What do we expect from SUSY

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1. Introduction: soft SUSY-breaking terms and flavour universality

2. Gauge Mediation and the status of pure Gauge Mediation
   3 types of experimental constraints

3. Living with heavy (few TeV) scalars:
   return of generic gravity models without flavour universality
   Comments on fine-tuning.

4. Conclusions

--- Here will not consider models which try to split flavours
by making stops much lighter than first two generations;
no `flavoured' gauge mediation.

Also will mostly stick to the MSSM reasoning.

Soft SUSY breaking terms (MSSM)

Majorana gaugino masses (complex):

$$M_1\,, \qquad M_2\,, \qquad M_3$$

Squark and slepton squared masses (3×3 matrices, real):

$$\mathbf{m^2_Q}\,, \quad \mathbf{m^2_{\bar{u}}}\,, \quad \mathbf{m^2_{\bar{d}}}\,, \quad \mathbf{m^2_L}\,, \quad \mathbf{m^2_{\bar{e}}}$$

Higgs-sector masses (real):

$$\mathcal{L}_{eff} \supset m_u^2|H_u|^2 + m_d^2|H_d|^2 + (B_\mu H_u H_d + c.c.)$$

The μ-parameter (not a soft term; complex):

$$\mathcal{W}_{eff} \supset \mu\, H_u H_d$$

Trilnear scalar self-couplings (complex):

$$\mathcal{L}_{eff} \supset a_u^{ij} H_u Q^i \overline{u}^j + a_d^{ij} H_d Q^i \overline{d}^j + a_L^{ij} H_d L^i \bar{E}^j$$

Flavour universality

Dangerous flavour-chaging (FCNC) processes in SUSY extensions of the SM are automatically evaded if one assumes (or can justify) the universal flavour structure of the soft terms:

$$\mathbf{m_Q^2} = \begin{pmatrix} m_Q^2 & 0 & 0 \\ 0 & m_Q^2 & 0 \\ 0 & 0 & m_Q^2 \end{pmatrix}, \quad \mathbf{m_{\bar{u}}^2} = \begin{pmatrix} m_{\bar{u}}^2 & 0 & 0 \\ 0 & m_{\bar{u}}^2 & 0 \\ 0 & 0 & m_{\bar{u}}^2 \end{pmatrix}, \quad \mathbf{m_{\bar{d}}^2} = \begin{pmatrix} m_{\bar{d}}^2 & 0 & 0 \\ 0 & m_{\bar{d}}^2 & 0 \\ 0 & 0 & m_{\bar{d}}^2 \end{pmatrix}$$

$$\mathbf{m_L^2} = \begin{pmatrix} m_L^2 & 0 & 0 \\ 0 & m_L^2 & 0 \\ 0 & 0 & m_L^2 \end{pmatrix}, \quad \mathbf{m_{\bar{e}}^2} = \begin{pmatrix} m_{\bar{e}}^2 & 0 & 0 \\ 0 & m_{\bar{e}}^2 & 0 \\ 0 & 0 & m_{\bar{e}}^2 \end{pmatrix}$$

and also that the trilinear couplings $\mathbf{a} \propto \mathbf{yukawa}$:

$$\mathbf{a_u} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_u \end{pmatrix}, \quad \mathbf{a_d} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_d \end{pmatrix}, \quad \mathbf{a_L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_L \end{pmatrix}$$

at the high scale M_{mess} or M_{Pl}.

Flavour universality

Gauge mediation is automatically flavour universal.

At the messenger scale it is *flavour-independent by construction*:

$$\mathbf{m}^2_{\tilde{\mathbf{f}}}(M_{mess}) = 2\sum_{i=1}^{3} C_i k_i \frac{\alpha_i^2(M_{mess})}{(4\pi)^2}\Lambda_S^2 \times \mathbf{1}_{3\times 3}$$

$$\mathbf{a}_{\mathbf{u}/\mathbf{d}/\mathbf{L}}(M_{mess}) = A_0(M_{mess}) \times \mathbf{yukawa} = 2\text{loop} \simeq 0$$

Below the messenger scale, this universality is not de-tuned by the RGE:

$$\mathbf{m}^2_{\mathbf{Q}} = \begin{pmatrix} m^2_{Q_1} & 0 & 0 \\ 0 & m^2_{Q_1} & 0 \\ 0 & 0 & m^2_{Q_3} \end{pmatrix}, \quad \mathbf{m}^2_{\bar{\mathbf{u}}} = \begin{pmatrix} m^2_{\bar{u}_1} & 0 & 0 \\ 0 & m^2_{\bar{u}_1} & 0 \\ 0 & 0 & m^2_{\bar{u}_3} \end{pmatrix}, \quad \mathbf{m}^2_{\bar{\mathbf{d}}} = \begin{pmatrix} m^2_{\bar{d}_1} & 0 & 0 \\ 0 & m^2_{\bar{d}_1} & 0 \\ 0 & 0 & m^2_{\bar{d}_3} \end{pmatrix}$$

$$\mathbf{m}^2_{\mathbf{L}} = \begin{pmatrix} m^2_{L_1} & 0 & 0 \\ 0 & m^2_{L_1} & 0 \\ 0 & 0 & m^2_{L_3} \end{pmatrix}, \quad \mathbf{m}^2_{\bar{\mathbf{e}}} = \begin{pmatrix} m^2_{\bar{e}_1} & 0 & 0 \\ 0 & m^2_{\bar{e}_1} & 0 \\ 0 & 0 & m^2_{\bar{e}_3} \end{pmatrix}$$

Flavour universality

Gravity mediation is not.   It is not guaranteed to be flavour-blind.

One can *set* it to be flavour-blind by assuming a minimal form of the Kahler potential, e.g. in the CMSSM one *chooses:*

$$
\begin{aligned}
&M_3 = M_2 = M_1 = m_{1/2}, \\
&\mathbf{m^2_Q} = \mathbf{m^2_{\bar{u}}} = \mathbf{m^2_{\bar{d}}} = \mathbf{m^2_L} = \mathbf{m^2_{\bar{e}}} = m_0^2\, \mathbf{1}, \qquad m^2_{H_u} = m^2_{H_d} = m_0^2, \\
&\mathbf{a_u} = A_0 \mathbf{y_u}, \qquad \mathbf{a_d} = A_0 \mathbf{y_d}, \qquad \mathbf{a_e} = A_0 \mathbf{y_e}, \\
&b = B_0 \mu,
\end{aligned}
$$

But even then, this universality would generally be de-tuned by the RG evolution down from the Planck scale to the Flavour Symmetry Breaking (flavour messenger scale). See e.g. Calibbi, Lalak, Pokorski, Ziegler 1203.1489

…unless one assumes some underlying symmetry from unknown higher theory…

CP violation

Potentially dangerous CP-violating phases are in the complex-valued soft terms:

$$\text{Arg}(a_d^* M_i)\,, \quad \text{Arg}(a_u \mu)\,, \quad \text{Arg}(a_d \mu)\,, \quad \text{Arg}(a_L \mu)$$

In general, i.e. in a generic gravity mediation theory these phases are present.

In a vanilla gauge mediation, such as pure gauge mediation (pGGM) there is only one non-trivial CP-violating phase associated with the phase of mu.

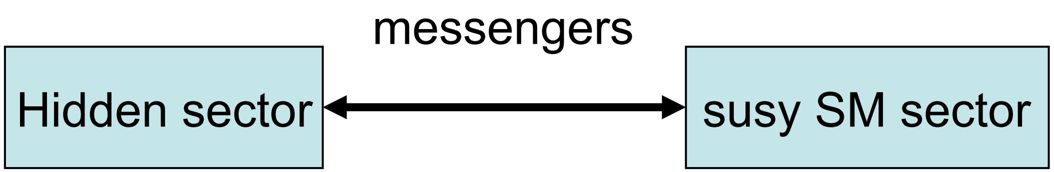
Gaugino masses in pGGM are governed by a single complex parameter Λ_G

$$M_i(M_{\text{mess}}) = k_i \frac{\alpha_i(M_{\text{mess}})}{4\pi} \Lambda_G \,, \qquad \text{Arg}(a^* M_i) = 0$$

so that the only surviving phase is: Arg(Λ_G μ)

To start, set Arg(Λ_G μ) = 0. Later on will revisit.

2. Gauge mediation

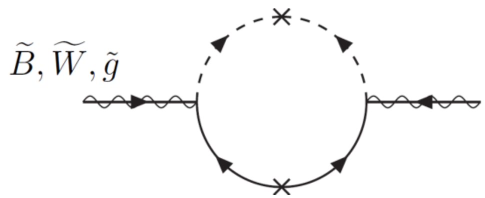


Messenger fields are coupled to the SUSY-breaking sector and to the SM sector. Importantly, in the SM sector they are coupled only to gauge multiplets, not to the matter fields.

Gauge mediation manifestly does not give raise to new flavour changing processes since SM gauge interactions are flavour blind.

LSP of gauge mediation is gravitino. Contrary to gravity mediation the NLSP is neutralino or stau and it will ultimately decay into gravitino (inside or outside of the detector). A possibility of gravitino dark matter.

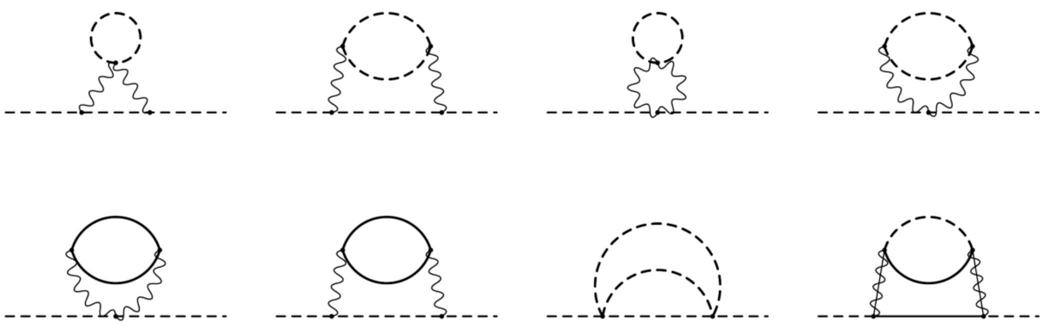
- Gaugino masses are generated by:



← messenger loop

$$M_i(M_{\text{mess}}) = k_i \frac{\alpha_i(M_{\text{mess}})}{4\pi} \Lambda_G \ , \qquad k_i = (5/3, 1, 1)$$

- Scalar masses squared are generated by:



← messenger loop

$$m_{\tilde{f}}^2(M_{mess}) = 2 \sum_{i=1}^{3} C_i k_i \frac{\alpha_i^2(M_{mess})}{(4\pi)^2} \Lambda_S^2 \ , \qquad C_i = (Y^2, 3/4, 4/3)$$

[in a one-scale model $\Lambda_G \simeq \Lambda_S = \frac{F}{M_{\text{mess}}}$.]

Pure General Gauge Mediation

Abel, Dolan, Jaeckel, VVK 0910.2674 and 1009.1164

GGM models with 3 input parameters, Λ_G, Λ_S and M_{mess}. and $B_0 = 0\,, A_0 = 0$.

EWSB and Z-mass determine μ and $\tan\beta$. Take $\mu\Lambda_G =$ Real.

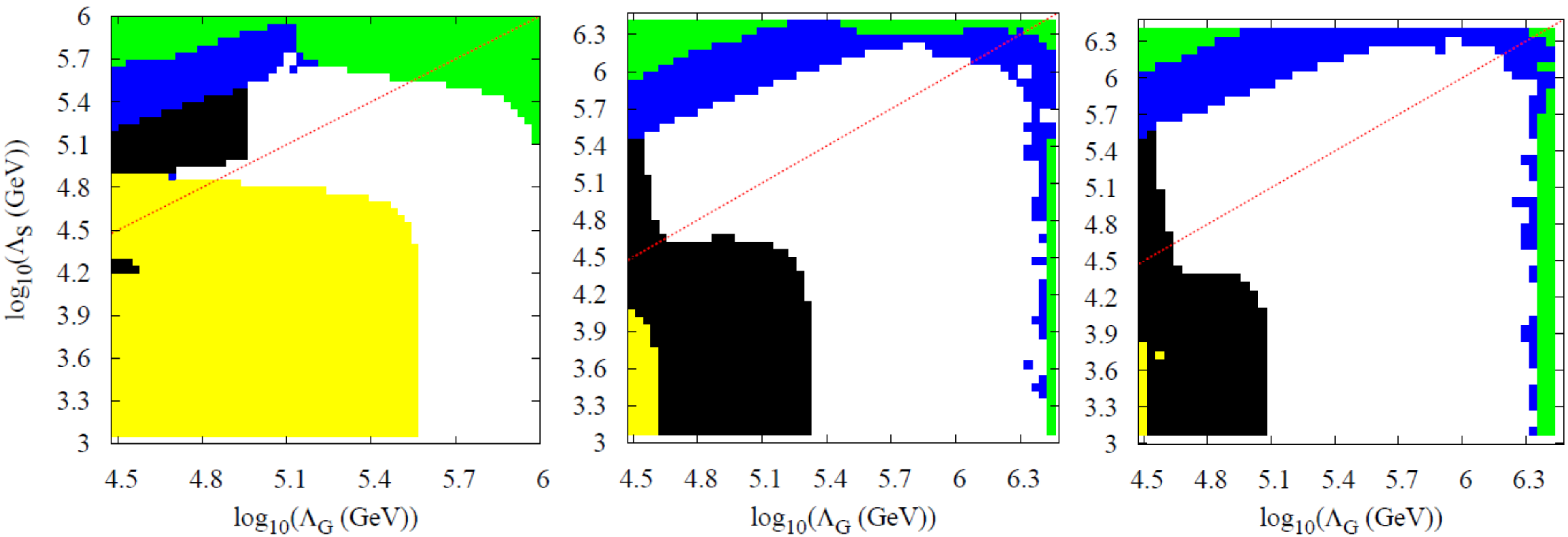
This is a vanilla gauge mediation with automatic flavour and CP-conservation and minimal number of parameters – theoretically sound and predictive .

Gaugino and scalar masses are determined via

$$M_{\tilde{\lambda}_i}(M_{mess}) = k_i \frac{\alpha_i(M_{mess})}{4\pi} \Lambda_G$$

$$m_{\tilde{f}}^2(M_{mess}) = 2 \sum_{i=1}^{3} C_i k_i \frac{\alpha_i^2(M_{mess})}{(4\pi)^2} \Lambda_S^2$$

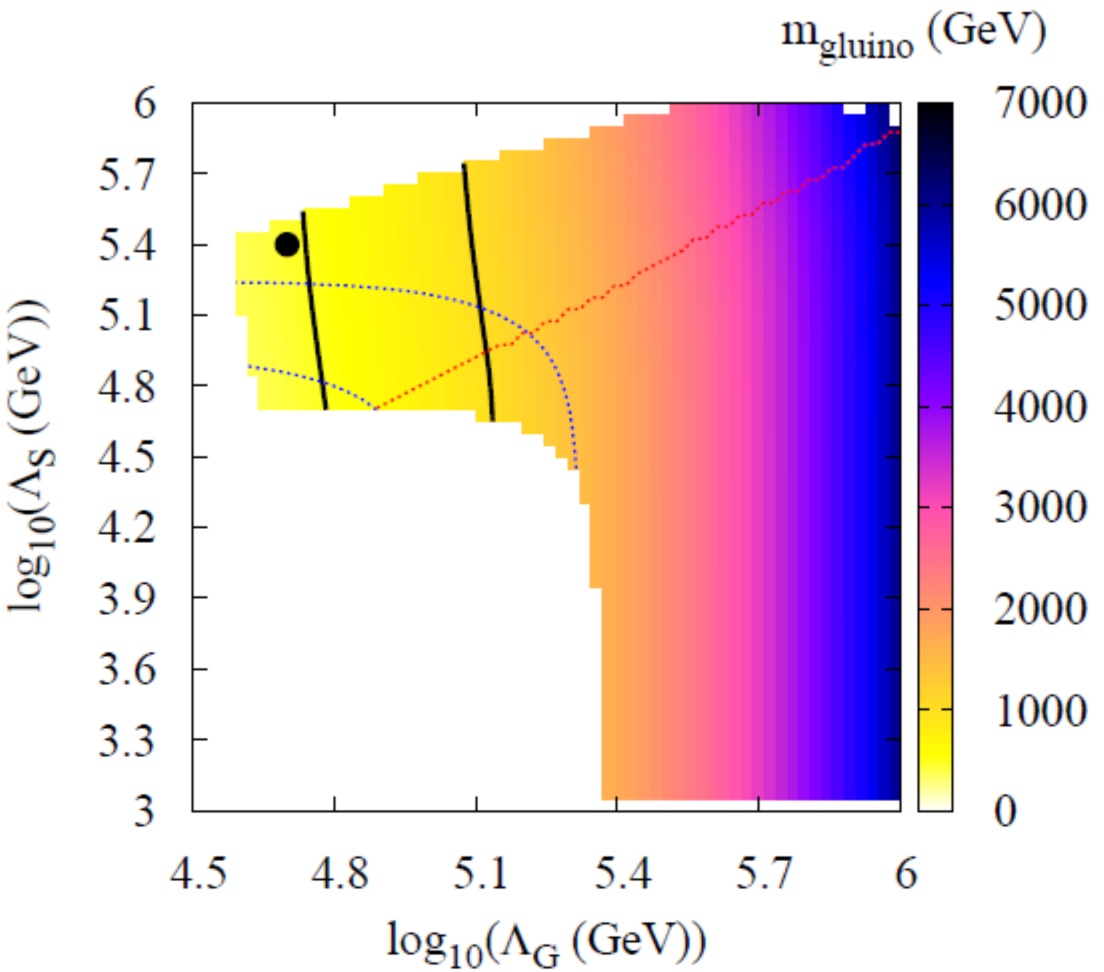
Pre-LHC: Pure GGM compact parameter space



$M_{\rm mess} = 10^8$ GeV $\qquad M_{\rm mess} = 10^{10}$ GeV $\qquad M_{\rm mess} = 10^{14}$ GeV.

Yellow is excluded by tachyons; Black is excluded by pre-LHC direct search limits. In the blue region SoftSUSY has not converged and in the green region a coupling reaches a Landau pole during RG evolution. The red dotted line indicates the ordinary gauge mediation scenario where $\Lambda_G = \Lambda_S$.

Pure GGM: mass spectrum



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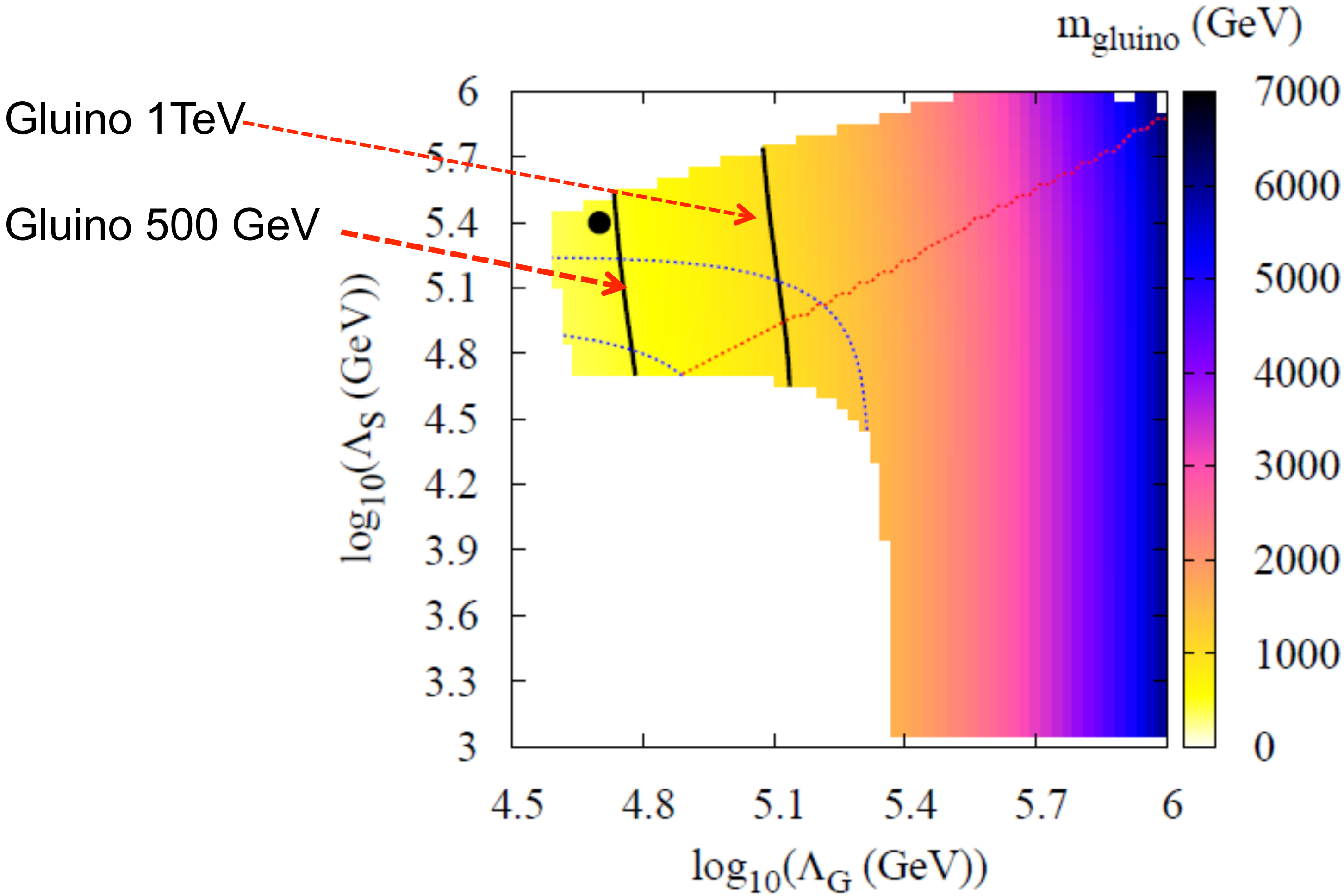
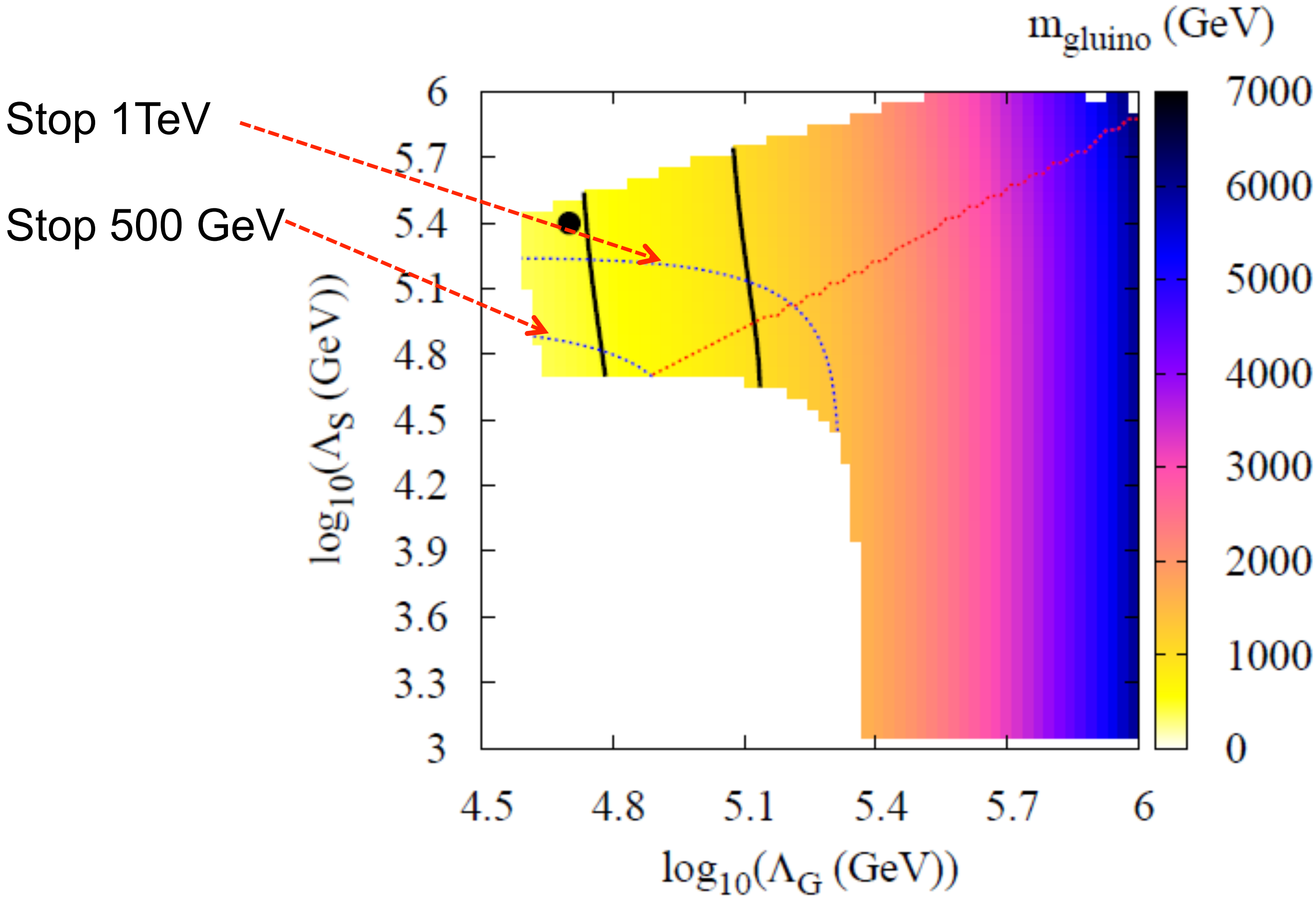
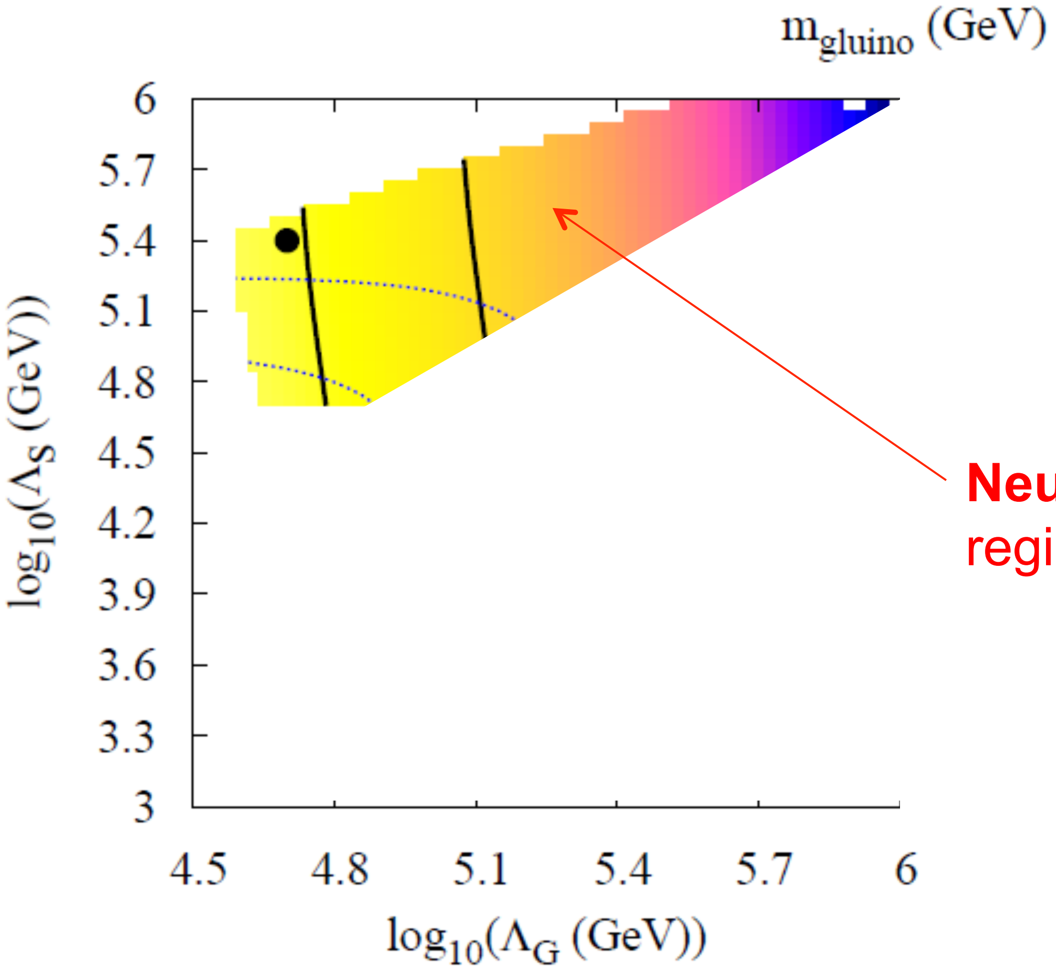


Pure GGM: mass spectrum

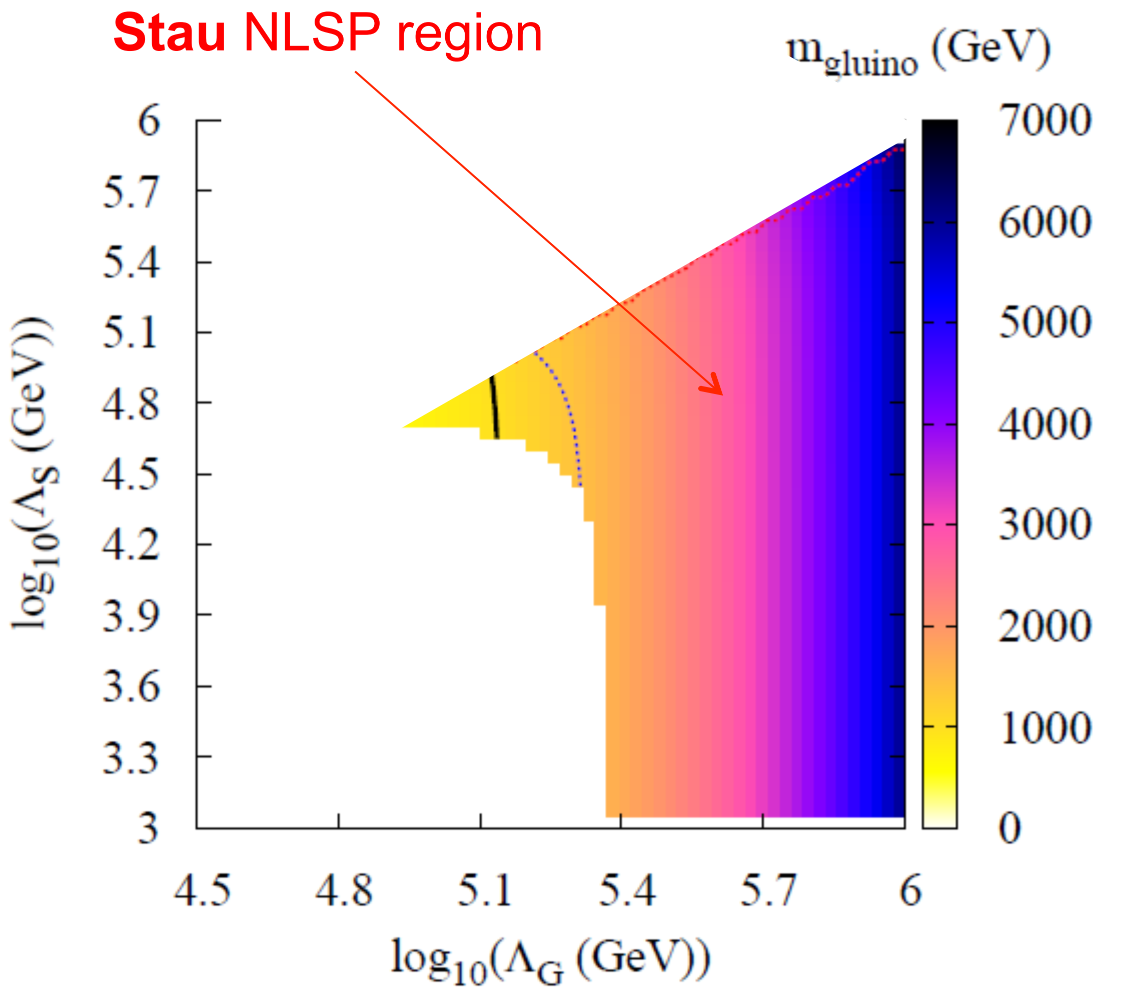


Pure GGM: mass spectrum



Neutralino NLSP region

Pure GGM: mass spectrum



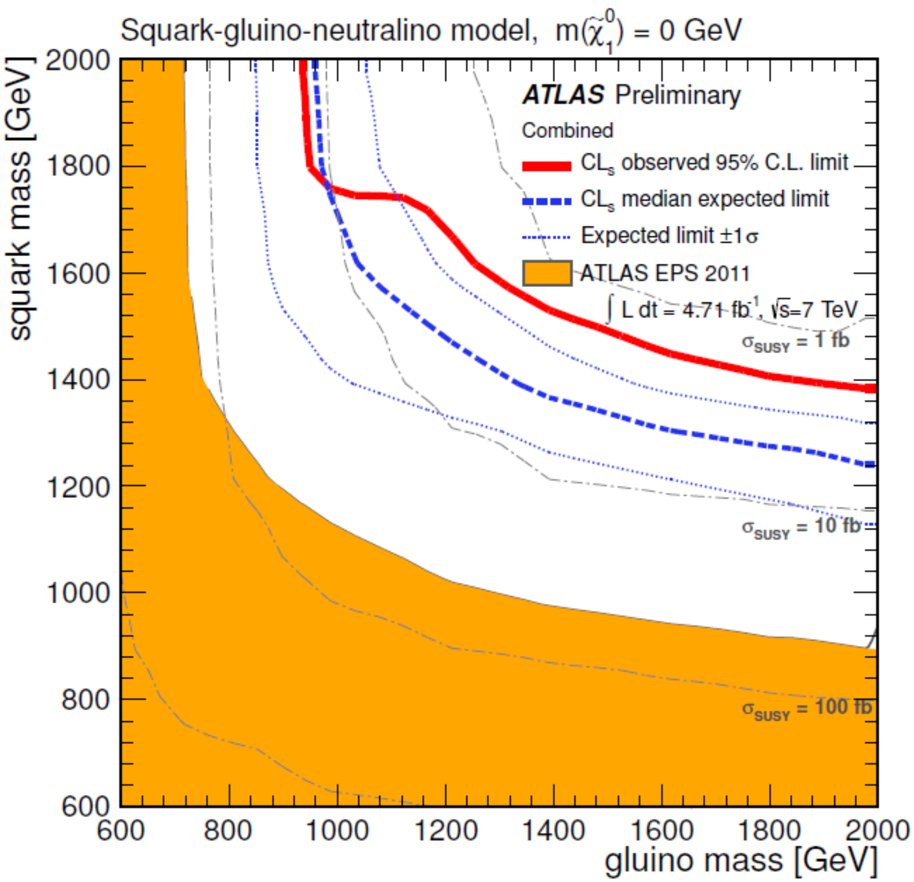
LHC searches

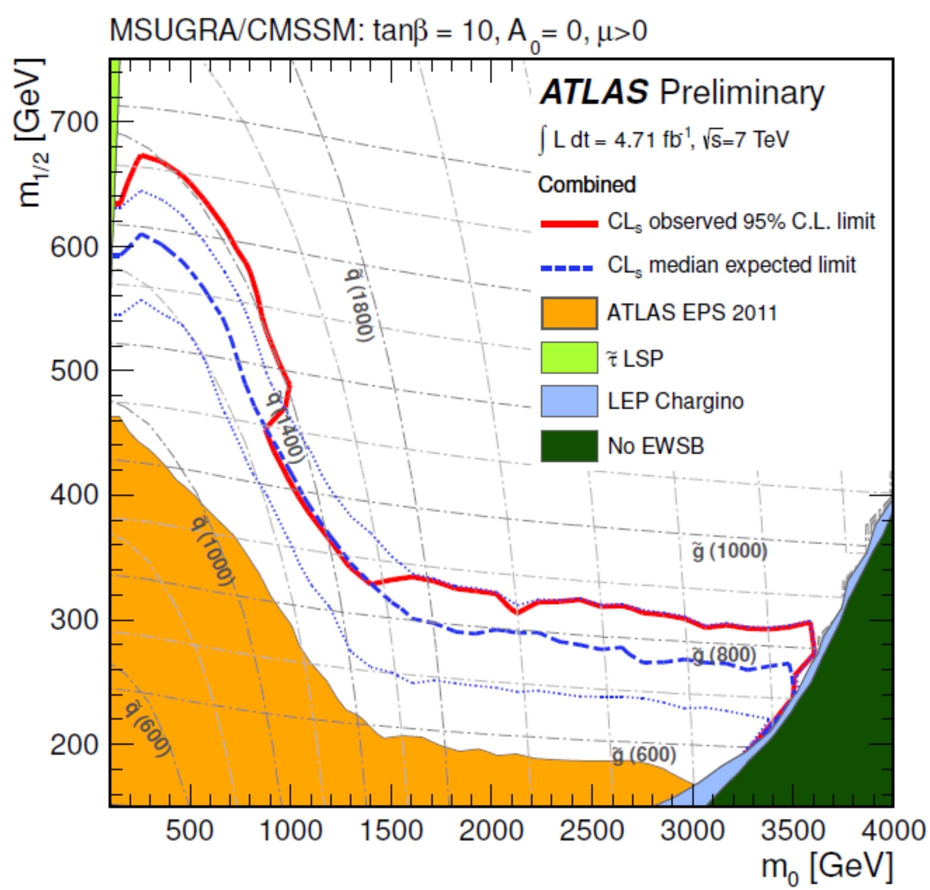
- Jets and Missing Energy searches of gluinos and squarks (at 940 GeV and 1380 GeV in simplified models)
- Serches of stable (or long-lived) charged superpartners: $\tilde{\tau}$

  (a) model-independent Drell-Yan -based exclusion $m_{\tilde{\tau}} \geq 223\text{GeV}$

  (b) more model-dependent exclusion $m_{\tilde{\tau}} \geq 314\text{GeV}$
- Higgs exclusions and the possibility of 125 GeV Higgs.

Jets and MET searches of SUSY (ATLAS & CMS)





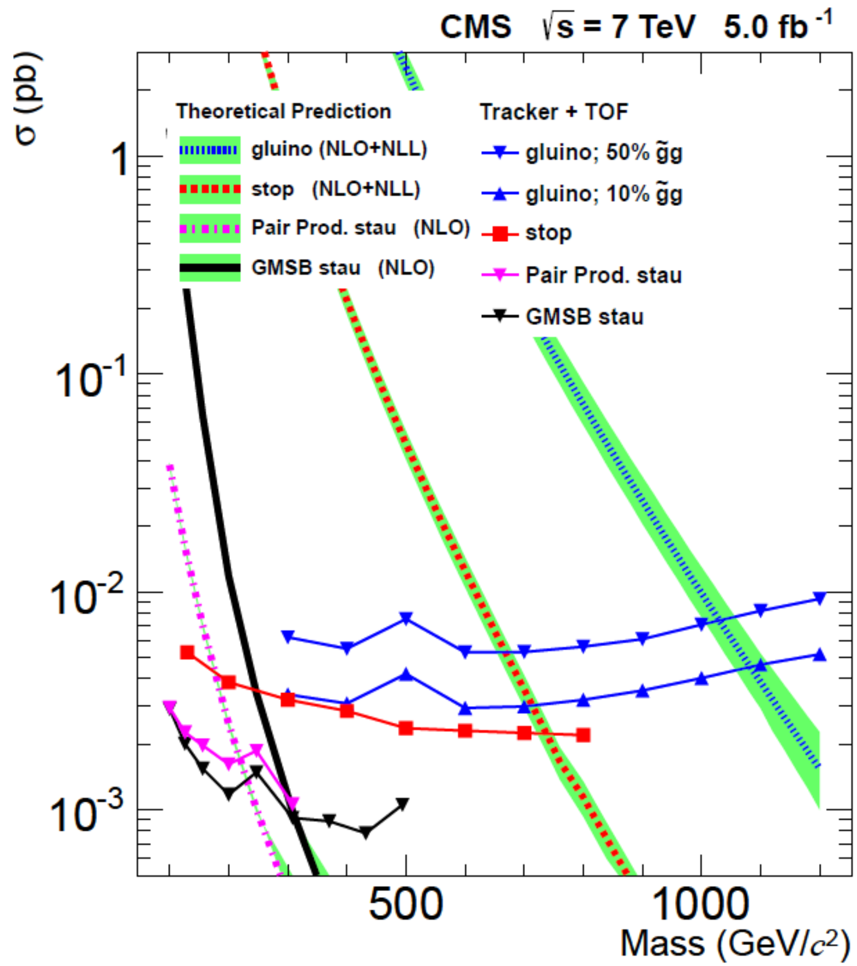
ATLAS 4.7 fb^{-1} at $\sqrt{s} = 7\text{TeV}$ complete 2011 sample

Searches for long-lived stau's

CMS 5.0 fb^{-1}

at $\sqrt{s} = 7\text{TeV}$

observed cross-sections



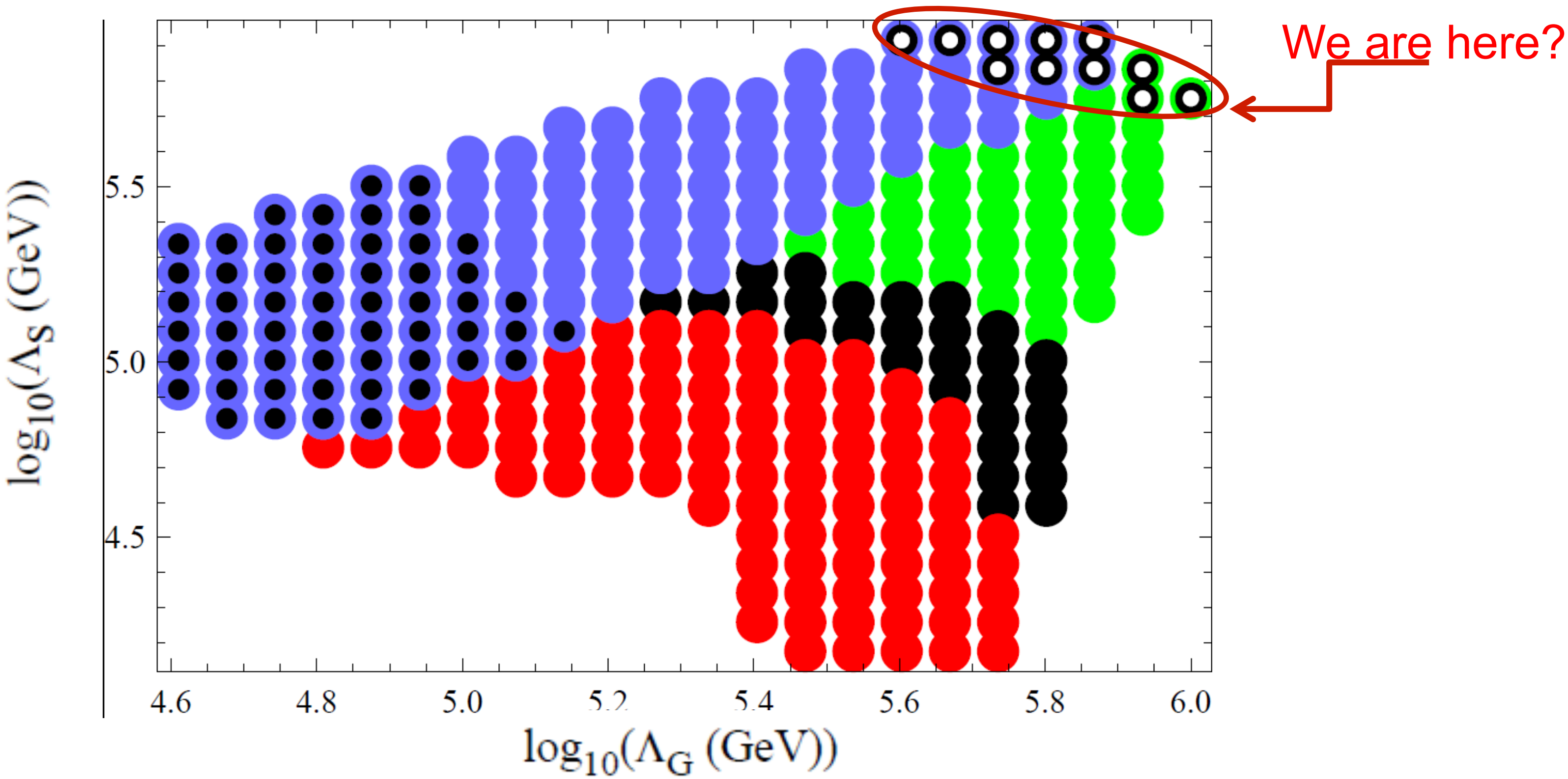
The model-independent limit on pair-produced stau is $m_{\tilde{\tau}} \geq 223\text{GeV}$.

The model-dependent GMSB limit is $m_{\tilde{\tau}} \geq 314\text{GeV}$.

Pure GGM @ M=10^8 GeV what's left of…

Excluded by Jets&MET

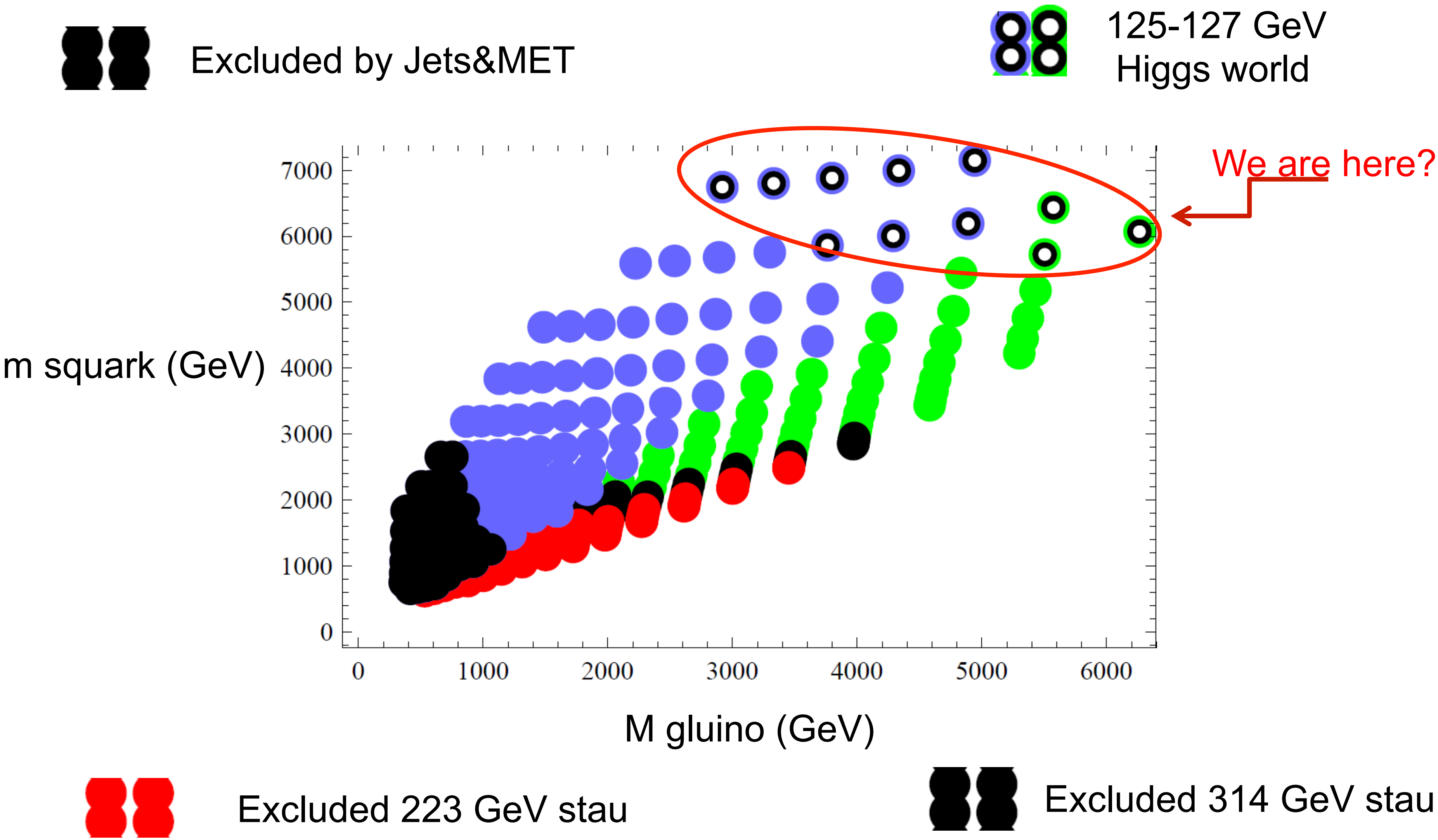
125-127 GeV Higgs world



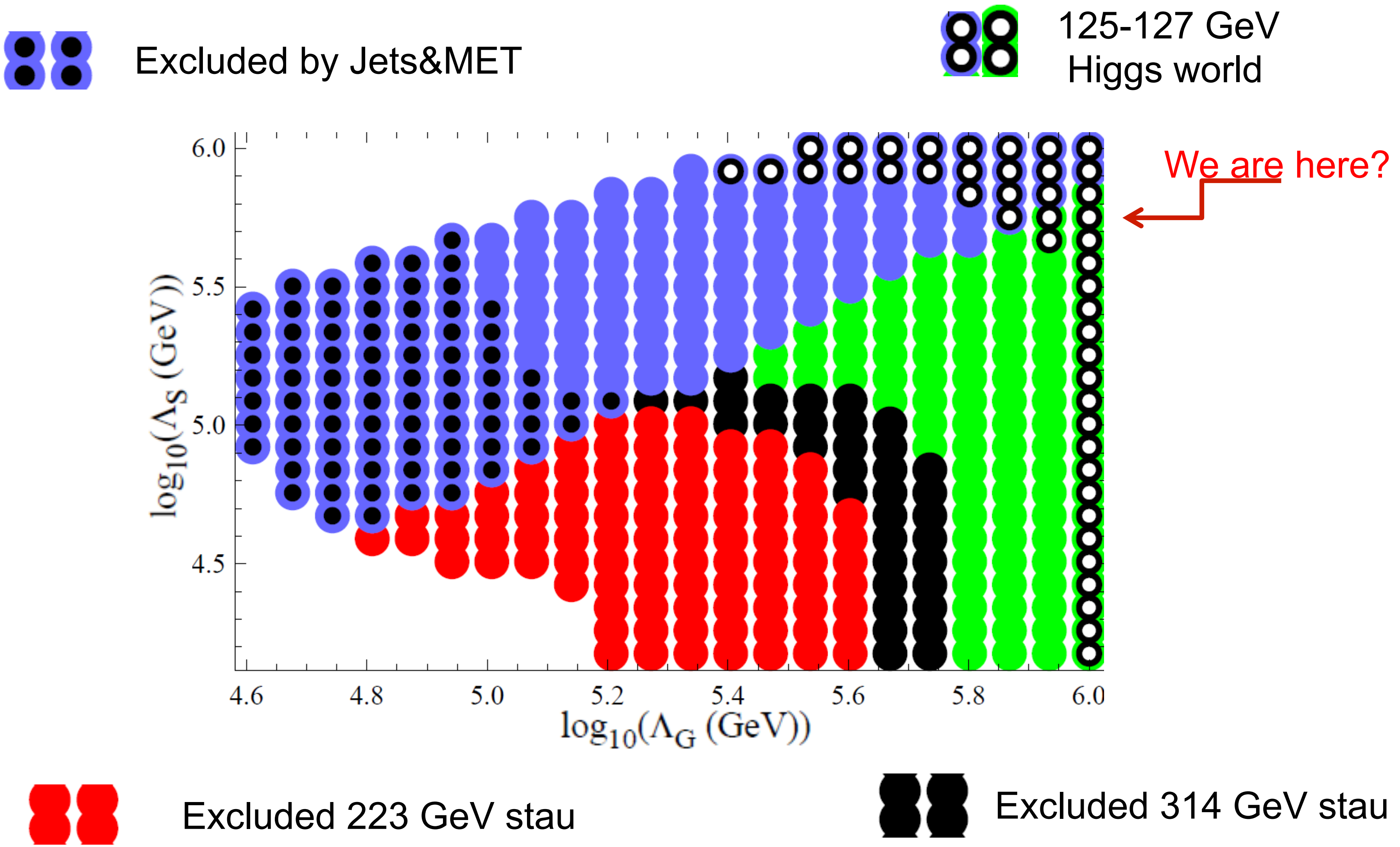
Excluded 223 GeV stau

Excluded 314 GeV stau

Pure GGM @ M=10^8 GeV what's left of…



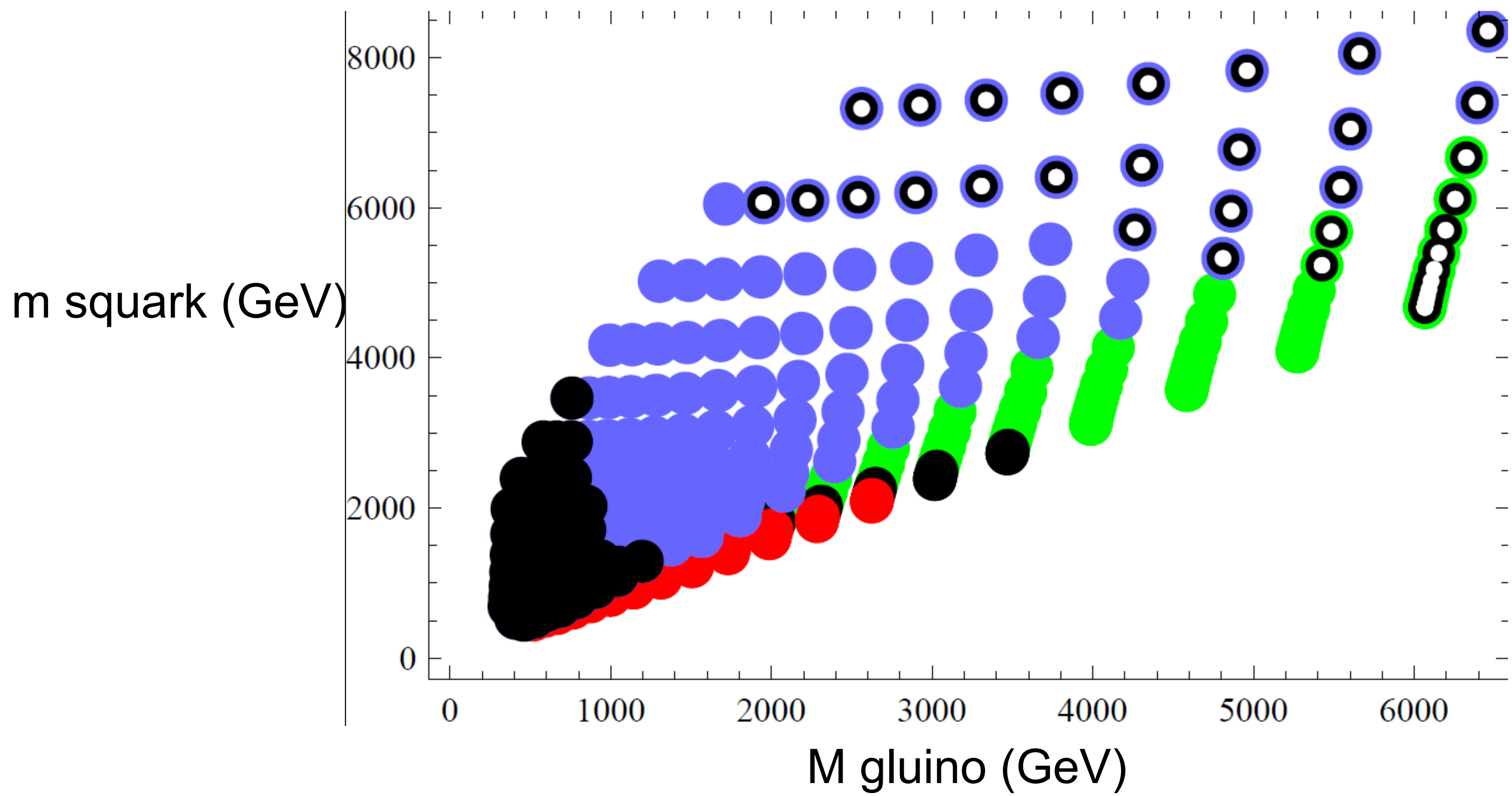
Pure GGM @ M=10^{10} GeV what's left of…



Pure GGM @ M=10^{10} GeV what's left of…

Excluded by Jets&MET

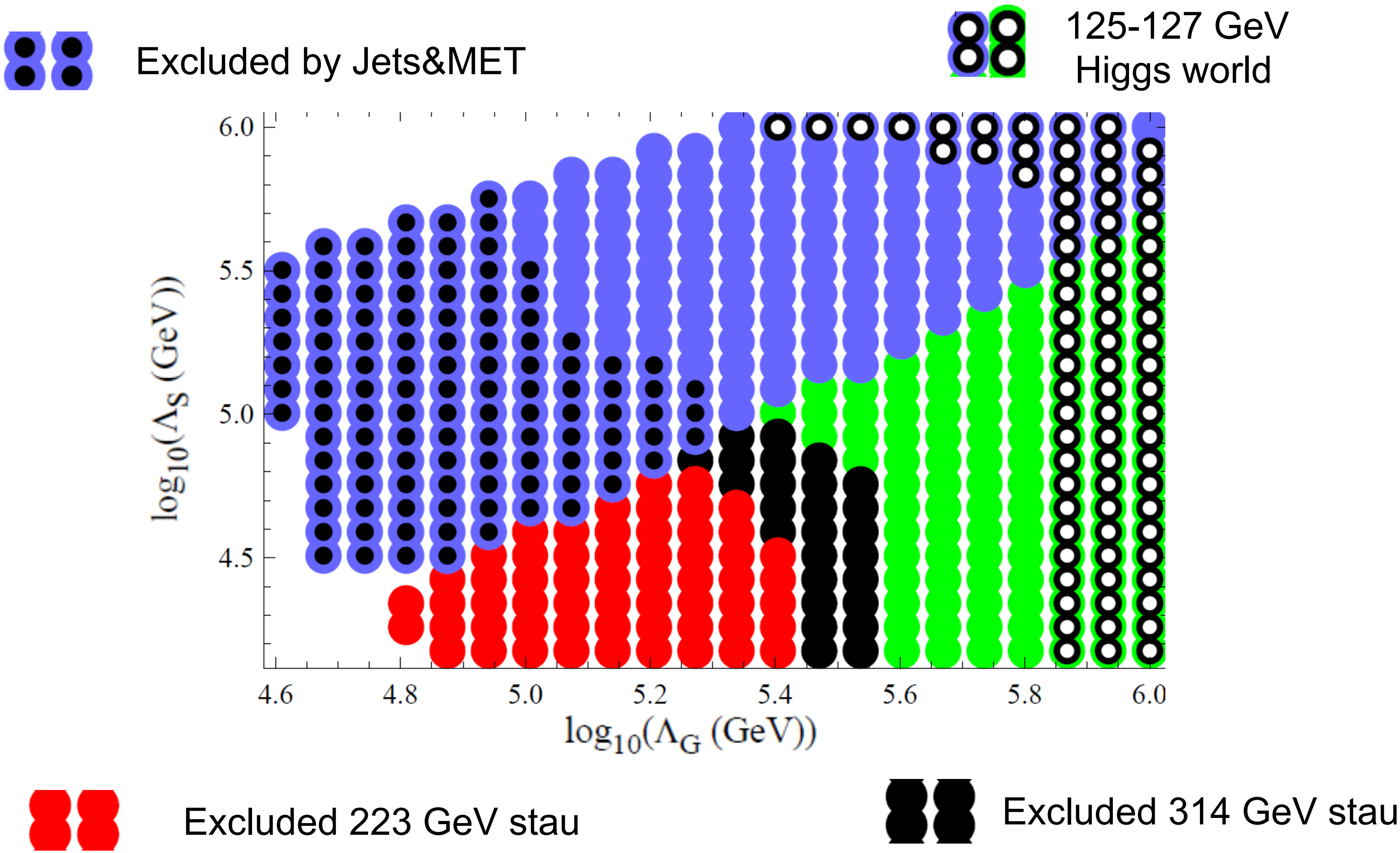
125-127 GeV
Higgs world



Excluded 223 GeV stau

Excluded 314 GeV stau

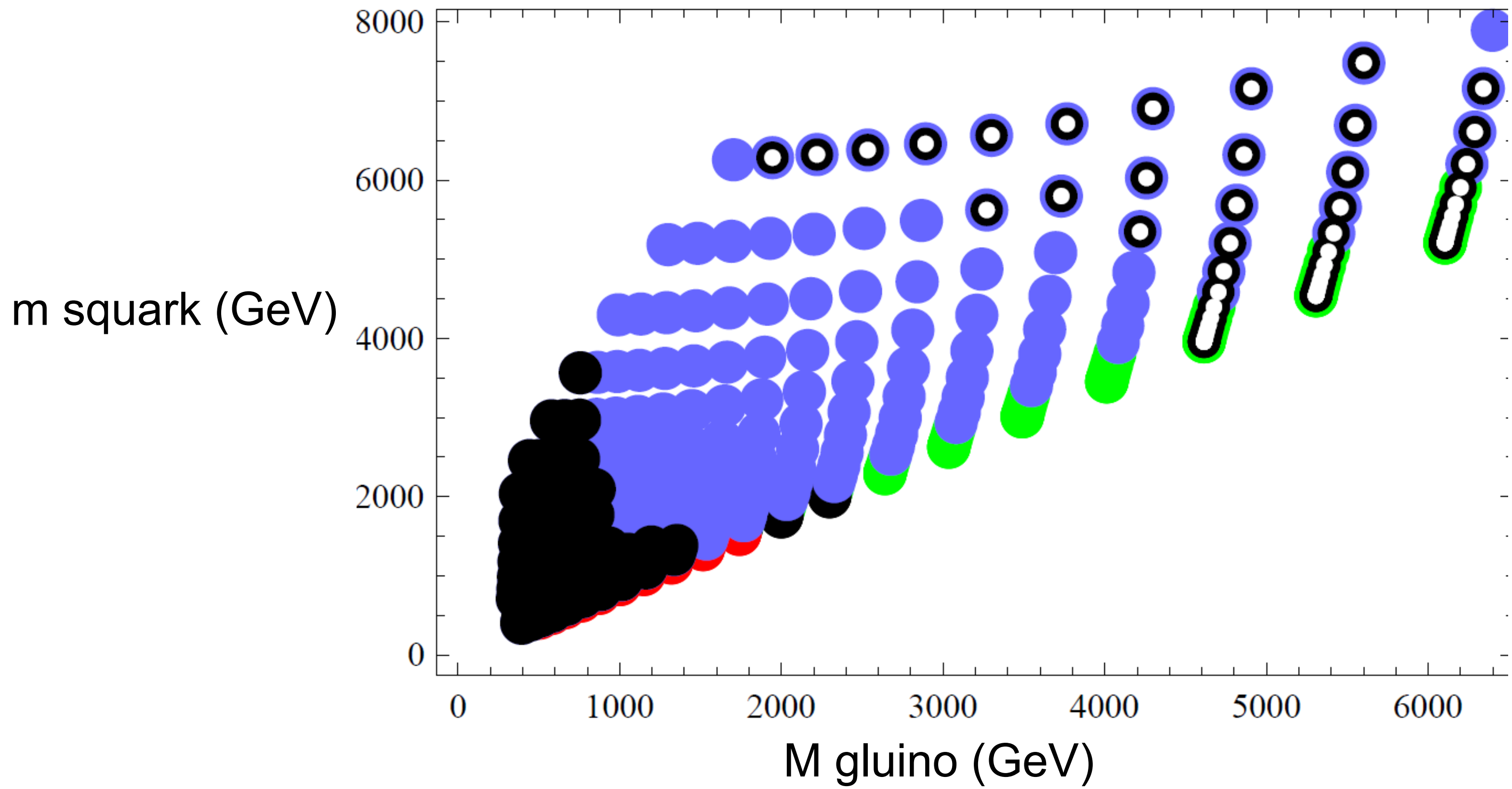
Pure GGM @ M=10^{14} GeV what's left of…



Pure GGM @ M=10^{14} GeV what's left of…

Excluded by Jets&MET

125-127 GeV Higgs world



Excluded 223 GeV stau

Excluded 314 GeV stau

Pure GGM, or what's left of it:

Vanilla gauge mediation – pGGM – highly predictive, falsifiable & clean theoretical set-up:

1. Jets & MET + long-lived stau + Higgs searches give complimentary info and coverage of the parameter space.
2. Higgs @ 125 GeV pushes scalars to ~4-6-8 TeV region.
3. Starting to run out of parameter space for these models
   - even though extreme top end hard to exclude at the LHC-

=> need to re-examine theoretical motivation for gauge mediation => re-examine need for flavour and CP-universality.

3. Return of general gravity models

SUSY with sfermions in the TeV range:

In the remaining part of the talk I'll argue that:

If we accept having all squarks and sleptons in the TeV (or 10 TeV) range – there is no immediate need to restrict our SUSY models at the high scale to be flavour-universal (same for CP).

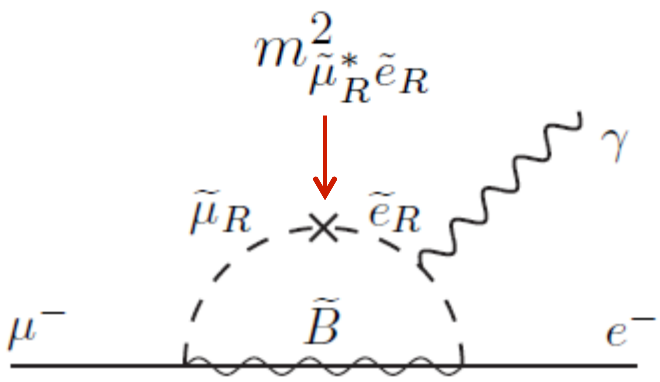
In gravity mediation expect that roughly the same effect ~ F/M_{Pl} governs all *diagonal* and *off-diagonal* entries for masses of *squarks* and of *sleptons* as well as the *a-terms* (at the high input scale):

i.e. if the input for squark masses is a few TeV => from universality of gravity it is likely that same few TeV is the input value for slepton masses. Also no a priori difference between diagonal and off-diagonal elements.

Flavour violation

Experimental constraint MEGA collaboration:

$$\mathrm{Br}\,(\mu \to e\gamma) < 1.2 \times 10^{-11}$$



There are also other diagrams similarly constraining m_L^2 and a_e

(see Martin's PRIMER for a review)

Hisano et al 1995

$$\mathrm{Br}(\mu \to e\gamma) = \left(\frac{|m^2_{\tilde{\mu}^*_R \tilde{e}_R}|}{m^2_{\tilde{\ell}_R}}\right)^2 \left(\frac{100\ \mathrm{GeV}}{m_{\tilde{\ell}_R}}\right)^4 10^{-6} \times \begin{cases} 15 & \text{for } m_{\tilde{B}} \ll m_{\tilde{\ell}_R}, \\ 5.6 & \text{for } m_{\tilde{B}} = 0.5 m_{\tilde{\ell}_R} \\ 1.4 & \text{for } m_{\tilde{B}} = m_{\tilde{\ell}_R}, \\ 0.13 & \text{for } m_{\tilde{B}} = 2 m_{\tilde{\ell}_R}, \end{cases}$$

Already at $m_{\tilde{l}_R} = 3$ TeV get $1.2 \times 10^{-6} \times 10^{-6}$

The off-diagonal ratio can be ~ 1

Flavour violation

Fine-tuning in Br $(\mu \to e\gamma)$

Take a non-diagonal $\mathbf{m_Q^2}$ matrix and diagonalise it:

$$\mathbf{m_L^2} = \begin{pmatrix} m_0^2 & \delta m^2 & 0 \\ \delta m^2 & m_0^2 & 0 \\ 0 & 0 & m_0^2 \end{pmatrix} => \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_0^2 \end{pmatrix}$$

where $m_{1,2}^2 = m_0^2 \pm \delta m^2$. The measure of flavour fine-tuning is

$$\frac{m_1^2}{\mathrm{Br}} \frac{\partial \mathrm{Br}}{\partial m_1^2} \simeq \frac{m_0^2}{\delta m^2} \simeq \left(\frac{100\,\mathrm{GeV}}{m_0}\right)^2 \sqrt{\frac{10^{-5}}{\mathrm{Br}}} = 10 \times \left(\frac{1\,\mathrm{TeV}}{m_0}\right)^2$$

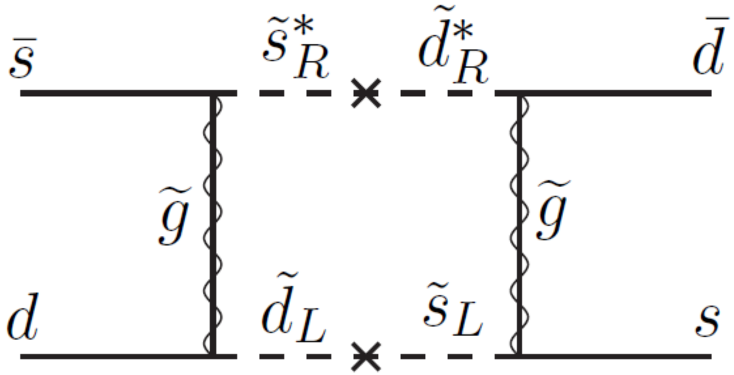
Check against the usual fine-tuning arising from the EW scale

$$\frac{m_1^2}{v^2} \frac{\partial v^2}{\partial m_1^2} \simeq \frac{m_0^2}{m_z^2} \simeq 500 \qquad \text{at } m_0 = 2{,}000\,\mathrm{GeV}$$

they run in opposite directions with m_0.

Flavour violation

More extreme (most extreme) constraint areises from $K^0 \leftrightarrow \overline{K}^0$



(see Martin's PRIMER for a review)

Ciuchini et al 9808328

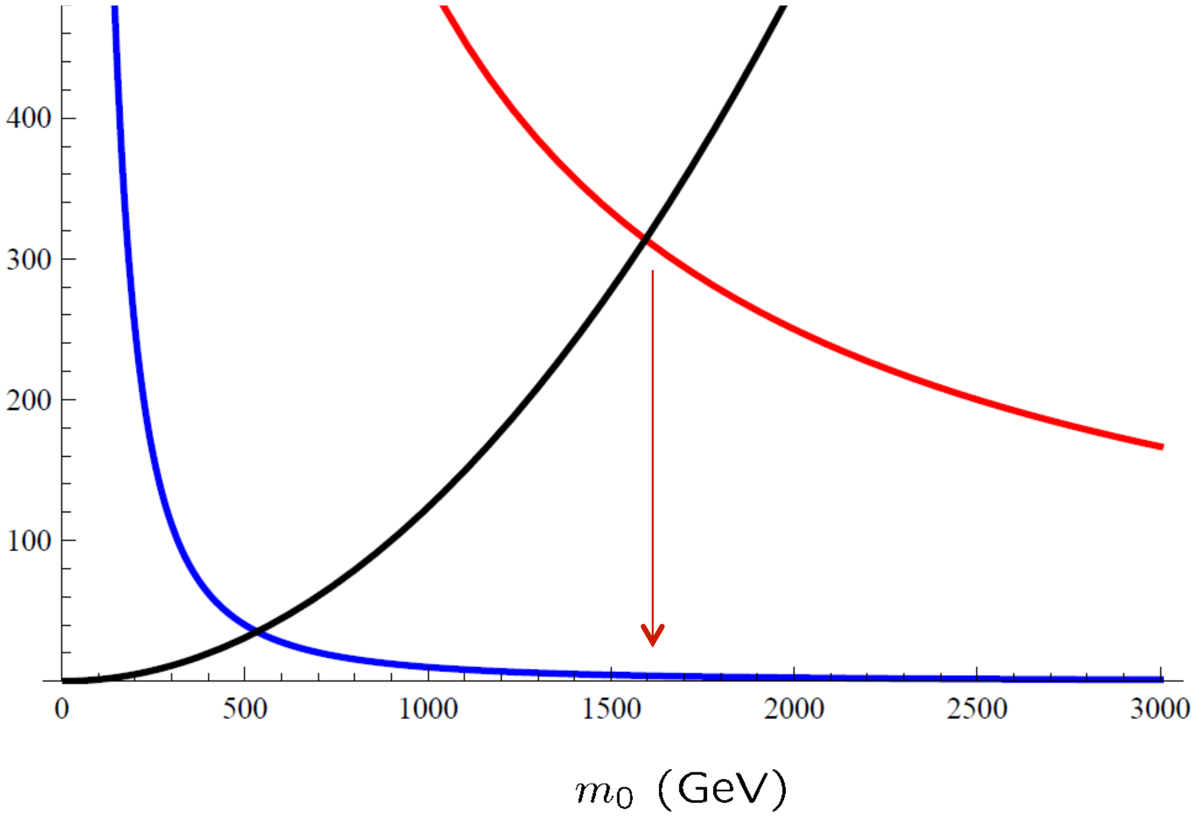
$$\frac{|\mathrm{Re}[m^2_{\tilde{s}^*_R \tilde{d}_R} m^2_{\tilde{s}^*_L \tilde{d}_L}]|^{1/2}}{m^2_{\tilde{q}}} < \left(\frac{m_{\tilde{q}}}{1000\ \mathrm{GeV}}\right) \times \begin{cases} 0.0016 & \text{for } m_{\tilde{g}} = 0.5 m_{\tilde{q}}, \\ 0.0020 & \text{for } m_{\tilde{g}} = m_{\tilde{q}}, \\ 0.0026 & \text{for } m_{\tilde{g}} = 2 m_{\tilde{q}}. \end{cases}$$

At $m_{\tilde{q}} = 10$ TeV the off-diagonal mass-squared ratio is ~ 0.02

On the other hand it gives a huge fine-tunning for lighter scalars.

Flavour versus EW-scale fine-tuning

Measures of fine-tuning: $\Delta_{\mu\to e\gamma} = \frac{m_0^2}{\delta m^2} \simeq 10^3 \times \left(\frac{100\,\mathrm{GeV}}{m_0}\right)^2$ and $\Delta_{K^0\leftrightarrow\overline{K}^0} = \frac{m_0^2}{\delta m^2} = 10^4 \times \frac{100\,\mathrm{GeV}}{2m_0}$ vs the usual m_Z-scale fine-tuning $\Delta_{m_Z} = \frac{m_0^2}{m_z^2}$



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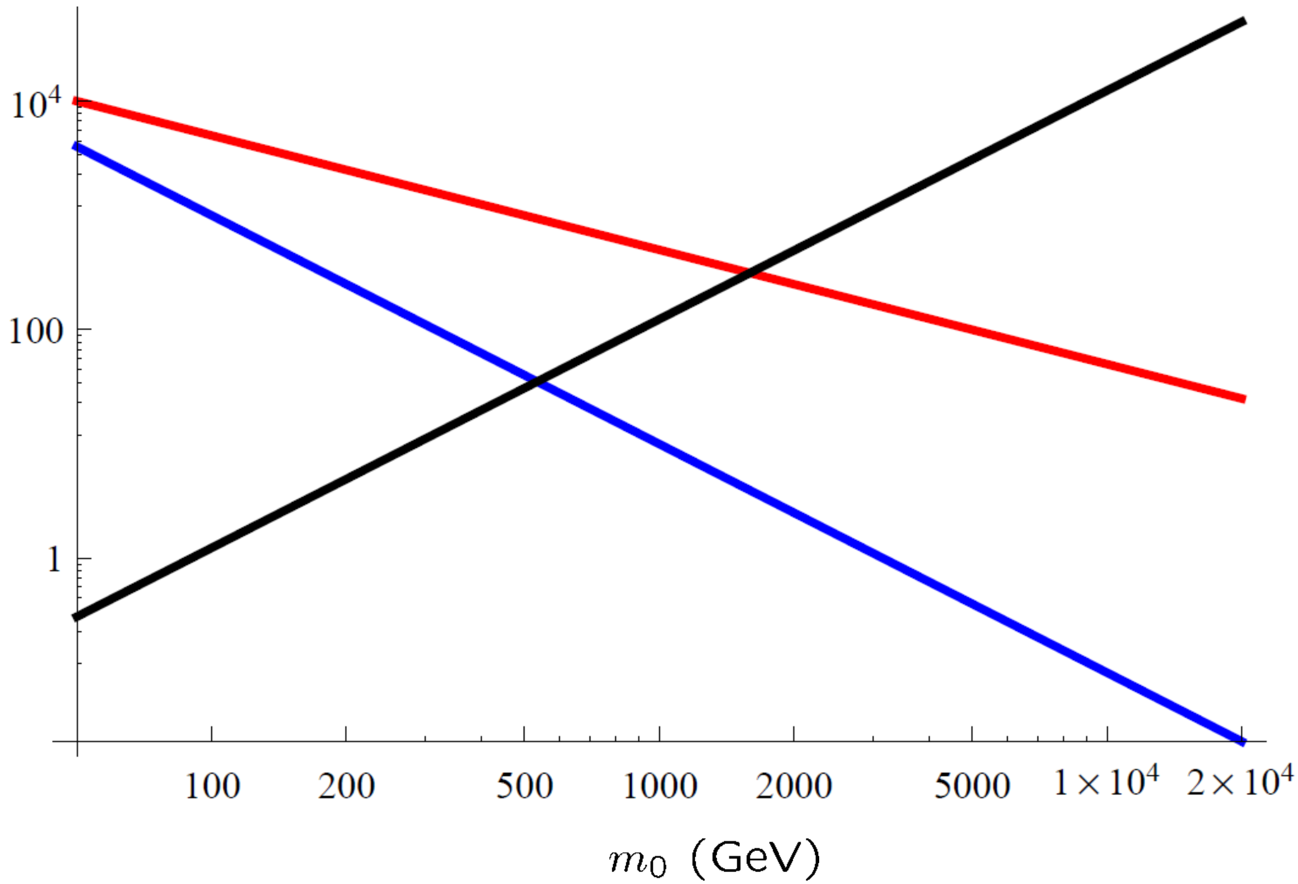


CP violation

Allow general CP-violating phases into the underlying SUSY theory

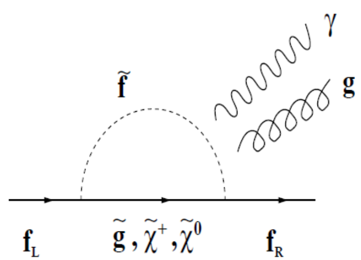
$$\text{Arg}(a_d^* M_i)\,,\quad \text{Arg}(a_u \mu)\,,\quad \text{Arg}(a_d \mu)\,,\quad \text{Arg}(a_L \mu)$$

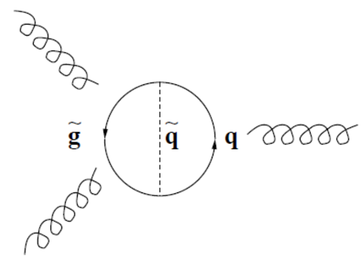
not assuming any need to impose CP-universality:
How heavy should the SUSY scalars be to decouple CP-violation?

Experimental limits on EDM's of neutron, electron and mercury atom:

$$d_n < 2.9 \times 10^{-26}\, e\,\text{cm}$$
$$d_e < 1.7 \times 10^{-27}\, e\,\text{cm}$$
$$d_n < 2 \times 10^{-28}\, e\,\text{cm}$$

for a review see Ibrahim & Nath

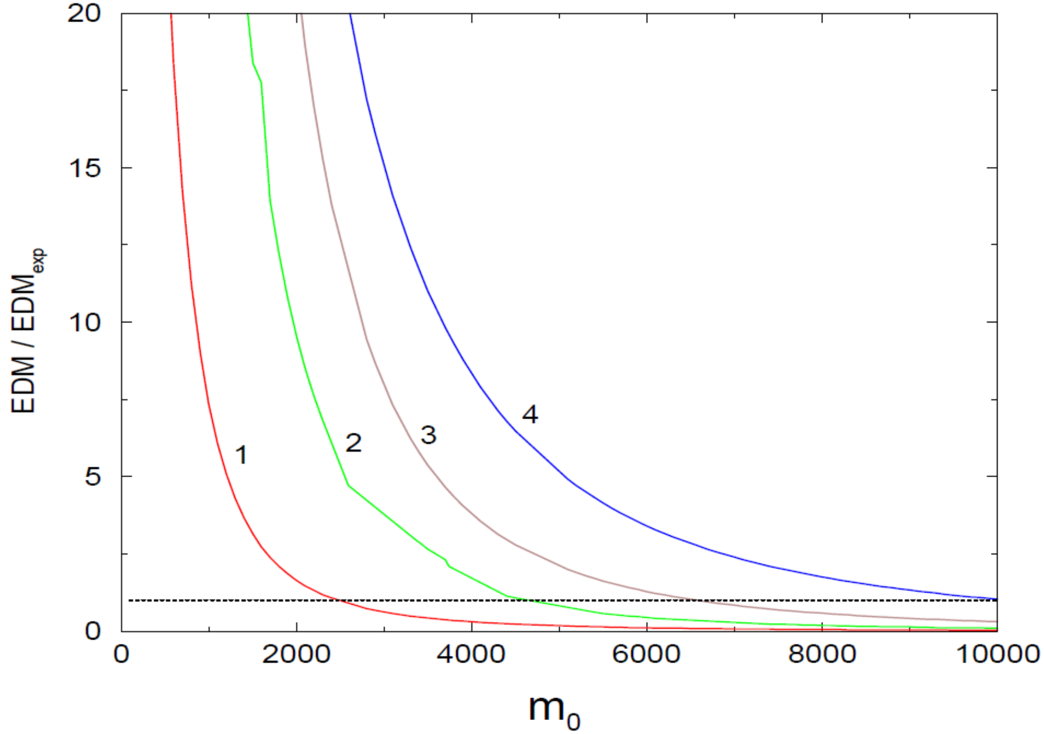




Electric Dipole Moment d_f of a spin-1/2 particle: $\mathcal{L} = -\frac{i}{2} d_f \bar{\psi} \sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu}$

CP violation

plot from Abel, Khalil, Lebedev 0103320



1 – electron EDM

2 – neutron EDM

3 – neutron EDM (parton model)

4 – mercury EDM

We thus conclude:

Scalar masses > 2.5 TeV – to – 10 TeV make CP-violation go away!

Conclusions

SUSY with sfermions in the TeV range:

Part 1: status of pure Gauge Mediation models & experimental constraints
=> 4 - 8TeV squarks (driven by 125 GeV Higgs, but also by direct searches)

If we accept having all squarks and sleptons in the TeV range => no need to restrict SUSY models at the high scale to be flavour-universal (same for CP).

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SUSY with sfermions in the TeV range:

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Part 2: A strong argument in favour of *generic* Gravity Mediation (or other completely general models).

-This is not `the' Split SUSY – scalar masses are ~1-10 TeV not at MPlanck.

- Fine-tuning arising from stabilising the electro-weak scale is complemented by fine-tuning to erase FCNC and CP, the latter favour large scalar masses.

Extra slides

B and mu in pGGM

In pure GGM we have no direct couplings of the SUSY-breaking sector to the Higgs sectorand $B_\mu \approx 0$ at the messenger scale.

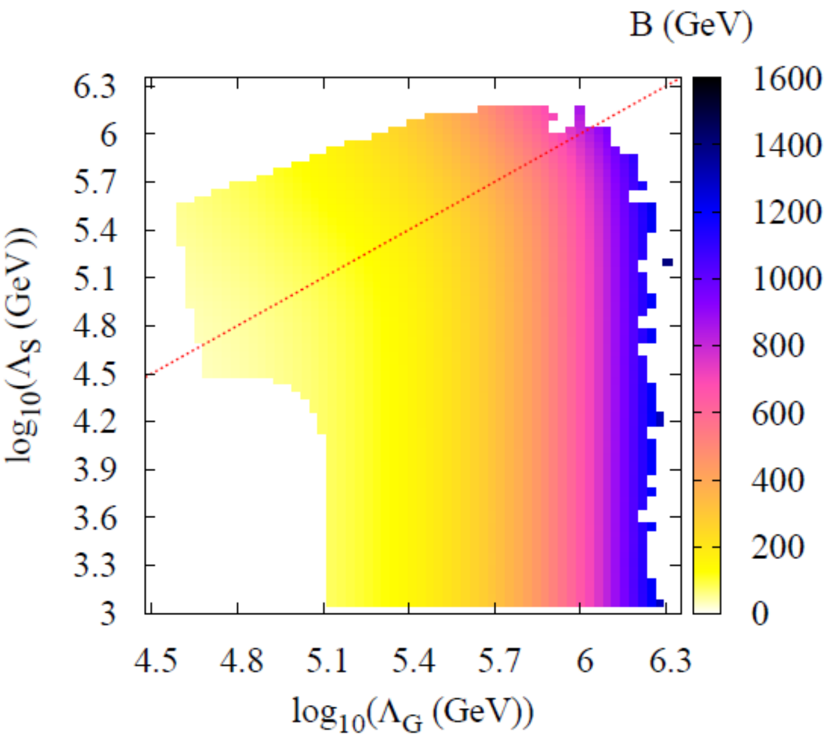
From this B_μ is generated radiatively at the electroweak scale.

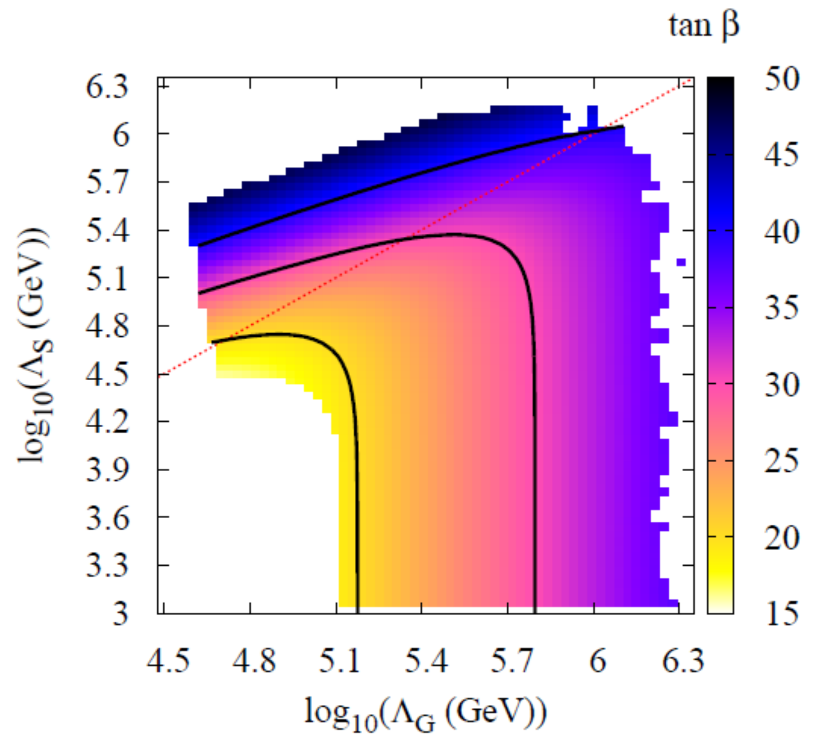
$\tan\beta$ and μ are obtained from the requirement of electroweak symmetry breaking.

B_μ is responsible for communicating the vev of H_u to H_d, hence the ratio of these two vevs, $\tan\beta$ is large.

Alternatively, one can use a more common approach where $\tan\beta$ is an arbitrary input and B_μ at the high scale is obtained from it. This is no longer a simple vanilla gauge mediation, but not much changes apart from $\tan\beta$ not constrained to be large.

Pure GGM: generating B and tan(beta)





Left: radiative generation of B .

Right: $\tan\beta$ obtained from the electroweak breaking. Contours of $\tan\beta = 20, 30, 40, 50$.