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(in collaboration with:
R. Barbieri, **E. Bertuzzo**, **M. Farina**,
D. Pappadopulo)

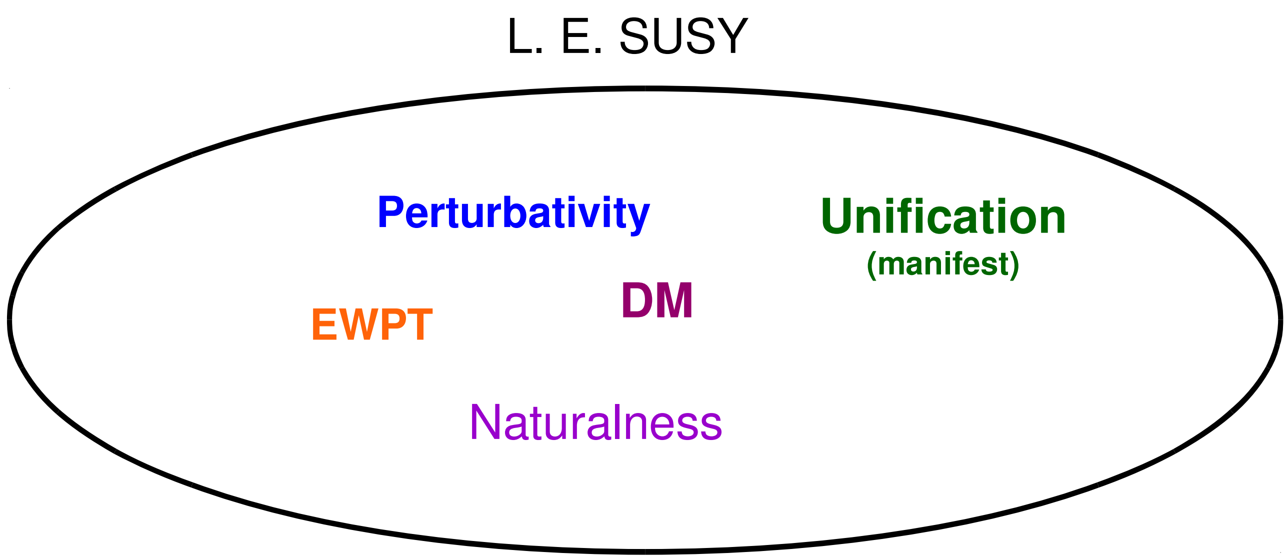
SCUOLA NORMALE SUPERIORE PISA

Naturalness bounds in extensions of the MSSM without a light Higgs boson

Reference: P.L. [1004.1271]; see also R. Barbieri *et al* [1004.2256].

1/6) Motivations

- Test of Low Energy Suspersymmetry: <u>crucial</u> at the LHC



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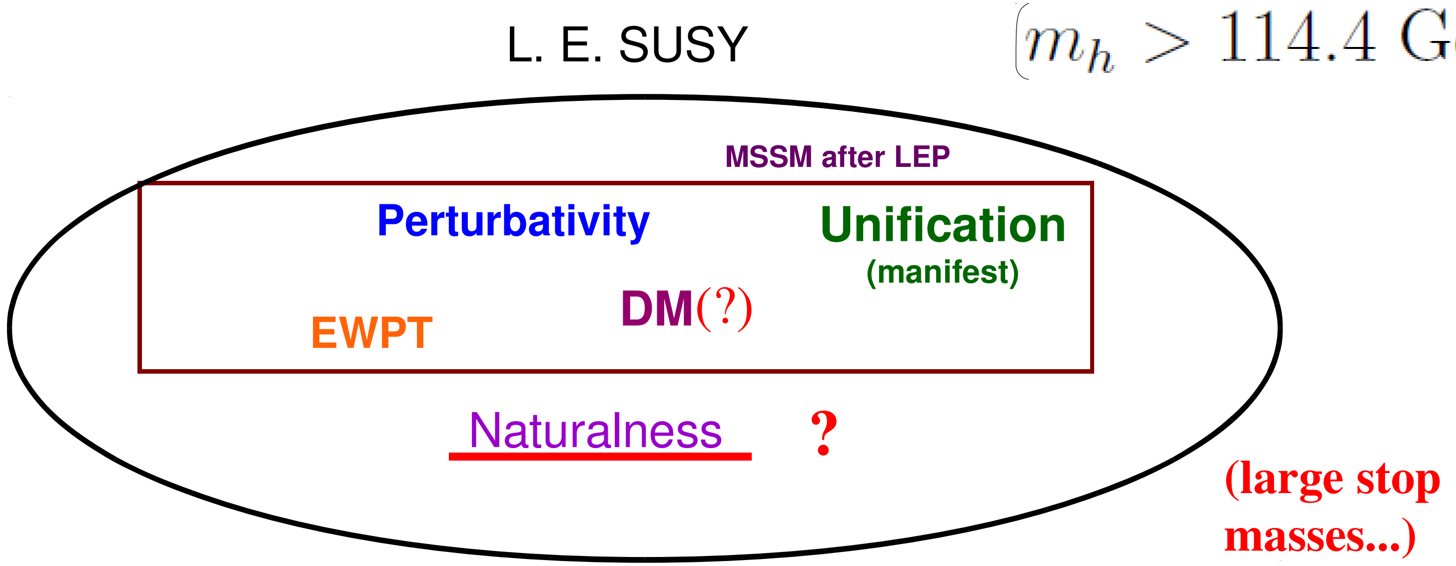
- Test of Low Energy Suspersymmetry: <u>crucial</u> at the LHC
- Status of the MSSM:

$(m_h > 114.4 \text{ GeV})$



$m_h \lesssim 120 \text{ GeV}$

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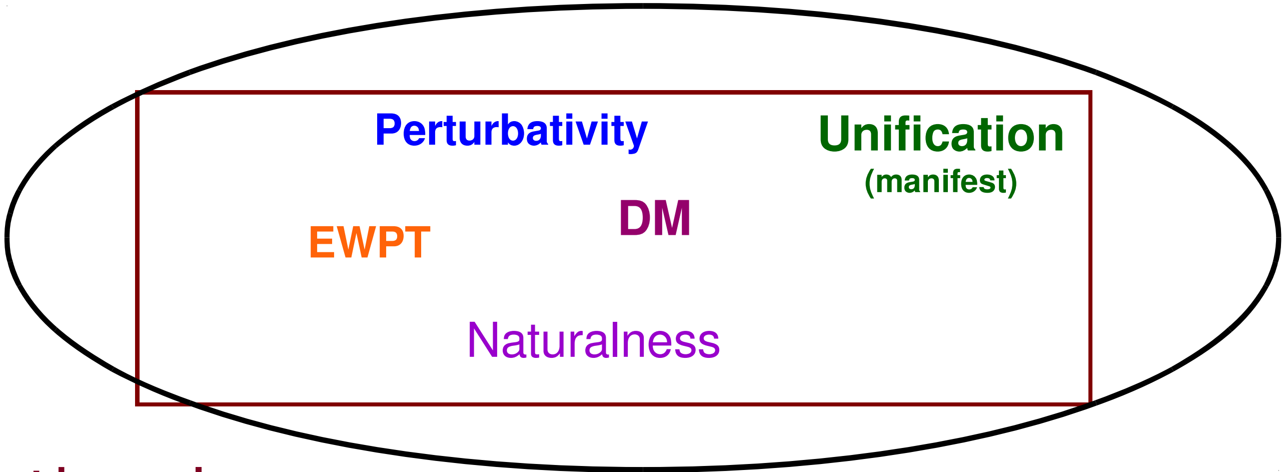
L. E. SUSY $m_h > 114.4 \text{ GeV}$



Conventional extensions: (typically) $m_h \lesssim 150 \text{ GeV}$

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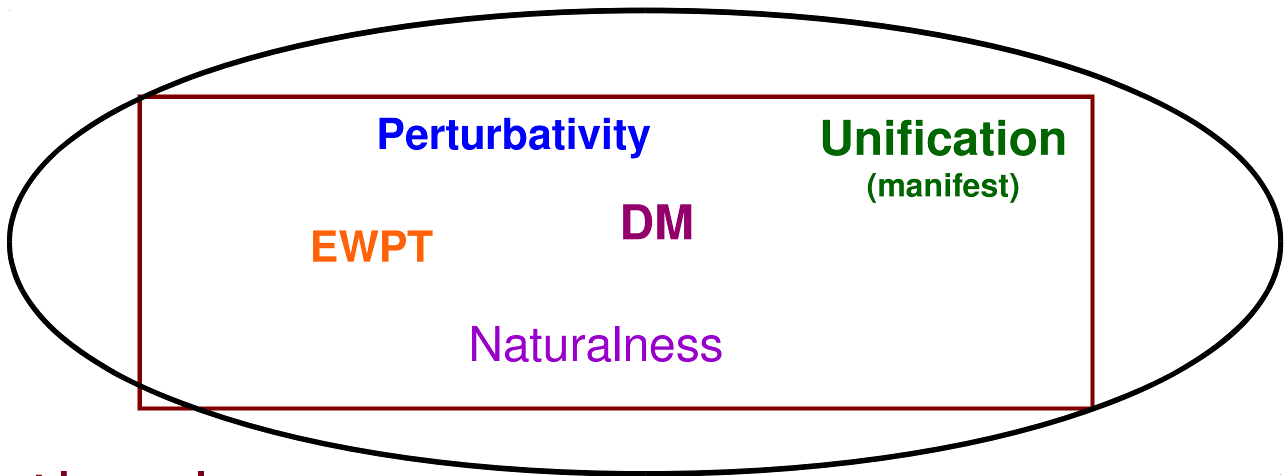

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What if larger at the LHC?

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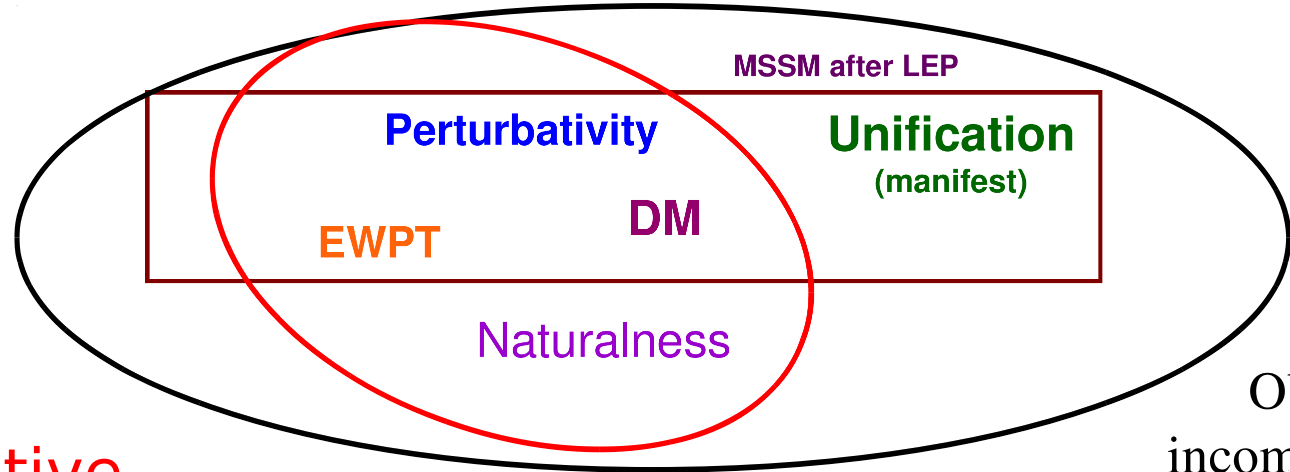

Alternative approach:

($m_h \sim$ 200-300 GeV ?)

Obs: NOT incompatible with unification! (eg: "Fat Higgs" 0311349, 0405267, 0408329, 0504224)

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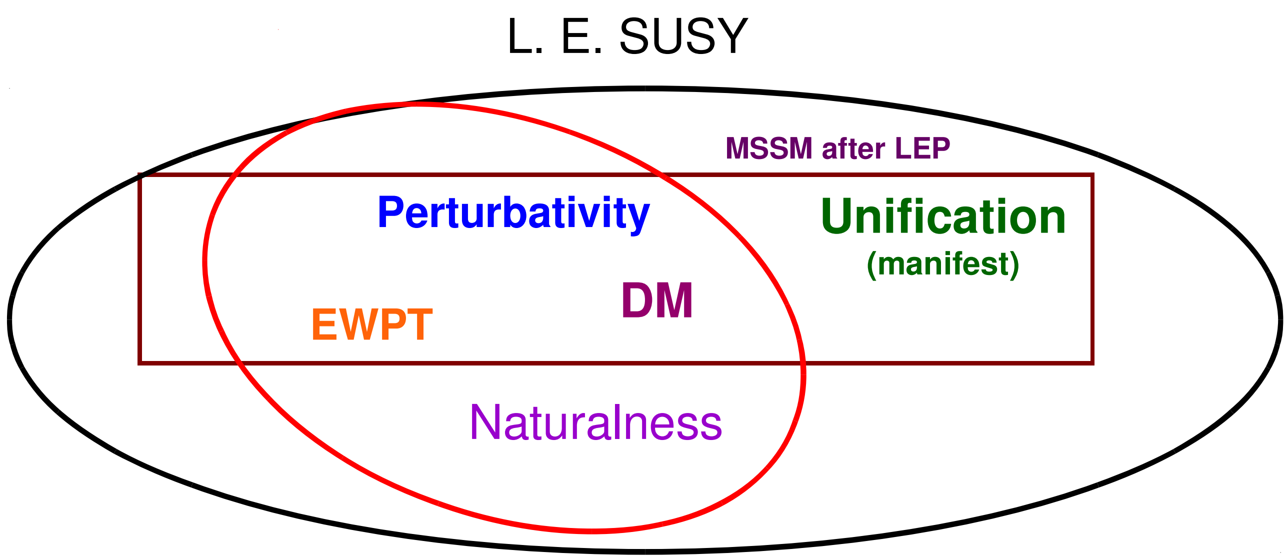

- Scope: <u>comparative study</u> of the simplest models from bottom-up p.o.v. (semipert. at Λ)

2/6) Models

lightest Higgs mass
↔ quartic coupling

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- Gauge ext U(1): $$m_h^2 \leq \left(m_Z^2 + \frac{g_x^2 v^2}{2(1+\frac{M_X^2}{2M_\phi^2})}\right)\cos^2 2\beta$$

  P. Batra, A. Delgado, E. Kaplan, T. M. P. Tait, (2004)

- Gauge ext SU(2): $$m_h^2 \leq m_Z^2 \frac{g'^2 + \eta g^2}{g'^2 + g^2}\cos^2 2\beta \qquad \eta = \frac{1+\frac{g_I^2 M_\Sigma^2}{g^2 M_X^2}}{1+\frac{M_\Sigma^2}{M_X^2}}$$

  P. Batra, A. Delgado, E. Kaplan, T. M. P. Tait, (2004)
  A. Maloney, A. Pierce, J. G. Wacker (2006)

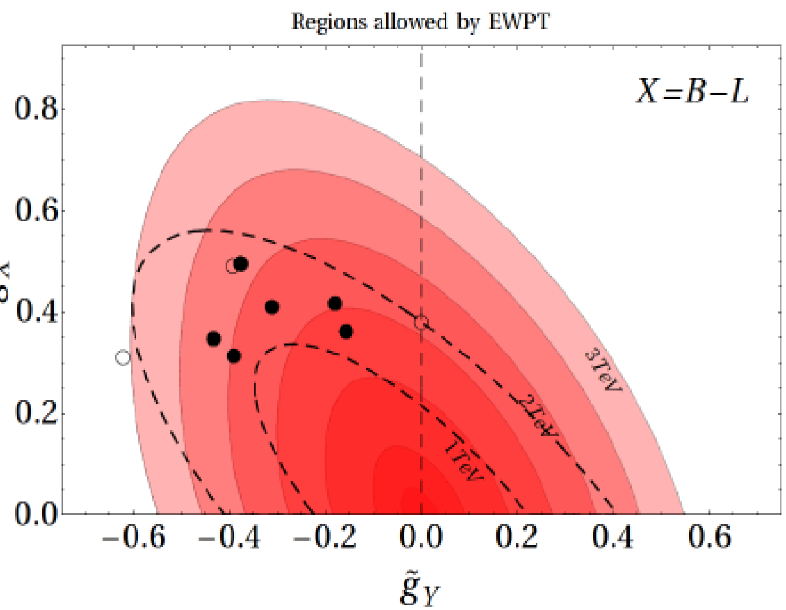
- λSUSY: $$m_h^2 \leq m_Z^2\left(\cos^2 2\beta + \frac{2\lambda^2}{g^2+g'^2}\sin^2 2\beta\right)$$

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

3/6) Electroweak Precision Tests

- Gauge ext U(1): $M_X \gtrsim 5 \text{ TeV}$

$(m_h = 2m_Z)$



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

3/6) Electroweak Precision Tests

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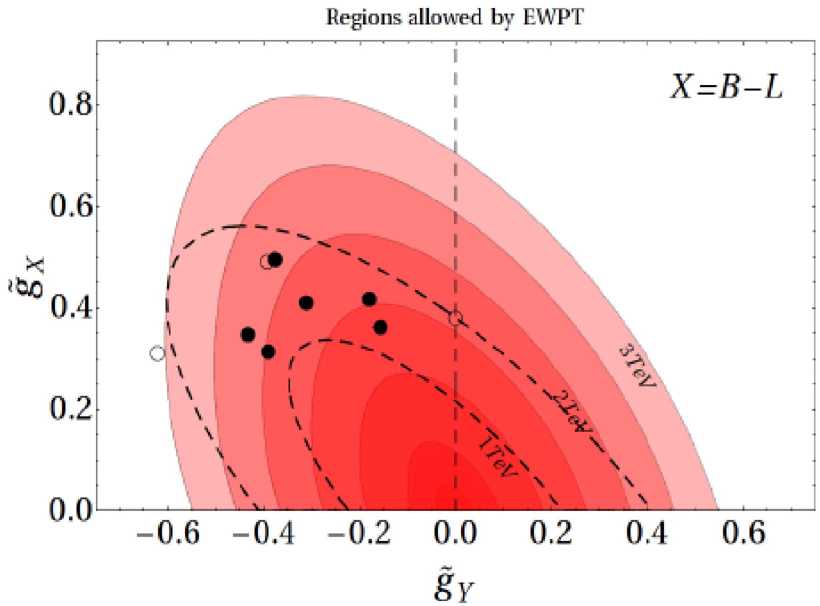
- Gauge ext SU(2): $\dfrac{M_X}{5\ \mathrm{TeV}} \gtrsim \dfrac{g_X}{g_Z}$ (estimate)



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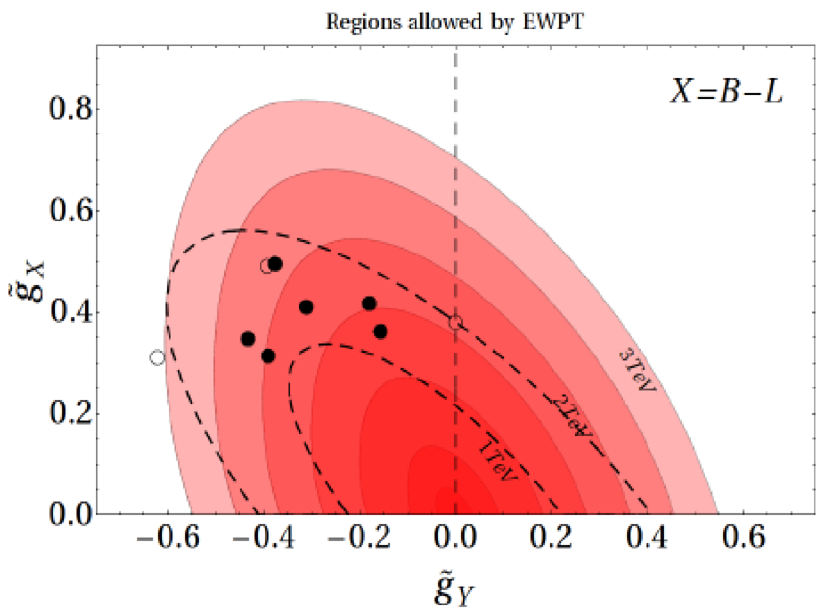

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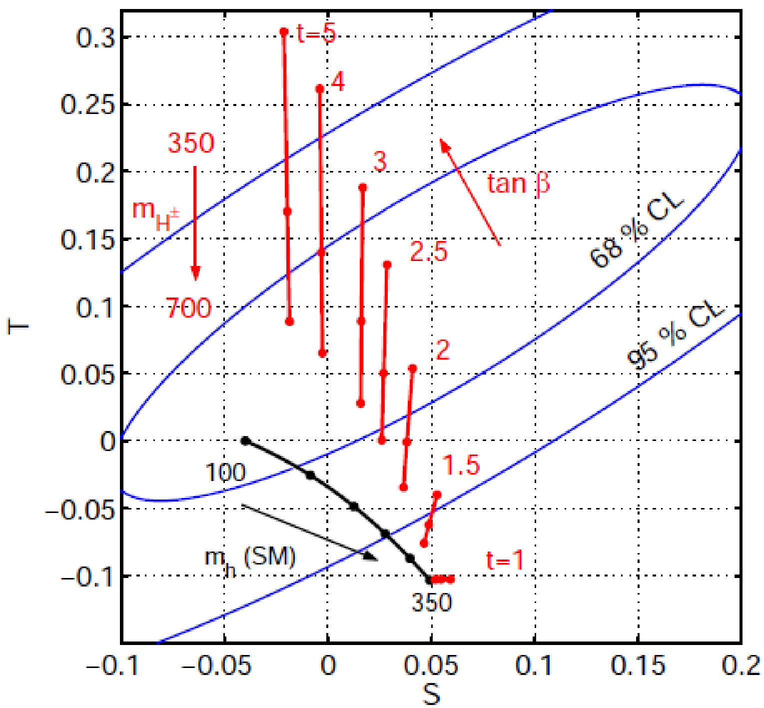


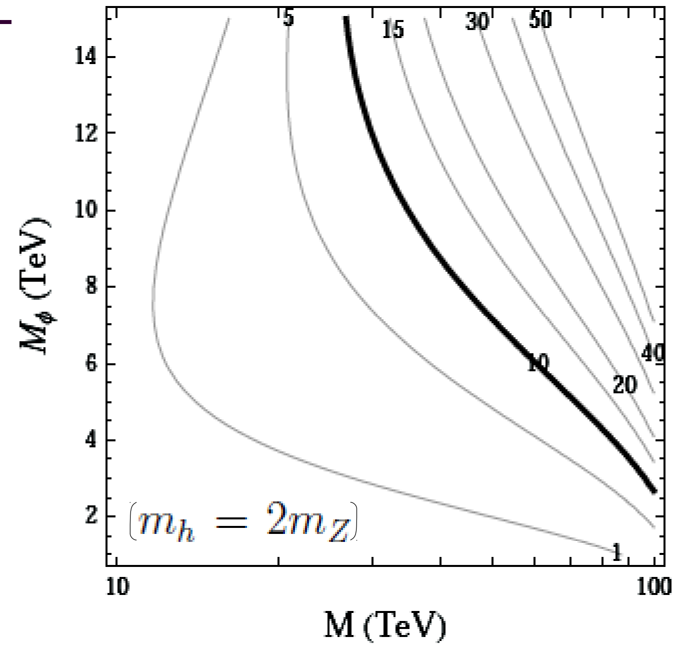
R. Barbieri, L. J. Hall, Y. Nomura, V. S. Rychkov (2007)

4/6) Naturalness bounds: tree + loop

- Gauge ext U(1):

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

+



4/6) Naturalness bounds: tree + loop

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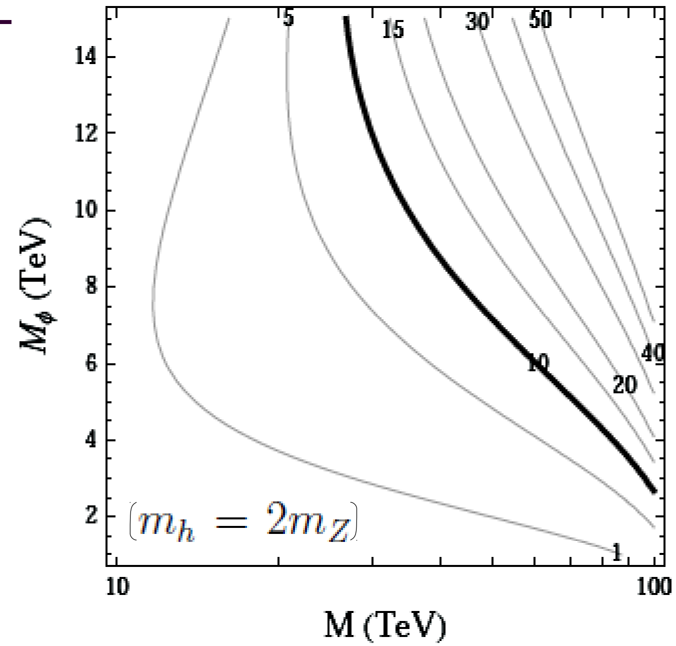
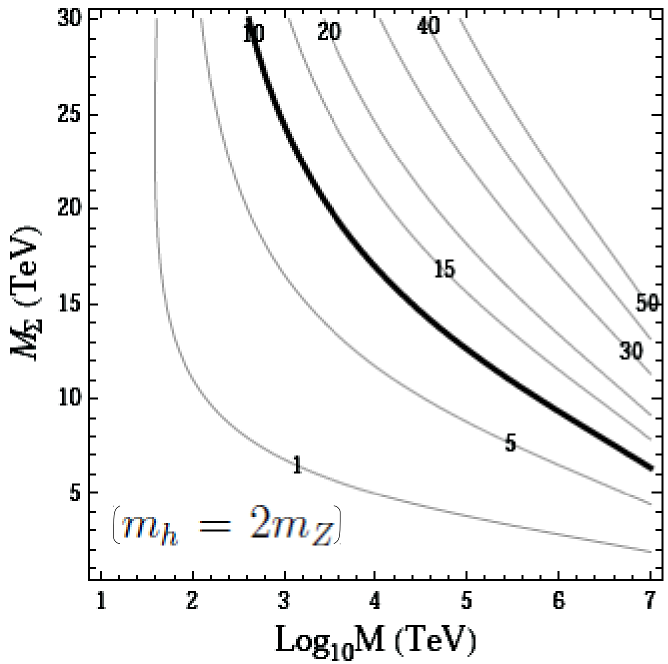


- Gauge ext SU(2):



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

4/6) Naturalness bounds: tree + loop

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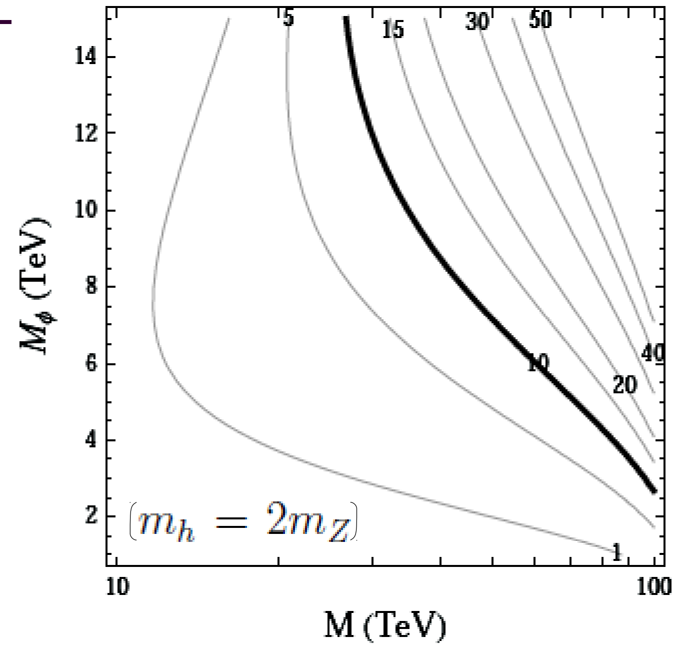

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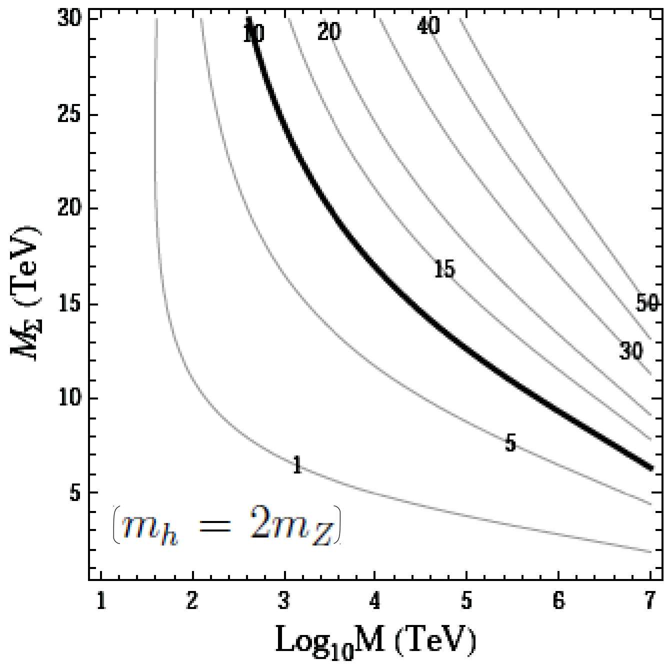


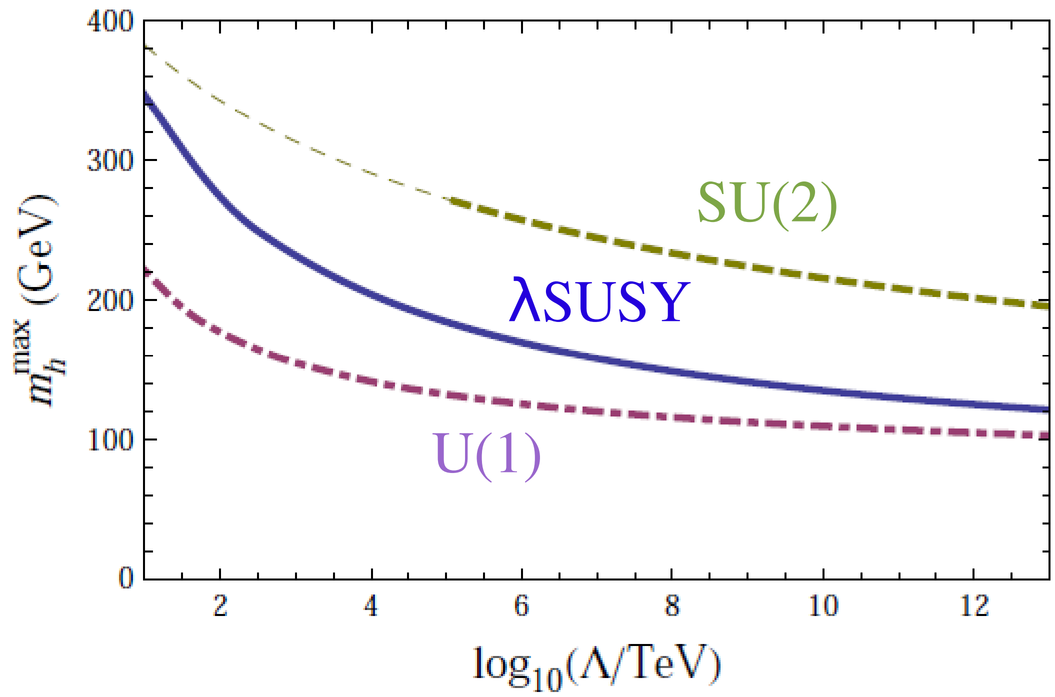
+ $M_X \geq 0.22 M_\Sigma$

- λSUSY: $m_s \lesssim 1$ TeV

(but no problem)

5/6) Conclusions

From a bottom-up point of view, the goal can be achieved.

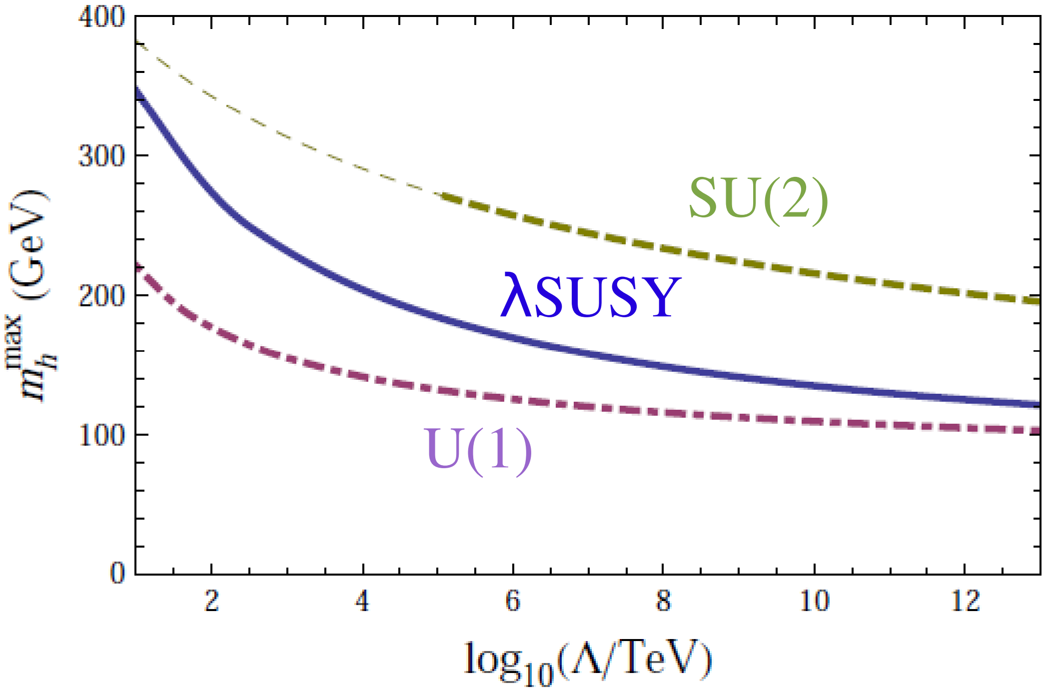


5/6) Conclusions

From a bottom-up point of wiew, the goal can be achieved.

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)

6/6) Phenomenological consequences

in brief (discussed yesterday by R. Barbieri, see [1004.2256])

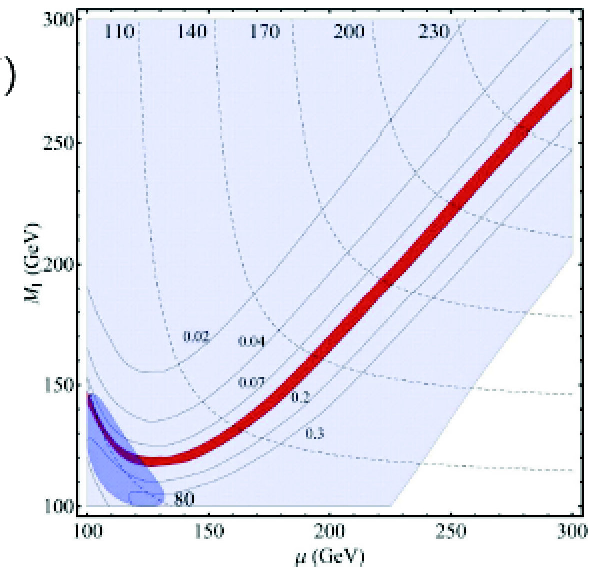
- Peculiar signature

$$\tilde{g} \to t\bar{t}\chi,\ t\bar{b}\chi\ (\bar{t}b\chi),\ b\bar{b}\chi$$
$$h \to ZZ,\ H \to hh,\ hhh$$

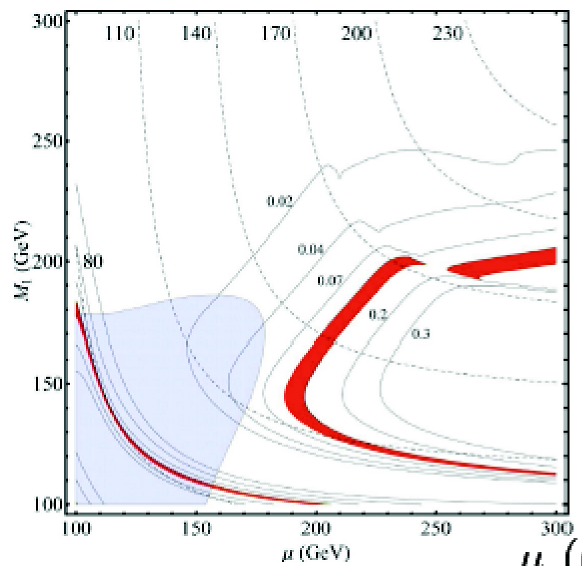
- Dark matter: no 'well temperament' (Ark.-Hamed, Delgado, Giudice [0601041])

M_2 large

$M_1 (GeV)$



MSSM $m_h = 120\ GeV$



$\mu\ (GeV)$

λSusy: $m_h = 200\ GeV$

dark blu: CDMS now
light blu: XENON100

- If $m_{1,2} \sim$ 15-20 TeV → possible to alleviate Flavour (...)

Backup Slides

B1) Flavour problem: hierarchy

Simplified discussion

- Flavour probl.
  (How to suppress corrections from squark mass matrices and trilinears) → -Alignement, -Degeneracy, -Hierarchy

- Only hierarchy: not enough

$$m_{\tilde{q}_{1,2}} \gtrsim 35\ TeV \quad (\text{from } \Delta S = 2)$$

$$m_{\tilde{q}_{1,2}} \gtrsim 800\ TeV \quad (\text{from } \epsilon_K)$$

- If:

$$\delta^{LL} >> \delta^{RR}, \delta^{LR} \ (\text{or } \delta^{RR} >> \delta^{LL}, \delta^{LR})$$

$$\delta^{LL}_{12} \approx \lambda, \quad \frac{|m_1^2 - m_2^2|}{(m_1^2 + m_2^2)/2} \approx \lambda$$

$$\sin \phi_{CP} \approx 0.3$$

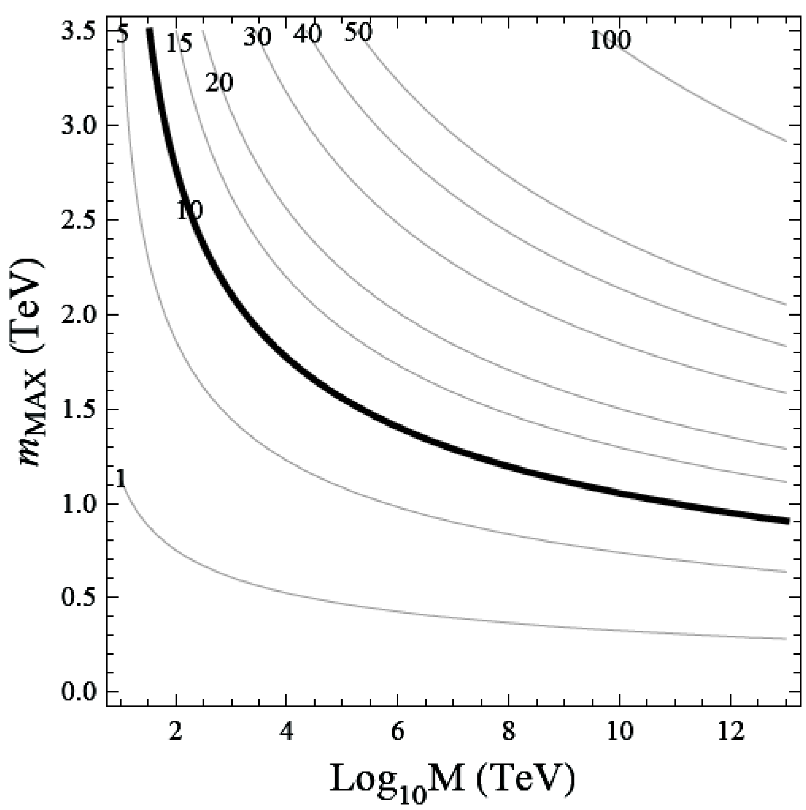
$$\delta_{i3} \approx \frac{m^2_{\tilde{q}_3}}{m^2_{\tilde{q}_{1,2}}}$$

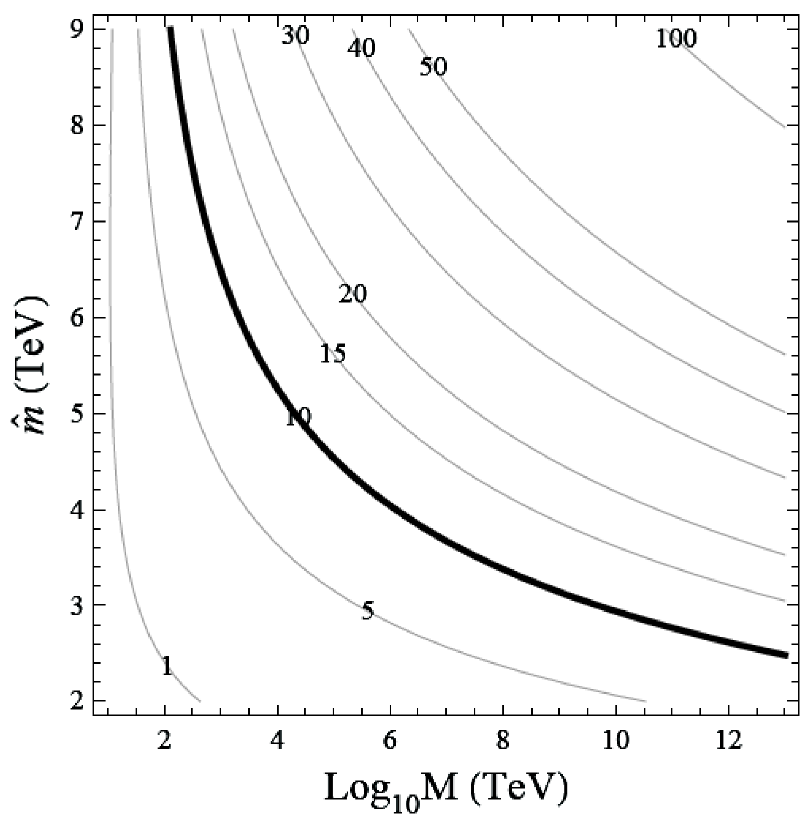
→ Then one can defend:

$$m_{\tilde{q}_{1,2}} \gtrsim 15\ TeV$$

Statement based on the analisys:
G. F. Giudice, M. Nardecchia, A. Romanino, *Hierarchical soft terms and flavour physics*, Nucl Phys B **813** (2009) 156-173.

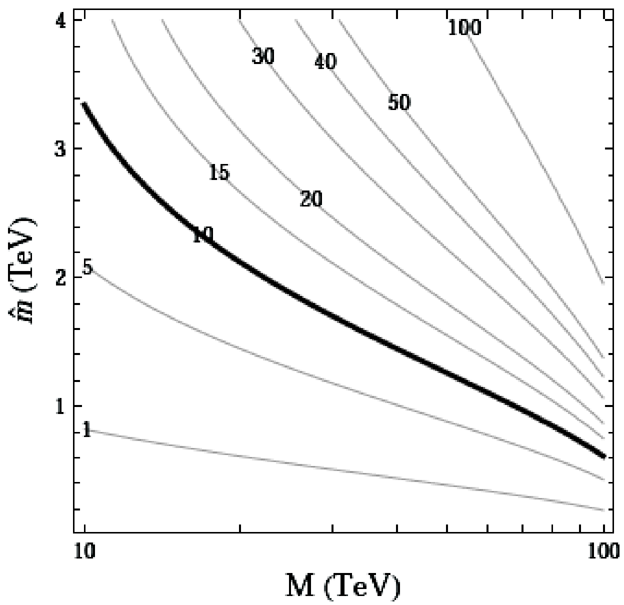
B2) Naturalness in MSSM (1°-2° gen)





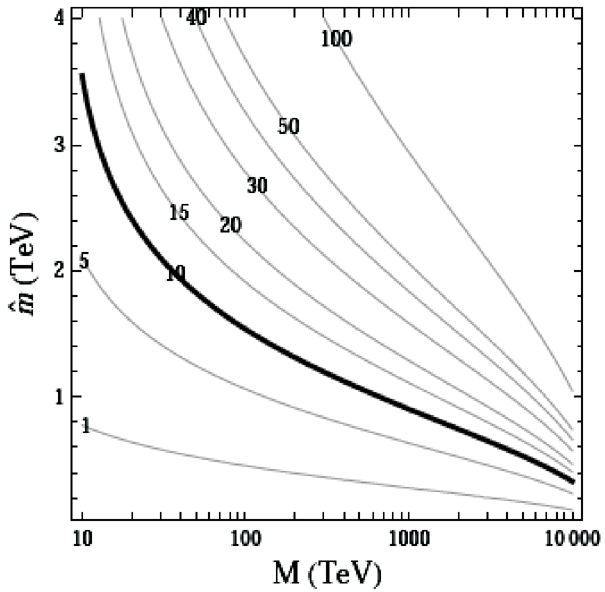
B3) Naturalness in Extended Models

U(1)



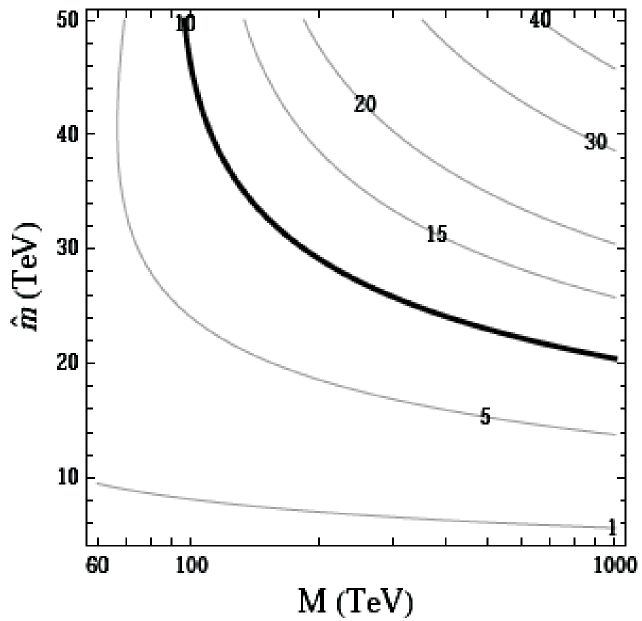
$m_h = 180$ GeV

SU(2)



$m_h = 250$ GeV

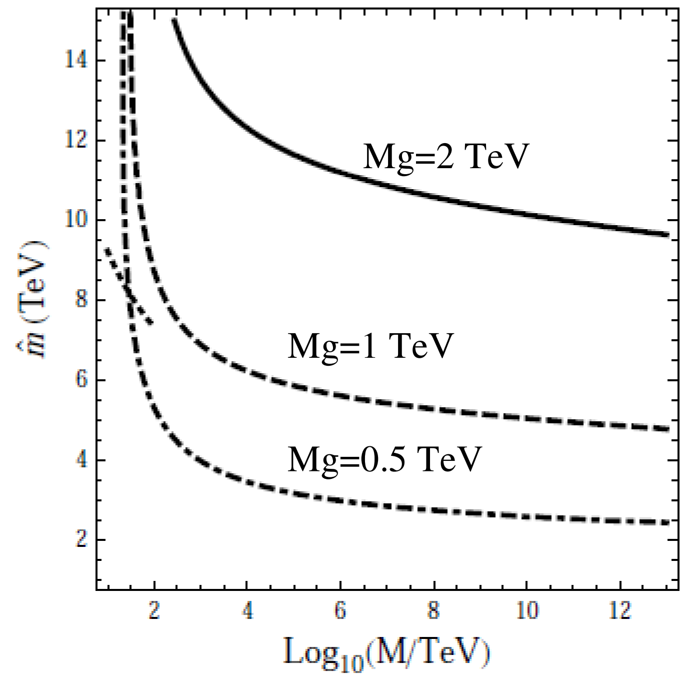
λSUSY

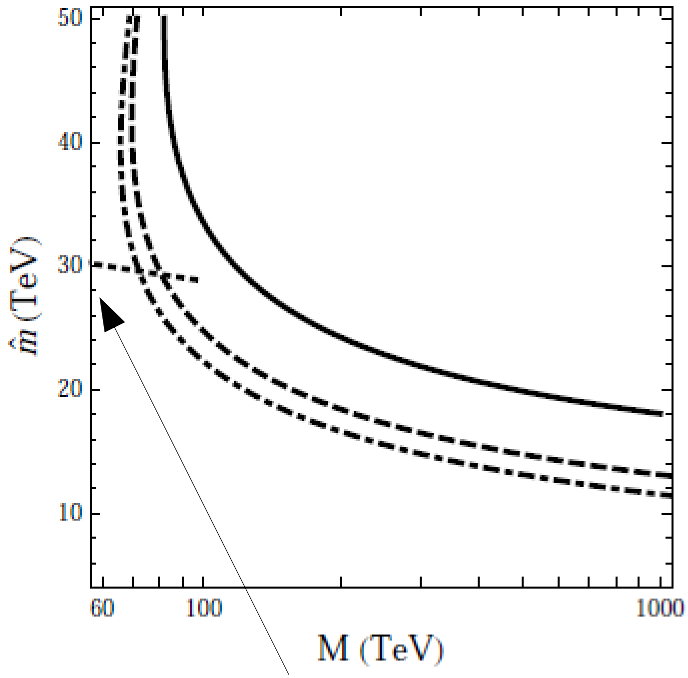


$m_h = 250$ GeV

B4) Colour/EM conservation

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

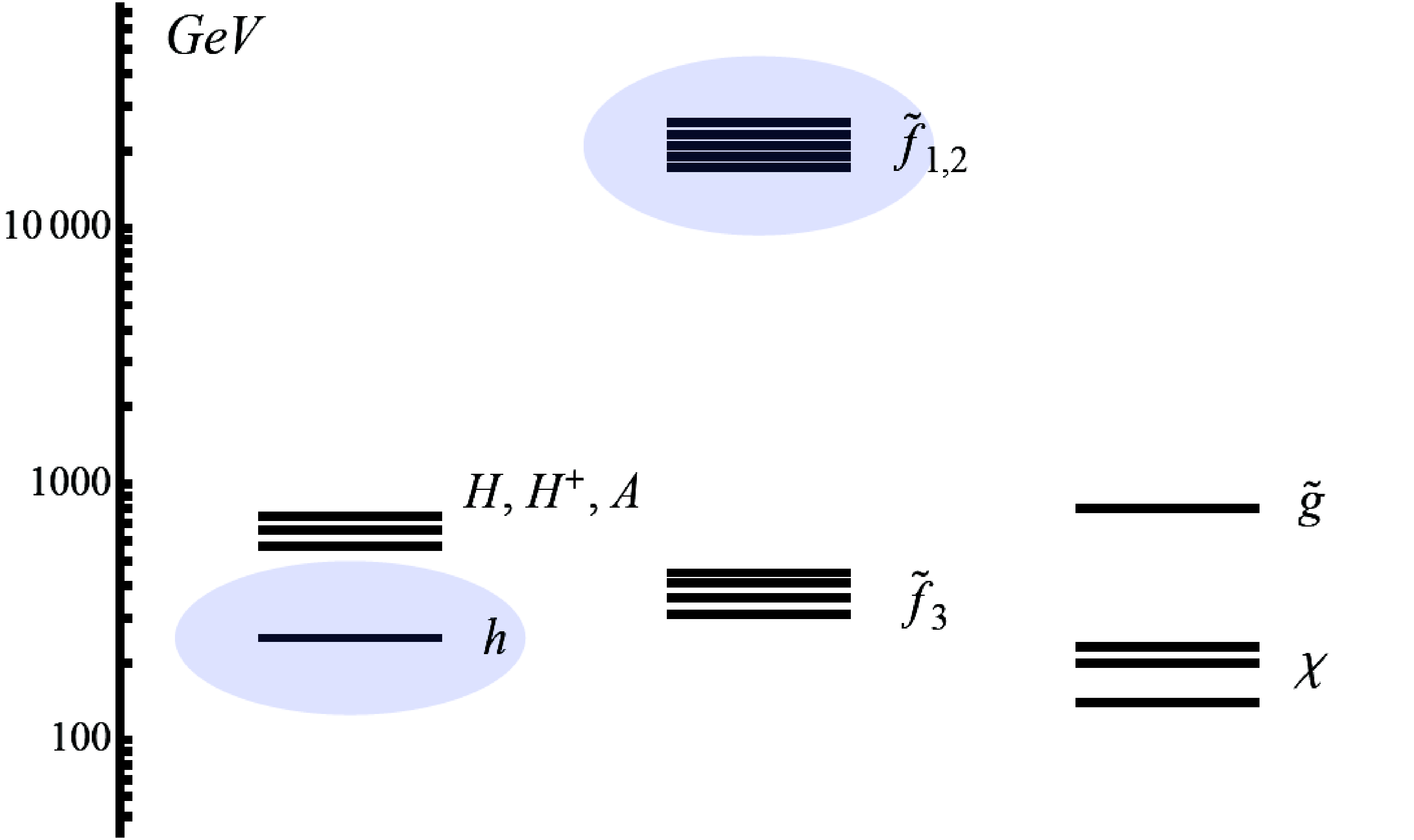




See also: Arkani-Hamed, Murayama [9703259]; Agashe, Graesser [9801446]

B5) "A Non Standard Supersymmetric Spectrum"

R. Barbieri, E. Bertuzzo, M. Farina, P.L., D. Pappadopulo, [1004.2256]



P. Batra, A. Delgado, E. Kaplan, T. M. P. Tait, JHEP 02(2004)043, [arXiv:hep-ph/0309149].

B6) Gauge extension U(1)

- Idea: increase D-term:
  - -New gauge group $U(1)_x$
  - -Extra scalars s, ϕ, ϕ^c

	ϕ	ϕ^c	H_u	H_d	d	u	Q	e	n	L
Y	0	0	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{3}$	$-\frac{2}{3}$	$\frac{1}{6}$	1	0	$-\frac{1}{2}$
$X = \frac{L-B}{2} + X_\phi$	q	$-q$	0	0	$\frac{1}{6}$	$\frac{1}{6}$	$-\frac{1}{6}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$
$Y + X$	q	$-q$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	0	$\frac{1}{2}$	$-\frac{1}{2}$	0

- Potential for scalars: $V = V_{MSSM} + V_{H\phi} + V_\phi$

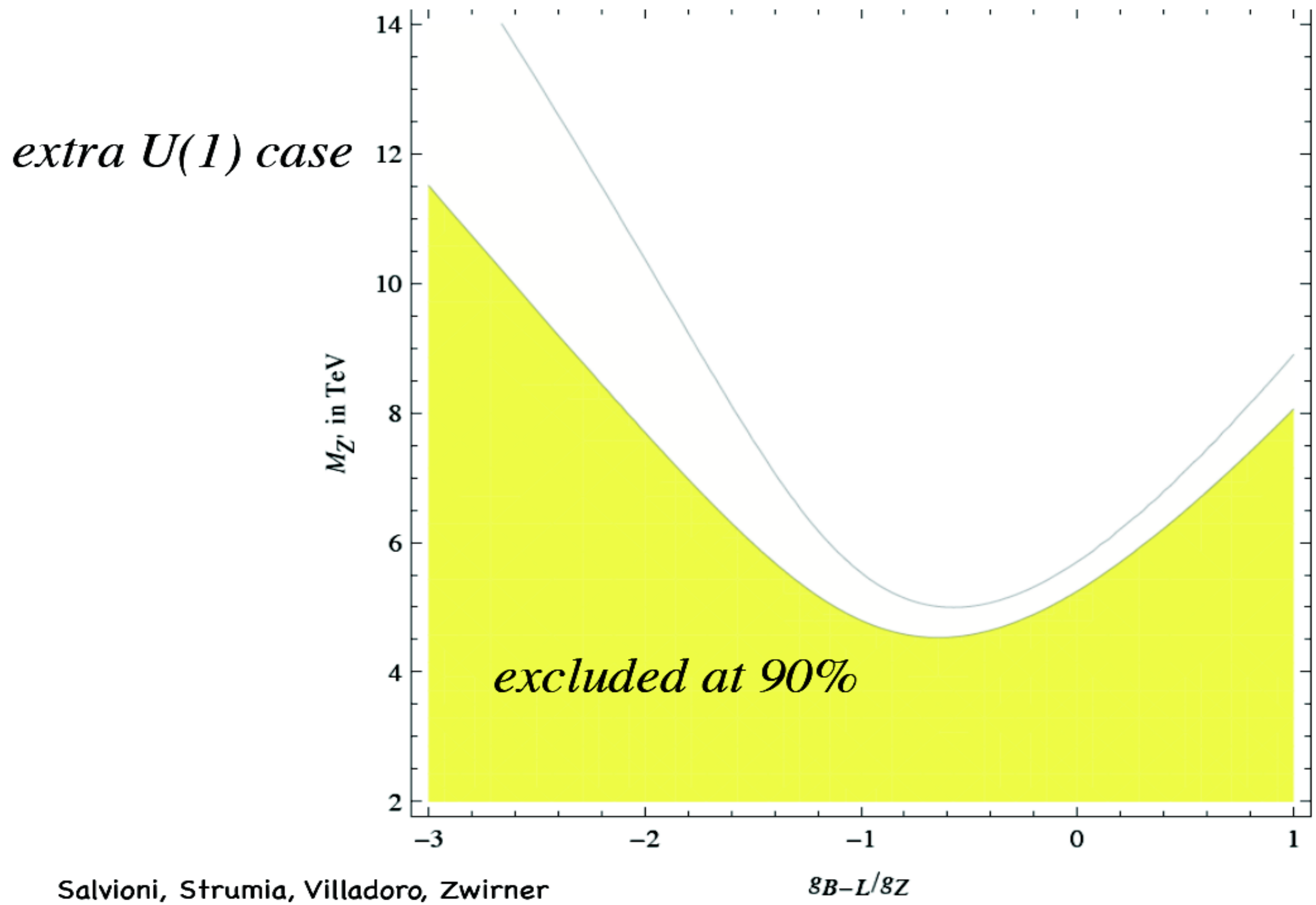
new D-term

$$V_{H\phi} = \frac{1}{2} g_x^2 \left(\frac{1}{2}|H_u|^2 - \frac{1}{2}|H_d|^2 + q|\phi|^2 - q|\phi^c|^2 + .. \right)^2$$

$$V_\phi = \lambda^2 |\phi|^2 |\phi^c|^2 - B(\phi\phi^c + h.c.) + M_{(\phi)}^2 |\phi|^2 + M_{(\phi^c)}^2 |\phi^c|^2$$

(- Superpotential $W = \lambda\, s\, (\phi\phi^c - w^2)$ + soft terms)

B7) EWPT in U(1) case



Salvioni, Strumia, Villadoro, Zwirner

P. Batra, A. Delgado, E. Kaplan, T. M. P. Tait, JHEP 02(2004)043, [arXiv:hep-ph/0309149].

B8) Gauge extension SU(2)

- Gauge group: $SU(2)_I \times SU(2)_{II} \times U(1)_Y$
- Fields: Σ $(2,2)$, s (singlet), MSSM fields charged under $SU(2)_I$
- Potential of scalar sector: $V = V_{H\Sigma} + V_\Sigma$

$$\begin{aligned} V_{H\Sigma} \;=\; & \mu_u^2|H_u|^2 + \mu_d^2|H_d|^2 + \mu_3^2(H_uH_d + h.c.) \\ & + \frac{1}{2}g'^2\left(\frac{1}{2}|H_u|^2 - \frac{1}{2}|H_d|^2 + ..\right)^2 + \frac{1}{2}g_{II}^2\sum_a\left(\mathrm{Tr}\left[\Sigma T^a\Sigma^+\right]\right)^2 \\ & + \frac{1}{2}g_I^2\sum_a\left(\mathrm{Tr}\left[\Sigma^+T^a\Sigma\right] + H_u^+T^aH_u + H_d^+T^aH_d + ..\right)^2 \end{aligned}$$