Supersymmetric Dark Matter or Not

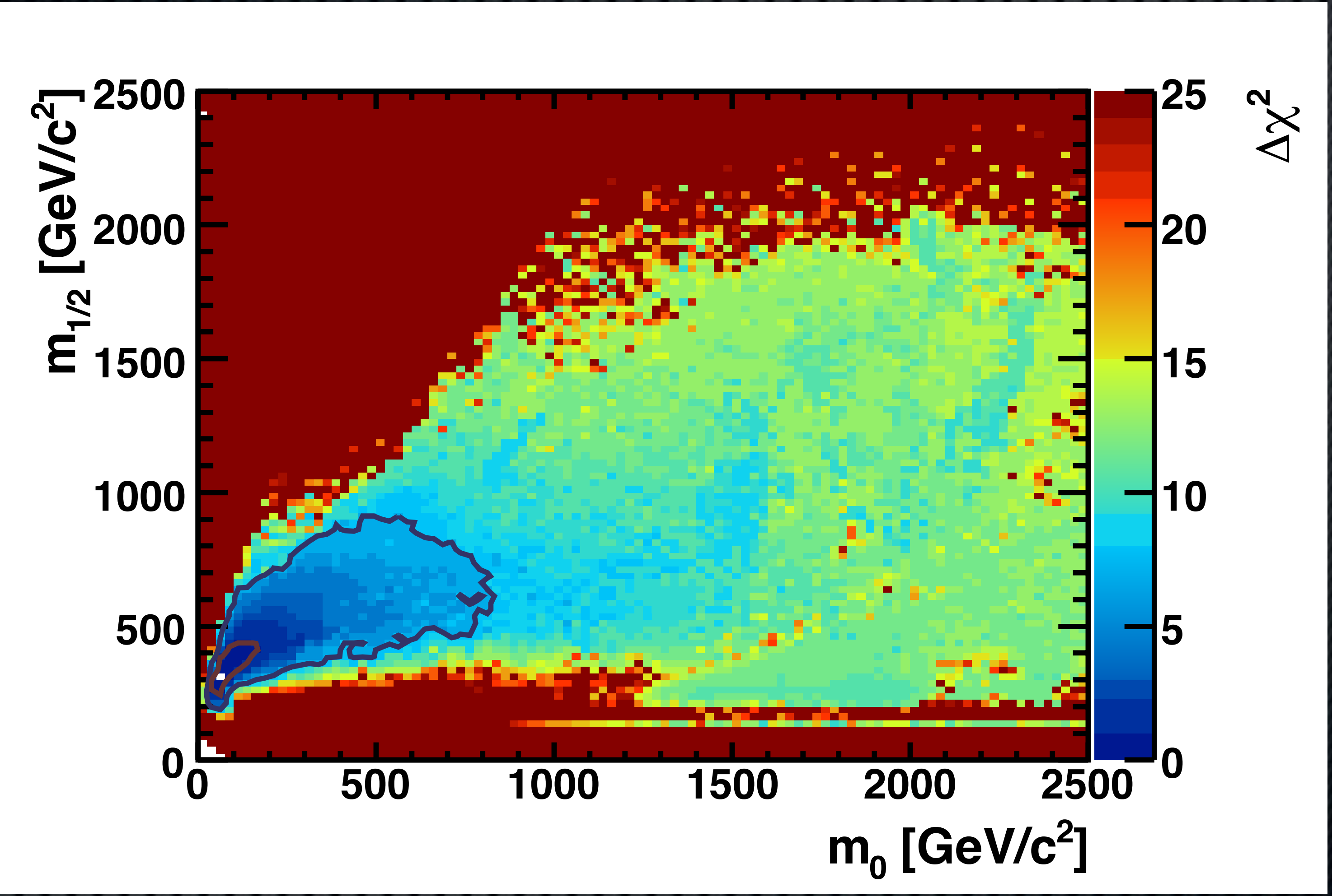
1) With CMSSM-like models pushed to high mass scales, can we still ‘guarantee’ Supersymmetry’s discovery at the LHC. Viable dark matter models in the CMSSM tend to lie in strips (co-annihilation, funnel, focus point), how far up in energy do these strips extend?

2) Non-Supersymmetric SO(10) - gauge coupling unification; neutrino masses; AND DARK MATTER.

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

Mastercode

2009



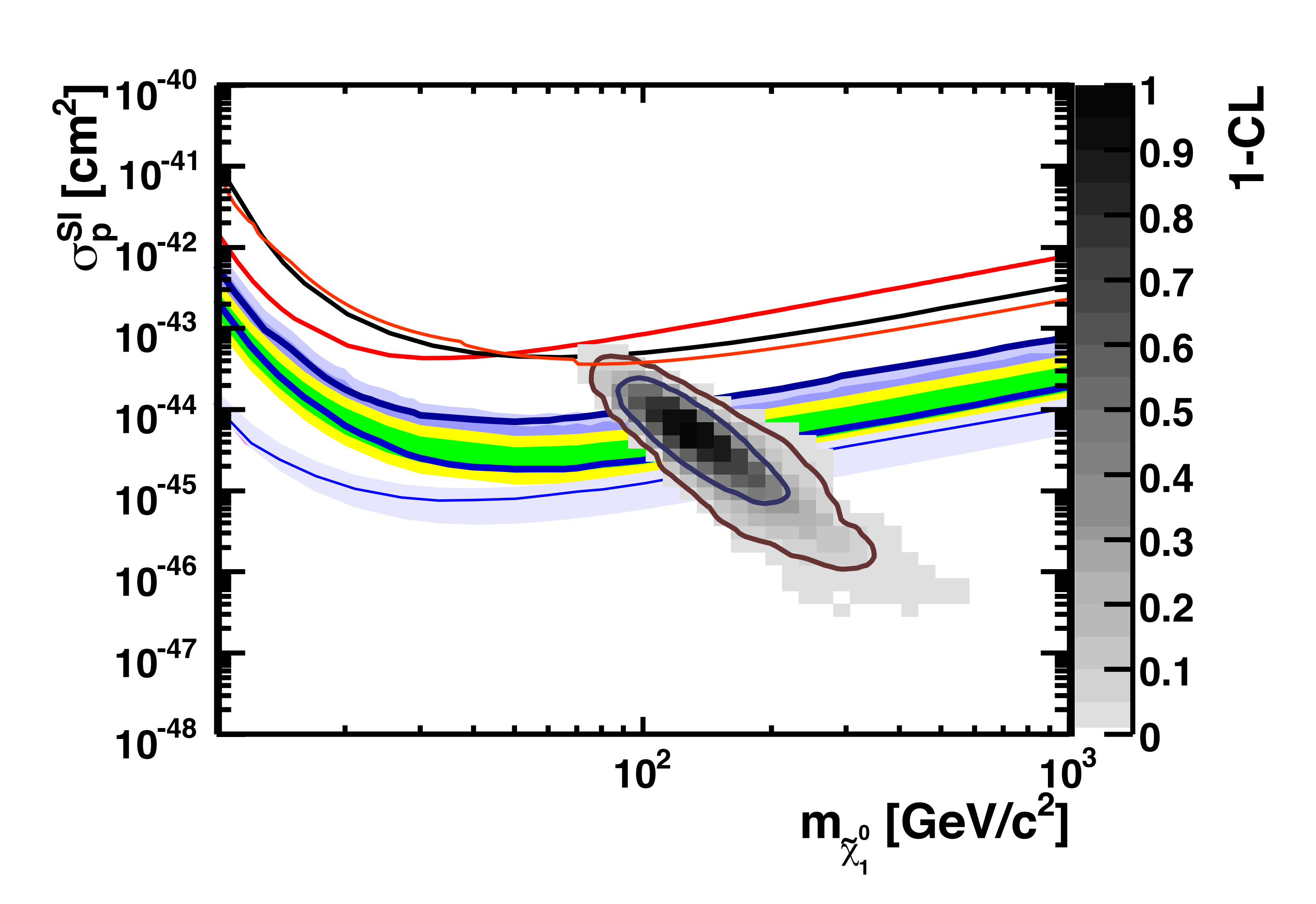
- CMSSM

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

Elastic scaterring cross-section

Mastercode

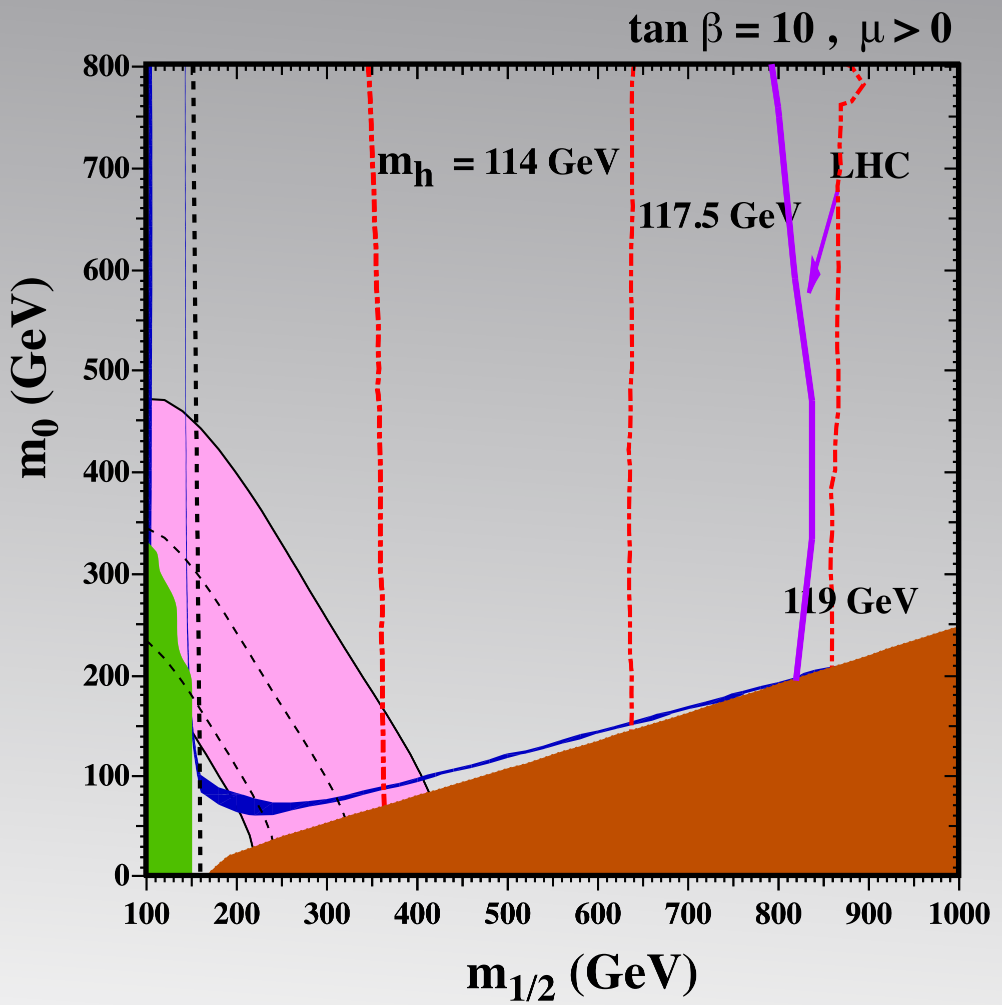
2009

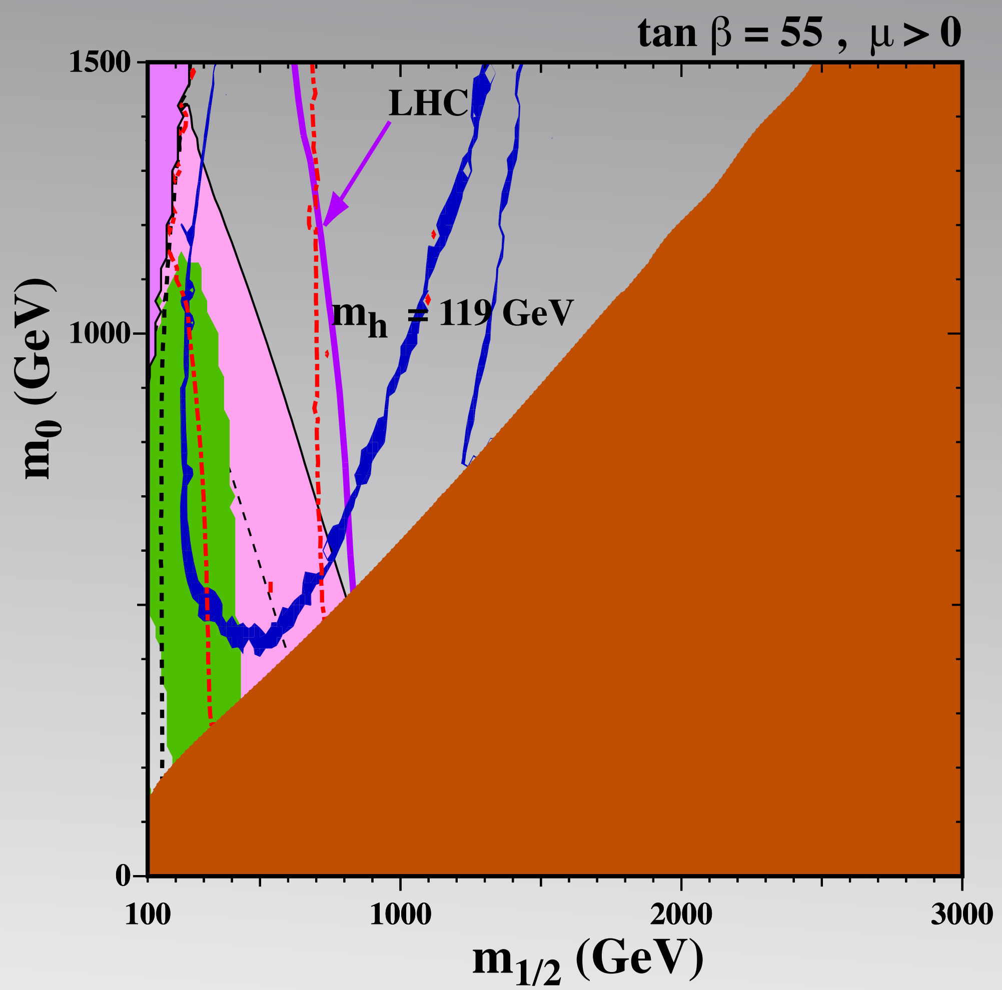


- CMSSM

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

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





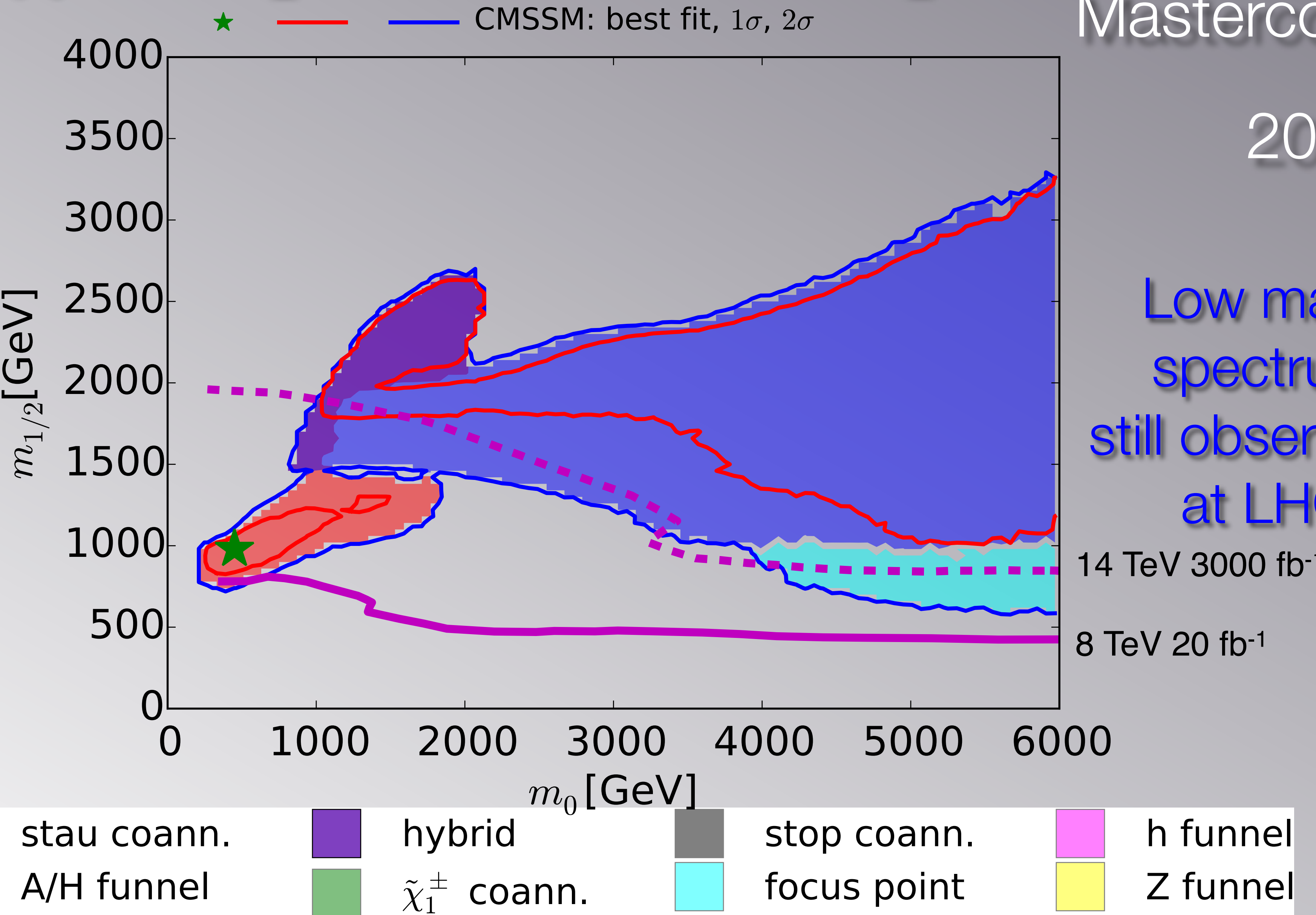
- CMSSM

Ellis, Olive, Santoso, Spanos

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

Mastercode

2015



Low mass spectrum still observable at LHC

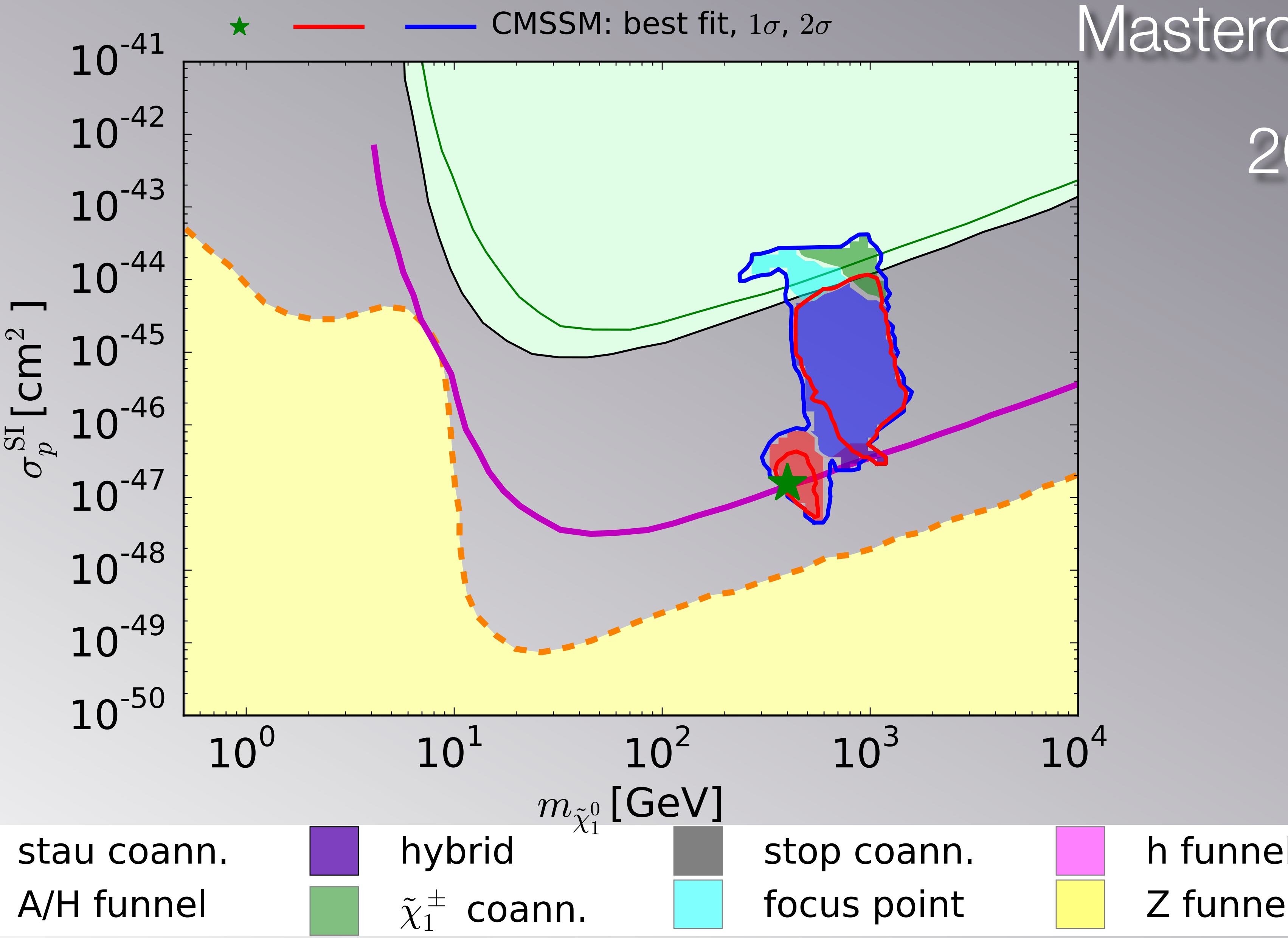
Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

- CMSSM

Elastic scaterring cross-section

Mastercode

2015



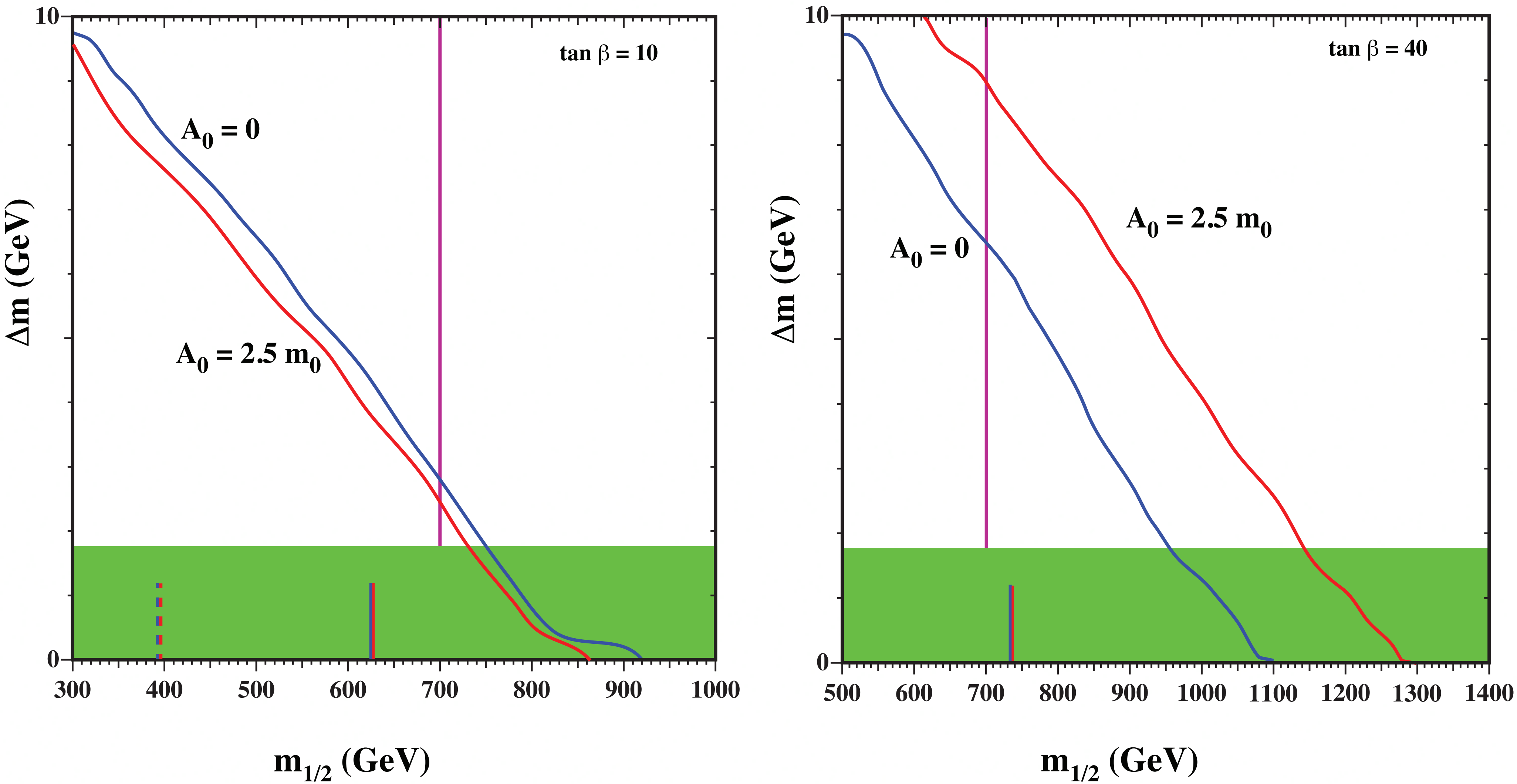
Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

- CMSSM

The Strips:

- Stau-coannhilation Strip
  - extends only out to ~1 TeV

Stau strip (end points)

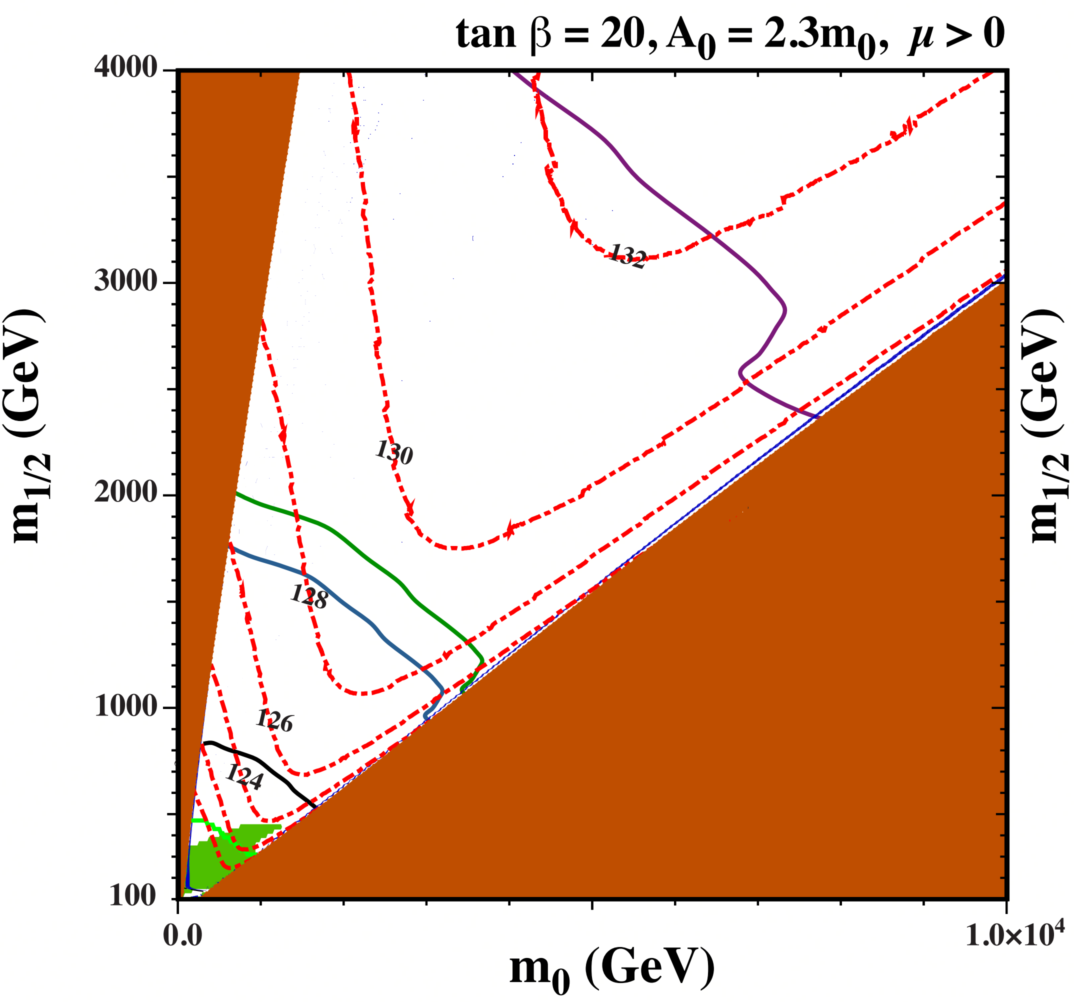


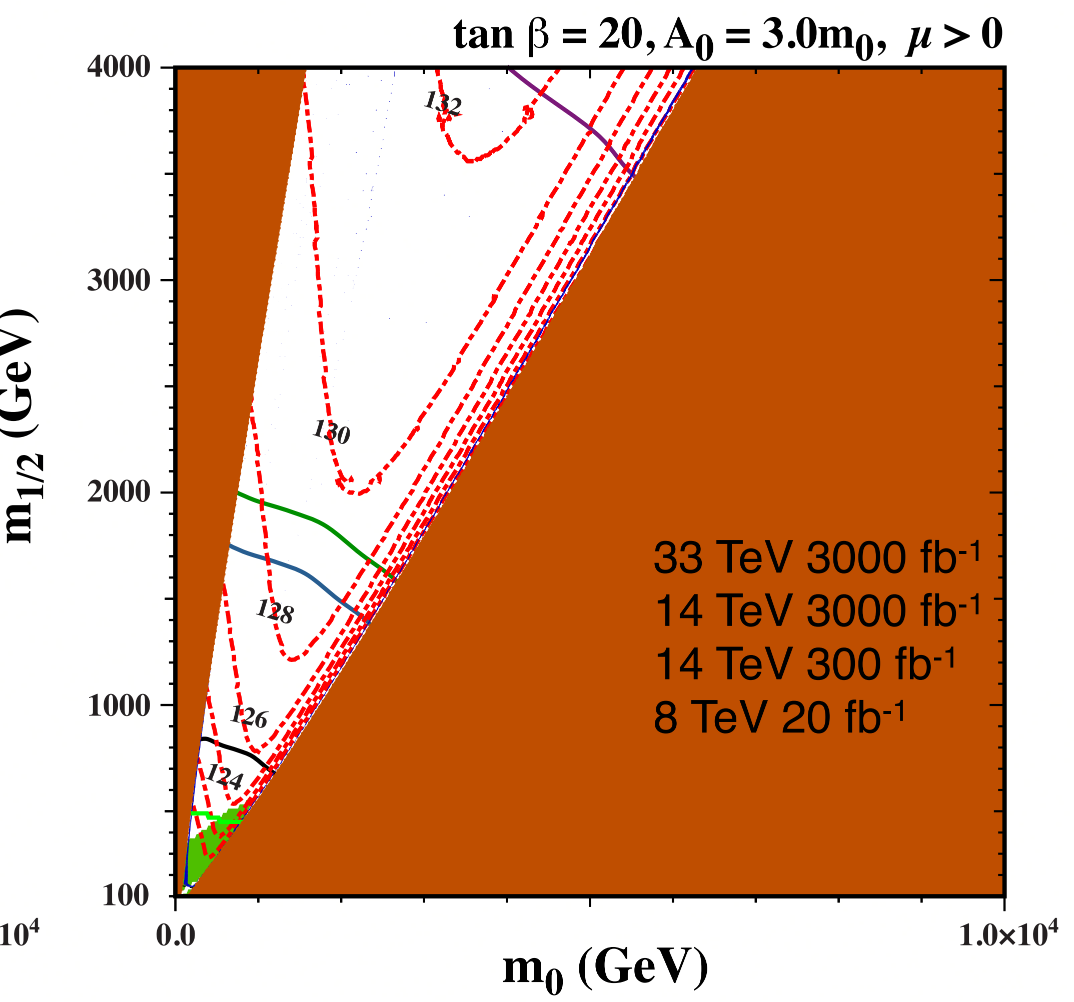
Citron, Ellis, Luo, Marrouche, Olive, de Vries

The Strips:

- Stau-coannhilation Strip
  - extends only out to ~1 TeV
- Stop-coannihilation Strip

Stop strip

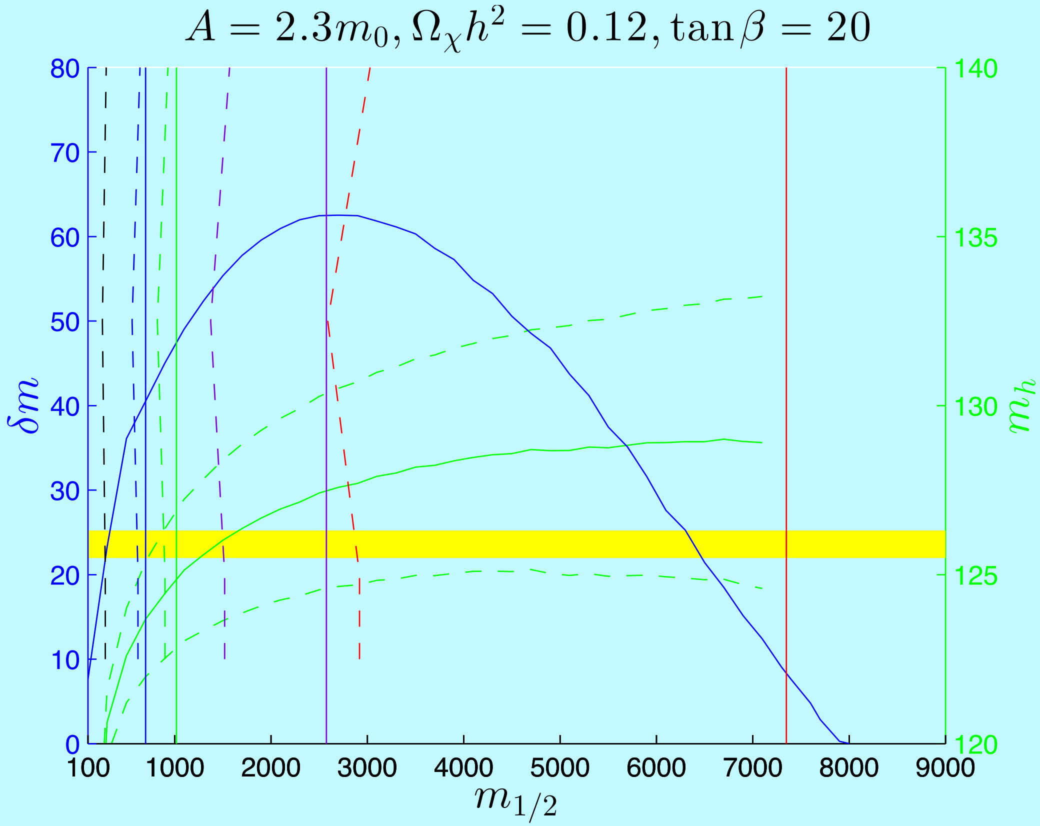


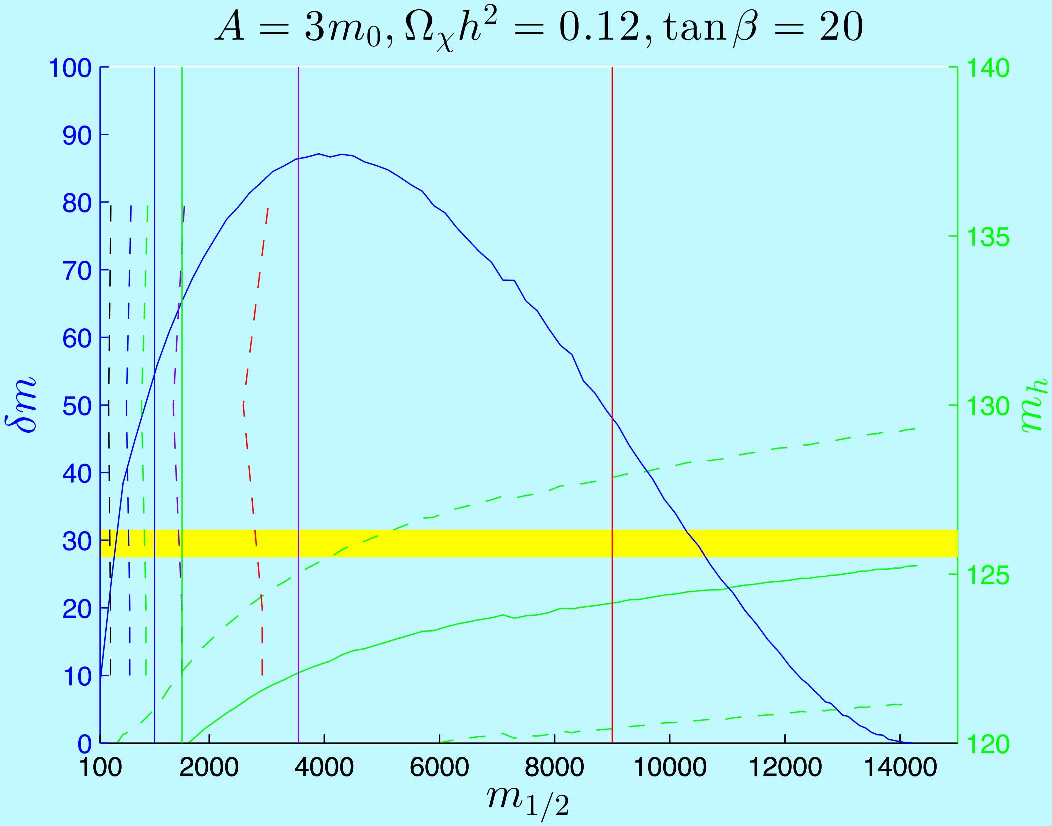


Buchmueller, Citron, Ellis, Guha, Marrouche, Olive, de Vries, Zheng

Ellis, Olive, Zheng

Stop strip





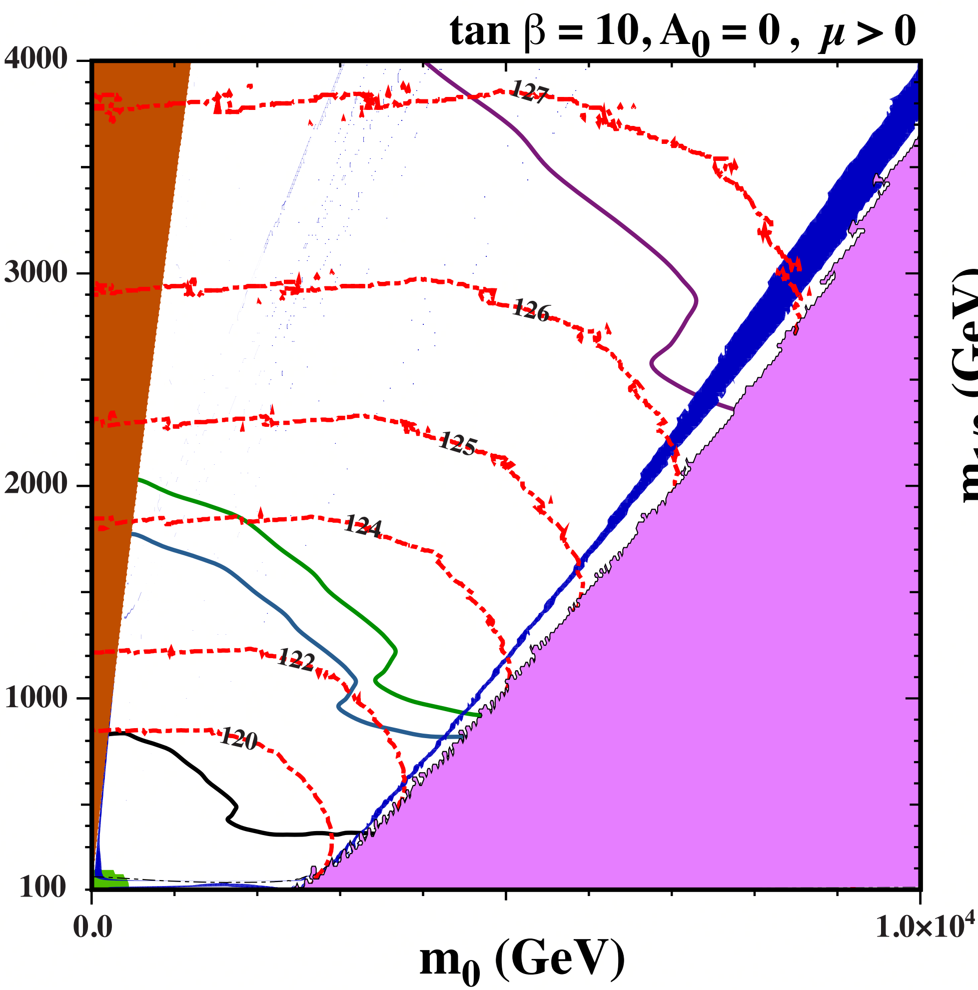
Buchmueller, Citron, Ellis, Guha, Marrouche, Olive, de Vries, Zheng

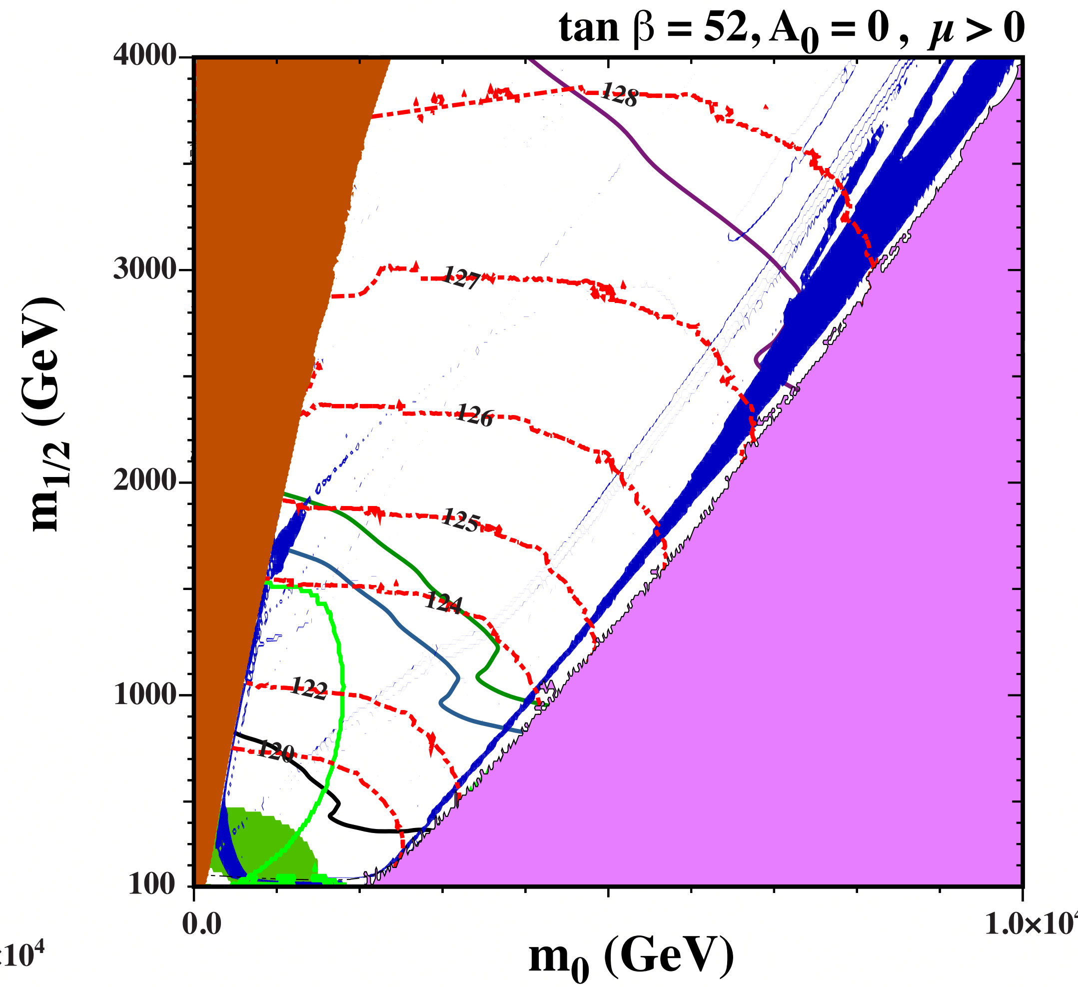
Ellis, Olive, Zheng

The Strips:

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

Focus Point

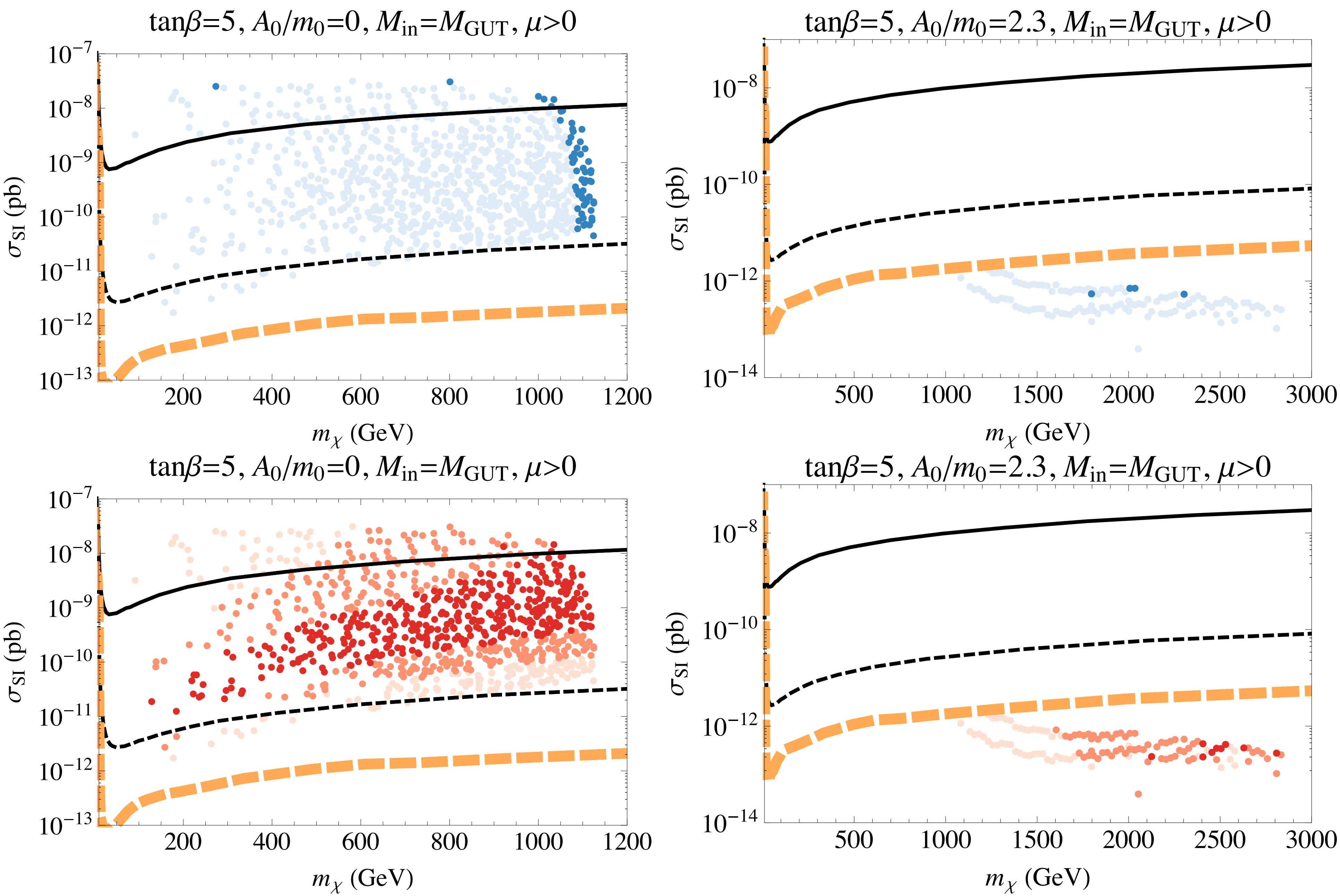




Buchmueller, Citron, Ellis, Guha, Marrouche, Olive, de Vries, Zheng

Ellis, Olive, Zheng

Direct detectability

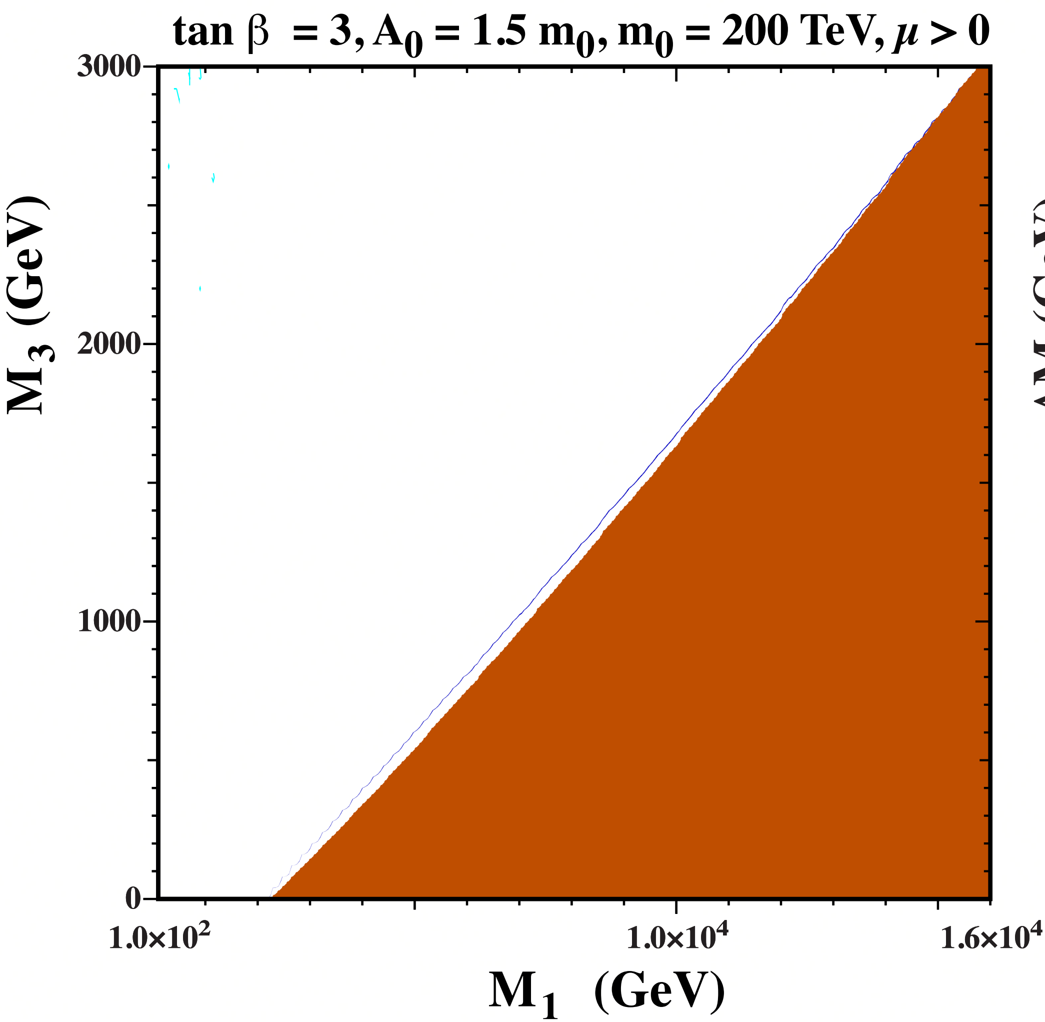


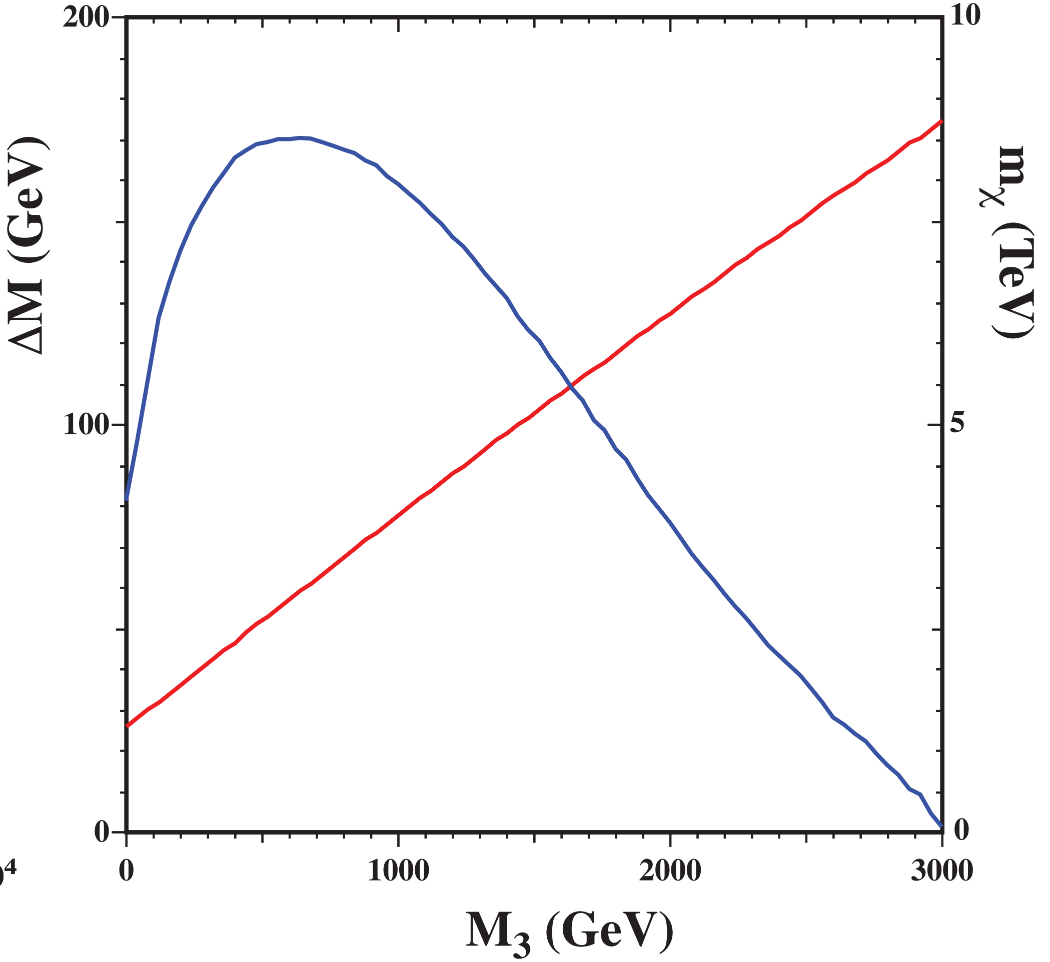
Ellis,Evans, Nagata, Olive, Sandick, Zheng

The Strips:

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

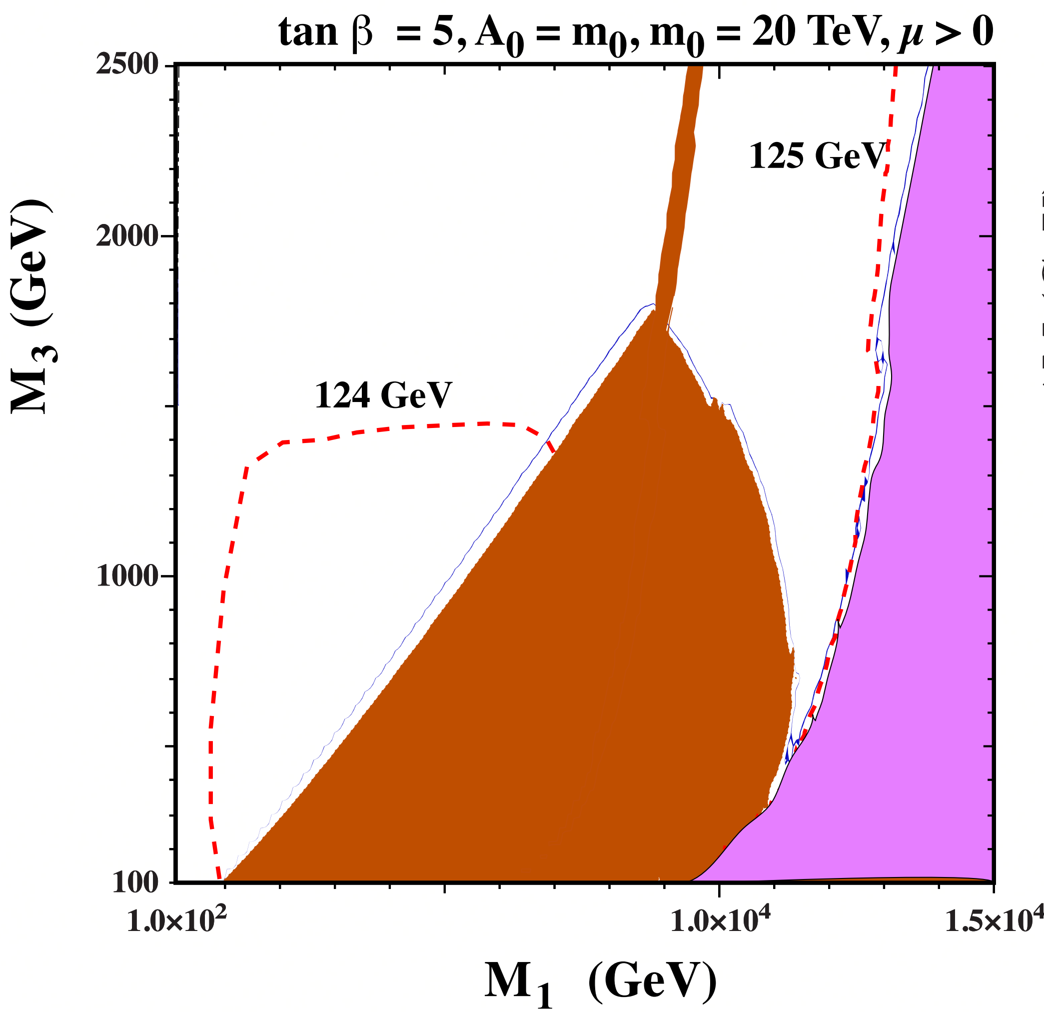
Gluino Strips ($M_3 \neq M_1 = M_2$ @ M_{GUT})

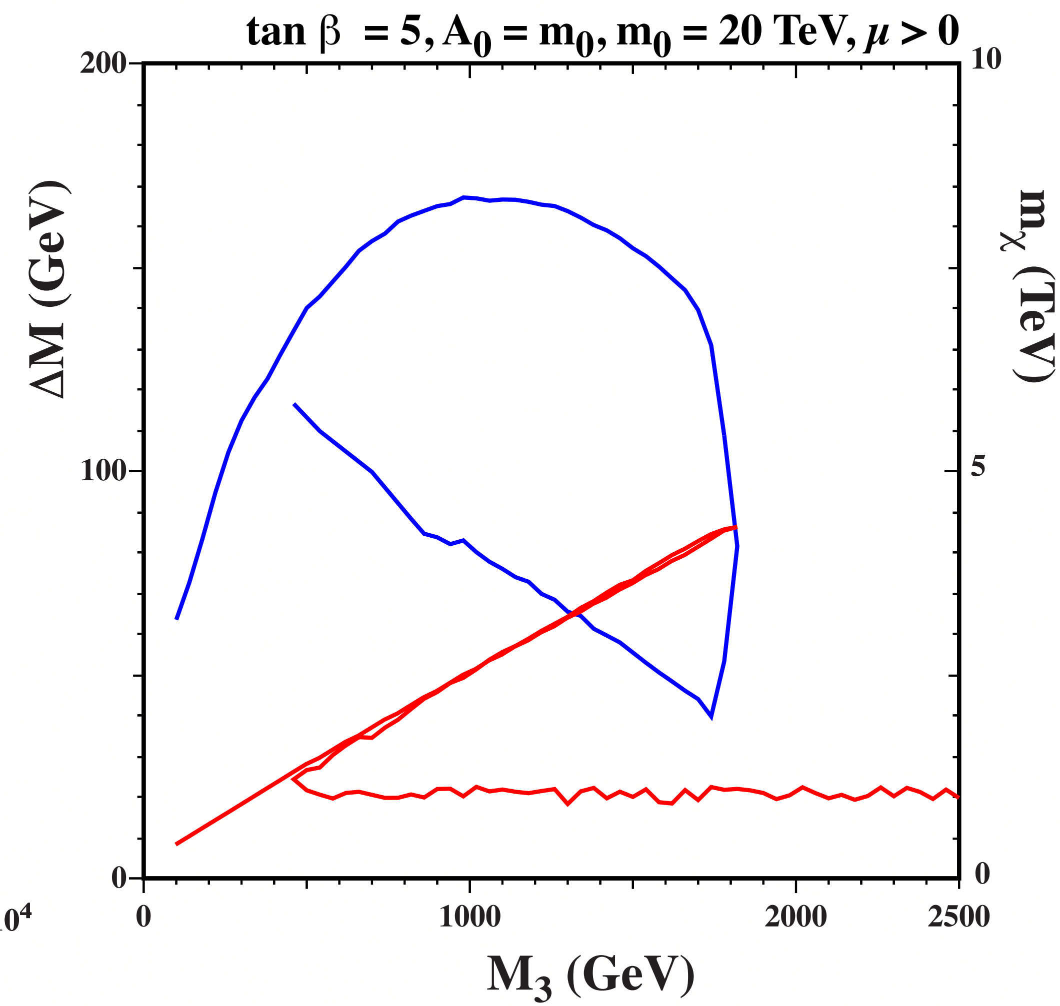




Ellis, Evans, Luo, Olive

Gluino Strips ($M_3 \neq M_1 = M_2$ @ M_{GUT})





Ellis, Evans, Luo, Olive

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

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 ~ 126 GeV, and no SUSY?

SO(10) GUT?

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

Neutrino masses…

Recipe for constructing an SO(10) DM model

0. Get a copy of Slansky's review (Phys Rep 79 (1981) 1) (or something equivalent)

Table 42

SO_{10} tensor products

$10\times 10 = 1_s + 45_a + 54_s$
$\overline{16}\times 10 = 16 + 144$
$16\times 16 = 10_s + 120_a + 126_s$
$\overline{16}\times 16 = 1 + 45 + 210$
$45\times 10 = 10 + 120 + 320$
$45\times 16 = 16 + 144 + 560$
$45\times 45 = 1_s + 45_a + 54_s + 210_s + 770_s + 945_a$
$54\times 10 = 10 + 210' + 320$
$54\times 16 = 144 + 720$
$54\times 45 = 45 + 54 + 945 + 1386$
$54\times 54 = 1_s + 45_a + 54_s + 660_s + 770_s + 1386_a$
$120\times 10 = 45 + 210 + 945$
$120\times \overline{16} = 16 + 144 + 560 + 1200$
$120\times 45 = 10 + 120 + 126 + \overline{126} + 320 + 1728 + 2970$
$120\times 54 = 120 + 320 + 1728 + 4312$
$120\times 120 = 1_s + 45_a + 54_s + 210_s + 210_a + 770_s + 945_a + 1050_s + \overline{1050}_s + 4125_s + 5940_a$
$126\times 10 = 210 + 1050$
$\overline{126}\times \overline{16} = 144 + 672 + 1200$
$126\times \overline{16} = 16 + 560 + 1440$
$126\times 45 = 120 + 126 + 1728 + 3696$
$126\times 54 = \overline{126} + 1728 + 4950$
$126\times 120 = 45 + 210 + 945 + 1050 + 5940 + 6930$
$126\times 126 = 54_s + 945_a + 1050_s + 2772_s + 4125_s + 6930_a$
$\overline{126}\times 126 = 1 + 45 + 210 + 770 + 5940 + 8910$
$\overline{144}\times 10 = 16 + 144 + 560 + 720$
$\overline{144}\times 16 = 45 + 54 + 210 + 945 + 1050$
$\overline{144}\times \overline{16} = 10 + 120 + 126 + 320 + 1728$
$144\times 45 = 16 + 144_1 + 144_2 + 560 + 720 + 1200 + 3696'$
$144\times 54 = 16 + 144 + 560 + 720 + 2640 + 3696'$
$\overline{144}\times 120 = 16 + 144_1 + 144_2 + 560_1 + 560_2 + 720 + 1200 + 1440 + 3696' + 8800$
$\overline{144}\times 126 = 144 + 560 + 720 + 1200 + 1440 + 5280 + 8800$
$\overline{144}\times \overline{126} = 16 + 144 + 560 + 1200 + 1440 + 3696' + 11088$
$144\times 144 = 10_s + 120_{a1} + 120_{a2} + 126_s + \overline{126}_s + 210'_s + 320_s + 320_a + 1728_s + 1728_a + 2970_s + 3696_a + 4312_a + 4950_s$
$\overline{144}\times 144 = 1 + 45_1 + 45_2 + 54 + 210_1 + 210_2 + 770 + 945_1 + 945_2 + 1050 + \overline{1050} + 1386 + 5940 + 8085$
$210\times 10 = 120 + 126 + \overline{126} + 1728$
$210\times 16 = 16 + 144 + 560 + 1200 + 1440$
$210\times 45 = 45 + 210_1 + 210_2 + 945 + 1050 + \overline{1050} + 5940$
$210\times 54 = 210 + 945 + \overline{1050} + 1050 + 8085$
$210\times 120 = 10 + 120_1 + 120_2 + 126 + \overline{126} + 320 + 1728_1 + 1728_2 + 2970 + 3696 + \overline{3696} + 10560$
$210\times 126 = 10 + 120 + 126 + 320 + 1728 + 2970 + 3696 + 6930' + 10560$
$210\times 144 = 16 + 144_1 + 144_2 + 560_1 + 560_2 + 672 + 720 + 1200_1 + 1200_2 + 1440 + 3696' + 8800 + 11088$
$210\times 210 = 1_s + 45_s + 45_a + 54_s + 210_s + 210_a + 770_s + 945_{a1} + 945_{a2} + \overline{1050}_s + 1050_s + 4125_s + 5940_s + 5940_a + 6930_a + \overline{6930}_a + 8910_s$

GROUP THEORY FOR UNIFIED MODEL BUILDING

R. SLANSKY

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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

0. Get a copy of Slansky's review (Phys Rep 79 (1981) 1) (or something equivalent)

1. Pick an Intermediate Scale Gauge Group

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

G_{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 $\mathrm{SU}(5) \otimes \mathrm{U}(1)$	$\mathbf{45}, \mathbf{210}$

Recipe for constructing an SO(10) DM model

0. Get a copy of Slansky's review (Phys Rep 79 (1981) 1)
   (or something equivalent)

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 ν_R from 16 16 126 → $m_{\nu R} \sim M_{int}$

Recipe for constructing an SO(10) DM model

0. Get a copy of Slansky's review (Phys Rep 79 (1981) 1)
   (or something equivalent)

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

0. Get a copy of Slansky's review (Phys Rep 79 (1981) 1) (or something equivalent)

1. Pick an Intermediate Scale Gauge Group

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

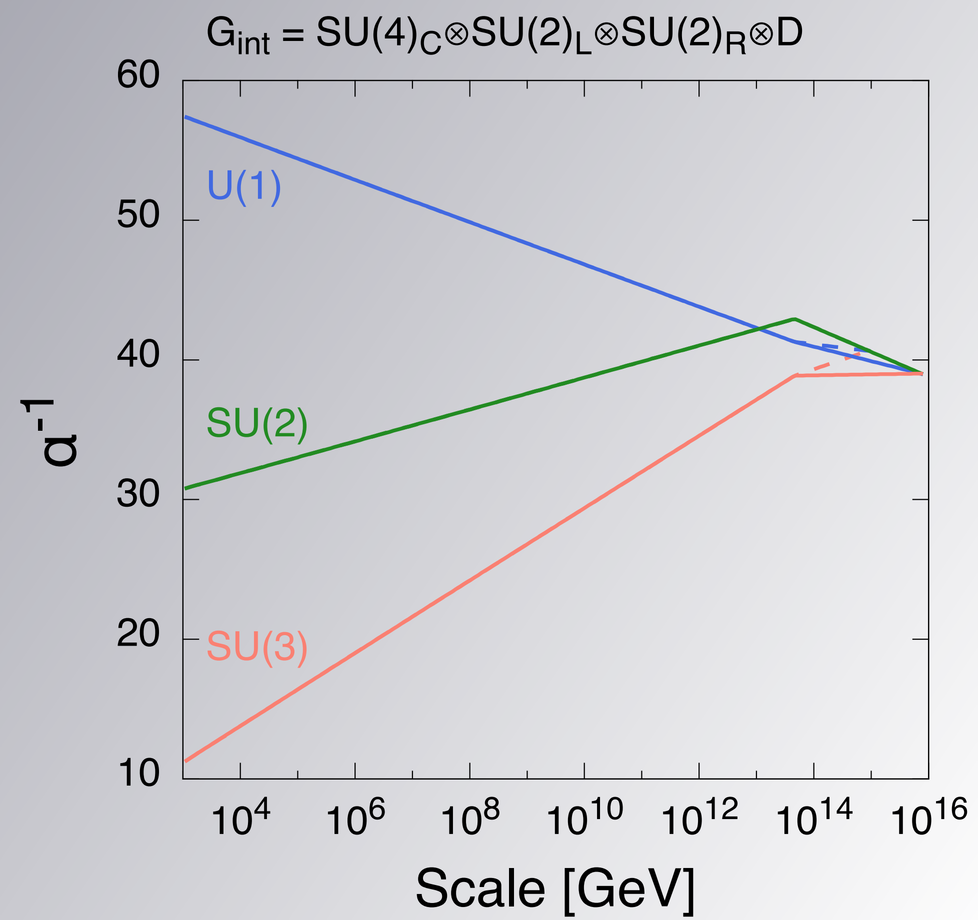
3. Pick DM representation and insure proper splitting within the multiplet, and pick low energy field content

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}, α_{GUT}



Examples:

Scalars

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

Nagata, Olive, Zheng

Examples:

Scalars

Higgs portal models
Inert Higgs doublet models

Model	$\log_{10} M_{\rm GUT}$	$\log_{10} M_{\rm int}$	$\alpha_{\rm GUT}$	$\log_{10} \tau_p(p \to e^+\pi^0)$
$G_{\rm int} = {\rm SU}(4)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R$				
$\texttt{SA}_{422}$	16.33	11.08	0.0218	36.8 ± 1.2
$\texttt{SB}_{422}$	15.62	12.38	0.0228	34.0 ± 1.2
$G_{\rm int} = {\rm SU}(3)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R \otimes {\rm U}(1)_{B-L}$				
$\texttt{SA}_{3221}$	16.66	8.54	0.0217	38.1 ± 1.2
$\texttt{SB}_{3221}$	16.17	9.80	0.0223	36.2 ± 1.2
$\texttt{SC}_{3221}$	15.62	9.14	0.0230	34.0 ± 1.2
$G_{\rm int} = {\rm SU}(3)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R \otimes {\rm U}(1)_{B-L} \otimes D$				
$\texttt{SA}_{3221D}$	15.58	10.08	0.0231	33.8 ± 1.2
$\texttt{SB}_{3221D}$	15.40	10.44	0.0233	33.1 ± 1.2

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

mass splitting:

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

Examples:

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

Mambrini, Olive, Quevillon, Zaldivar

To aid in gauge coupling unification, DM should be
a SM singlet but a non-singlet under the Intermediate gauge group.
Requires splitting multiplets

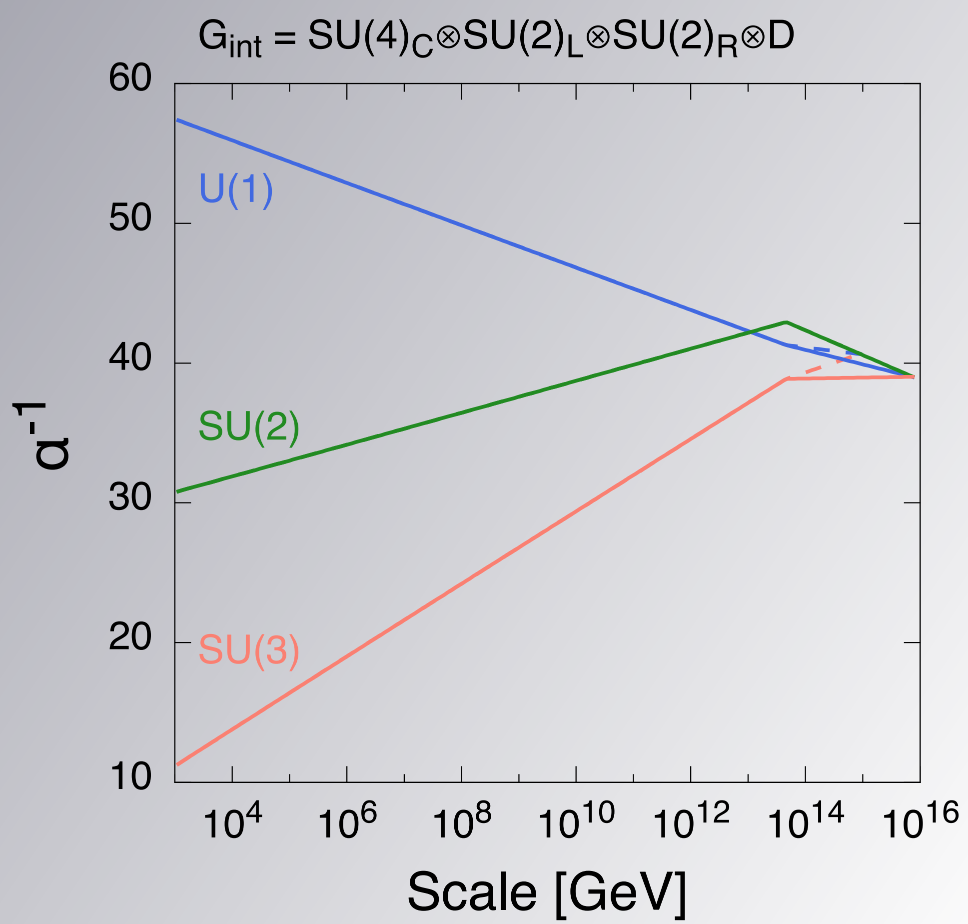
G_{int}	R_{DM}	SO(10)
$SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$	$(\mathbf{1}, \mathbf{1}, \mathbf{3})$	$\mathbf{45}$
	$(\mathbf{15}, \mathbf{1}, \mathbf{1})$	$\mathbf{45}, \mathbf{210}$
	$(\mathbf{10}, \mathbf{1}, \mathbf{3})$	$\mathbf{126}$
	$(\mathbf{15}, \mathbf{1}, \mathbf{3})$	$\mathbf{210}$
$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$	$(\mathbf{15}, \mathbf{1}, 0)$	$\mathbf{45}, \mathbf{210}$
	$(\mathbf{10}, \mathbf{1}, 1)$	$\mathbf{126}$
$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$	$(\mathbf{1}, \mathbf{1}, \mathbf{3}, 0)$	$\mathbf{45}, \mathbf{210}$
	$(\mathbf{1}, \mathbf{1}, \mathbf{3}, -2)$	$\mathbf{126}$
$SU(3)_C \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L}$	$(\mathbf{1}, \mathbf{1}, 1, -2)$	$\mathbf{126}$

Mambrini, Nagata, Olive, Quevillon, Zheng

Gauge Coupling Unification

Also fix particle content below M_{GUT}

R_{DM}	R_2	$\log_{10}(M_{int})$	$\log_{10}(M_{GUT})$	g_{GUT}
$SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$				
$(\mathbf{1},\mathbf{1},\mathbf{3})_W$	$(\mathbf{10},\mathbf{1},\mathbf{3})_C$ $(\mathbf{1},\mathbf{1},\mathbf{3})_R$	10.8	15.9	0.53
$(\mathbf{1},\mathbf{1},\mathbf{3})_D$	$(\mathbf{10},\mathbf{1},\mathbf{3})_C$ $(\mathbf{1},\mathbf{1},\mathbf{3})_R$	9.8	15.7	0.53
$SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \otimes D$				
R_{DM}	R_2	$\log_{10}(M_{int})$	$\log_{10}(M_{GUT})$	g_{GUT}
$(\mathbf{15},\mathbf{1},\mathbf{1})_W$	$(\mathbf{10},\mathbf{1},\mathbf{3})_C$ $(\overline{\mathbf{10}},\mathbf{3},\mathbf{1})_C$ $(\mathbf{15},\mathbf{1},\mathbf{1})_R$	13.7	16.2	0.56
$(\mathbf{15},\mathbf{1},\mathbf{1})_W$	$(\mathbf{10},\mathbf{1},\mathbf{3})_C$ $(\overline{\mathbf{10}},\mathbf{3},\mathbf{1})_C$ $(\mathbf{15},\mathbf{1},\mathbf{3})_R$ $(\mathbf{15},\mathbf{3},\mathbf{1})_R$	14.2	15.5	0.56
$(\mathbf{15},\mathbf{1},\mathbf{1})_D$	$(\mathbf{10},\mathbf{1},\mathbf{3})_C$ $(\overline{\mathbf{10}},\mathbf{3},\mathbf{1})_C$ $(\mathbf{15},\mathbf{1},\mathbf{3})_R$ $(\mathbf{15},\mathbf{3},\mathbf{1})_R$	14.4	16.3	0.58
$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$				
R_{DM}	R_2	$\log_{10}(M_{int})$	$\log_{10}(M_{GUT})$	g_{GUT}
$(\mathbf{1},\mathbf{1},\mathbf{3},0)_W$	$(\mathbf{1},\mathbf{1},\mathbf{3},-2)_C$ $(\mathbf{1},\mathbf{1},\mathbf{3},0)_R$	6.1	16.6	0.52



Examples:

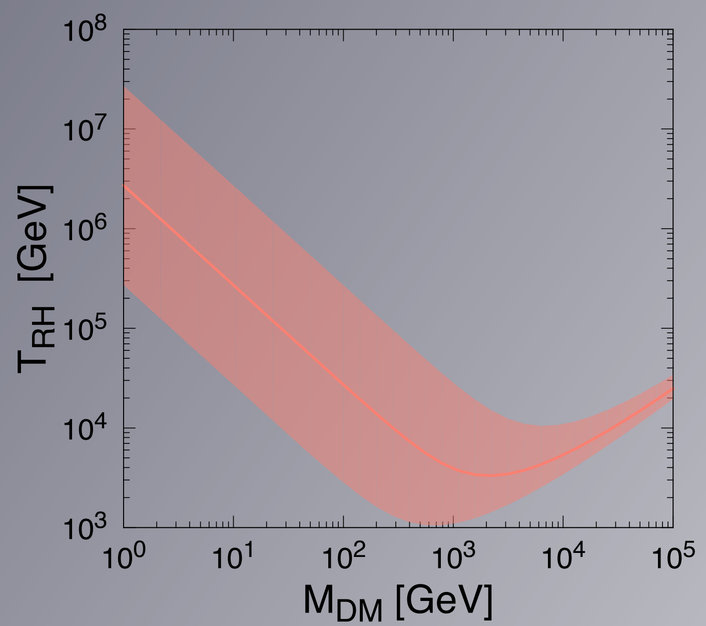
SM Fermion Singlets: Produced thermally out of equilibrium
⇒ Fermionic candidates (NETDM)

For mass splittings:

$$\mathcal{L}_{\rm int} = -\frac{M_{45_W}}{2}\mathbf{45}_W\mathbf{45}_W - \frac{y_{54}}{2}\mathbf{45}_W\mathbf{45}_W\mathbf{54}_R - \frac{y_{210}}{2}\mathbf{45}_W\mathbf{45}_W\mathbf{210}_R + \text{h.c.}\ ,$$

$15 = 8 + 3 + \overline{3} + 1$

$M_{15} \sim M_{45W} - y_{54}\, v_{54} \sim M_{int}$;
$M_1 \sim M_{15} - y_{210}\, v_{210}$



$G_{\rm int}$	$SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \otimes D$
$R_{\rm DM}$	$(\mathbf{15},\mathbf{1},\mathbf{1})_W$ in $\mathbf{45}_W$
R_1	$\mathbf{54}_R$
R_2	$(\mathbf{10},\mathbf{1},\mathbf{3})_C \oplus (\mathbf{10},\mathbf{3},\mathbf{1})_C \oplus (\mathbf{15},\mathbf{1},\mathbf{1})_R$
$\log_{10}(M_{\rm int})$	13.664(5)
$\log_{10}(M_{\rm GUT})$	15.87(2)
$g_{\rm GUT}$	0.5675(2)

$(10,1,3)_C$, $(10,3,1)_C \in 126$; $(15,1,1)_R \in 210$

Examples:

Non-Singlets: Fermions

Model	$B-L$	$SU(2)_L$	Y	SO(10) representations
F_1^0		$\mathbf{1}$	0	$\mathbf{45},\ \mathbf{54},\ \mathbf{210}$
$F_2^{1/2}$		$\mathbf{2}$	1/2	$\mathbf{10},\ \mathbf{120},\ \mathbf{126},\ \mathbf{210}'$
F_3^0	0	$\mathbf{3}$	0	$\mathbf{45},\ \mathbf{54},\ \mathbf{210}$
F_3^1		$\mathbf{3}$	1	$\mathbf{54}$
$F_4^{1/2}$		$\mathbf{4}$	1/2	$\mathbf{210}'$
$F_4^{3/2}$		$\mathbf{4}$	3/2	$\mathbf{210}'$

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

SM Triplets (Wino)

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

SM Doublets (Higgsino)

SM Singlets for mixing (Bino)

Nagata, Olive, Zheng

Examples:

Non-Singlets: Fermions

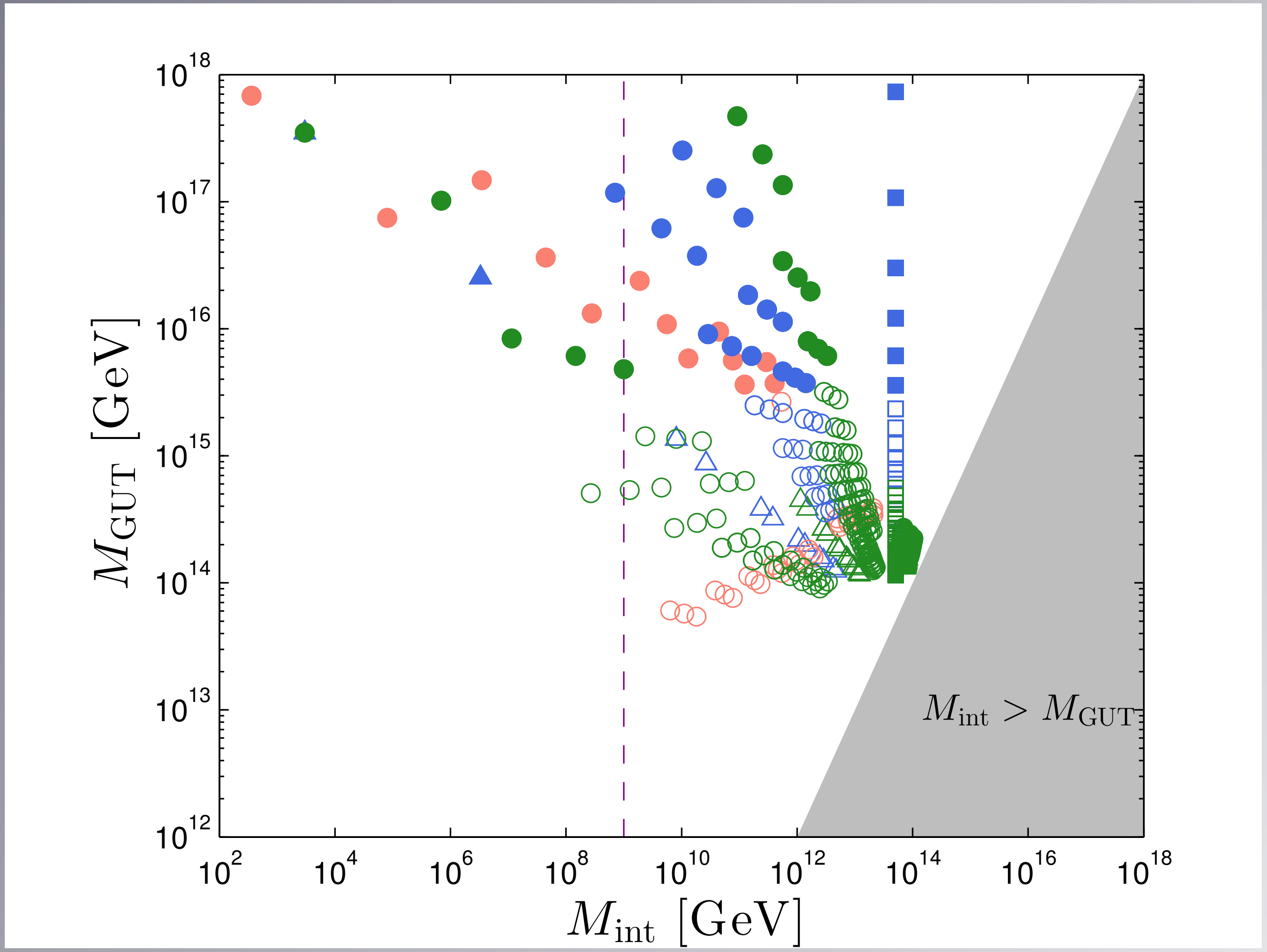
$R_{\rm DM}$	Additional Higgs in R_1	$\log_{10} M_{\rm int}$	$\log_{10} M_{\rm GUT}$	$\alpha_{\rm GUT}$	$\log_{10}\tau_p(p\to e^+\pi^0)$
	$G_{\rm int} = {\rm SU}(4)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R$				
$(\mathbf{1},\mathbf{3},\mathbf{1})$	$(\mathbf{15},\mathbf{1},\mathbf{1})$ $(\mathbf{15},\mathbf{1},\mathbf{3})$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

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

Examples:

Non-Singlets: Fermions

Summary Plot



Summary

- LHC susy and Higgs searches have pushed CMSSM-like models to “corners”
- Though some phenomenological solutions are still viable typically along “strips” in parameter space
- NUHM models with “low” μ still promising as are subGUT models; PGM (with wino DM or Higgsino DM)
- Several possibilities in non-SUSY SO(10) models
- Challenge lies in detection strategies