Naturalness in the SM and beyond

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Outline

- Naturalness (or the natural solution to the hierarchy problem) has been one of the driving forces for BSM for the last 40 years or so
- So it is time to stop for a moment and gently think on it [1]
- The outline

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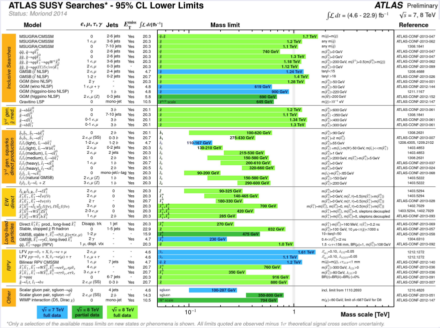
INTRODUCTION

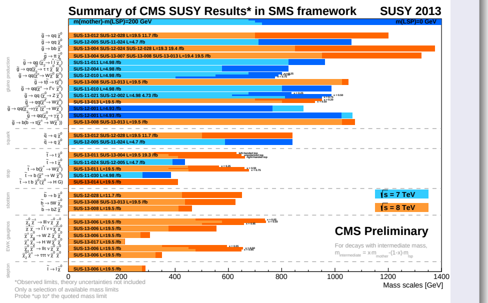
- The Higgs has been found at LHC with a mass

$$m_H = 125.9 \pm 0.4 \;\; GeV$$

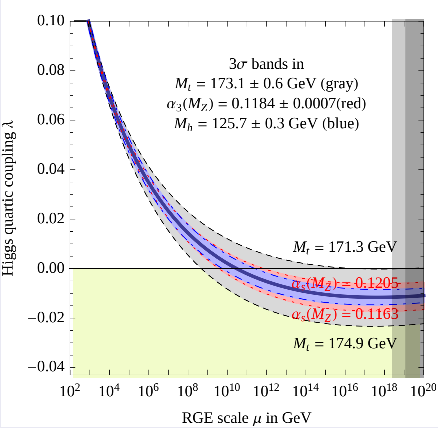
and approximately SM-couplings

- No track of new physics found





- The SM is consistent at high scales [2] depending on m_t and m_H



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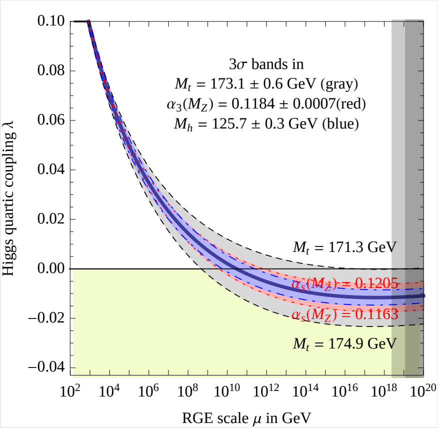

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Naturalness in an effective theory

- An effective theory is one with a physical cutoff Λ
- There are "(finite) quadratic divergences" in the CW effective potential as

$$\frac{1}{32\pi^2}\frac{\partial Str\mathcal{M}^2}{\partial\phi^2}\Lambda^2$$

In particular if the SM is an effective theory

Tree-level potential

$$V(H)=-m^2|H|^2+\frac{\lambda}{2}|H|^4$$

then "quadratic divergences" provide the Veltman correction

$$\Delta m^2=-\frac{3}{32\pi^2 v^2}\left(m_H^2+2m_W^2+m_Z^2-4m_t^2\right)\Lambda^2$$

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- An effective theory is the low energy theory of a more fundamental theory which UV completes it at scales larger than Λ
- In an effective theory the cutoff is not a mathematical device which regularizes the theory in the limit $\Lambda \to \infty$
- In this sense unnatural theories are not related to theories with quadratic divergences

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Naturalness in a fundamental theory

- A fundamental theory is one which is valid at all scales
- In the absence of a knowledge of the quantum theory of gravity it is difficult to tell that a given theory is a fundamental one
- However if we decouple gravity from the game we can assume that some field theories are fundamental

For instance for the moment (except for the Landau pole in the hypercharge coupling at trans-Planckian energies) we can assume that the SM is a fundamental theory

- In fact, the non-finding of new physics by LHC

supports this idea!!!

- However as it is hard to swallow that there are not heavy states coupled to the Higgs or new scales in the sector of quantum gravity we prefer to view the SM as an effective theory $\Lambda \simeq M_P$

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When is there a naturalness problem in a (fundamental) theory?

- When there are light (e.g. Higgs in the SM sector) and heavy (e.g. in GUT, gravitational sectors) scalars in the theory with hierarchically different (square) masses

$$v^2 \sim m^2 \ll M^2$$

and with coupling g, which are connected by radiative corrections

$$|\Delta m^2| = \mathcal{O}\left(\frac{g^2}{16\pi^2}\right) M^2 \gg m^2$$

- When there is a heavy dynamical UV scale in the theory, where a non-perturbative CFT takes over, even if created by dimensional transmutation and not corresponding to the mass of heavy states [a]

[a] Marques-Schmaltz-Skiba, arXiv:1308.0025

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Naturalness problem $\Rightarrow$ fine-tuning problem

If $|\Delta m^2| \gg v^2$ then we have to tune $|m^2| \sim |\Delta m^2| \gg v^2$ such that

$$m^2 + \Delta m^2 = \mathcal{O}(v^2)$$

This fine-tuning IS NOT natural

Tuning $\not\Rightarrow$ (automatically) naturalness problem

If m^2, $\Delta m^2 = \mathcal{O}(v^2)$ the tuning in

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i) Simplest example: SM+coupled heavy scalar

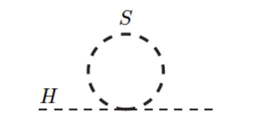
Typical example is the SM Higgs (H) in the presence of a heavy complex scalar (S) as

$$V(H,S) = -m^2 H^2 + \frac{\lambda}{2} H^4 + M^2 |S|^2 + g^2 H^2 |S|^2$$

- At tree level

$$v^2 = \frac{m^2}{\lambda}$$

- At one loop, from the one-loop tadpole diagram in $\overline{MS}$ at $Q = M$



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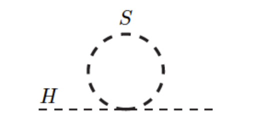

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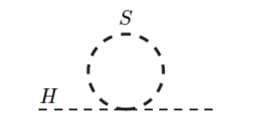

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Second example: $N_\nu = 3$ right-handed degenerated neutrinos ν_R

ii) $\mathcal{L} = \mathcal{L}_{SM} + h_\nu H \bar{\ell}_L \nu_R + M \nu_R^T \nu_R$

- At $Q > M$ propagating ν_R
- At $Q < M$ ν_R integrated out
- At $Q = M$ the integration of ν_R leaves threshold effect such that

$$\Delta m^2 = -\frac{N_\nu h_\nu^2}{4\pi^2} M^2$$

- Using a degenerate spectrum $m_\nu \simeq 0.05$ eV

NATURALNESS $\Rightarrow M \lesssim 5 \times 10^6$ GeV

SM+right-handed neutrinos with masses $\sim 10^6$ GeV

AND NOTHING ELSE AT ALL

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Third example: massive matter uncoupled to the Higgs

iii) $\mathcal{L} = \mathcal{L}_{SM} + M\bar{\Psi}\Psi$

- No loop corrections from CW in the system $SM + \Psi$
- While the full quantum theory of gravity is unknown, low energy gravitational interactions can mediate corrections to m^2

- The main contribution comes from the three-loop diagram [a]
- $$\Delta m^2 \sim \frac{h_t^2}{(16\pi^2)^3}\frac{M^6}{M_P^4}$$
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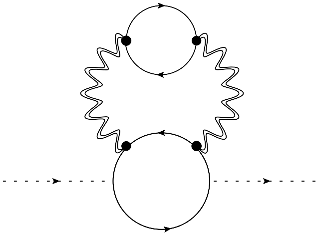

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Fourth example: MSSM [3]

iv) MSSM: $m_0 = m_{1/2} = \mu \equiv M$

- For $Q > M$: MSSM
- For $Q < M$: SM
- At $Q = M$ matching $SM \equiv MSSM$ and using the SM potential

$$V = -m^2|H|^2 + \frac{\lambda}{2}|H|^4$$

$$\Delta m^2 = -\frac{1}{32\pi^2}\left(6\lambda + 3/2g_1^2 + 9/2g_2^2 - 12h_t^2\right) M^2$$

It corresponds to the Veltman condition for $\Lambda = M$

$$\Delta m^2 = -\frac{3}{32\pi^2 v^2}\left(m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right)\Lambda^2$$

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$$\Delta m^2 = -\frac{3}{32\pi^2 v^2}\left(m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right)\Lambda^2$$

for the SM with cut-off $\Lambda = M$

[3] G. Nardini, I. Masina, MQ, in progress

Fourth example: MSSM [3]

iv) MSSM: $m_0 = m_{1/2} = \mu \equiv M$

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- For $\mathcal{Q} < M$: SM
- At $\mathcal{Q} = M$ matching $SM \equiv MSSM$ and using the SM potential

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Naturalness in BSM

- If we believe there is BSM physics at the Planck (or GUT) scale, then
- In the absence of a concrete (fundamental) UV completion describing the gravity degrees of freedom

THE THEORY BELOW M_P IS AN EFFECTIVE THEORY

- Several possibilities for the theory after imposing the requirement of naturalness

- Either the Higgs is composite, for scales $\Lambda \gtrsim \Lambda_{comp}$ the Higgs dissolves into its constituents and there is a phase transition at $\Lambda \simeq \Lambda_{comp}$ to the theory of constituents
- Or the Higgs is fundamental in which case there should exist a symmetry such that

$$\frac{\partial Str\mathcal{M}^2}{\partial \phi^2} = 0$$

The paradigm of these theories is SUSY

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In both cases there are constraints from naturalness

For a composite Higgs

- The scale Λ_{comp} is dynamical and naturalness requires

$$\Lambda_{comp} \lesssim \mathcal{O}\,(TeV)$$

- Prototype theories are technicolor or the modern warped dimensional (RS) models based on the AdS/CFT duality
- PROS: Mechanism already used by nature: QCD
- CONS: Theory non-perturbative beyond Λ_{comp}; UV completion not known; difficulties in encompassing EWPD,. . .

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- SUSY theory soft breaking terms (e.g. squark masses) $m_{\tilde{f}}$ should be

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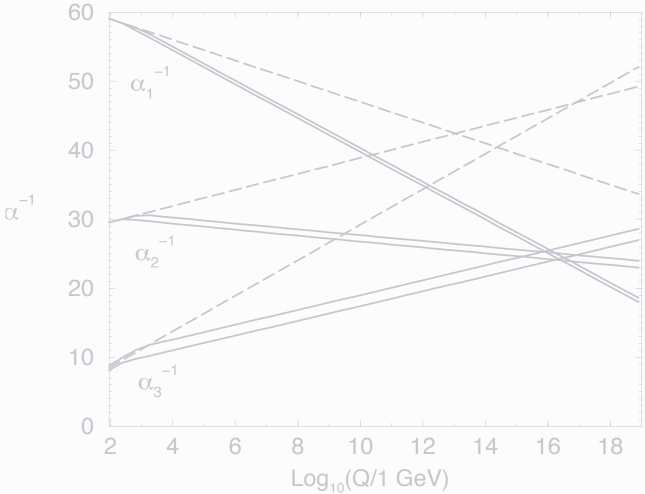
Gauge unification for SM (dashed) and MSSM (solid)



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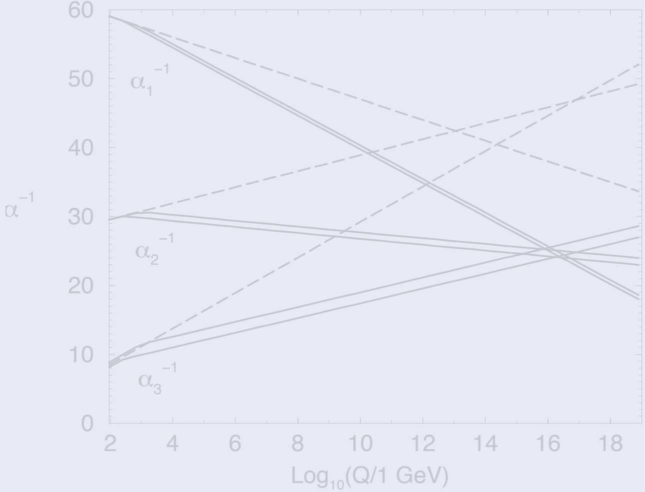

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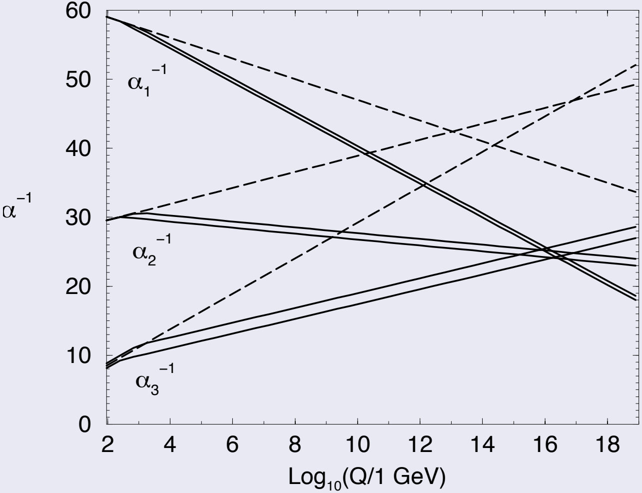
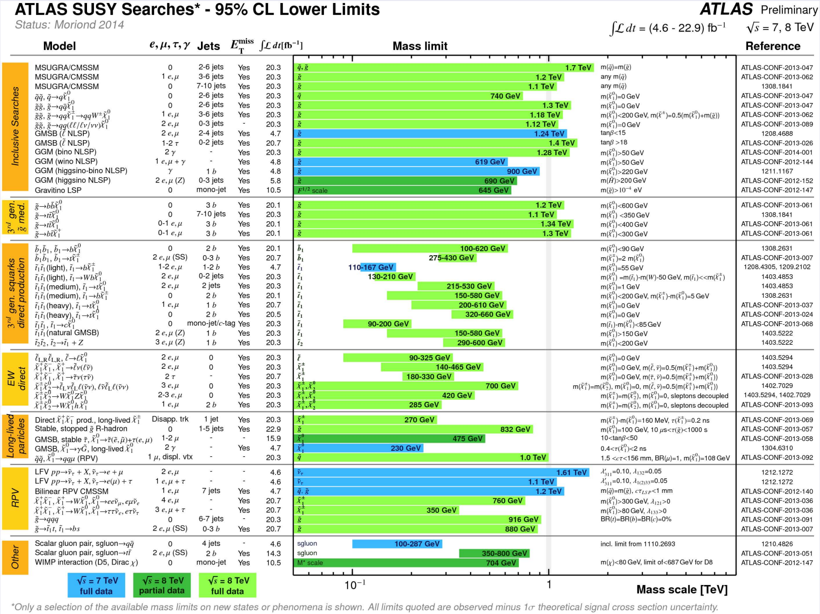
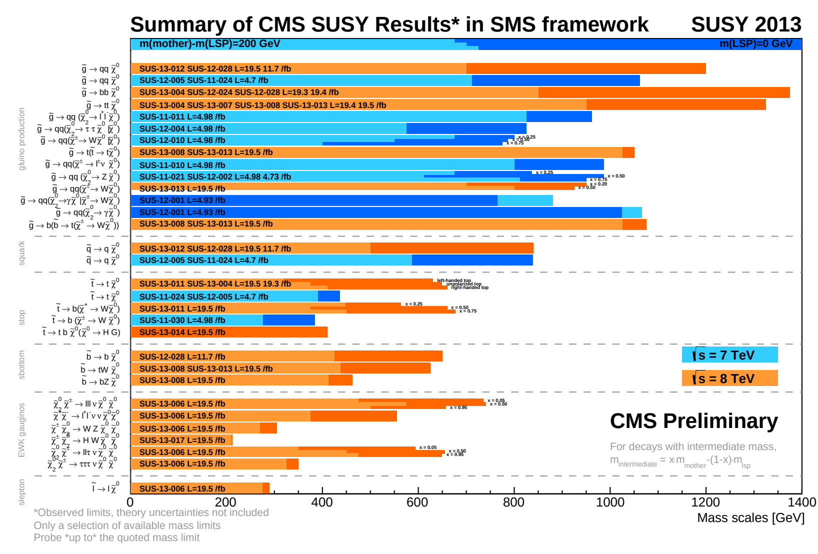


BUT...


ATLAS SUSY Searches* - 95% CL Lower Limits
Status: Moriond 2014
ATLAS Preliminary
$\int \mathcal{L} dt$ = (4.6 - 22.9) fb^{-1}
$\sqrt{s}$ = 7, 8 TeV
Model
e, μ, τ, γ
Jets
E_T^{miss}
$\int \mathcal{L} dt$[fb^{-1}]
Mass limit
Reference
Inclusive Searches
3rd gen. $\tilde{g}$ med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
$\sqrt{s}$ = 7 TeV full data
$\sqrt{s}$ = 8 TeV partial data
$\sqrt{s}$ = 8 TeV full data
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

AND...



Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
SUS-13-014 L=19.5 /fb
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
x = 0.25
x = 0.50
x = 0.75
x = 0.20
x = 0.05
x = 0.95
$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 8 TeV
CMS Preliminary
For decays with intermediate mass,
$m_{intermediate} = x \cdot m_{mother} - (1-x) \cdot m_{lsp}$
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

- Present bounds are already a naturalness hazard
- In view of future stronger bounds people are re-analyzing and trying to improve naturalness in the MSSM (and minimal extensions)
- One idea to alleviate the fine-tuning is if the high supersymmetry scale is the Focus Point (FP) of the RGE [4] for large $\tan\beta$
- As experimental data suggest that gluinos and sfermion masses may be much larger than the weak scale
- These particles would decouple at some scale $\mathcal{Q}_0 \gg \mathcal{Q}_{EW}$, and therefore the matching between the SM and the SUSY extension should be performed at the scale $\mathcal{Q}_0$, at which the heavy particles are decoupled
- The matching condition yields a relationship between the SM Higgs boson potential parameters

$$V(H) = -m^2|H|^2 + \frac{\lambda}{2}|H|^4,$$

where $m^2(\mathcal{Q}_{EW}) = \frac{1}{2}m_H^2$, and the supersymmetric parameters at $\mathcal{Q}_0$

[4] J. L. Feng, K. T. Matchev and T. Moroi, hep-ph/9909334

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$$m_H^2/2 = \frac{m_{H_D}^2(\mathcal{Q}_0) - m_{H_U}^2(\mathcal{Q}_0)}{\tan^2\beta - 1} - m_{H_U}^2(\mathcal{Q}_0) - |\mu(\mathcal{Q}_0)|^2$$

$$\lambda = \frac{1}{4}(g_1^2 + g_2^2)\cos^2 2\beta + \frac{3h_t^4}{8\pi^2}X_t^2\left(1 - \frac{X_t^2}{12}\right), \quad X_t = \frac{(A_t - \mu/\tan\beta)}{\mathcal{Q}_0}$$

- For a heavy supersymmetric spectrum, i.e. large soft-breaking terms $a \equiv (m_Q^2, m_U^2, m_{H_U}^2, M_a)$ at the high scale M (messenger scale) at which they are generated, one expects $m_{H_U}^2(\mathcal{Q}_0)$ to be large, thus triggering a huge fine-tuning in matching equation

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$$\Delta = \max_a\{\Delta_a\}, \quad \Delta_a = \left|\frac{\partial \log m_H^2}{\partial \log a}\right|$$

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$$m^2_{H_U}(\mathcal{Q}_0) = m^2_{H_U} + \eta^0_Q(M)(m^2_Q + m^2_U + m^2_{H_U}) + \sum_a \eta^0_a(M) M^2_a$$
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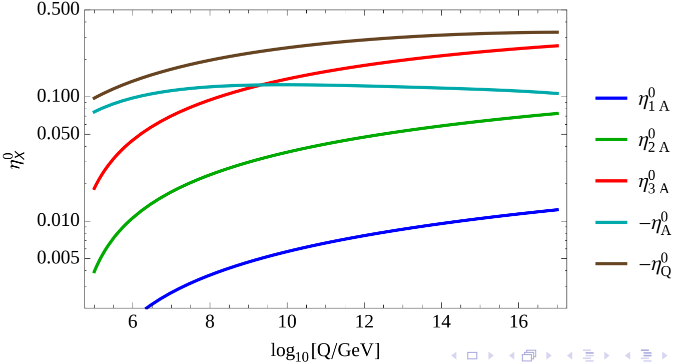

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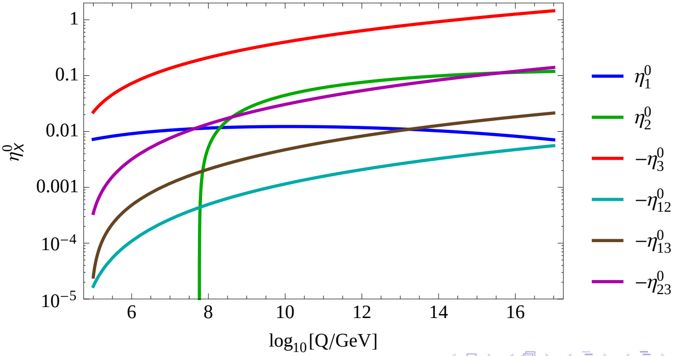

- At the FP

$$m_{H_U}^2(\mathcal{Q}_0) = 0$$

invariant under

$$(m_Q^2,\, m_U^2,\, m_{H_U}^2,\, M_a,\, A_t) \to \ (\lambda^2\, m_Q^2,\, \lambda^2\, m_U^2,\, \lambda^2\, m_{H_U}^2,\, \lambda\, M_a,\, \lambda\, A_t)$$

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$$\frac{m_H^2}{2} \simeq \frac{m_{H_D}^2(\mathcal{Q}_0)}{\tan^2\beta} - |\mu(\mathcal{Q}_0)|^2, \quad m_3^2 \simeq m_{H_D}^2/\tan\beta$$

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- A scatter plot of the sensitivity Δ with respect to the soft-breaking parameters $(m^2_Q,\, m^2_U,\, m^2_{H_U},\, M_a)$ at the messenger scale M would show, for large $\tan\beta$, a minimum fine-tuning for configurations of $(m^2_Q,\, m^2_U,\, m^2_{H_U},\, M_a)$ such that there is the FP at the scale $\mathcal{Q}_0$

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- If we consider a particular theory of supersymmetry breaking

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IMPLEMENTED BY THE SYMMETRIES OF THE UV THEORY

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THE HIDDEN FINE-TUNING IS UNCOMPUTABLE AND WE CAN NOT CONSIDER IT

- Instead of making a scatter plot of sensitivity we can study the existence of FP's for different models of boundary condition. In particular [5]

- CMSSM MODELS
- GAUGE MEDIATION MODELS
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UNIVERSAL BOUNDARY CONDITIONS

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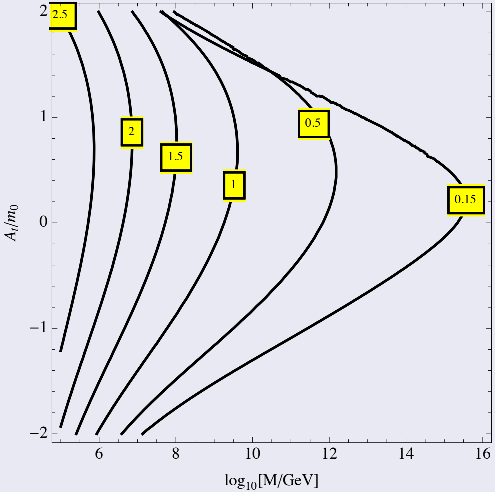
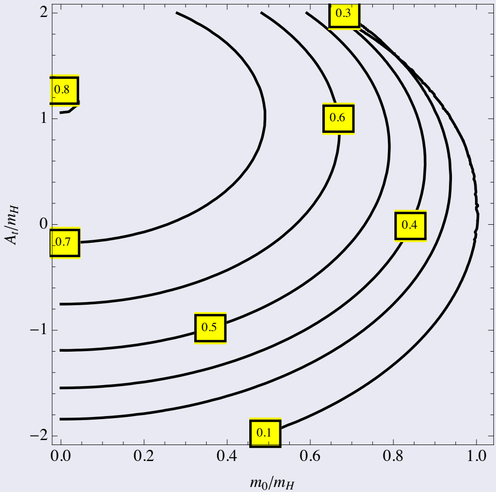


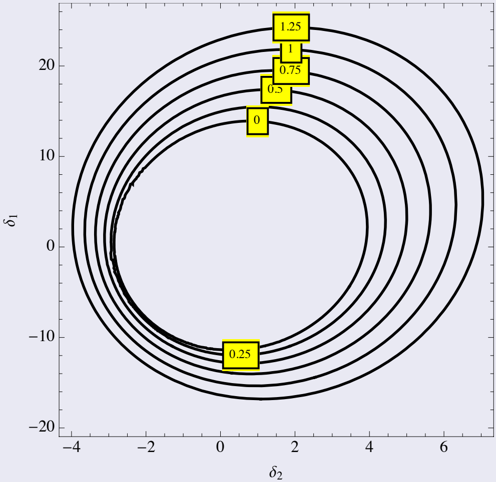
NON-UNIVERSAL HIGGSES: $M = 10^{16}$ GEV

$m_Q = m_U \equiv m_0, \quad m_{H_U} = m_{H_D} \equiv m_H, \quad M_a \equiv m_{1/2}$ (fixed $m_{1/2}/m_H$)



NON-UNIVERSAL GAUGINOS: $M = 10^{16}$ GeV

$m_Q = m_U = m_{H_U} \equiv m_0, \quad M_a \equiv \delta_a m_{1/2}, \; A_t = -2.5 m_0$ (fixed $m_{1/2}/m_0$)



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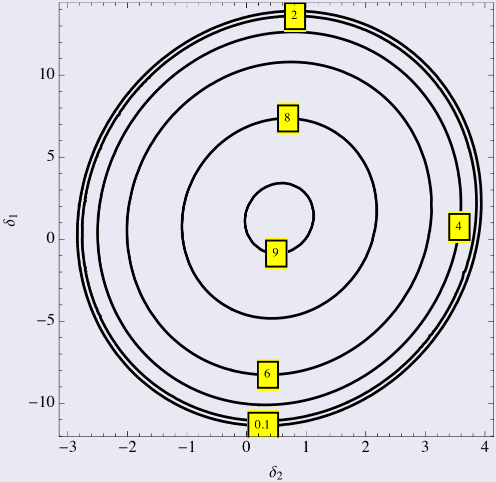

Gauge mediation

- Supersymmetry is broken in a hidden sector by fields

$$X_i = M_i + F_i\theta^2$$

- It is communicated to the messenger fields by superpotential couplings

$$W = \Phi^I X \overline{\Phi}_I + \lambda_U H_U \mathcal{O}_D + \lambda_D H_D \mathcal{O}_U + X_{\mathcal{O}} \mathcal{O}_U \mathcal{O}_D$$

$\Lambda_G = NF/4\pi M, \quad \Lambda_S = \Lambda_G/\sqrt{N}$

$$m_Q^2 = 2\left(\frac{4}{3}\alpha_3^2 + \frac{3}{4}\alpha_2^2 + \frac{1}{60}\alpha_1^2\right)\Lambda_S^2$$

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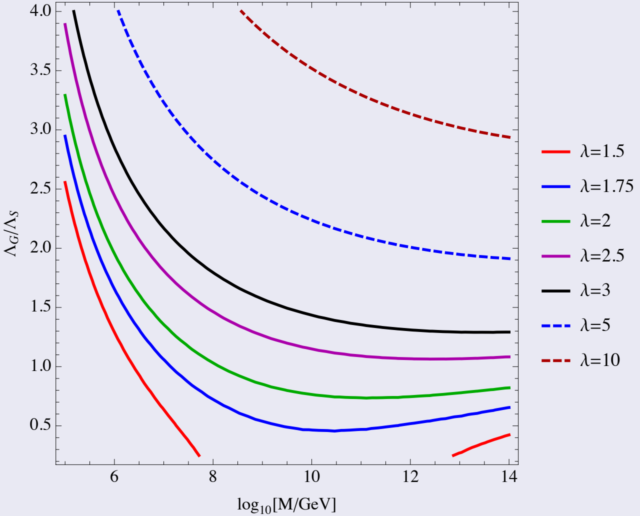
Lines of constant λ



Mirage mediation

Mirage mediation assumes that the contributions from gravity and anomaly mediation are comparable in size

$\widetilde{m}_{3/2} = m_{3/2}/4\pi,$ $[+\mathcal{O}(\alpha_1^2)]$

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$$m_Q^2 \simeq m_0^2 + \left[\alpha_t\left(6\alpha_t - \frac{16}{3}\alpha_3 - 3\alpha_2 - \frac{13}{15}\alpha_1\right) - \frac{8}{3}\alpha_3^2 b_3 - \frac{3}{2}\alpha_2^2 b_2\right]\widetilde{m}_{3/2}^2$$

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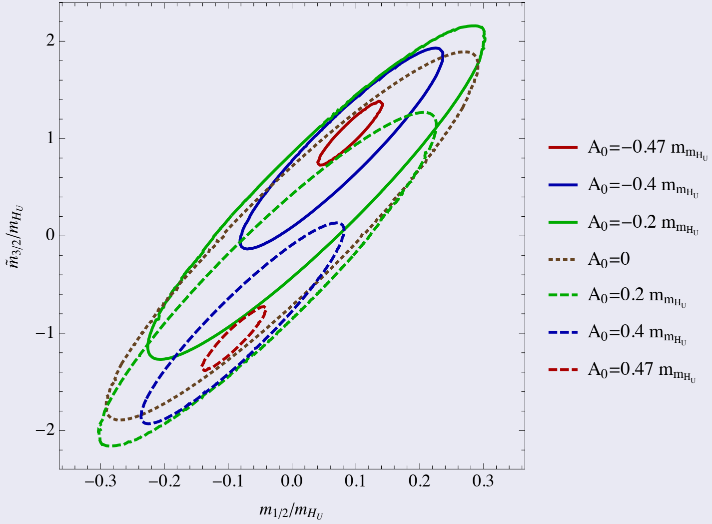
$$m_U^2 \simeq m_0^2 + \left[2\alpha_t\left(6\alpha_t - \frac{16}{3}\alpha_3 - 3\alpha_2 - \frac{13}{15}\alpha_1\right) - \frac{8}{3}\alpha_3^2 b_3\right]\widetilde{m}_{3/2}^2$$

$$A_t = A_0 - \left(6\alpha_t - \frac{16}{3}\alpha_3 - 3\alpha_2 - \frac{13}{15}\alpha_1\right)\widetilde{m}_{3/2}$$

$$M_a = m_{1/2} + \alpha_a b_a \widetilde{m}_{3/2}$$

Lines of constant A_0, for $M = 10^{16}$ GeV



Conclusion

In the SM

- If the SM is a fundamental theory (up to the Landau pole at trans-Planckian energies for g_1) there is no problem with naturalness
- However some miracles should happen in particular in the quantum theory of gravity
  - No massive (Planckian) particles strongly coupled to the Higgs or massive Planckian particles with couplings

$$g \lesssim 4\pi m_H/M_P \simeq 10^{-15}!!!$$

  - No large dynamical scales
- These miracles do not happen if there is a GUT [e.g. $SU(5)$] at very high scale
- These miracles do not happen in the known version of quantum gravity: string theory. The Kaluza-Klein modes of gauge bosons are strongly (gauge) coupled to the Higgs

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If we do not believe in miracles. . .

- We should protect the SM naturalness by BSM
  - Either the scale of new physics is at the TeV (composite Higgs)
  - Or there is a symmetry protecting the SM quadratic sensitivity (supersymmetry)
- Anyway we might need BSM to complete the SM: Dark Matter, Baryogenesis, strong CP problem, flavour problem,. . .
- This NP should be at the TeV scale to not perturb naturalness

The next run of LHC should be essential to explore the few TeV region

- If NP is found then we should try to interpret it as part of the solution to the naturalness problem
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