# The status of Supersymmetric Dark Matter after LHC Run I and alternatives from Grand Unification

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1) After the results of Run I, can we still ‘guarantee’ Supersymmetry’s discovery at the LHC?
   Viable dark matter models in CMSSM-like tend to lie in strips (co-annihilation, funnel, focus point).
   How far up in energy do these strips extend?

# The status of Supersymmetric Dark Matter after LHC Run I and alternatives from Grand Unification

1) After the results of Run I, can we still ‘guarantee’ Supersymmetry’s discovery at the LHC?
   Viable dark matter models in CMSSM-like tend to lie in strips (co-annihilation, funnel, focus point).
   How far up in energy do these strips extend?

2) Can Non-Supersymmetric GUTs such as SO(10) provide an alternative?

# Why Supersymmetry?

- Gauge Hierarchy Problem
- Gauge Coupling Unification
- Stabilization of the Electroweak Vacuum
- Radiative Electroweak Symmetry Breaking
- Dark Matter
- Improvement to low energy phenomenology?

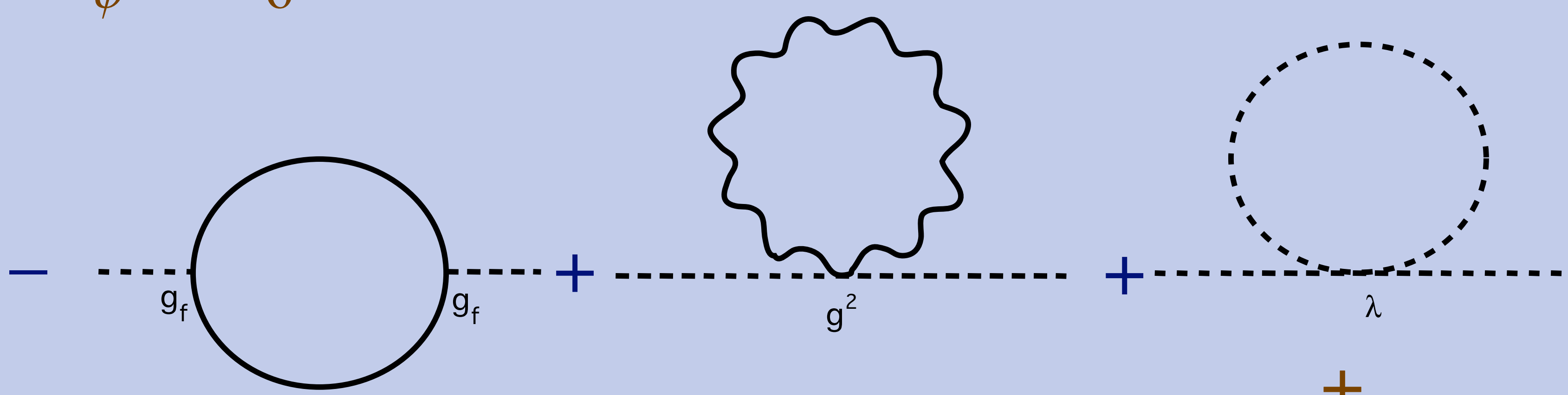
but, $m_h \sim 125$ GeV, and no SUSY?

# *Gauge Hierarchy Problem*

$$\delta m_H^2 \simeq O(\frac{\alpha}{4\pi})(\Lambda^2 + m_B^2) - O(\frac{\alpha}{4\pi})(\Lambda^2 + m_F^2) = O(\frac{\alpha}{4\pi})(m_B^2 - m_F^2)$$

Scalar masses corrected by loops

$m_\phi{}^2 = m_o{}^2 +$




$+ \ldots.$

$= m_o{}^2$

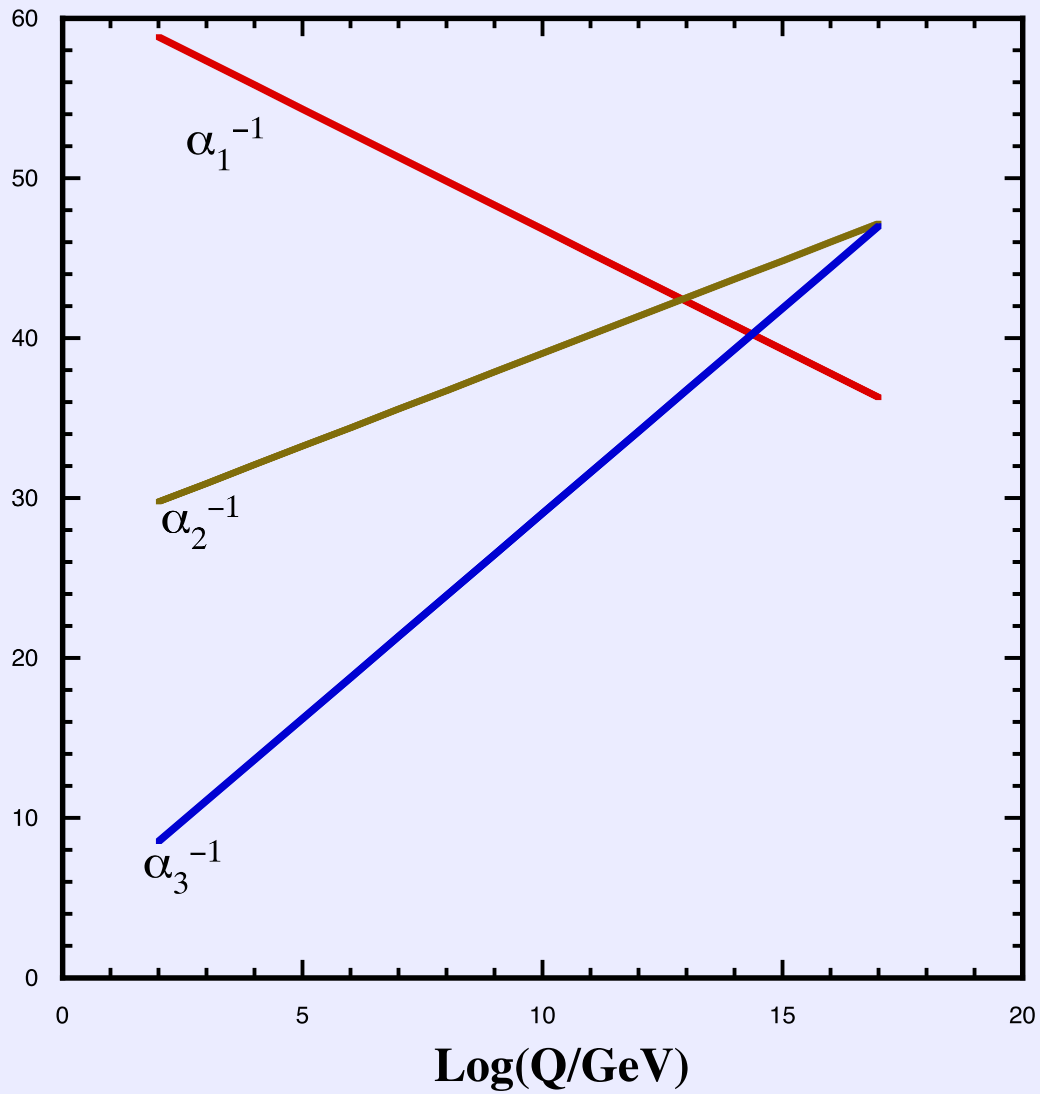
Set it and Forget it!

$$|m_B^2 - m_F^2| \lesssim 1 \text{ TeV}^2$$

GUTS

# SU(5) Grand Unified Theory

$$b_i = \begin{pmatrix} 41/10 \\ -19/6 \\ -7 \end{pmatrix}$$

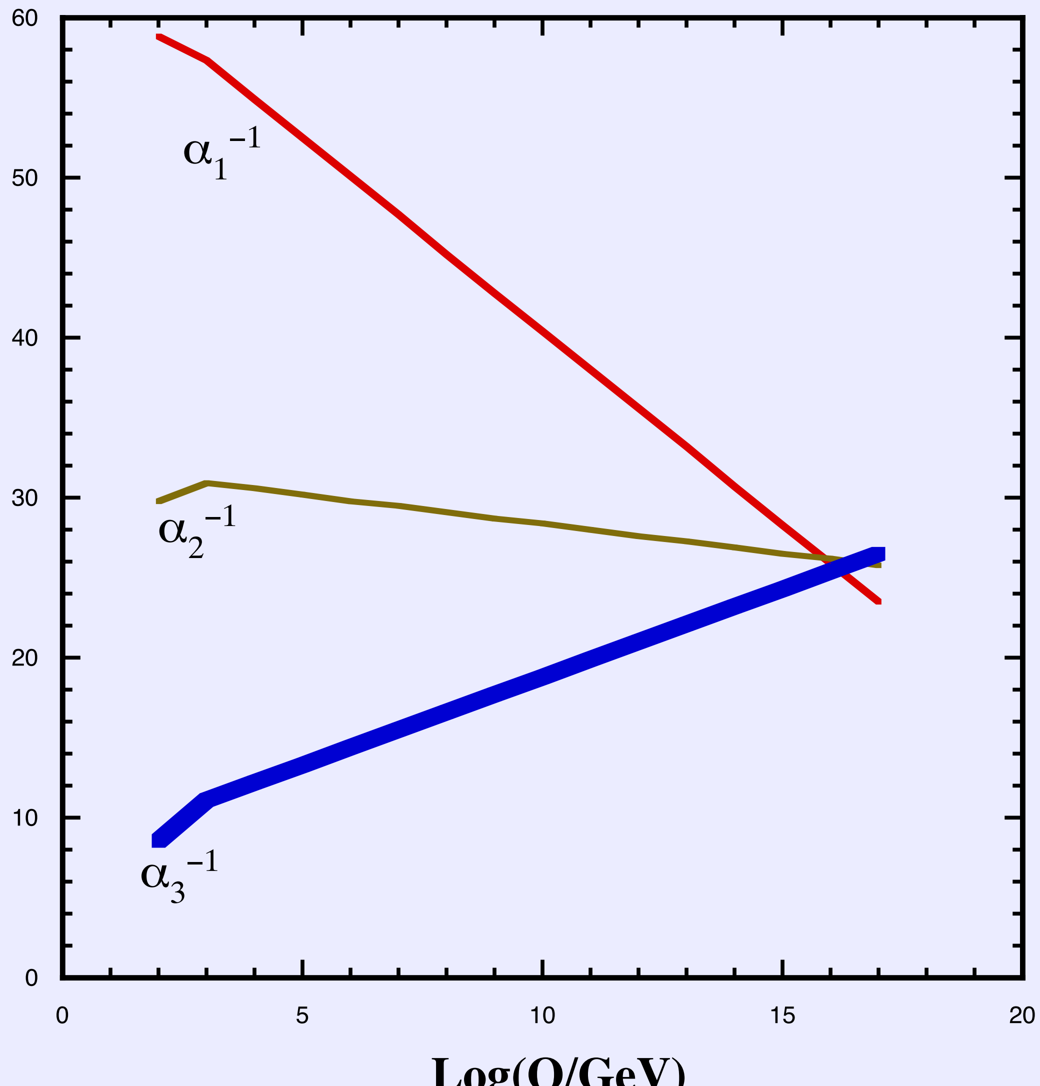


GUTS

# Supersymmetric SU(5) Grand Unified Theory

$$b_i = \begin{pmatrix} 33/5 \\ 1 \\ -3 \end{pmatrix}$$

is now



GUTS

Standard Model Higgs potential

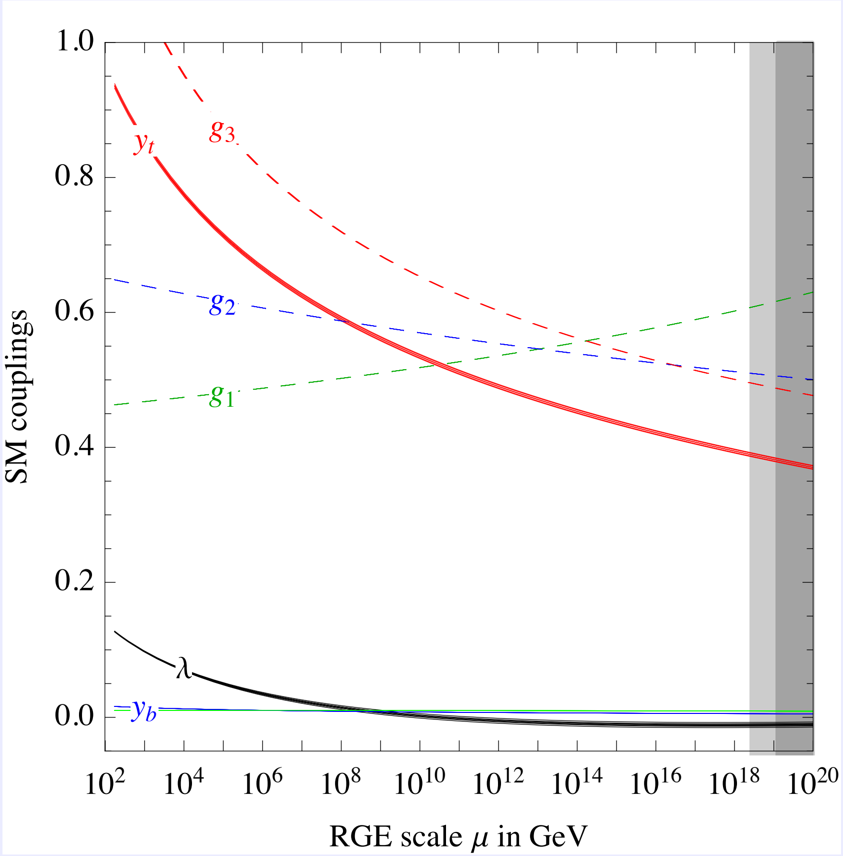
$$V = \frac{\lambda}{4}\phi^4 + \frac{m^2}{2}\phi^2$$

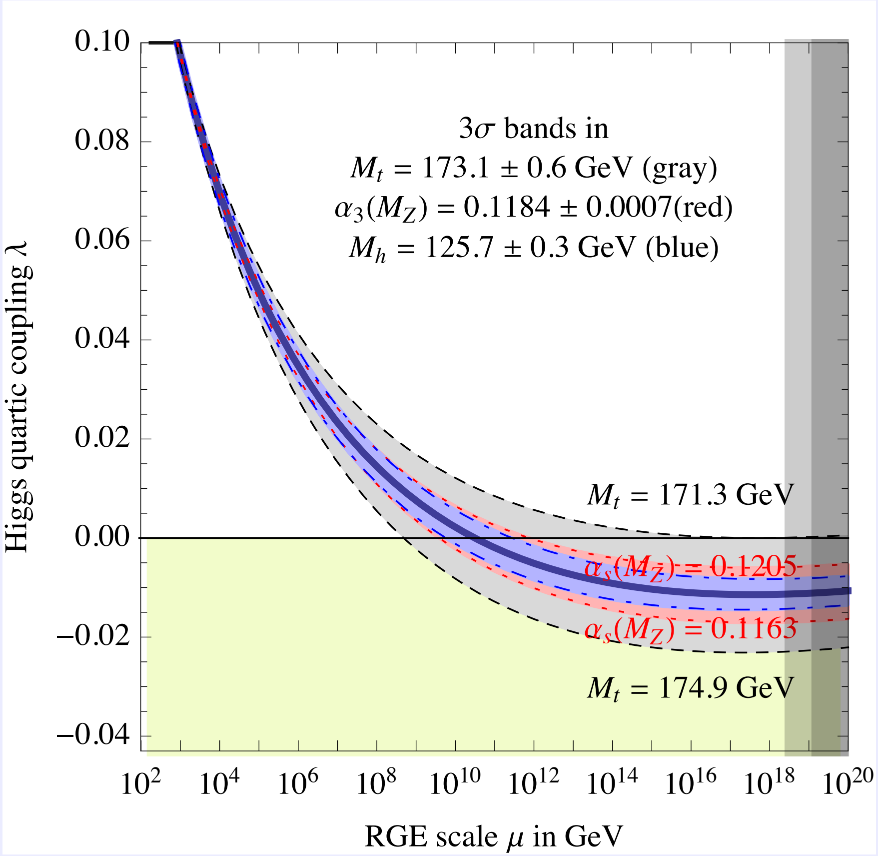
GUTS

# Standard Model Higgs potential

$$V = \frac{\lambda}{4}\phi^4 + \frac{m^2}{2}\phi^2$$

## Running of the Higgs quartic coupling




Degrassi et al.

SusyGUTS

Standard Model Higgs potential

$$V = \frac{\lambda}{4}\phi^4 + \frac{m^2}{2}\phi^2$$

$$\lambda = \frac{g_1^2 + g_2^2}{2}$$

Positive definite

Stability of the vacuum ensured

SusyGUTS

Standard Model Higgs potential

$$V = \frac{\lambda}{4}\phi^4 + \frac{m^2}{2}\phi^2$$

$$\lambda = \frac{g_1^2 + g_2^2}{2}$$

Positive definite

Stability of the vacuum ensured

Also for free: radiatively induced symmetry breaking

# What is the MSSM

1) Add minimal number of new particles:
Partners for all SM particles + 1 extra Higgs EW doublet.

2) Add minimal number of new interactions:
Impose R-parity to eliminate many UNWANTED interactions.

$$R = (-1)^{3B+L+2S}$$

# CMSSM Boundary Conditions

# CMSSM Boundary Conditions

- Gaugino mass Unification

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

# CMSSM Boundary Conditions

- Gaugino mass Unification
- A-term Unification

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

# CMSSM Boundary Conditions

- Gaugino mass Unification
- A-term Unification
- Scalar mass unification

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

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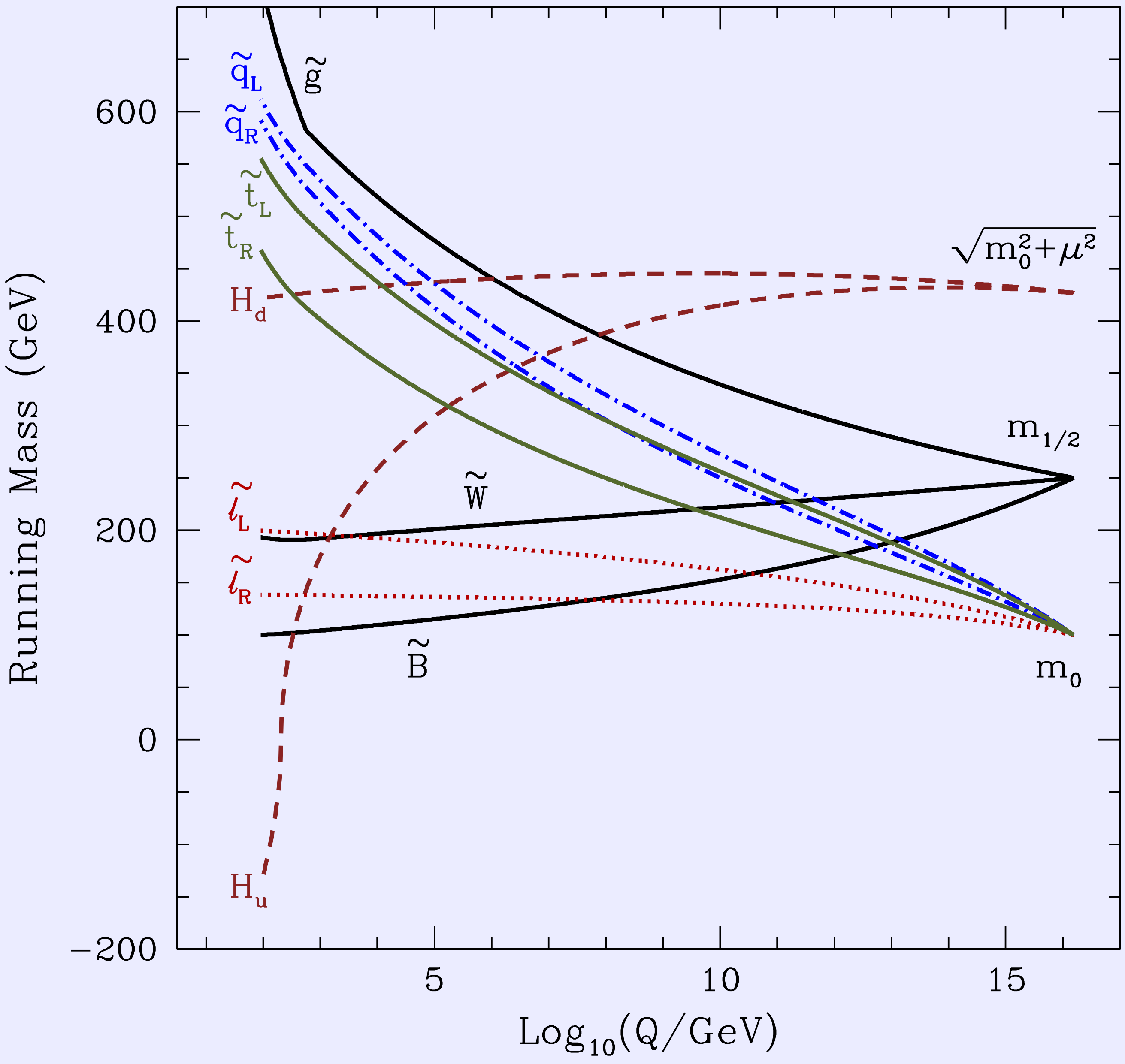
\end{aligned}
$$

$+ \tan\beta$

# CMSSM Spectra




Unification to rich spectrum

\+

EWSB

Falk

# SUSY Dark Matter

MSSM and R-Parity $\Longrightarrow$ Stable DM candidate

1) Neutralinos

$$\chi_i = \alpha_i \widetilde{B} + \beta_i \widetilde{W} + \gamma_i \widetilde{H}_1 + \delta_i \widetilde{H}_2$$

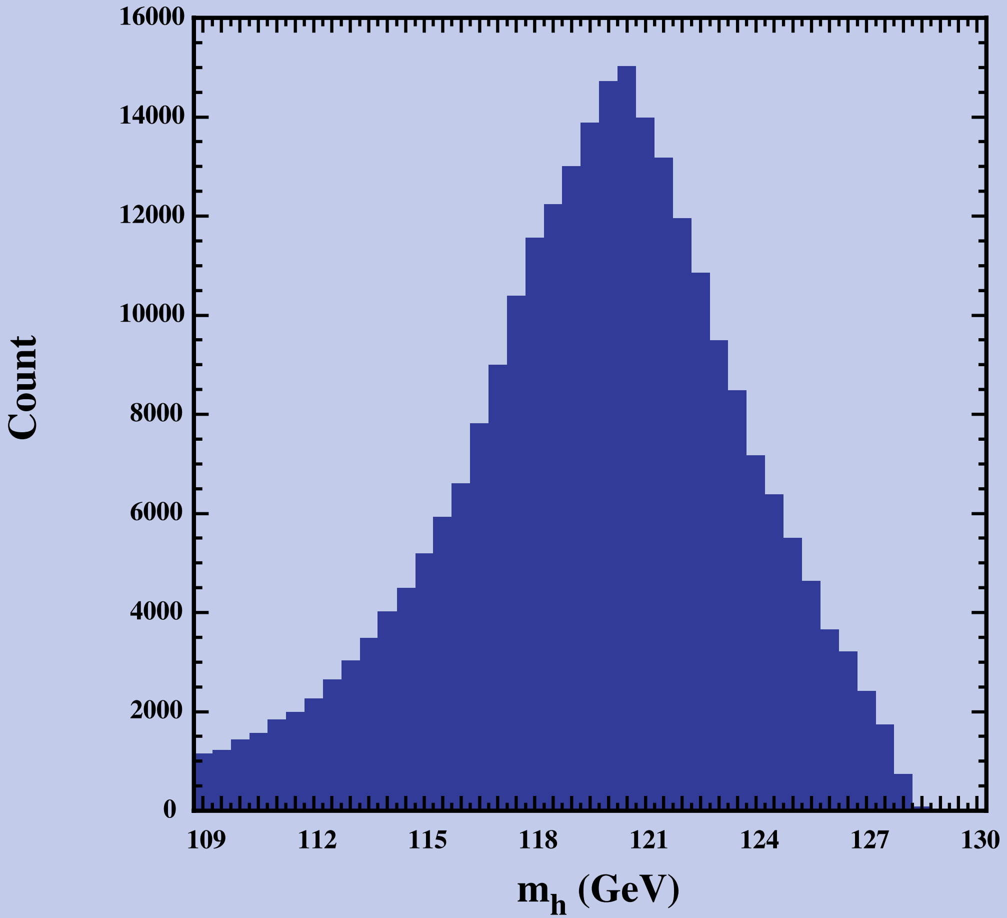
2) Sneutrino

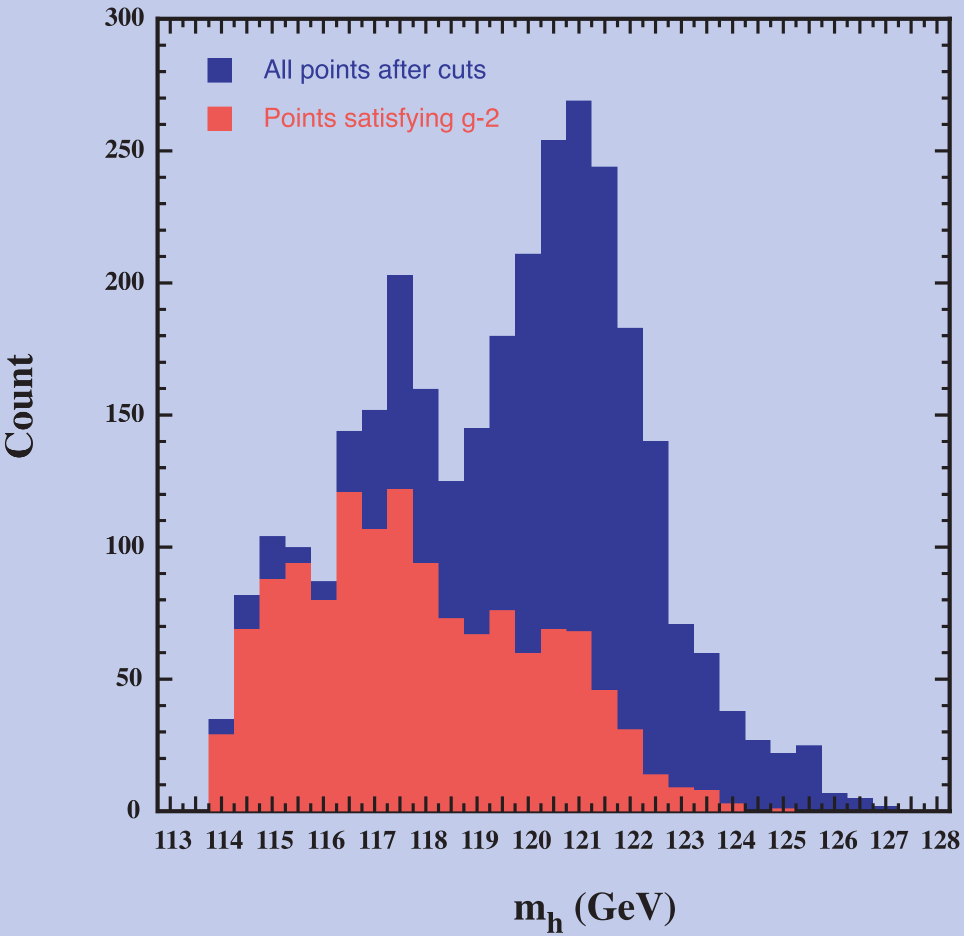
Excluded (unless add L-violating terms)

3) Other:

Axinos, Gravitinos, etc

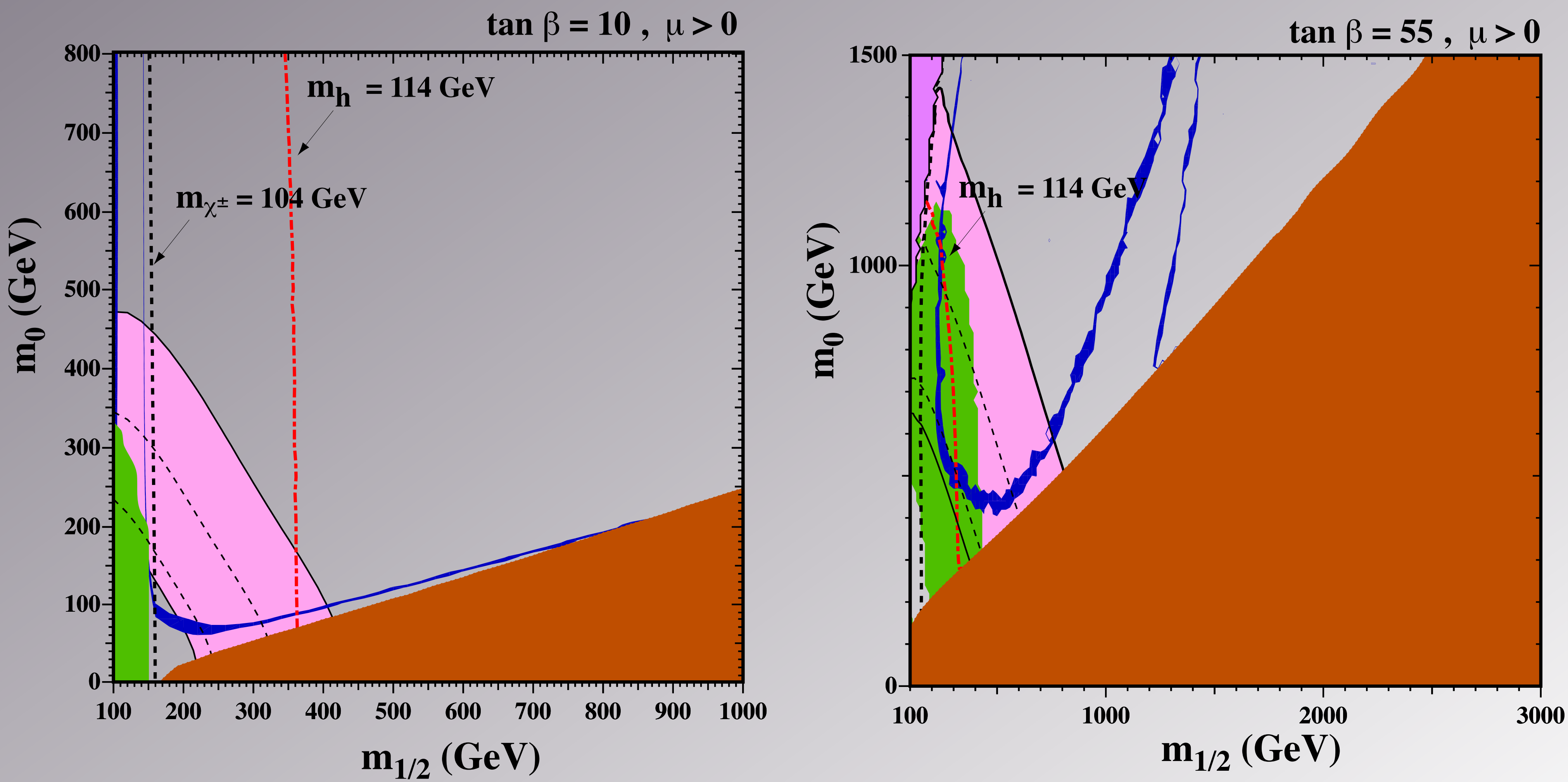
# The Higgs mass in the CMSSM




Ellis, Nanopoulos, Olive, Santoso

# The Pre-LHC CMSSM




Ellis, Olive, Santoso, Spanos

# Mastercode - MCMC

Long list of observables to constrain CMSSM parameter space

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

Multinest

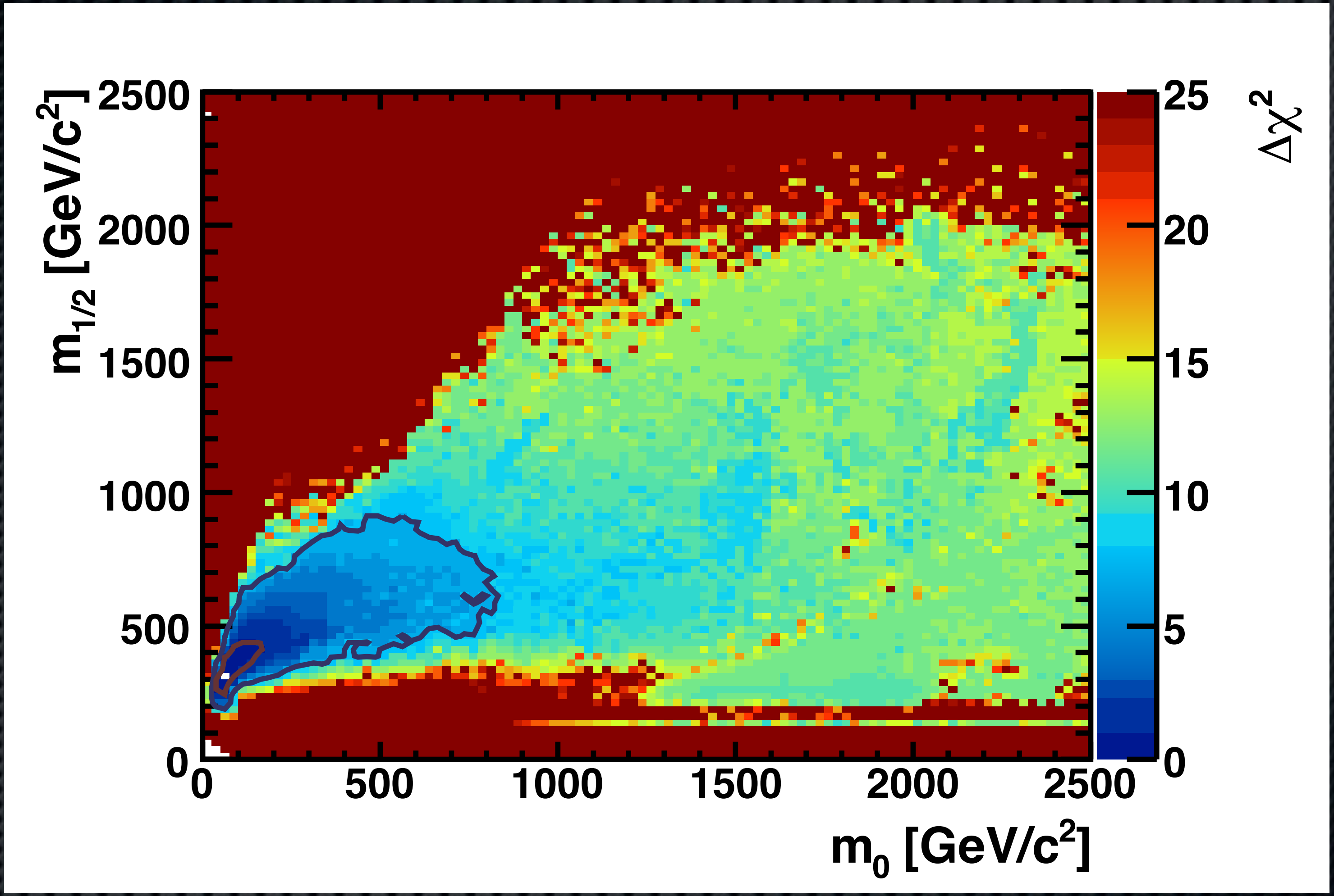
- ~~MCMC~~ technique to sample efficiently the SUSY parameter space, and thereby construct the $\chi^2$ probability function
- Combines SoftSusy, FeynHiggs, SuperFla, SuperIso, MicrOmegas, and SSARD
- Purely frequentist approach (no priors) and relies only on the value of $\chi^2$ at the point sampled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

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

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

Mastercode

2009

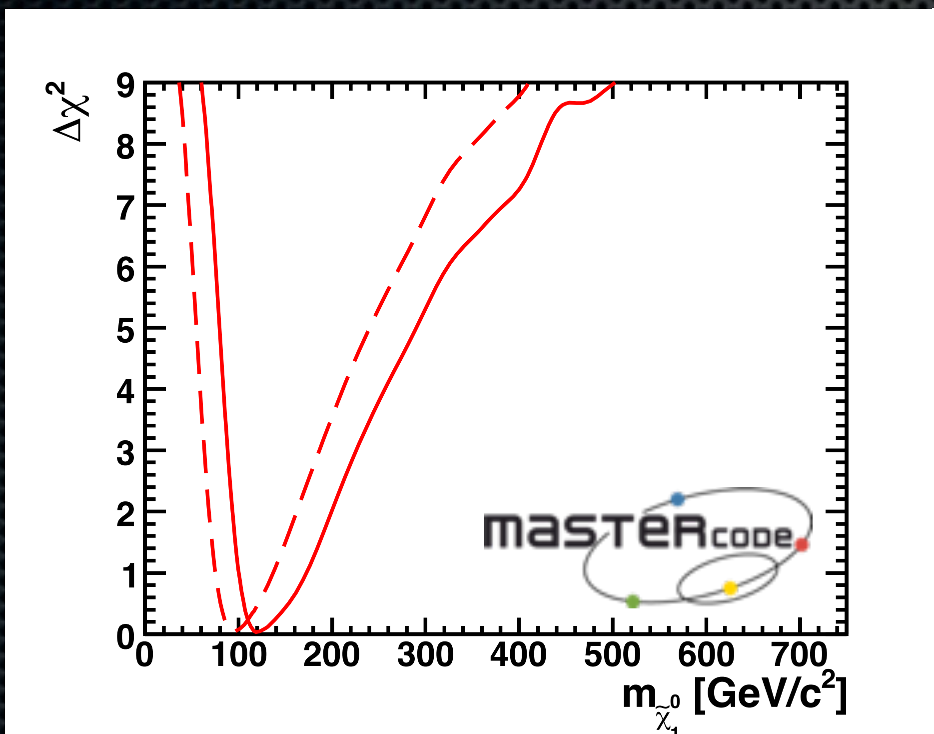


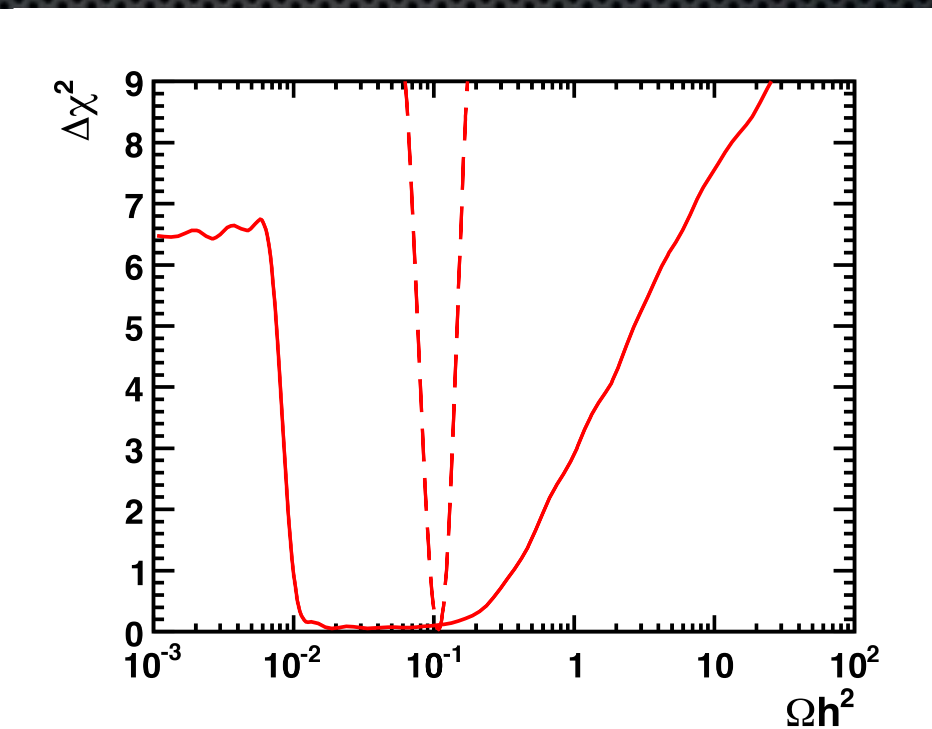

- CMSSM

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

# Neutralino mass and Relic Density from MCMC analysis

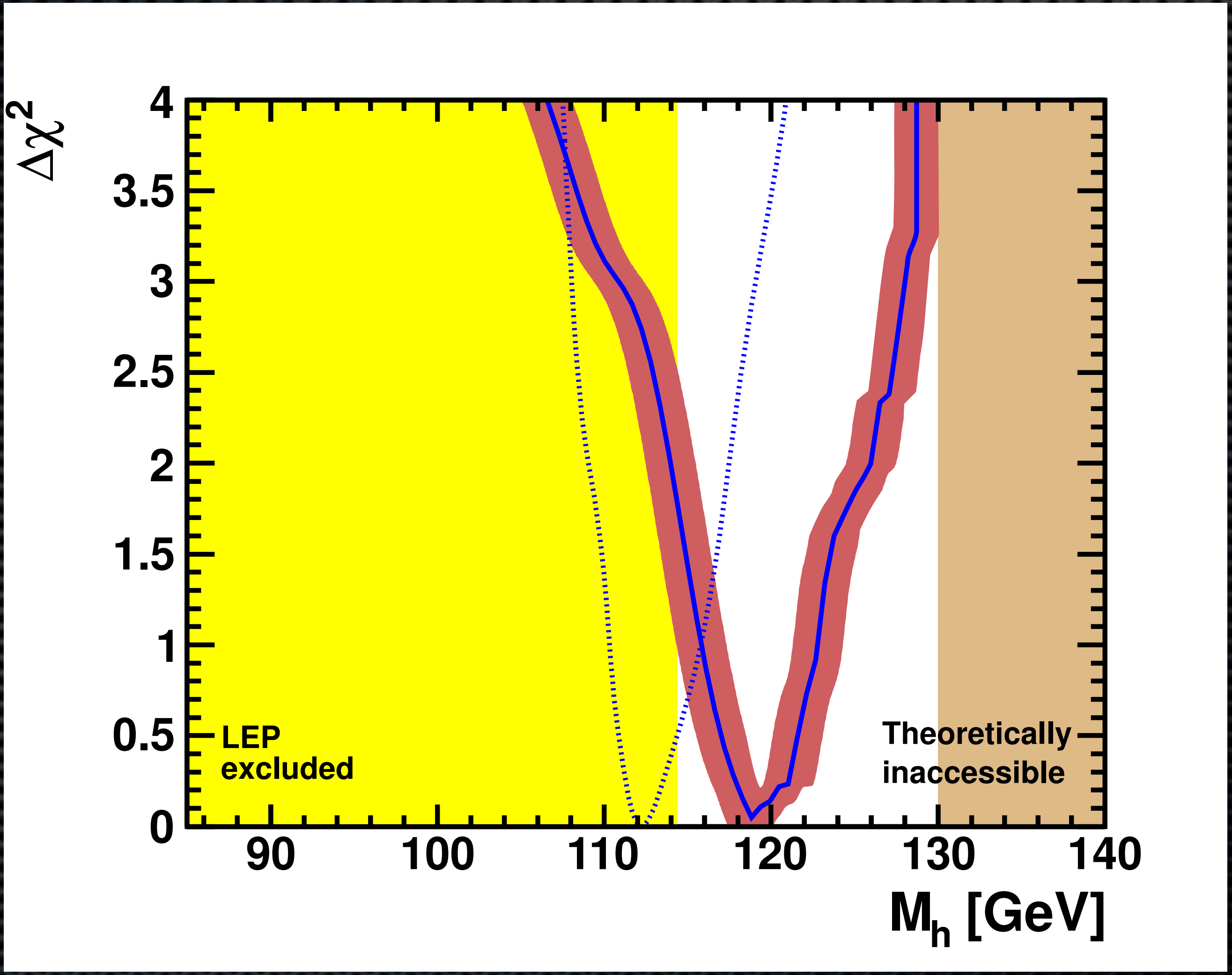
Mastercode



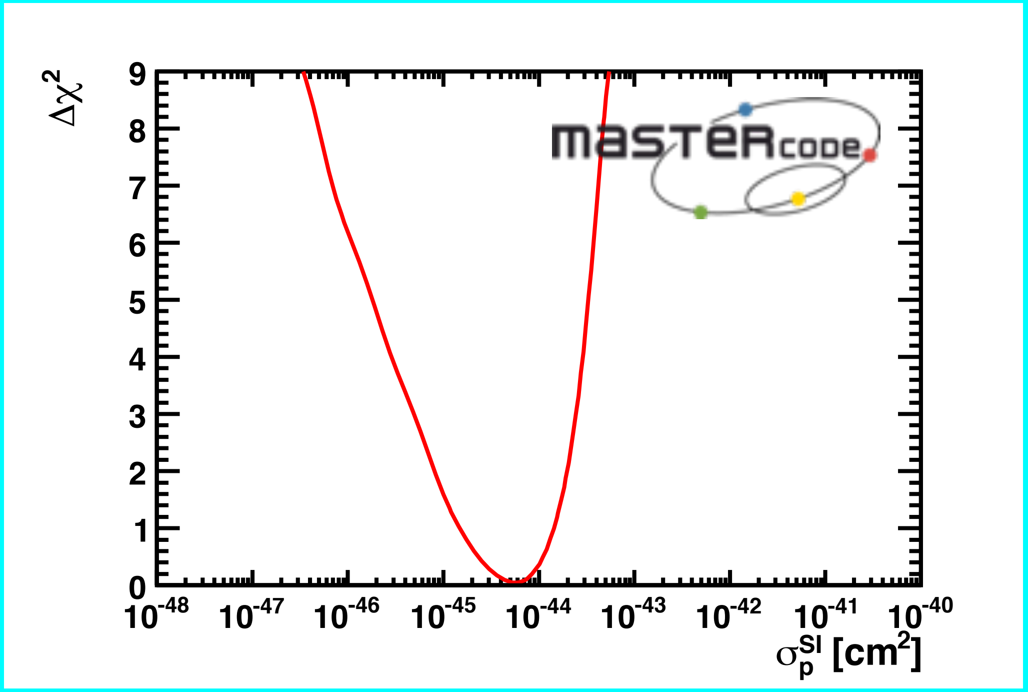

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein

# Pre-Higgs Predictions




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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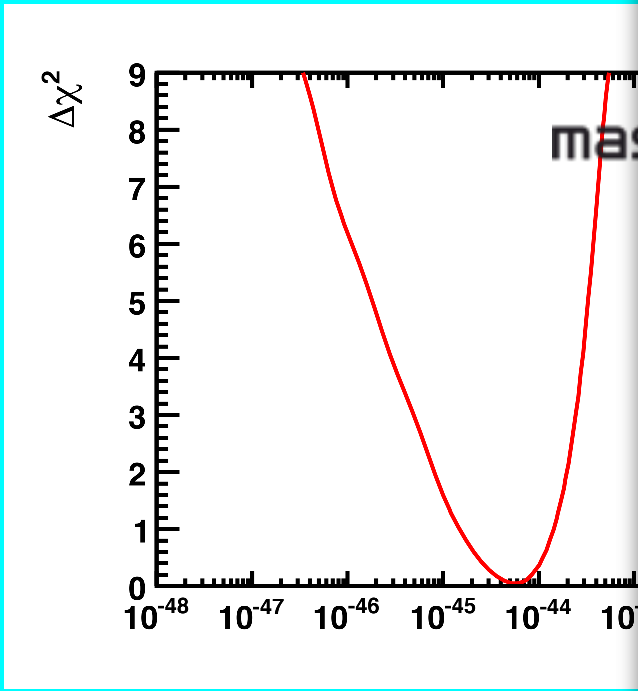
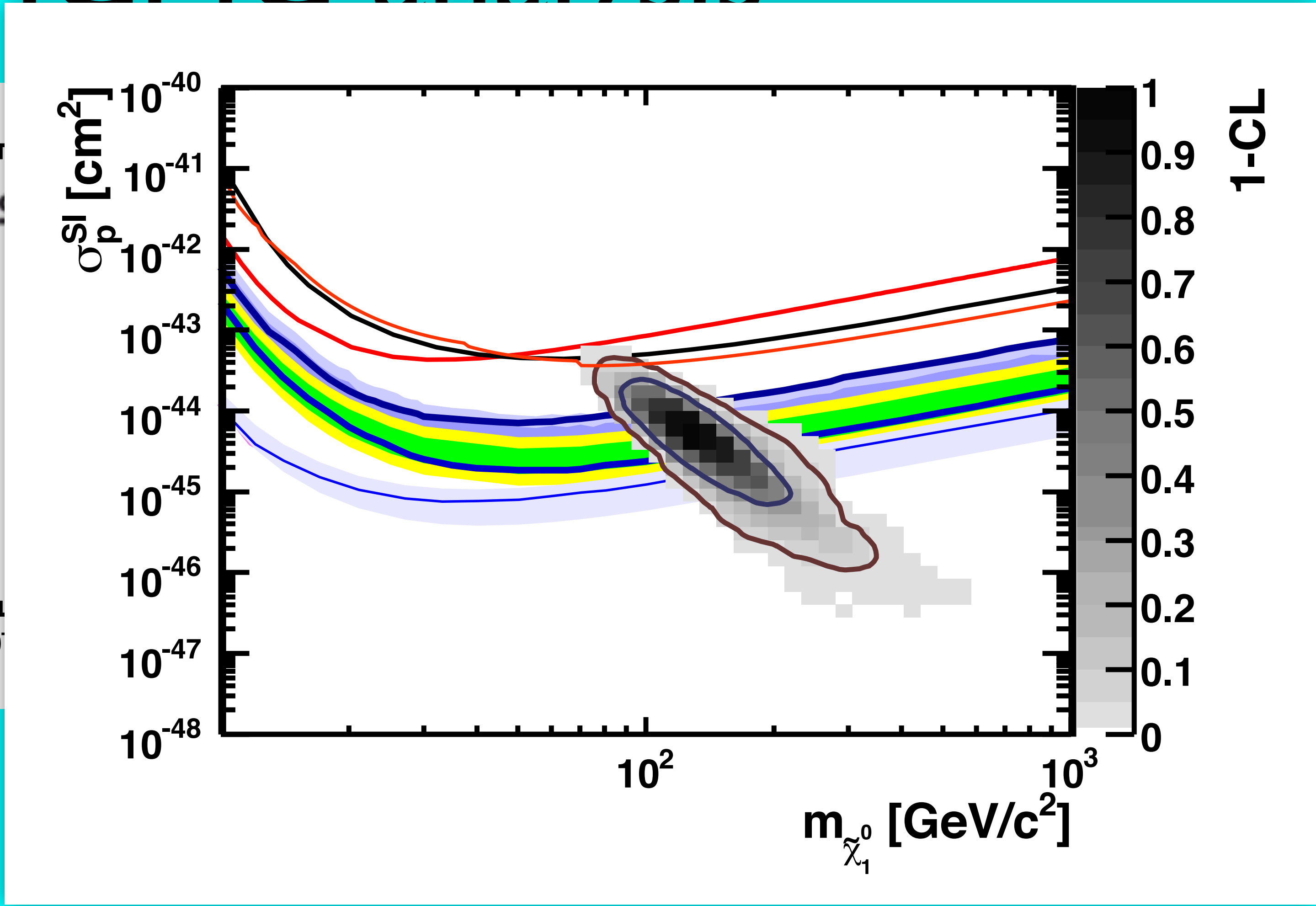


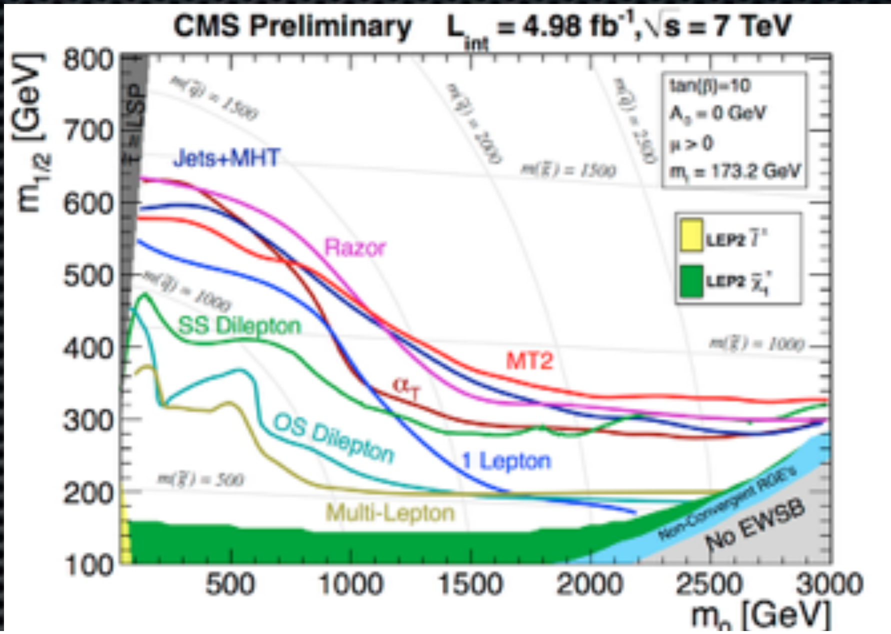

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Paradisi, Ronga, Weiglein

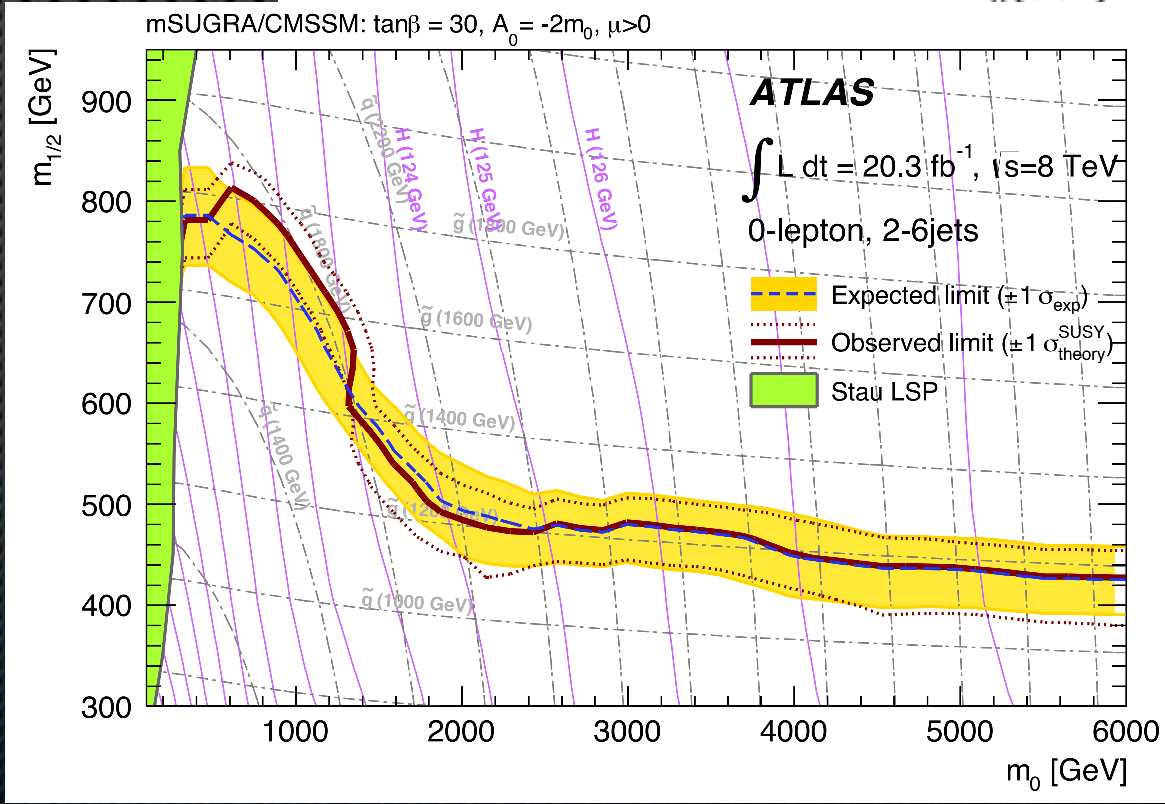
# Effect of Results from LHC

~5fb$^{-1}$ @ 7 TeV

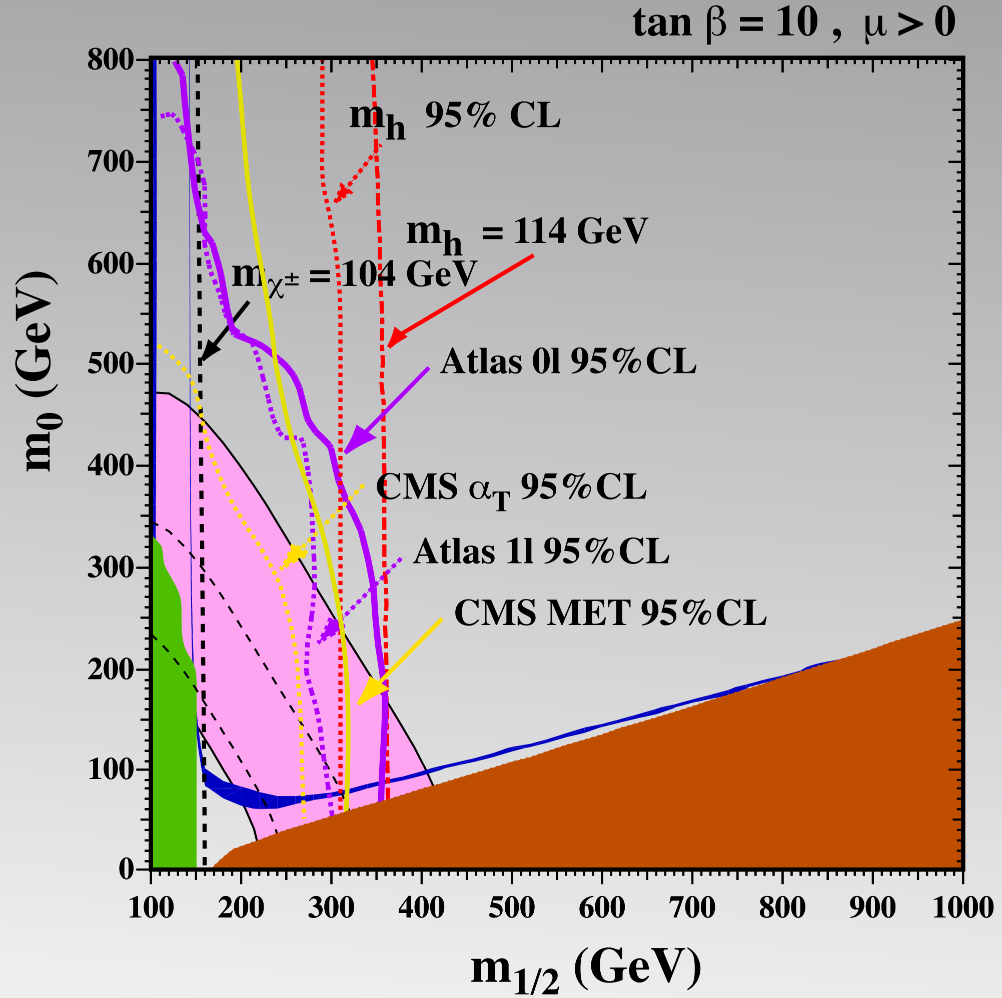
- jets + missing $E_T$ with/without leptons
- Heavy Higgs to ττ
- B to μμ

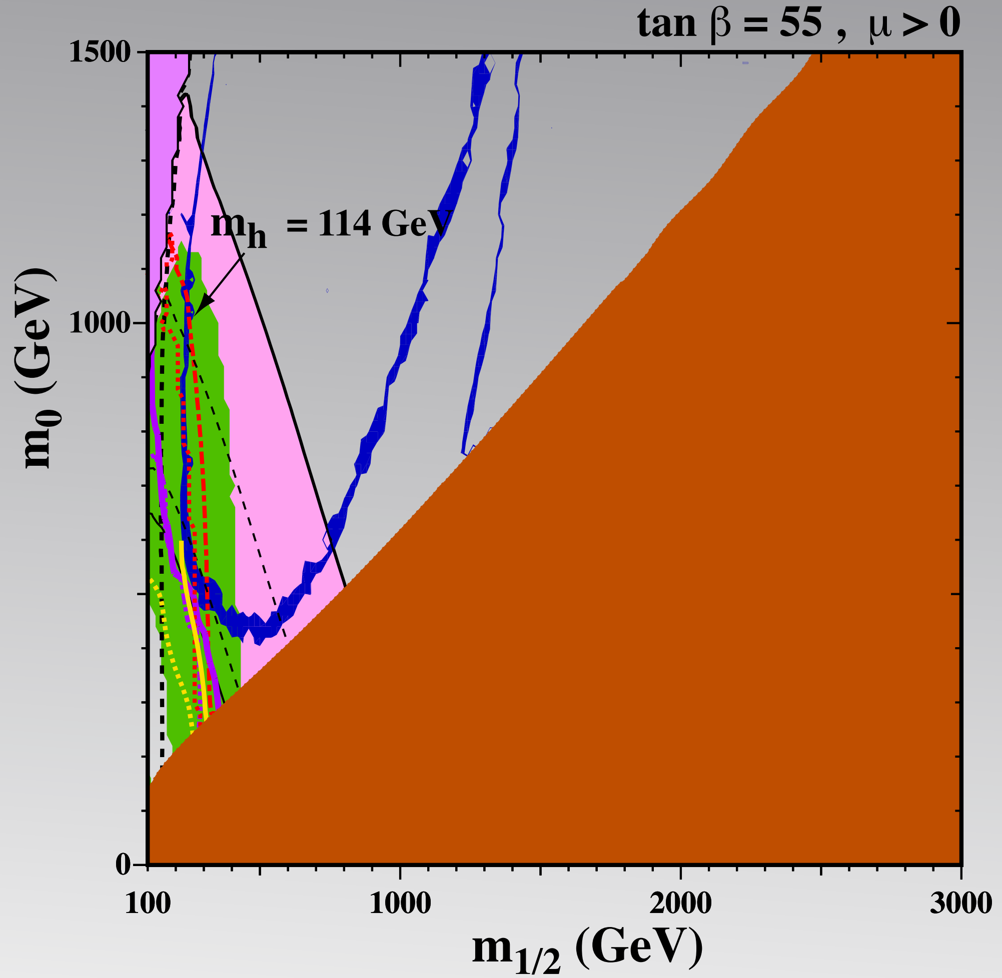
~20fb$^{-1}$ @ 8 TeV



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




CMSSM

Ellis, Olive, Santoso, Spanos

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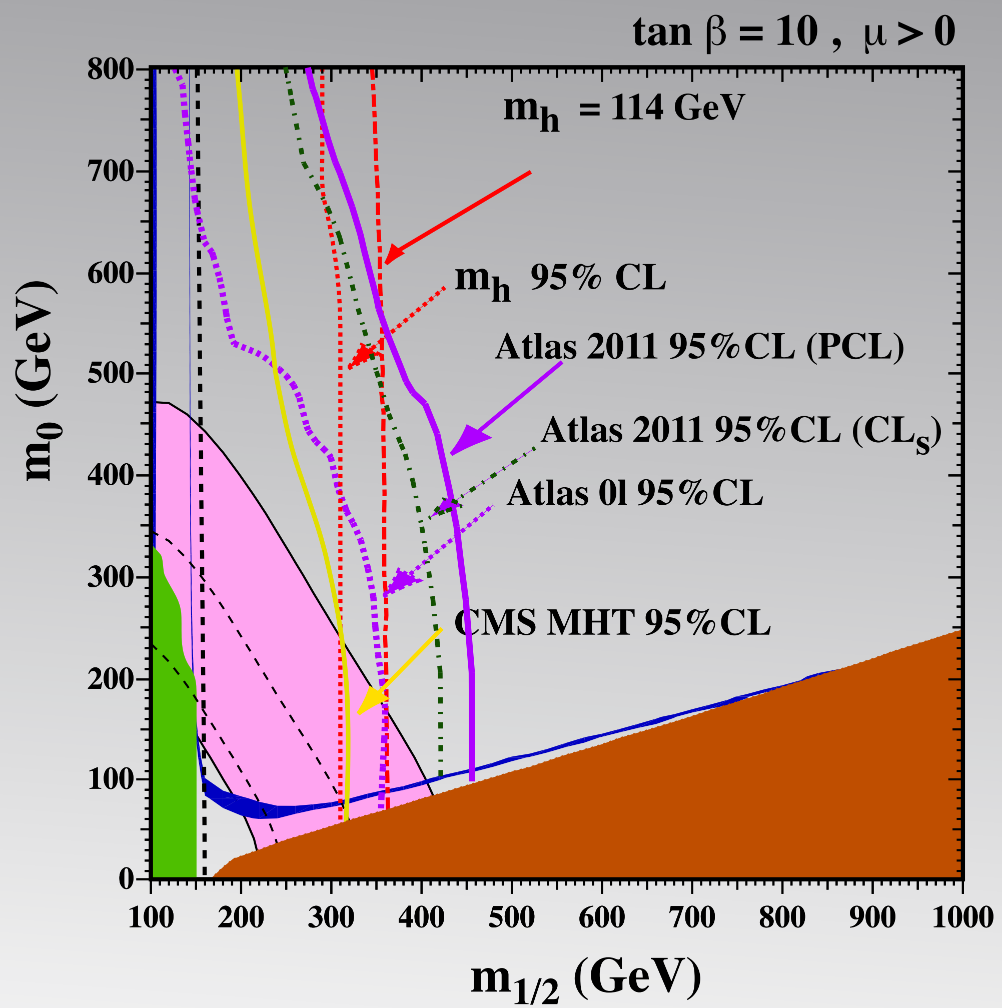


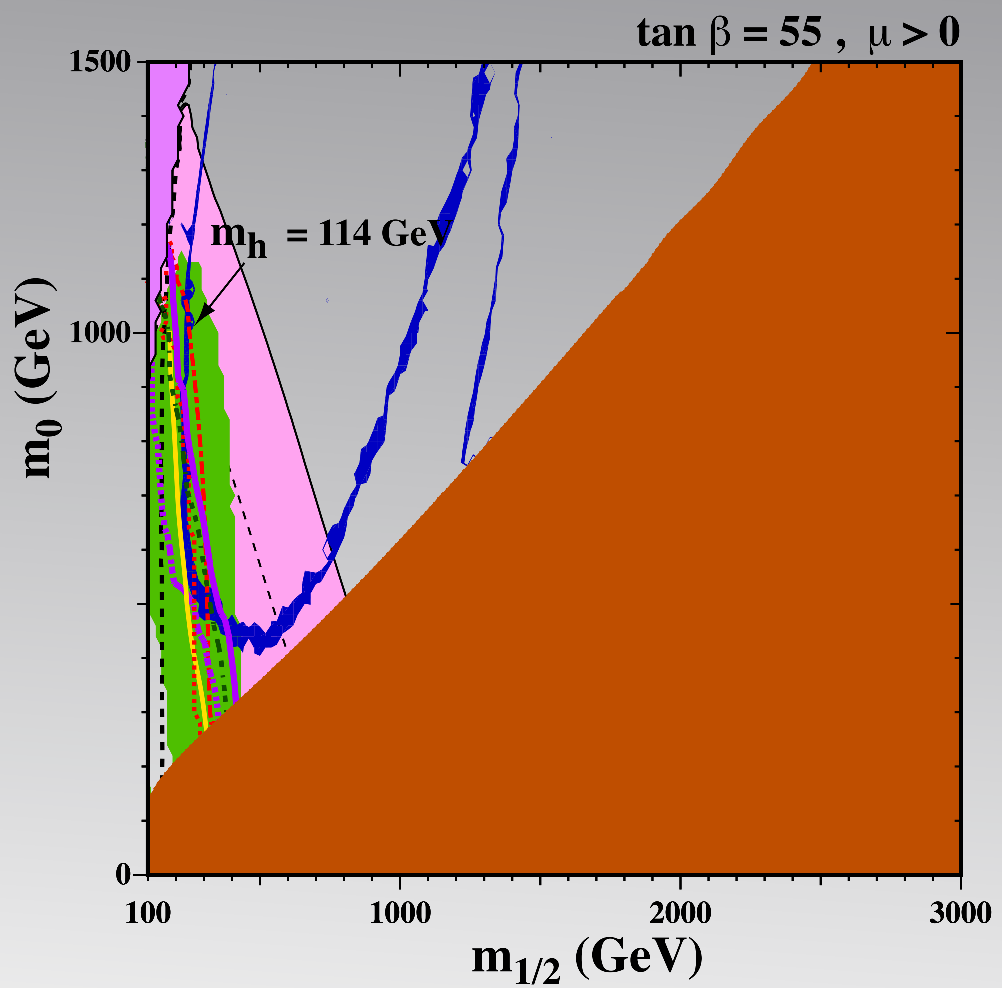


CMSSM

Ellis, Olive, Santoso, Spanos

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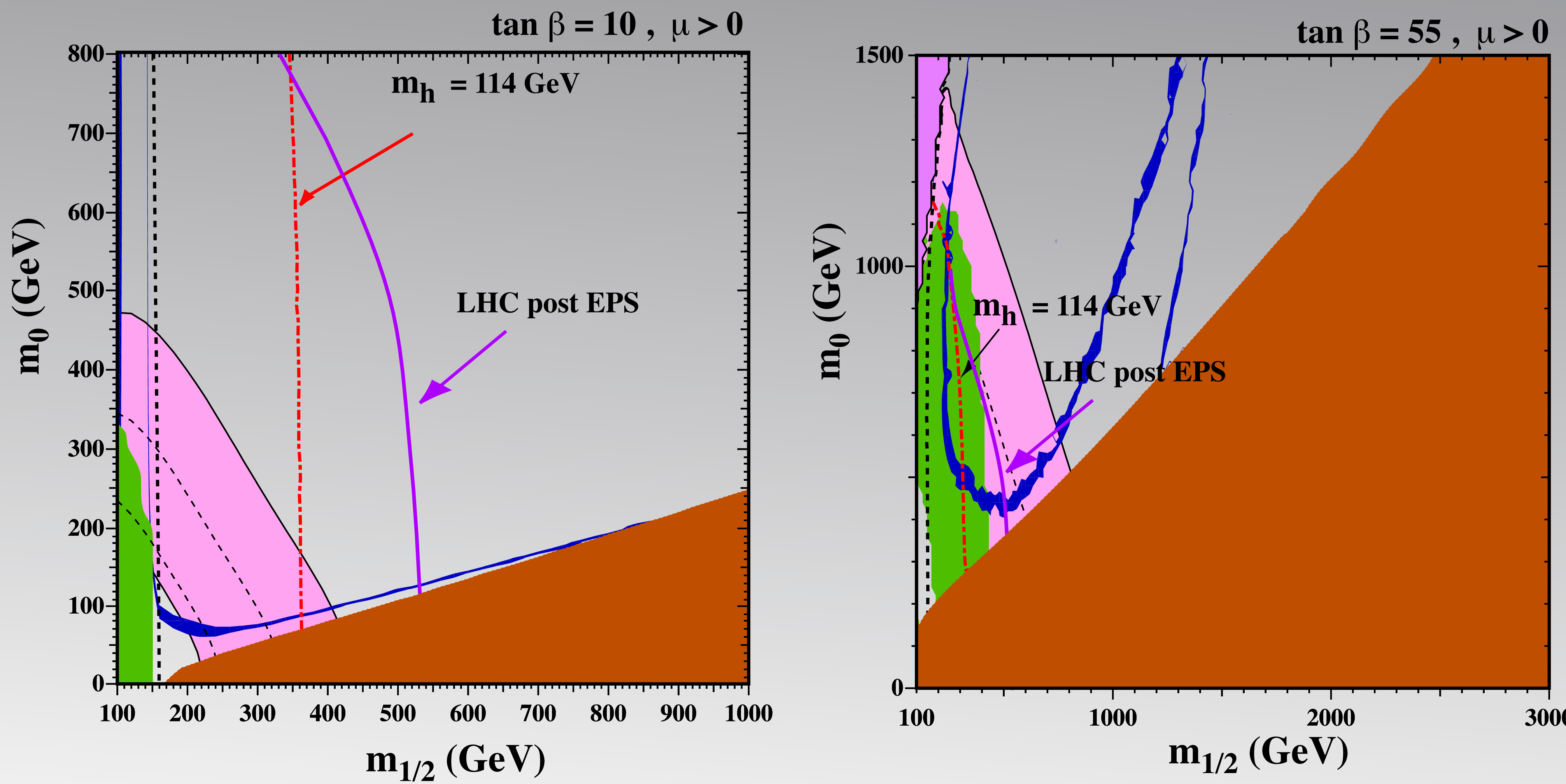


- CMSSM

Ellis, Olive, Santoso, Spanos

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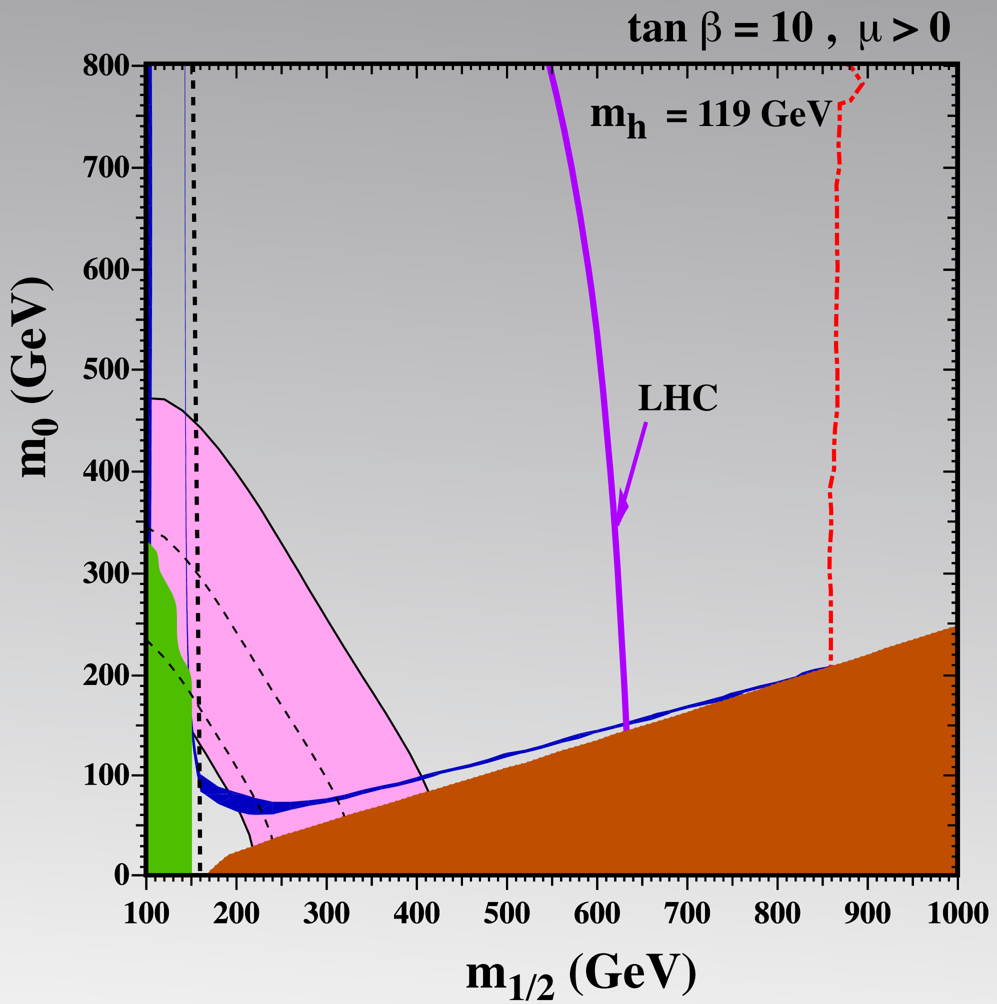


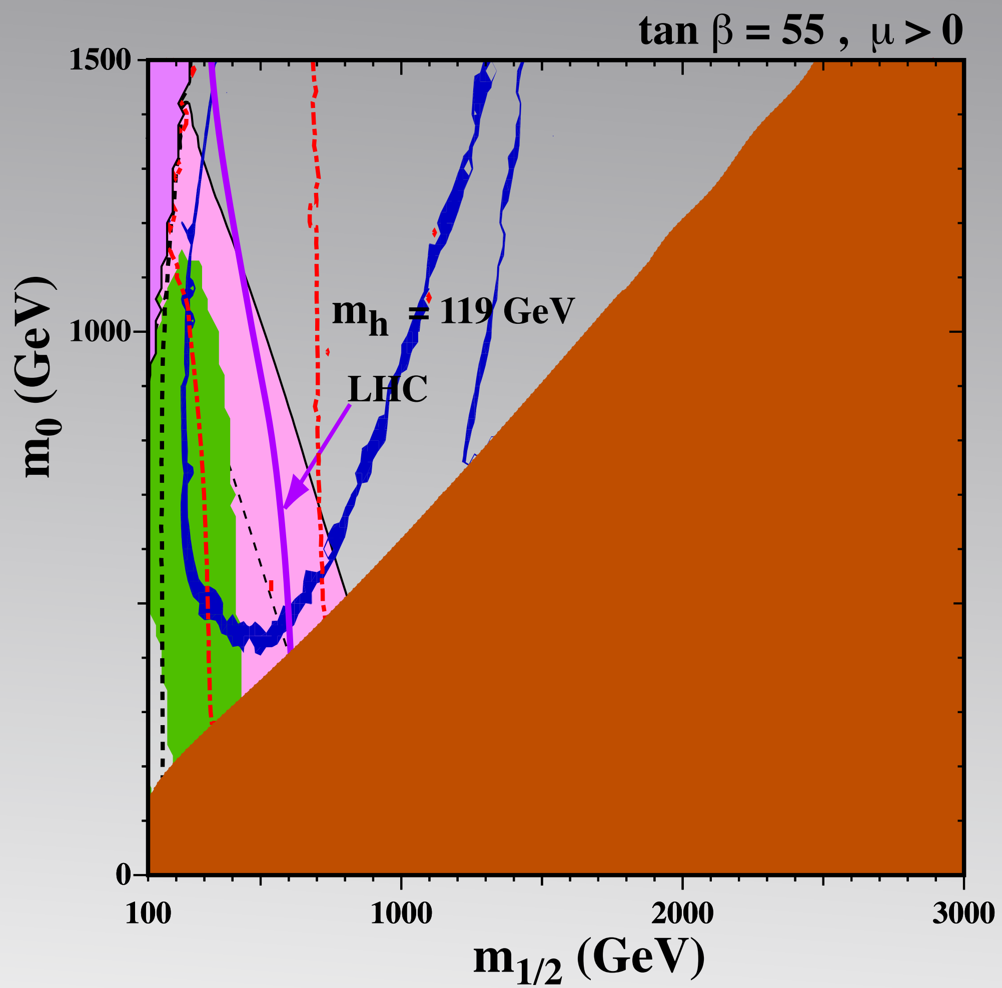


- CMSSM

Ellis, Olive, Santoso, Spanos

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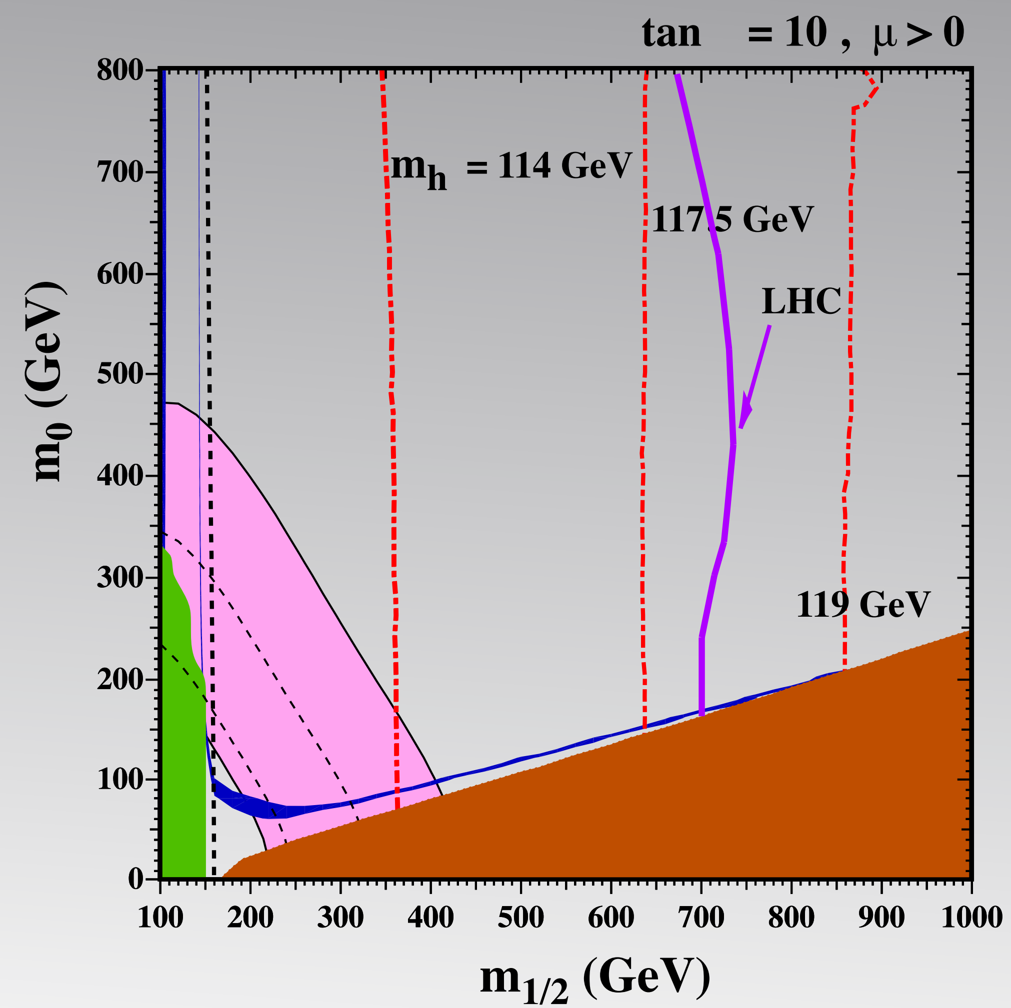


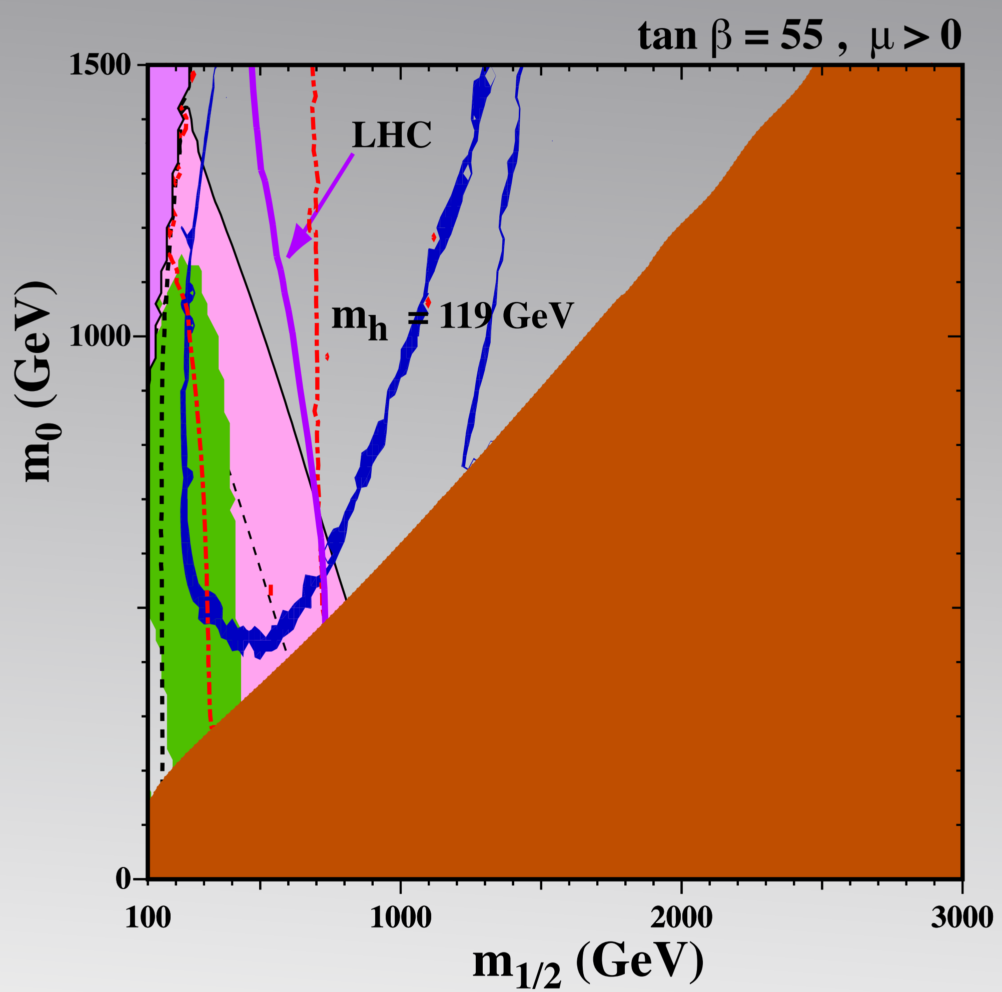


- CMSSM

Ellis, Olive, Santoso, Spanos

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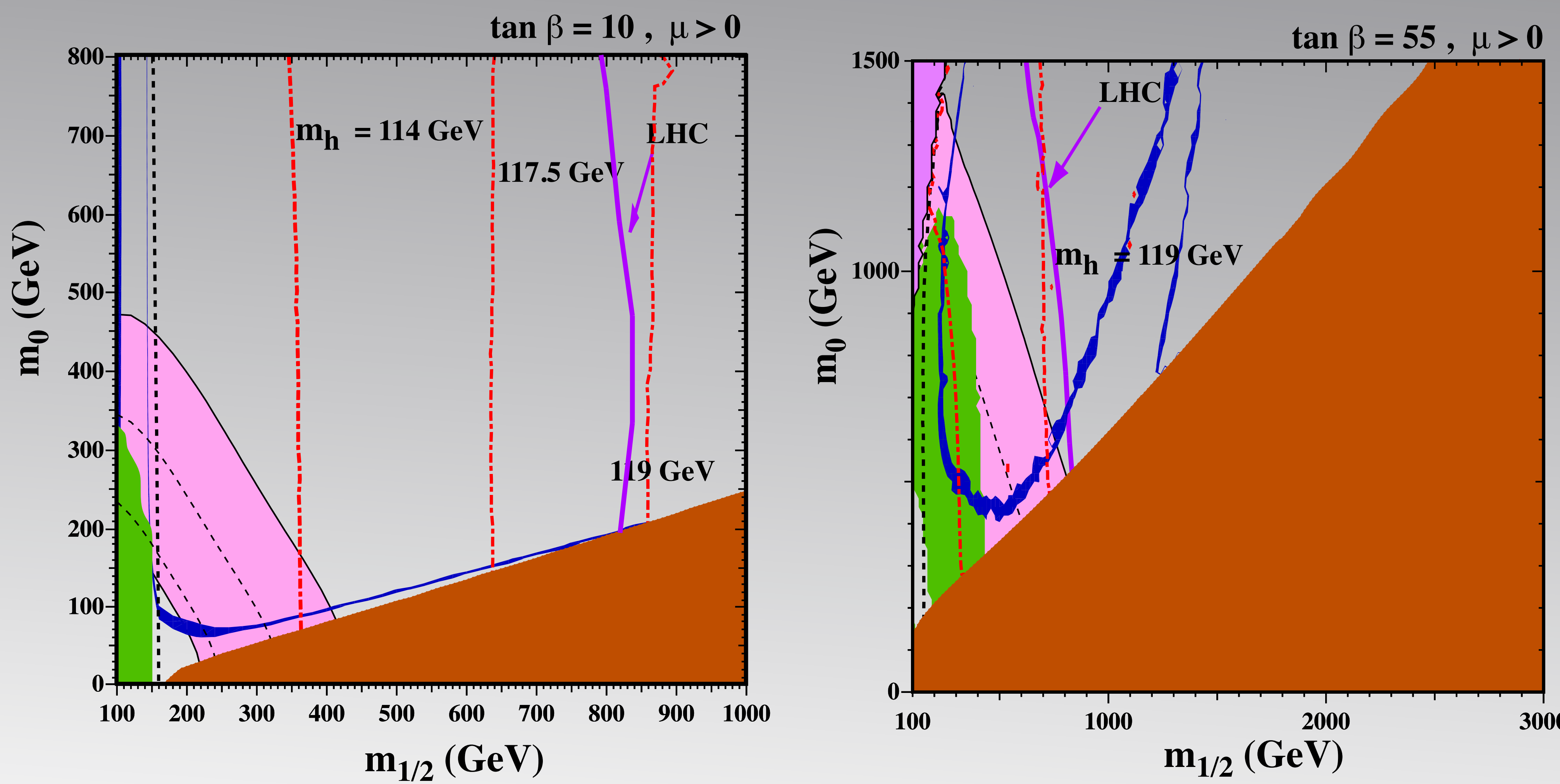


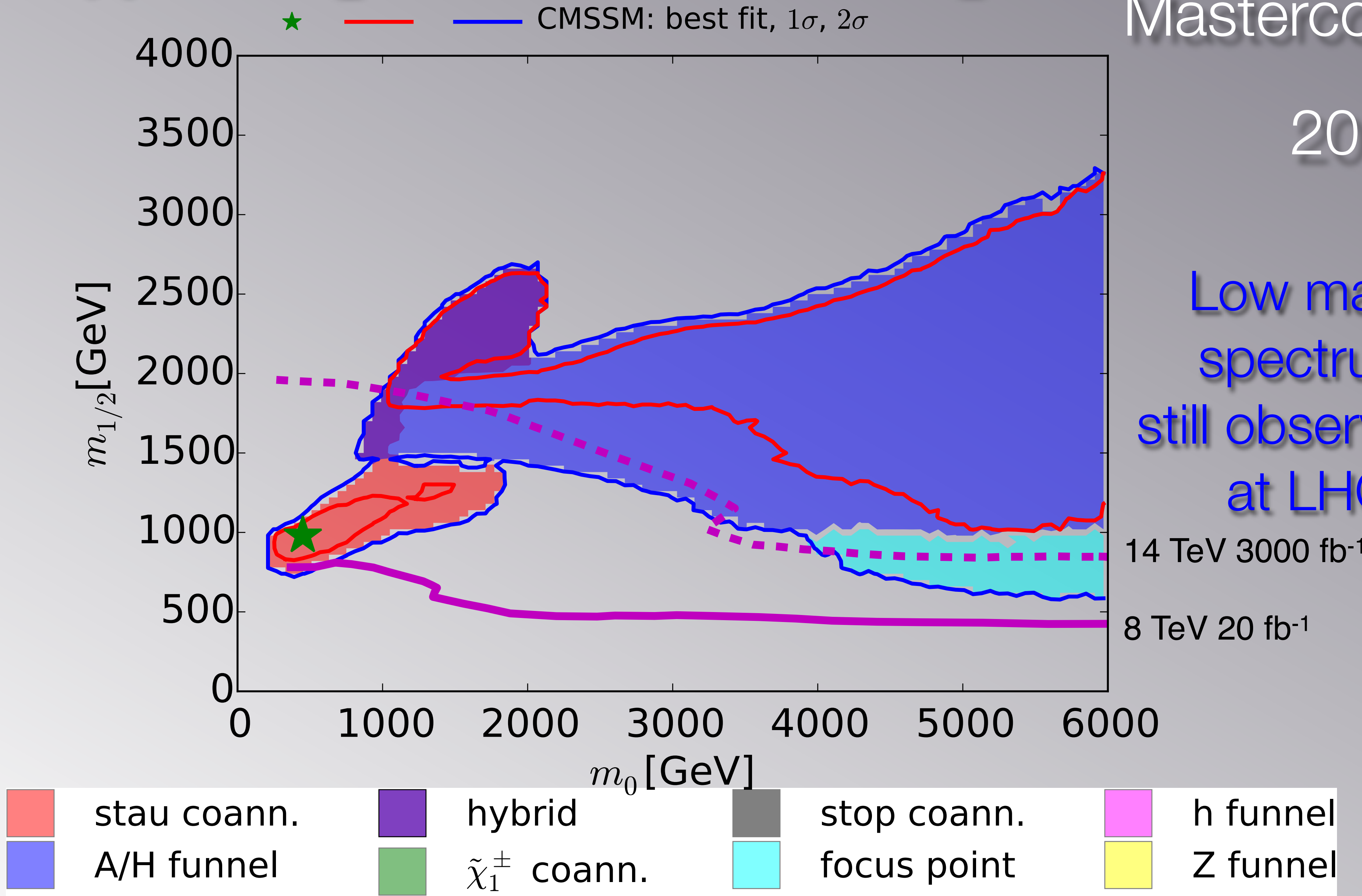

- CMSSM

Ellis, Olive, Santoso, Spanos

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

Mastercode

2015




Low mass spectrum still observable at LHC

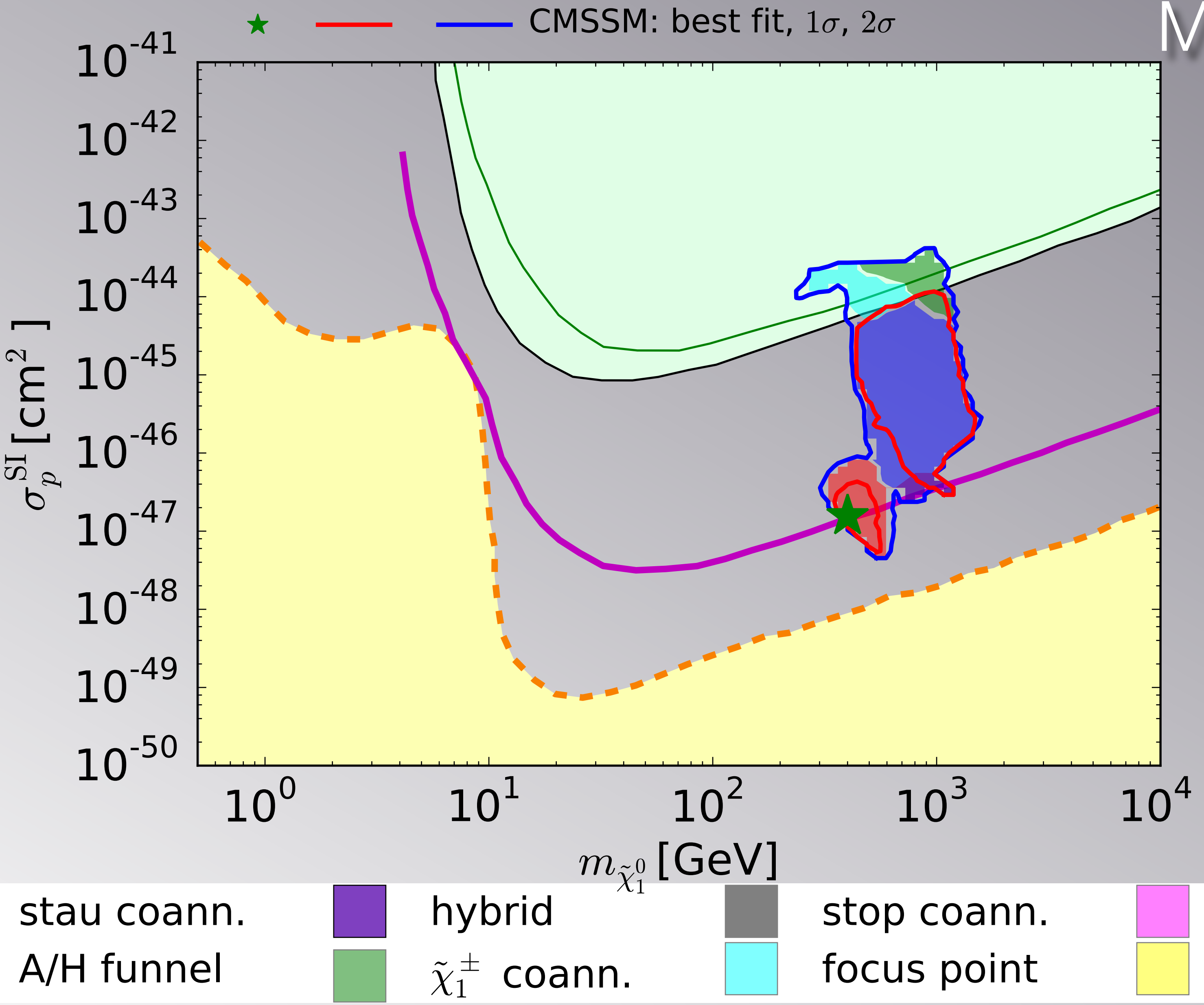
- CMSSM

Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

# Elastic scaterring cross-section

Mastercode

2015




- CMSSM

Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

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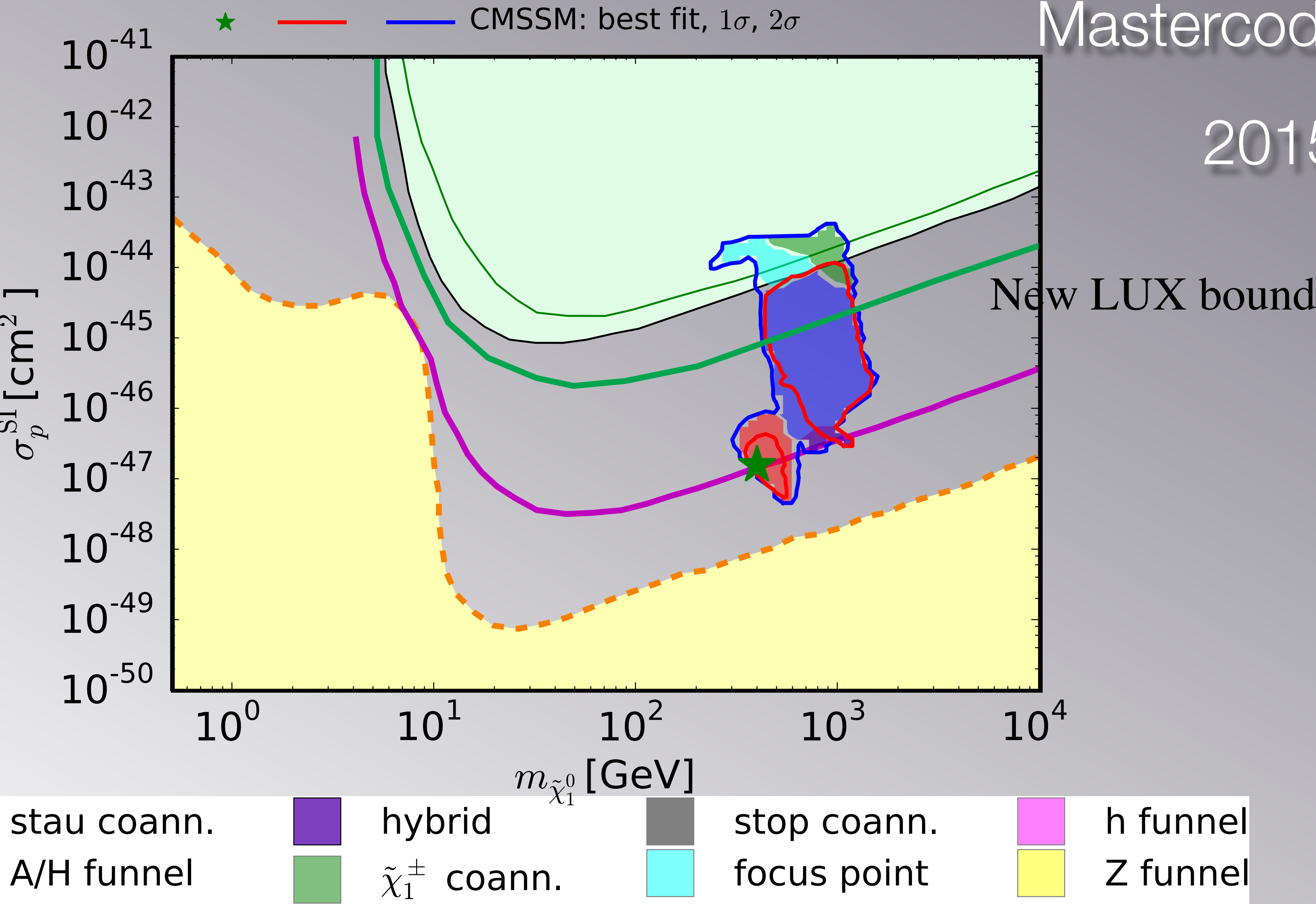


- CMSSM

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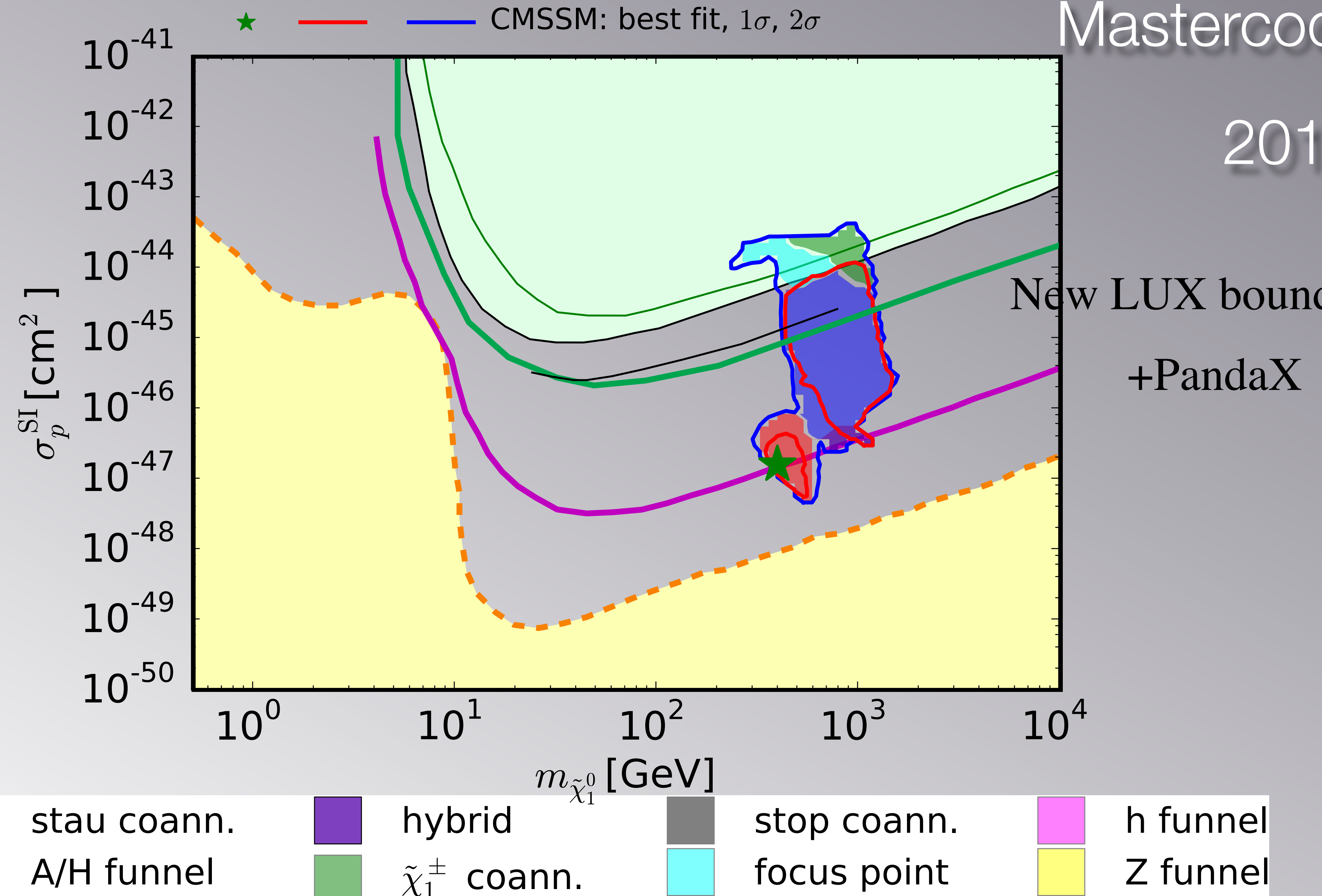


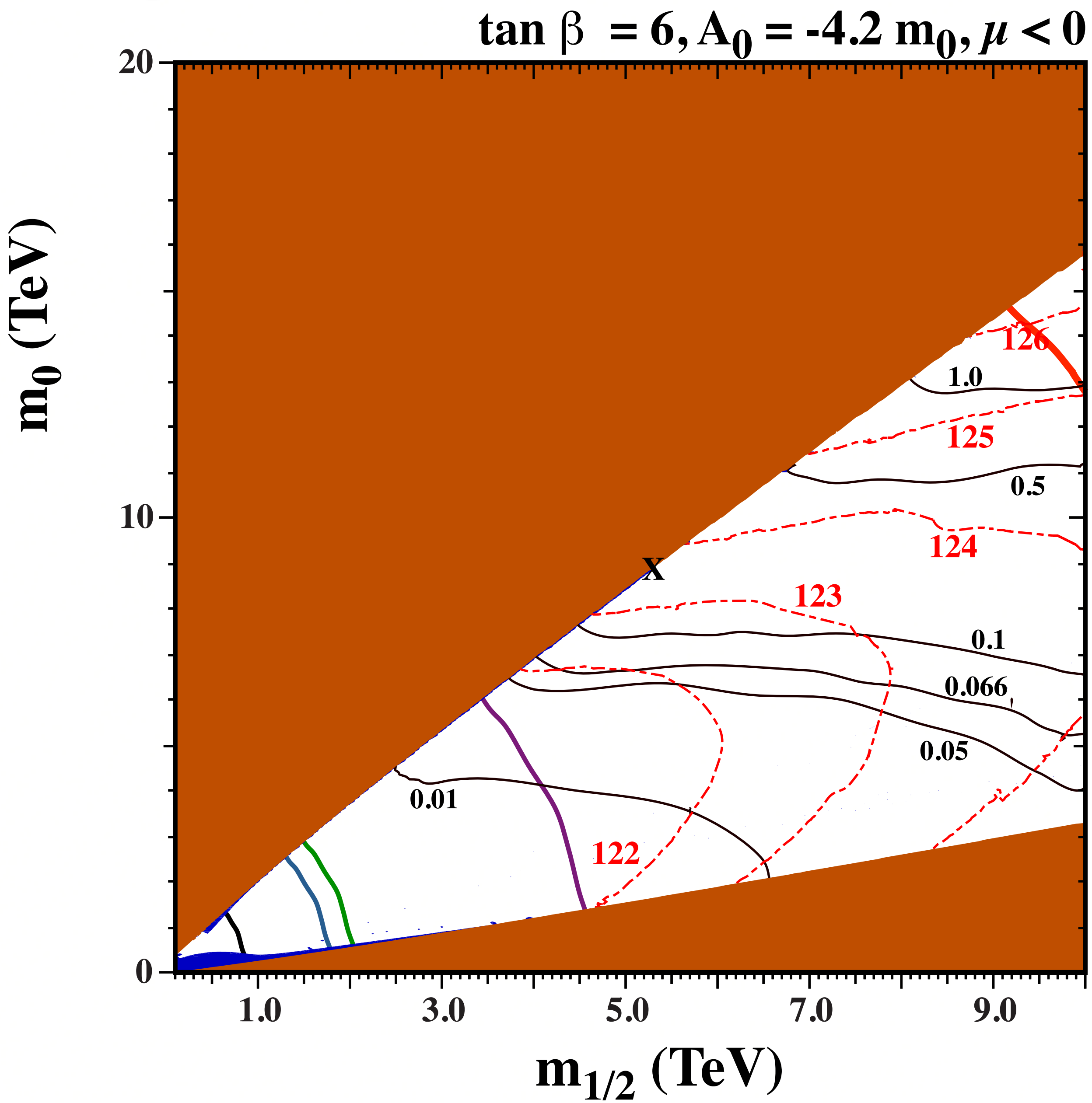

- CMSSM

Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

# The Strips:

- Stau-coannhilation Strip
  - extends only out to ~1 TeV
- Stop-coannihilation Strip
- Funnel
  - associated with high tan β, problems with $B \to \mu\mu$
- Focus Point

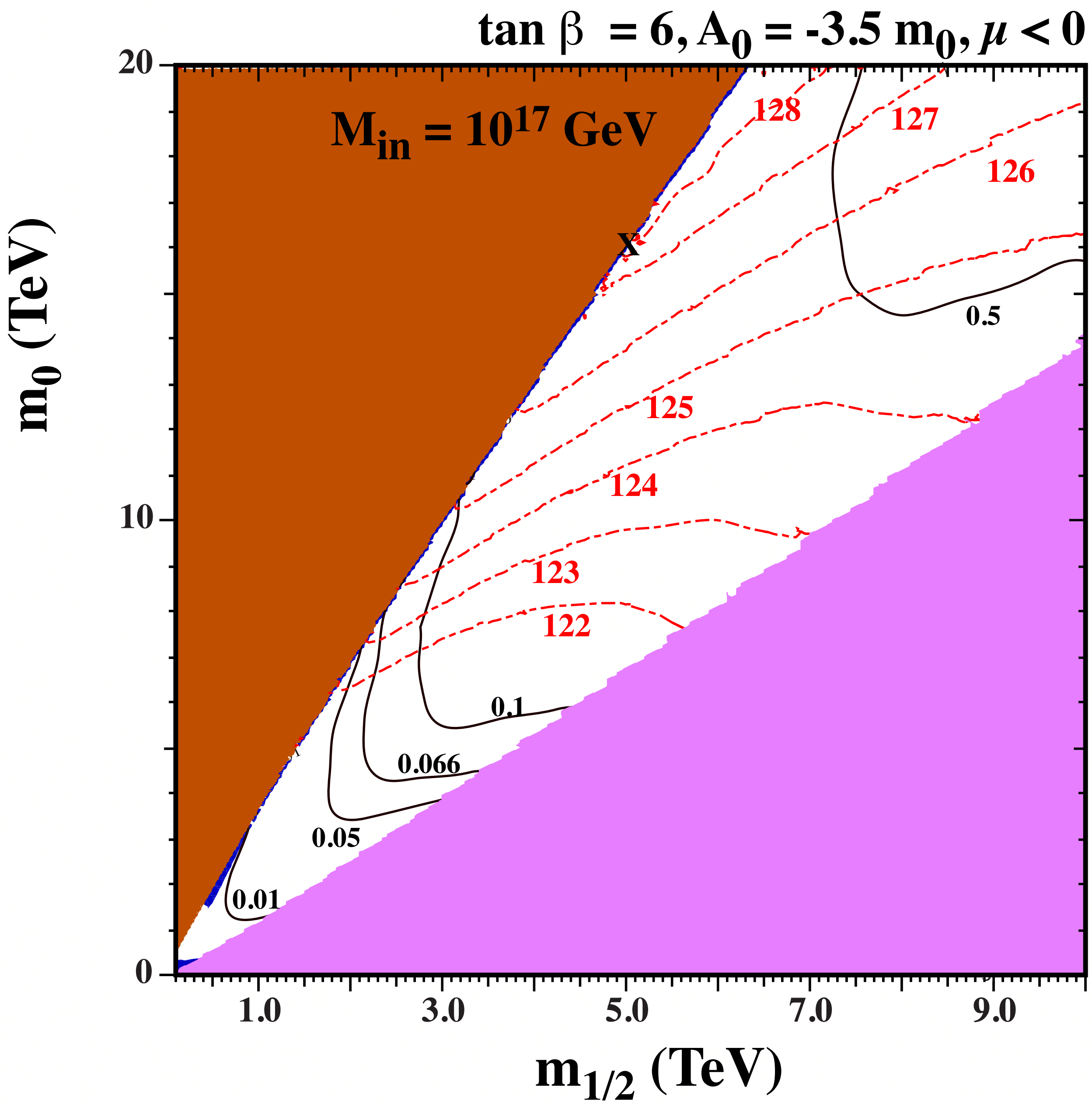
# Stop strip




100 TeV 3000 fb$^{-1}$
33 TeV 3000 fb$^{-1}$
14 TeV 3000 fb$^{-1}$
14 TeV 300 fb$^{-1}$
8 TeV 20 fb$^{-1}$

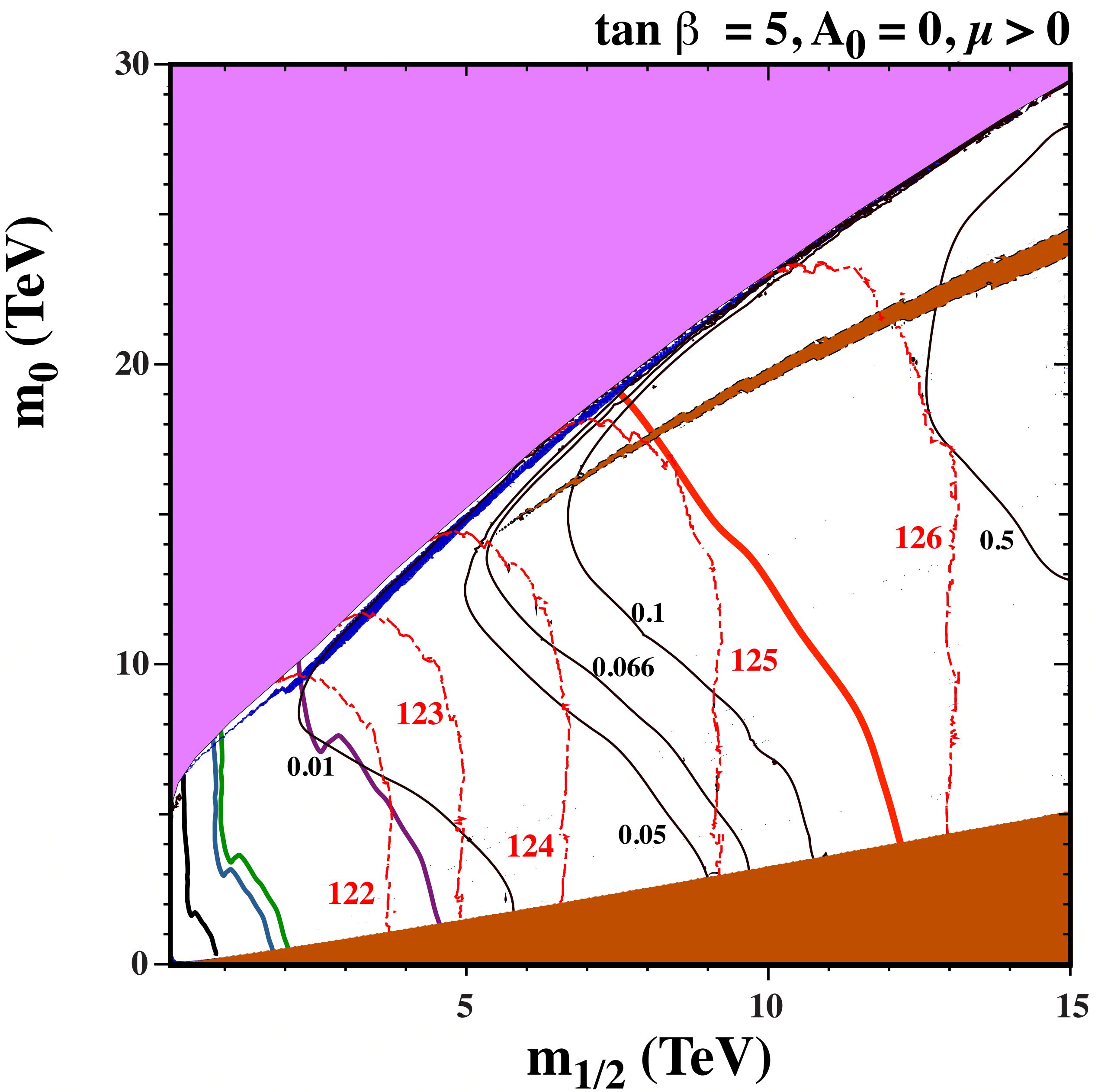
Ellis, Evans, Mustafayev, Nagata, Olive

# Improved in an SU(5) superGUT extension




Ellis, Evans, Mustafayev, Nagata, Olive

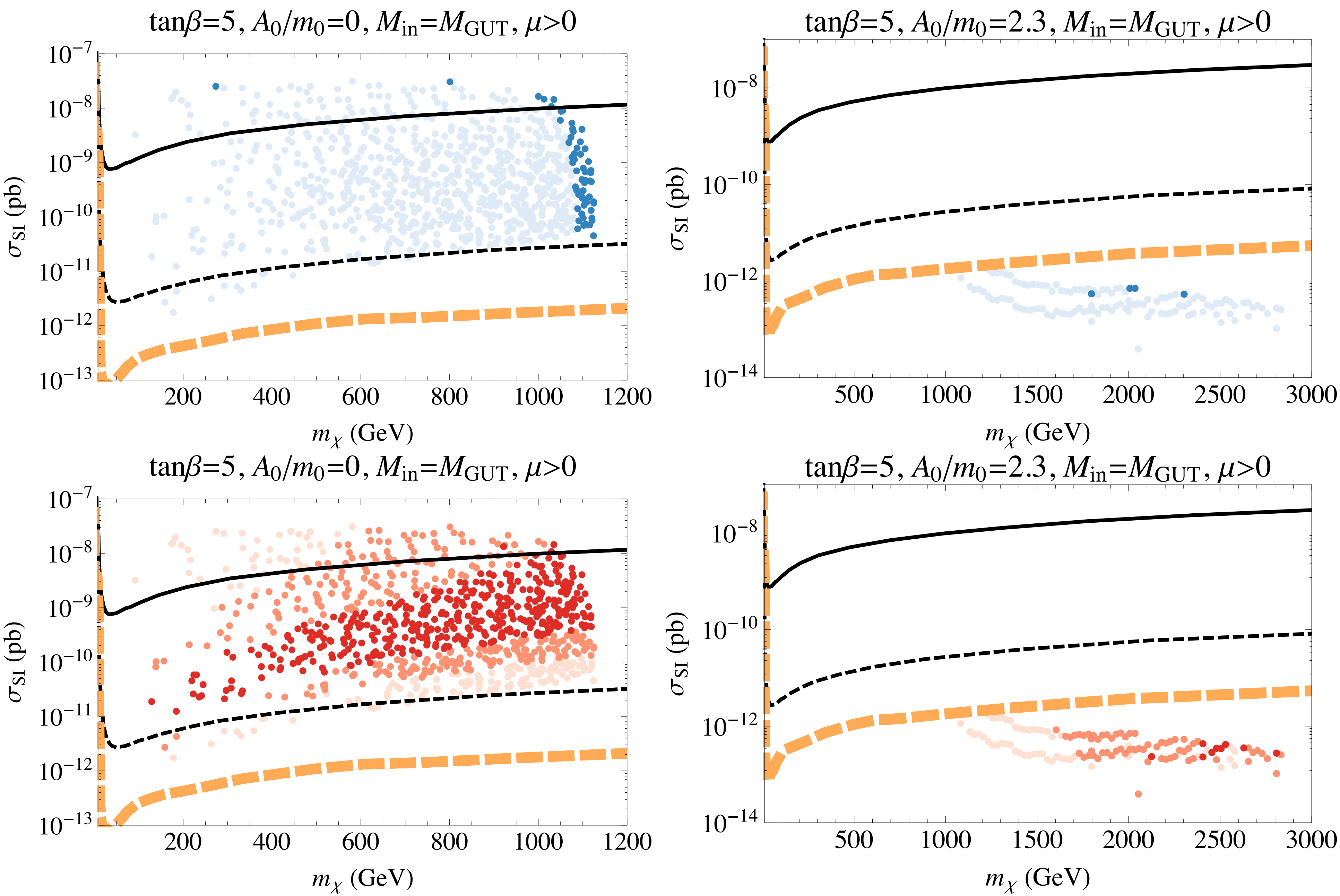
# Focus Point




100 TeV 3000 fb$^{-1}$
33 TeV 3000 fb$^{-1}$
14 TeV 3000 fb$^{-1}$
14 TeV 300 fb$^{-1}$
8 TeV 20 fb$^{-1}$

Ellis, Evans, Mustafayev, Nagata, Olive

# Direct detectability



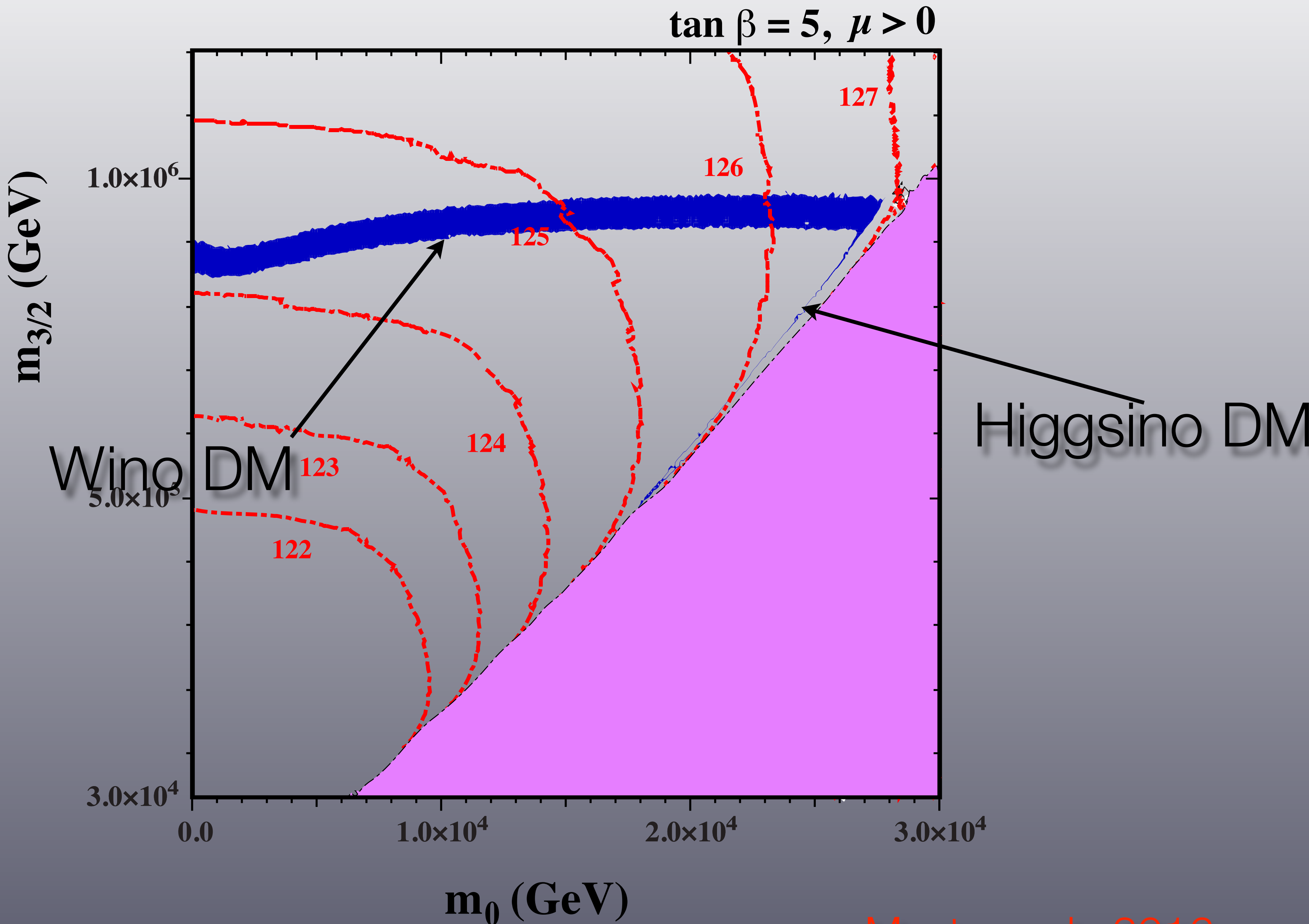

Ellis, Evans, Nagata, Olive, Sandick, Zheng

# Other Possibilities

More Constrained (fewer parameters)

- Pure Gravity Mediation
  - 2 parameter model with very large scalar masses
  - $m_0 = m_{3/2}$, tan β
- mAMSB
  - similar to PGM, but allow $m_0 \neq m_{3/2}$
- mSUGRA
  - $B_0 = A_0 - m_0 \Rightarrow$ tan β no longer free

# mAMSB



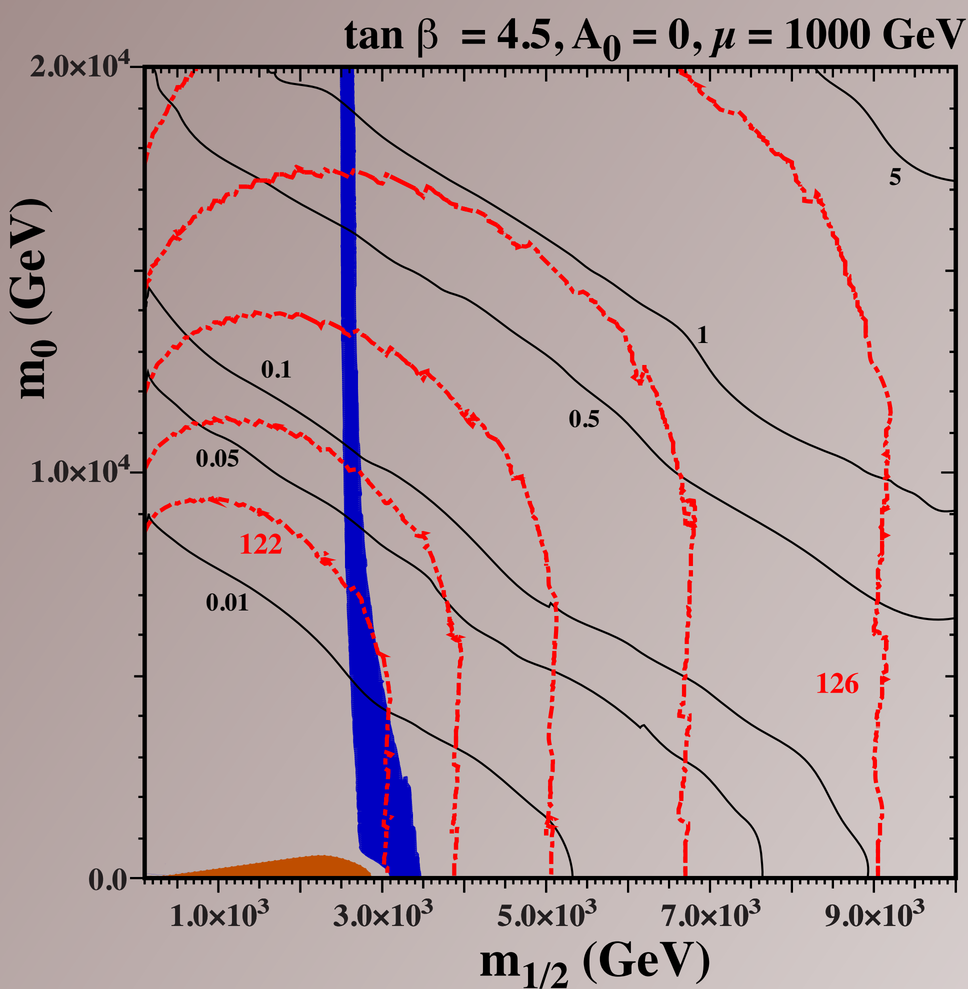

Mastercode 2016

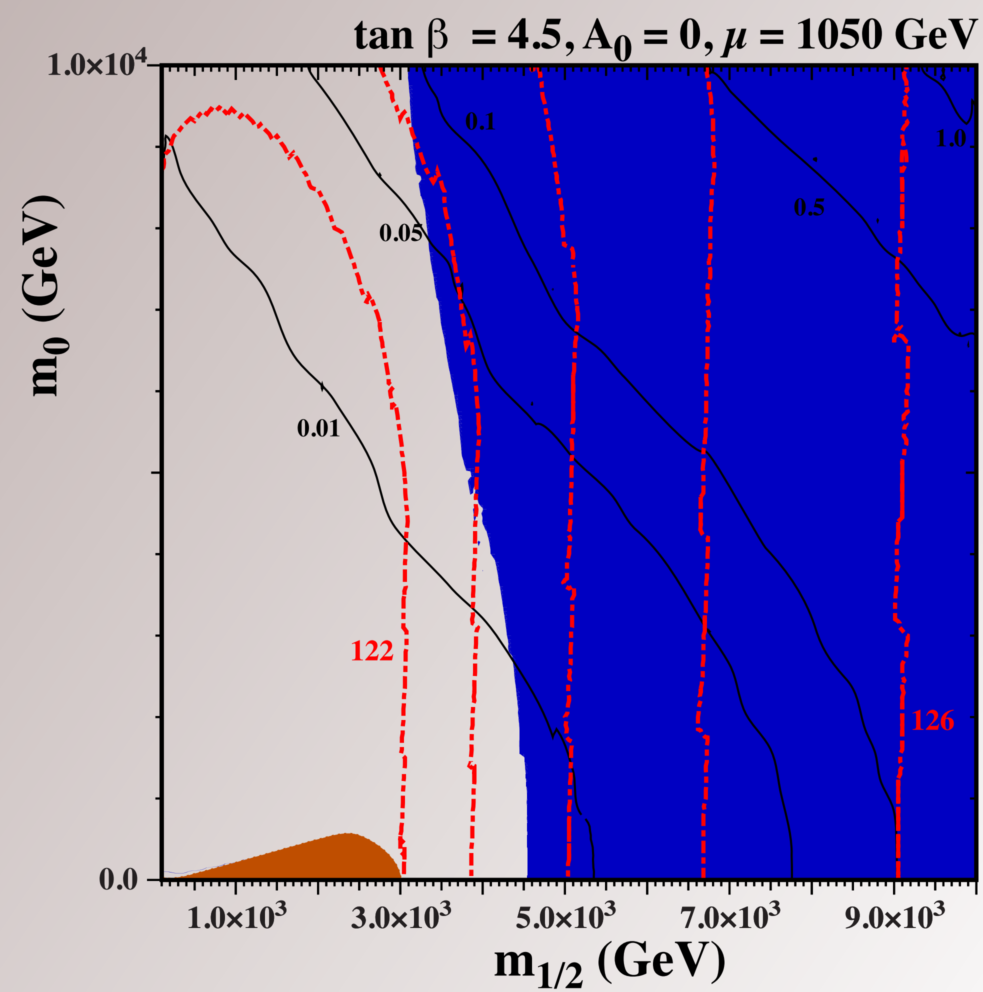
# Other Possibilities

Less Constrained (more parameters)

- NUHM1,2: $m_1^2 = m_2^2 \neq m_0^2$, $m_1^2 \neq m_2^2 \neq m_0^2$
  - $\mu$ and/or $m_A$ free
- NUGM
  - gluino coannihilation
- subGUT models: $M_{in} < M_{GUT}$
  - new parameter $M_{in}$
- SuperGUT models: $M_{in} > M_{GUT}$
  - requires SU(5) input couplings

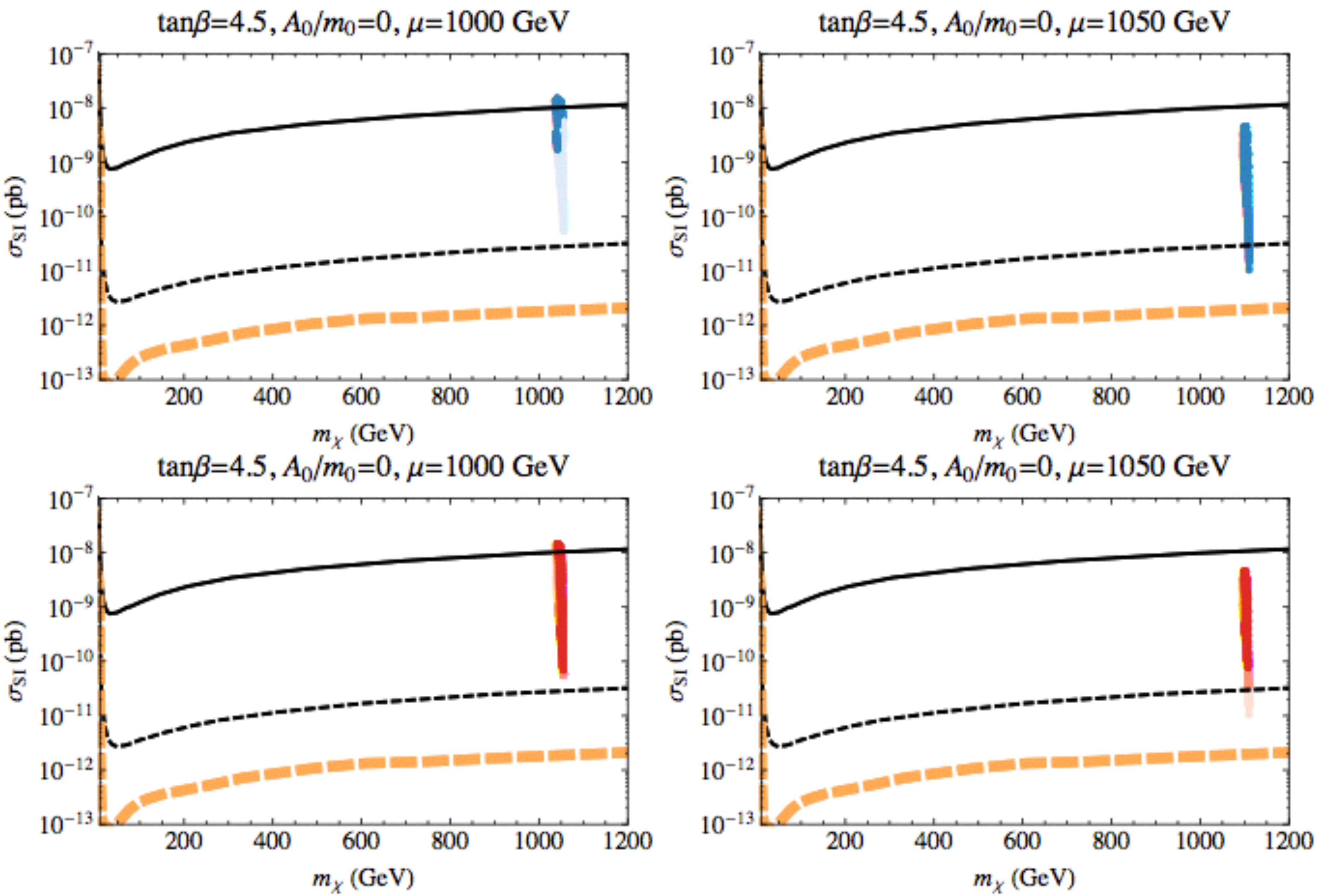
# NUHM1 models with μ free ($m_1 = m_2$)




Ellis, Luo, Olive, Sandick;
Ellis, Evans, Luo, Nagata, Olive, Sandick

# Direct detectability




Ellis,Evans, Nagata, Olive, Sandick, Zheng

# Why Supersymmetry (still)?

- Gauge Coupling Unification
- Gauge Hierarchy Problem
- Stabilization of the Electroweak Vacuum
- Radiative Electroweak Symmetry Breaking
- Dark Matter
- Improvement to low energy phenomenology?

but, $m_h$ ~ 125 GeV, and no SUSY?

# SO(10) GUT?

- Gauge Coupling Unification
- 
- Stabilization of the Electroweak Vacuum
- Radiative Electroweak Symmetry Breaking
- Dark Matter
- Improvement to low energy phenomenology?

Neutrino masses…

# What is SO(10)

Georgi
Fritzsch,Minkowski

$$\mathrm{SO}(10) \supset \mathrm{SU}(5) \times \mathrm{U}(1)$$
$$\supset \mathrm{SU}(4) \times \mathrm{SU}(2) \times \mathrm{SU}(2)$$
$$\supset \text{others}$$

Gauge degrees of freedom: 45

decomposition of the **45**

SU(5) × U(1): $\mathbf{45 = (24,0) + (10,4) + (\overline{10},-4) + (1,0)}$

SU(4) × SU(2) × SU(2): $\mathbf{45 = (15,1,1) + (6,2,2) + (1,1,0) + (1,3,1) + (1,1,3)}$

(SU(4) decomposition in terms of SU(3): $\mathbf{15 = 8 + 3 + \overline{3} + 1;\ 6 = 3 + \overline{3}}$)

# What is SO(10)

$SO(10) \supset SU(5) \times U(1)$
$\supset SU(4) \times SU(2) \times SU(2)$
$\supset$ others

Matter degrees of freedom: fundamental 16

new: right-handed neutrino

decomposition of the **16**

SU(5) × U(1): $\mathbf{16 = (10,-1) + (\bar{5},3) + (1,-5)}$

SU(4) × SU(2) × SU(2): $\mathbf{16 = (4,1,2) + (\bar{4},2,1)}$

(SU(4) decomposition in terms of SU(3): **4 = 3 + 1**

# What is SO(10)

$$\begin{aligned} SO(10) &\supset SU(5) \times U(1) \\ &\supset SU(4) \times SU(2) \times SU(2) \\ &\supset \text{others} \end{aligned}$$

Higgs: see below

# Recipe for constructing an SO(10) DM model

## 1. Pick an Intermediate Scale Gauge Group

$$\mathrm{SO}(10) \xrightarrow{R_1} G_{\mathrm{int}}$$

| $G_{\mathrm{int}}$ | $R_1$ |
|---|---|
| $\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$ | $\mathbf{210}$ |
| $\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes D$ | $\mathbf{54}$ |
| $\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_R$ | $\mathbf{45}$ |
| $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}$ | $\mathbf{45}$ |
| $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L} \otimes D$ | $\mathbf{210}$ |
| $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_R \otimes \mathrm{U}(1)_{B-L}$ | $\mathbf{45}, \mathbf{210}$ |
| $\mathrm{SU}(5) \otimes \mathrm{U}(1)$ | $\mathbf{45}, \mathbf{210}$ |
| Flipped $\mathrm{SU}(5) \otimes \mathrm{U}(1)$ | $\mathbf{45}, \mathbf{210}$ |

Georgi, Nanopoulos; Vayonakis;
Masiero; Shafi, Sondermann, Wetterich;
del Aguila, Ibanez;
Mohapatra, Senjanovic;
Mambrini, Nagata,
Olive, Quevillon, Zheng;
Nagata, Olive, Zheng

# Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

2. Use **126** to break $G_{int}$ to SM

$$\mathrm{SO}(10) \xrightarrow{R_1} G_{\rm int} \xrightarrow{R_2} G_{\rm SM} \otimes \mathbb{Z}_2$$

$R_2$ = **126** + …

Neutrino see-saw: Majorana mass for $\nu_R$
from 16 16 126 → $m_{\nu R} \sim M_{int}$ and $m_\nu \sim v^2/M_{int}$

$Z_2$ related to matter parity and B-L

Unlike SUSY R-parity, this $Z_2$ is not put in by hand!

# Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

2. Use **126** to break $G_{int}$ to SM

3. Pick DM representation and insure proper splitting within the multiplet, and pick low energy field content

Remnant $Z_2$ symmetry

Fermions from **10**,**45**, **54**, **120**, **126**, or **210** representations;

Scalars from **16**, **144**

| Model | $B-L$ | $SU(2)_L$ | $Y$ | SO(10) representations |
|---|---|---|---|---|
| $F_{\mathbf{1}}^{0}$ | 0 | **1** | 0 | **45**, **54**, **210** |
| $F_{\mathbf{2}}^{1/2}$ | | **2** | 1/2 | **10**, **120**, **126**, **210′** |
| $F_{\mathbf{3}}^{0}$ | | **3** | 0 | **45**, **54**, **210** |
| $F_{\mathbf{3}}^{1}$ | | **3** | 1 | **54** |
| $F_{\mathbf{4}}^{1/2}$ | | **4** | 1/2 | **210′** |
| $F_{\mathbf{4}}^{3/2}$ | | **4** | 3/2 | **210′** |
| $S_{\mathbf{1}}^{0}$ | 1 | **1** | 0 | **16**, **144** |
| $S_{\mathbf{2}}^{1/2}$ | | **2** | 1/2 | **16**, **144** |
| $S_{\mathbf{3}}^{0}$ | | **3** | 0 | **144** |
| $S_{\mathbf{3}}^{1}$ | | **3** | 1 | **144** |
| $\widehat{F}_{\mathbf{1}}^{0}$ | 2 | **1** | 0 | **126** |
| $\widehat{F}_{\mathbf{2}}^{1/2}$ | | **2** | 1/2 | **210** |
| $\widehat{F}_{\mathbf{3}}^{1}$ | | **3** | 1 | **126** |

Kadastik, Kannike, Raidal;
Frigerio, Hambye;
Mambrini, Nagata,
Olive, Quevillon, Zheng;
Nagata, Olive, Zheng

# Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

2. Use **126** to break $G_{int}$ to SM

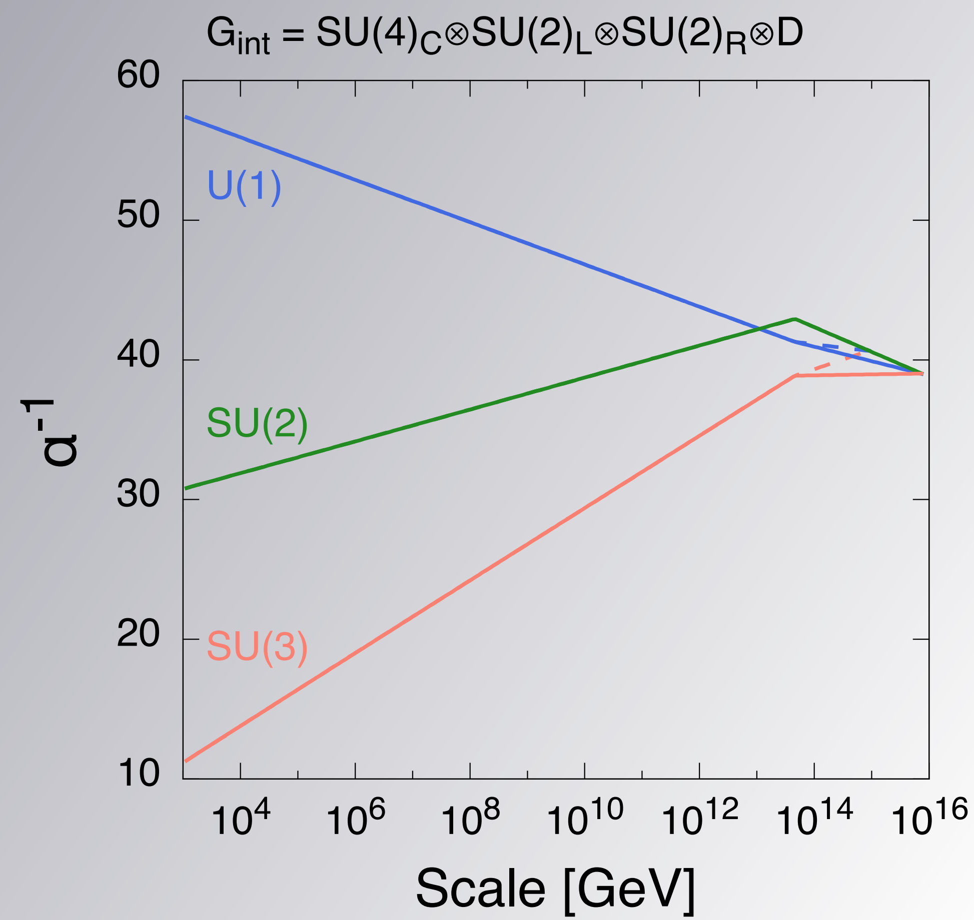
3. Pick DM representation and insure proper splitting within the multiplet, and pick low energy field content

4. Use RGEs to obtain Gauge Coupling Unification

# Recipe for constructing an SO(10) DM model

4. Use RGEs to obtain Gauge Coupling Unification

Fixes $M_{GUT}$, $M_{int}$, $\alpha_{GUT}$



# Examples:

## Scalars

| Model | $R_{\mathrm{DM}}$ | $\mathtt{S}^{\mathtt{Y}}_{\mathbf{n}}$ | SO(10) representation |
|---|---|---|---|
| $G_{\mathrm{int}} = \mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R (\otimes D)$ | | | |
| $\mathtt{SA}_{\mathtt{422(D)}}$ | $\mathbf{4}, \mathbf{1}, \mathbf{2}$ | $\mathtt{S}^{0}_{\mathbf{1}}$ | $\mathbf{16},\ \mathbf{144}$ |
| $\mathtt{SB}_{\mathtt{422(D)}}$ | $\mathbf{4}, \mathbf{2}, \mathbf{1}$ | $\mathtt{S}^{1/2}_{\mathbf{2}}$ | $\mathbf{16},\ \mathbf{144}$ |
| $\mathtt{SC}_{\mathtt{422(D)}}$ | $\mathbf{4}, \mathbf{2}, \mathbf{3}$ | $\mathtt{S}^{1/2}_{\mathbf{2}}$ | $\mathbf{144}$ |
| $\mathtt{SD}_{\mathtt{422(D)}}$ | $\mathbf{4}, \mathbf{3}, \mathbf{2}$ | $\mathtt{S}^{1}_{\mathbf{3}}$ | $\mathbf{144}$ |
| $\mathtt{SE}_{\mathtt{422(D)}}$ | $\mathbf{4}, \mathbf{3}, \mathbf{2}$ | $\mathtt{S}^{0}_{\mathbf{3}}$ | $\mathbf{144}$ |
| $G_{\mathrm{int}} = \mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_R$ | | | |
| $\mathtt{SA}_{\mathtt{421}}$ | $\mathbf{4}, \mathbf{1}, -1/2$ | $\mathtt{S}^{0}_{\mathbf{1}}$ | $\mathbf{16},\ \mathbf{144}$ |
| $\mathtt{SB}_{\mathtt{421}}$ | $\mathbf{4}, \mathbf{2}, 0$ | $\mathtt{S}^{1/2}_{\mathbf{2}}$ | $\mathbf{16},\ \mathbf{144}$ |
| $\mathtt{SC}_{\mathtt{421}}$ | $\mathbf{4}, \mathbf{2}, 1$ | $\mathtt{S}^{1/2}_{\mathbf{2}}$ | $\mathbf{144}$ |
| $\mathtt{SD}_{\mathtt{421}}$ | $\mathbf{4}, \mathbf{3}, 1/2$ | $\mathtt{S}^{1}_{\mathbf{3}}$ | $\mathbf{144}$ |
| $\mathtt{SE}_{\mathtt{421}}$ | $\mathbf{4}, \mathbf{3}, -1/2$ | $\mathtt{S}^{0}_{\mathbf{3}}$ | $\mathbf{144}$ |
| $G_{\mathrm{int}} = \mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L} (\otimes D)$ | | | |
| $\mathtt{SA}_{\mathtt{3221(D)}}$ | $\mathbf{1}, \mathbf{1}, \mathbf{2}, 1$ | $\mathtt{S}^{0}_{\mathbf{1}}$ | $\mathbf{16},\ \mathbf{144}$ |
| $\mathtt{SB}_{\mathtt{3221(D)}}$ | $\mathbf{1}, \mathbf{2}, \mathbf{1}, -1$ | $\mathtt{S}^{1/2}_{\mathbf{2}}$ | $\mathbf{16},\ \mathbf{144}$ |
| $\mathtt{SC}_{\mathtt{3221(D)}}$ | $\mathbf{1}, \mathbf{2}, \mathbf{3}, -1$ | $\mathtt{S}^{1/2}_{\mathbf{2}}$ | $\mathbf{144}$ |
| $\mathtt{SD}_{\mathtt{3221(D)}}$ | $\mathbf{1}, \mathbf{3}, \mathbf{2}, 1$ | $\mathtt{S}^{1}_{\mathbf{3}}$ | $\mathbf{144}$ |
| $\mathtt{SE}_{\mathtt{3221(D)}}$ | $\mathbf{1}, \mathbf{3}, \mathbf{2}, 1$ | $\mathtt{S}^{0}_{\mathbf{3}}$ | $\mathbf{144}$ |

Nagata, Olive, Zheng

# Examples:

## Scalars

Higgs portal models
Inert Higgs doublet models

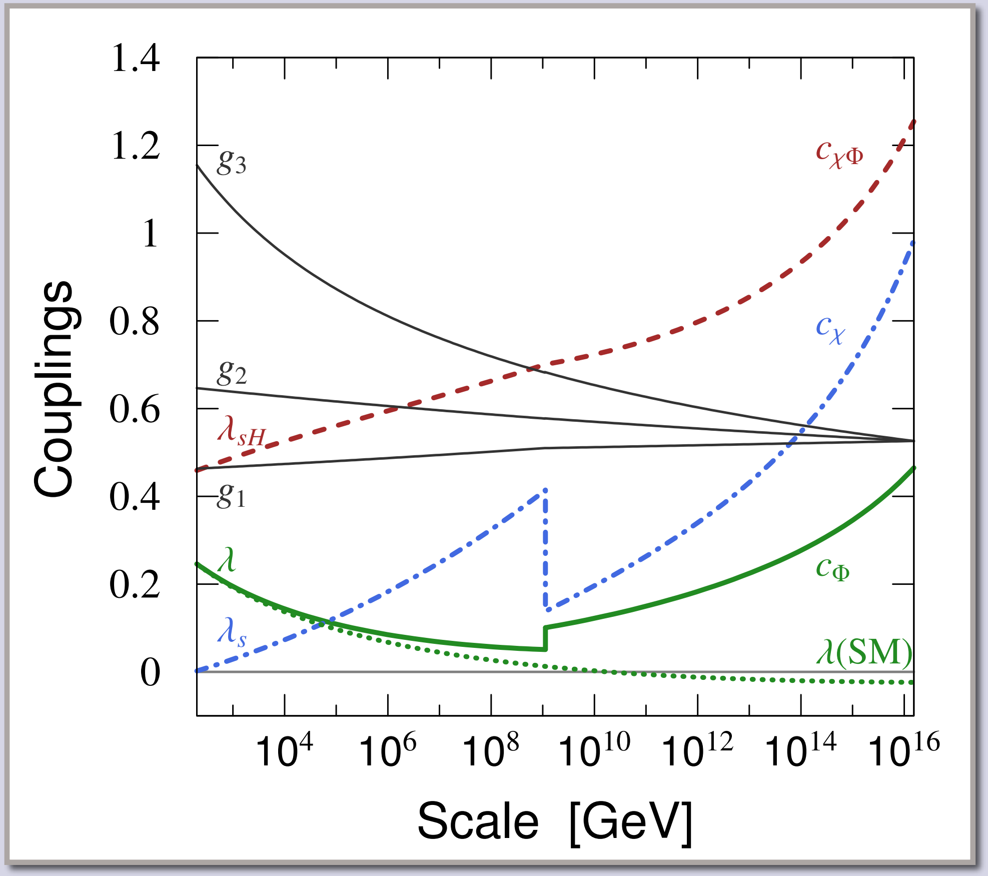
| Model | $\log_{10} M_{\rm GUT}$ | $\log_{10} M_{\rm int}$ | $\alpha_{\rm GUT}$ | $\log_{10}\tau_p(p\to e^+\pi^0)$ |
|---|---|---|---|---|
| $G_{\rm int} = {\rm SU}(4)_C\otimes{\rm SU}(2)_L\otimes{\rm SU}(2)_R$ | | | | |
| $\mathtt{SA}_{422}$ | 16.33 | 11.08 | 0.0218 | $36.8\pm1.2$ |
| $\mathtt{SB}_{422}$ | 15.62 | 12.38 | 0.0228 | $34.0\pm1.2$ |
| $G_{\rm int} = {\rm SU}(3)_C\otimes{\rm SU}(2)_L\otimes{\rm SU}(2)_R\otimes{\rm U}(1)_{B-L}$ | | | | |
| $\mathtt{SA}_{3221}$ | 16.66 | 8.54 | 0.0217 | $38.1\pm1.2$ |
| $\mathtt{SB}_{3221}$ | 16.17 | 9.80 | 0.0223 | $36.2\pm1.2$ |
| $\mathtt{SC}_{3221}$ | 15.62 | 9.14 | 0.0230 | $34.0\pm1.2$ |
| $G_{\rm int} = {\rm SU}(3)_C\otimes{\rm SU}(2)_L\otimes{\rm SU}(2)_R\otimes{\rm U}(1)_{B-L}\otimes D$ | | | | |
| $\mathtt{SA}_{3221\rm D}$ | 15.58 | 10.08 | 0.0231 | $33.8\pm1.2$ |
| $\mathtt{SB}_{3221\rm D}$ | 15.40 | 10.44 | 0.0233 | $33.1\pm1.2$ |

other models have $M_{\rm GUT}$ too low

mass splitting:

$$
\begin{aligned}
-\mathcal{L}_{\rm int} &= M^2|R_{\rm DM}|^2 + \kappa_1 R^*_{\rm DM}R_{\rm DM}R_1 + \{\kappa_2 R_{\rm DM}R_{\rm DM}R_2^* + {\rm h.c.}\} \\
&+ \lambda_1^{\bf 1}|R_{\rm DM}|^2|R_1|^2 + \lambda_2^{\bf 1}|R_{\rm DM}|^2|R_2|^2 + \left\{\lambda_{12}^{\bf 126}\left(R_{\rm DM}R_{\rm DM}\right)_{\bf 126}\left(R_1R_2^*\right)_{\overline{\bf 126}} + {\rm h.c.}\right\} \\
&+ \lambda_1^{\bf 45}\left(R^*_{\rm DM}R_{\rm DM}\right)_{\bf 45}\left(R_1^*R_1\right)_{\bf 45} + \lambda_1^{\bf 210}\left(R^*_{\rm DM}R_{\rm DM}\right)_{\bf 210}\left(R_1^*R_1\right)_{\bf 210} \\
&+ \lambda_2^{\bf 45}\left(R^*_{\rm DM}R_{\rm DM}\right)_{\bf 45}\left(R_2^*R_2\right)_{\bf 45} + \lambda_2^{\bf 210}\left(R^*_{\rm DM}R_{\rm DM}\right)_{\bf 210}\left(R_2^*R_2\right)_{\bf 210} ~,
\end{aligned}
$$

# Vacuum stability and radiative EWSB




Example based on scalar singlet DM ($SA_{3221}$) with

$$G_{\rm int} = {\rm SU}(3)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R \otimes {\rm U}(1)_{B-L} \cdot$$

with scalar potential

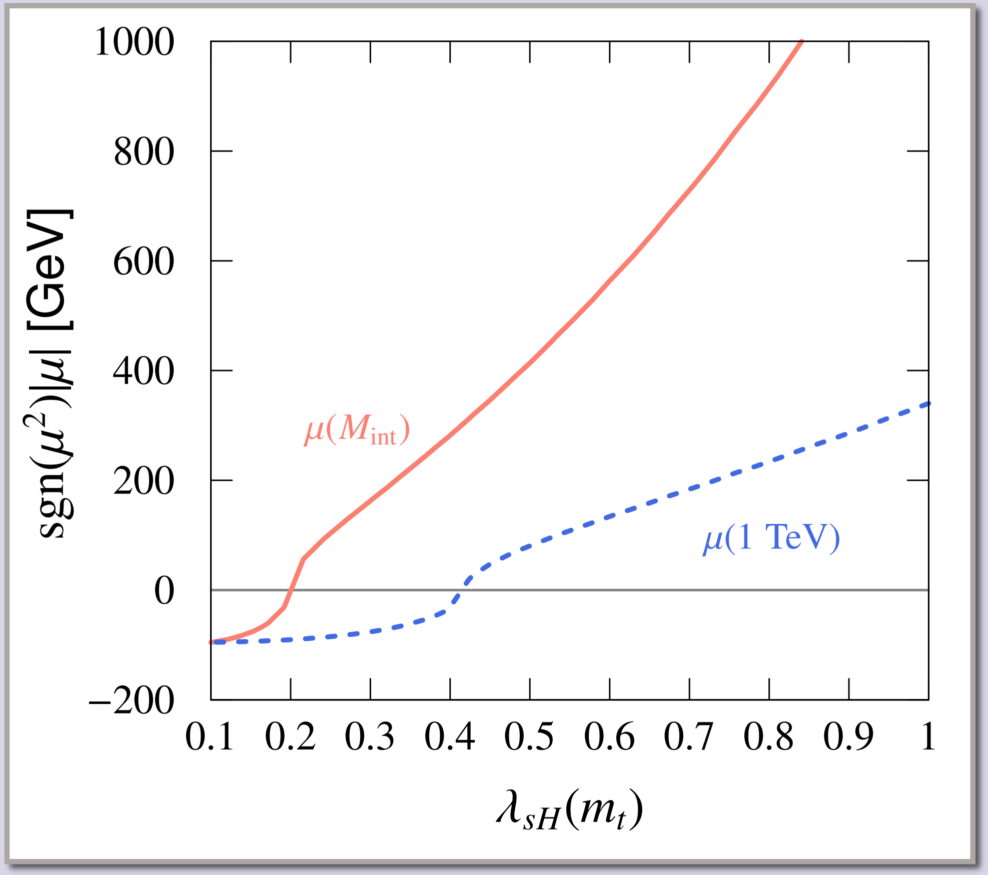
$$V_{\rm blw} = \mu^2|H|^2 + \frac{1}{2}\mu_s^2 s^2 + \frac{\lambda}{2}|H|^4 + \frac{\lambda_{sH}}{2}|H|^2 s^2 + \frac{\lambda_s}{4!}s^4 \, .$$

Additional fields appear at the intermediate scale.

Kadastik, Kannike, Raidal;
Mambrini, Nagata, Olive, Zheng

perturbatitivity implies $m_{DM}$ < 2 TeV

# Vacuum stability and radiative EWSB

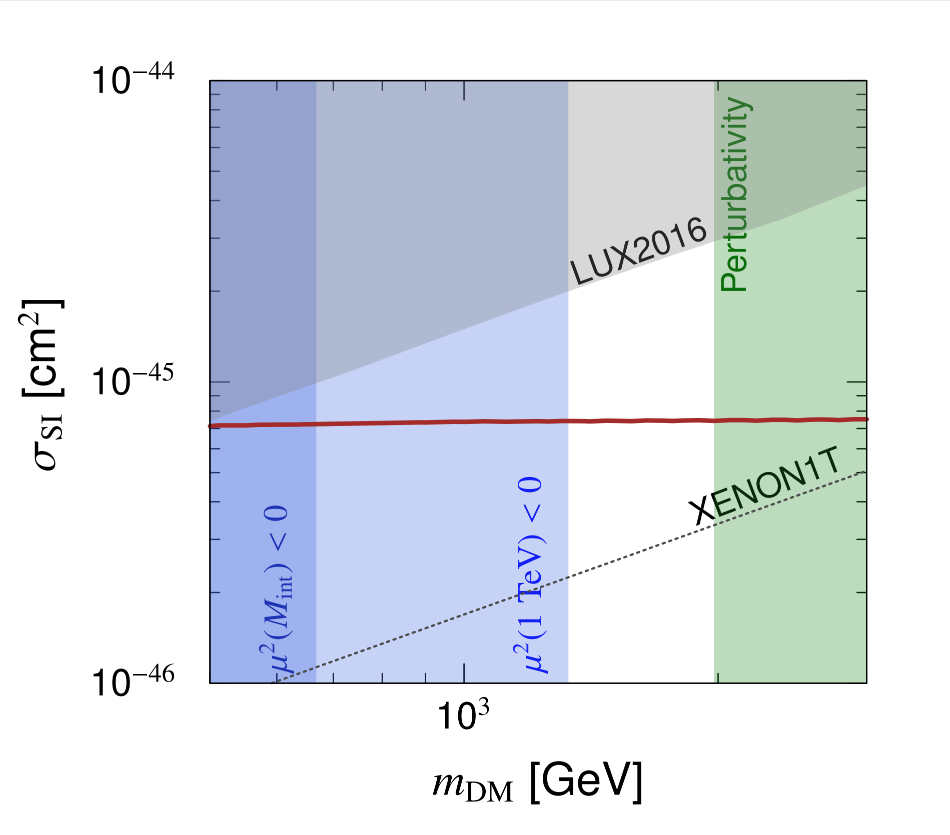



Higgs mass term runs negative and depends on $\lambda_{sH}$

$\mu^2 < 0$ @ $Q < 1$ TeV requires $\lambda_{sH} > .4$ or $m_{DM} > 1.35$ TeV

Kadastik, Kannike, Raidal;
Mambrini, Nagata, Olive, Zheng

# Vacuum stability and radiative EWSB




Direct Detection of this candidate can be probed at XENON1T

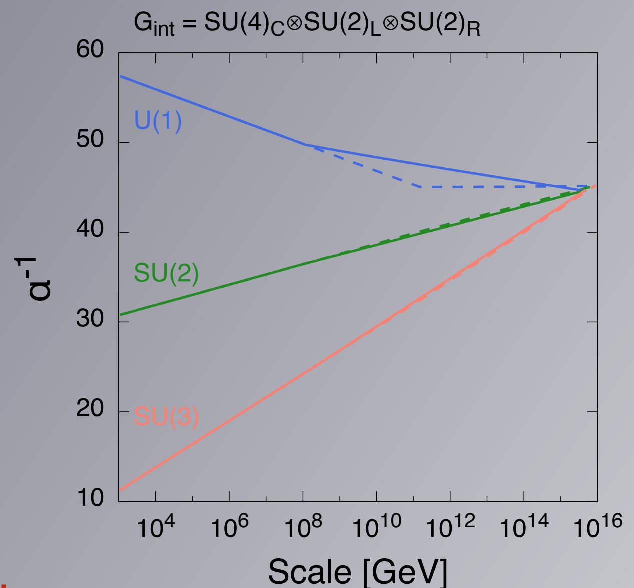
Mambrini, Nagata, Olive, Zheng

# Examples:

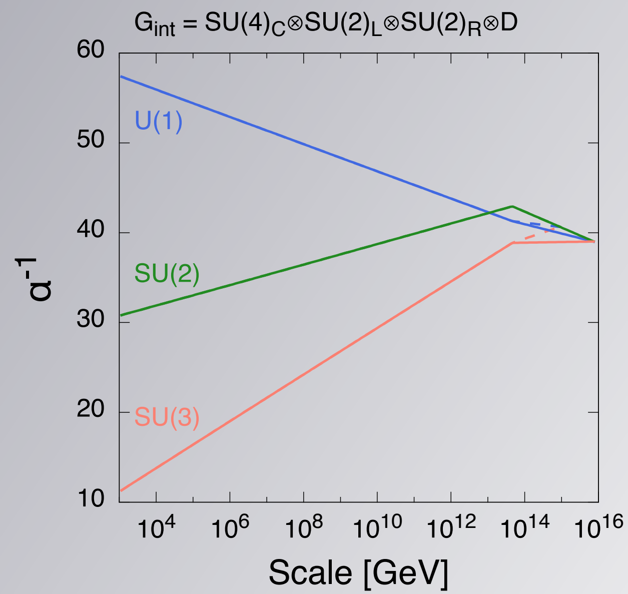
SM Fermion Singlets: Produced thermally out of equilibrium
$\Rightarrow$ Fermionic candidates (NETDM)

Mambrini, Olive, Quevillon, Zaldivar

| | Model I | Model II |
|---|---|---|
| $G_{\rm int}$ | $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$ | $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \otimes D$ |
| $R_{\rm DM}$ | $(\mathbf{1},\mathbf{1},\mathbf{3})_D$ in $\mathbf{45}_D$ | $(\mathbf{15},\mathbf{1},\mathbf{1})_W$ in $\mathbf{45}_W$ |
| $R_1$ | $\mathbf{210}_R$ | $\mathbf{54}_R$ |
| $R_2$ | $(\mathbf{10},\mathbf{1},\mathbf{3})_C \oplus (\mathbf{1},\mathbf{1},\mathbf{3})_R$ | $(\mathbf{10},\mathbf{1},\mathbf{3})_C \oplus (\mathbf{10},\mathbf{3},\mathbf{1})_C \oplus (\mathbf{15},\mathbf{1},\mathbf{1})_R$ |
| $\log_{10}(M_{\rm int})$ | 8.08(1) | 13.664(5) |
| $\log_{10}(M_{\rm GUT})$ | 15.645(7) | 15.87(2) |
| $g_{\rm GUT}$ | 0.53055(3) | 0.5675(2) |




(a) Model I




(b) Model II

Mambrini, Nagata, Olive, Quevillon, Zheng

# Examples:

## Non-Singlets: Fermions

| Model | $B-L$ | $\mathrm{SU}(2)_L$ | $Y$ | SO(10) representations |
|---|---|---|---|---|
| $\mathrm{F}_1^0$ | 0 | **1** | 0 | **45**, **54**, **210** |
| $\mathrm{F}_2^{1/2}$ | | **2** | 1/2 | **10**, **120**, **126**, **210′** |
| $\mathrm{F}_3^0$ | | **3** | 0 | **45**, **54**, **210** |
| $\mathrm{F}_3^1$ | | **3** | 1 | **54** |
| $\mathrm{F}_4^{1/2}$ | | **4** | 1/2 | **210′** |
| $\mathrm{F}_4^{3/2}$ | | **4** | 3/2 | **210′** |

| SO(10) representation | $\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$ |
|---|---|
| **45** | $(\mathbf{1}, \mathbf{3}, \mathbf{1})$ |
| **54** | $(\mathbf{1}, \mathbf{3}, \mathbf{3})$ |
| **210** | $(\mathbf{15}, \mathbf{3}, \mathbf{1})$ |

SM Triplets (Wino)

| SO(10) representation | $\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$ | $B-L$ |
|---|---|---|
| **10**, **120**, **210′** | $(\mathbf{1}, \mathbf{2}, \mathbf{2})$ | 0 |
| **120**, **126** | $(\mathbf{15}, \mathbf{2}, \mathbf{2})$ | 0 |
| **210** | $(\mathbf{10}, \mathbf{2}, \mathbf{2}) \oplus (\overline{\mathbf{10}}, \mathbf{2}, \mathbf{2})$ | $\pm 2$ |
| **210′** | $(\mathbf{1}, \mathbf{4}, \mathbf{4})$ | 0 |
| **54**, **210** | $(\mathbf{1}, \mathbf{1}, \mathbf{1})$ | 0 |
| **45** | $(\mathbf{1}, \mathbf{1}, \mathbf{3})$ | 0 |
| **45**, **210** | $(\mathbf{15}, \mathbf{1}, \mathbf{1})$ | 0 |
| **210** | $(\mathbf{15}, \mathbf{1}, \mathbf{3})$ | 0 |
| **126** | $(\mathbf{10}, \mathbf{1}, \mathbf{3})$ | 2 |

SM Doublets (Higgsino)

SM Singlets for mixing (Bino)

Nagata, Olive, Zheng

# Examples:

## Non-Singlets: Fermions

| $R_{\rm DM}$ | Additional Higgs in $R_1$ | $\log_{10} M_{\rm int}$ | $\log_{10} M_{\rm GUT}$ | $\alpha_{\rm GUT}$ | $\log_{10} \tau_p(p \to e^+\pi^0)$ |
|---|---|---|---|---|---|
| | | $G_{\rm int} = {\rm SU}(4)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R$ | | | |
| $(\mathbf{1}, \mathbf{3}, \mathbf{1})$ | $(\mathbf{15}, \mathbf{1}, \mathbf{1})$<br>$(\mathbf{15}, \mathbf{1}, \mathbf{3})$ | 6.54 | 17.17 | 0.0252 | $39.8 \pm 1.2$ |

| Model | $R_{\rm DM}$ | $R'_{\rm DM}$ | Higgs | $\log_{10} M_{\rm int}$ | $\log_{10} M_{\rm GUT}$ | $\alpha_{\rm GUT}$ | $\log_{10} \tau_p$ |
|---|---|---|---|---|---|---|---|
| | | | $G_{\rm int} = {\rm SU}(4)_C \otimes {\rm SU}(2)_L \otimes {\rm U}(1)_R$ | | | | |
| $\texttt{FA}_{421}$ | $(\mathbf{1}, \mathbf{2}, 1/2)_D$ | $(\mathbf{15}, \mathbf{1}, 0)_W$ | $(\mathbf{15}, \mathbf{1}, 0)_R$<br>$(\mathbf{15}, \mathbf{2}, 1/2)_C$ | 3.48 | 17.54 | 0.0320 | $40.9 \pm 1.2$ |
| | | | $G_{\rm int} = {\rm SU}(4)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R$ | | | | |
| $\texttt{FA}_{422}$ | $(\mathbf{1}, \mathbf{2}, \mathbf{2})_W$ | $(\mathbf{1}, \mathbf{3}, \mathbf{1})_W$ | $(\mathbf{15}, \mathbf{1}, \mathbf{1})_R$<br>$(\mathbf{15}, \mathbf{1}, \mathbf{3})_R$ | 9.00 | 15.68 | 0.0258 | $34.0 \pm 1.2$ |
| $\texttt{FB}_{422}$ | $(\mathbf{1}, \mathbf{2}, \mathbf{2})_W$ | $(\mathbf{1}, \mathbf{3}, \mathbf{1})_W$ | $(\mathbf{15}, \mathbf{1}, \mathbf{1})_R$<br>$(\mathbf{15}, \mathbf{2}, \mathbf{2})_C$<br>$(\mathbf{15}, \mathbf{1}, \mathbf{3})_R$ | 5.84 | 17.01 | 0.0587 | $38.0 \pm 1.2$ |

Nagata, Olive, Zheng

# Summary

- LHC susy and Higgs searches have pushed CMSSM-like models to “corners” or strips
- SO(10) models contain almost all of the benifits of SUSY models:
  - gauge coupling unification, radiative EWSB, stable Higgs vacuum, stable DM candidate….
- Several possibilities in non-SUSY SO(10) models which are phenomenologically consistent with p-decay limits
- Challenge lies in detection strategies