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SCUOLA NORMALE SUPERIORE PISA

Can the Supersymmetric Flavour Problem decouple in case of a Non Standard Supersymmetric Spectrum?

Main ref: R. Barbieri *et al*, *"A Non Standard Supersymmetric Spectrum"* [1004.2256].

1/7) Motivation: naturalness (not a theorem)

- Higgs mass Problem

MSSM: $m_h \lesssim m_Z |\cos 2\beta|$ + rad. corr. (↔**finetuning**)

→ alleviated if $m_h^{(tree)} \uparrow$

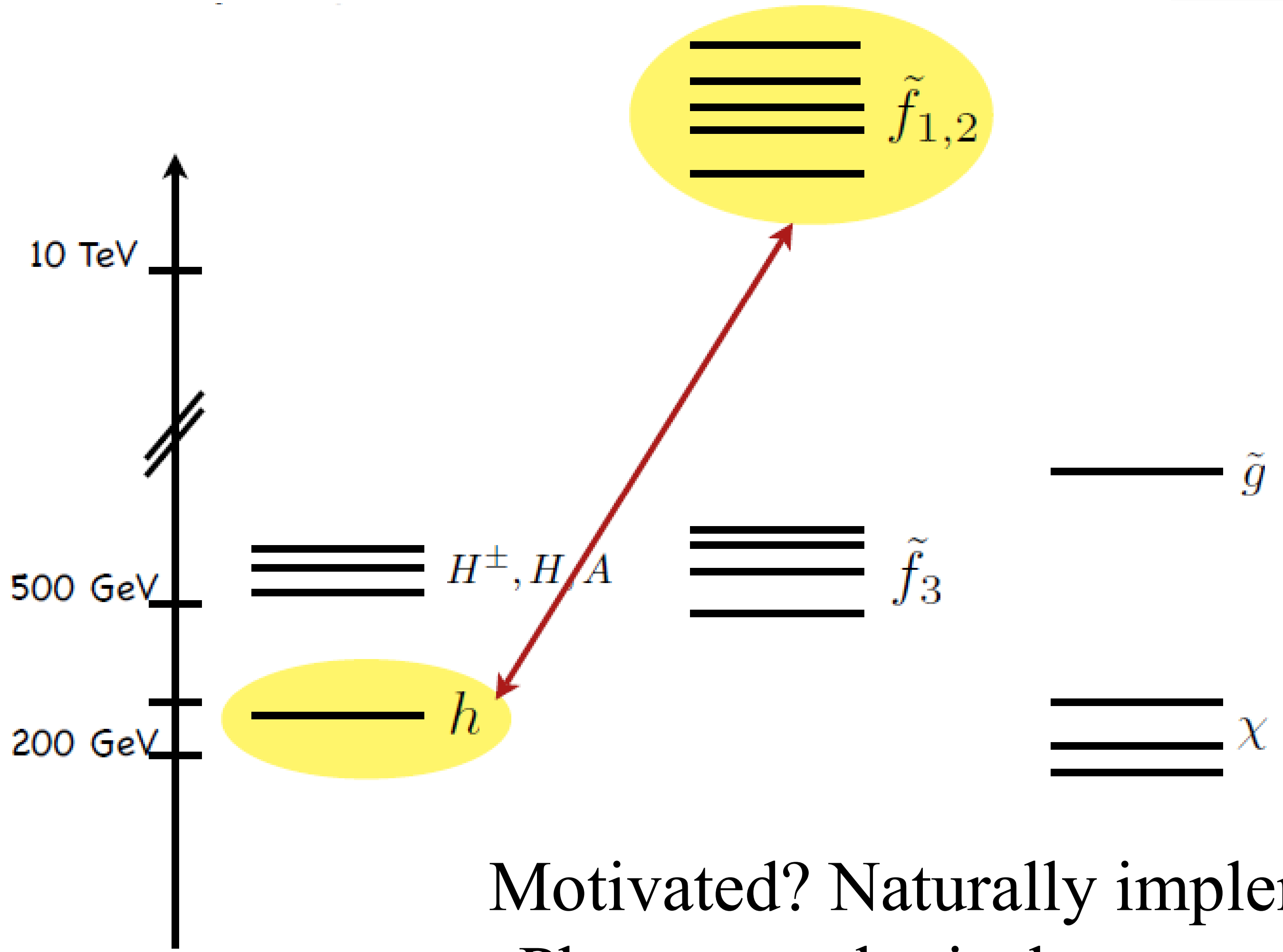
- Supersymmetric Flavour Problem

Ameliorated by hierarchical sfermions.
Obstruction: **finetuning** (+ colour cons.) $\frac{m^2_{\tilde{f}_{1,2}}}{m_h^2} \frac{\delta m_h^2}{\delta m^2_{\tilde{f}_{1,2}}}$

→ alleviated if $m_h^{(tree)} \uparrow$

Related issues?

Idea: Non Standard Supersymmetric Spectrum



Motivated? Naturally implemented?
Phenomenological consequences?

2/7) Hierarchical sfermions and flavour physics

- No degeneracy nor alignement: $m_{\tilde{q}_{1,2}}$ > hundreds of TeV
  [Dine, Kagan Samuel 1990] [Pomarol Tommasini 1996] [Cohen, Kaplan, Nelson 1996]
- If $\delta_{12}^{LL} \approx \frac{|m_1^2 - m_2^2|}{(m_1^2 + m_2^2)/2} \approx \lambda \approx 0.22$ and $\delta^{LL} \approx \delta^{RR} >> \delta^{LR}$:

Recent analysis:
[Giudice, Nardecchia, Romanino 2009]

$$Real\ \Delta S = 2 \Rightarrow m_{\tilde{q}_{1,2}} \gtrsim 18\ TeV\,,$$
$$Im\ \Delta S = 2,\ \ \sin\phi_{CP} \approx 0.3 \Rightarrow m_{\tilde{q}_{1,2}} \gtrsim 120\ TeV\,.$$

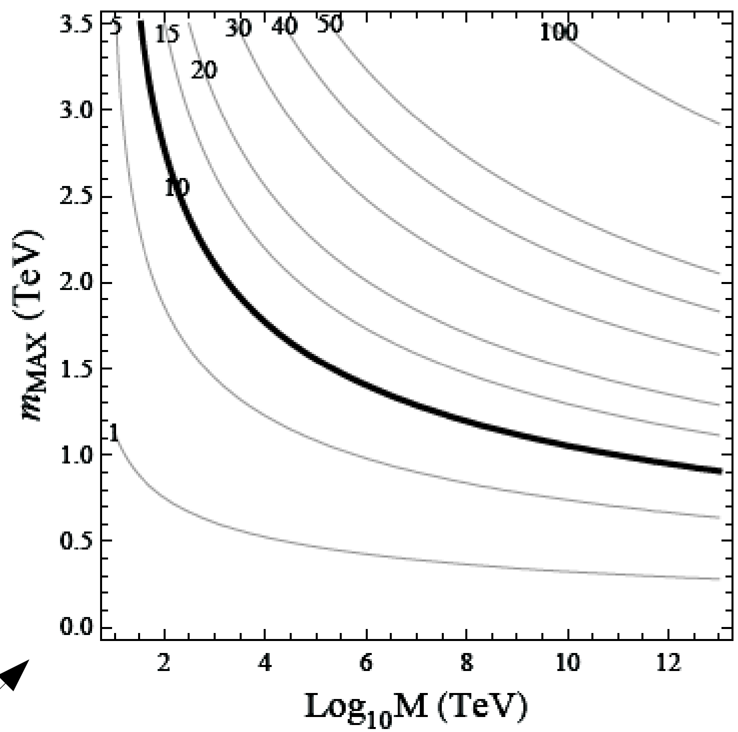
- If as above but $\delta^{LL} >> \delta^{RR}, \delta^{LR}$ (or $\delta^{RR} >> \delta^{LL}, \delta^{LR}$) :

$$\Delta C = 2 \Rightarrow m_{\tilde{q}_{1,2}} \gtrsim 3\ TeV$$
$$Im\ \Delta S = 2,\ \ \sin\phi_{CP} \approx 0.3 \Rightarrow m_{\tilde{q}_{1,2}} \gtrsim 12\ TeV$$

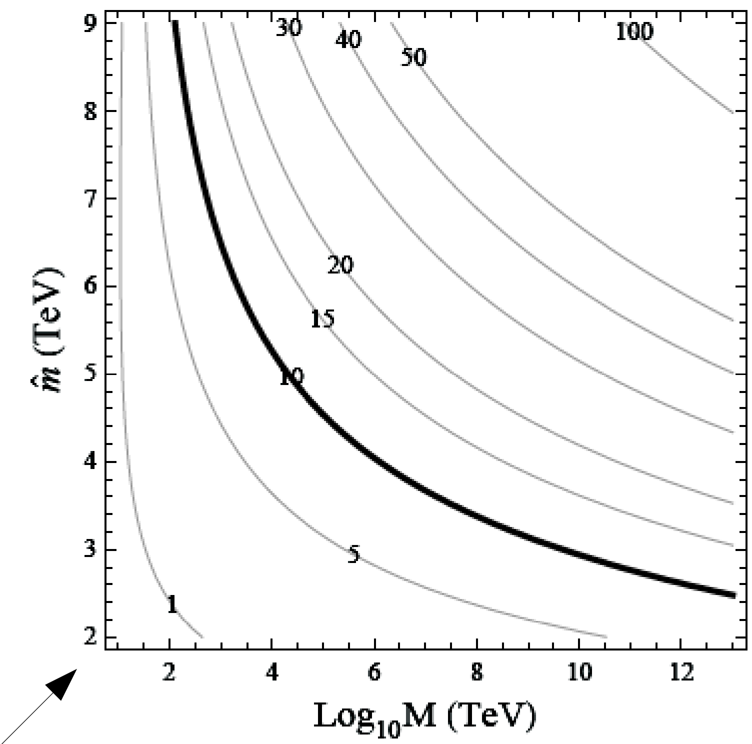
$\Rightarrow\ m_{\tilde{f}_{1,2}} \gtrsim 20 \div 30\ TeV \quad m_{\tilde{f}_3} \approx 0.5 \div 1\ TeV$
may be a way to solve the flavour problem

3/7) Bounds on $m^2_{\tilde{f}_{1,2}}$ in the MSSM: I) naturalness

$$\frac{\partial m_h^2}{\partial t} \approx \frac{\alpha'}{4\pi} Tr(Y \tilde{m}^2_{1,2}) + \frac{\alpha^2}{16\pi^2} \tilde{m}^2_{1,2} \qquad \& \qquad \frac{m^2_{\tilde{q}_{1,2}}}{m_h^2} \frac{\delta m_h^2}{\delta m^2_{\tilde{q}_{1,2}}} < \Delta$$



No particular condition at M=Msusy



Vert. degeneracy at M=Msusy for 1st and 2nd gen.

$$\times \frac{m_h}{m_Z}$$

[Barbieri, Giudice, 1988][Dimopoulos, Giudice 1995]

3/7) Bounds on $m^2_{\tilde{f}_{1,2}}$ in the MSSM: II) colour conservation

$$\frac{d}{dt}m^2_{\tilde{f}} = -8\sum_i \tilde{\alpha}_i C^f_i M^2_i + 8\left[\left(\frac{1}{2}N_5 + \frac{3}{2}N_{10}\right)\sum_i \tilde{\alpha}^2_i C^f_i + (N_5 - N_{10})\frac{3}{5}Y_f\tilde{\alpha}_1\left(\frac{4}{3}\tilde{\alpha}_3 - \frac{3}{4}\tilde{\alpha}_2 - \frac{1}{12}\tilde{\alpha}_1\right)\right]\widetilde{m}^2_{1,2}.$$

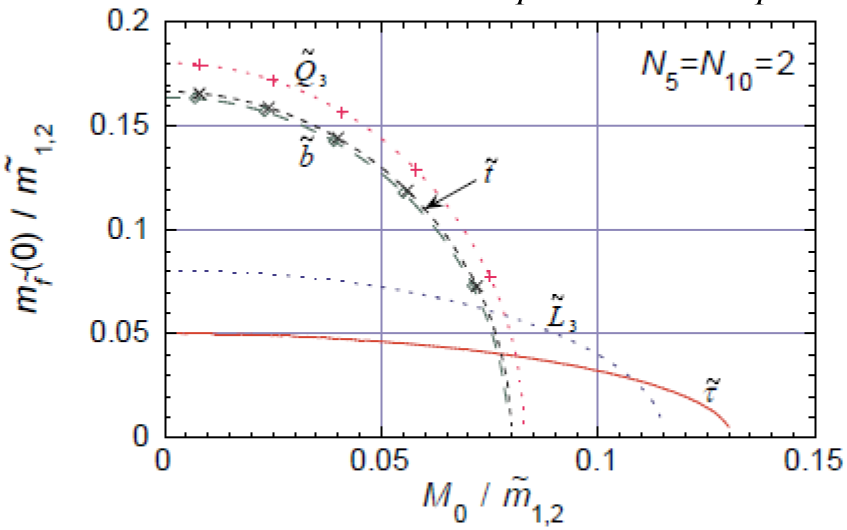
Large $m_{1\text{-}2}$ draws m_{f3}^2 negative at low energies!

Way out*:

- $M_{susy} << M_{GUT}$
- Larger $m_h^{(tree)}$

(because larger allowed $m_3(M_{susy})$ and M_g !)

[Arkani-Hamed, Murayama 1997]
"Can the SUSY Flavour problem decouple?"



*without peculiar initial cond. [Feng 2009][Bagger 2009]

4/7) Supersymmetry without a light Higgs boson

(to keep the success of EWPT, no effective theories)

★ Extra U(1)

$$m_h^2 \le (m_Z^2 + \frac{g_x^2 v^2}{2(1+\frac{M_X^2}{2M_\phi^2})}) \cos^2 2\beta$$

★ Extra SU(2)

$$m_h^2 \le m_Z^2 \frac{g'^2 + \Delta g^2}{g'^2 + g^2} \cos^2 2\beta$$

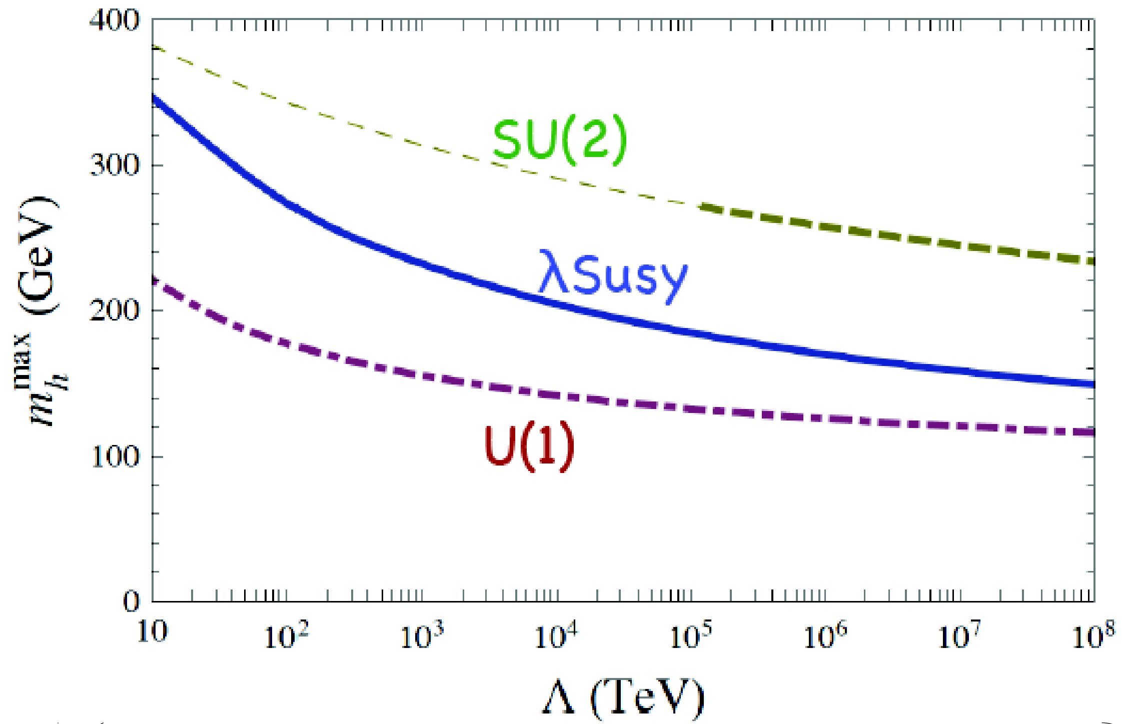
$$\Delta = \frac{1 + \frac{M_\Sigma^2}{M_X^2}\frac{g_I^2}{g^2}}{1 + \frac{M_\Sigma^2}{M_X^2}}$$

★ $\Delta f = \lambda S H_1 H_2$

$$m_h^2 \le m_Z^2(\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2}\sin^2 2\beta)$$

[Batra, Delgado, Kaplan, Tait 2004]
[Barbieri, Hall, Nomura, Rychkov 2007]

[P.L. 2010] [Barbieri et al 2010]

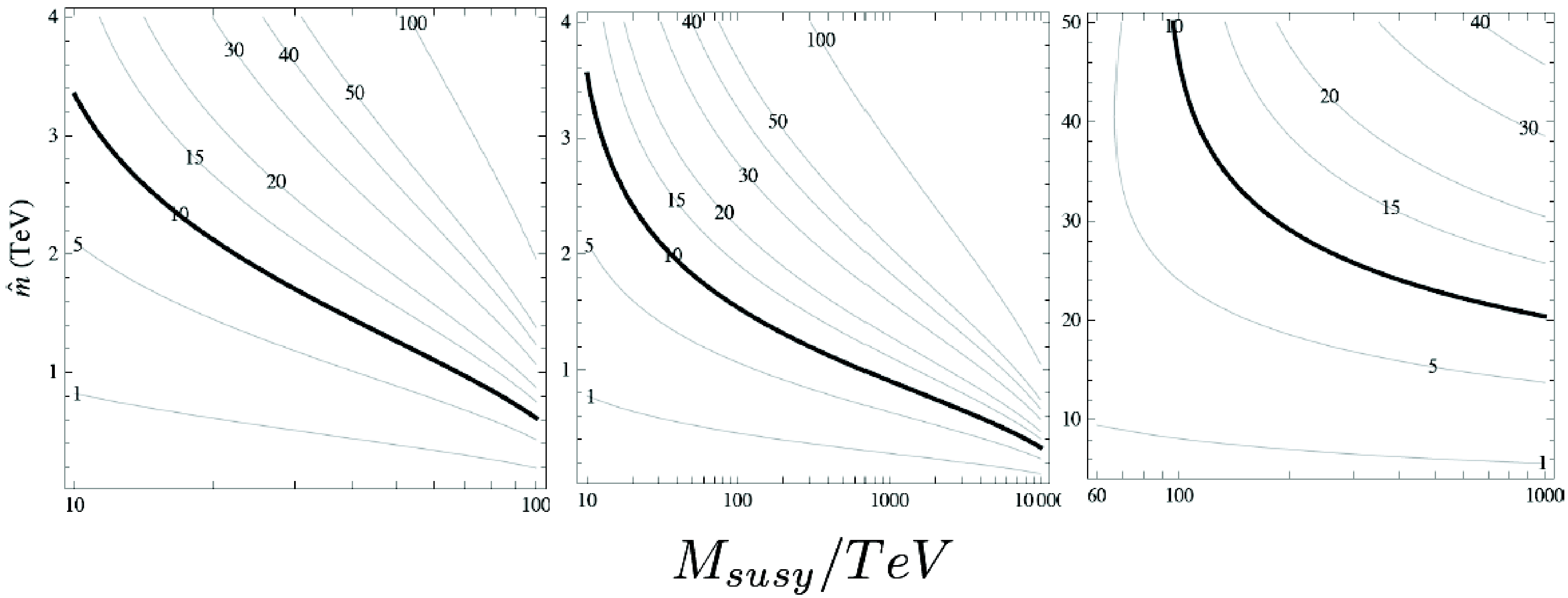


- Λ= scale at which some coupling gets semiperturbative
- In gauge extensions $M_{\phi,\Sigma}/M_X$ is maximized consistently with naturalness of the higher vev

With *low* Λ, m_h can be sign. raised

5/7) Bounds with larger $m_h^{(tree)}$: I) naturalness

U(1) $m_h^{max} = 180\ GeV$ SU(2) $m_h^{max} = 250\ GeV$ λSusy $m_h^{max} = 250\ GeV$



$\hat{m}$ is $m_{\tilde{f}_{1,2}}$ with vertical degeneracy among $\tilde{f}$'s at M_{susy}

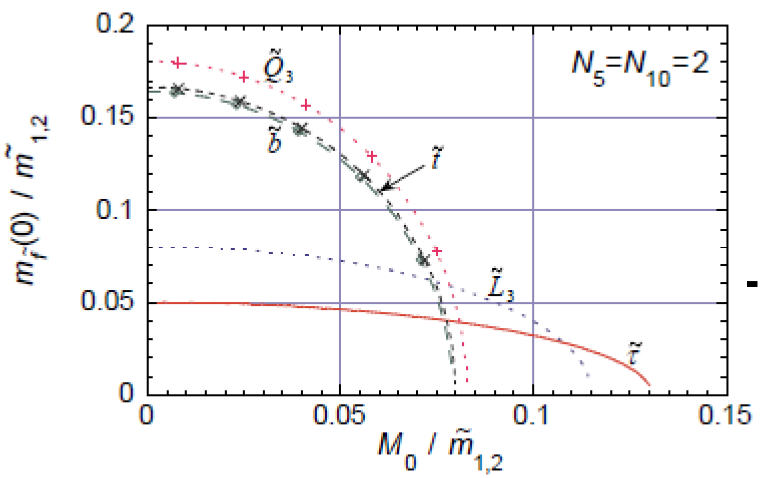
⇒ $m_{\tilde{f}_{1,2}} \gtrsim 20\ TeV$ OK in λSusy at M = 100÷1000 TeV

5/7) Bounds with larger $m_h^{(tree)}$:

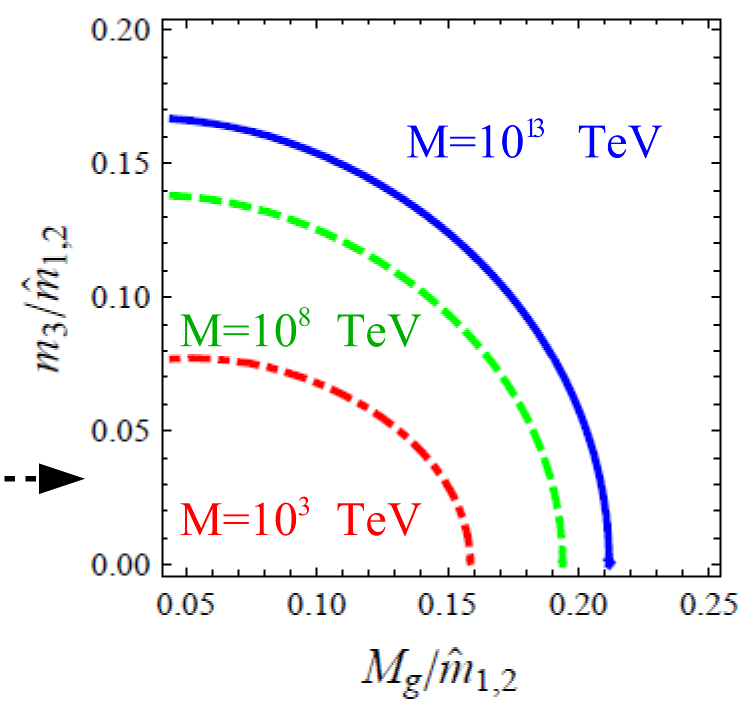
II) colour conservation (can the SUSY Flavour Problem decouple?)

- RGE for m_3: $$\frac{dm^2_{\tilde{Q}_3}}{d\log\mu} = -\frac{1}{16\pi^2}\frac{32}{3}g_3^2 M_g^2 + \frac{8}{(16\pi^2)^2}\left(\frac{1}{15}g_1^4 + 3g_2^4 + \frac{16}{3}g_3^4\right)\hat{m}^2_{1,2}$$

- Imposing $m_3(G_F^{-1/2})>0$:



[Arkani-Hamed, Murayama 1997]



We neglect lighter gauginos; Mg=gluino mass at low energy.

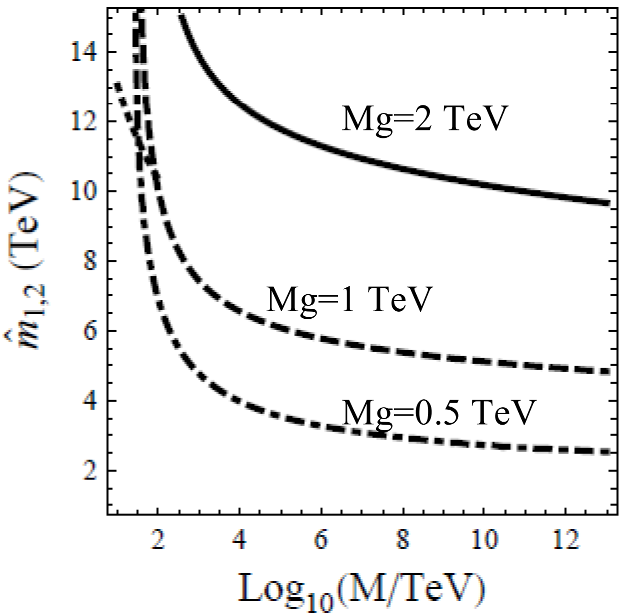
Is it sufficient?

5/7) Bounds with larger $m_h^{(tree)}$:

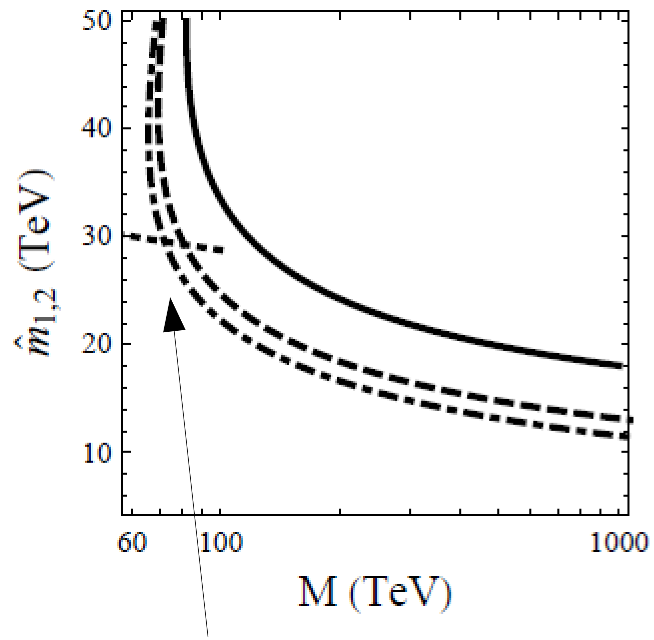
II) colour conservation (can the SUSY Flavour Problem decouple?)

- Fix maximum m3 from: $\frac{\partial \log v^2}{\partial \log m_3^2} \approx \frac{6\,(m_t/175\ \mathrm{GeV})^2}{16\pi^2}\frac{m_3^2}{m_h^2/2}\log\frac{M}{200\ \mathrm{GeV}} \leq 10$
- Then impose positive squared masses:

MSSM



λSUSY with mh=250 GeV



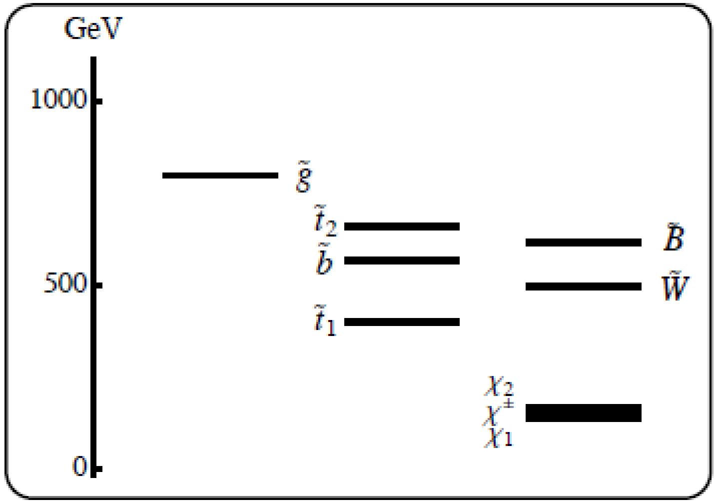
Crucial role played by increased quartic coupling!

Bound from threshold effects: $m_H/m_L<25$

[Agashe, Graesser 1998]

6/7) Phenomenological consequences: I) gluino pair production and decay

A typical configuration



See also [Barbieri, Pappadopulo 2009]

3 relevant semi-inclusive BR's

$\tilde{g} \to t\bar{t}\chi$

$\tilde{g} \to t\bar{b}\chi \; (\bar{t}b\chi)$

$\tilde{g} \to bb\chi$

with $B_{tt} + 2B_{tb} + B_{bb} \approx 1$

and $\chi = \chi_{LSP} + W, Z's$

⇒ multi top events

⇒ spherical events

⇒ 4 b's always, sometime only

More in general

$m_{\tilde{g}} = 400 \div 1800\ GeV$

$m_{\tilde{t}_1} < m_{\tilde{t}_2} < 800\ GeV \quad \theta_t = 0 \div \pi/2$

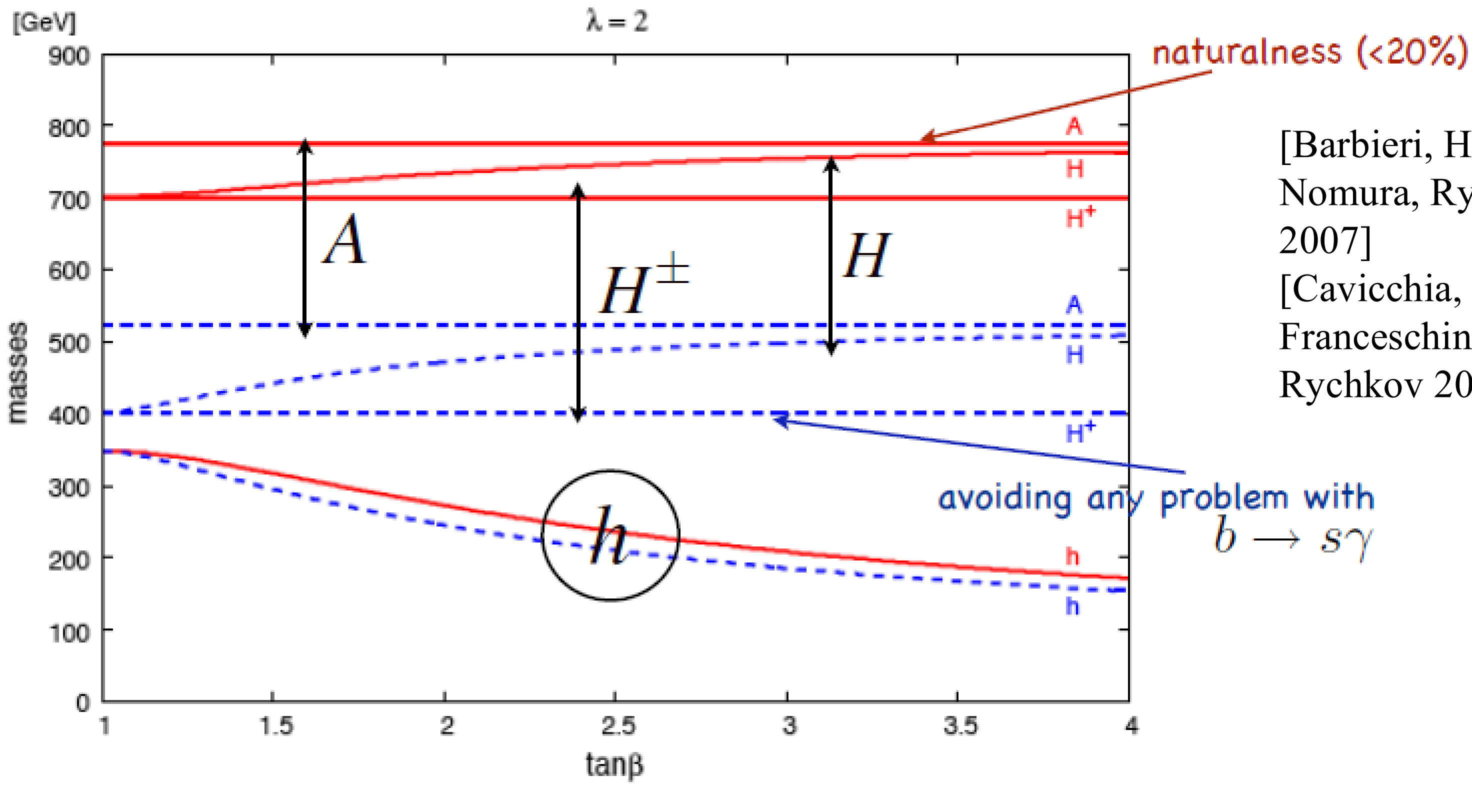
$\mu = 100 \div 400\ GeV$

$M_1,\ M_2 = 100 \div 500\ GeV$

$m_{\tilde{b}_R} \lesssim 600\ GeV$

(s-lepton masses almost always unimportant)

6/7) Phenomenological consequences: II) unconventional Higgs sector



[Barbieri, Hall, Nomura, Rychkov 2007]
[Cavicchia, Franceschini, Rychkov 2008]

$h \to ZZ \to l^+l^-\ l^+l^-$ Easy and very much non-susy like

$H \to hh \to 4V \to l^+l^-\ 6j$ $BR \propto \lambda^2$ much larger than normal

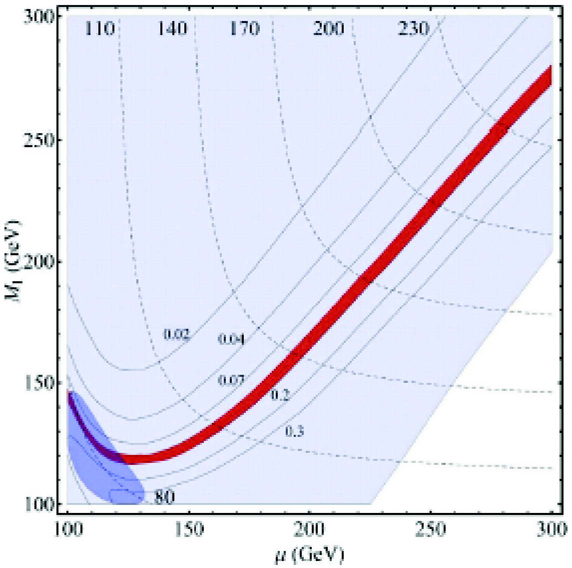
$A \to hZ \to VV\ Z \to l^+l^-\ 4j$

6/7) Phenomenological consequences: III) DM relic abundance

See also *"The well tempered neutralino"*
[Arkani-Hamed, Delgado, Giudice 2006]

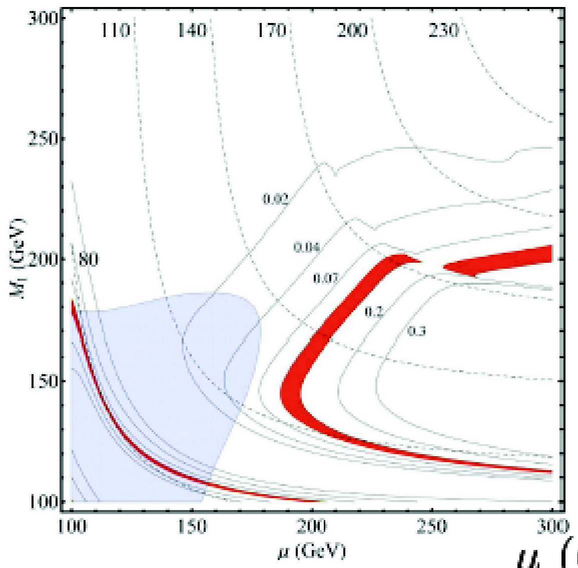
A strong effect of the s-channel heavier Higgs exchange
No "well-temperament"

$M_1 (GeV)$



MSSM $m_h = 120\ GeV$

M_2 large



$\mu\ (GeV)$

λSusy: $m_h = 200\ GeV$

dark blu: CDMS now
light blu: "XENON100"

Direct detection affected by $\sigma \propto \frac{1}{m_h^4}$ and different mixing

7/7) Conclusions

- Higgs mass problem and SUSY Flavour problem may be related and point towards a Non Standard Supersymmetric Spectrum:

$$m_h = 200 \div 250\ GeV$$
$$m_{\tilde{f}_{1,2}} \gtrsim 20 \div 30\ TeV >> m_{\tilde{f}_3}$$

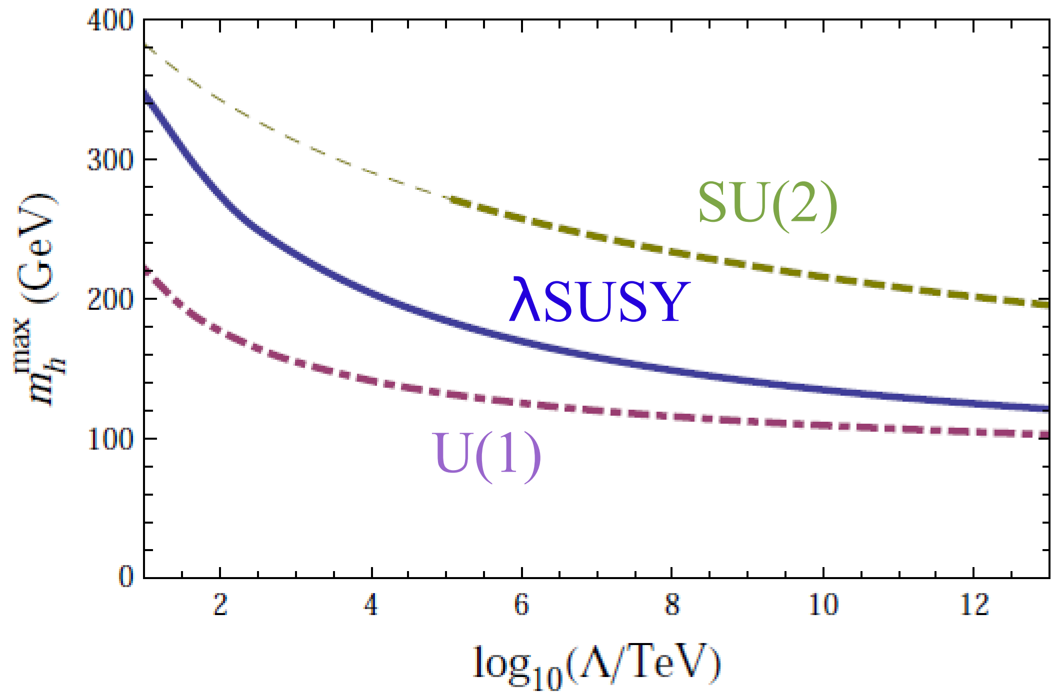
- **<u>Naturally</u>** possible in non minimal extensions (at least in λSUSY)
- The Supersymmetric Flavour Problem can decouple (**<u>no em/colour breaking)</u>** thanks not only to <u>low M</u> but also to <u>large m_h</u>.
- Peculiar phenomenology:
  - $\tilde{g} \to t\bar{t}\chi,\ t\bar{b}\chi\ (\bar{t}b\chi),\ b\bar{b}\chi$
  - $h \to ZZ,\ H \to hh,\ hhh$
  - DM: no "well-temperation" Direct Detection affected

Backup Slides

B1) Comparison of the three models:

<u>From a bottom-up point of view, m_h can be significantly raised.</u>

Price to pay:
1) low Λ
2) low M
3) diff. soft scales
4) need ΔT:

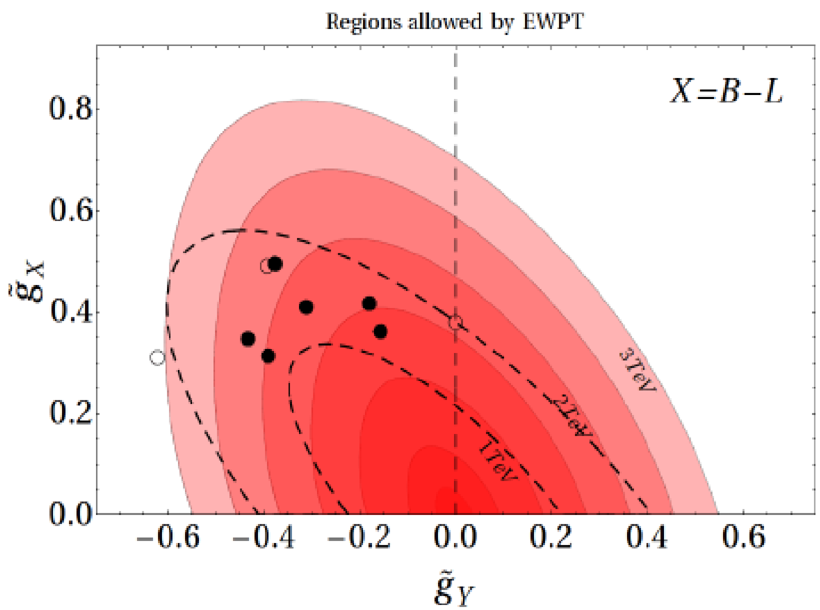


	m_h^{max}/m_Z	Price to pay
$U(1)$	2	(1),(2),(3)
$SU(2)$	2	(3)
$SU(2)$	3	(2),(3),(4)
λSUSY	2	–
λSUSY	3	(1)

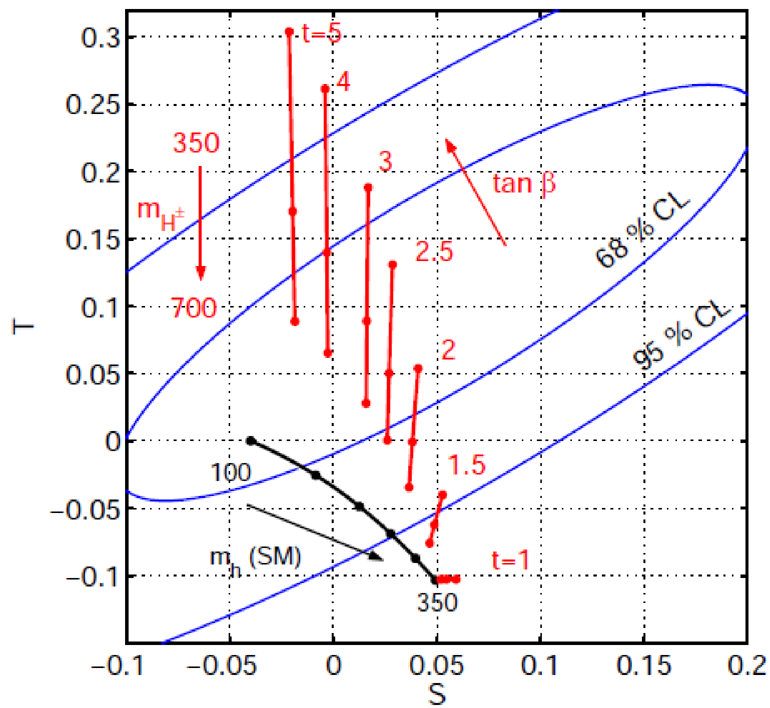
[P.L. 2010]

B2) Electroweak precision tests

- Gauge ext U(1): $M_X \gtrsim 5\ \mathrm{TeV}$
  $(m_h = 2m_Z)$
- Gauge ext SU(2): $\dfrac{M_X}{5\ \mathrm{TeV}} \gtrsim \dfrac{g_X}{g_Z}$
- λSUSY:

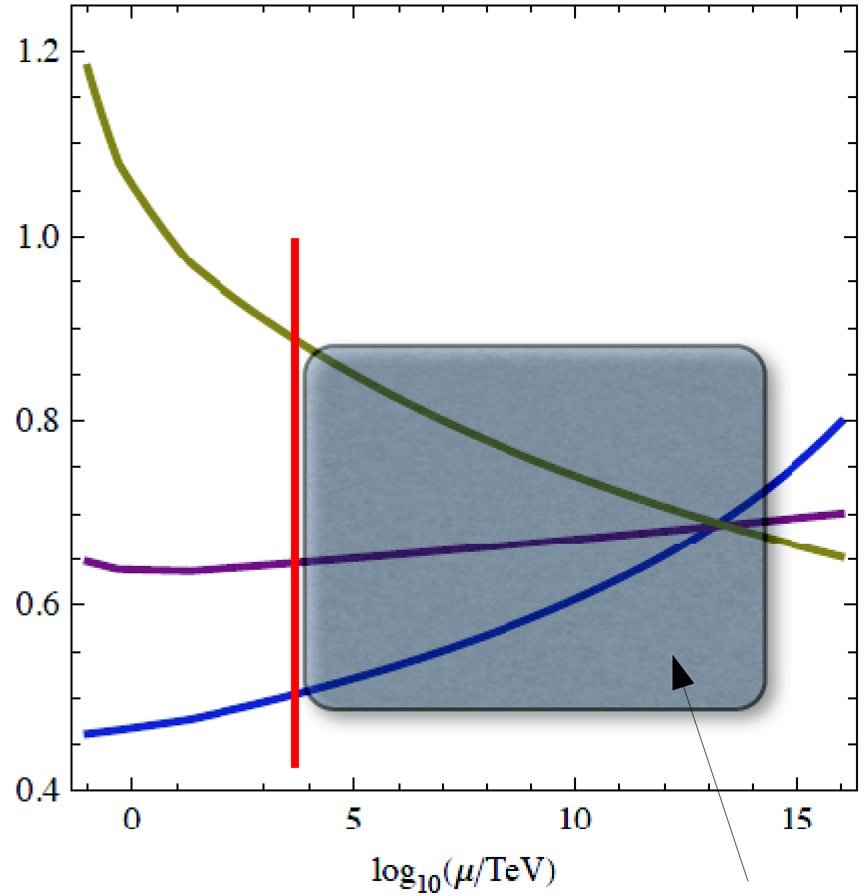


E. Salvioni, A. Strumia, G. Villadoro, F. Zwirner (2010)



R. Barbieri, L. J. Hall, Y. Nomura, V. S. Rychkov (2007)

B3) What about unification?



(we cannot say what happens here)

$\Lambda \sim M \sim 10^4$ TeV
$m_{1,2} = 20$ TeV

At $M \approx 10^4\ TeV$:
$g_1 \approx 0.5,\ g_2 \approx 0.7,\ g_3 \approx 0.85$

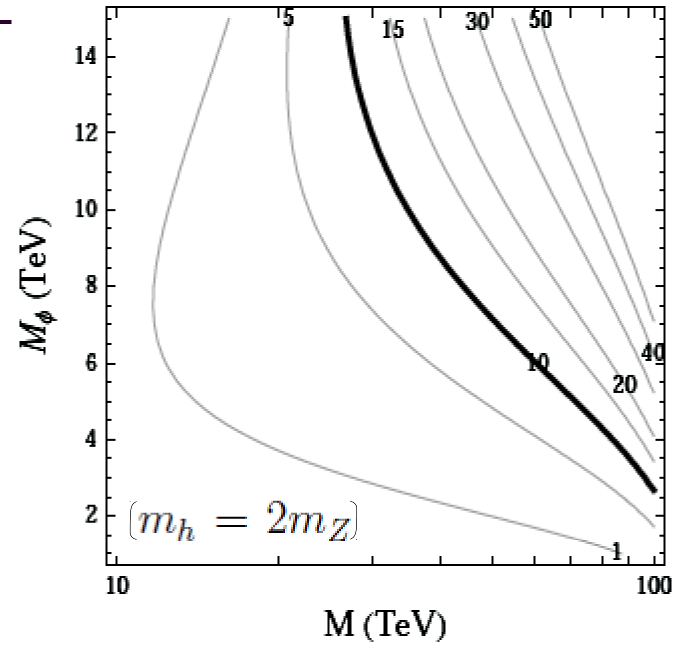
May it be a “sufficient” unification?

[suggested by R. Barbieri, 2010]

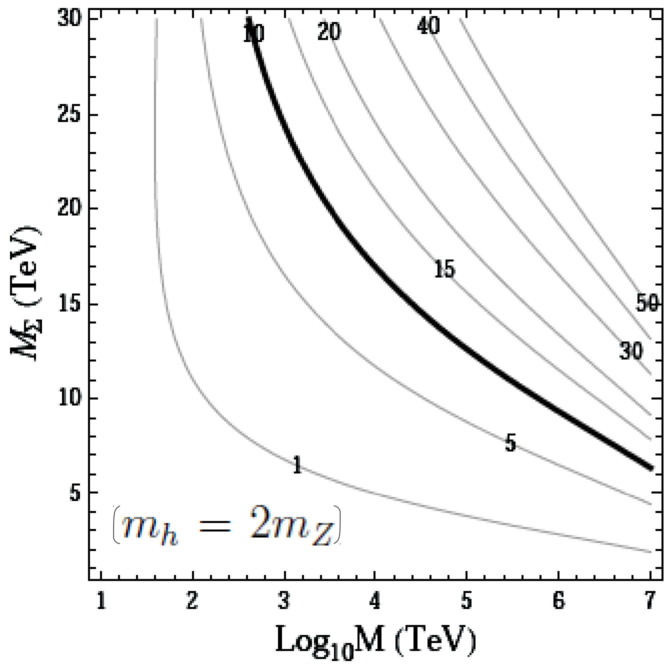
B4) Extra naturalness bounds (tree + loop)

- Gauge ext U(1):

$$M_X \geq 0.40\, M_\phi \qquad +$$



- Gauge ext SU(2):



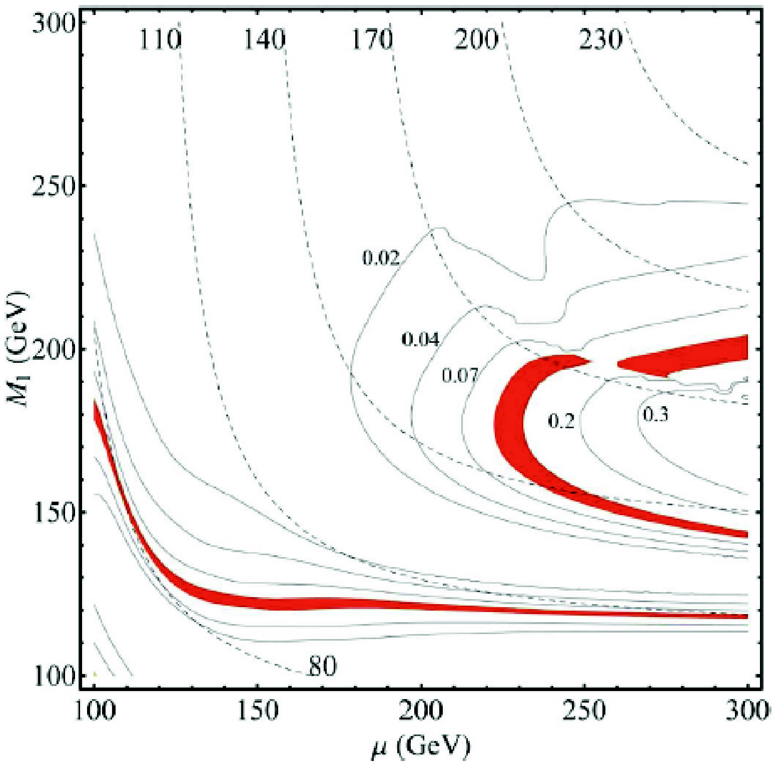
$$+ \qquad M_X \geq 0.22 M_\Sigma$$

- λSUSY: $m_s \lesssim 1$ TeV

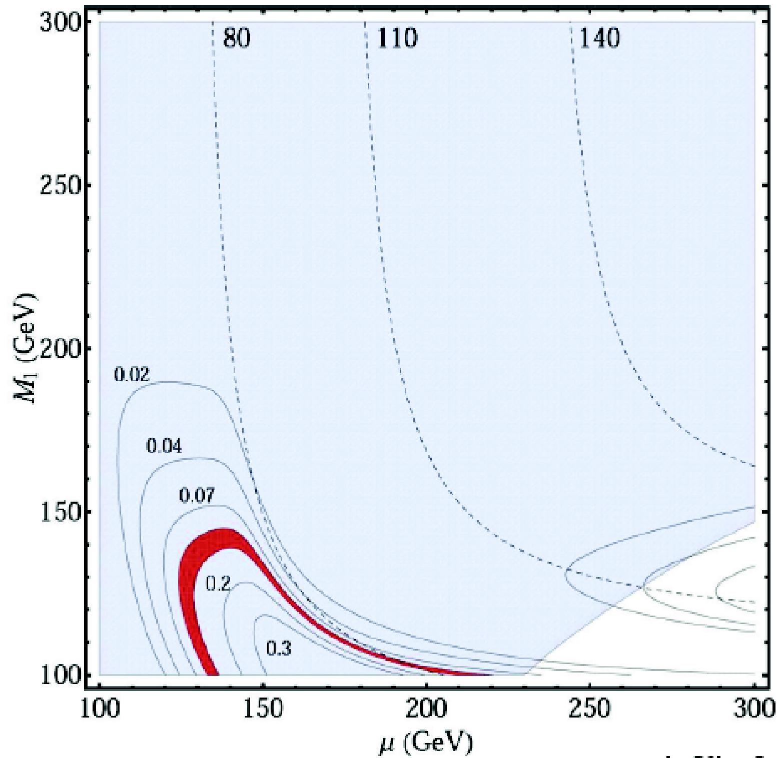
  (but no problem)

B5) DM: other deformations

$M_1 (GeV)$ — M_2 large



$M_2 = 200\ GeV$



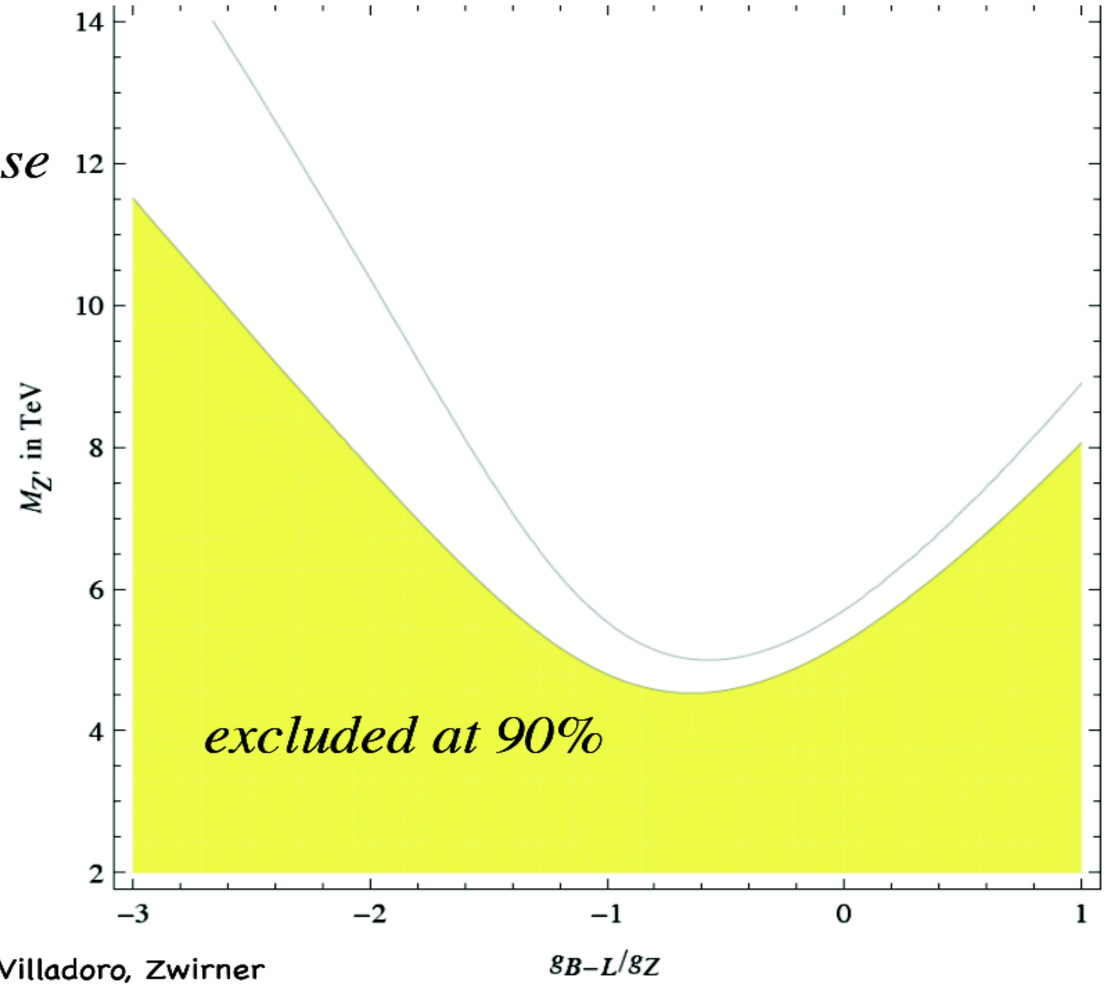
$\mu\ (GeV)$

λSusy: $m_h = 250\ GeV$

dark blu: CDMS now
light blu: "XENON100"

B6) EWPT in U(1) case

extra U(1) case



Salvioni, Strumia, Villadoro, Zwirner