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More like TeV (or PeV or EeV) susy.

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Dominant constraint from m_H, but also from Fermi-LAT, HESS, IceCube/DeepCore

Constrained Models (CMSSM)

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

Constrained Models (CMSSM)

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- Gaugino mass Unification

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

Constrained Models (CMSSM)

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

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- A-term Unification

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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 \\
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Constrained Models (CMSSM)

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

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- 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}_{\text{soft}} &= -\frac{1}{2} M_\alpha \lambda^\alpha \lambda^\alpha - m_{ij}^2 \phi^{i*} \phi^j \\
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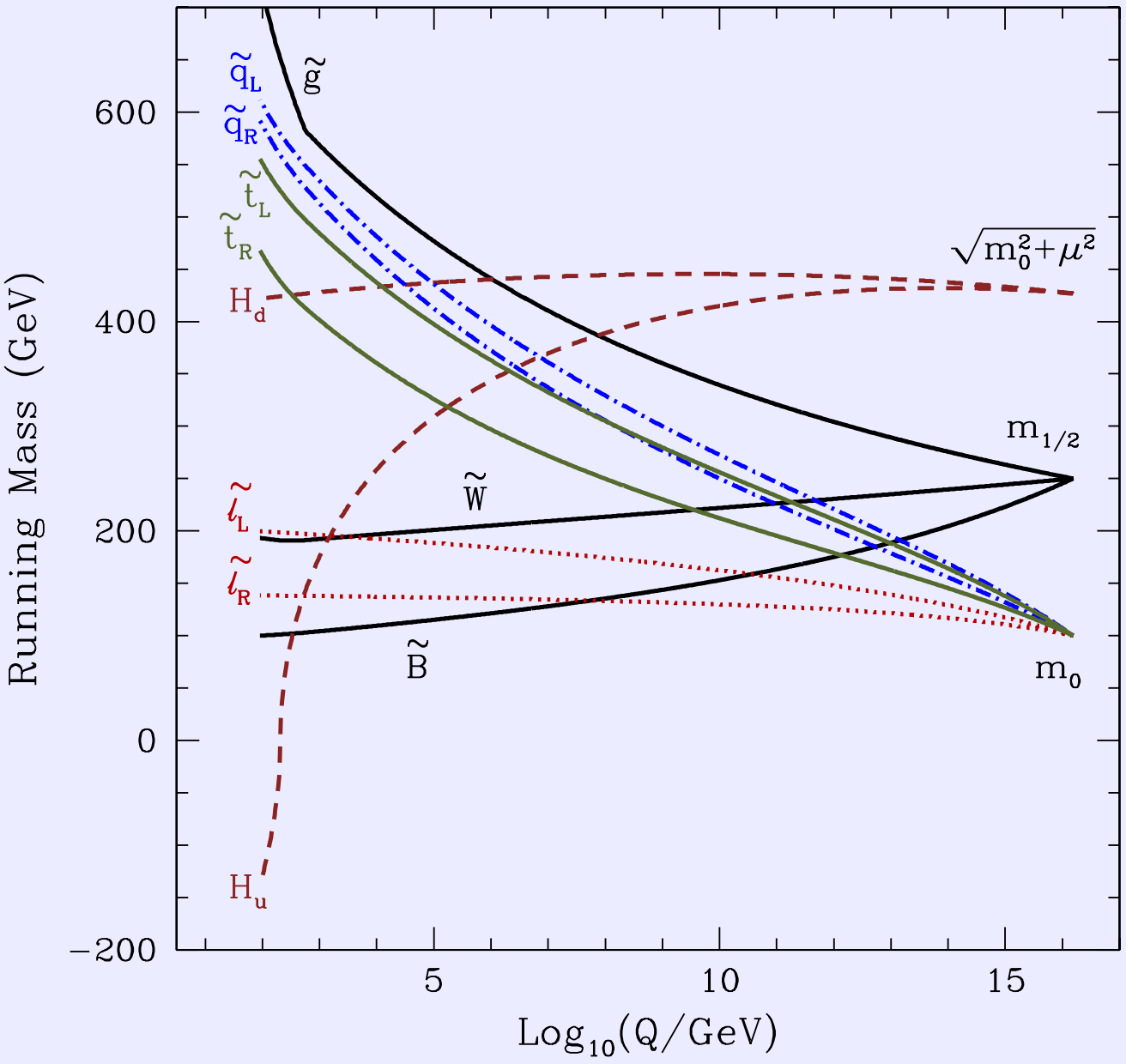
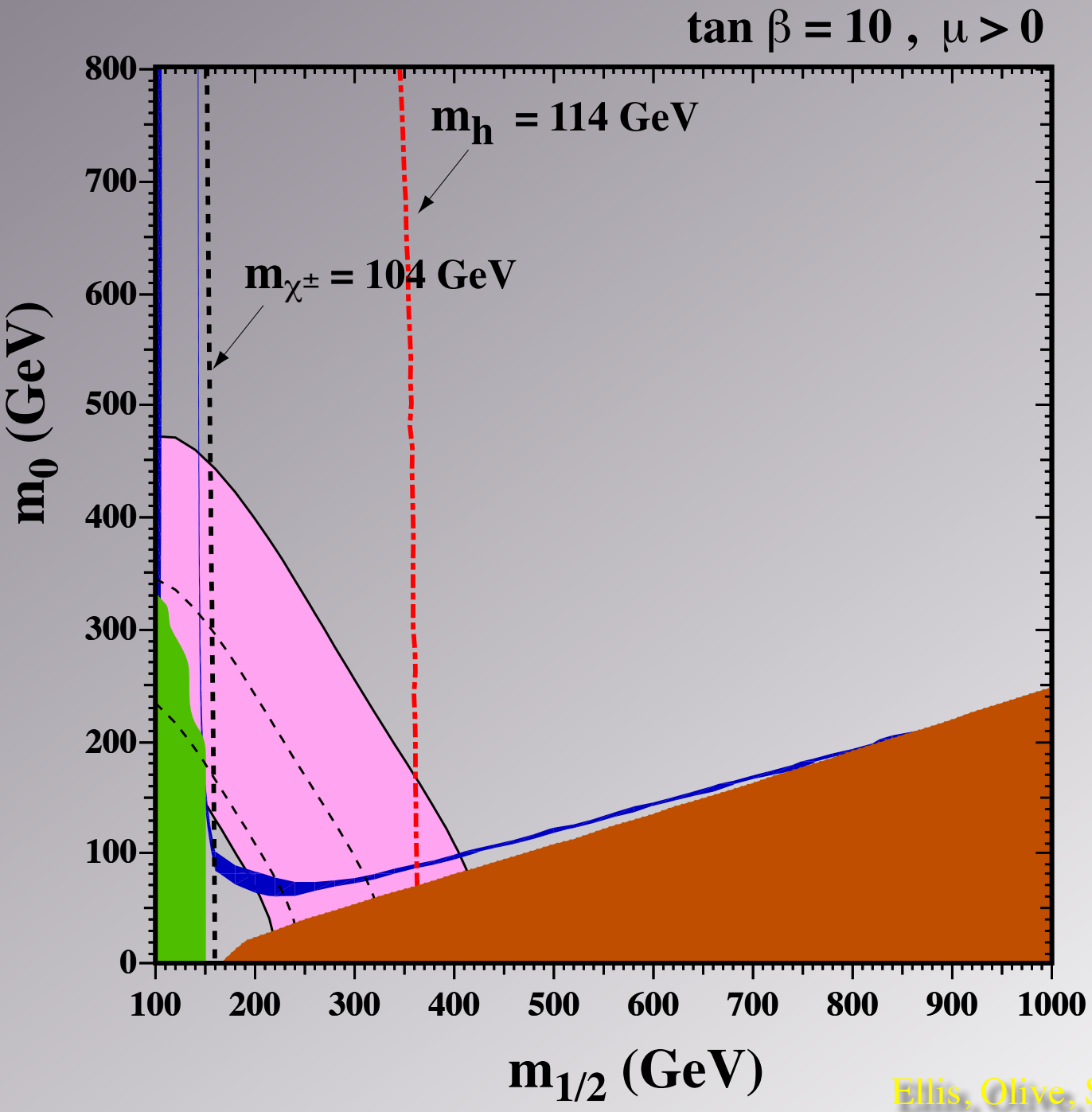
CMSSM Spectra



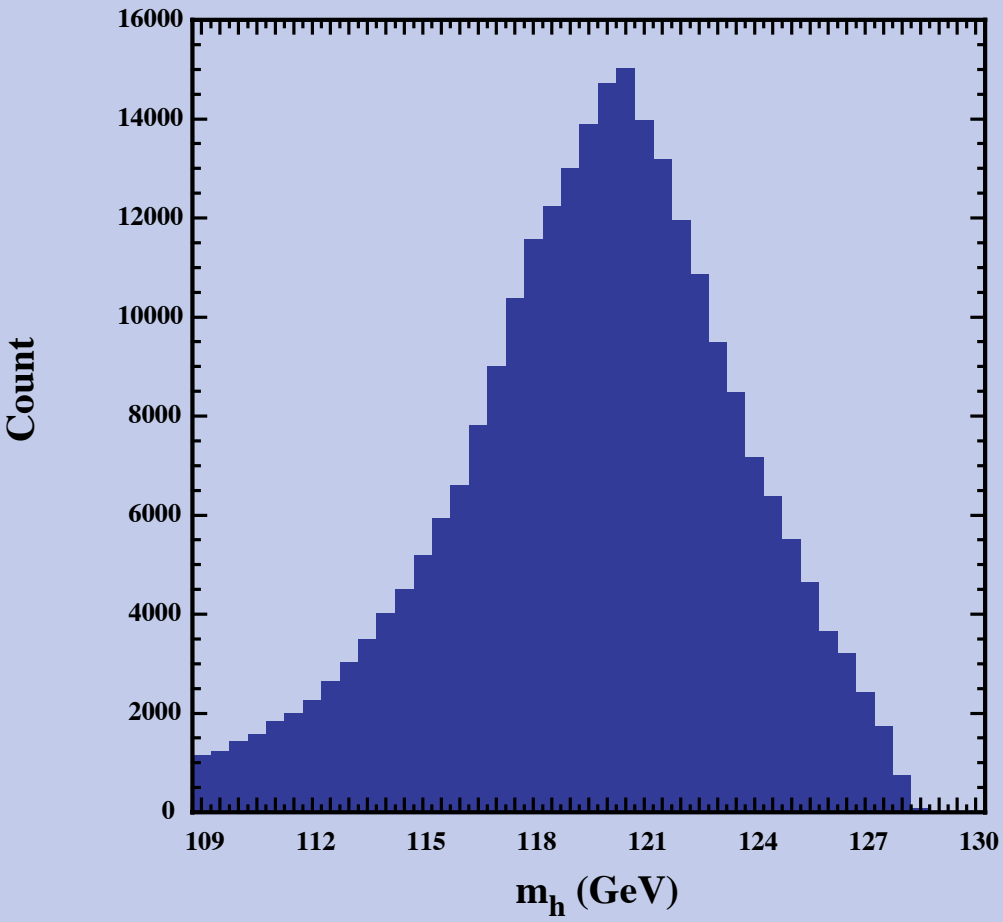
Unification to
rich spectrum
+
EWSB

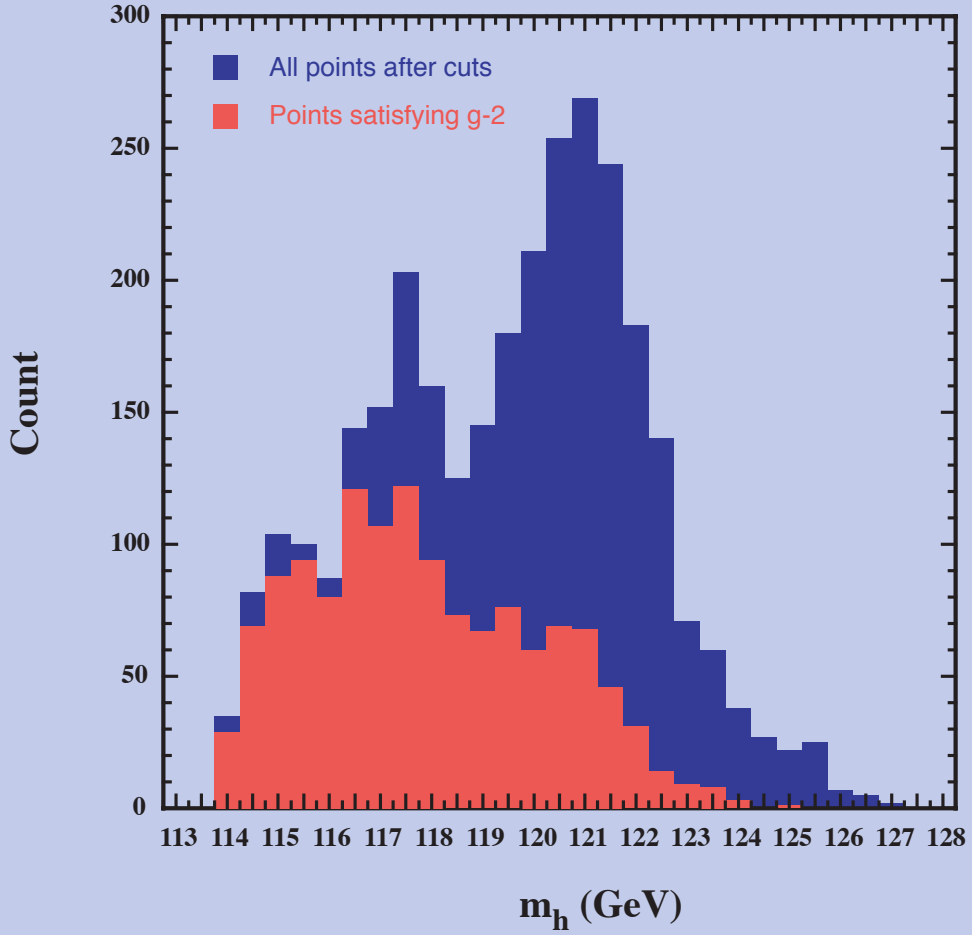
Falk



Ellis, Olive, Santoso, Spanos

The Higgs mass in the CMSSM



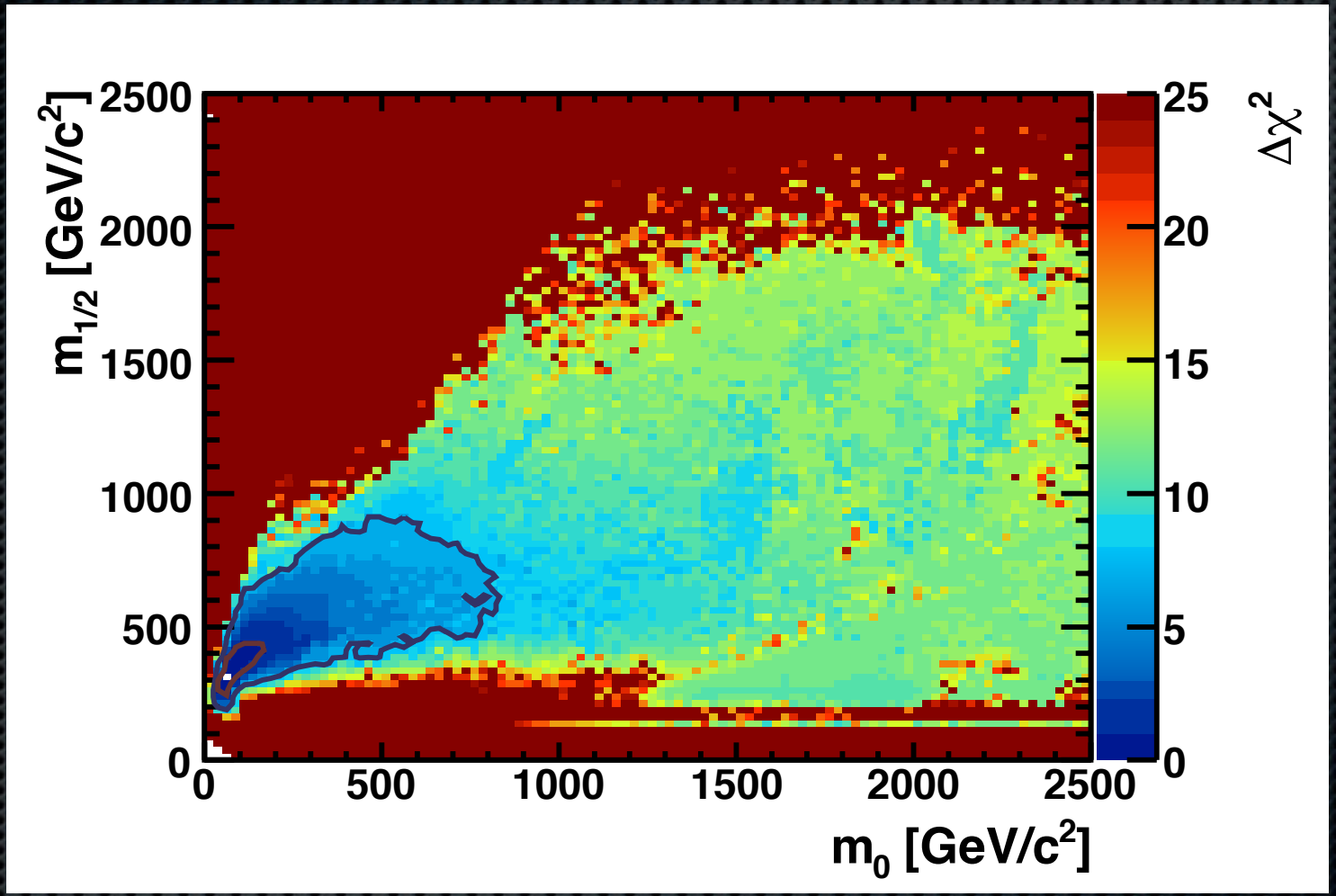


Ellis, Nanopoulos, Olive, Santoso

What happened to weak scale SUSY

Mastercode

2009



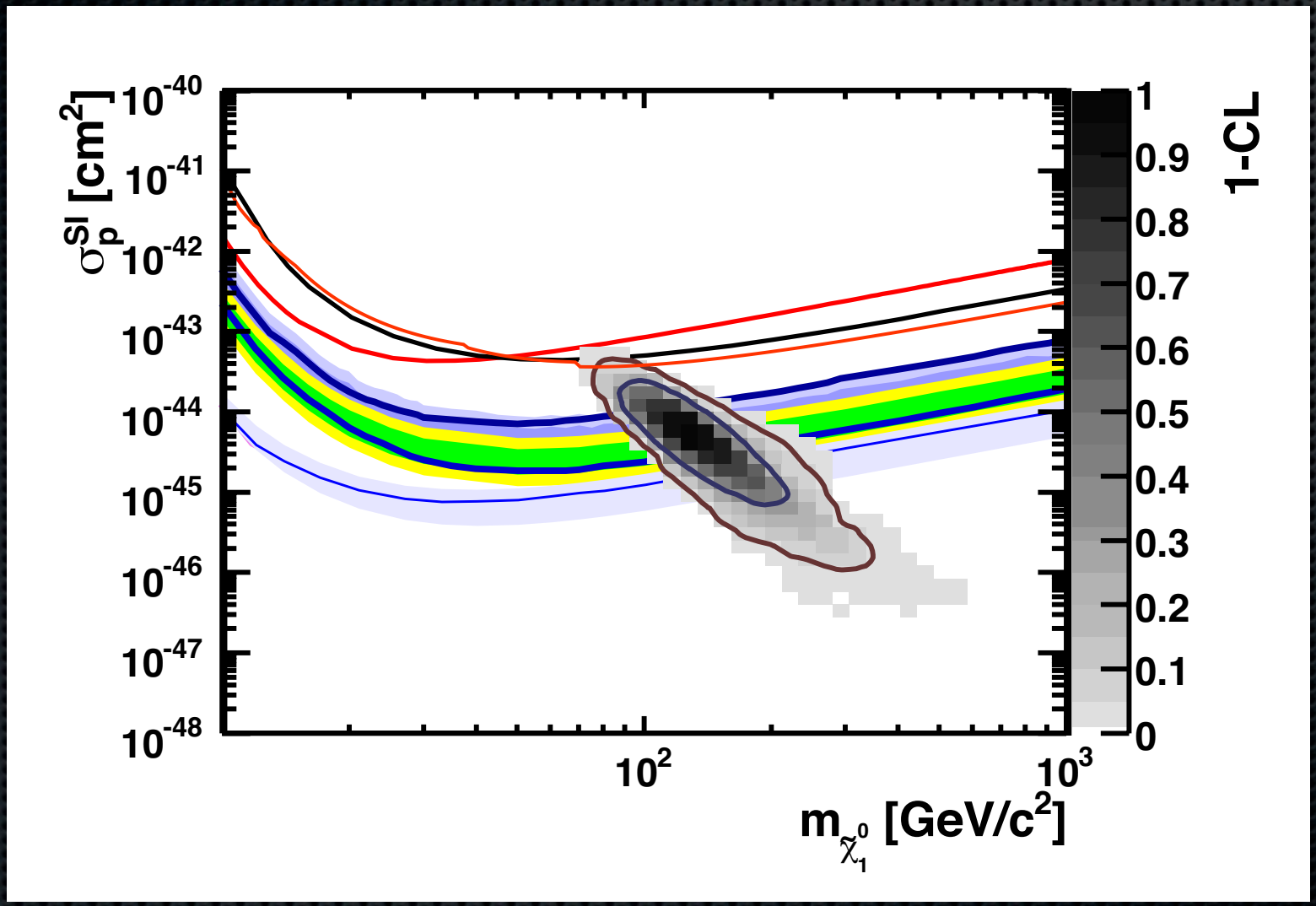
- CMSSM

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

Elastic scaterring cross-section

Mastercode

2009



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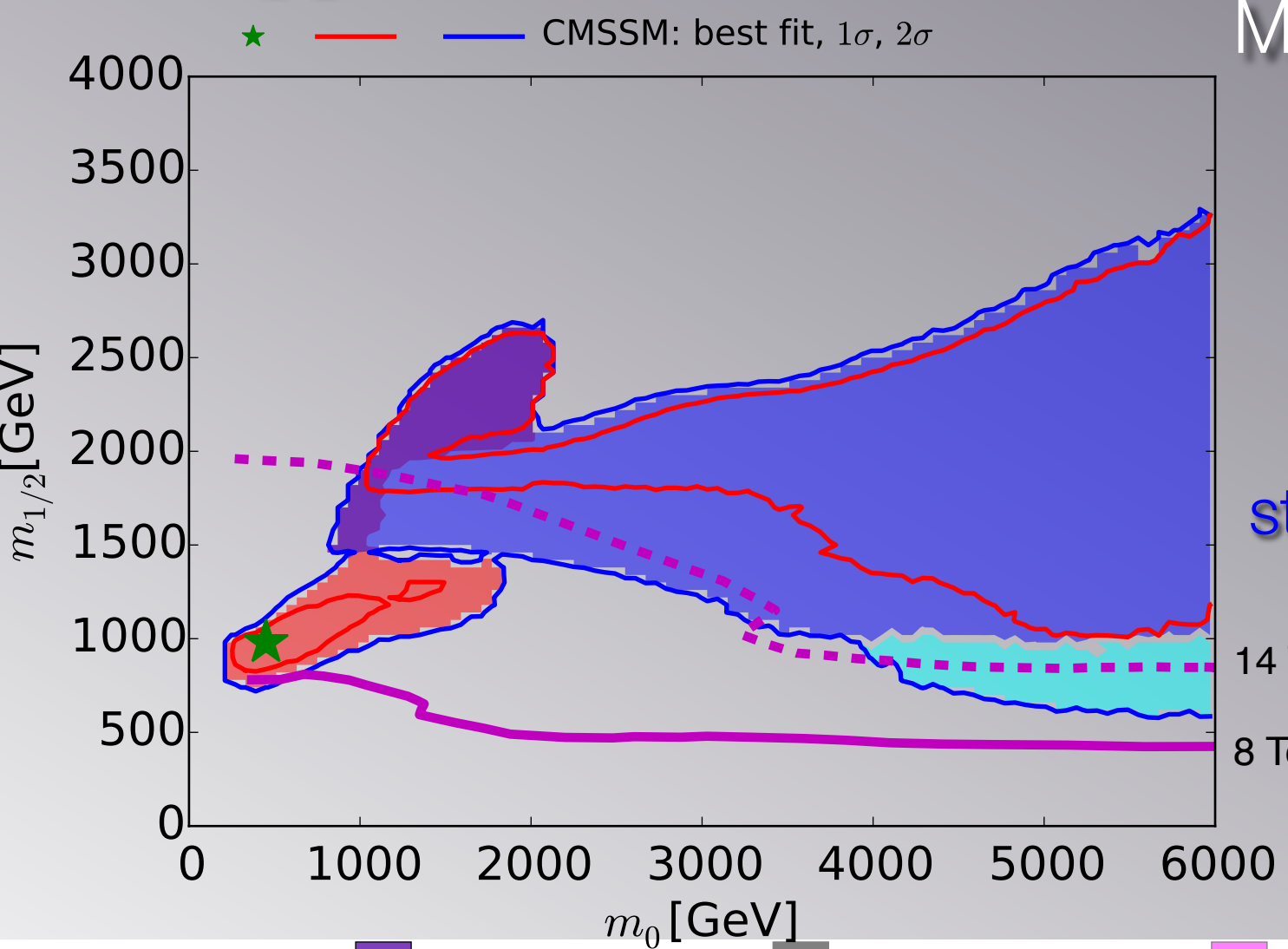
LHC Happened



Mastercode

2015

Low mass spectrum still observable at LHC

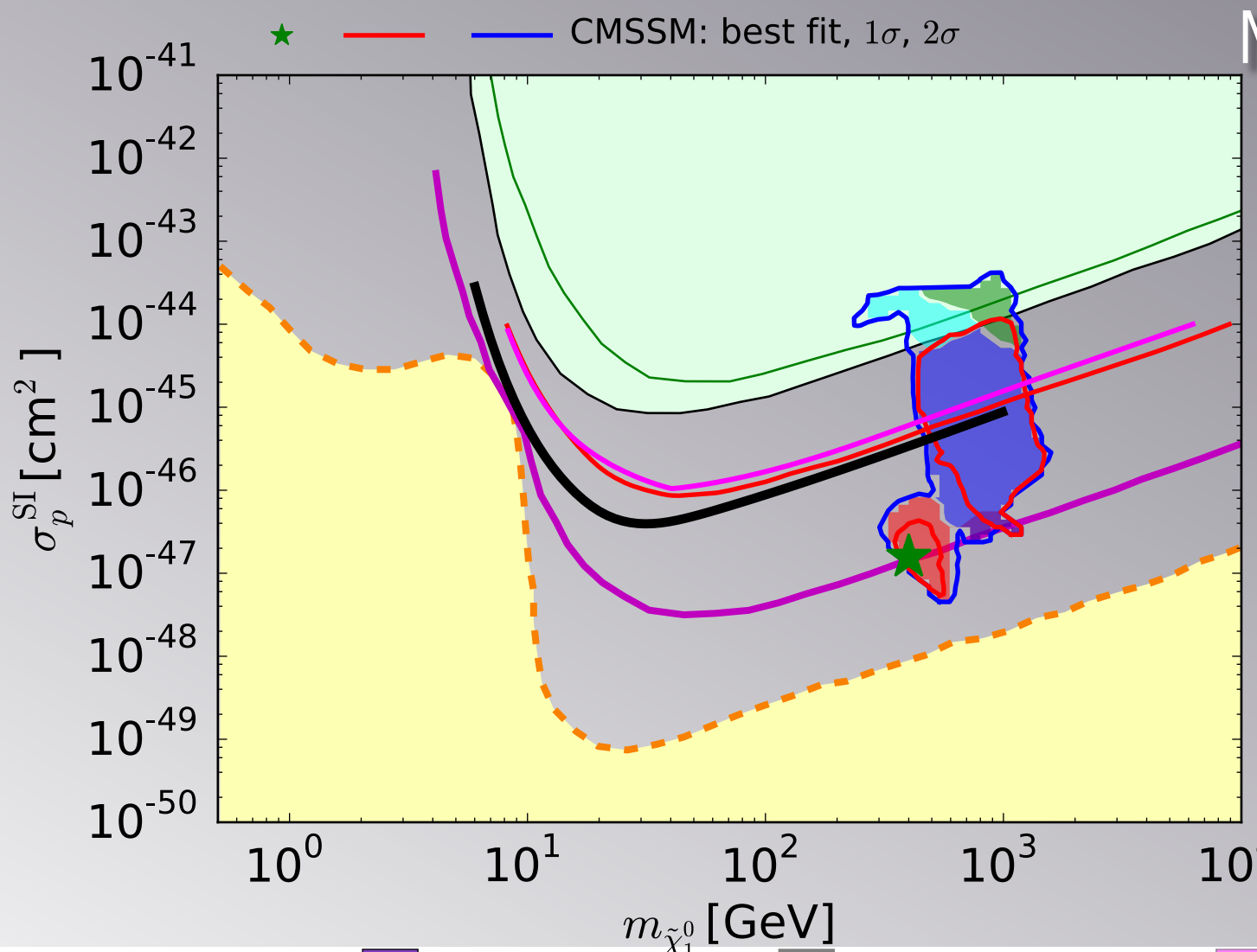
stau coann. | hybrid | stop coann. | h funnel

A/H funnel | $\tilde{\chi}_1^{\pm}$ coann. | focus point | Z funnel

- 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

New LUX bound
+ PandaX
+ XENON1t

LZ

stau coann.
hybrid
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A/H funnel
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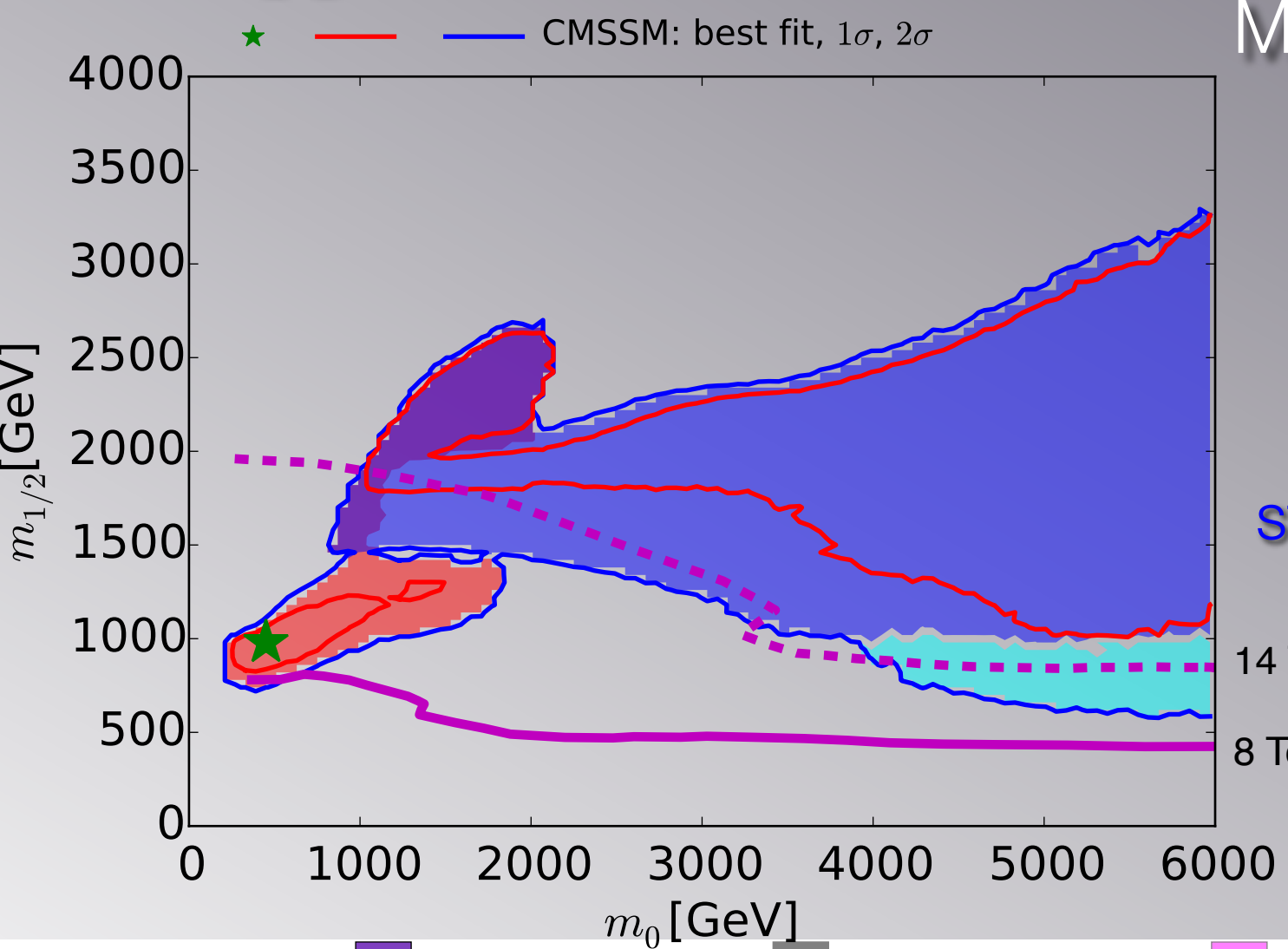

Mastercode

2015

Low mass spectrum still observable at LHC

14 TeV 3000 fb^{-1}

8 TeV 20 fb^{-1}

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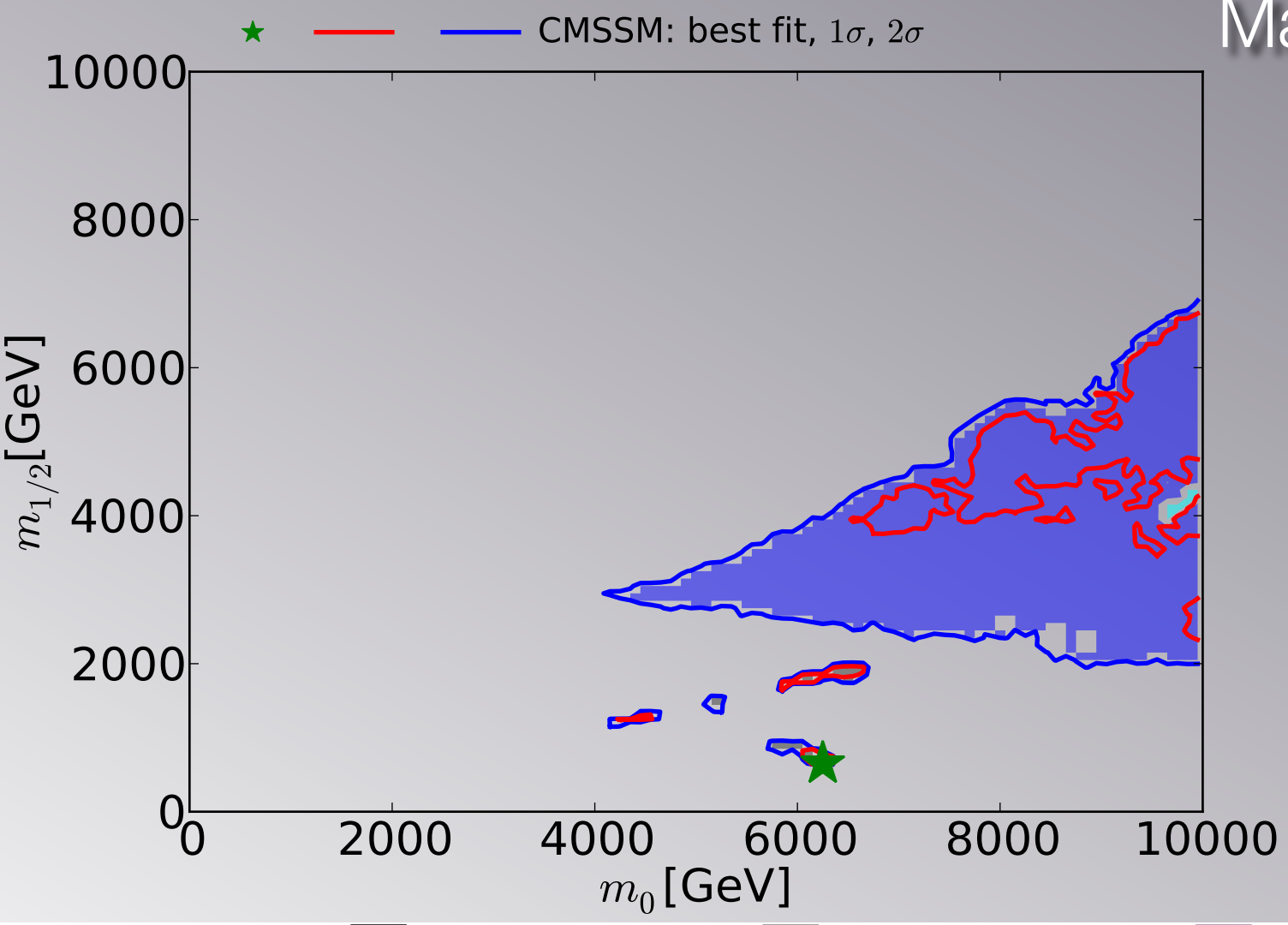
- CMSSM

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

LHC Happened

Mastercode

2023



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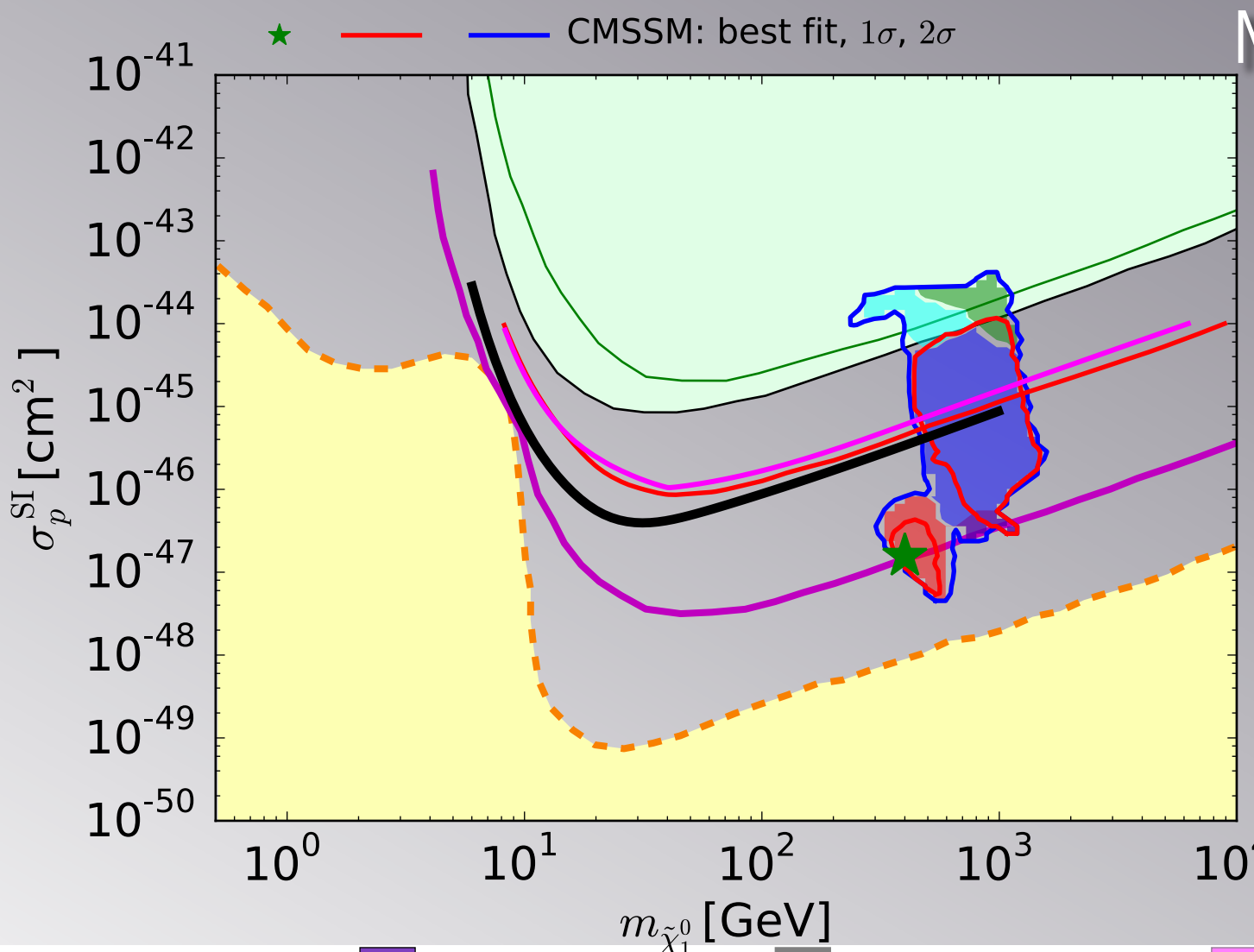

Mastercode 2015

New LUX bound
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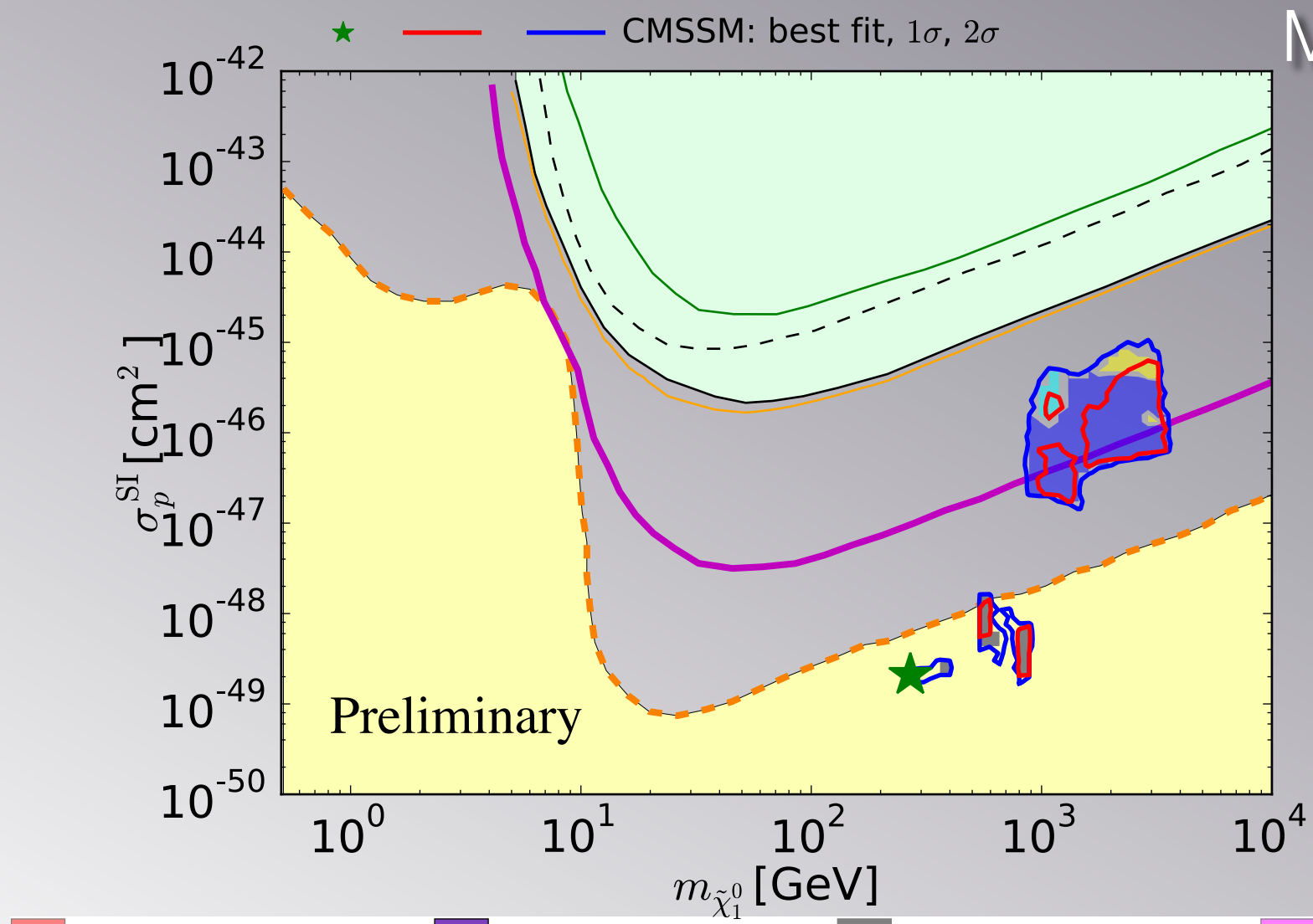
Elastic scaterring cross-section



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A/H funnel	$\tilde{\chi}_1^{\pm}$ coann.	focus point	Z funnel

- CMSSM

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

Weak (?) scale supersymmetric dark matter

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Viable regions of parameter space with dark matter is found along strips:

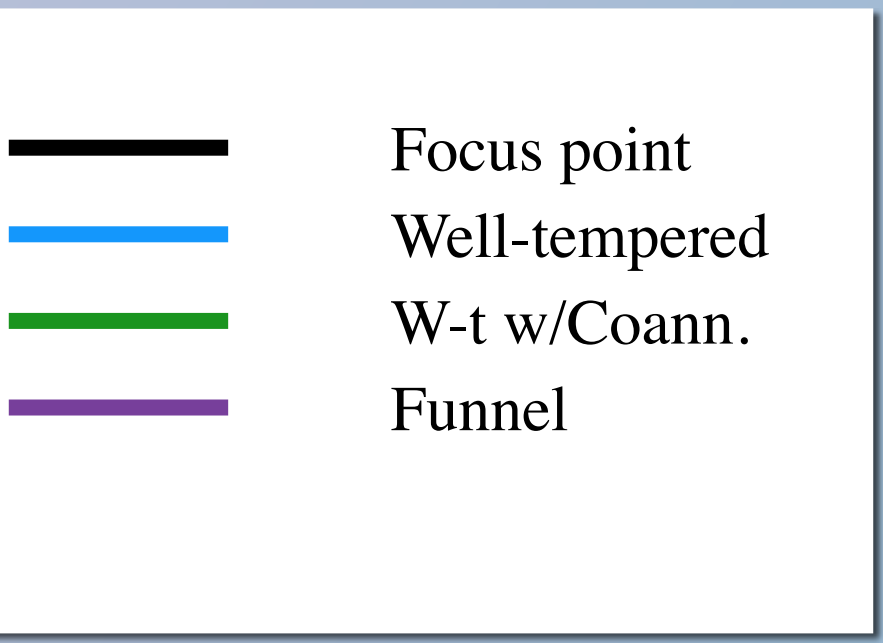
Weak (?) scale supersymmetric dark matter

Viable regions of parameter space with dark matter is found along strips:

- Stau-coannhilation Strip
  - extends only out to ~1 TeV
- Stop-coannihilation Strip
- Higgs Funnel
- Focus Point

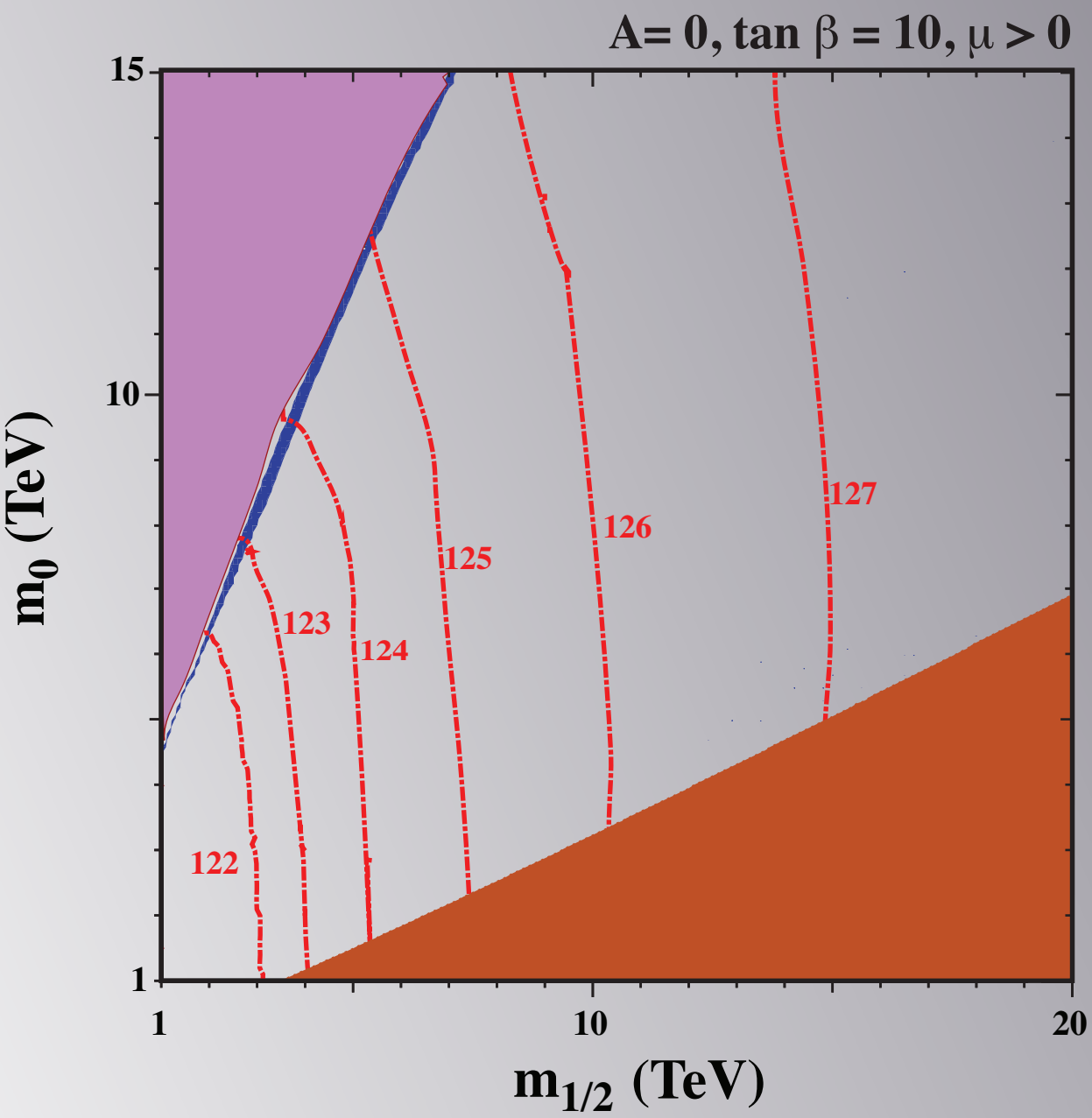
Requirements

- Relic Density*
- LHC constrains: Sparticle searches; Higgs mass
- Spin-Dependent and Spin-Independent scattering cross sections
- Gamma Ray Fluxes
- Neutrinos from the sun

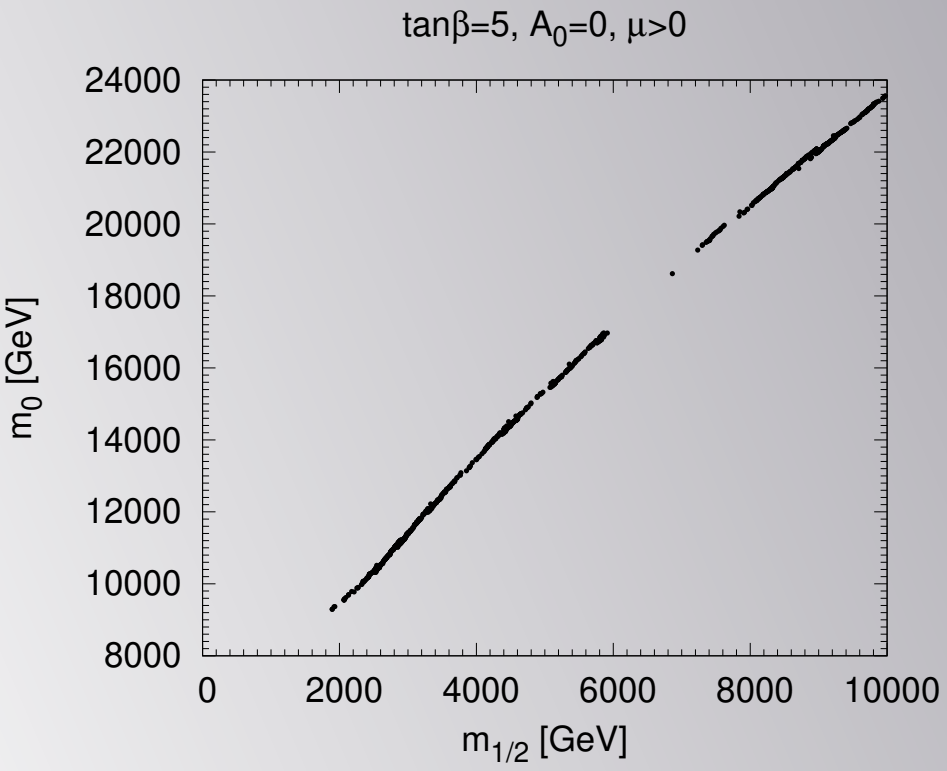


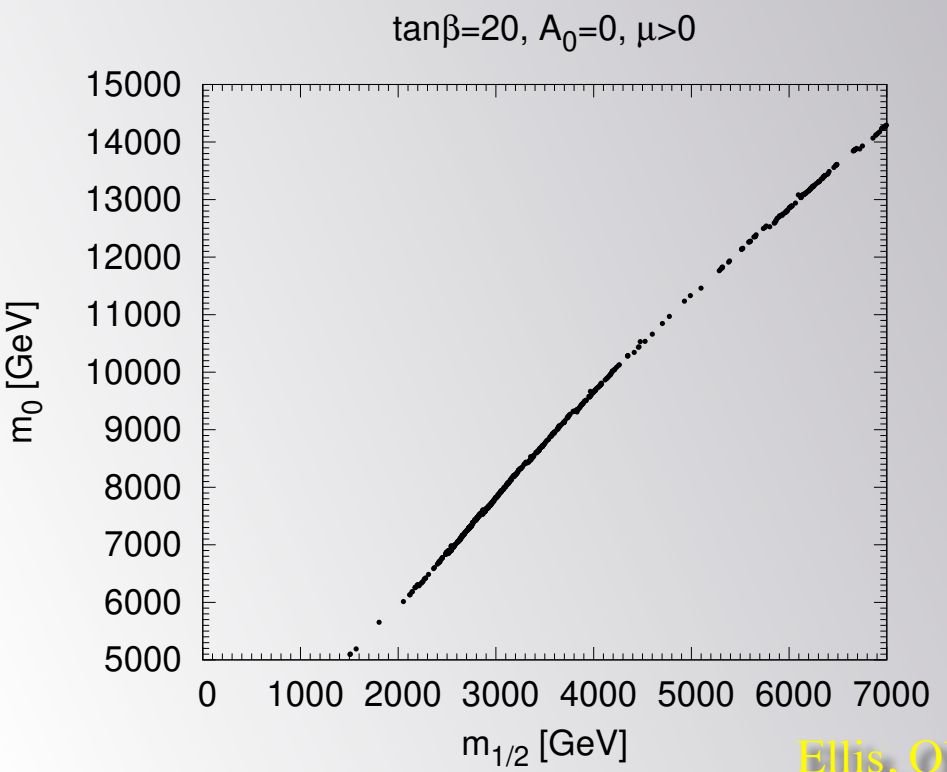
*Assuming no late entropy production

Focus Point

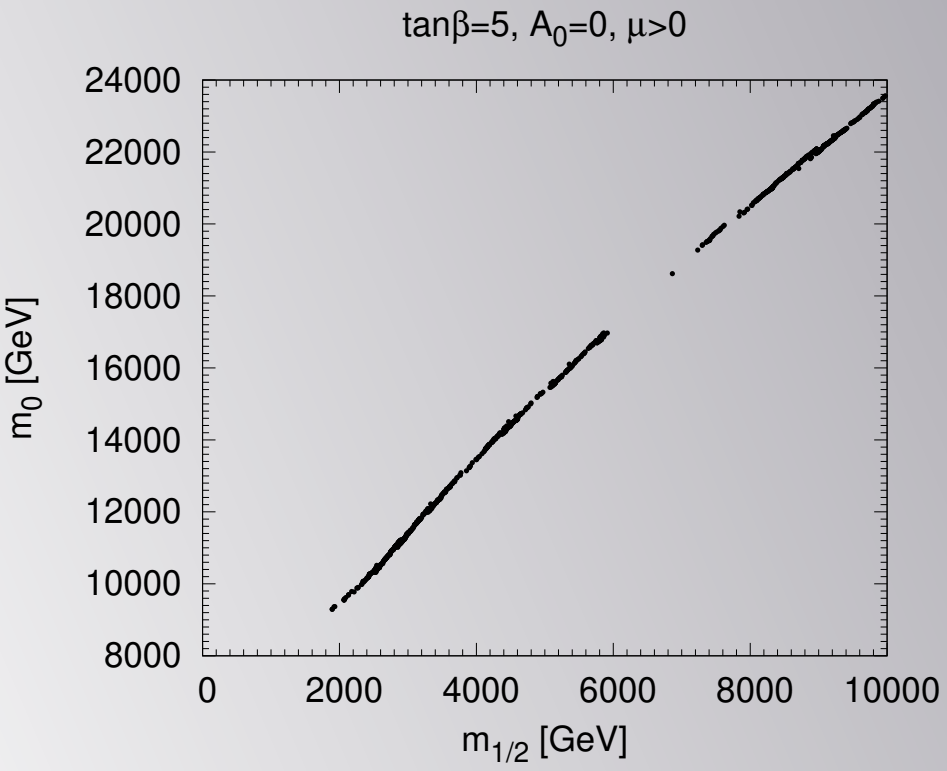


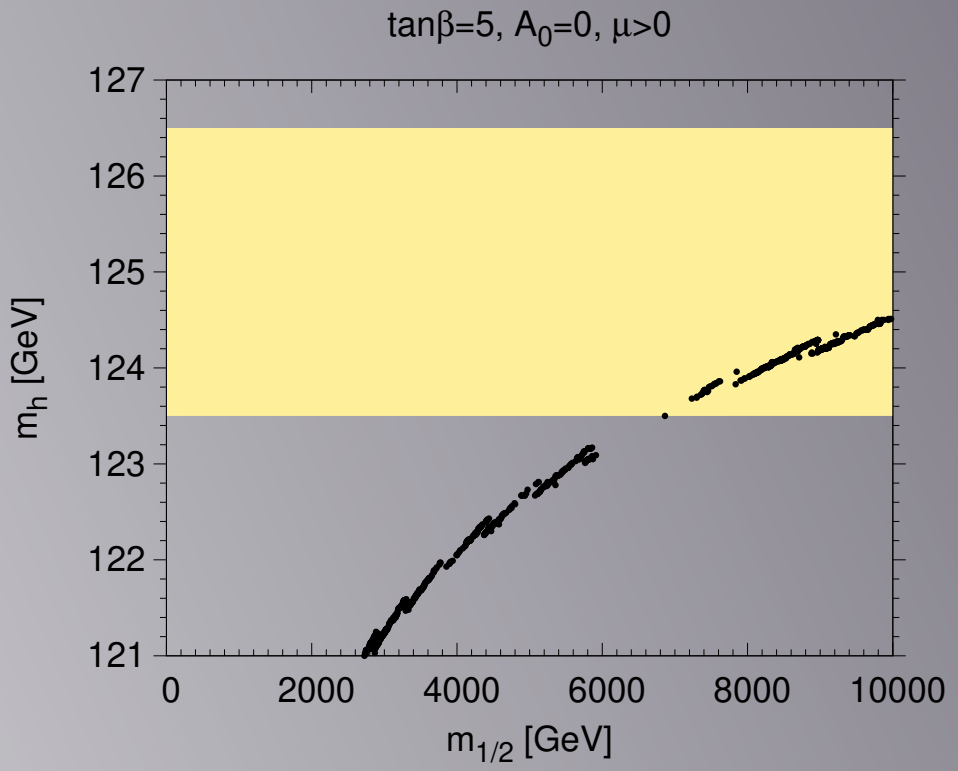
Ellis, Evans, Nagata, Olive, Velasco-Sevilla

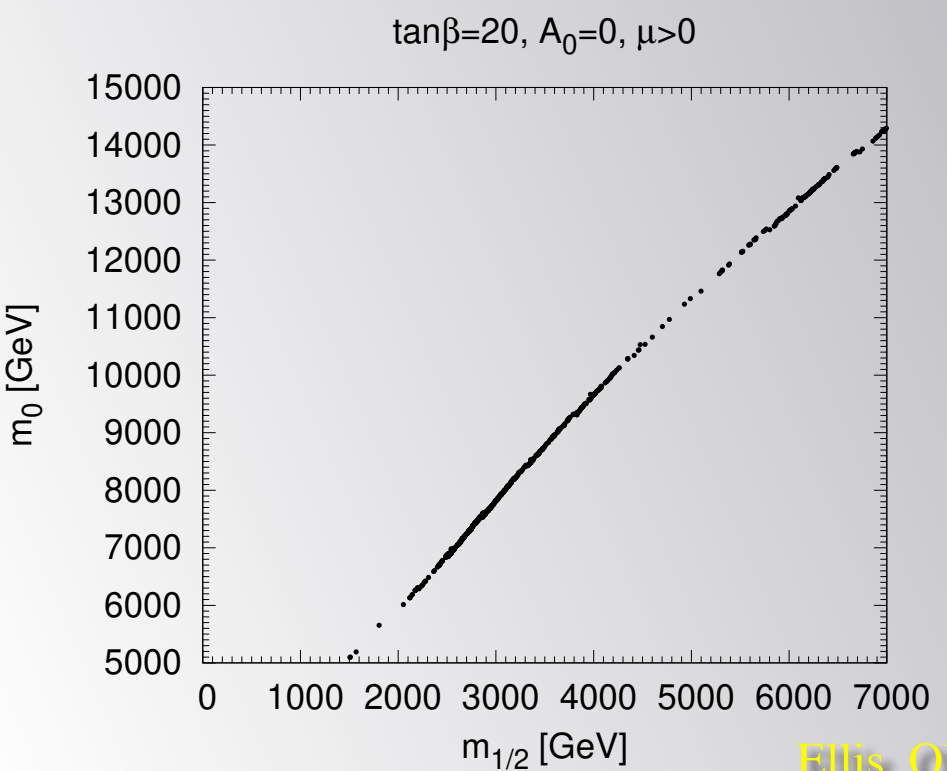


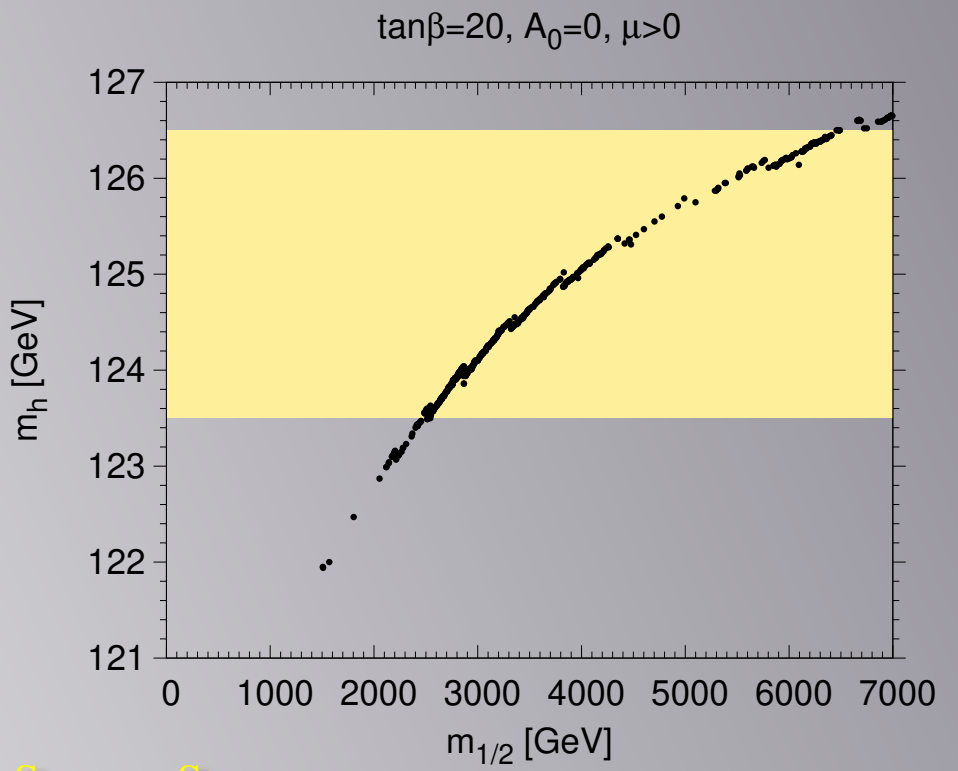


Ellis, Olive, Spanos, Stomou

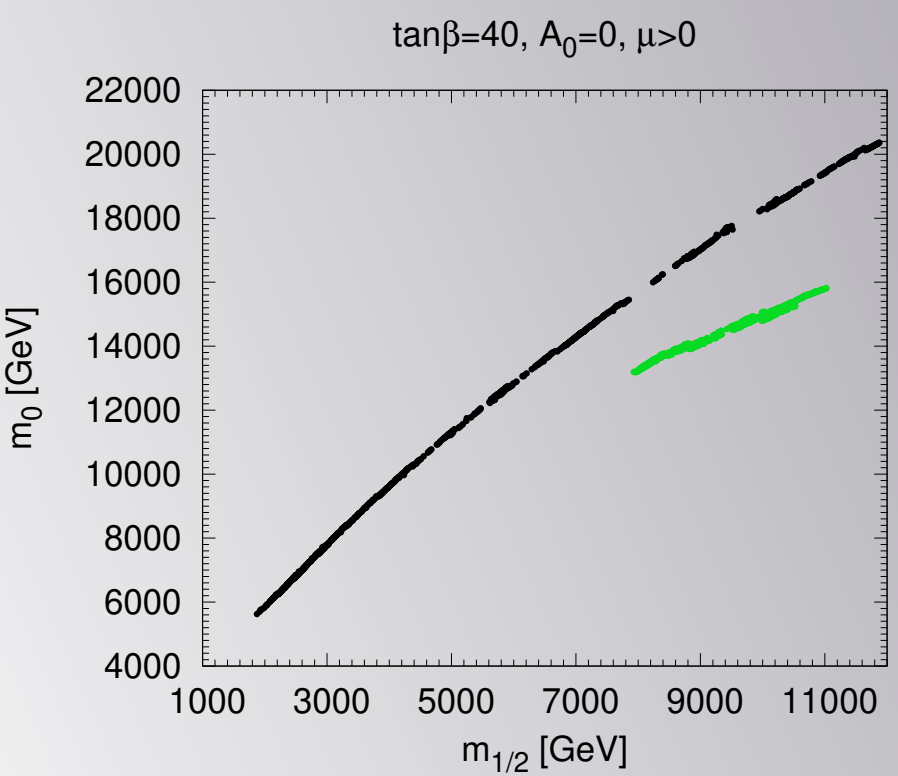


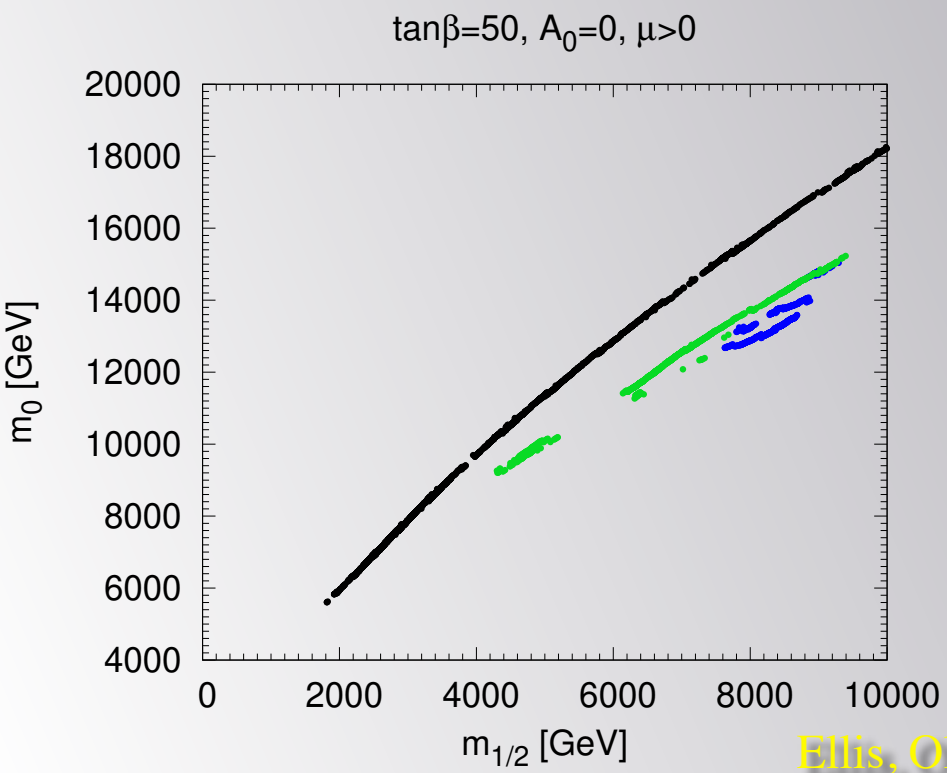






Ellis, Olive, Spanos, Stomou





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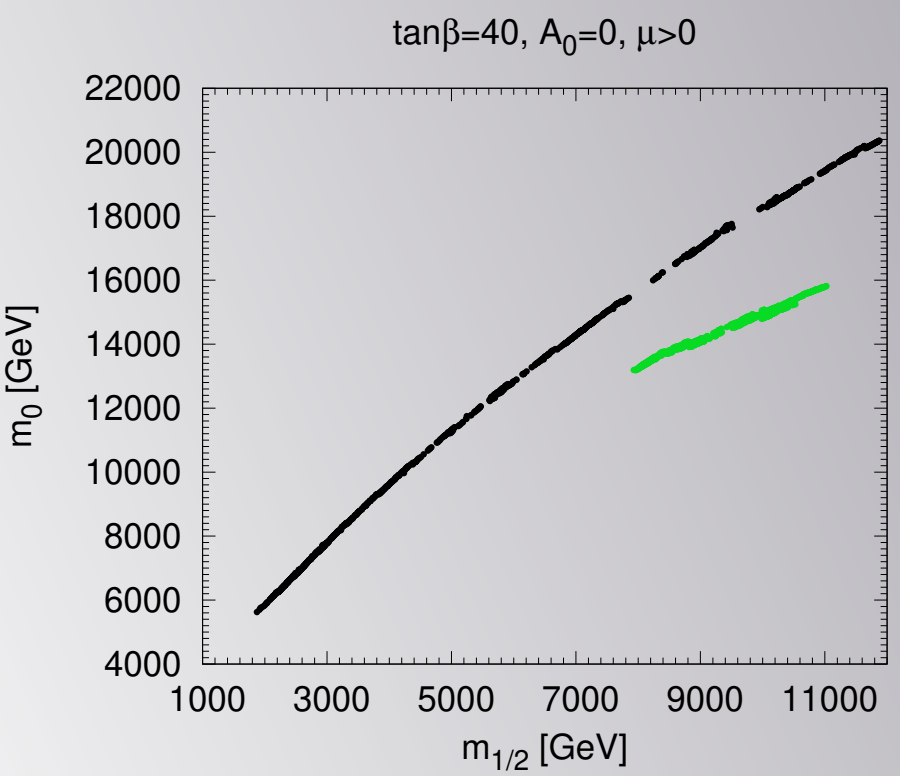
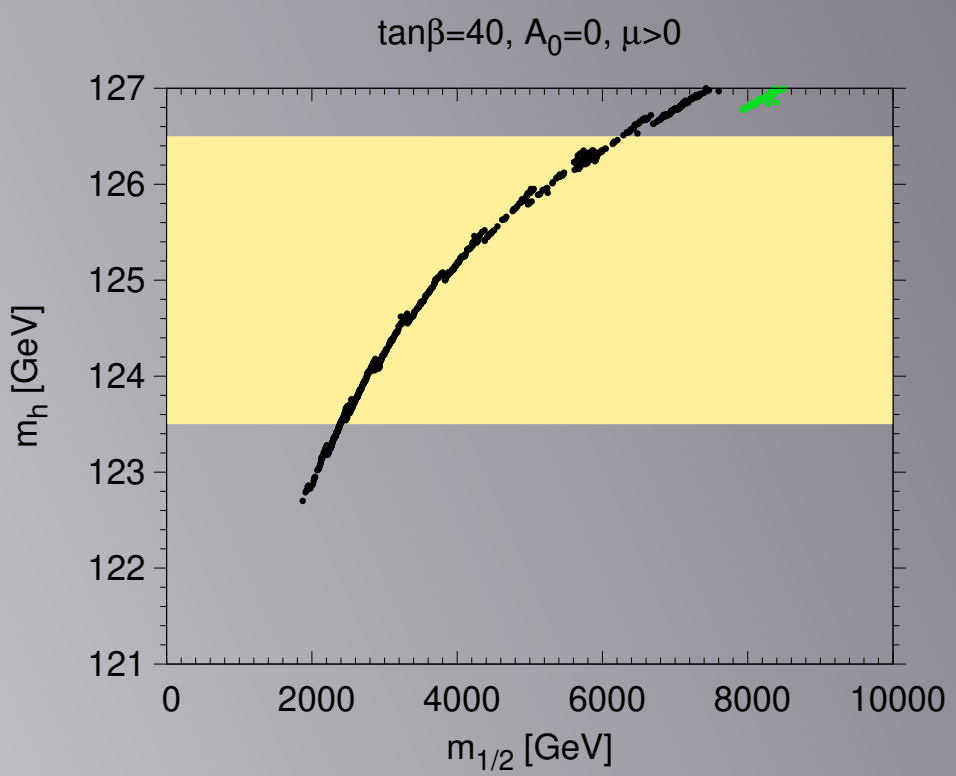
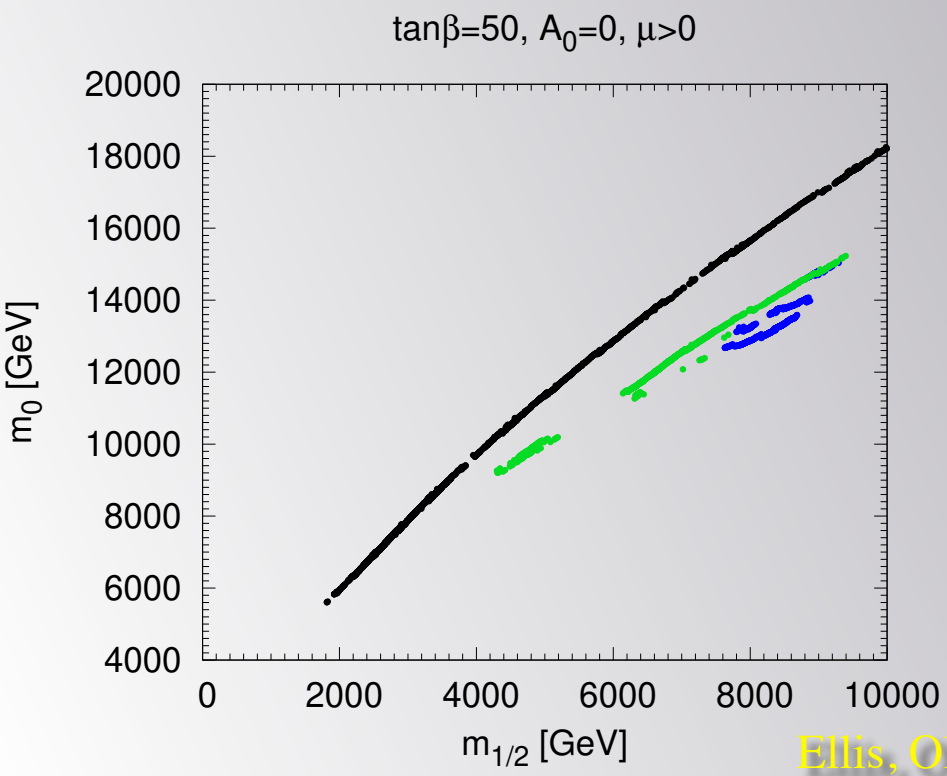
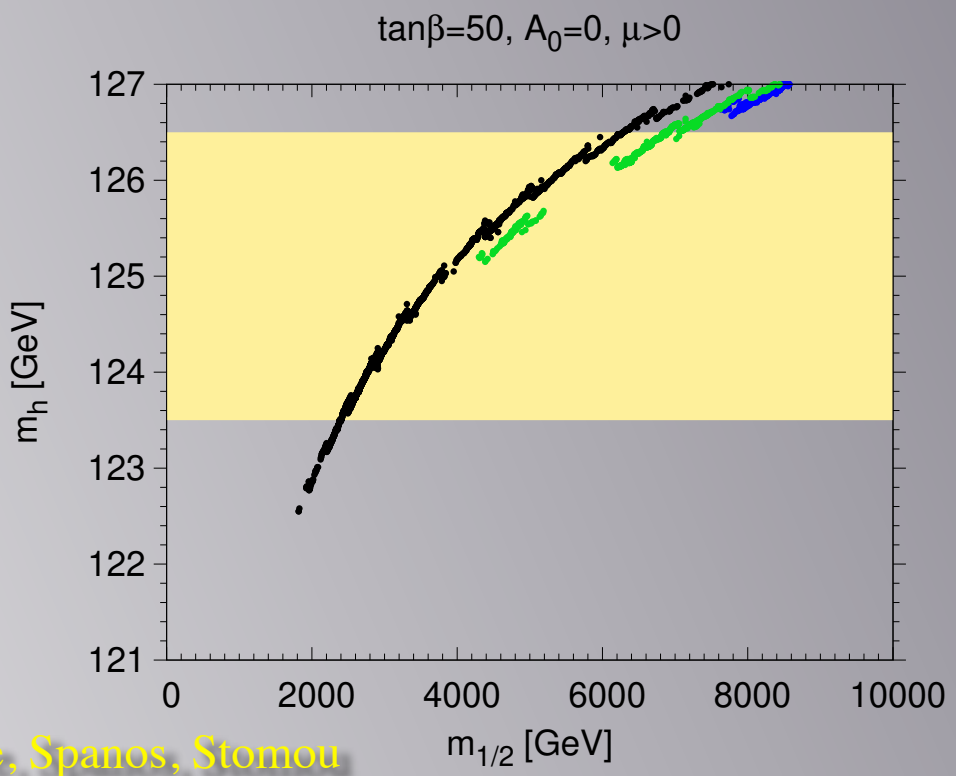
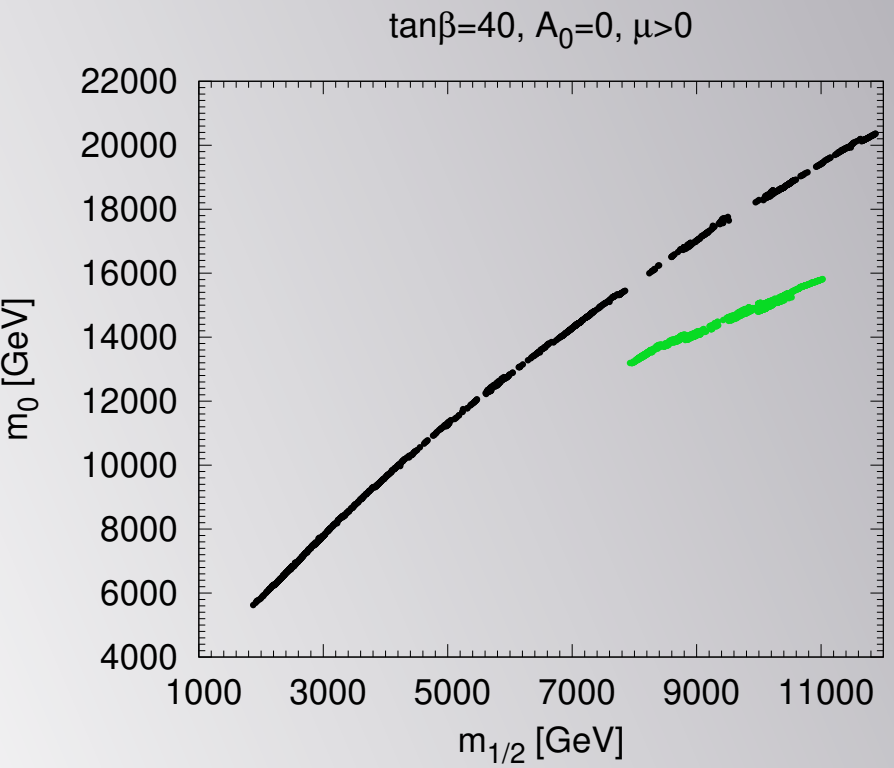


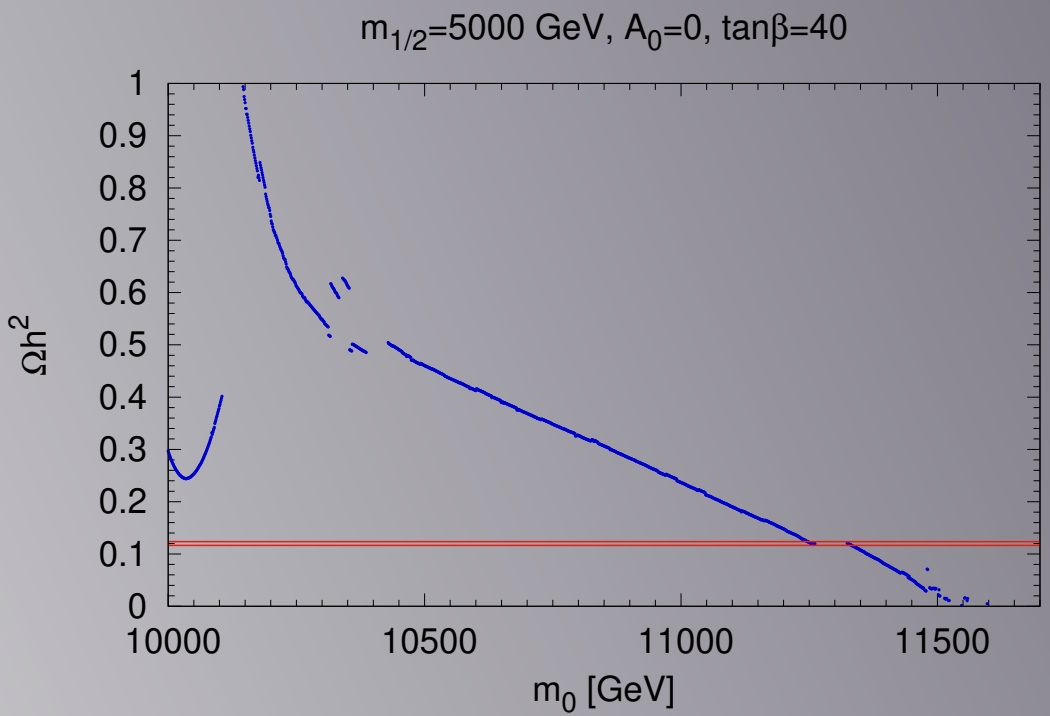




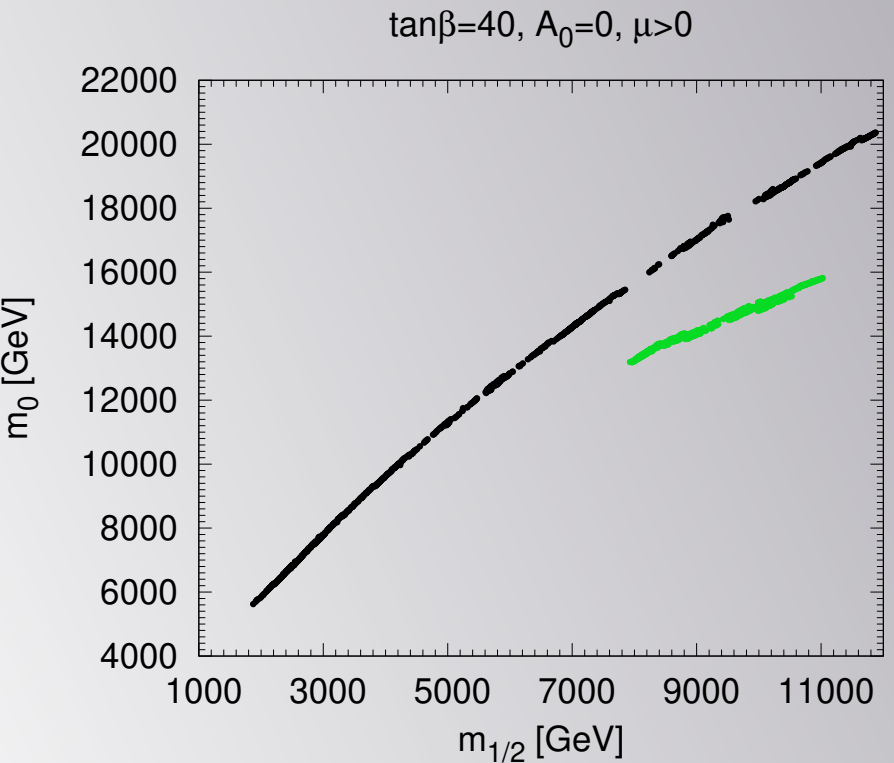


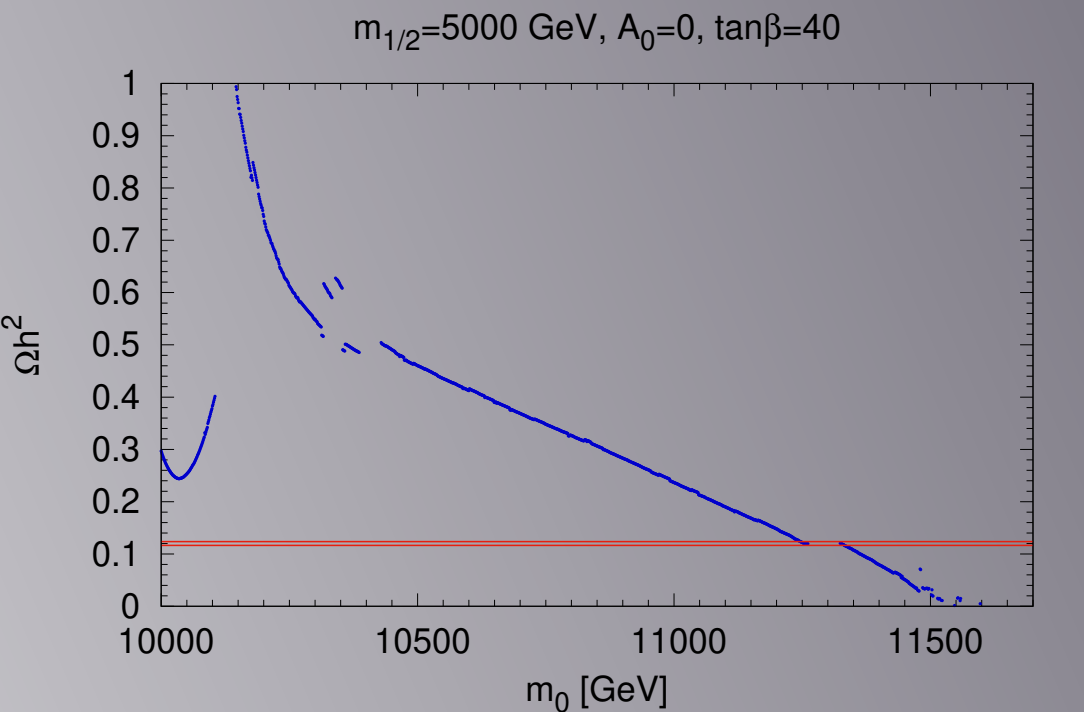
Ellis, Olive, Spanos, Stomou

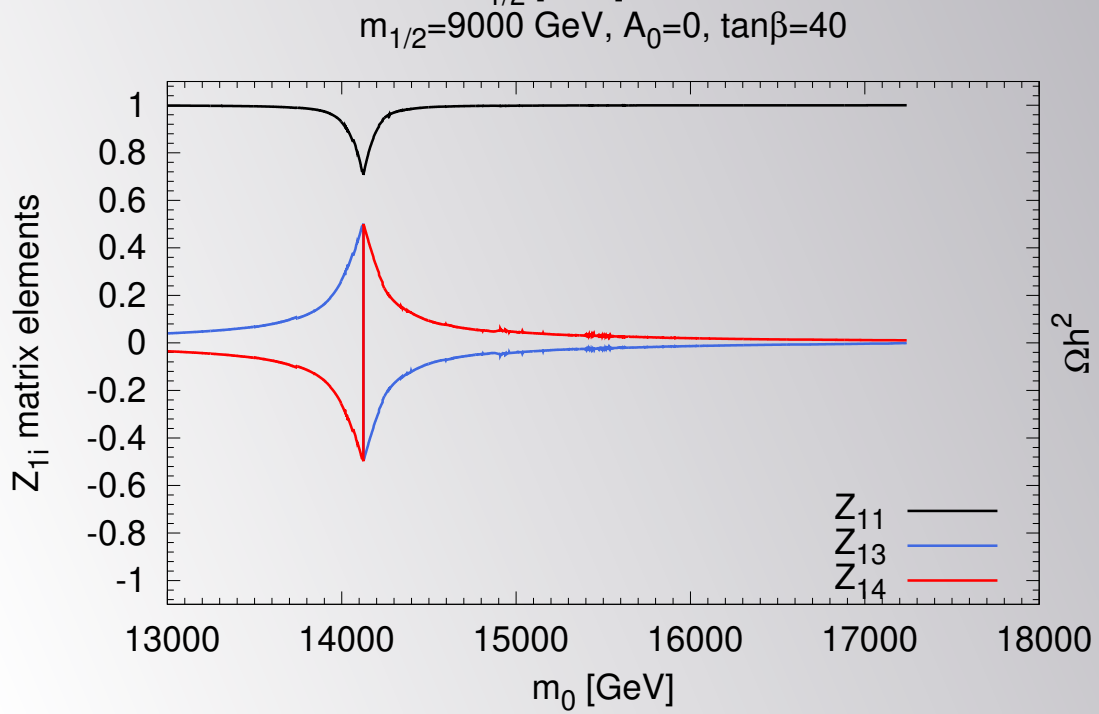


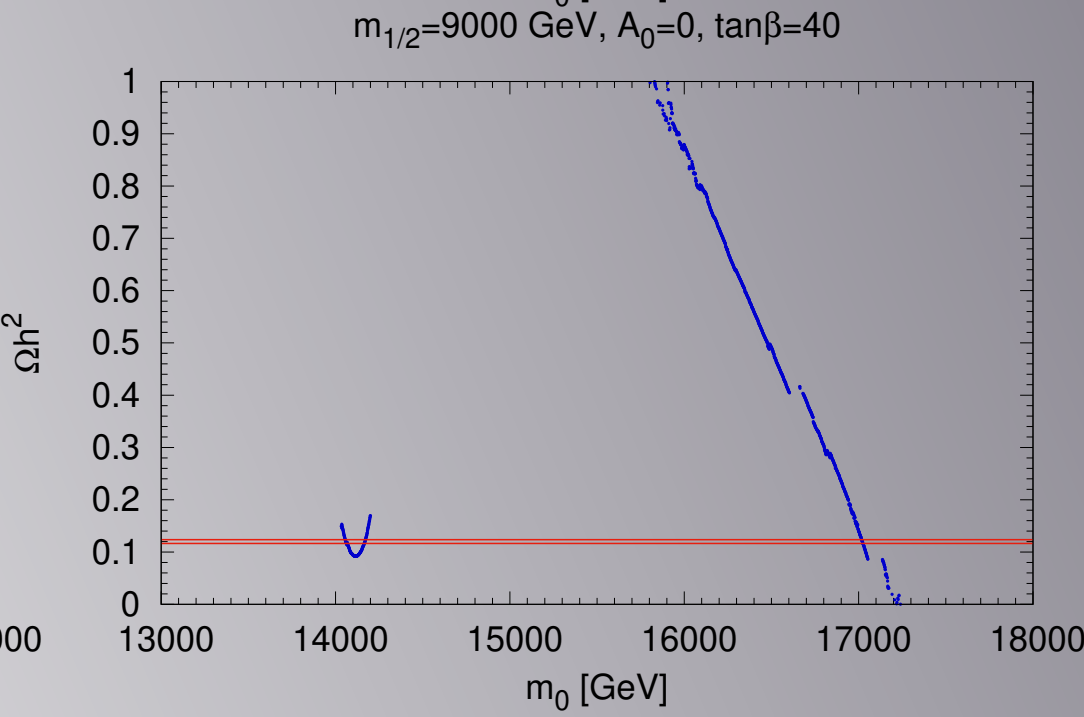


Ellis, Olive, Spanos, Stomou









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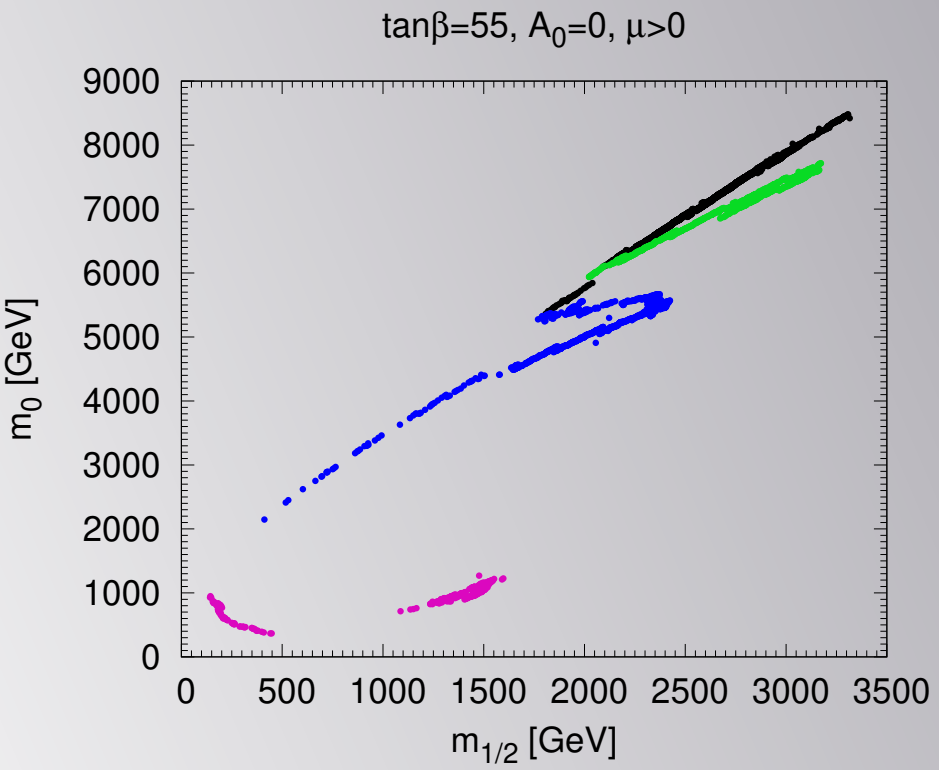

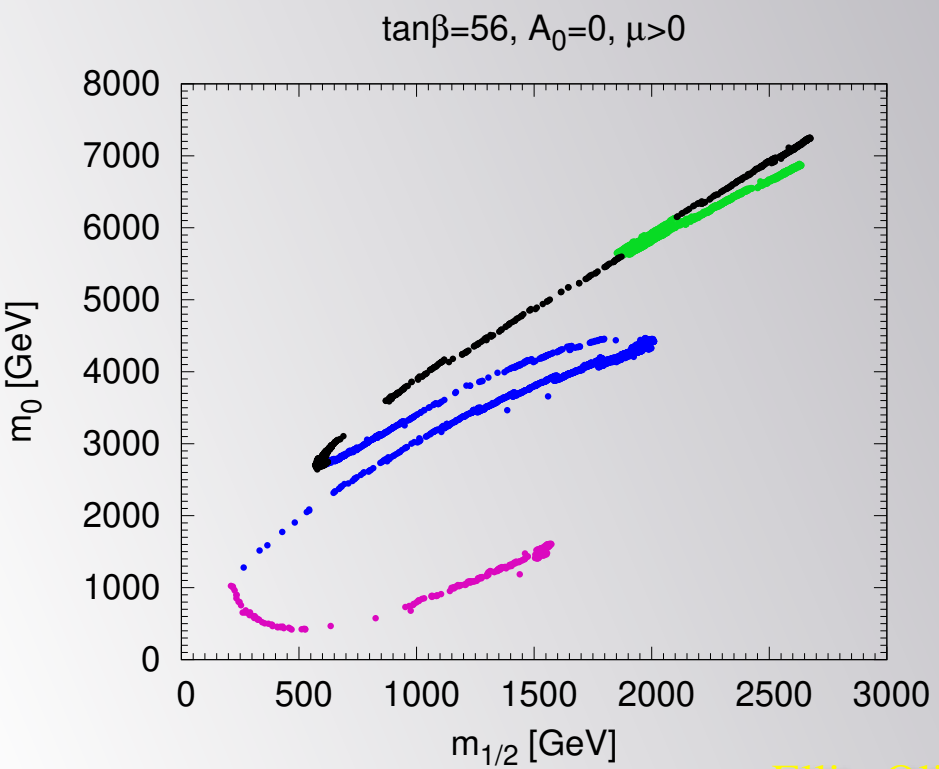

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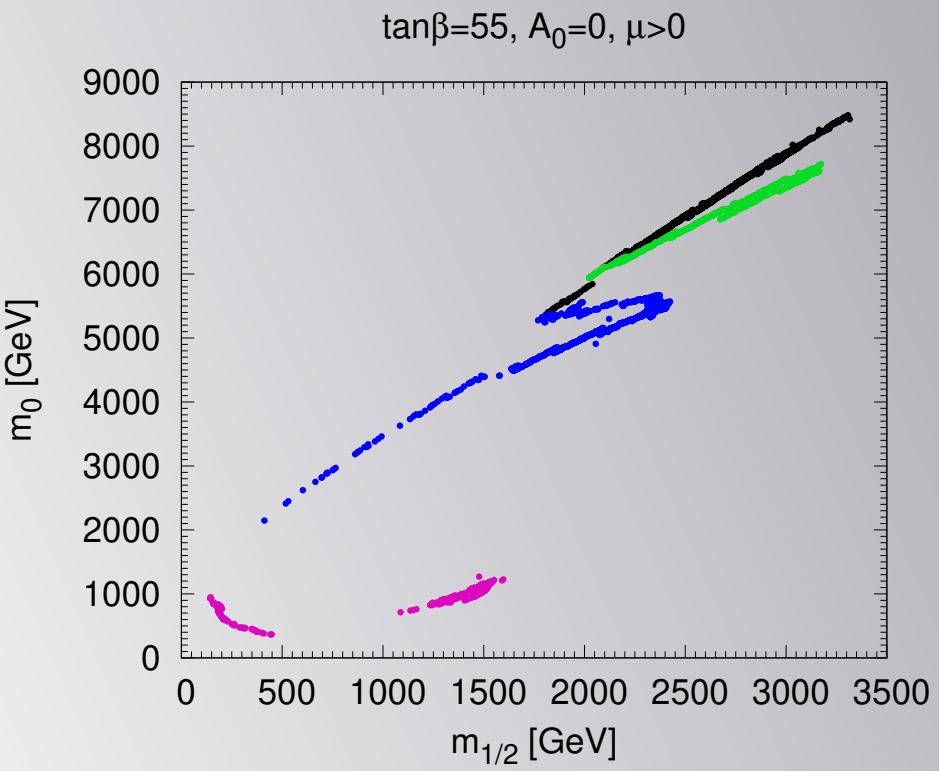

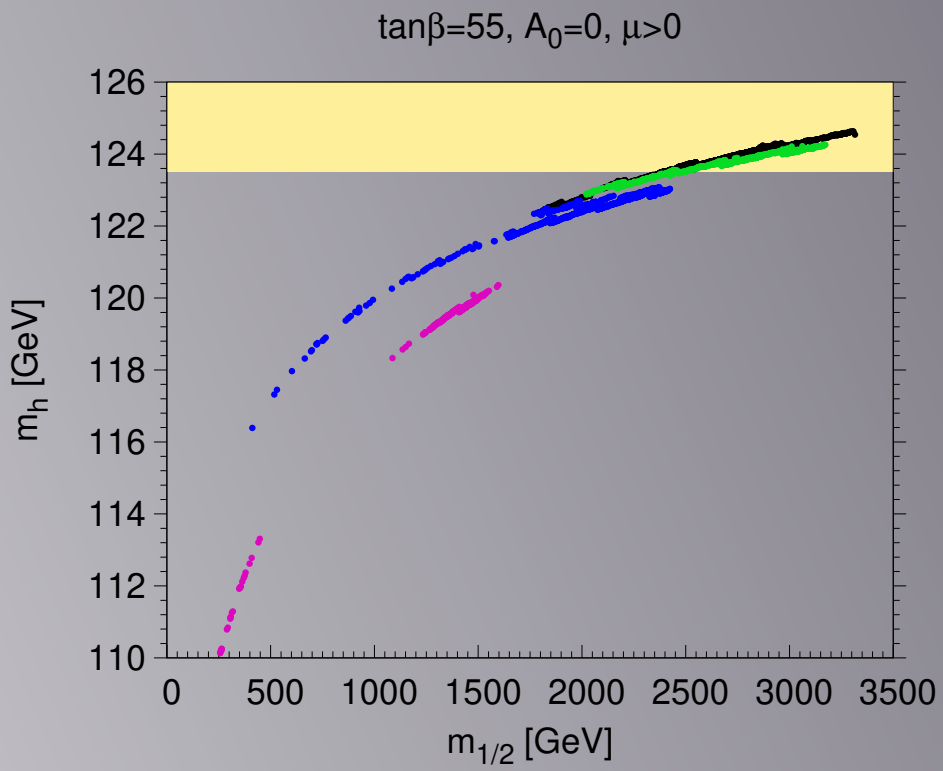

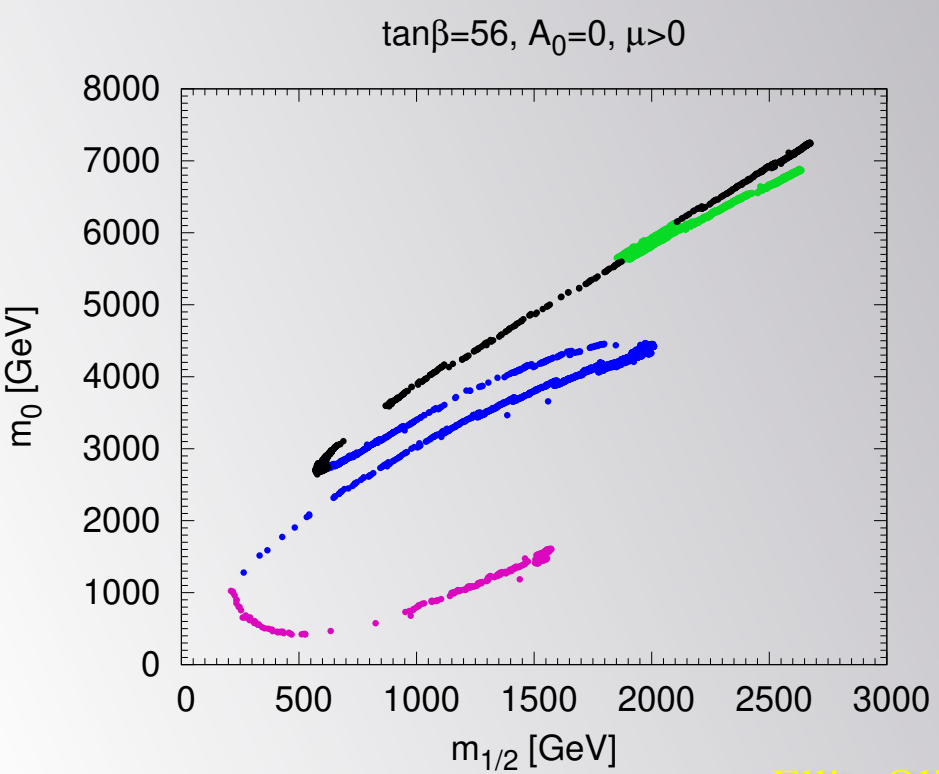

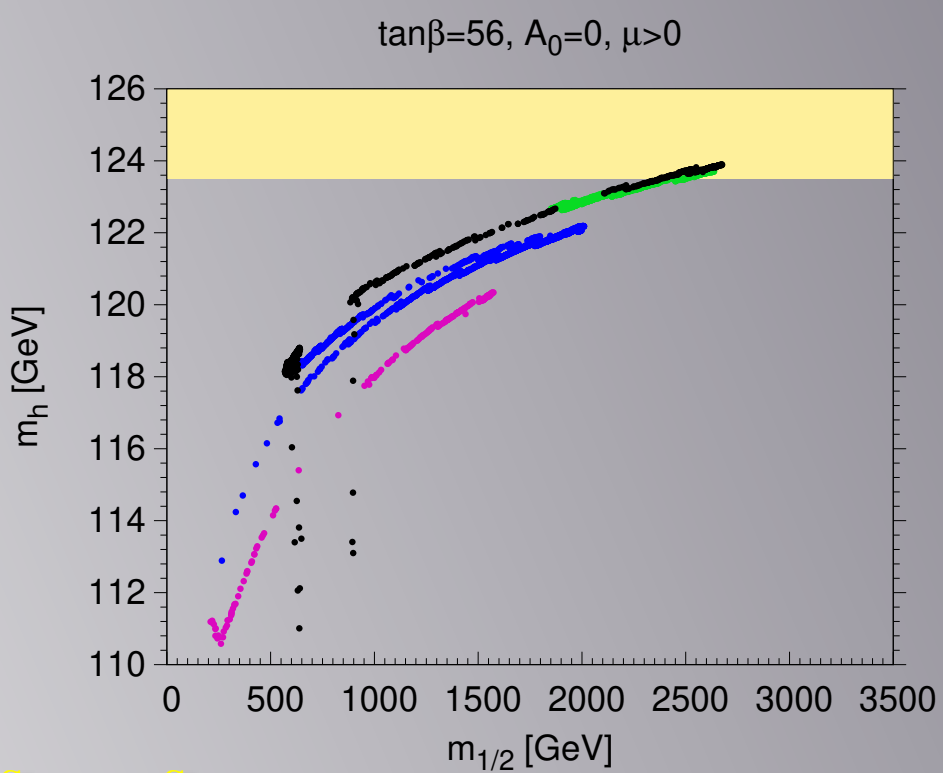

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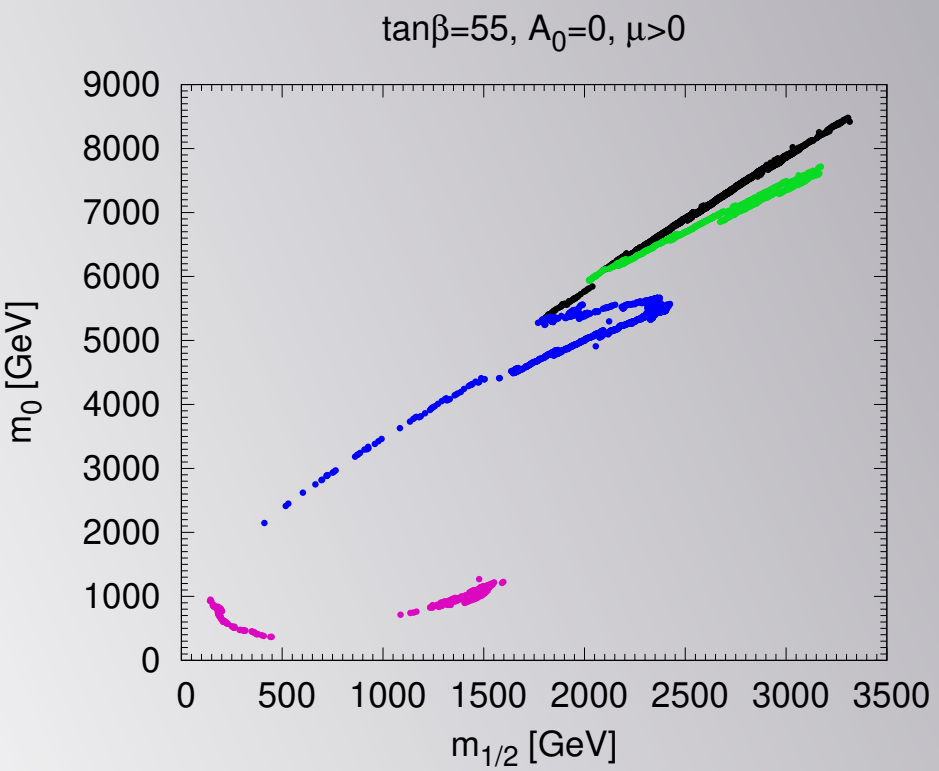
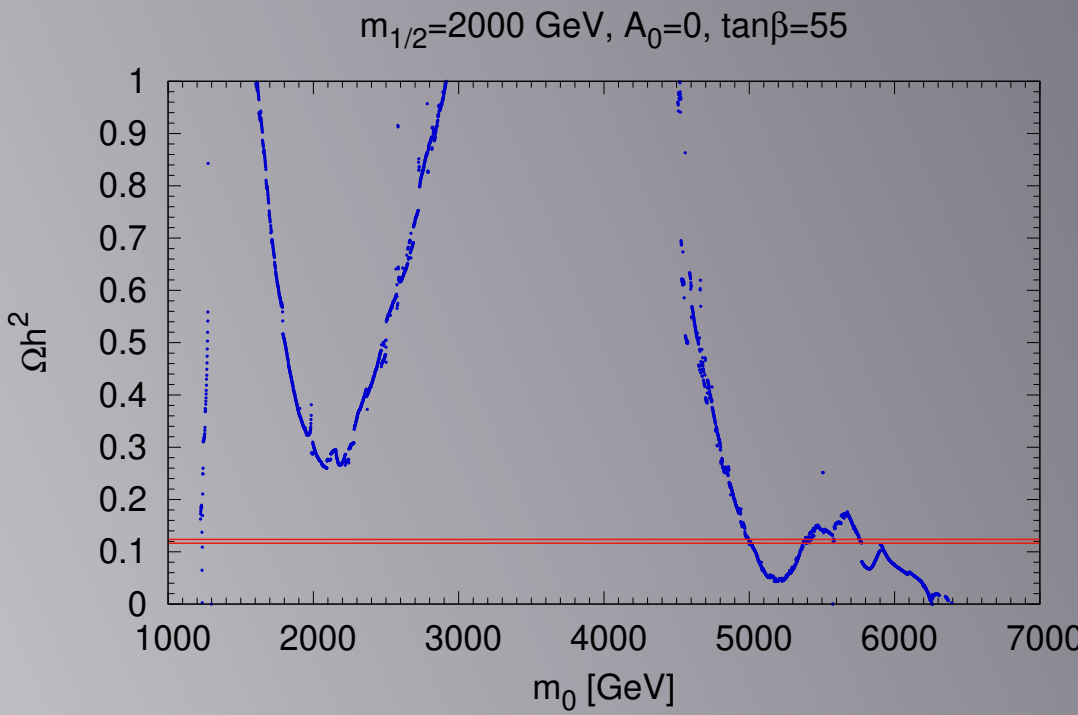
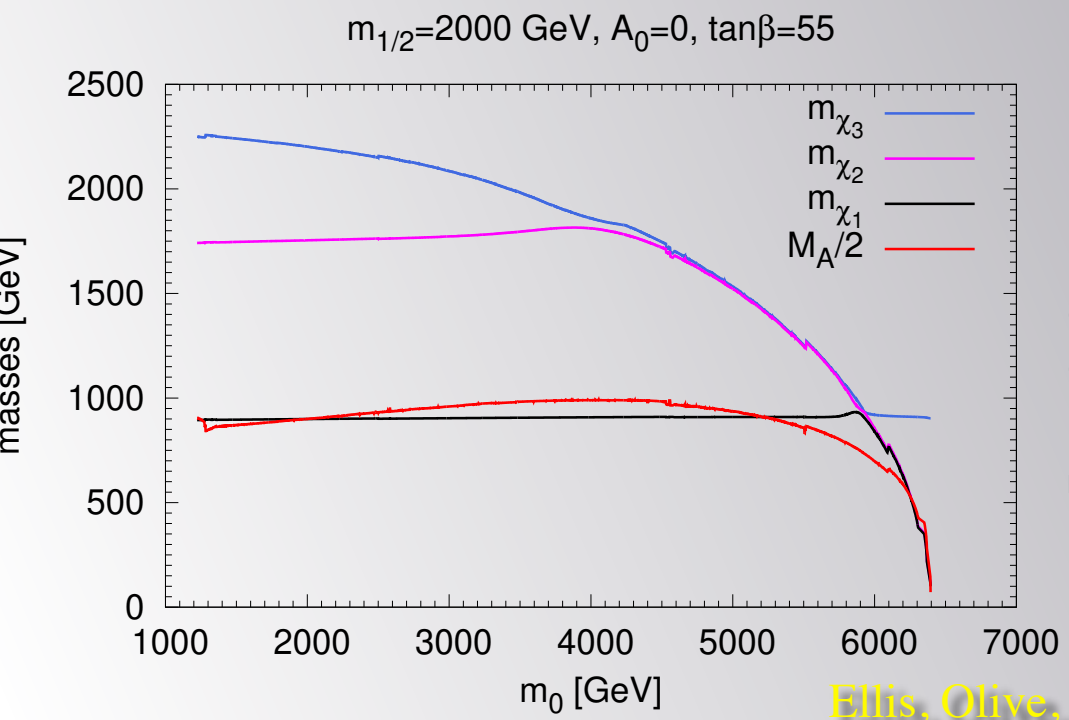
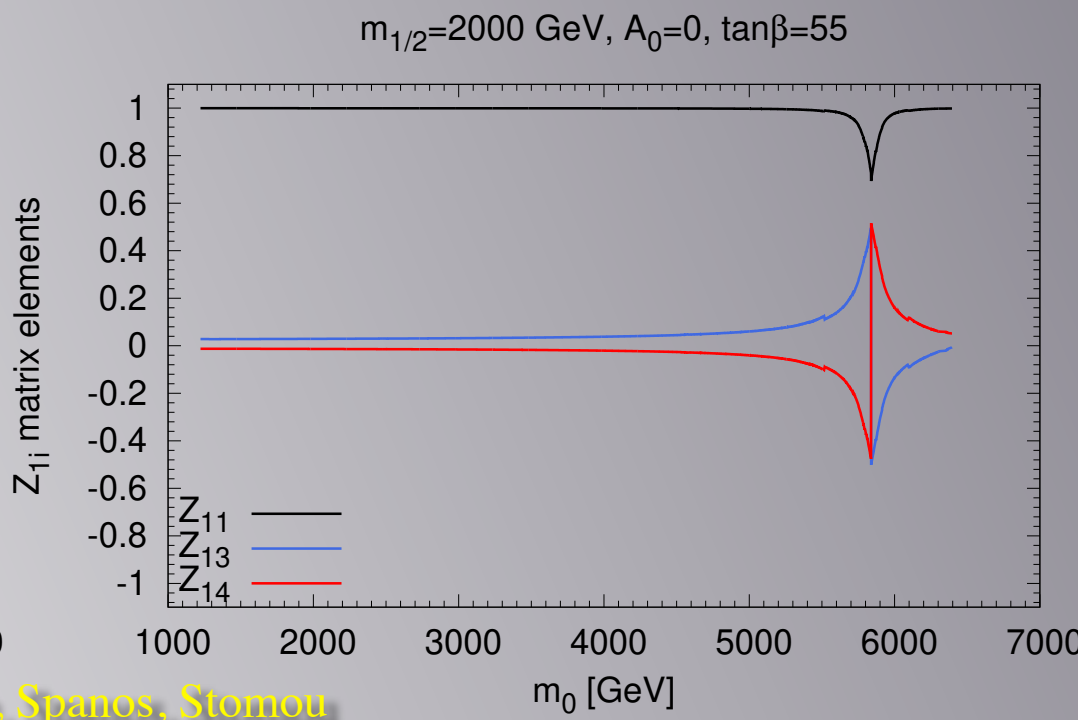
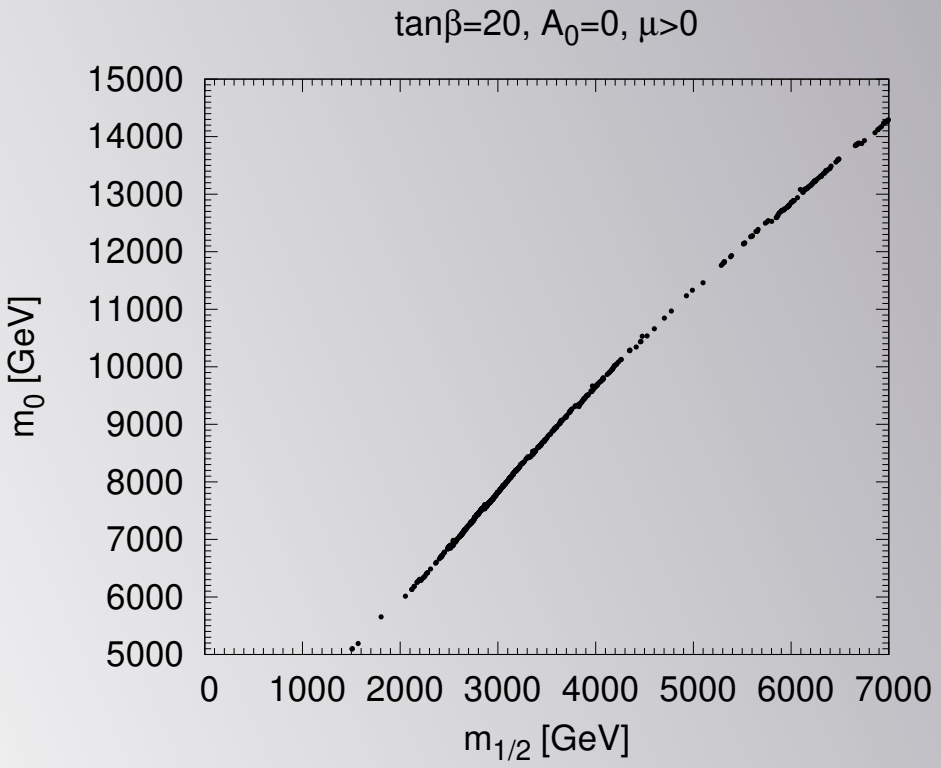


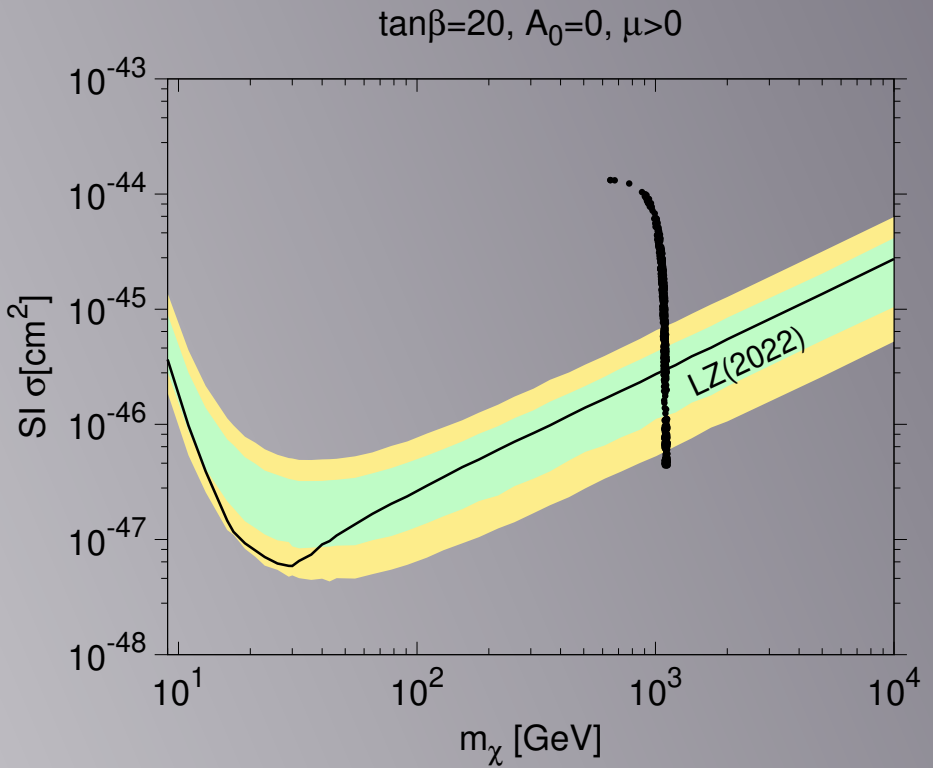


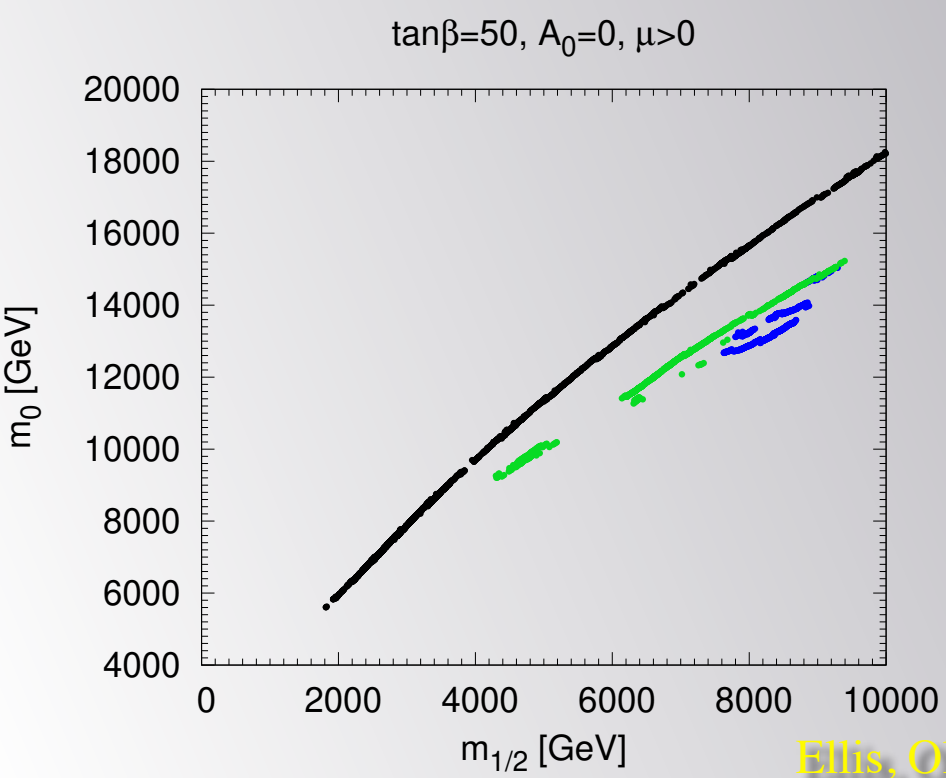


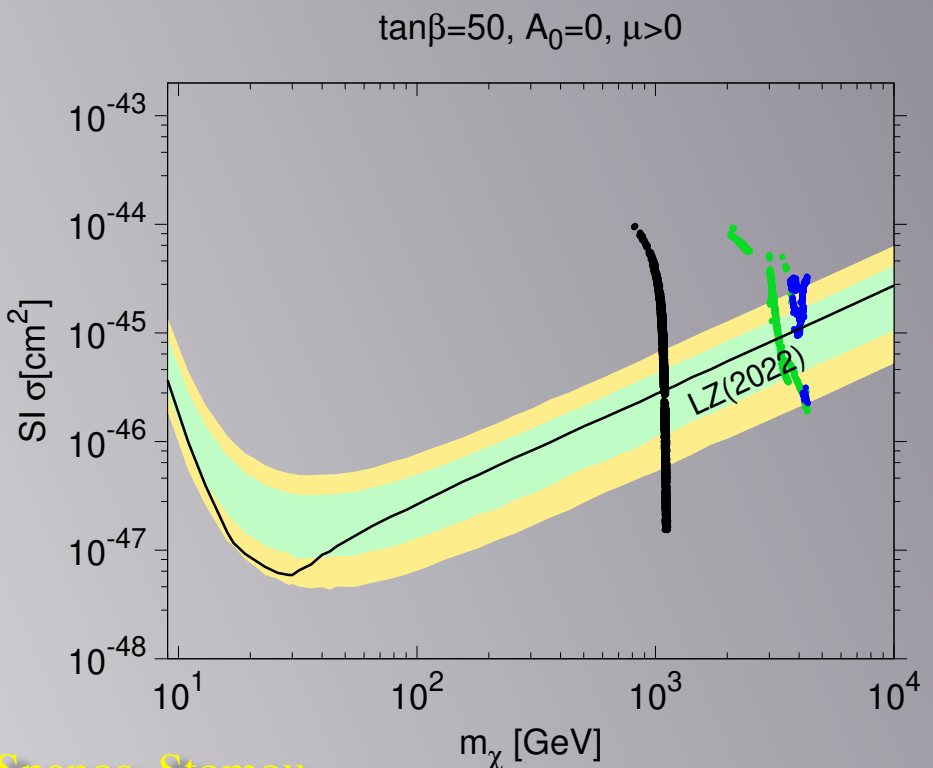


Ellis, Olive, Spanos, Stomou

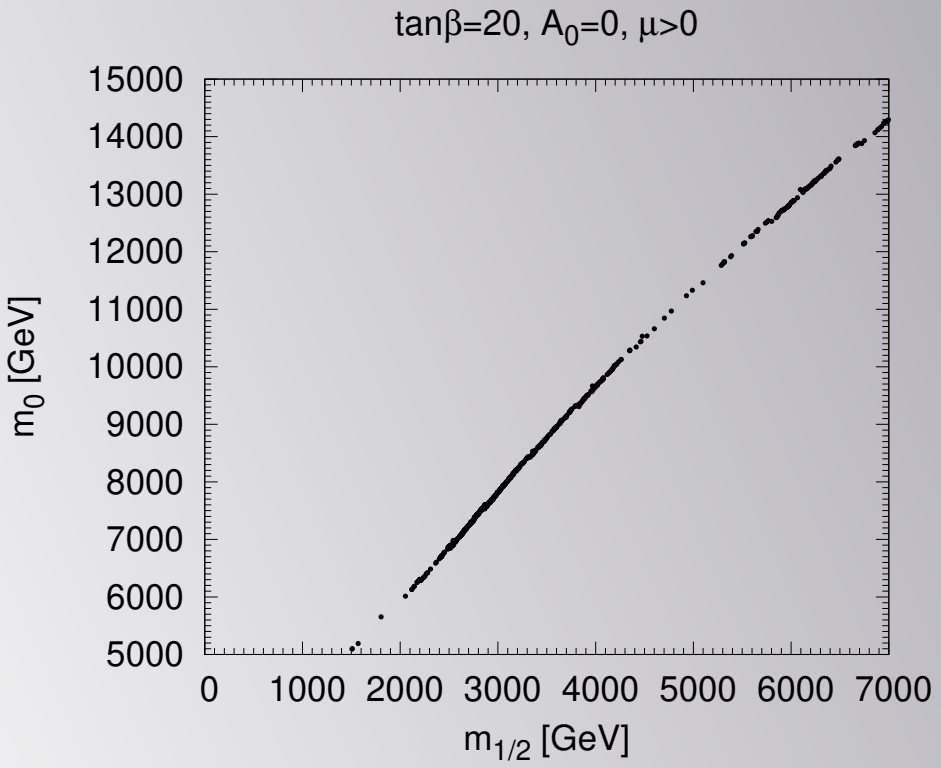


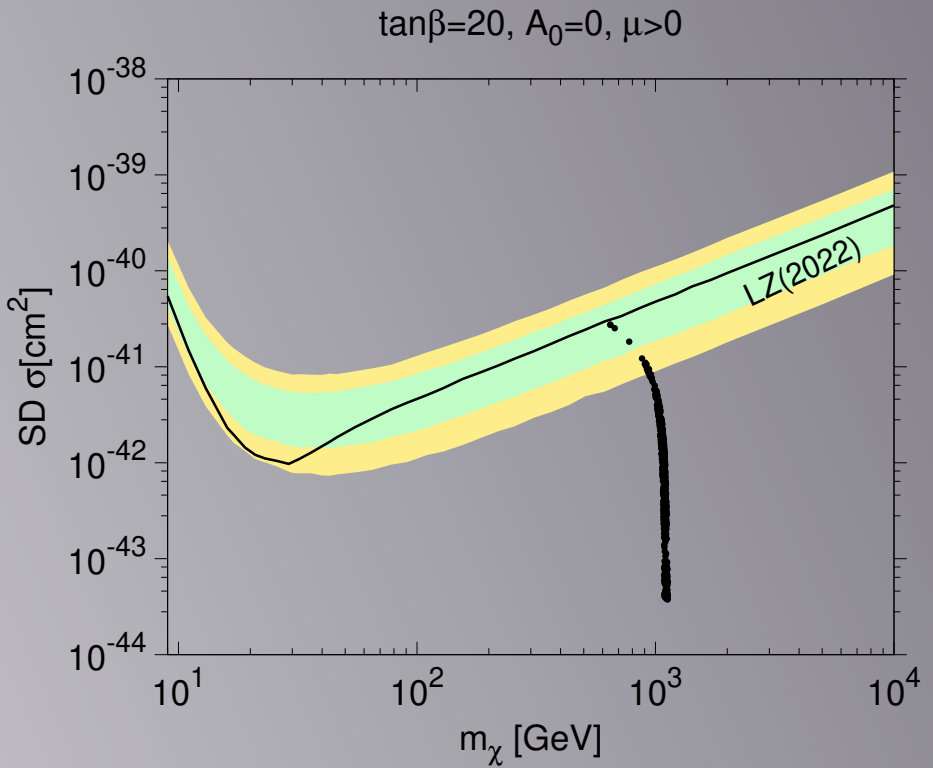


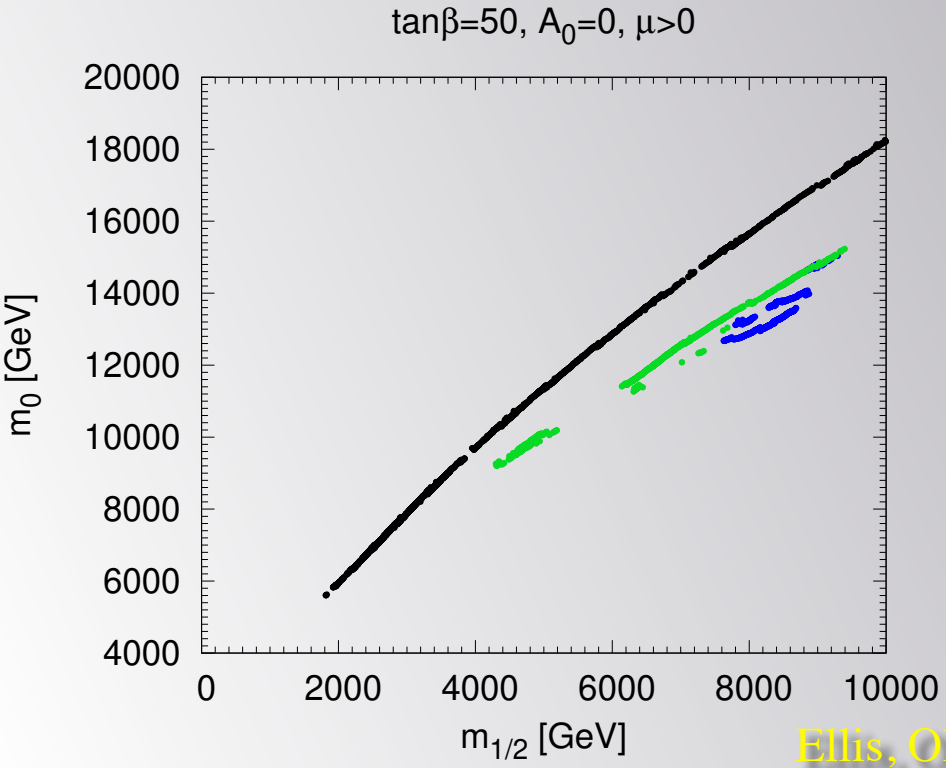


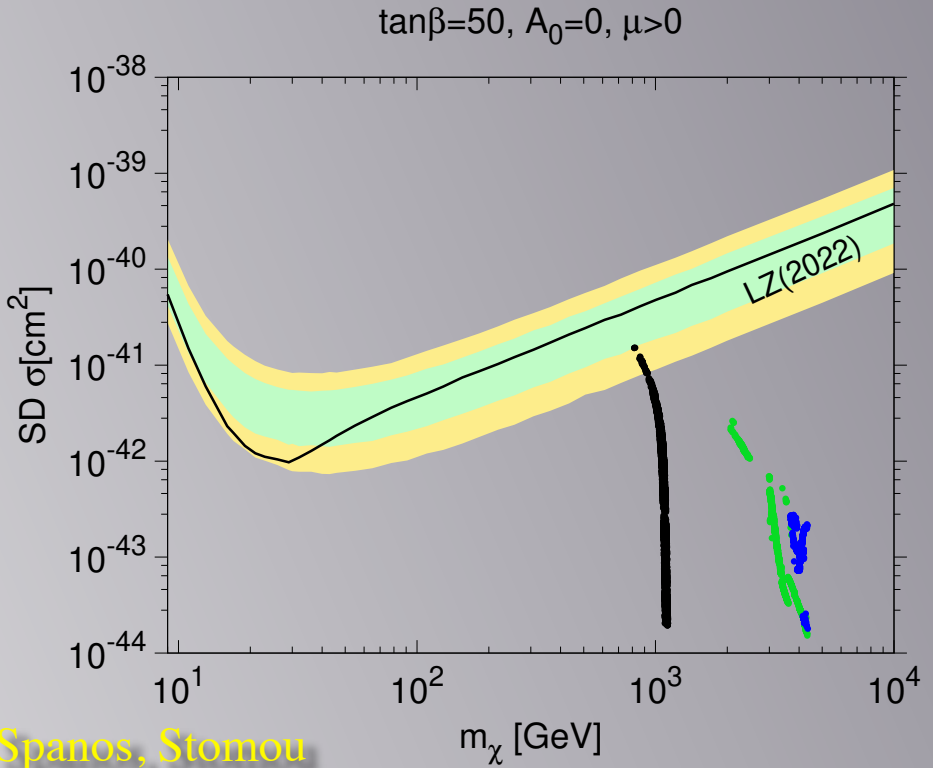


Ellis, Olive, Spanos, Stomou

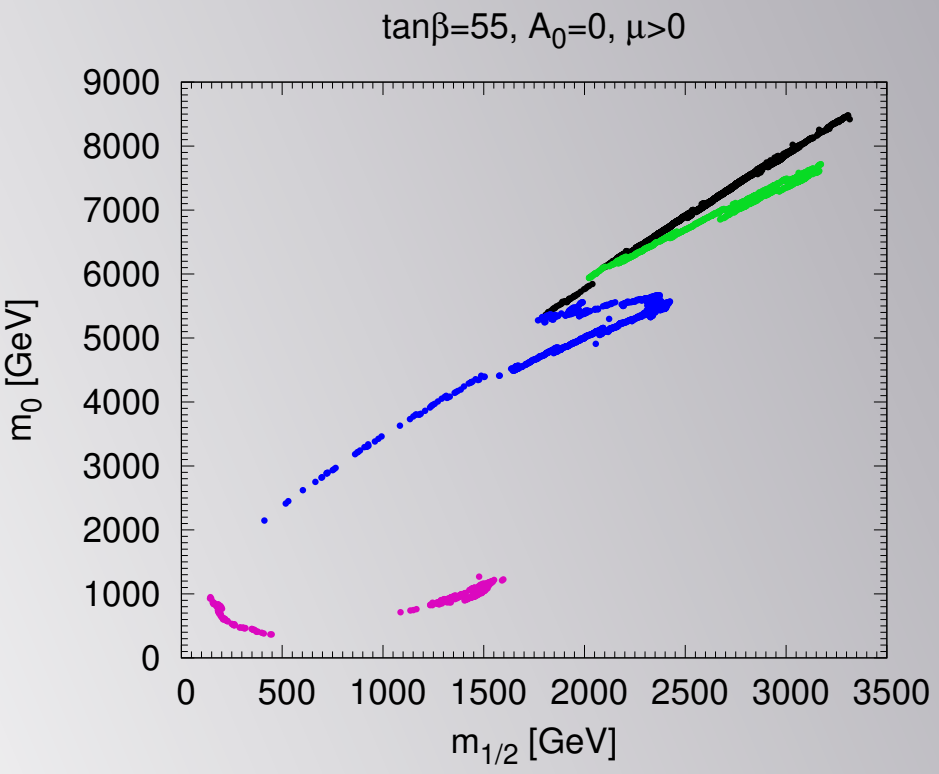


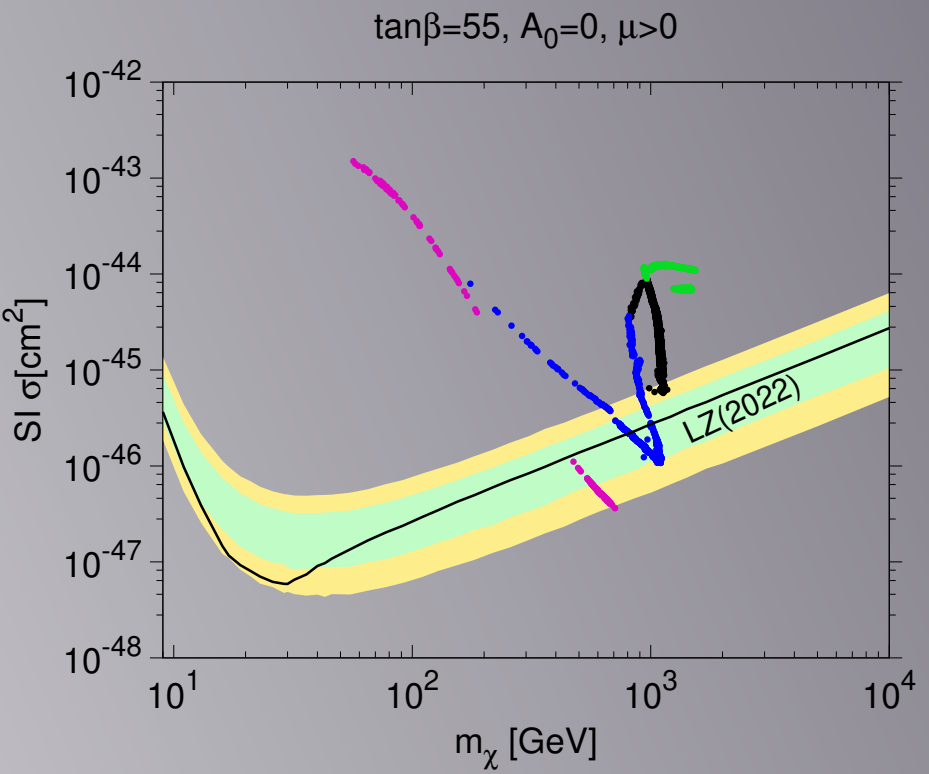


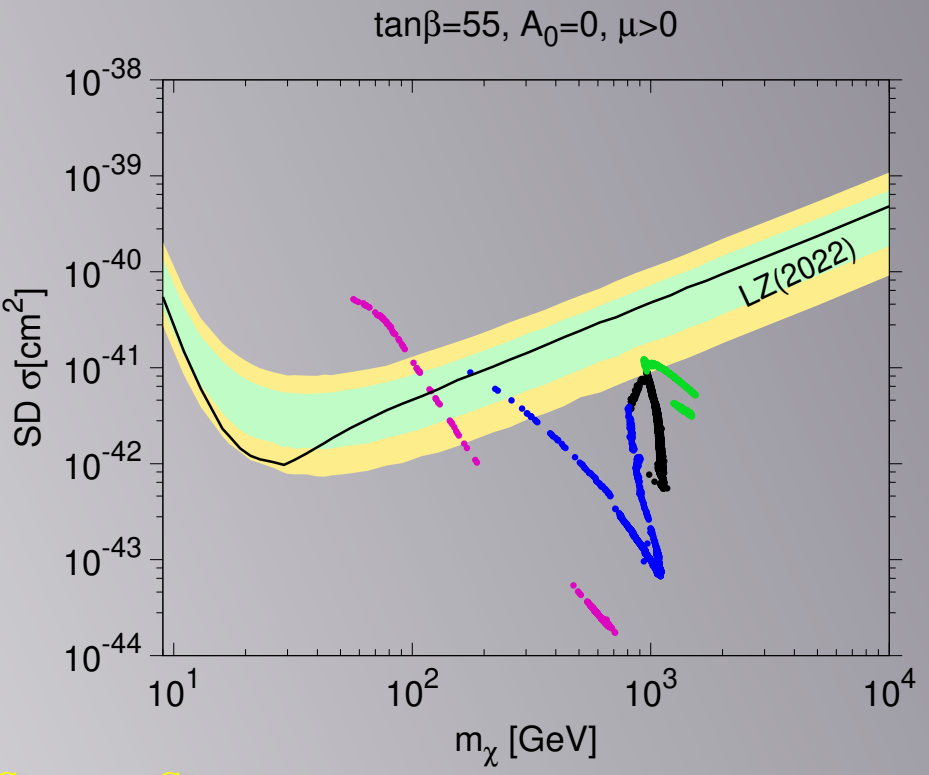




Ellis, Olive, Spanos, Stomou







Ellis, Olive, Spanos, Stomou

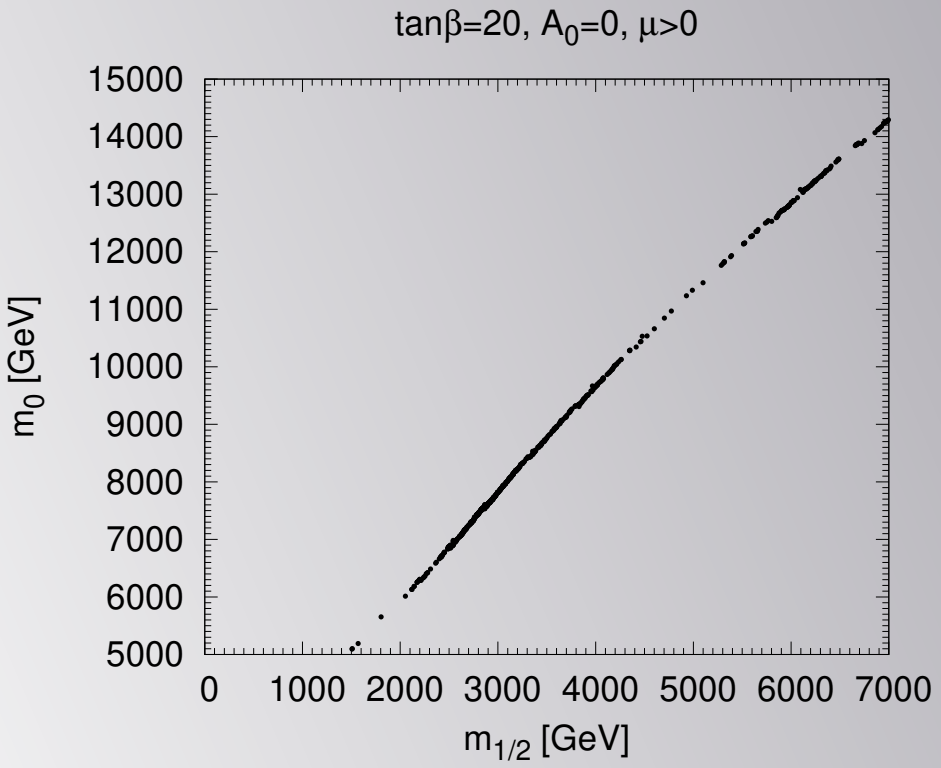
- Gamma Ray Fluxes

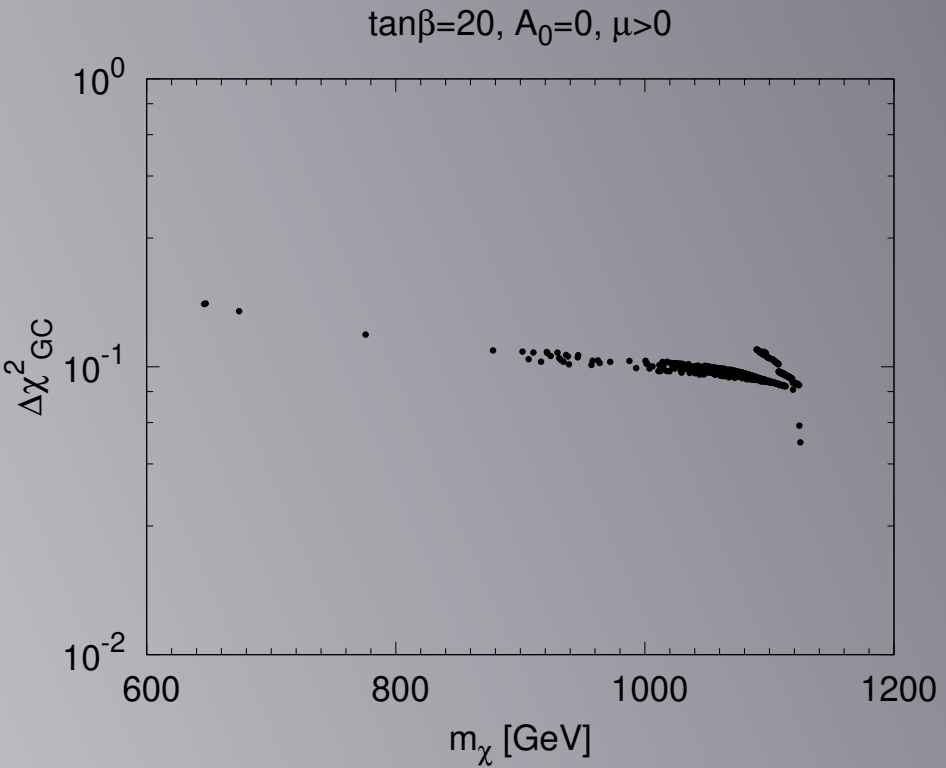
$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{DM}^2}\int_{E_{min}}^{E_{max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma}_{\Phi_{PP}} \times \underbrace{\int_{\Delta\Omega}\int_{l.o.s.}\rho_{DM}^2(r)dld\Omega'}_{\text{J factor}},$$

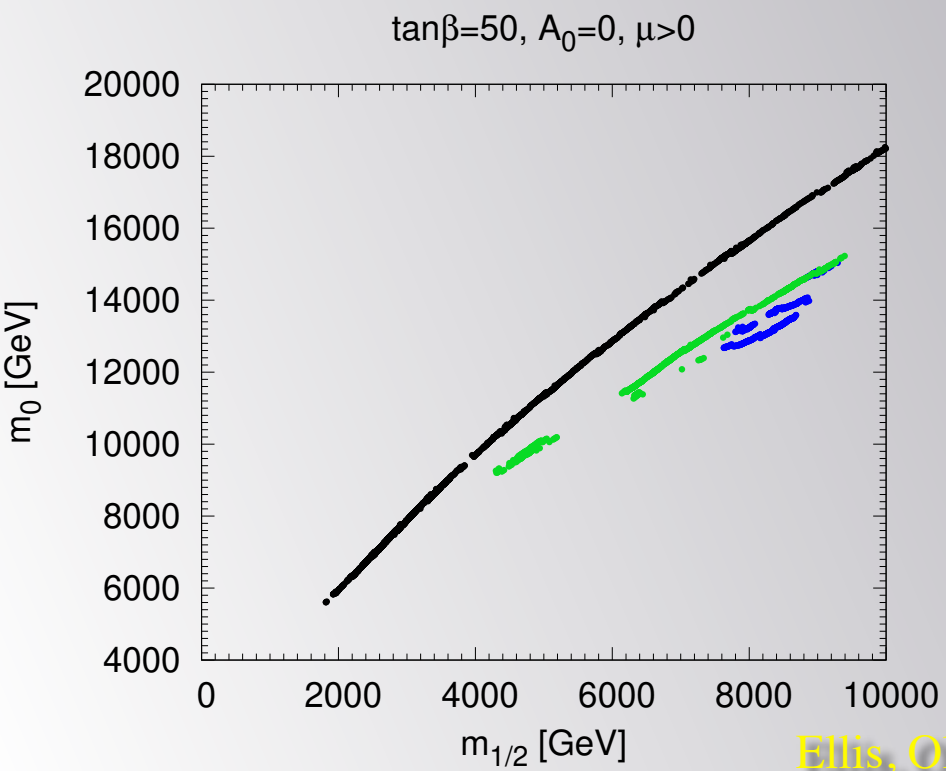
$$dN_\gamma/dE_\gamma = \sum_f B_f dN_\gamma^f/dE_\gamma\,,$$

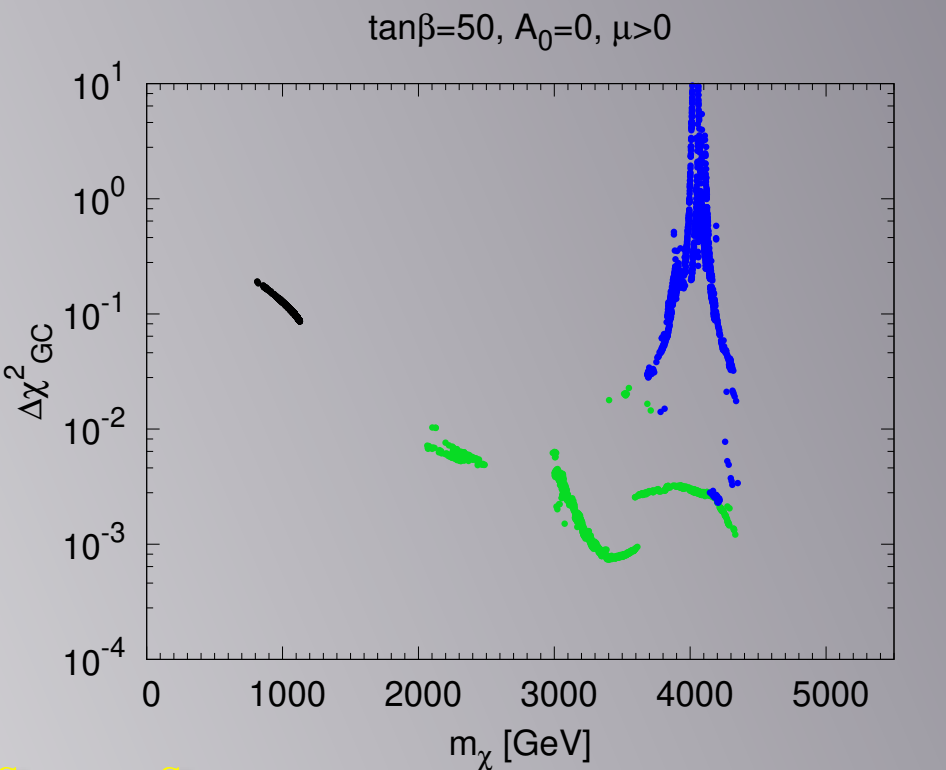
$$\rho_{DM}(r) = \frac{\rho r_s^3}{r(R+r)^2}\,.$$

- Neutrino Fluxes









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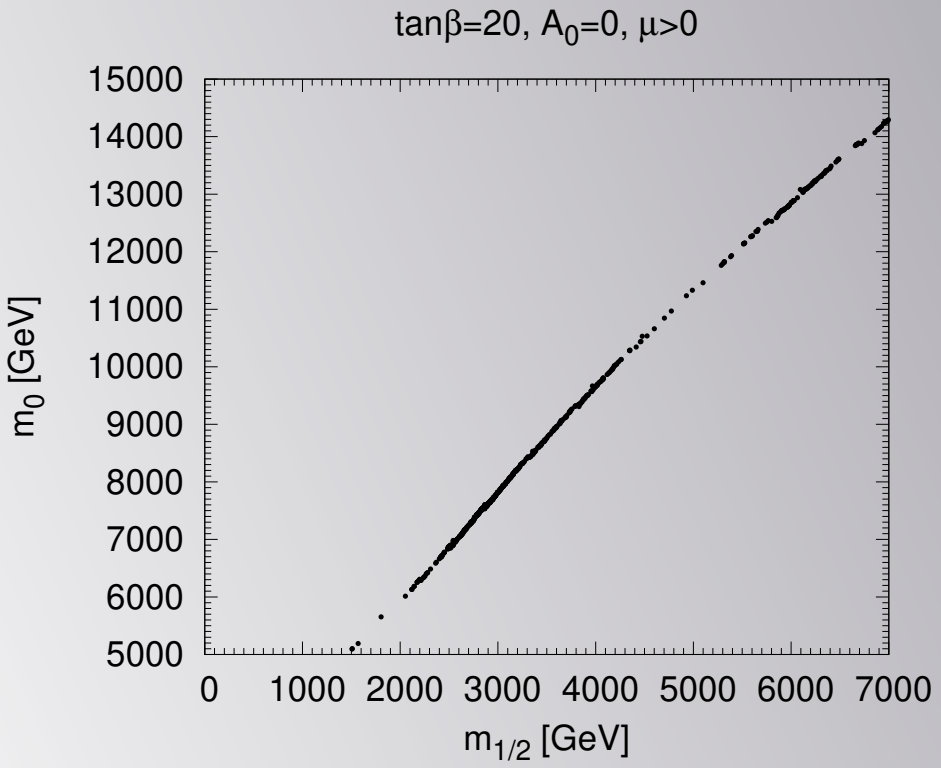

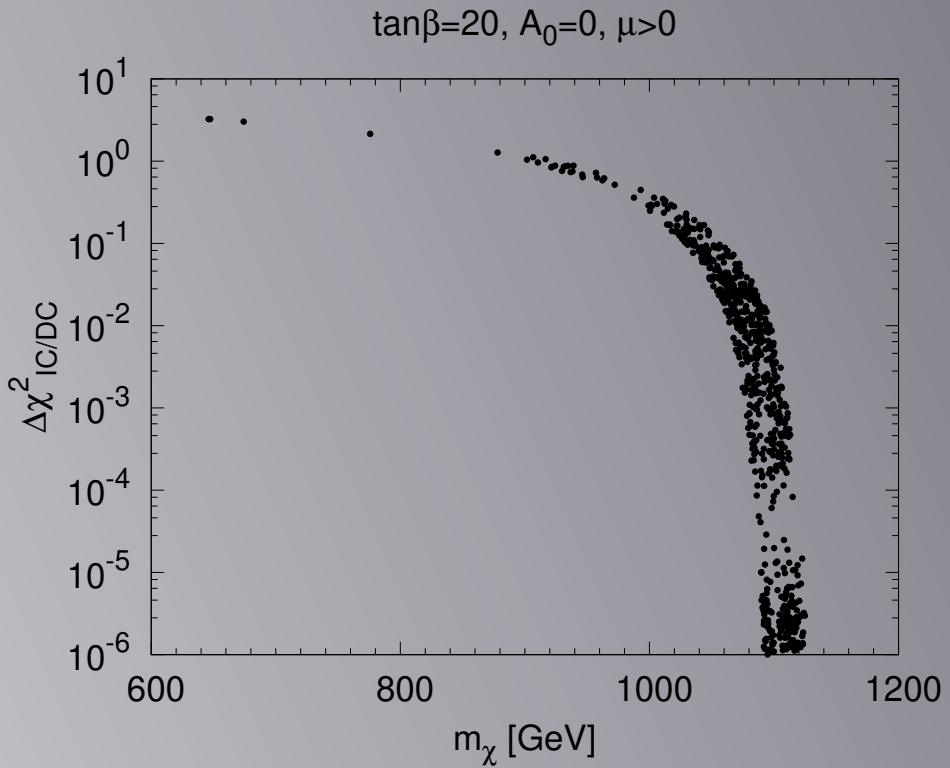

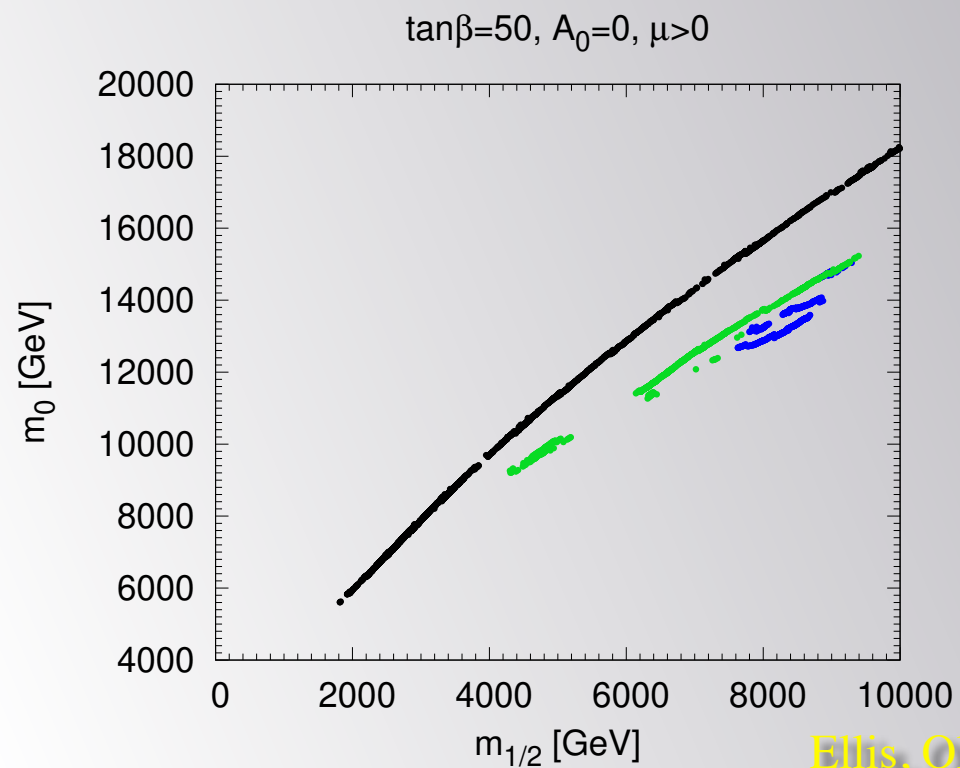

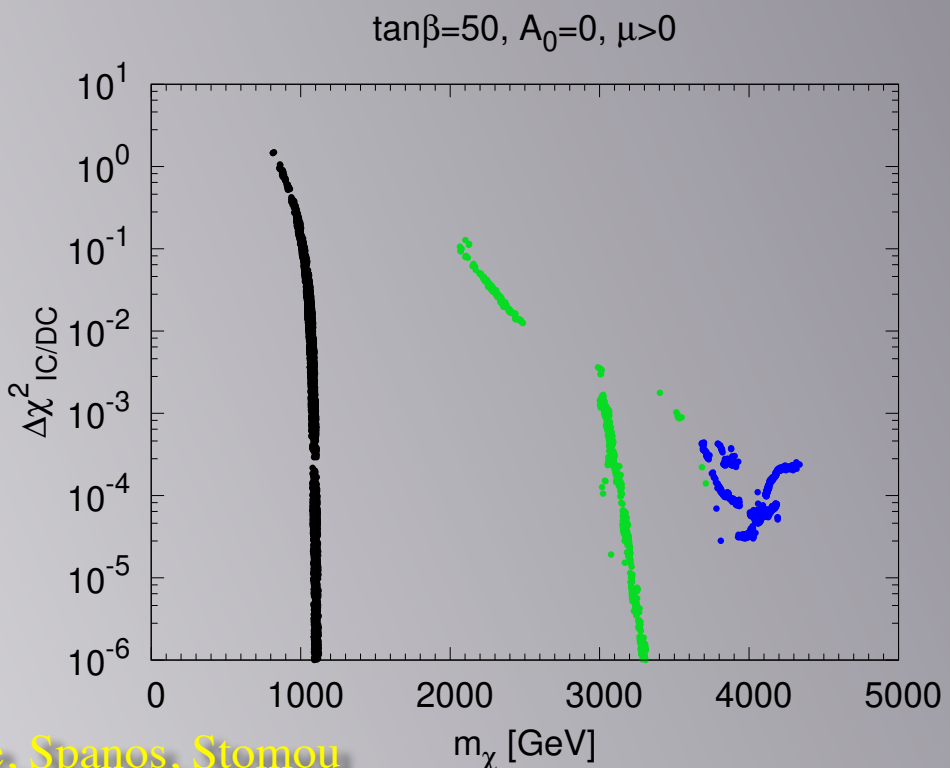

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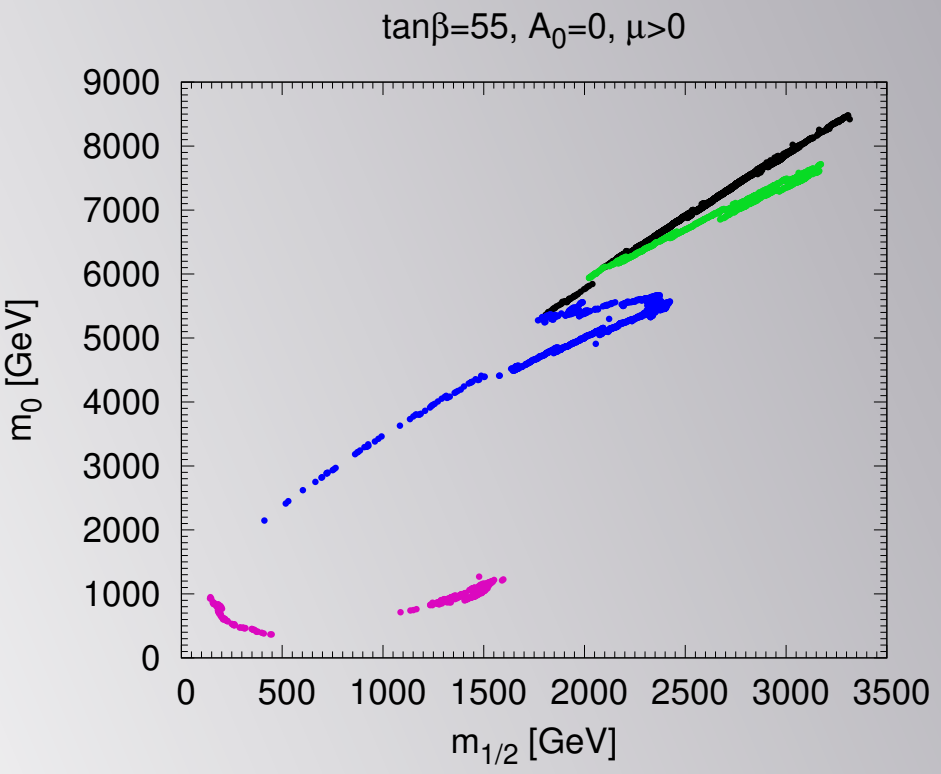
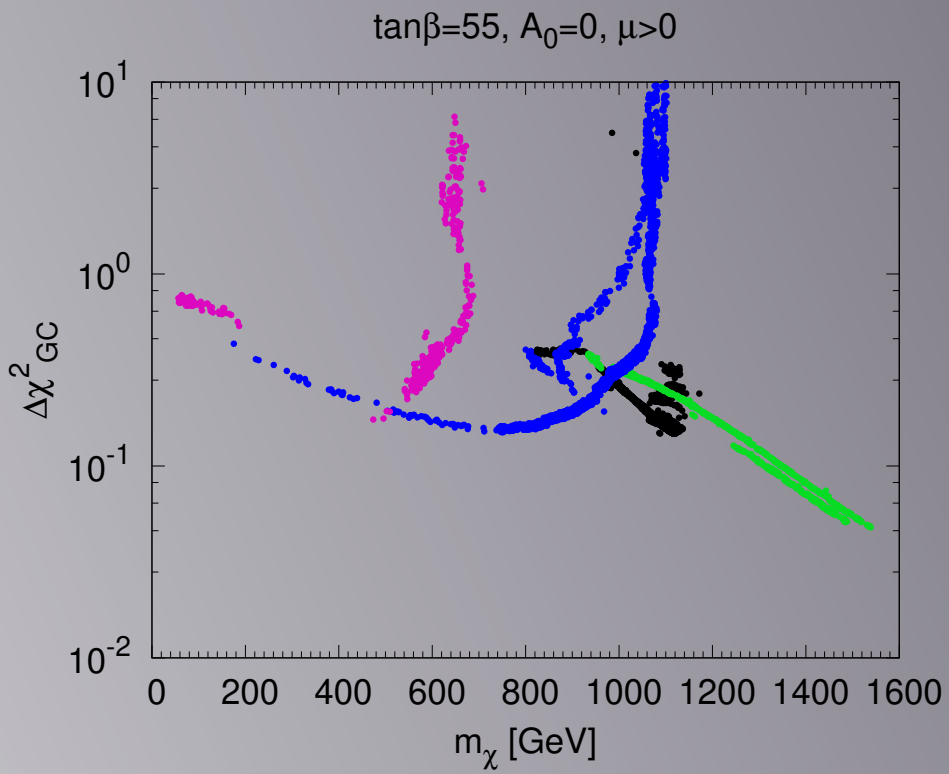
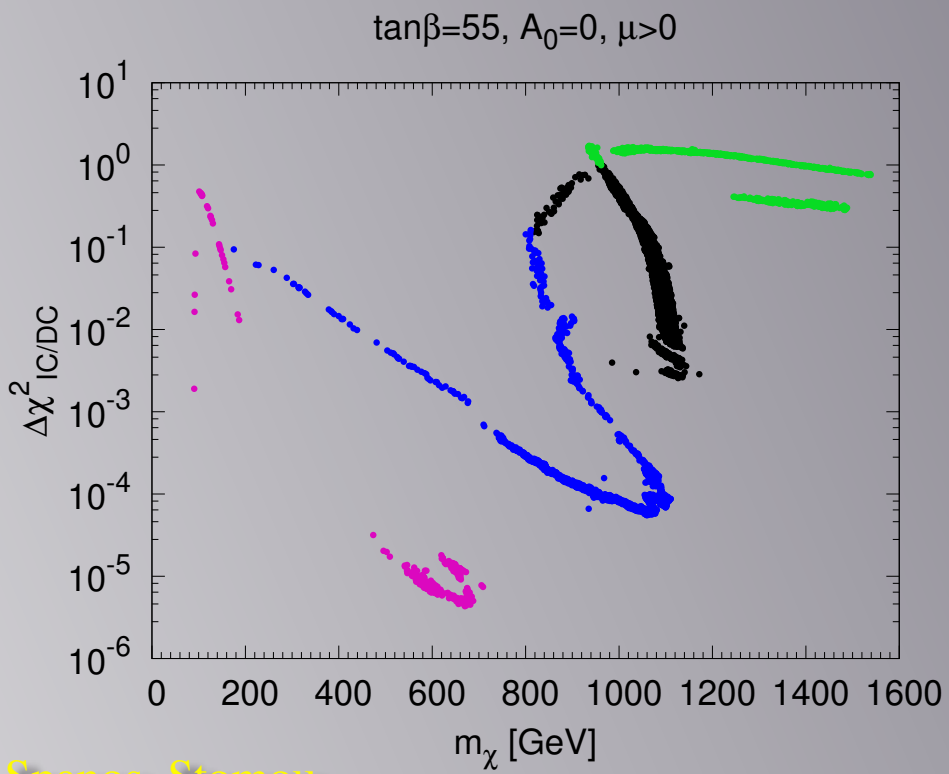
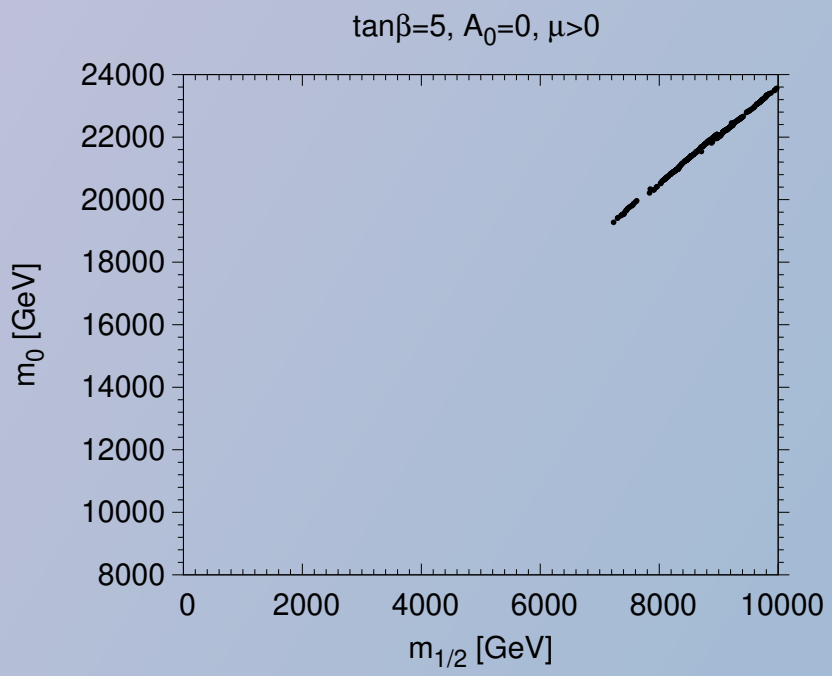






Ellis, Olive, Spanos, Stomou

What's left?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m0 [GeV]
m1/2 [GeV]
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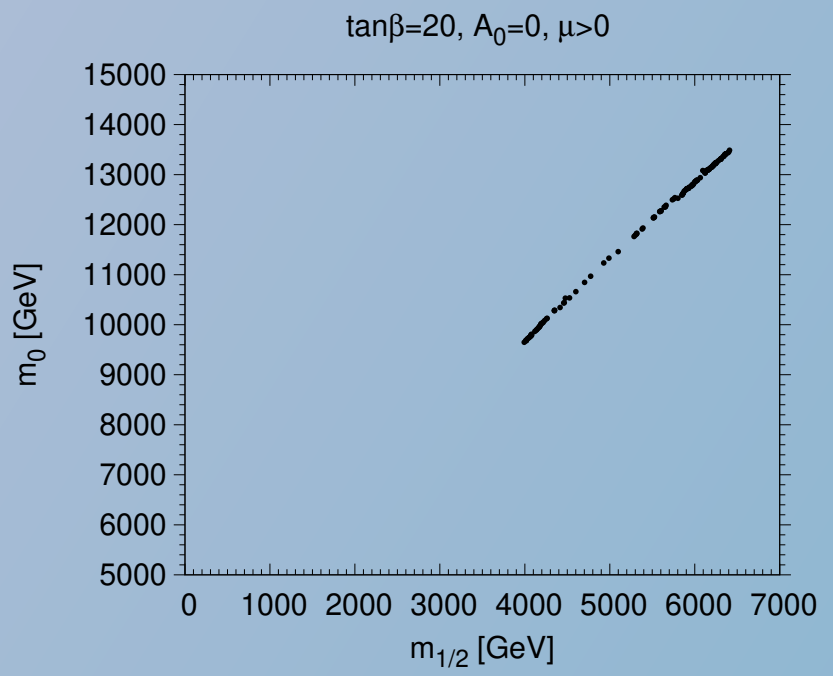
22000
20000
18000
16000
14000
12000
10000
8000
0
2000
4000
6000
8000
10000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m1/2 [GeV]
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13000
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11000
10000
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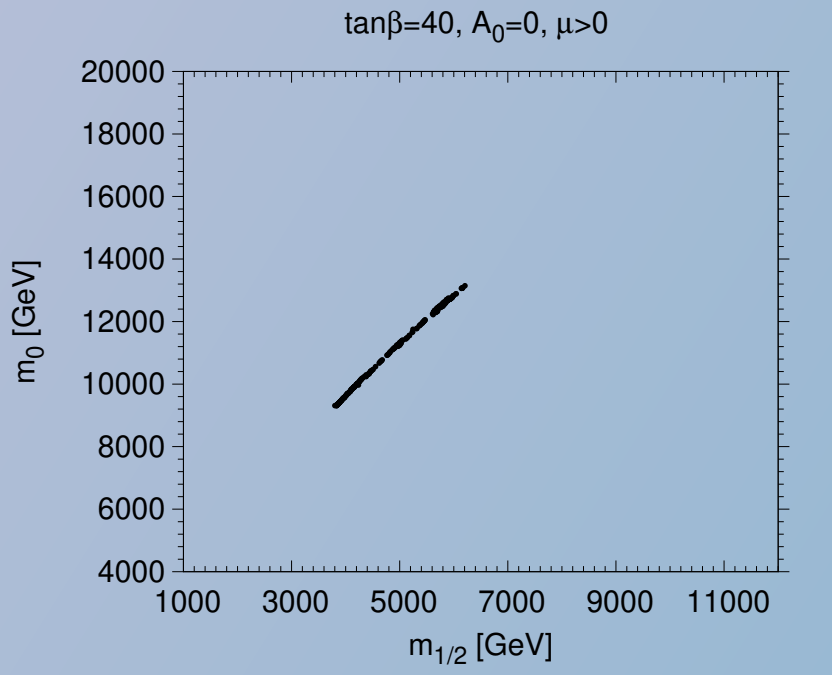
8000
7000
6000
5000
0
1000
2000
3000
4000
5000
6000
7000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m1/2 [GeV]
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18000
16000
14000
12000
10000
8000
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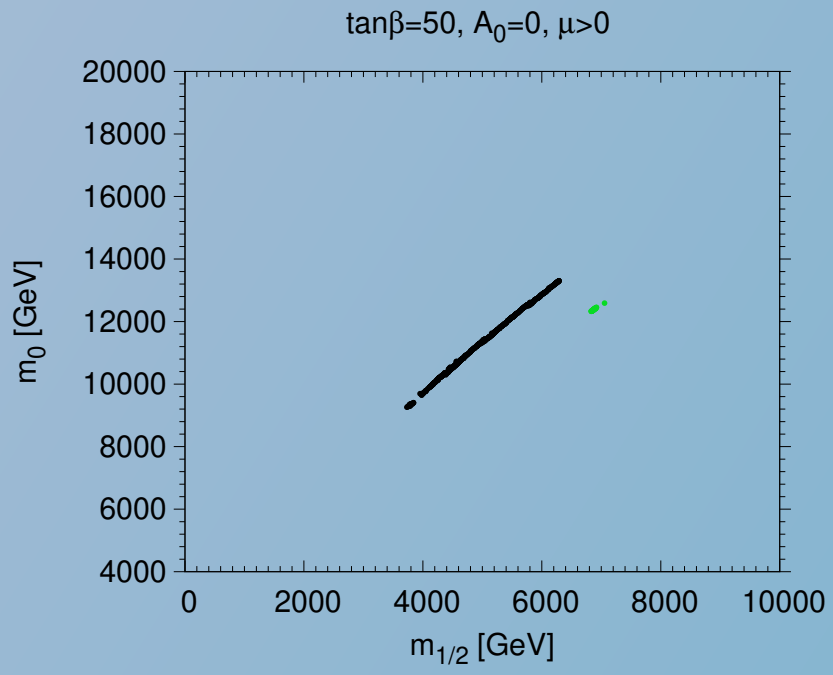
1000
3000
5000
7000
9000
11000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m1/2 [GeV]
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16000
14000
12000
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8000
6000
4000
0
2000
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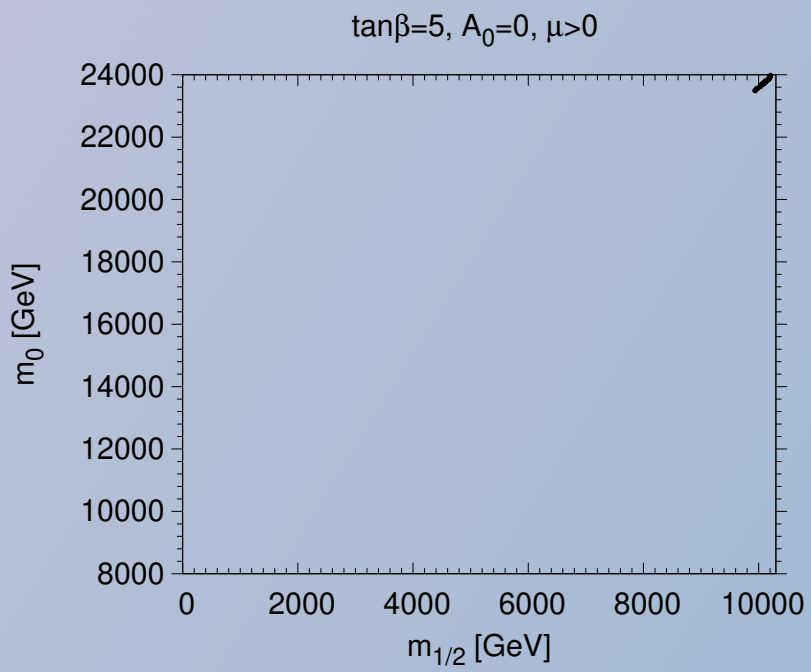
6000
8000
10000

What's left?


tanβ=5, A0=0, μ>0
m0 [GeV]
m1/2 [GeV]
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20000
18000
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8000
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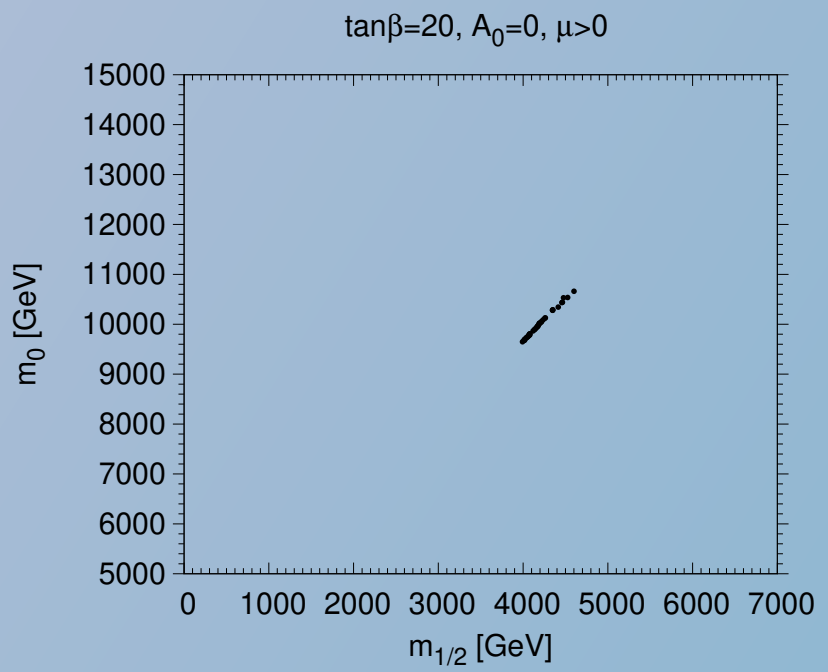
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m1/2 [GeV]
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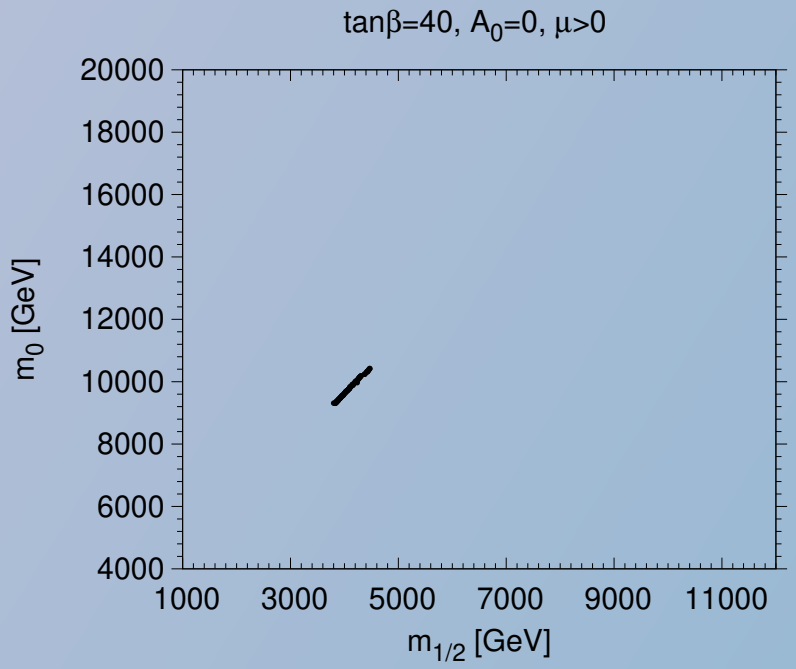
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m1/2 [GeV]
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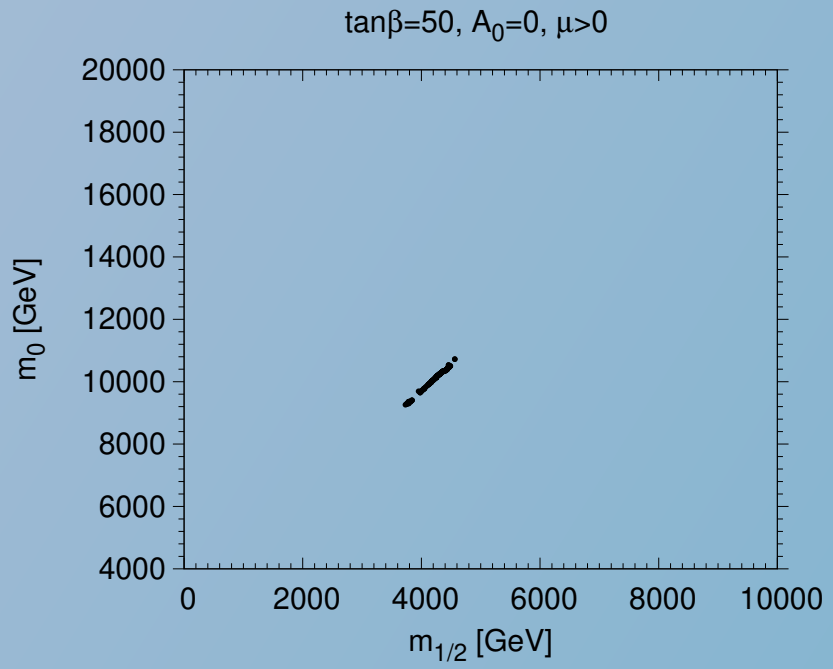
tanβ=50, A0=0, μ>0
m0 [GeV]
m1/2 [GeV]
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14000
12000
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8000
6000
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0
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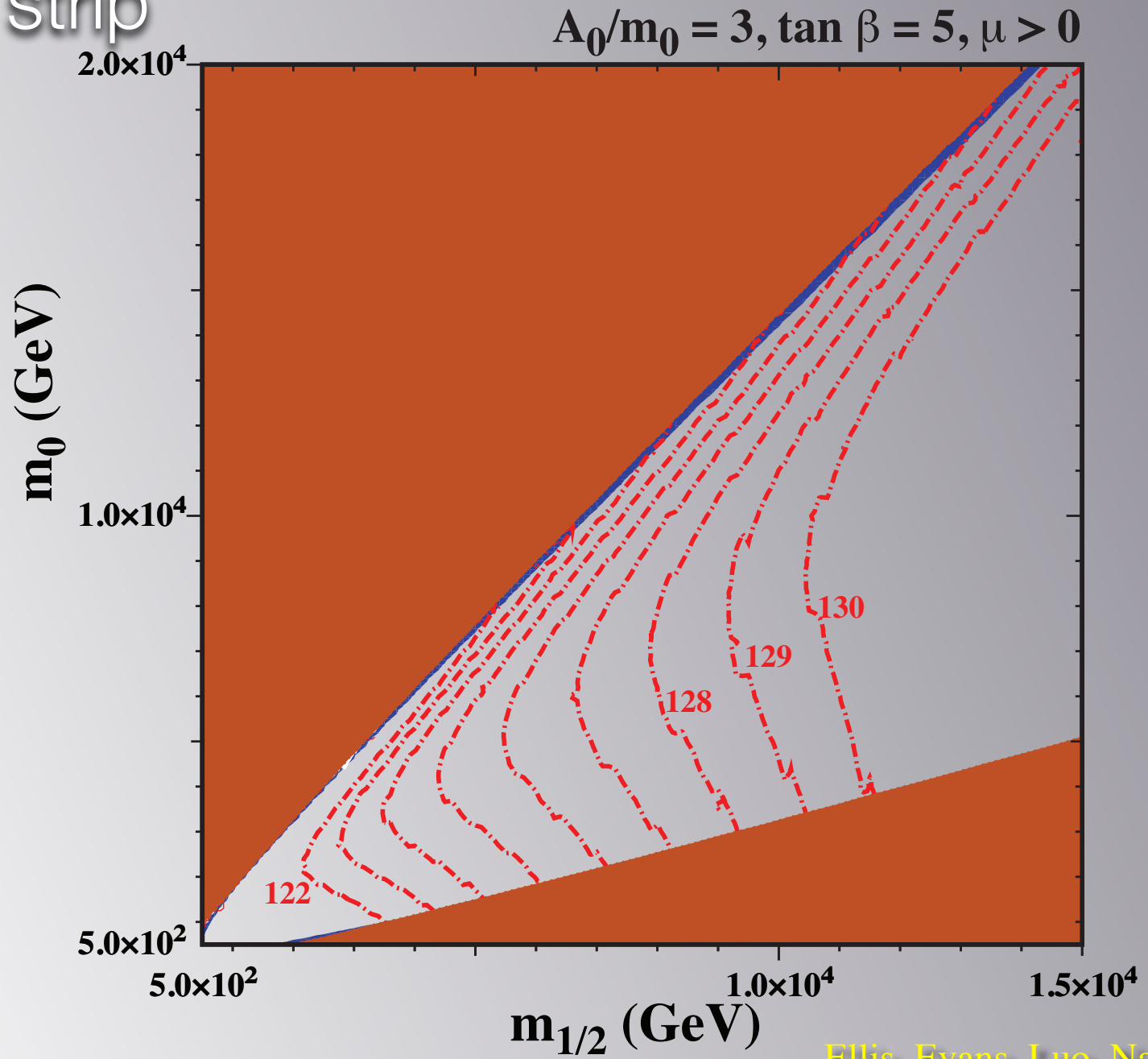
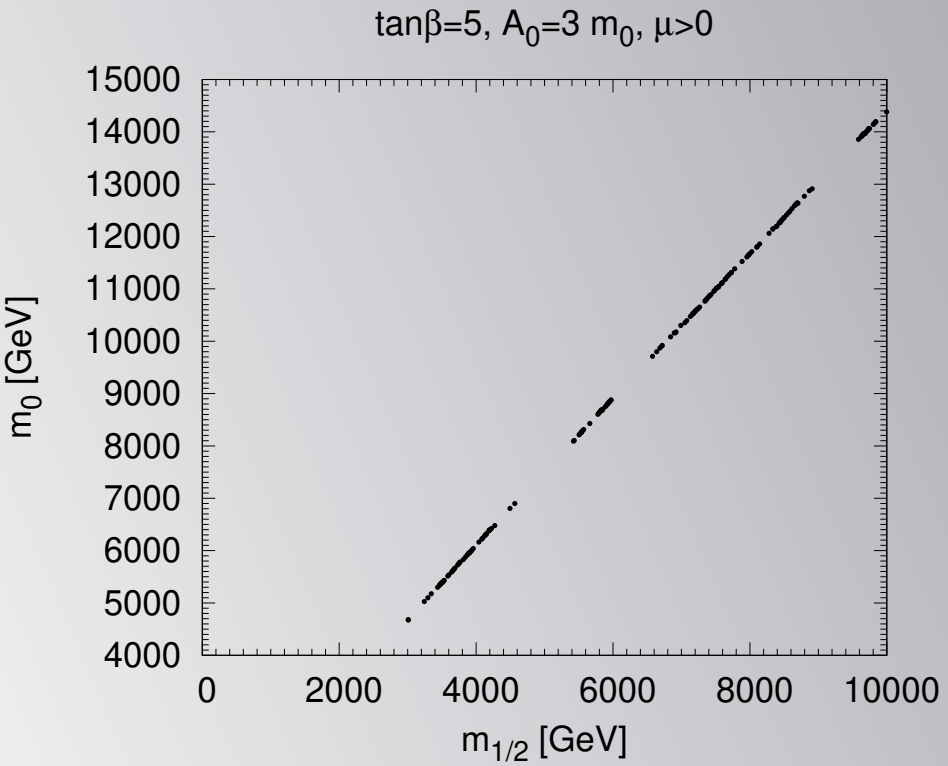
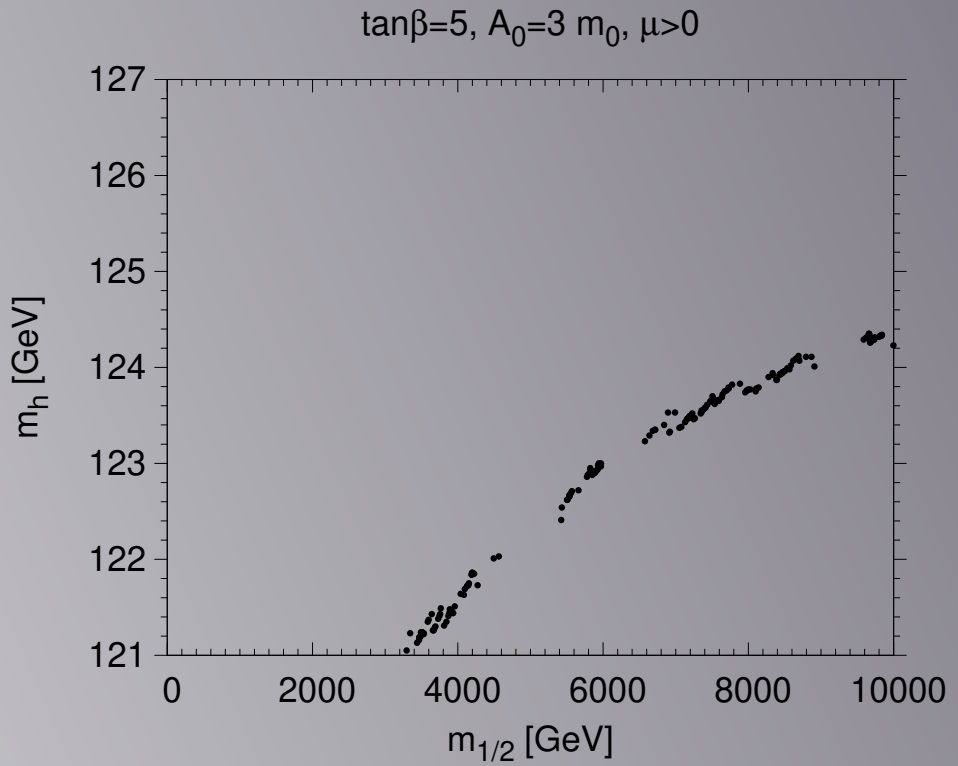
6000
8000
10000

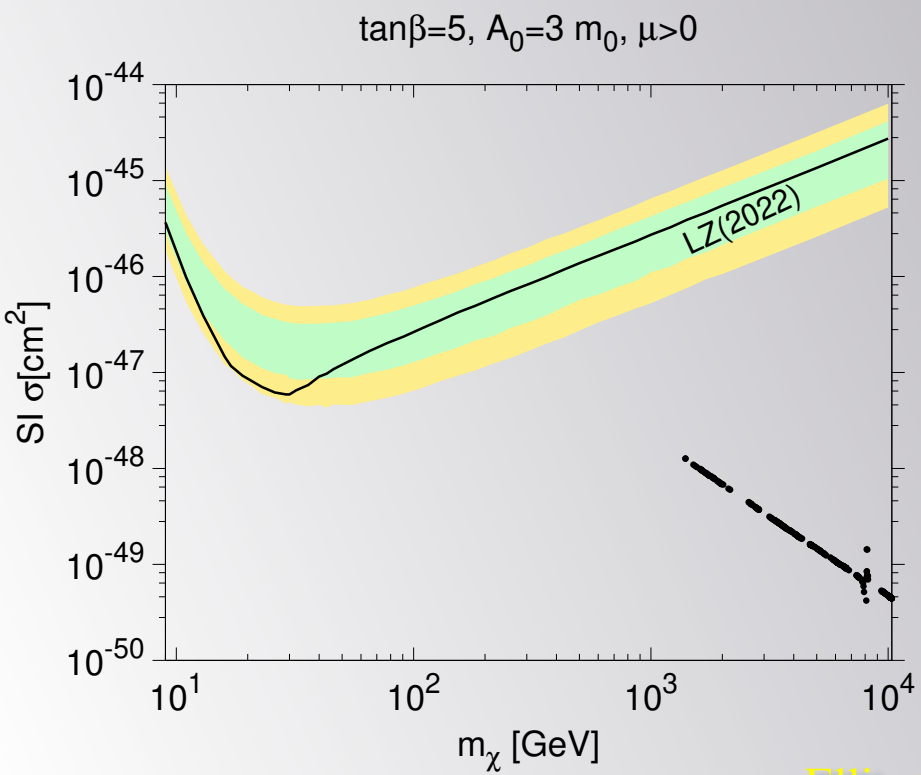
Stop strip

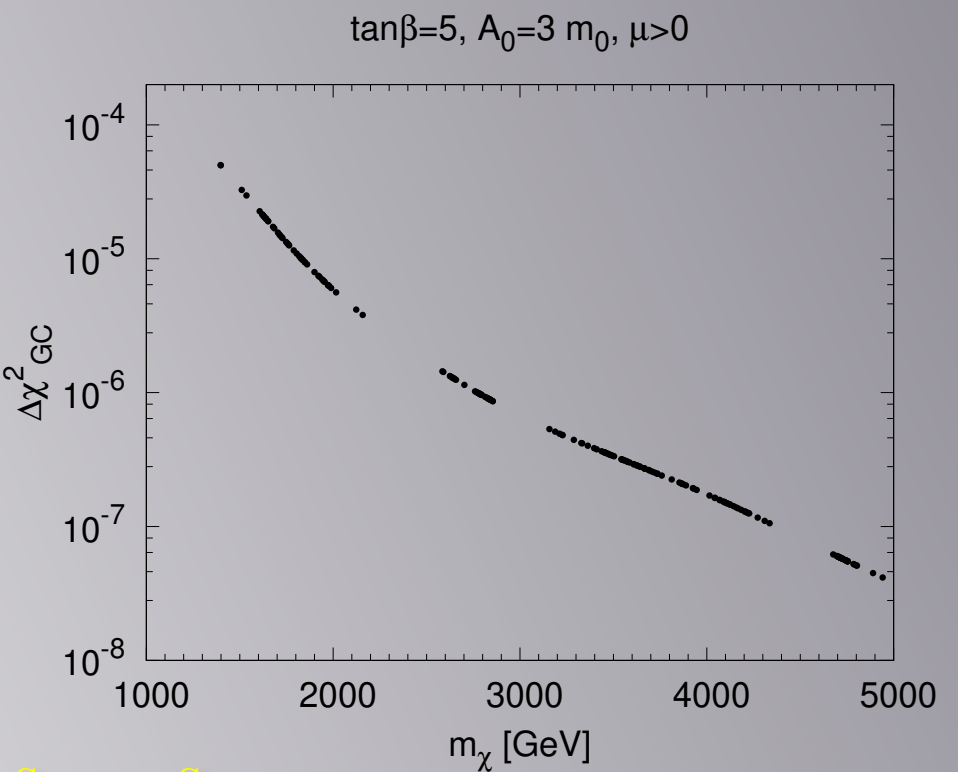


Ellis, Evans, Luo, Nagata, Olive, Sandick
Ellis, Evans, Luo, Olive, Zheng
Bagnaschi et al.
Ellis, Evans, Nagata, Olive, Velasco-Sevilla

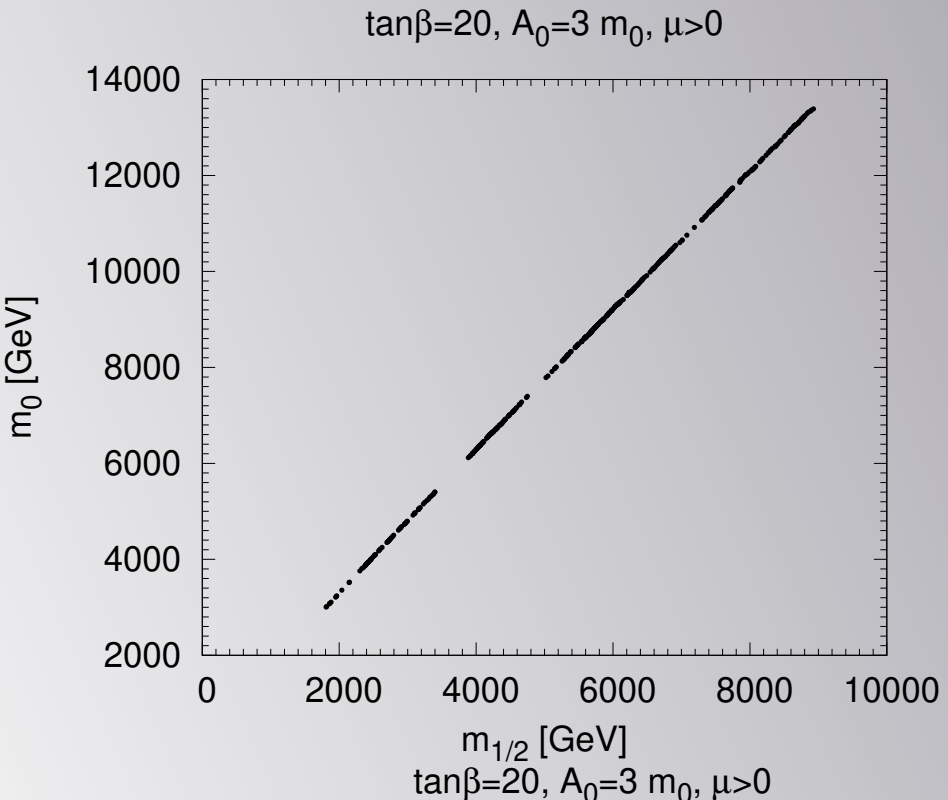


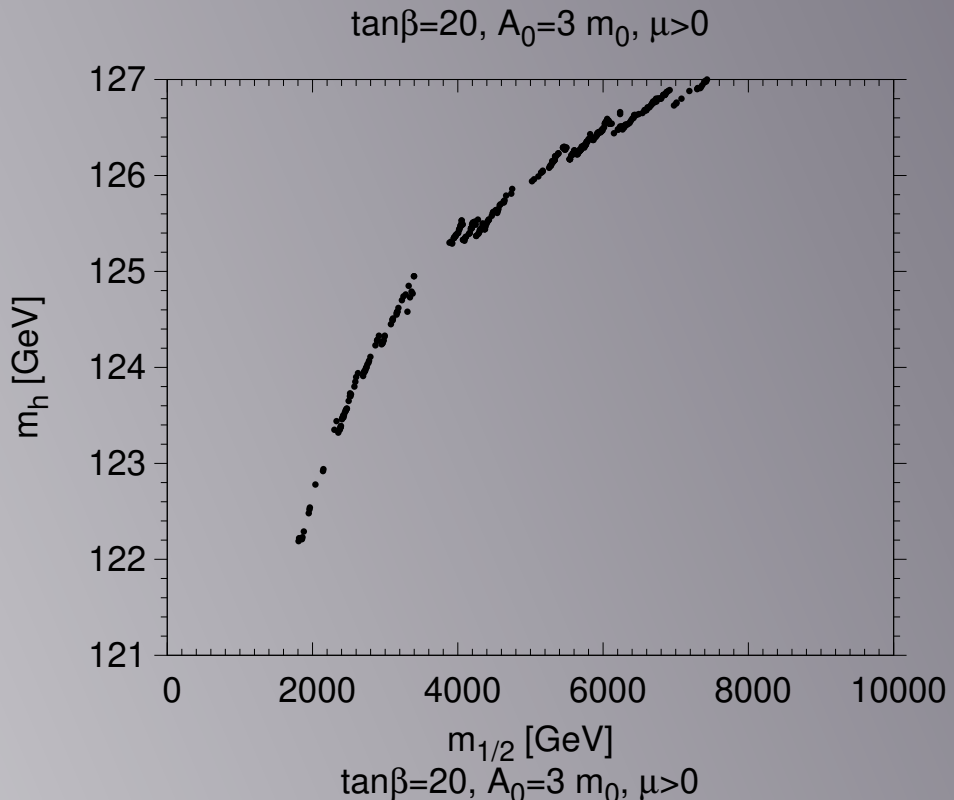


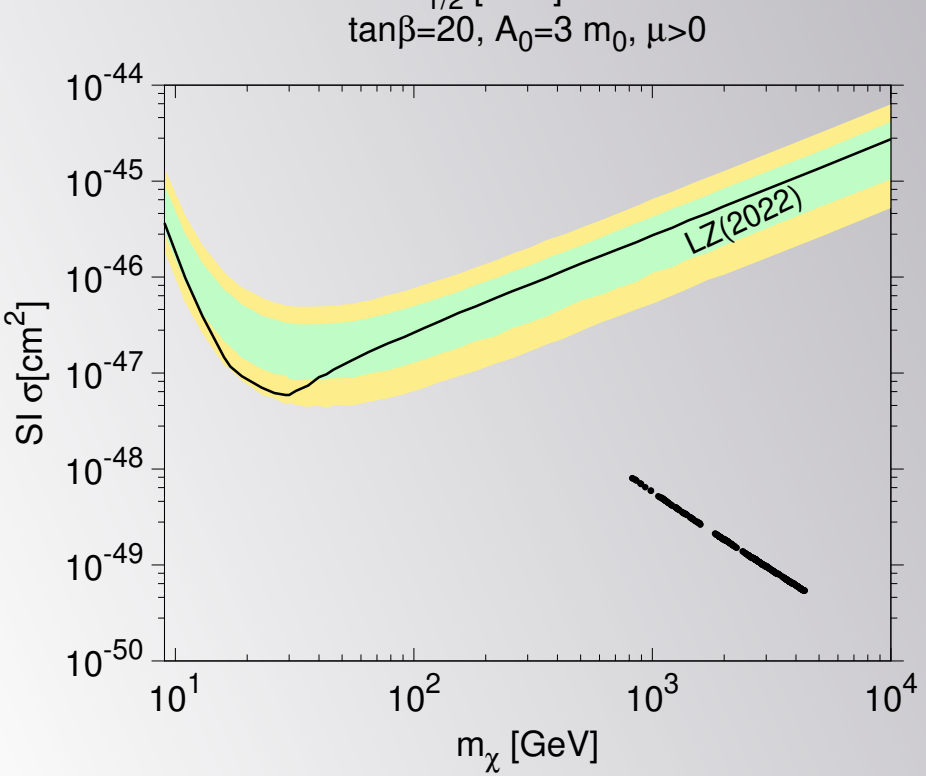


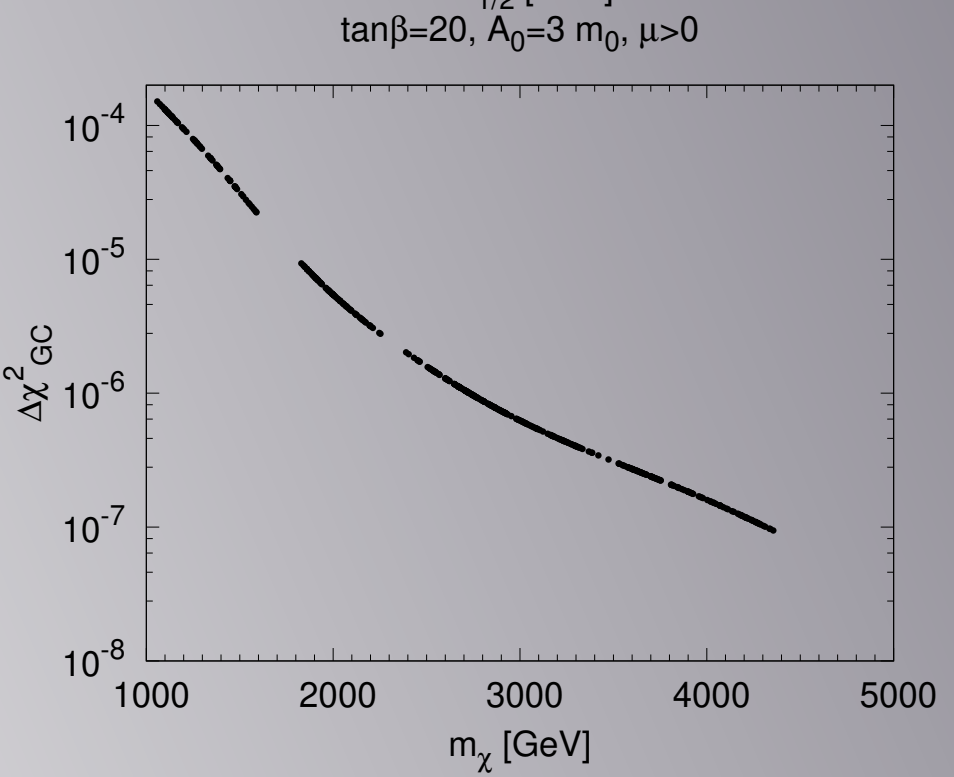


Ellis, Olive, Spanos, Stomou









Ellis, Olive, Spanos, Stomou

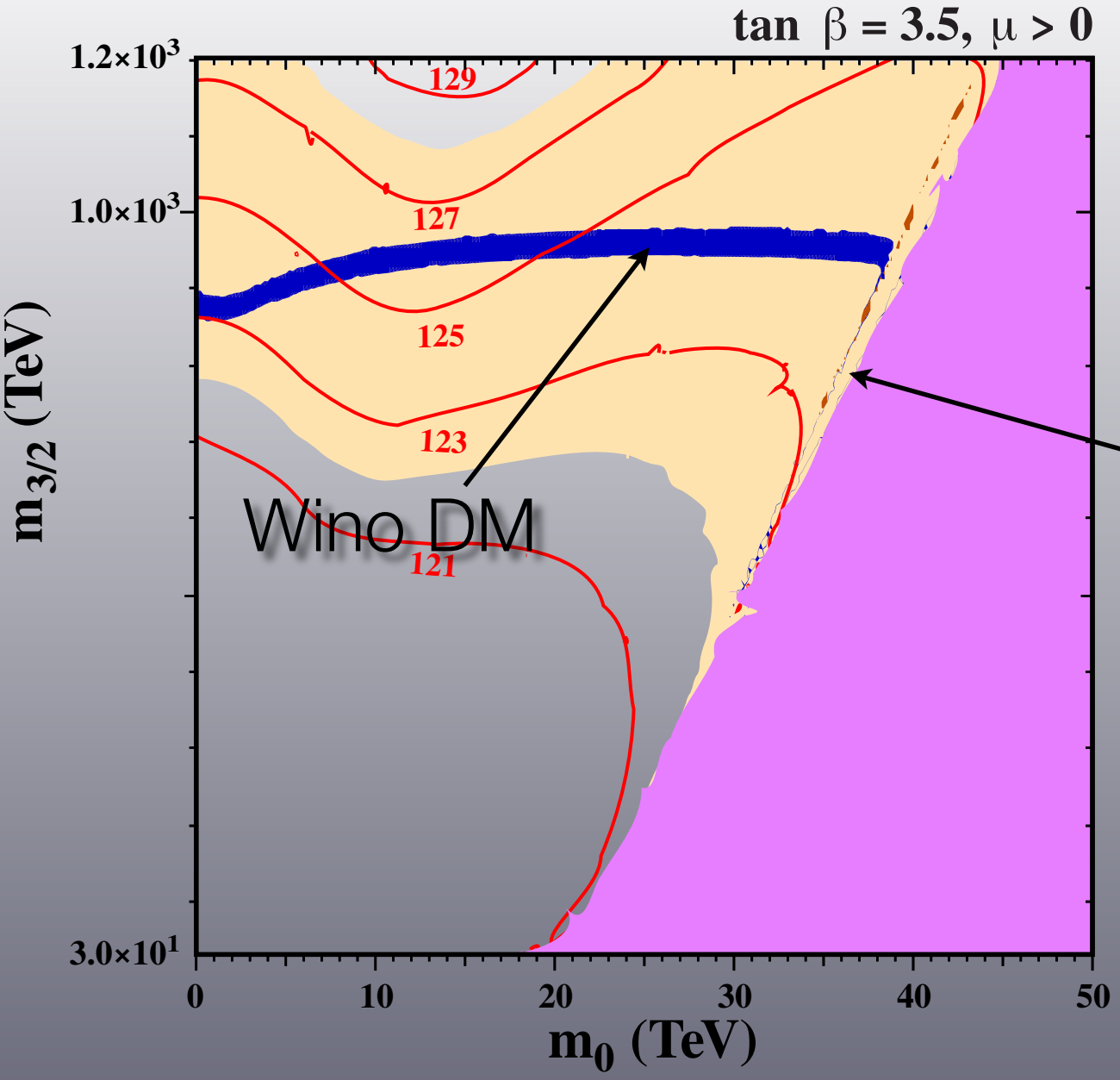
Other Possibilities

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 allows $m_0 \neq m_{3/2}$

(with PeV scales)

mAMSB



Scalar masses: $m_0 \neq m_{3/2}$

Mastercode 2016

Bagnaschi et al.

Other Possibilities

Less Constrained (more parameters)

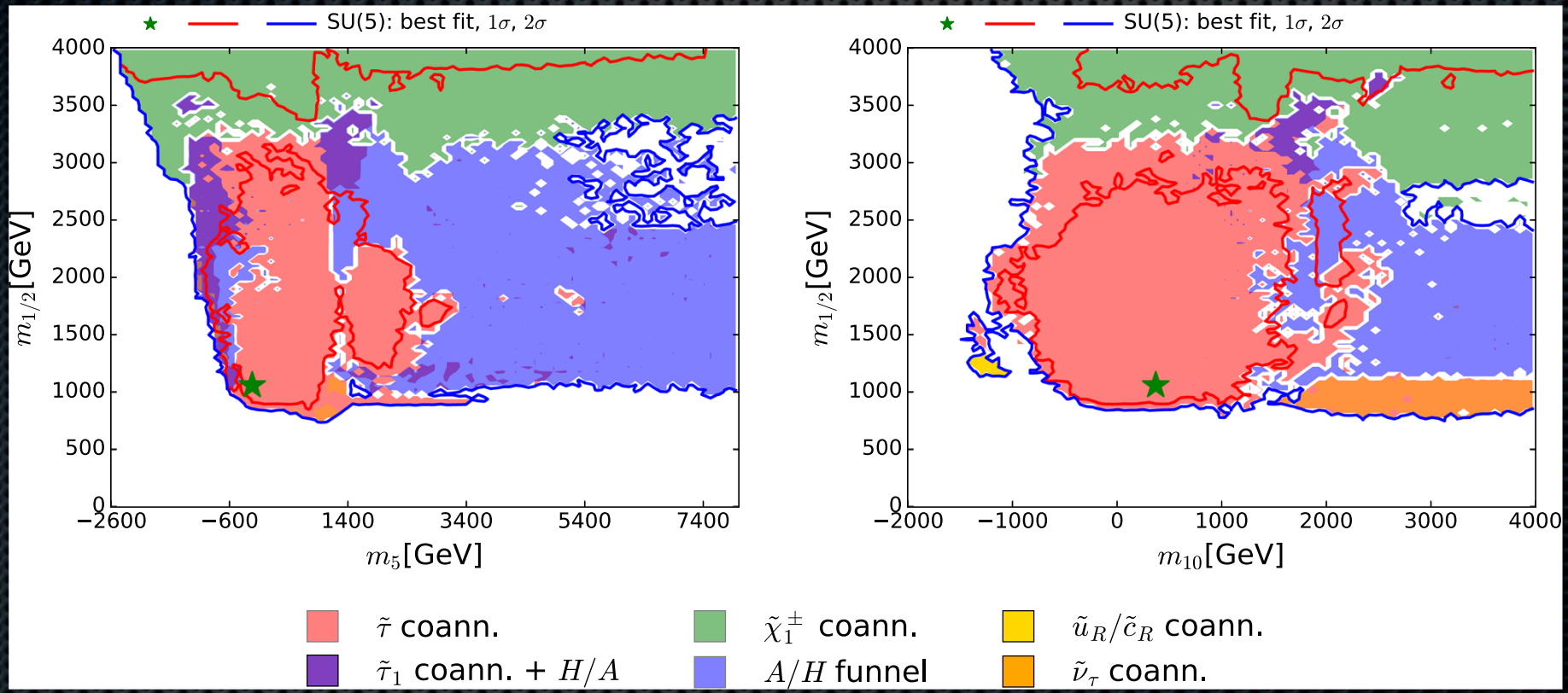
- NUHM1,2: $m_1^2 = m_2^2 \neq m_0^2$, $m_1^2 \neq m_2^2 \neq m_0^2$
  - μ and/or m_A free
- NUGM
  - gluino coannihilation
- subGUT models: $M_{in} < M_{GUT}$
  - new parameter M_{in}
- SuperGUT models: $M_{in} > M_{GUT}$
  - requires SU(5) input couplings

What about g_μ - 2?

See talk of Sven Heinemeyer

SU(5) - motivated

$m_{\bar{5}} \neq m_{10}$



Mastercode 2014

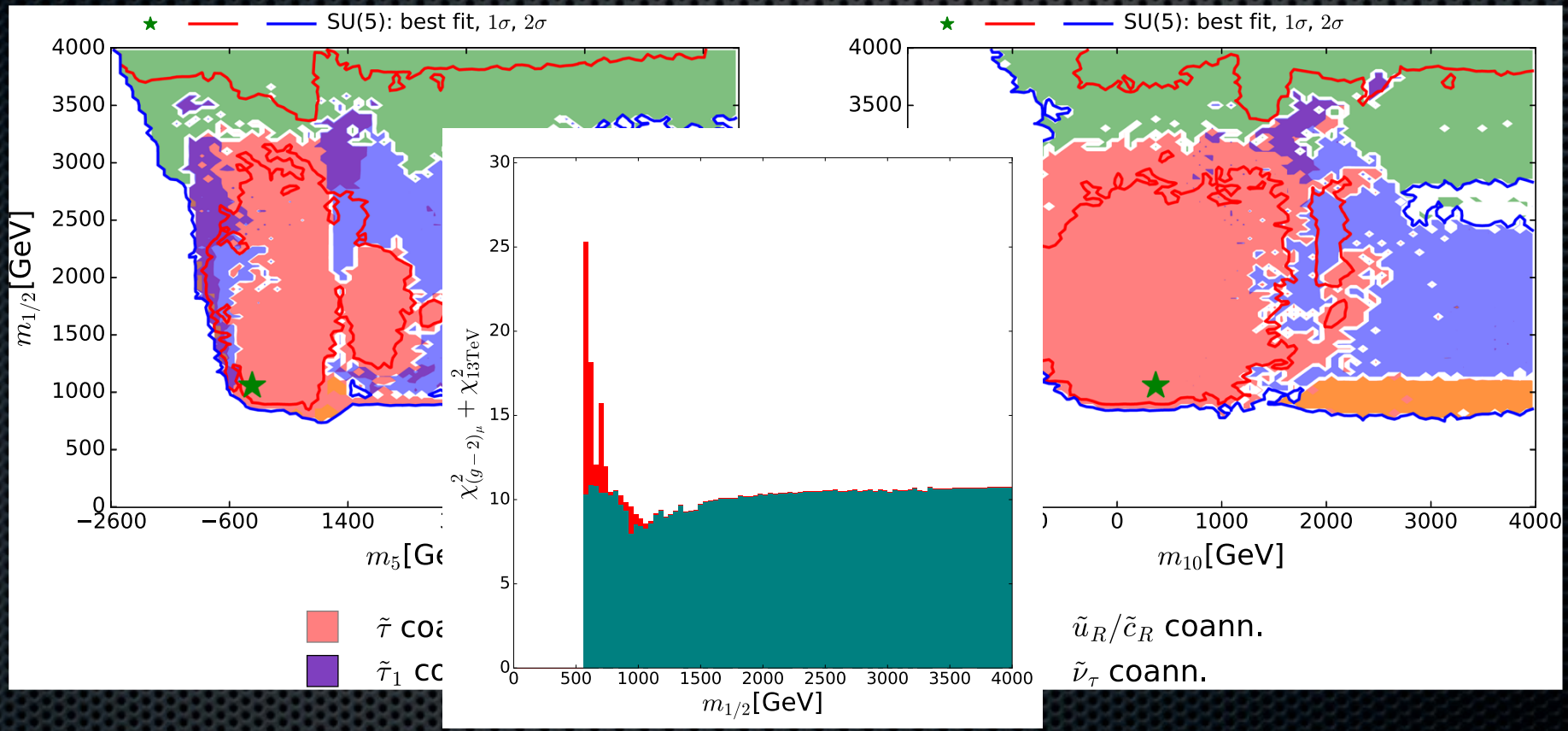
Bagnaschi, Costa, Sakurai, Borsato, Buchmueller, Cavanaugh, Chobanova, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Lucio,, Martinez Santos, Olive, Richards, de Vries, Weiglein

What about g_μ - 2?

See talk of Sven Heinemeyer

SU(5) - motivated

$m_{\bar{5}} \neq m_{10}$



Mastercode 2014

Bagnaschi, Costa, Sakurai, Borsato, Buchmueller, Cavanaugh, Chobanova, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Lucio,, Martinez Santos, Olive, Richards, de Vries, Weiglein

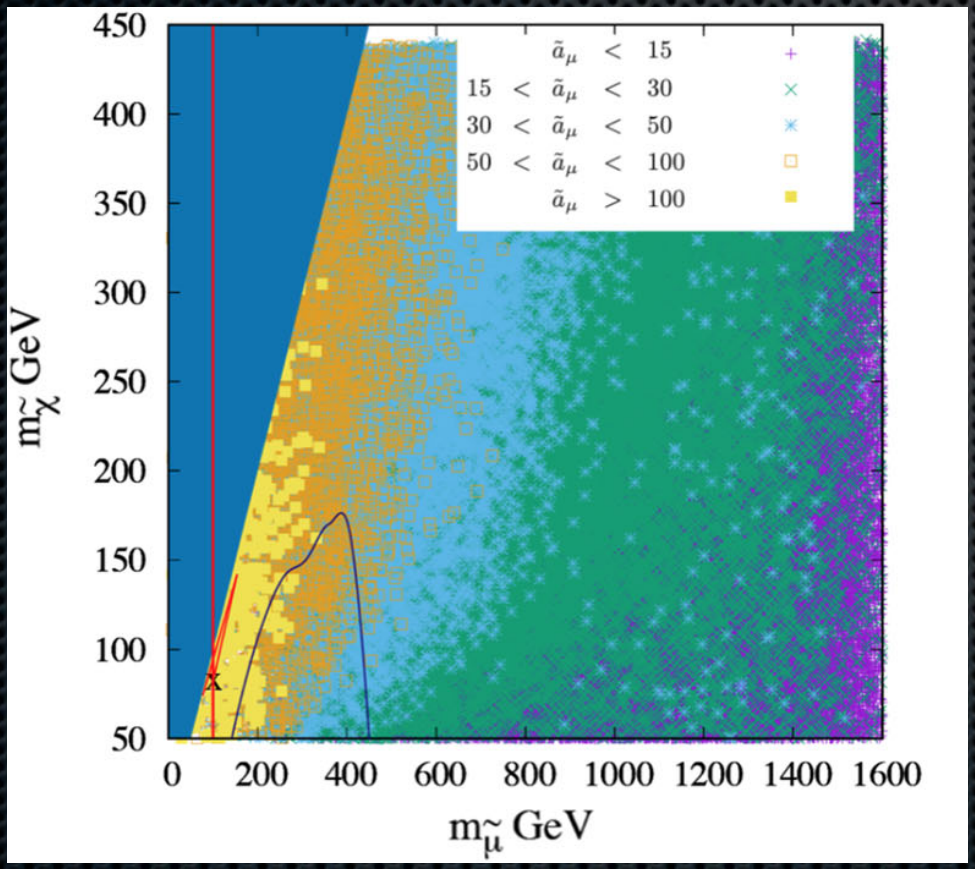
What about g_μ - 2?

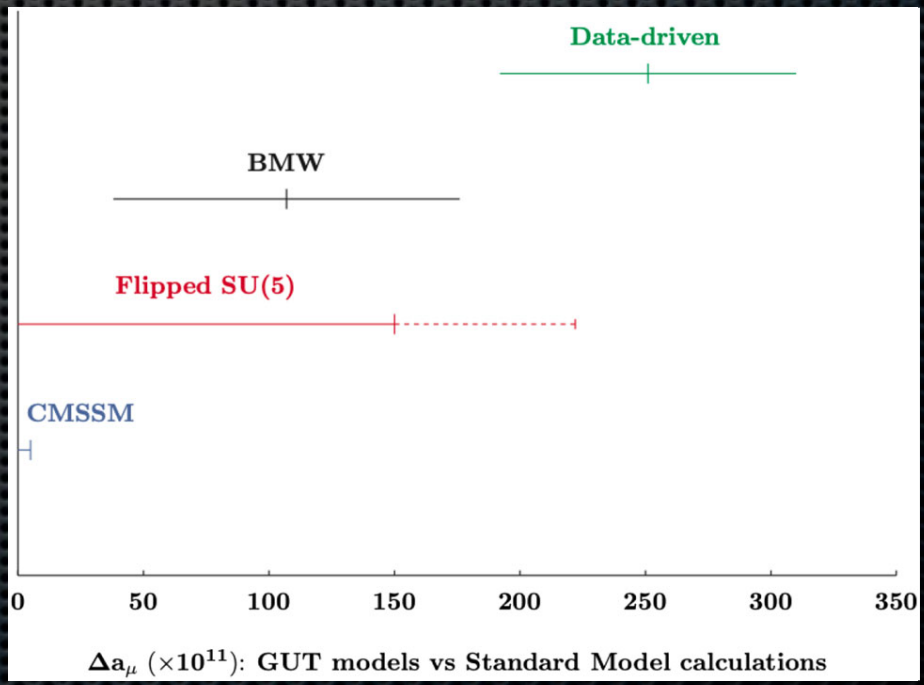
Flipped SU(5) - motivated

$M5 \neq M1$

$m_{\bar{5}} \neq m_{10} \neq m_1$

$$\bar{f}_i(\bar{\mathbf{5}}, -3) = \left\{U_i^c, L_i\right\}, \quad F_i(\mathbf{10}, 1) = \left\{Q_i, D_i^c, N_i^c\right\}$$
$$l_i(\mathbf{1}, 5) = E_i^c, \quad i = 1, 2, 3,$$





Ellis, Evans, Nagata, Nanopoulos, Olive

Gravitino Dark Matter

~ Weak Scale:

$$m_{3/2} = \frac{F}{\sqrt{3}M_P} > \frac{m_b^2}{\sqrt{3}M_P} \sim 0.2\,\mathrm{eV}$$

Gravitino Dark Matter

~ Weak Scale:

$m_\chi < 8$ TeV $\Rightarrow m_{3/2} < 4$ TeV

$$m_{3/2} = \frac{F}{\sqrt{3} M_P} > \frac{m_b^2}{\sqrt{3} M_P} \sim 0.2 \text{ TeV}$$

Gravitino Dark Matter

~ Weak Scale:

$m_\chi < 8$ TeV $\Rightarrow m_{3/2} < 4$ TeV

heavier gravitino → heavier neutralino
→ $\Omega_\chi h^2$ too large → $\Omega_{3/2} h^2$ too large

$$m_{3/2} = \frac{F}{\sqrt{3} M_P} > \frac{m_b^2}{\sqrt{3} M_P} \sim 0.2 \text{ keV}$$

Gravitino Dark Matter

~ Weak Scale:

$m_\chi < 8$ TeV $\Rightarrow m_{3/2} < 4$ TeV

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Summary

- LHC susy and Higgs searches have pushed CMSSM-like models to “corners” or strips
- However, still viable and more so beyond the CMSSM
- Proton decay may be a visible signature of these models
- Maybe the susy spectrum is very heavy
  - Is Susy at the multi-TeV or PeV or EeV scale?
- Need more input from Experiment!!!
- Can we learn more from a UV completion?
- Signatures at the EeV scale?