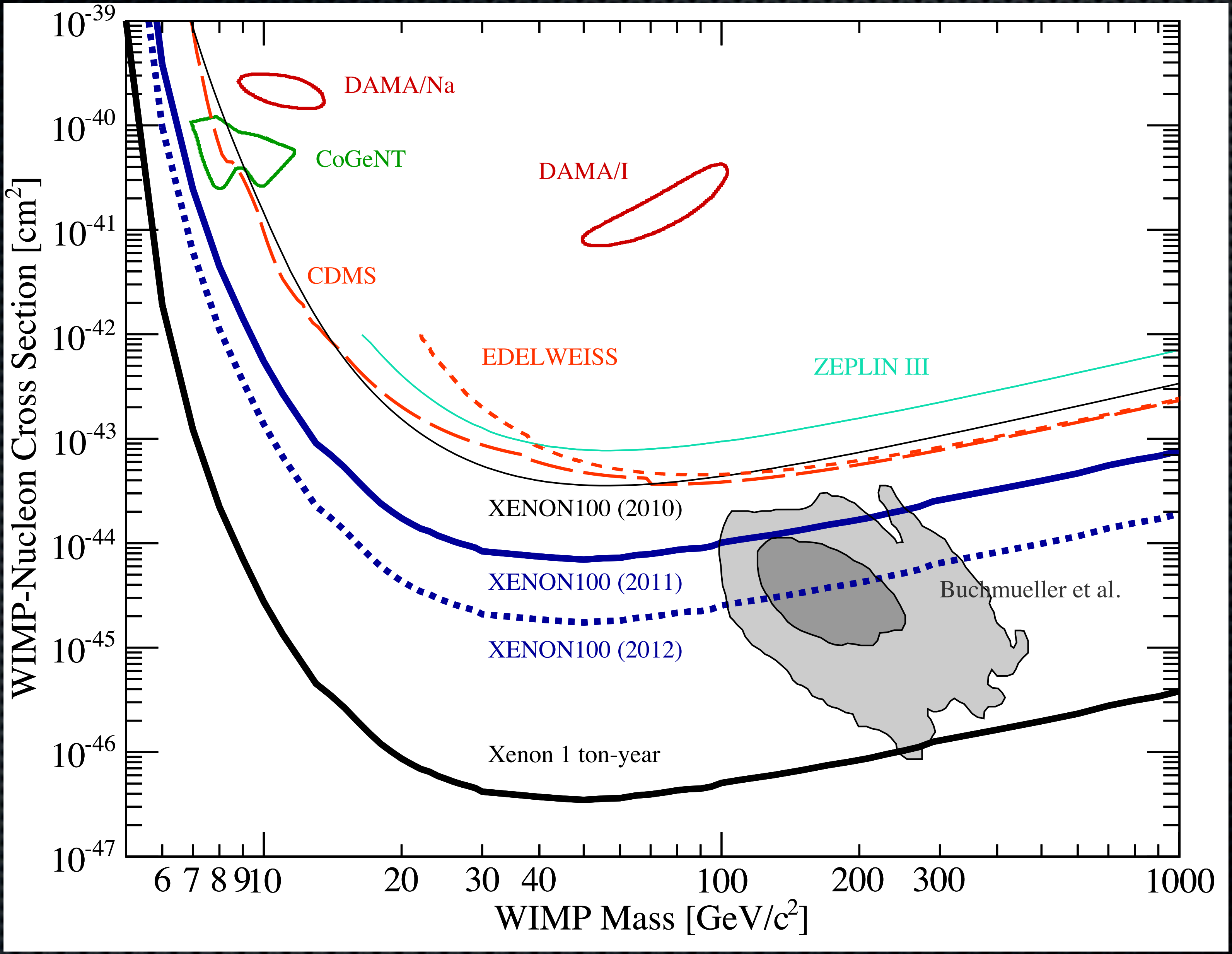




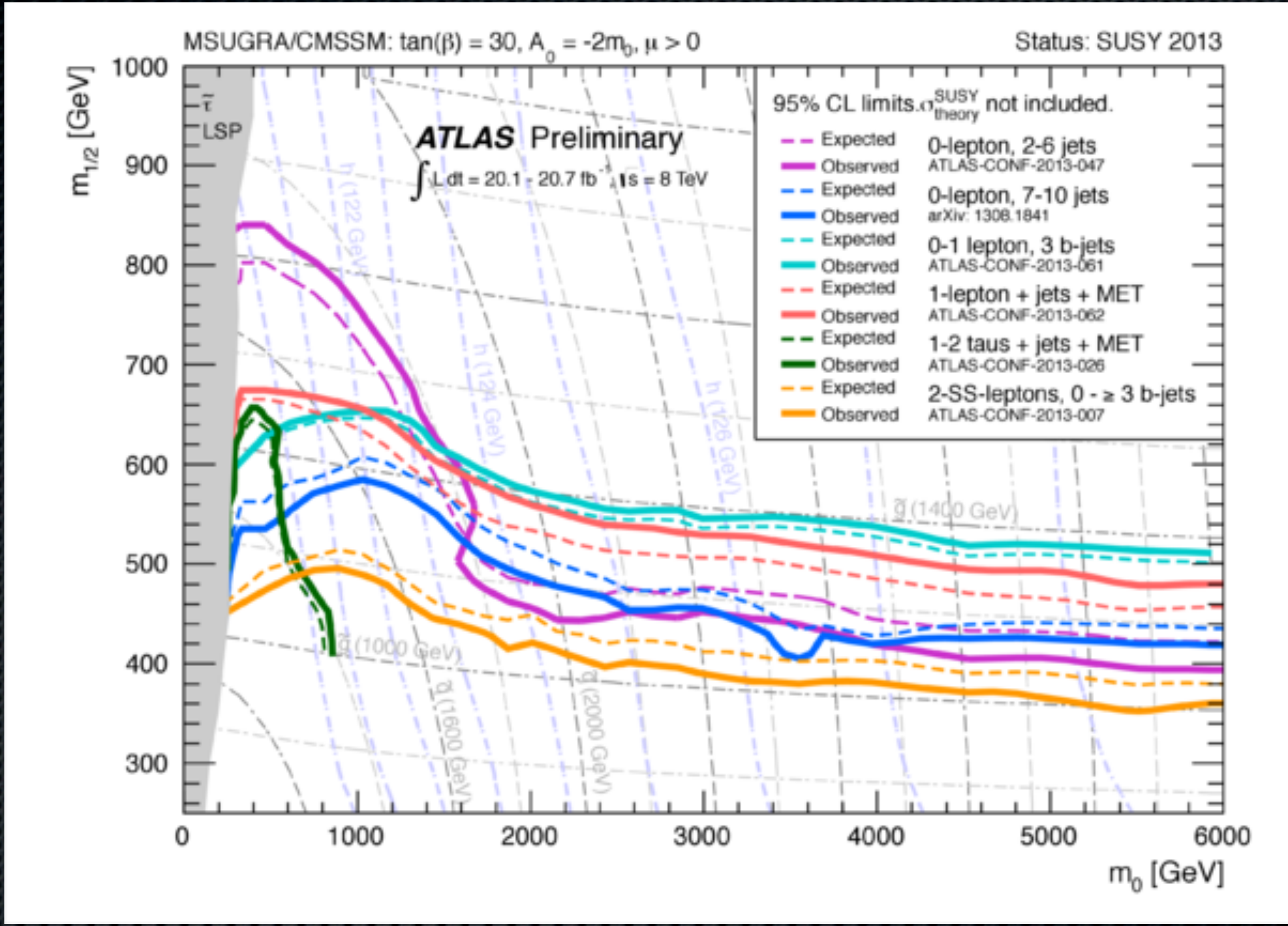
Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Paradisi, Ronga, Weiglein

Most recent result from XENON100



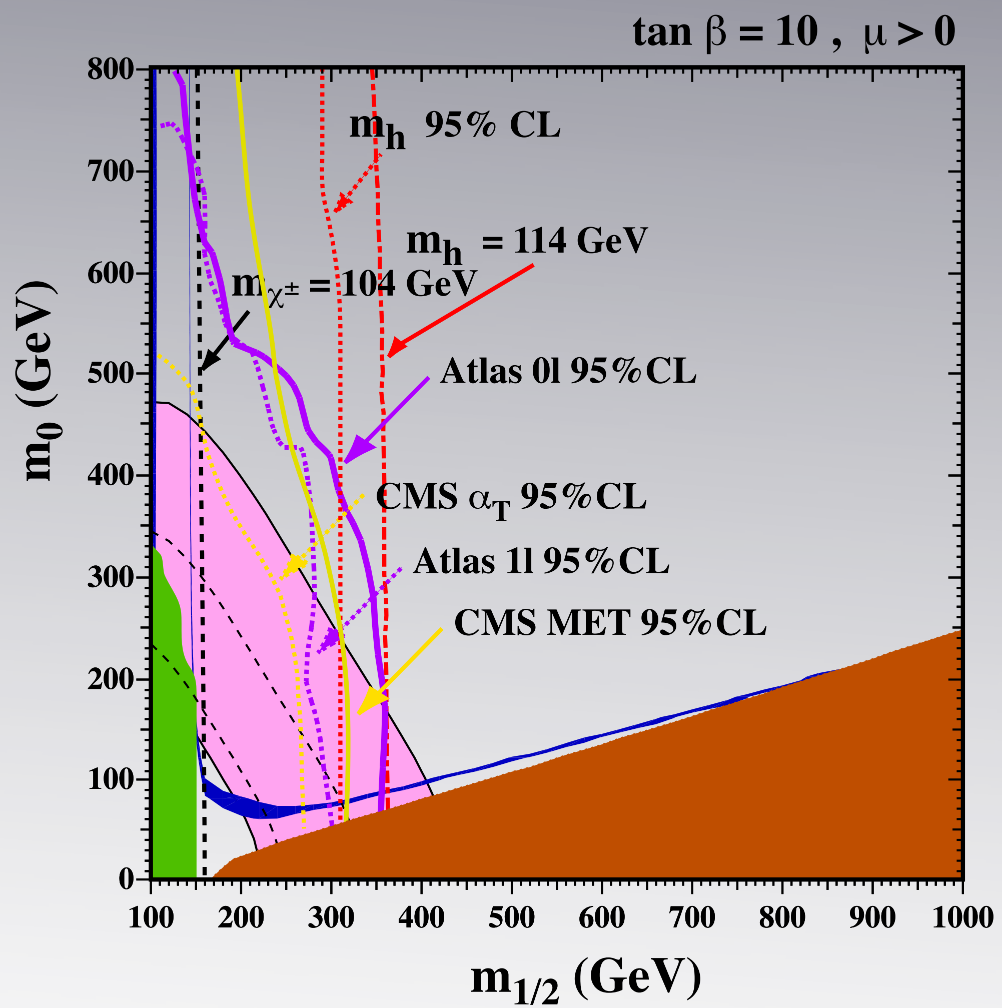
Aprile

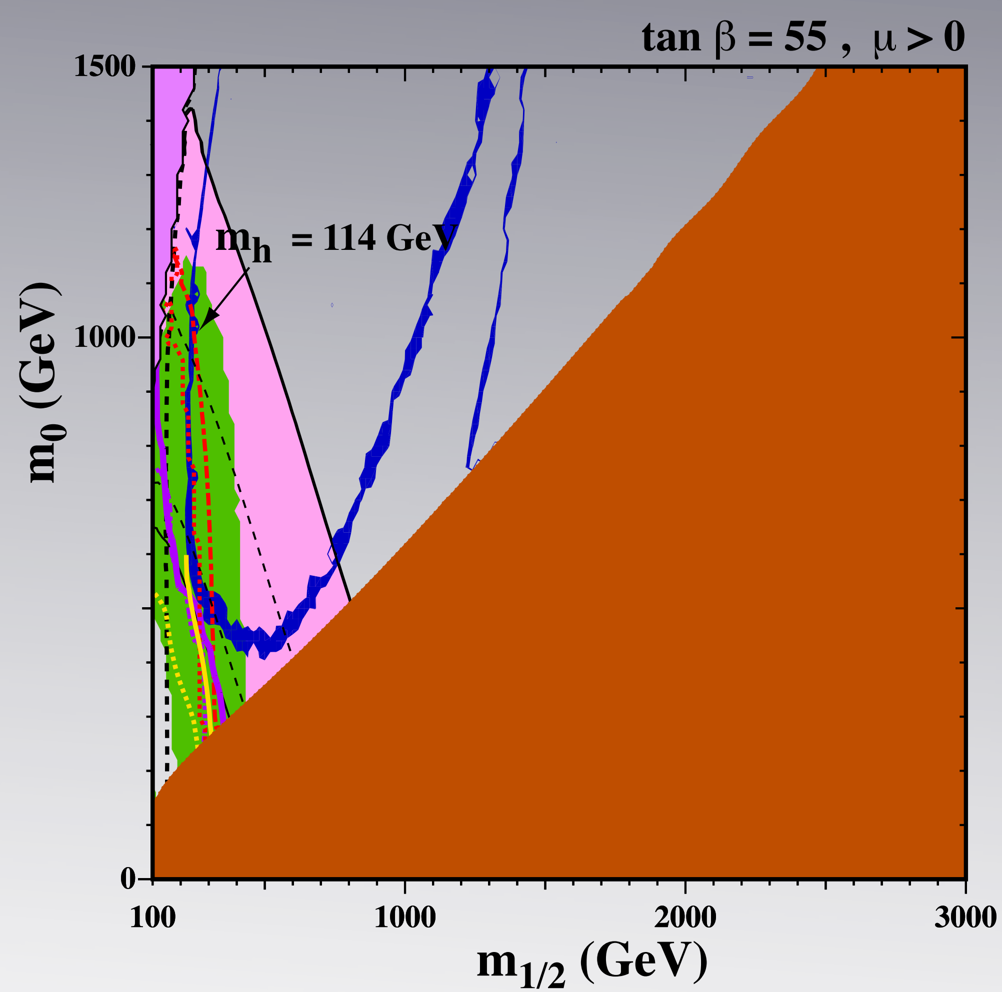
ATLAS Results from run I



$\sim 20.7 fb^{-1}$ @ 8 TeV

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





- CMSSM

Ellis, Olive, Santoso, Spanos

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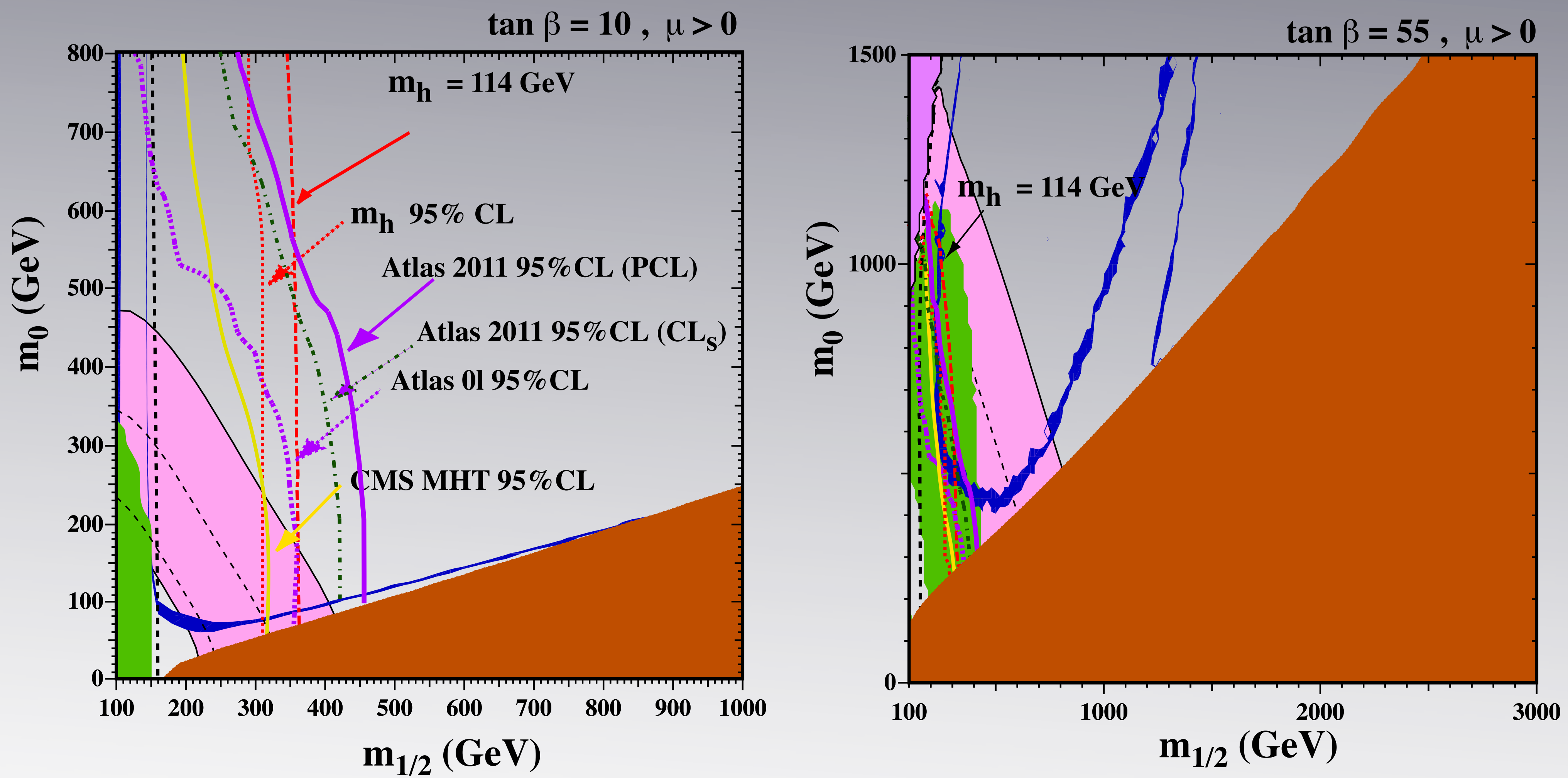

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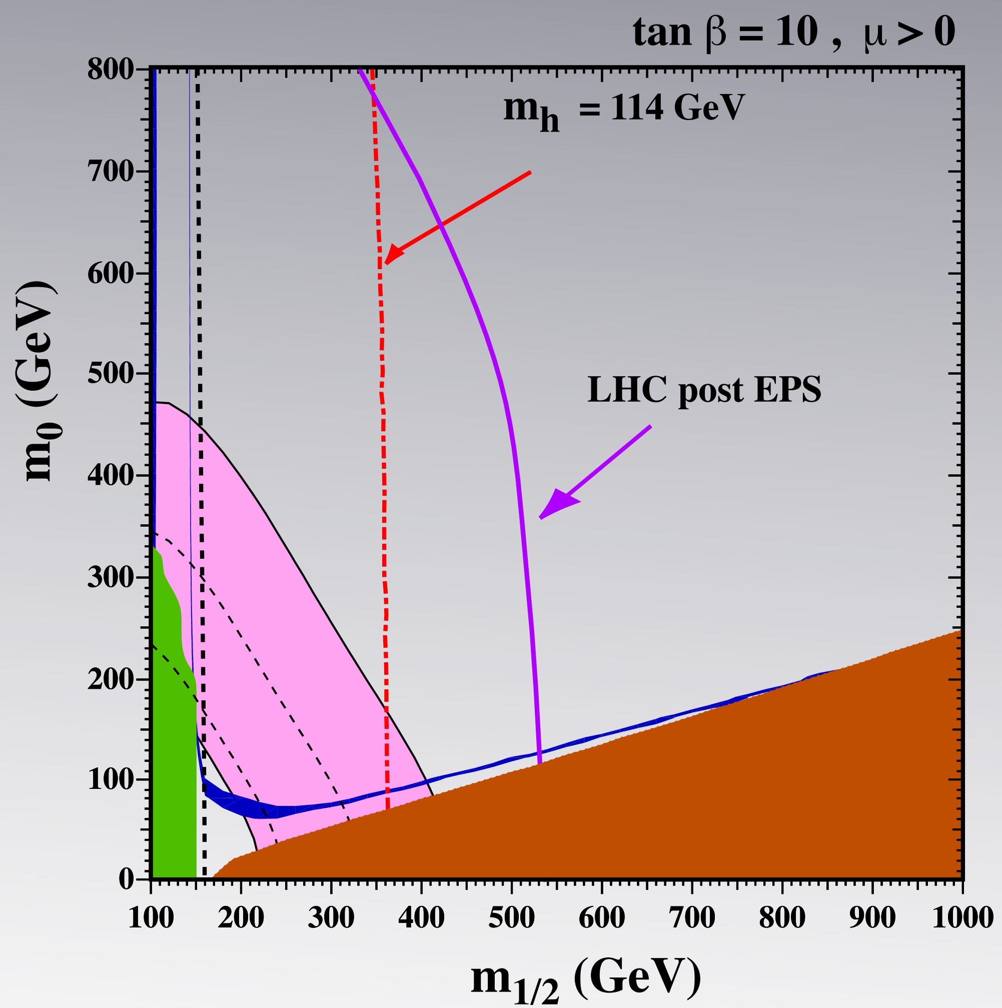

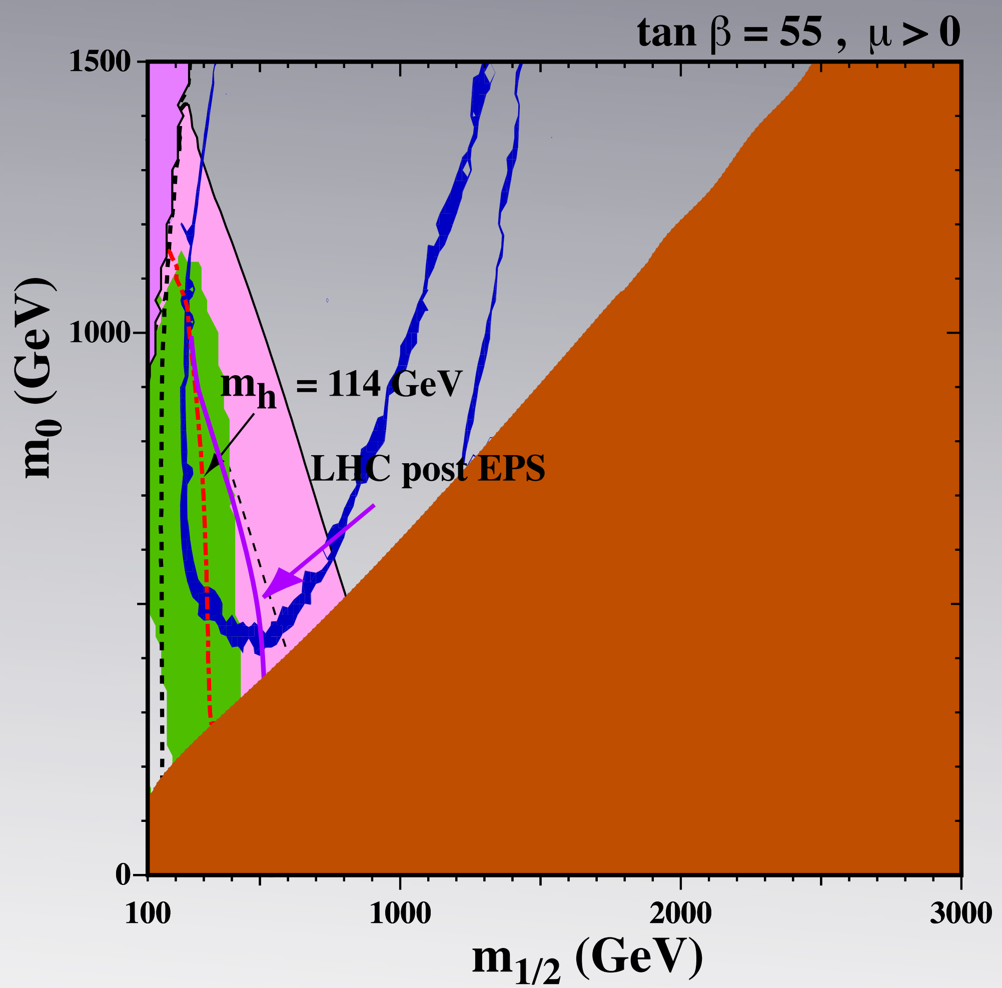

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Ellis, Olive, Santoso, Spanos

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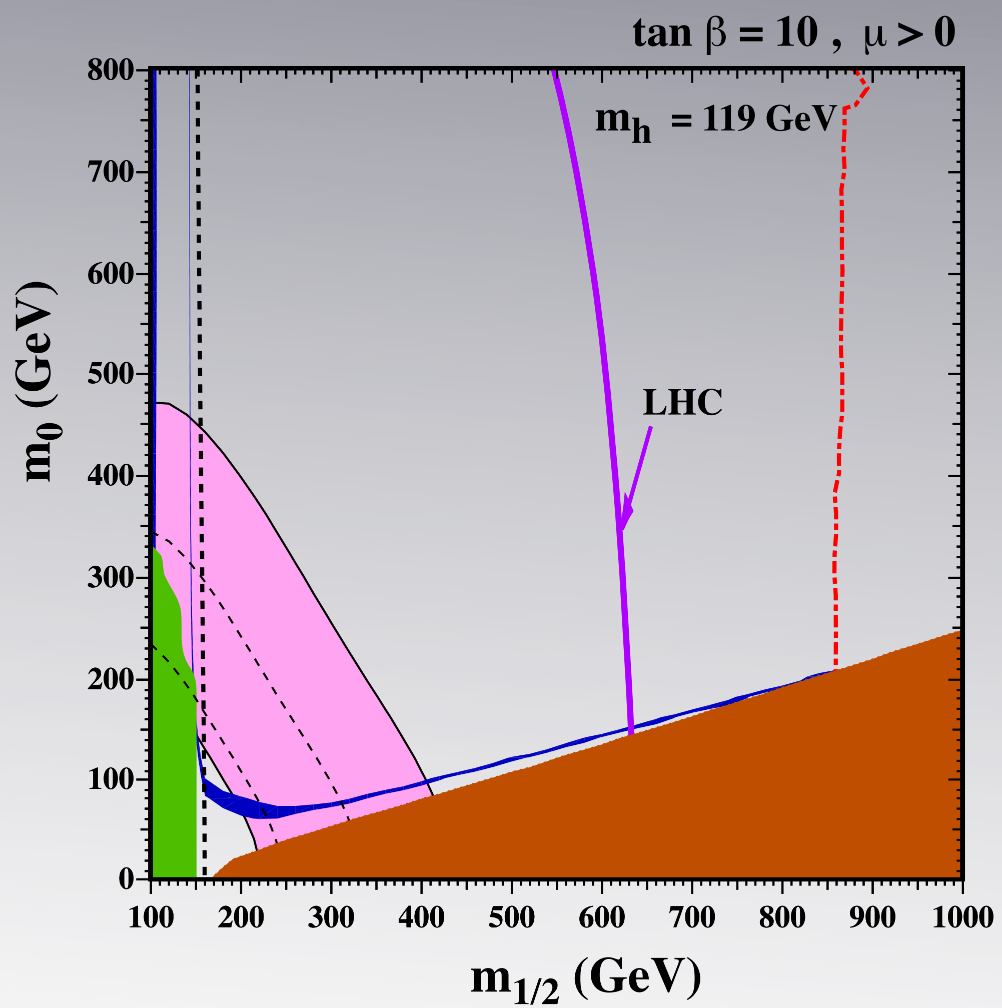

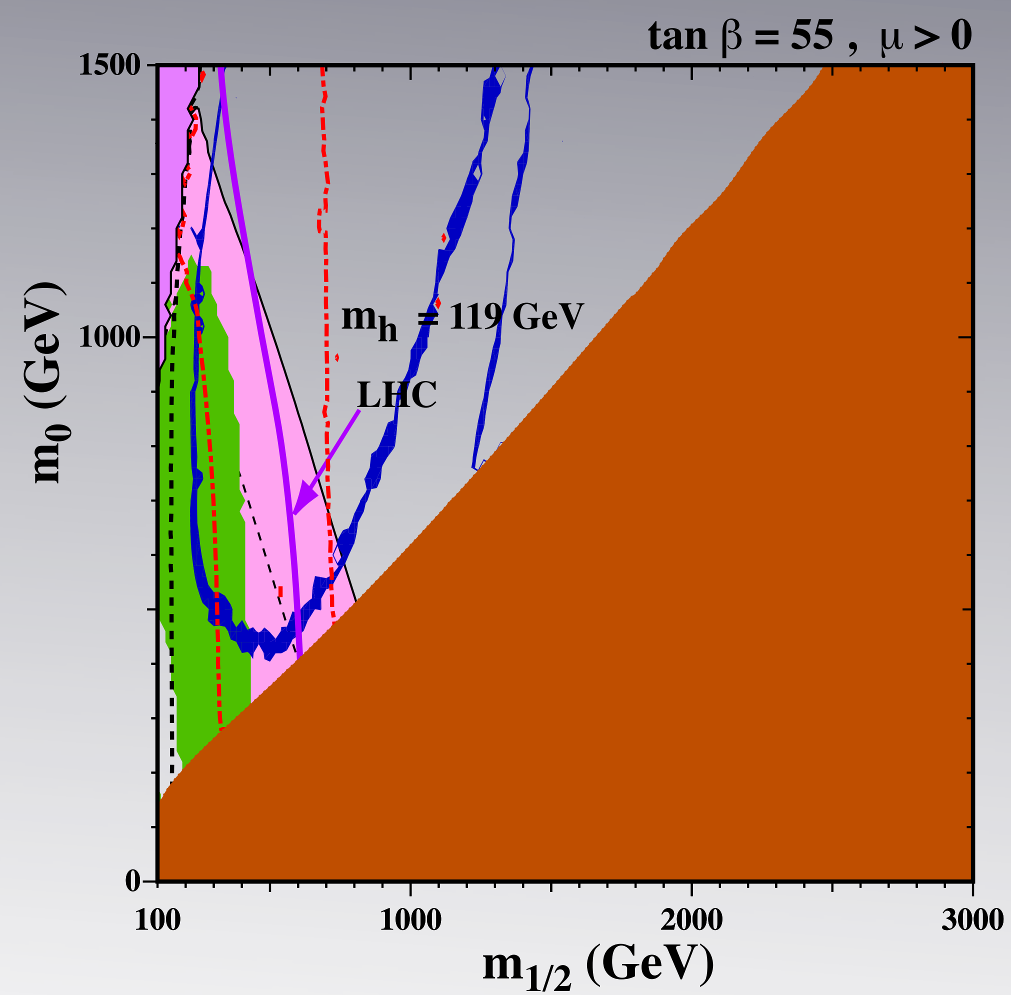

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Ellis, Olive, Santoso, Spanos

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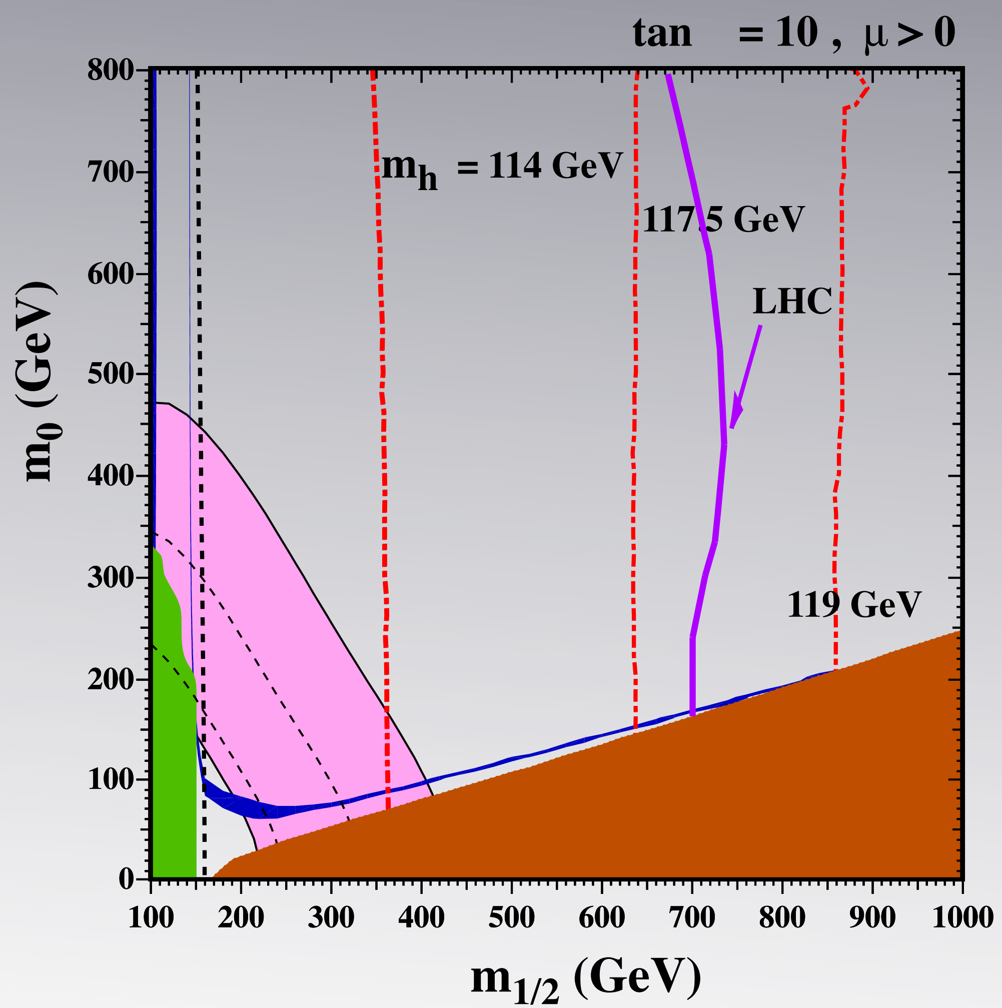

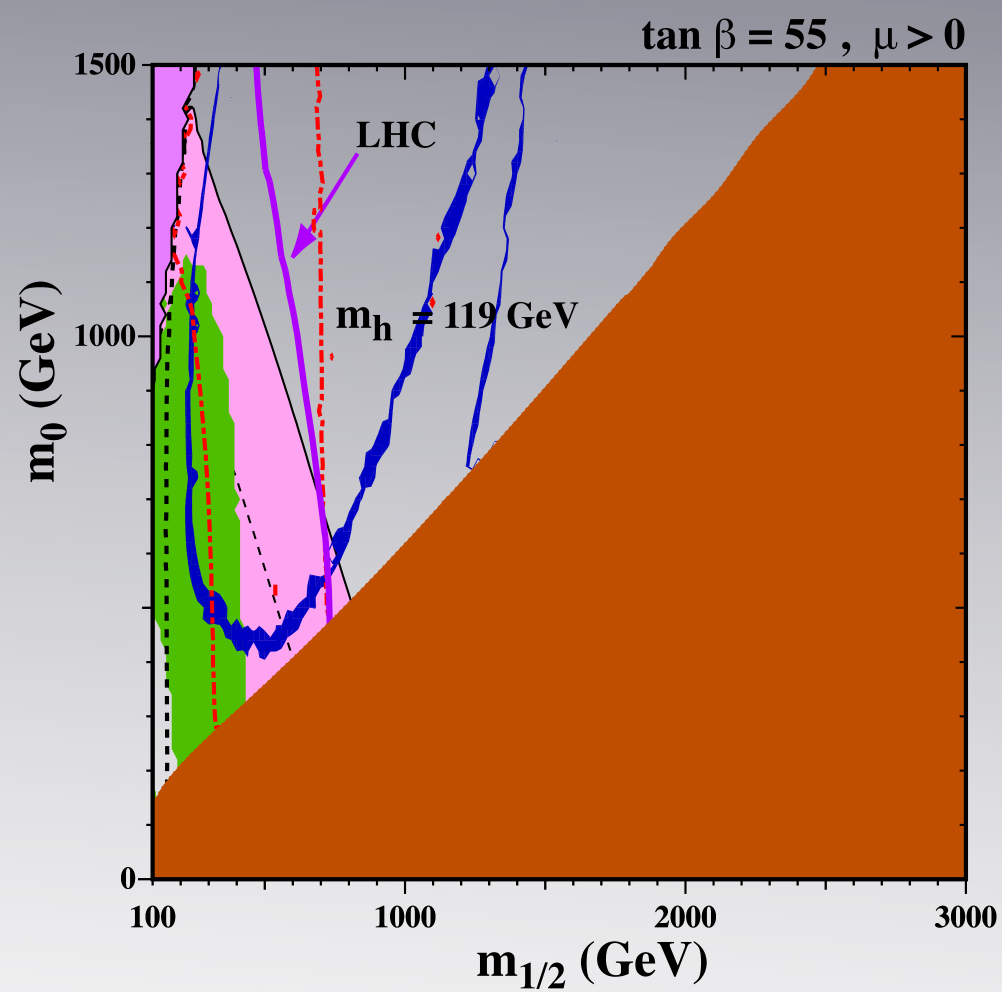

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Ellis, Olive, Santoso, Spanos

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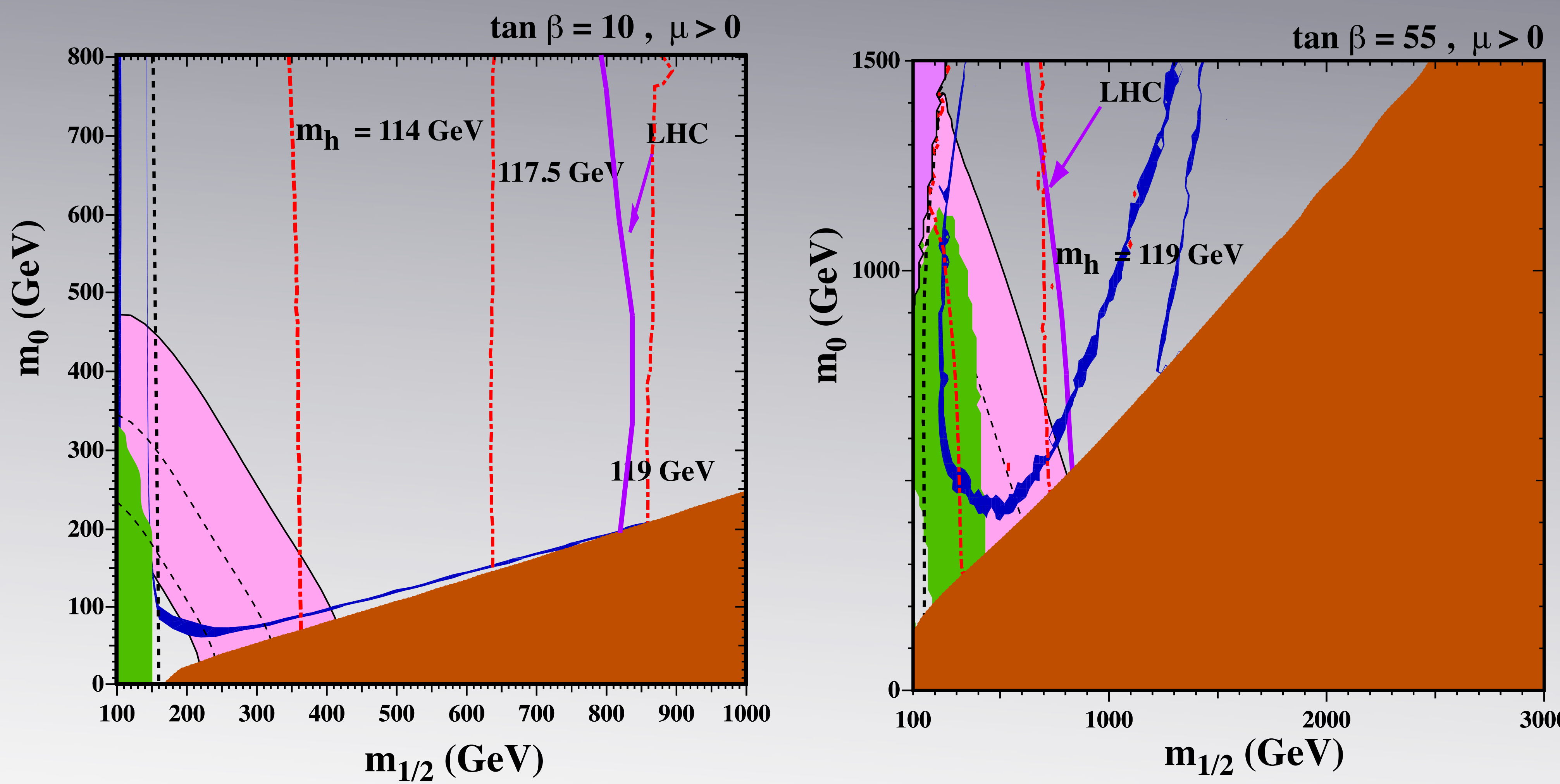
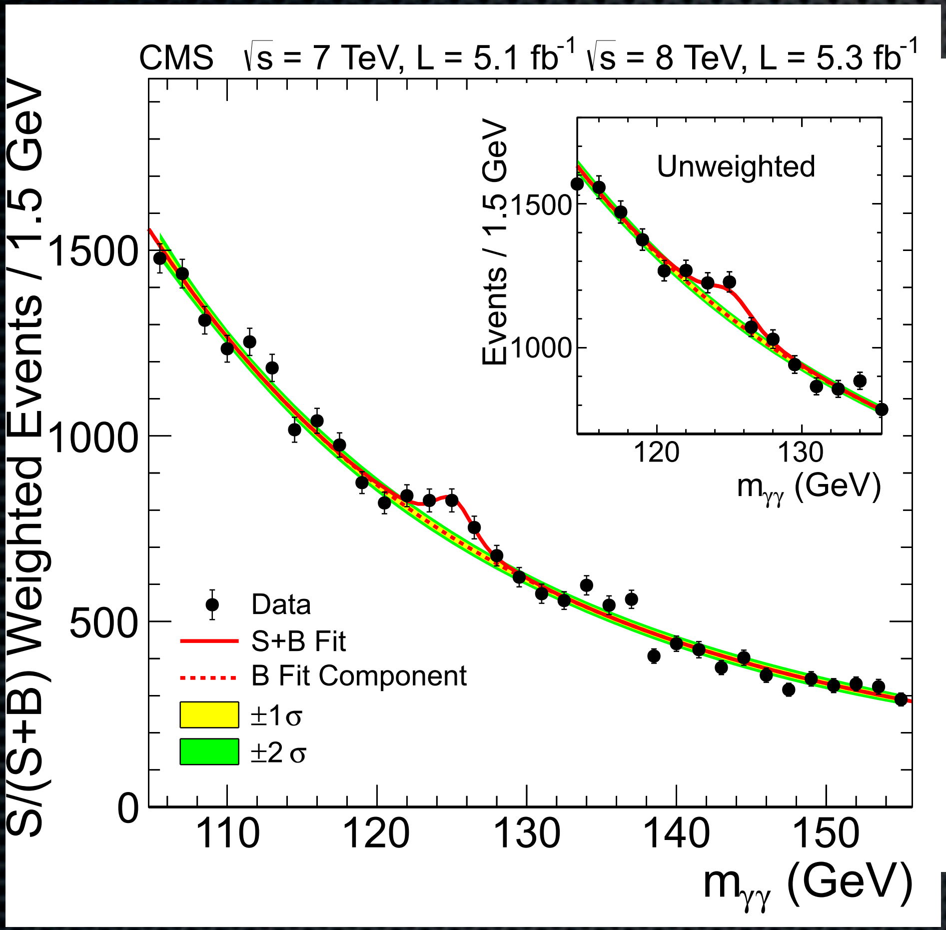
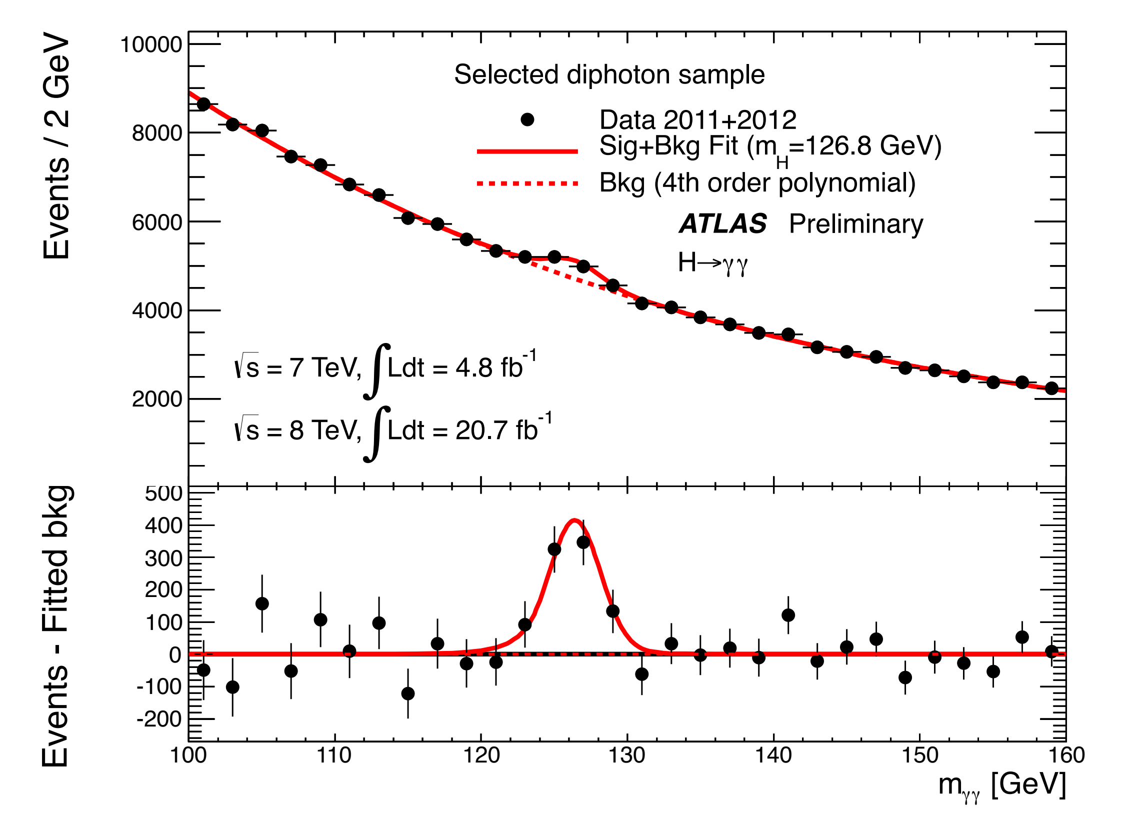


- CMSSM

Ellis, Olive, Santoso, Spanos

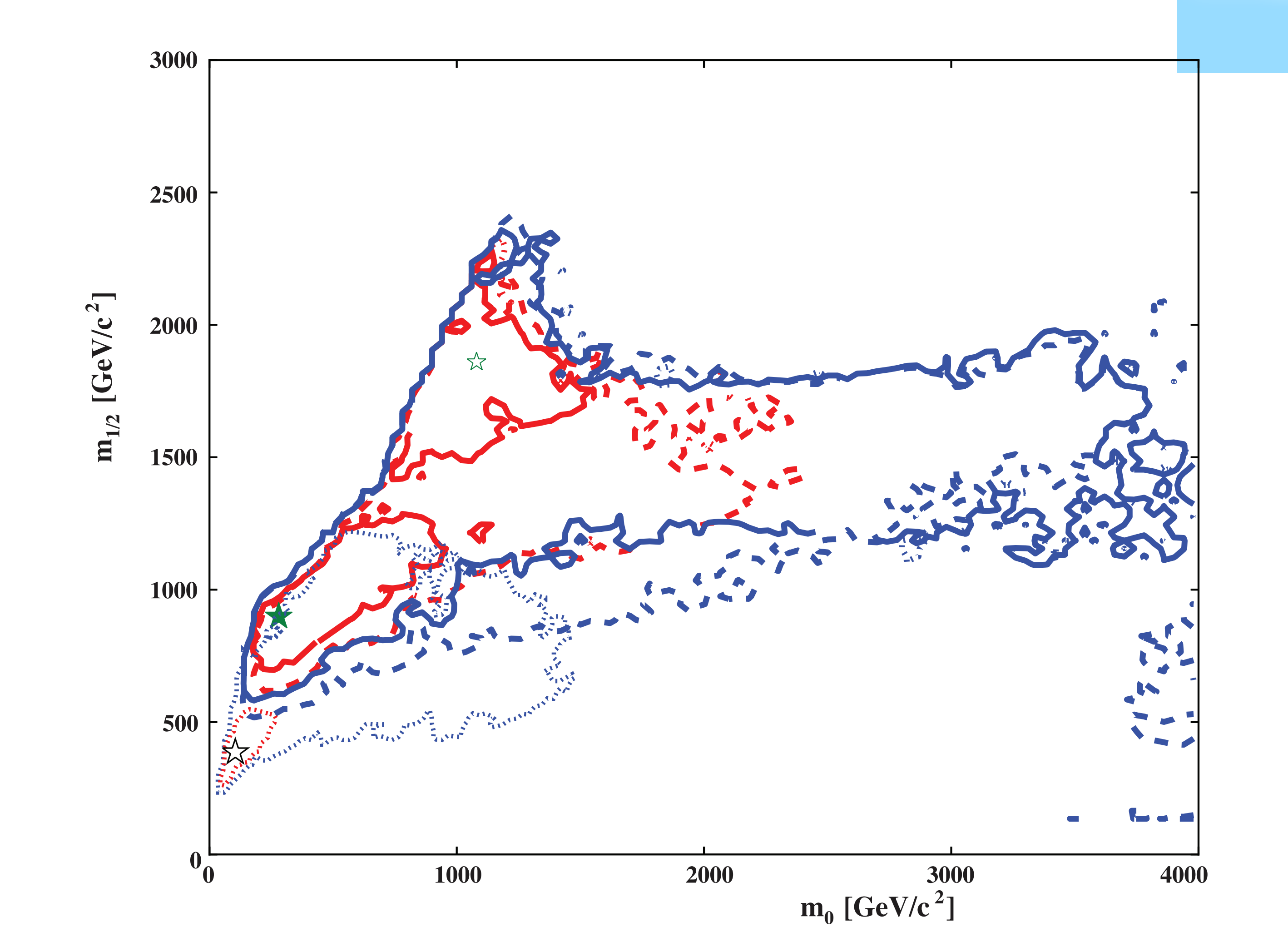
The Higgs Search
The LHC @ ~20.7/fb





$\Delta\chi^2$ 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

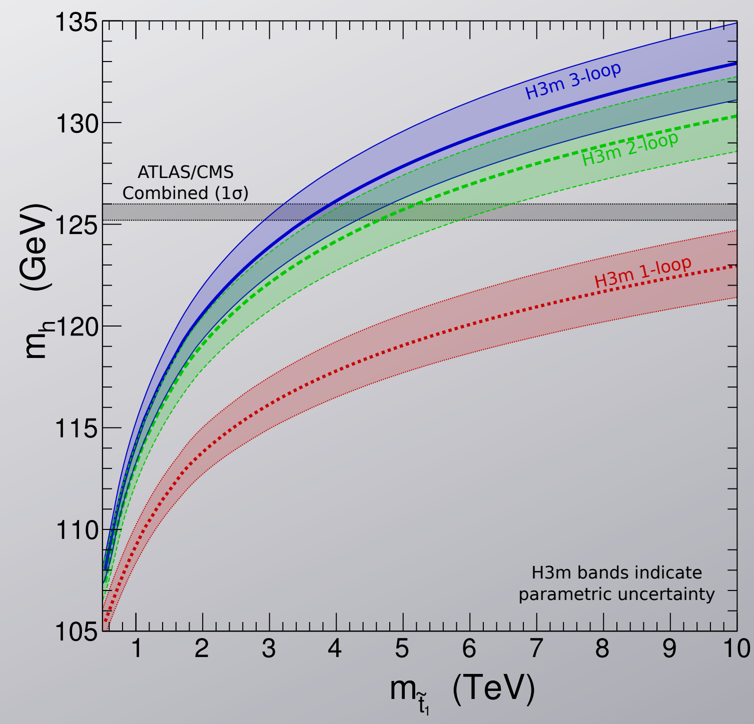
Comparison of best fit points pre and post LHC

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
	$\mathrm{LHC}_{1/\mathrm{fb}}$	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

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 $\mathrm{Log}(m_{\tilde{t}}/m_t)$ to all orders

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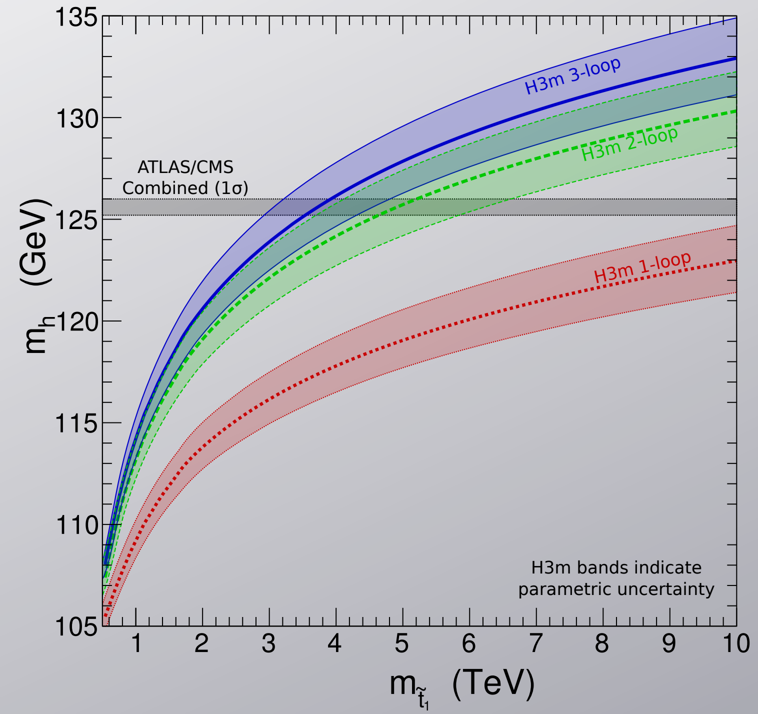


Feng, Kant, Profumo, Sanford

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

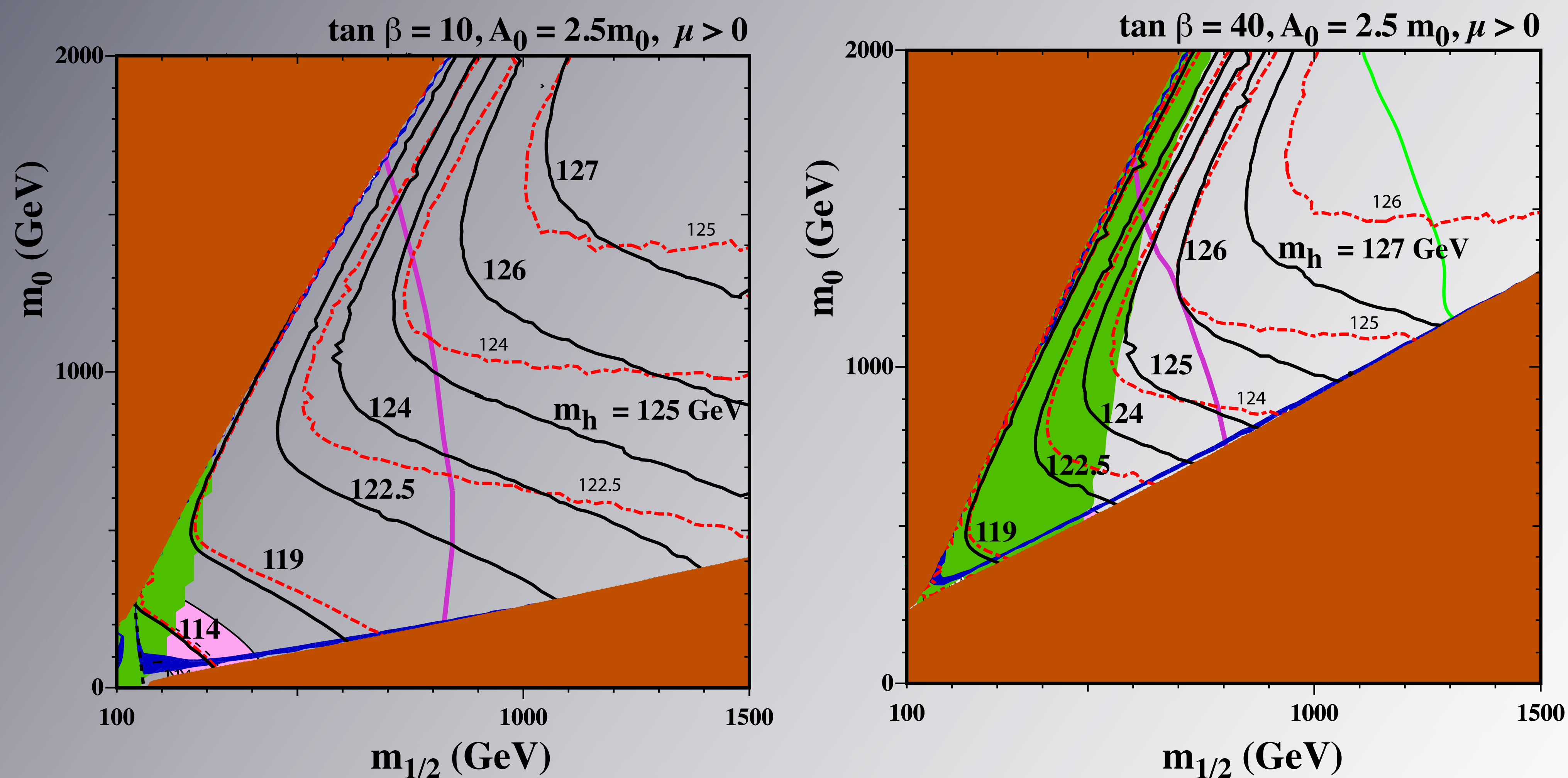
CMS: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}\,,$

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

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

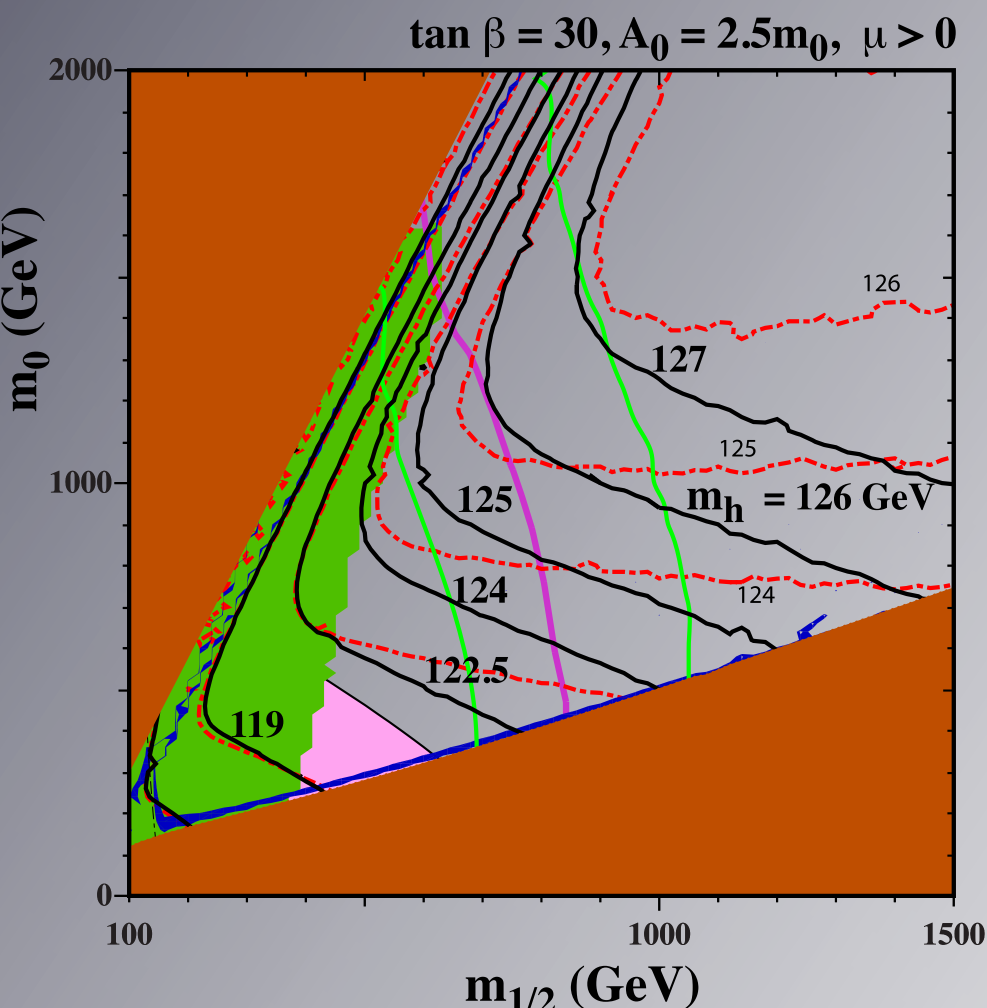
Buchmuller et al.

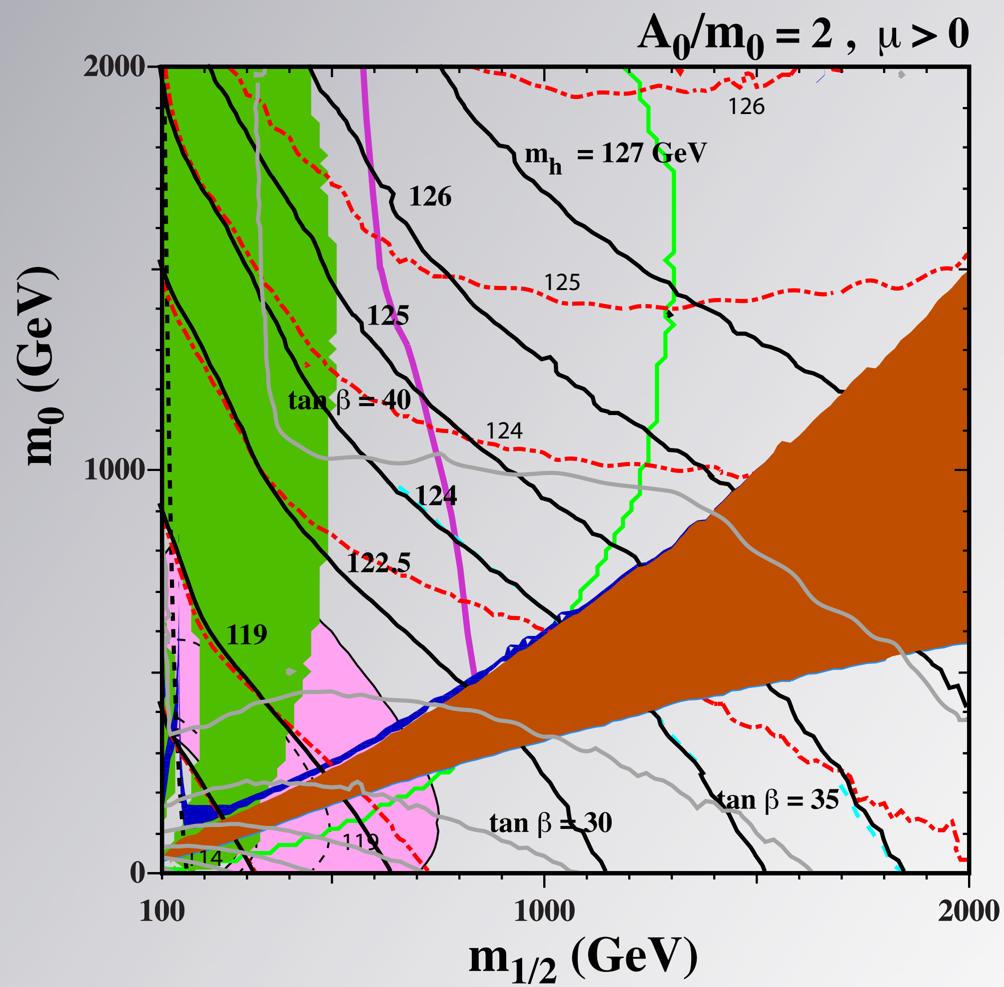
High and low tan β gone!



Buchmueller, Dolan, Ellis, Hahn, Heinemeyer, Hollik, Marrouche, Olive, Rzehak, de Vries, Weiglein

Something left?





CMSSM

mSUGRA

Buchmueller, Dolan, Ellis, Hahn, Heinemeyer, Hollik, Marrouche, Olive, Rzehak, de Vries, Weiglein

Mastercode - MCMC

Long list of observables to constrain CMSSM parameter space

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2}$$
$$+ \chi^2(M_h) + \chi^2(\mathrm{BR}(B_s \to \mu\mu))$$
$$+ \chi^2(\text{SUSY search limits})$$
$$+ \sum_i^M \frac{(f^{\text{obs}}_{\text{SM}_i} - f^{\text{fit}}_{\text{SM}_i})^2}{\sigma(f_{\text{SM}_i})^2}$$

- MCMC technique to sample efficiently the SUSY parameter space, and thereby construct the χ^2 probability function
- Combines SoftSusy, FeynHiggs, SuperFla, SuperIso, MicrOmegas, and SSARD
- Purely frequentist approach (no priors) and relies only on the value of χ^2 at the point sampled and not on the distribution of sampled points.
- 70 million points sampled (CMSSM)

Buchmueller, Cavanaugh, Colling, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Olive, Rogerson, Ronga, Weiglein

Mastercode - MultiNest

Long list of observables to constrain CMSSM parameter space

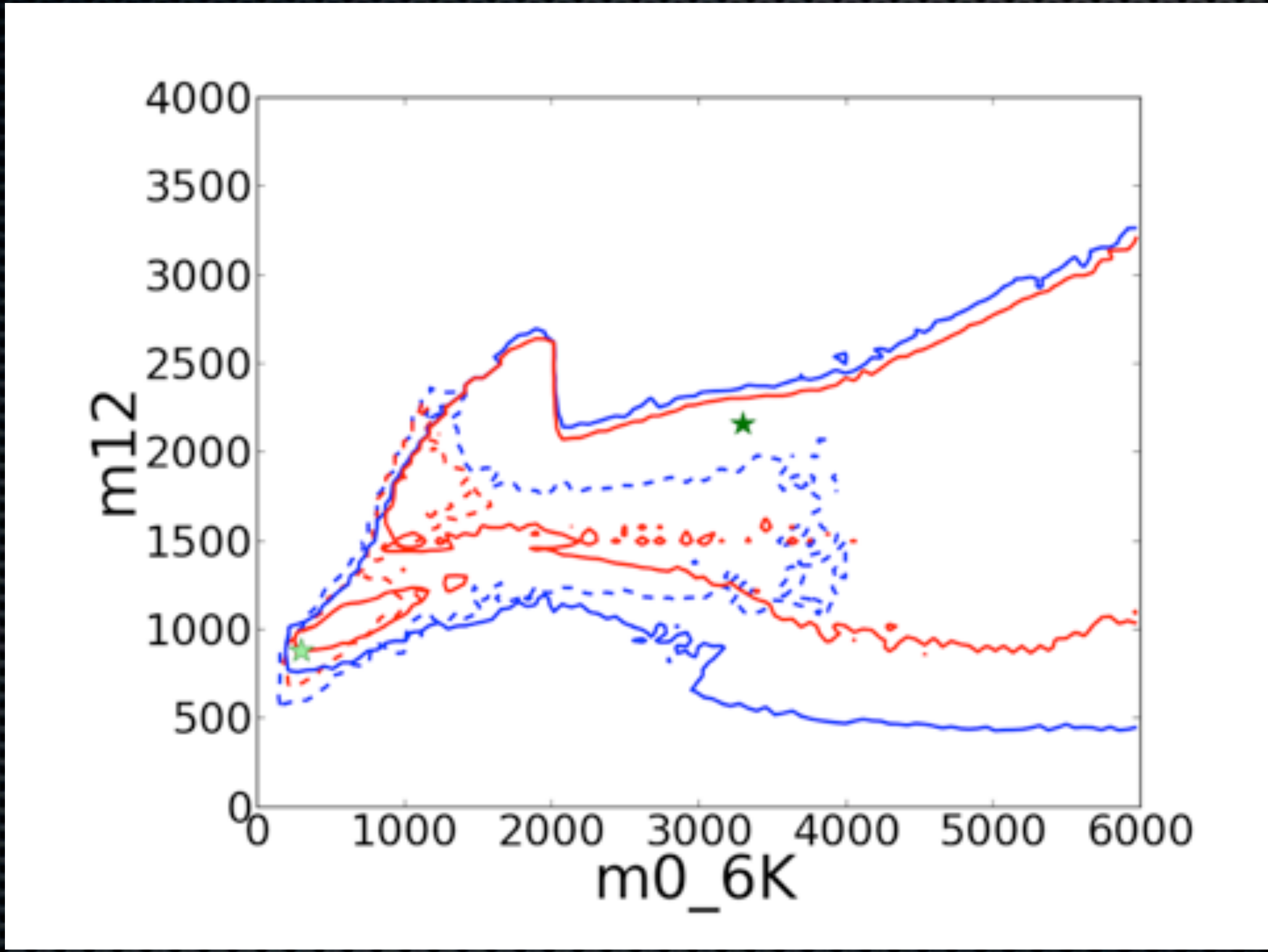
- MCMC technique to sample efficiently the SUSY parameter space, and thereby construct the χ^2 probability function
- Combines SoftSusy, FeynHiggs, SuperFla, SuperIso, MicrOmegas, and SSARD
- Purely frequentist approach (no priors) and relies only on the value of χ^2 at the point sampled and not on the distribution of sampled points.
- 12 million points sampled (CMSSM)

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2}$$
$$+ \chi^2(M_h) + \chi^2(\mathrm{BR}(B_s \to \mu\mu))$$
$$+ \chi^2(\mathrm{SUSY\ search\ limits})$$
$$+ \sum_i^M \frac{(f_{\mathrm{SM}_i}^{\mathrm{obs}} - f_{\mathrm{SM}_i}^{\mathrm{fit}})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

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

Preliminary

Comparison of best fit points pre and post LHC

Model	Data set	Minimum χ^2/d.o.f.	Probability	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$
CMSSM	ATLAS 7 TeV	32.6/23	8.8%	340	910	2670	12
$\mu > 0$	$\text{ATLAS}_{20/\text{fb}}$ (low)	35.6/23	4.5%	710	1070	3580	21
	$\text{ATLAS}_{20/\text{fb}}$ (high)	34.9/23	5.3%	3310	2180	-1490	51
CMSSM	$\text{ATLAS}_{20/\text{fb}}$ (low)	37.8/23	2.7%	2100	660	4930	11
$\mu < 0$	$\text{ATLAS}_{20/\text{fb}}$ (high)	36.9/23	3.3%	6490	2430	-3300	36
NUHM1	ATLAS 7 TeV	30.4/22	10.9%	360	1080	4990	9
$\mu > 0$	$\text{ATLAS}_{20/\text{fb}}$ (low)	33.1/22	6.0%	470	1270	5700	11
	$\text{ATLAS}_{20/\text{fb}}$ (high)	32.7/22	6.6%	1380	3420	-3140	39
"SM"	$\text{ATLAS}_{20/\text{fb}}$ (high)	36.5/24	5.0%	-	-	-	-

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

Effective four-fermion Lagrangian

$$\mathcal{L} = \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}_i\gamma_\mu(\alpha_{1i} + \alpha_{2i}\gamma^5)q_i + \alpha_{3i}\bar{\chi}\chi\bar{q}_i q_i$$

$$+ \alpha_{4i}\bar{\chi}\gamma^5\chi\bar{q}_i\gamma^5 q_i + \alpha_{5i}\bar{\chi}\chi\bar{q}_i\gamma^5 q_i + \alpha_{6i}\bar{\chi}\gamma^5\chi\bar{q}_i q_i$$

The terms proportional to α_1, α_4, α_5, α_6,
lead to velocity-dependent cross sections

Remaining terms:

α_2: Spin-dependent cross section
α_3: Spin-independent cross section

Uncertainties from hadronic matrix elements

The scalar cross section

$$\sigma_3 = \frac{4m_r^2}{\pi}\left[Z f_p + (A-Z) f_n\right]^2$$

where

$$\frac{f_p}{m_p} = \sum_{q=u,d,s} f_{Tq}^{(p)} \frac{\alpha_{3q}}{m_q} + \frac{2}{27} f_{TG}^{(p)} \sum_{c,b,t} \frac{\alpha_{3q}}{m_q}$$

and

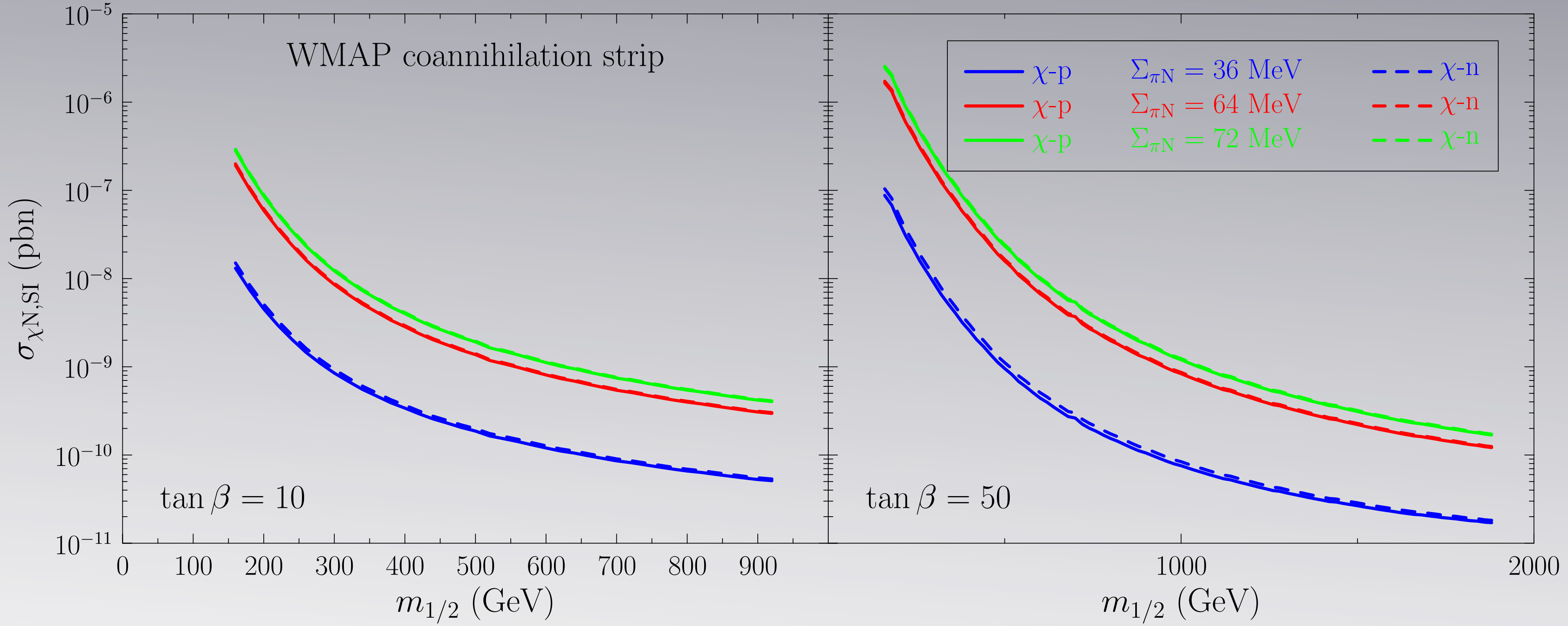
$$m_N f_{T_q}^{(N)} \equiv \langle N | m_q \bar{q} q | N \rangle \,,$$

determined by

$$f_{T_{u,d}} \propto \Sigma_{\pi N} \qquad f_{T_s} \propto \Sigma_{\pi N}\, y \qquad y = 1 - \sigma_0/\Sigma_{\pi N}$$

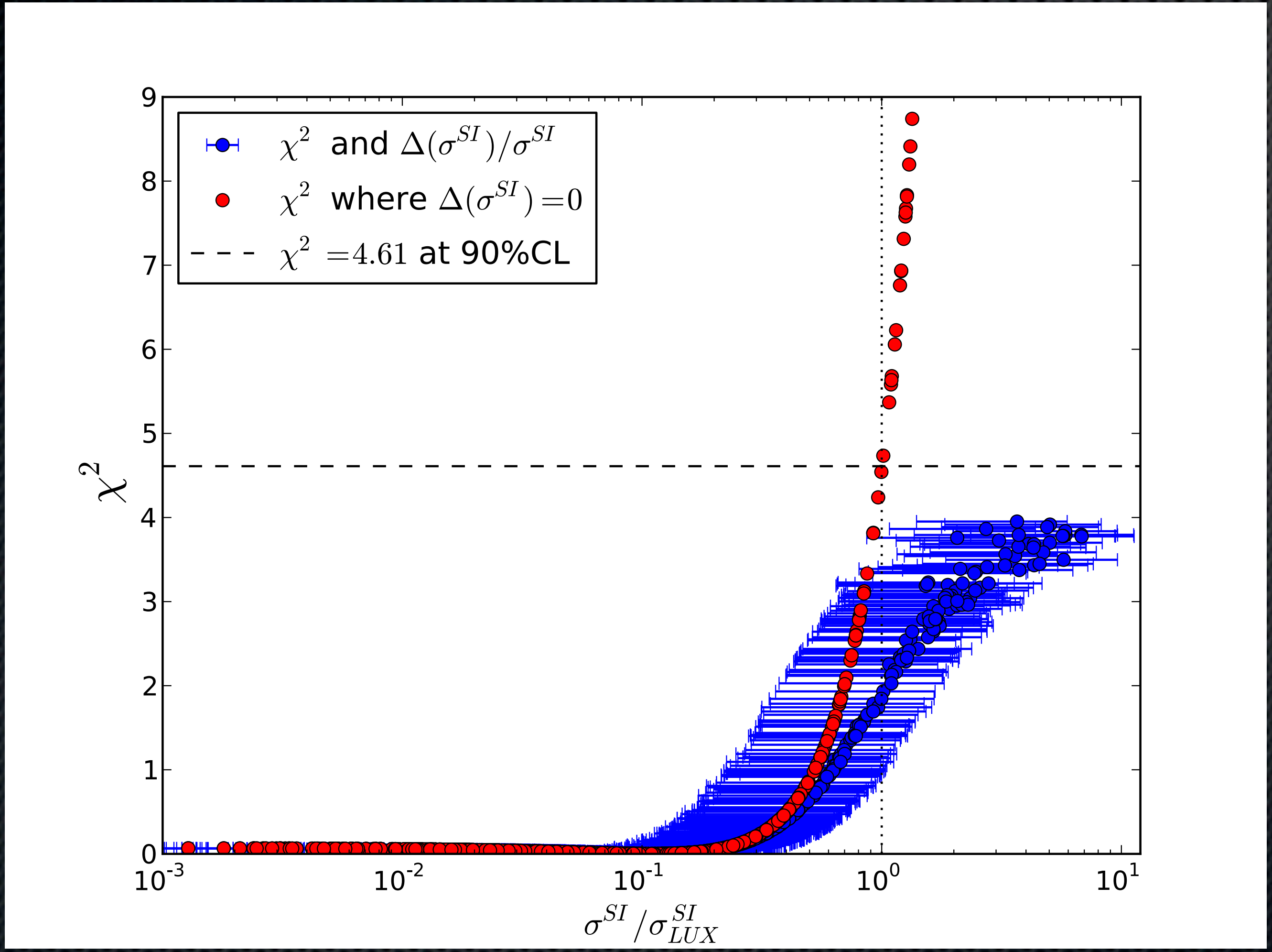
$$\Sigma_{\pi N} = 50 \pm 7 \text{ MeV} \qquad \sigma_0 = 36 \pm 7 \text{MeV}$$

Uncertainties due to $\Sigma_{\pi N}$



Ellis, Olive, and Savage

Elastic cross sections



Preliminary

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

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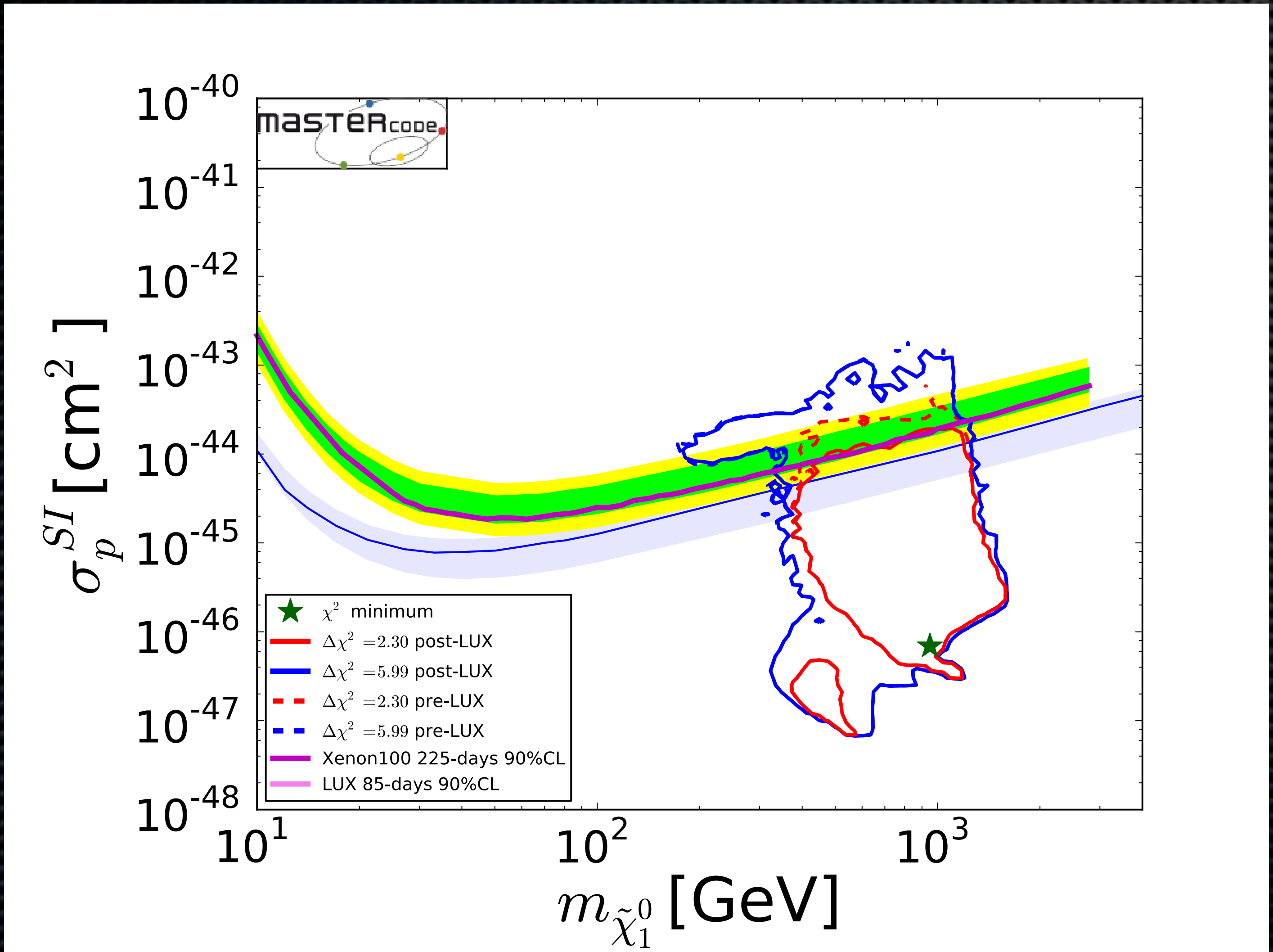

Preliminary

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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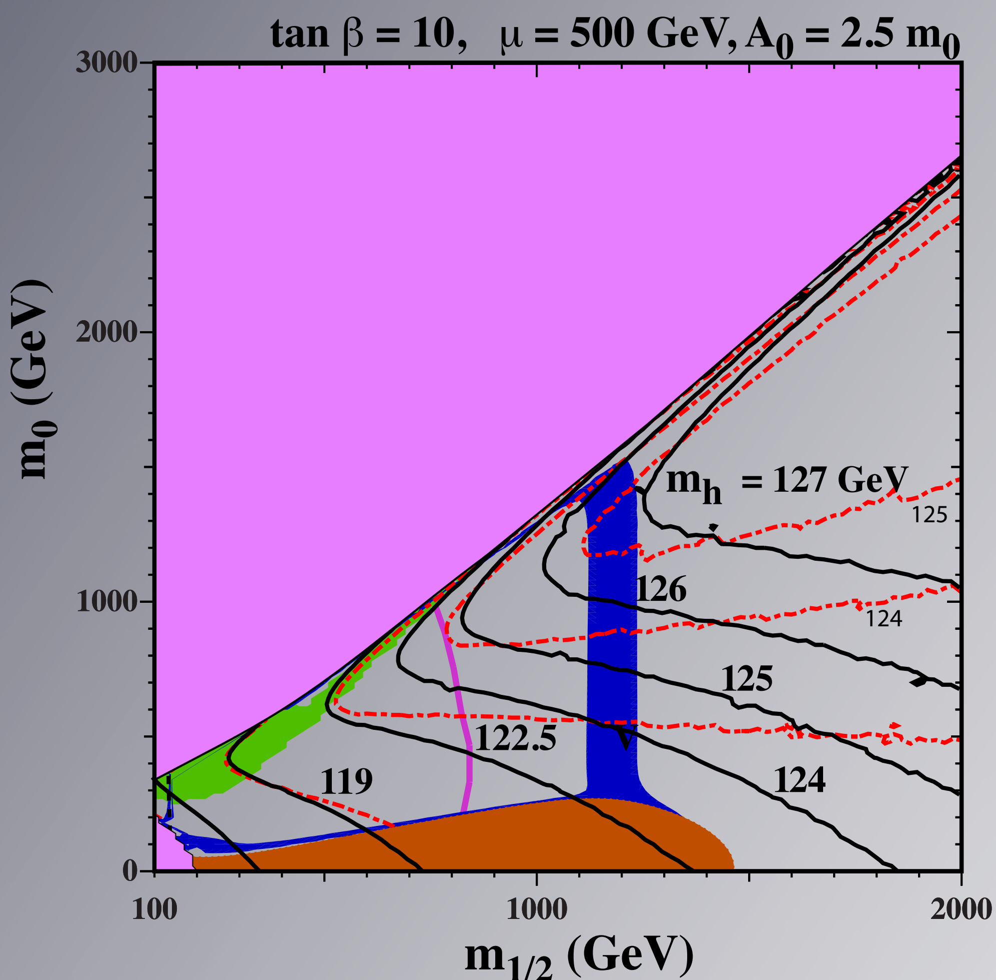
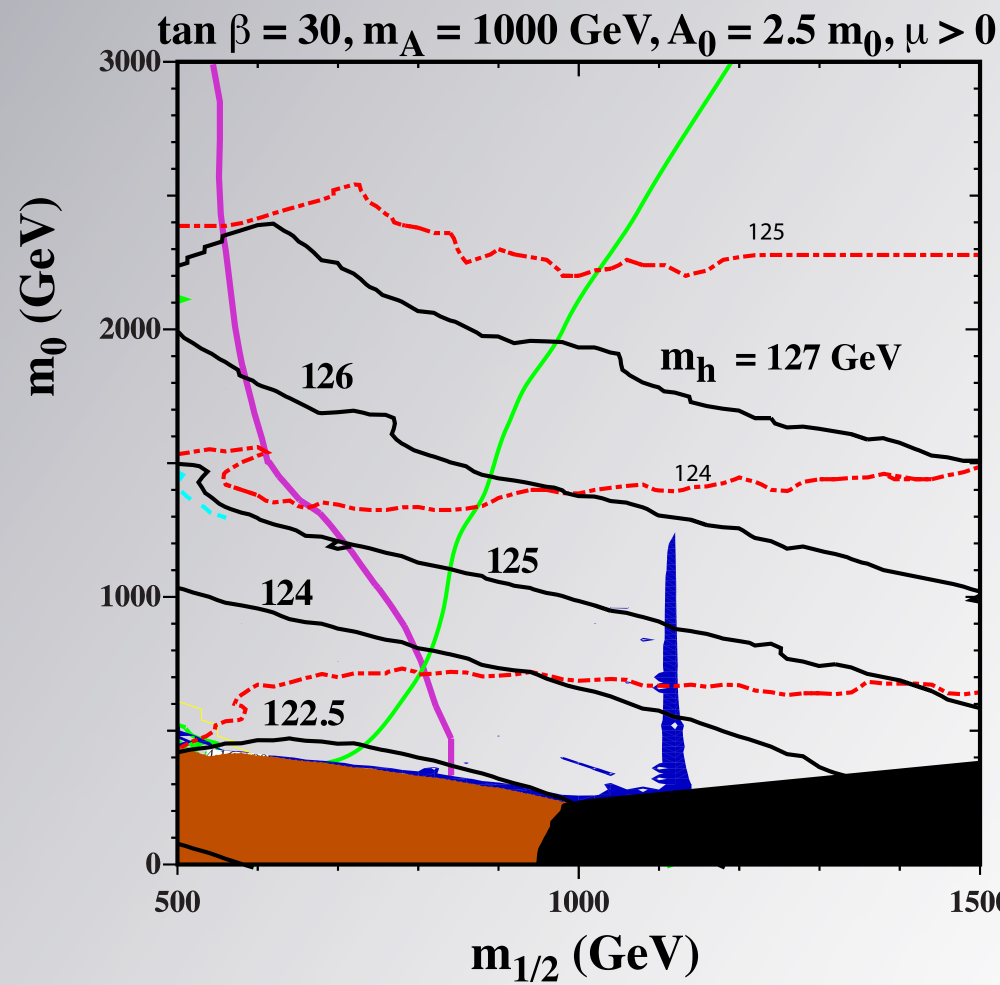
Other Possibilities

- 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

Buchmueller, Dolan, Ellis, Hahn, Heinemeyer, Hollik, Marrouche, Olive, Rzehak, de Vries, Weiglein

Moving beyond the CMSSM-like models

Moving beyond the CMSSM-like models

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

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gaugino masses $\quad$ 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

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

- ⇒ Push towards very large masses

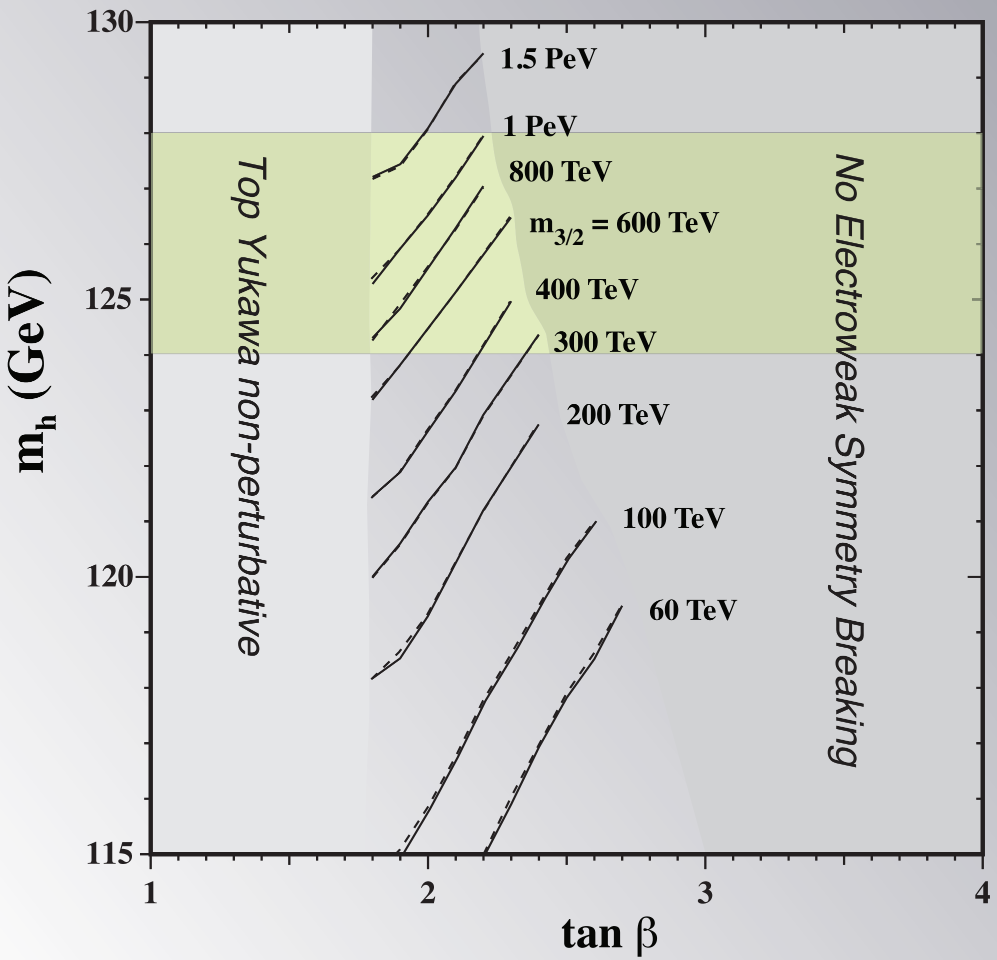
Evans, Ibe, Olive, Yanagida

Pure Gravity Mediation

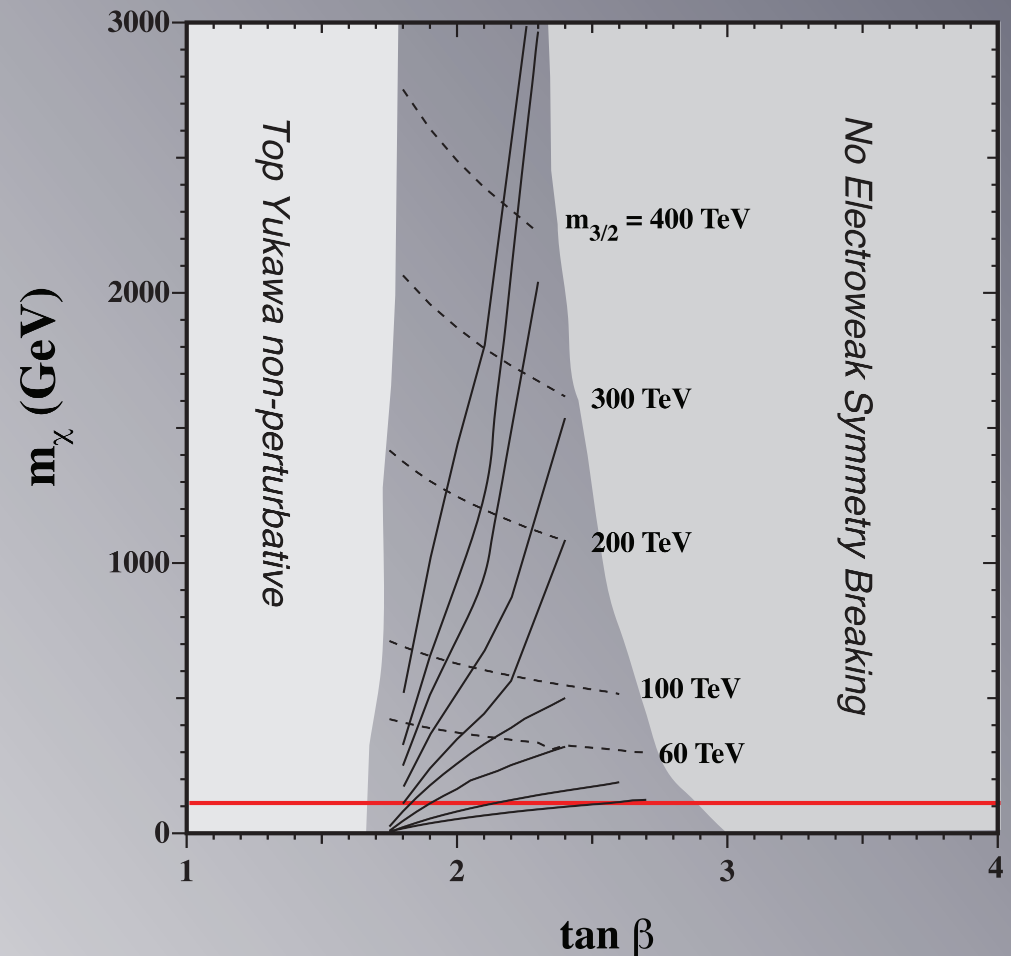
- The sfermion and gravitino have masses O(100) TeV.
- The higgsino and the heavier Higgs boson also have masses O(100) TeV.
- The gaugino masses are in the range of hundreds to thousands of GeV.
- The LSP is the neutral wino which is nearly degenerate with the charged wino.
- The lightest Higgs boson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

Phenomenological Aspects

Higgs Mass

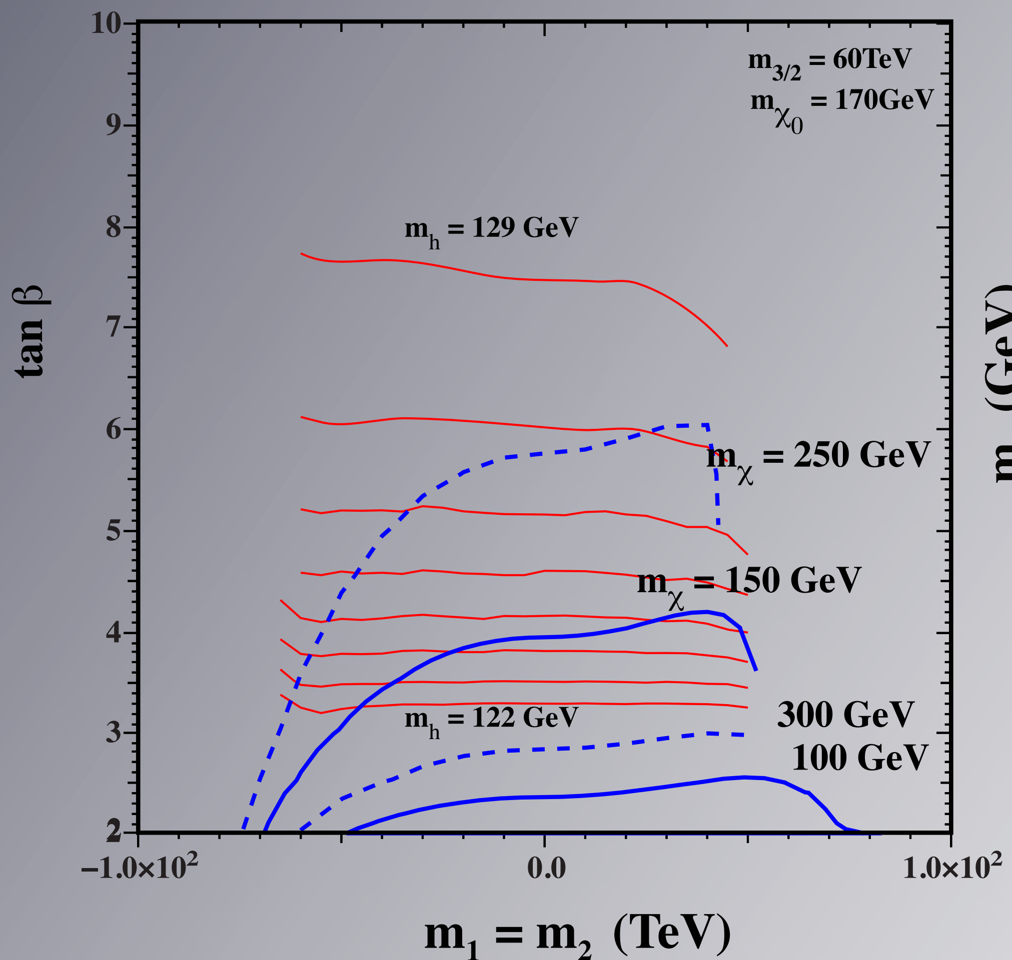


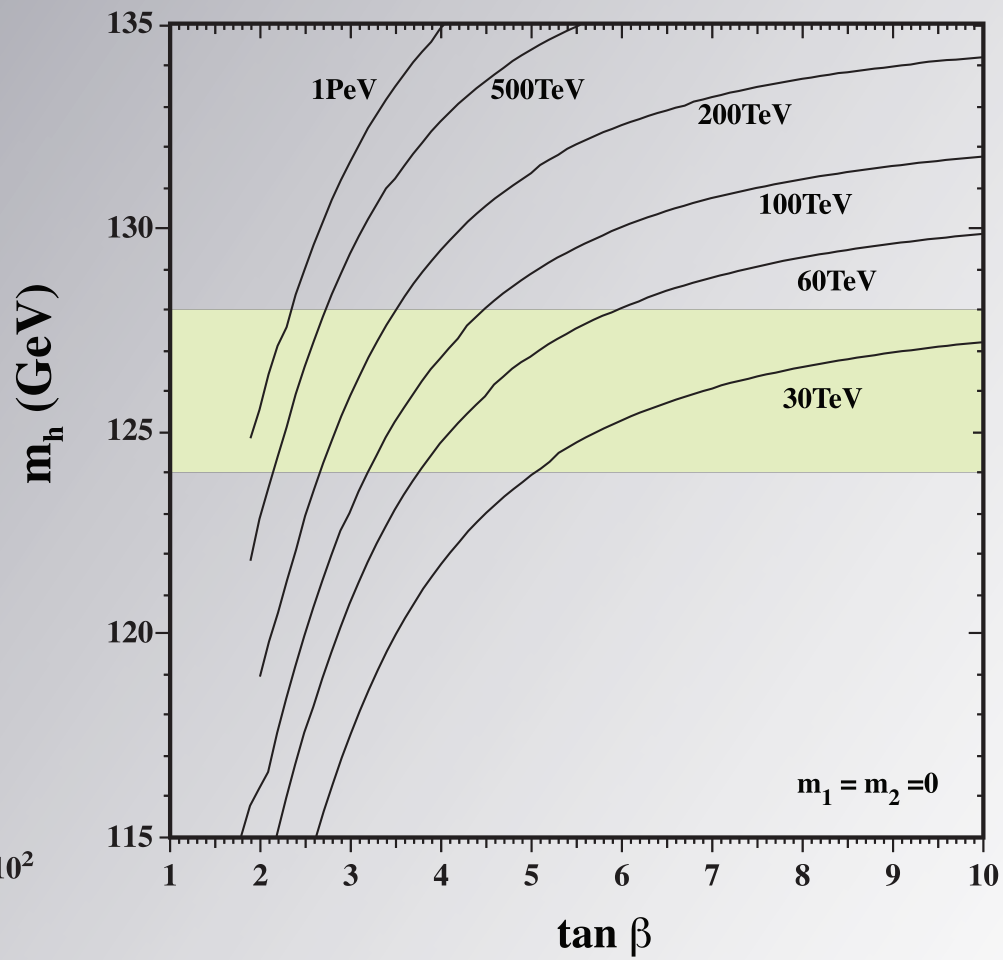
Neutralino mass



Evans, Ibe, Olive, Yanagida

Somewhat more freedom with non-universal Higgs masses

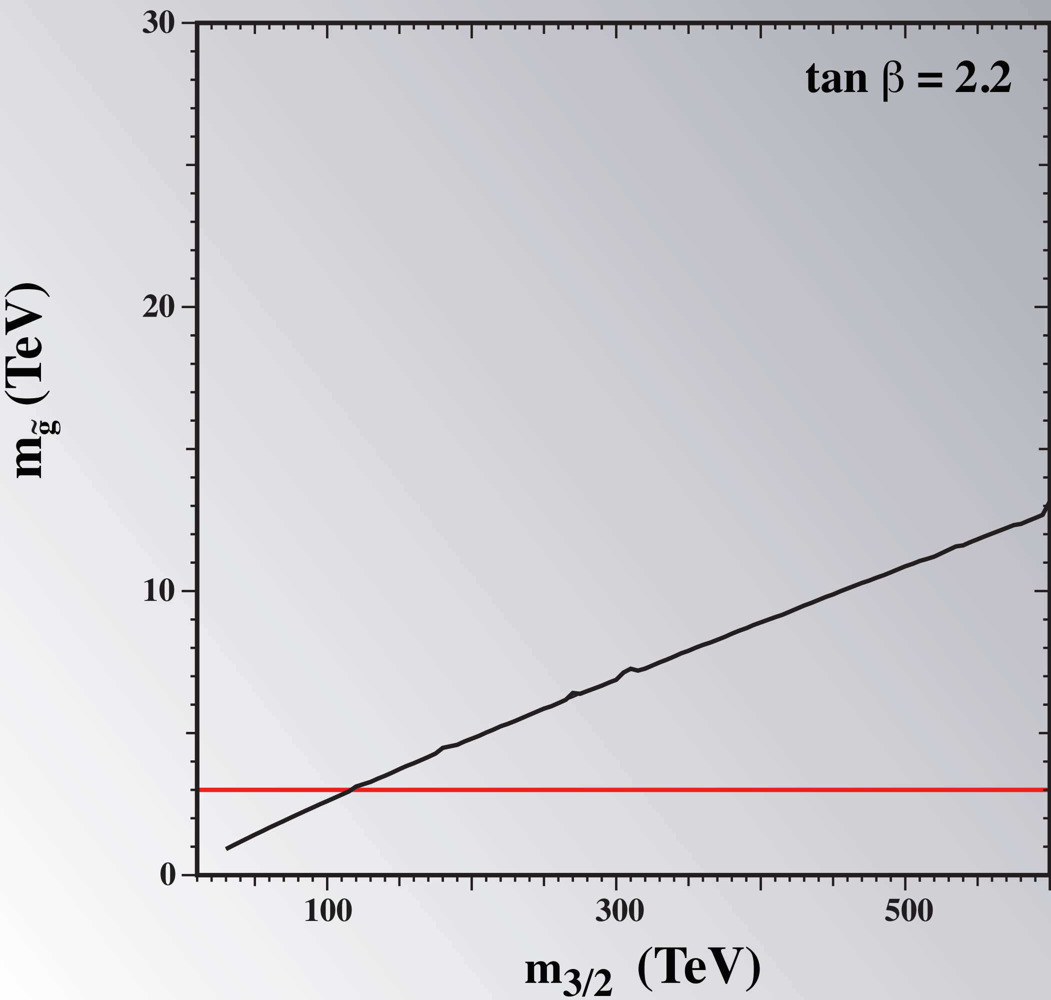




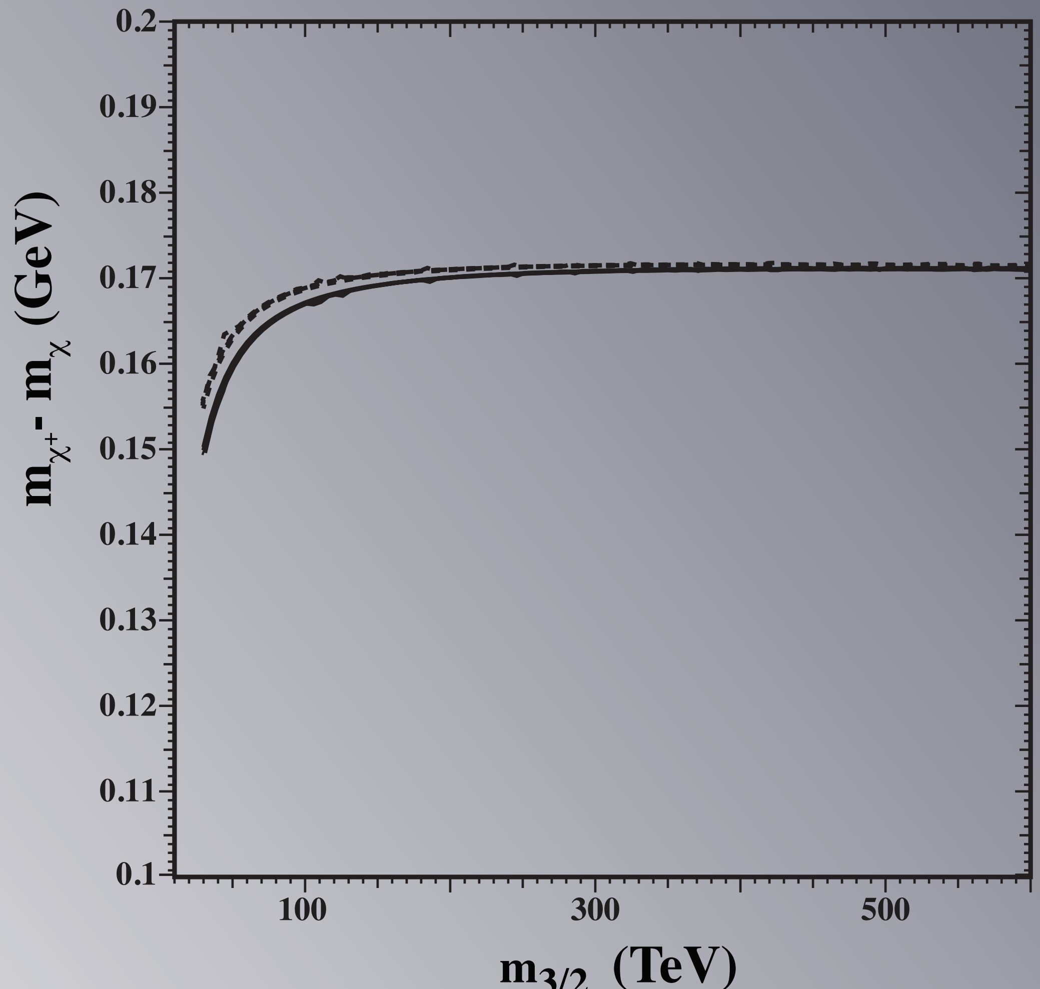
Evans, Ibe, Olive, Yanagida

Phenomenological Aspects

gluino Mass



chargino mass



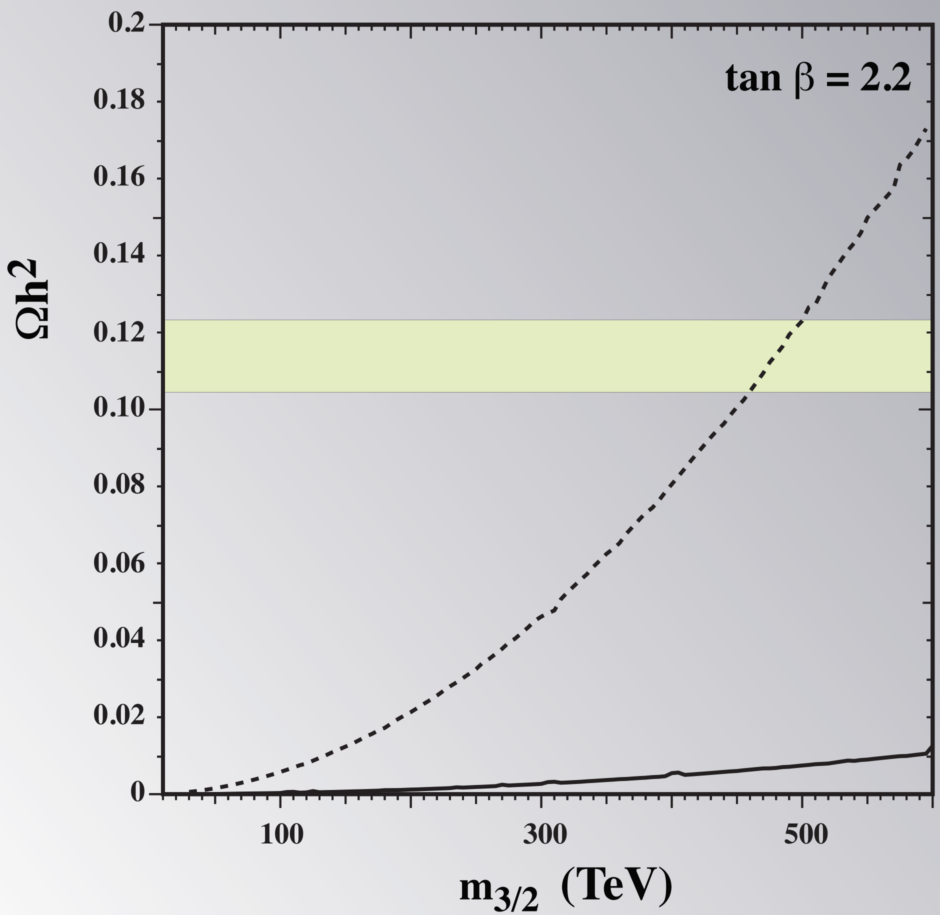
Dark Matter

- 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