Loop suppressed EWSB

and naturally heavy superpartners

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Indiana University, Bloomington
and
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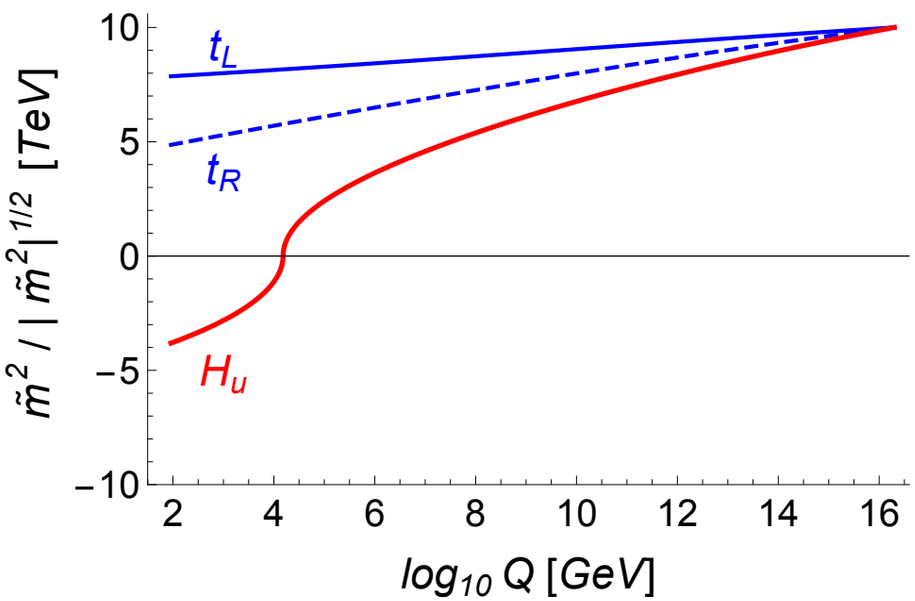
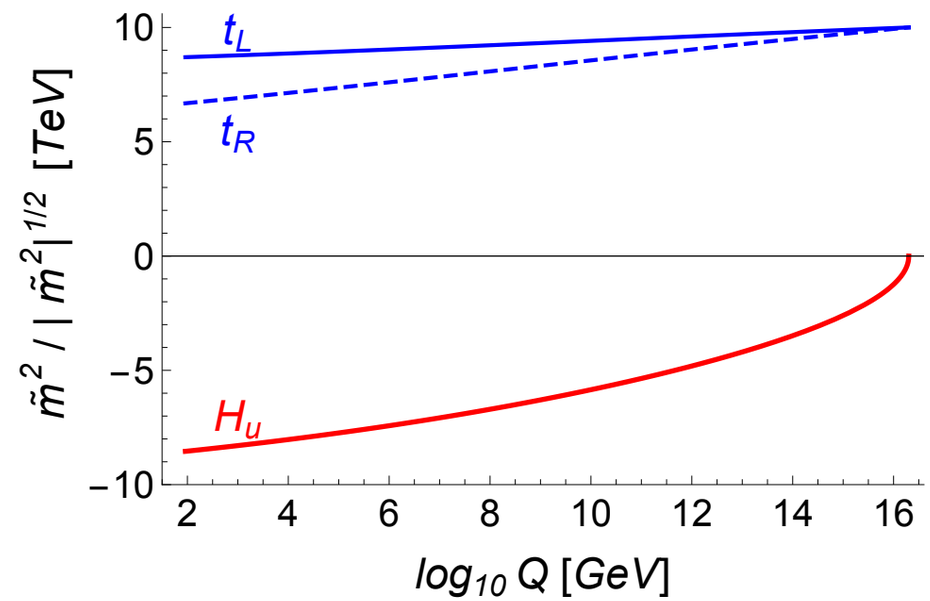
CERN, Charting the Unknown, August 11, 2016

Motivation

Elegant EWSB in SUSY

Radiatively driven EWSB (by stops or gluino):





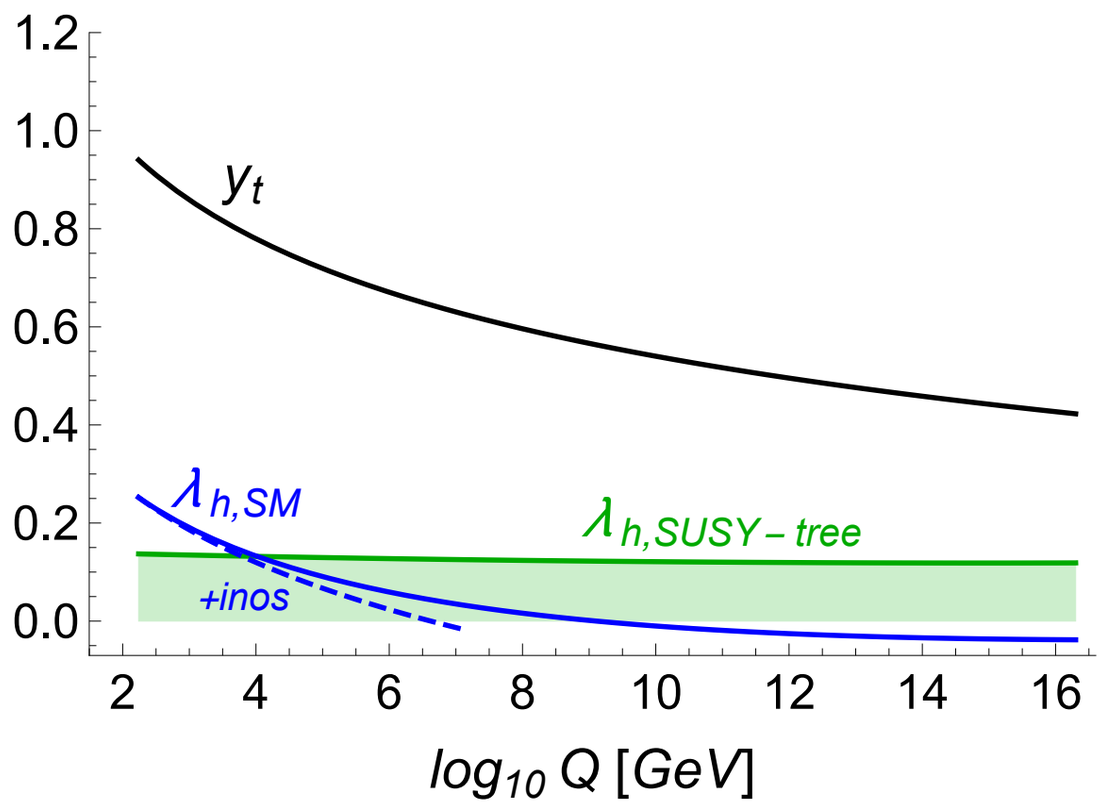
$$\beta_{\tilde{m}^2_{H_u}} = \frac{3y_t^2}{8\pi^2}\left(\tilde{m}^2_{H_u} + \tilde{m}^2_{t_L} + \tilde{m}^2_{t_R}\right) + \ldots$$

$$\tilde{m}^2_{H_u} \simeq -m^2_{\tilde{t}_{1,2}}$$

preference for EW symmetry to be broken

Situation in generic SUSY models

Assuming no significant new contributions to Higgs quartic coupling at $Q = m_{\tilde{t}_{1,2}}$ (this also ignores possible contributions from mixing in the stop sector):

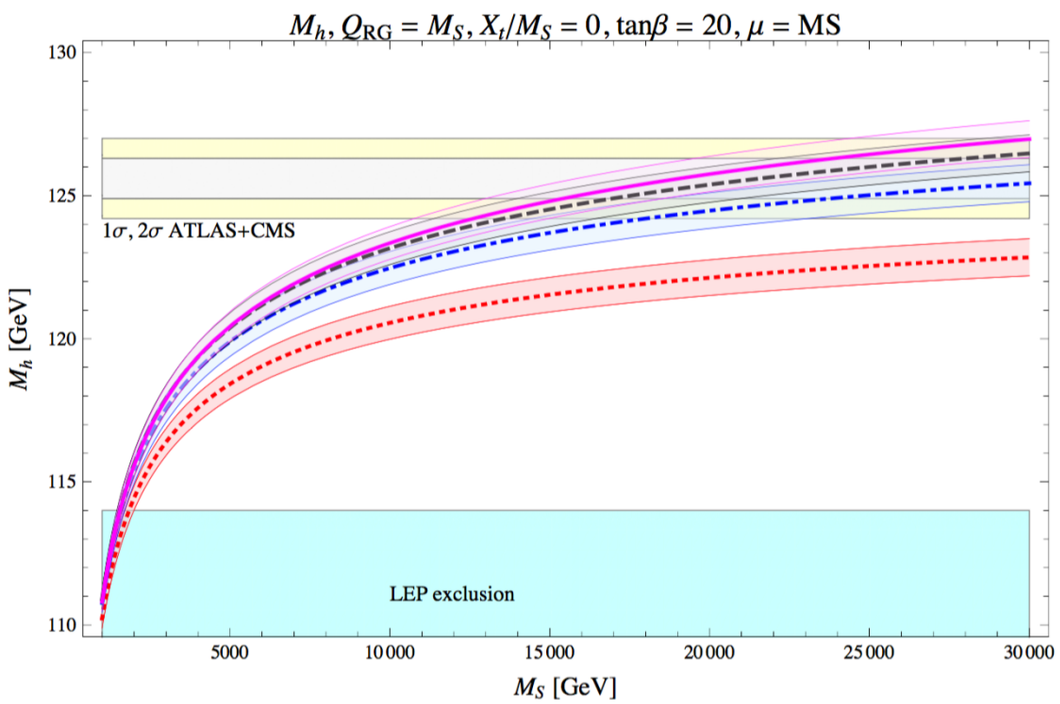


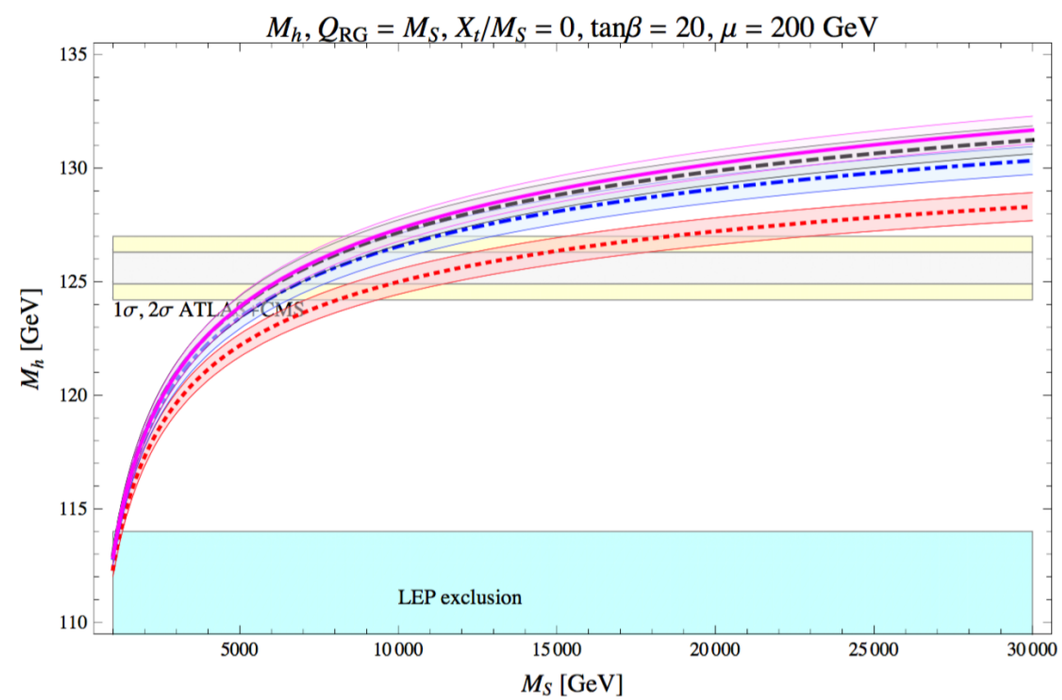
$$\lambda_{\mathbf{h,SUSY-tree}} = \frac{\mathbf{g_2^2 + g_Y^2}}{\mathbf{4}}$$

the stop masses should be ~10 TeV

Higgs mass in MSSM

P. Draper, G. Lee and C. Wagner, arXiv:1312.5743





effective potential calculation

also uses previous results:

G. F. Giudice and A. Strumia, arXiv:1108.6077

G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori and A. Strumia, arXiv:1205.6497

D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio and A. Strumia, arXiv:1307.3536

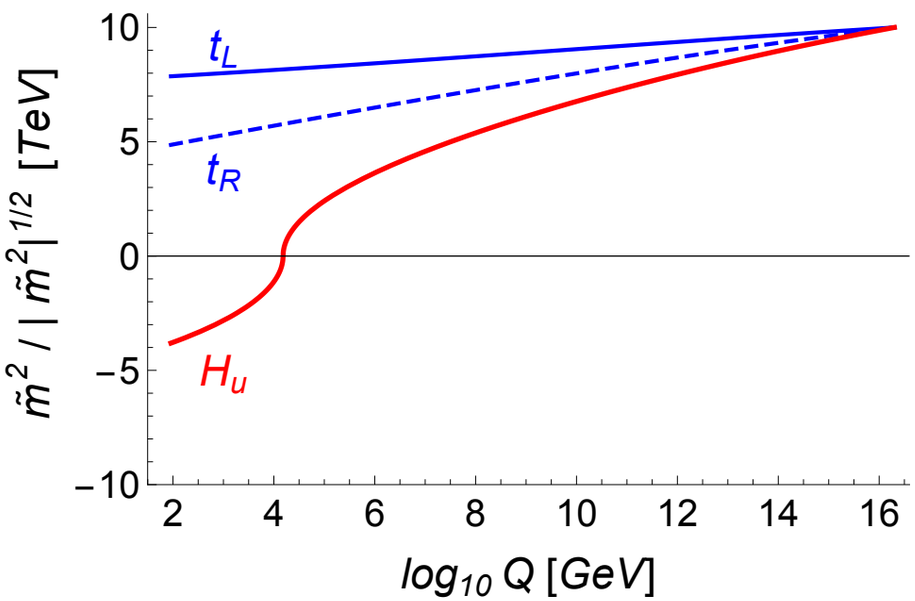
M. Binger, hep-ph/0408240

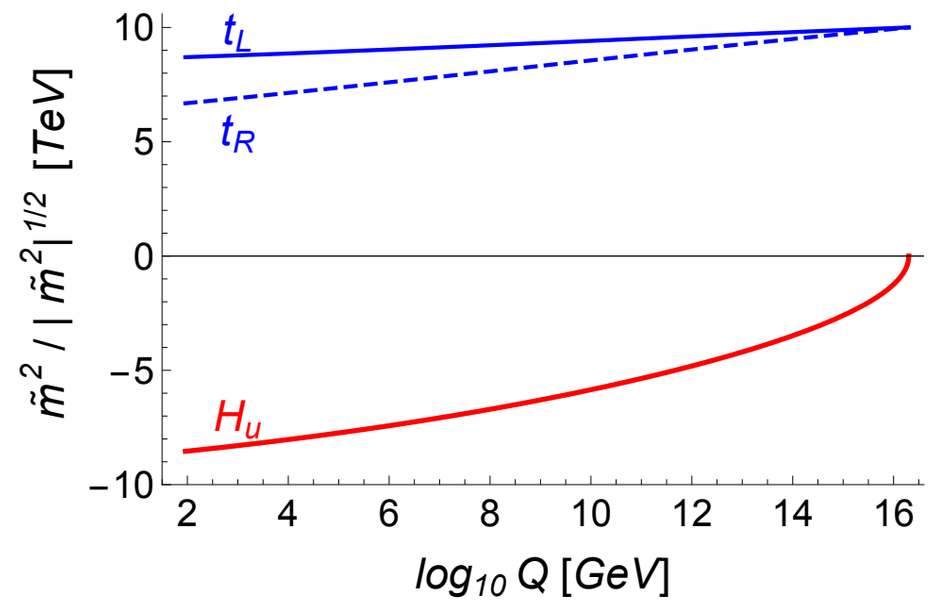
Higgs requires 7 - 18 TeV stops (assuming no mixing)

depending on the μ term and gaugino masses

Elegant EWSB in SUSY

Radiatively driven EWSB (by stops or gluino):





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$$\tilde{m}^2_{H_u} \simeq -m^2_{\tilde{t}_{1,2}}$$

but EW scale seems to be highly tuned

~0.01% for a high scale mediation

~0.1% from 1st decade of RG running

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Gluino drives stops up which in turn drive $\tilde{m}^2_{H_u}$ down

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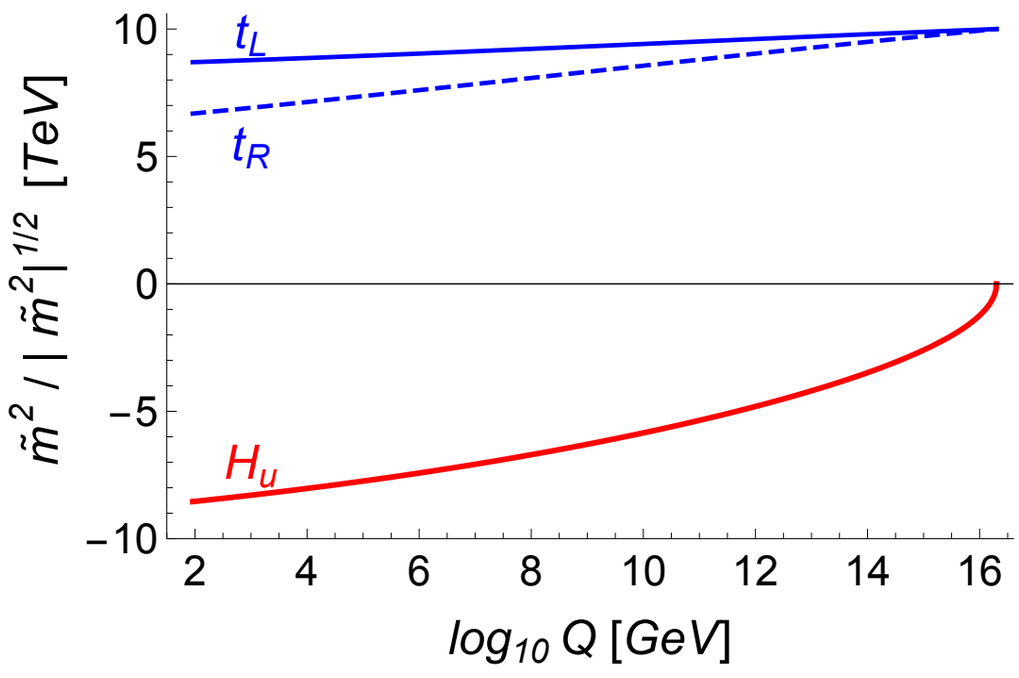
On a positive note:

The heavier the gluino is,
the more preferred low mediation scale is
and sooner we will be building a collider to search for messengers :)

No-go?

While gluino just prefers lower mediation scale, it seems impossible to have simultaneously:

- **10 TeV stops**
- **al least 1 decade of RG running from the mediation scale**
- **not contributing way too much to** $\tilde{m}^2_{H_u}$



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- models/par. space with as light stops as possible and **additional sources of the Higgs mass,** for example:
  - models with large A-terms - to maximize the Higgs mass
  - singlet extensions $\lambda S H_u H_d$
  - ...

with finite number of ugly (well motivated) steps
we can build a model for anything…. but

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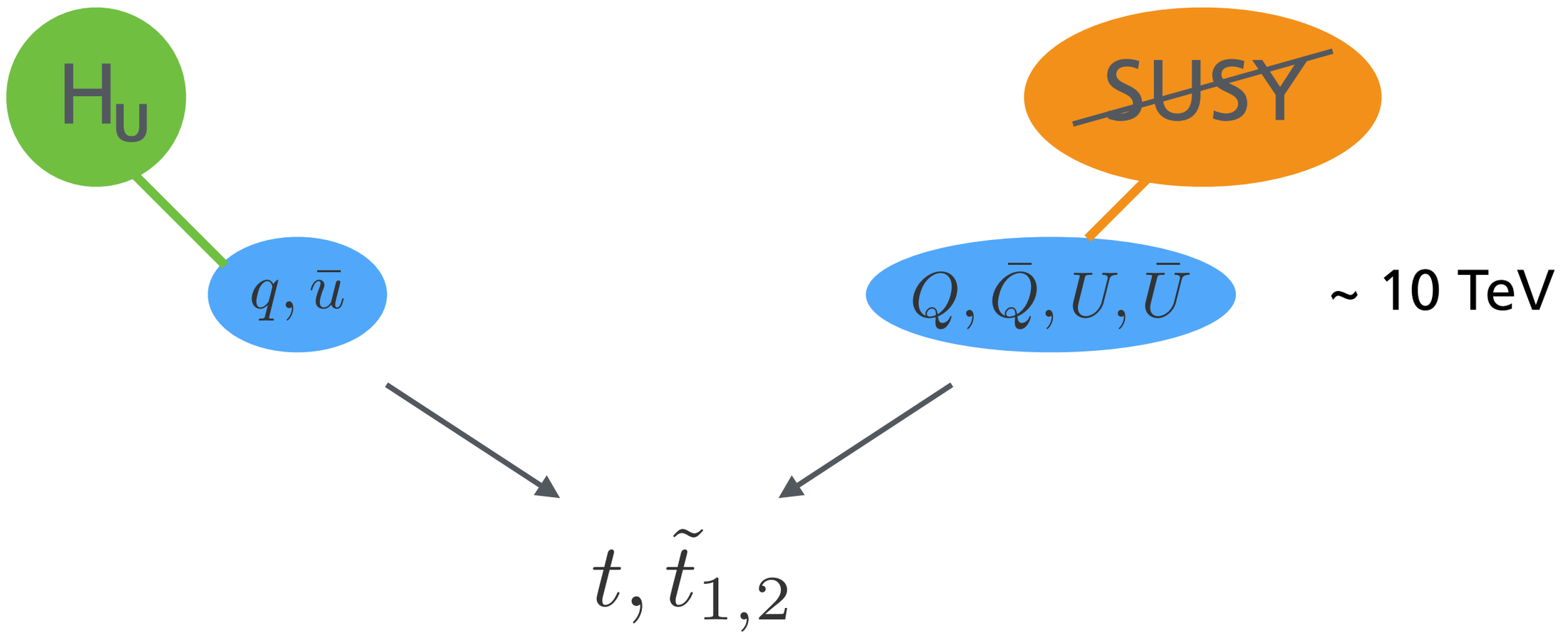
why would nature be like that just to increase the Higgs mass?

- natural in a different way - **crazy**[N] ideas

[N] "crazy" is a necessary ingredient of any good idea

Loophole

Stops are mixtures of states that couple to the Higgs but don't have large soft masses and states with large soft masses that don't couple to the Higgs



stops get large soft masses without ever contributing in RG evolution

“Instant” stop masses

Top sector of the model

Superpotential related to top quark:

$$W \supset \lambda q \bar{u} H_u + m_q q \bar{Q} + m_u U \bar{u} + M_Q Q \bar{Q} + M_U U \bar{U}$$

$f \supset \{q,\ \bar{u}\}$
up-type quark doublets and singlets

$\bar{F} \supset \{\bar{Q},\ U\}$
conjugate quantum numbers to f

$F \supset \{Q,\ \bar{U}\}$
another copy of up-type quark doublets and singlets

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explicit mass terms are general allowed by SM symmetries,
Yukawa couplings are not;
other Yukawa couplings can be small and thus neglected
or
not allowed by a simple U(1) if explicit masses originate from vevs of SM singlets:

$$m_{q,u} = \lambda_{q,u} \langle S_m \rangle \qquad M_{Q,U} = \lambda_{Q,U} \langle S_M \rangle$$

e.g.:

$Q_F = +1$

$Q_{\bar{F}} = -1$

$Q_{S_m} = +1$

the same charges can be extended to whole families

Top quark and fermion partners

Superpotential related to top quark:

$$W \supset \lambda q \bar{u} H_u + m_q q \bar{Q} + m_u U \bar{u} + M_Q Q \bar{Q} + M_U U \bar{U}$$

Fermion mass matrix:

$$(q \;\; Q \;\; U)\, M_F \begin{pmatrix} \bar{u} \\ \bar{Q} \\ \bar{U} \end{pmatrix} = (q \;\; Q \;\; U) \begin{pmatrix} \lambda v_u & m_q & 0 \\ 0 & M_Q & 0 \\ m_u & 0 & M_U \end{pmatrix} \begin{pmatrix} \bar{u} \\ \bar{Q} \\ \bar{U} \end{pmatrix}$$

Mass eigenvalues:

$$m_{top} \simeq \lambda v_u M^2/(m^2 + M^2)$$

$$m_{t_{2,3}} \simeq (M^2 + m^2)^{1/2}$$

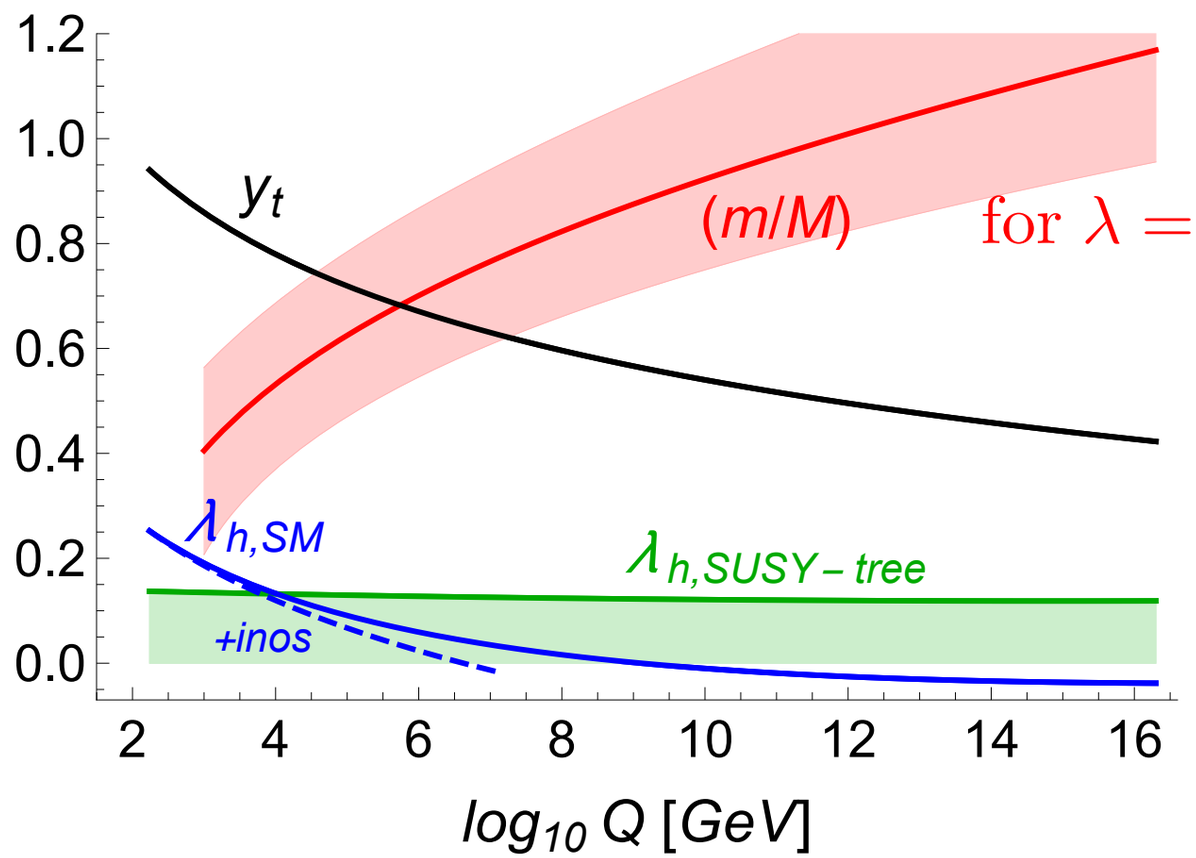
Simplification:

$$m_q = m_u \equiv m$$
$$M_Q = M_U \equiv M$$

Top quark and top partners

Top quark mass fixes m/M:

$$W \supset \lambda q \bar{u} H_u + m_q q \bar{Q} + m_u U \bar{u} + M_Q Q \bar{Q} + M_U U \bar{U}$$



for $\lambda = 1 \pm 0.1$ at $Q = (M^2 + m^2)^{1/2}$

$$m_{top} \simeq \lambda v_u M^2/(m^2 + M^2) \longrightarrow y_t = \lambda M^2/(m^2 + M^2)$$

Stops and stop partners

Scalar mass-squared matrix in the basis $(q, Q, U, \bar{u}^*, \bar{Q}^*, \bar{U}^*)$:

$$M_S^2 = \begin{pmatrix} M_F M_F^\dagger & 0 \\ 0 & M_F^\dagger M_F \end{pmatrix} + \text{diag}\left(\tilde{m}_q^2, \tilde{m}_Q^2, \tilde{m}_U^2, \tilde{m}_{\bar{u}}^2, \tilde{m}_{\bar{Q}}^2, \tilde{m}_{\bar{U}}^2\right)$$

$$M_F = \begin{pmatrix} \lambda v_u & m_q & 0 \\ 0 & M_Q & 0 \\ m_u & 0 & M_U \end{pmatrix}$$

Eigenvalues (neglecting λv_u):

$$m_{\tilde{t}_{1,2}}^2 = \frac{1}{2}\tilde{M}^2 - \frac{1}{2}\sqrt{\tilde{M}^4 - 4(M^2\tilde{m}_f^2 + m^2\tilde{m}_F^2 + \tilde{m}_f^2\tilde{m}_F^2)}$$

$$m_{\tilde{t}_{3,4}}^2 = \frac{1}{2}\tilde{M}^2 + \frac{1}{2}\sqrt{\tilde{M}^4 - 4(M^2\tilde{m}_f^2 + m^2\tilde{m}_F^2 + \tilde{m}_f^2\tilde{m}_F^2)}$$

$$\tilde{M}^2 \equiv M^2 + m^2 + \tilde{m}_f^2 + \tilde{m}_F^2$$

$$m_{\tilde{t}_{5,6}}^2 = M^2 + m^2 + \tilde{m}_{\bar{F}}^2$$

Simplification:

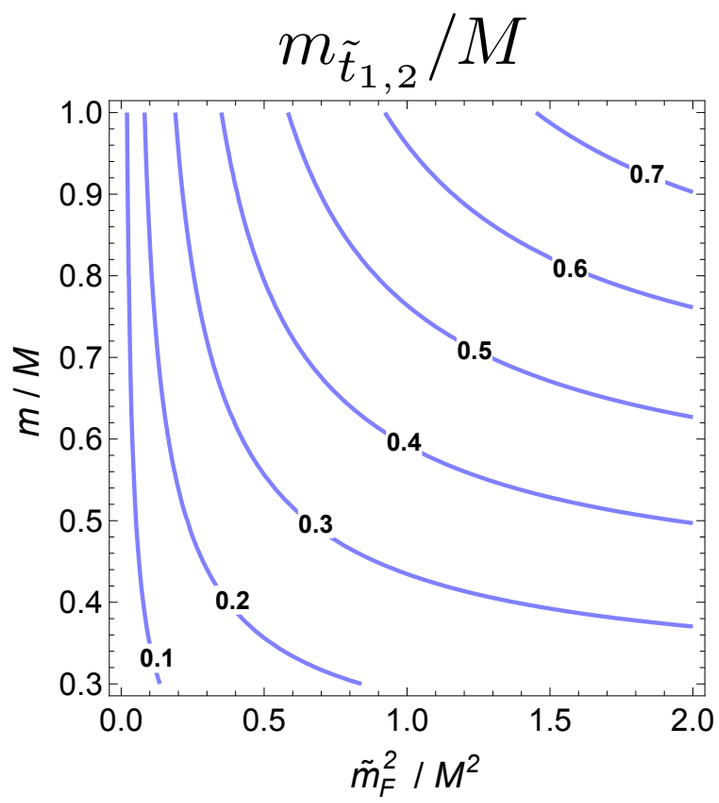
$$\tilde{m}_q^2 = \tilde{m}_{\bar{u}}^2 \equiv \tilde{m}_f^2$$

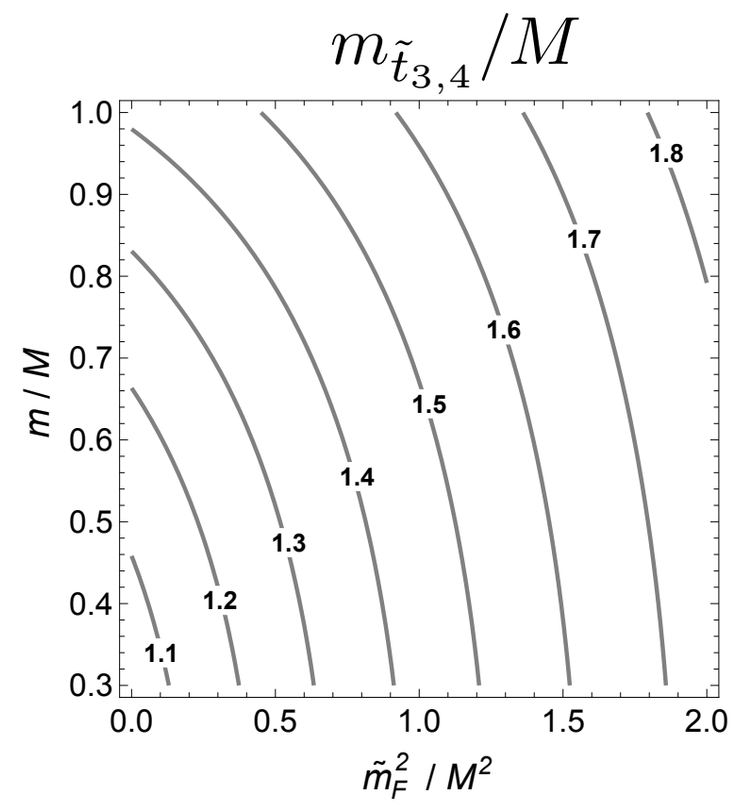
$$\tilde{m}_Q^2 = \tilde{m}_{\bar{U}}^2 \equiv \tilde{m}_F^2$$

$$\tilde{m}_U^2 = \tilde{m}_{\bar{Q}}^2 \equiv \tilde{m}_{\bar{F}}^2$$

Stops and stop partners

for $\tilde{m}_f^2 = 0$:





Eigenvalues:

$$m^2_{\tilde{t}_{1,2}} = \frac{1}{2}\tilde{M}^2 - \frac{1}{2}\sqrt{\tilde{M}^4 - 4(M^2\tilde{m}_f^2 + m^2\tilde{m}_F^2 + \tilde{m}_f^2\tilde{m}_F^2)}$$

$$m^2_{\tilde{t}_{3,4}} = \frac{1}{2}\tilde{M}^2 + \frac{1}{2}\sqrt{\tilde{M}^4 - 4(M^2\tilde{m}_f^2 + m^2\tilde{m}_F^2 + \tilde{m}_f^2\tilde{m}_F^2)}$$

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$$m^2_{\tilde{t}_{5,6}} = M^2 + m^2 + \tilde{m}^2_{\bar{F}}$$

Simplification:

$$\tilde{m}_q^2 = \tilde{m}_{\bar{u}}^2 \equiv \tilde{m}_f^2$$

$$\tilde{m}_Q^2 = \tilde{m}_{\bar{U}}^2 \equiv \tilde{m}_F^2$$

$$\tilde{m}_U^2 = \tilde{m}_{\bar{Q}}^2 \equiv \tilde{m}_{\bar{F}}^2$$

All scalars acquire masses even if $\tilde{m}_f^2 = 0$!

RG evolution to O(10 TeV) scale

In the RG evolution from an arbitrary scale,

$$\beta_{\tilde{m}^2_{H_u}} = \frac{3\lambda^2}{8\pi^2}\left(\tilde{m}^2_{H_u} + \tilde{m}^2_q + \tilde{m}^2_{\bar{u}}\right) + \cdots \simeq 0$$

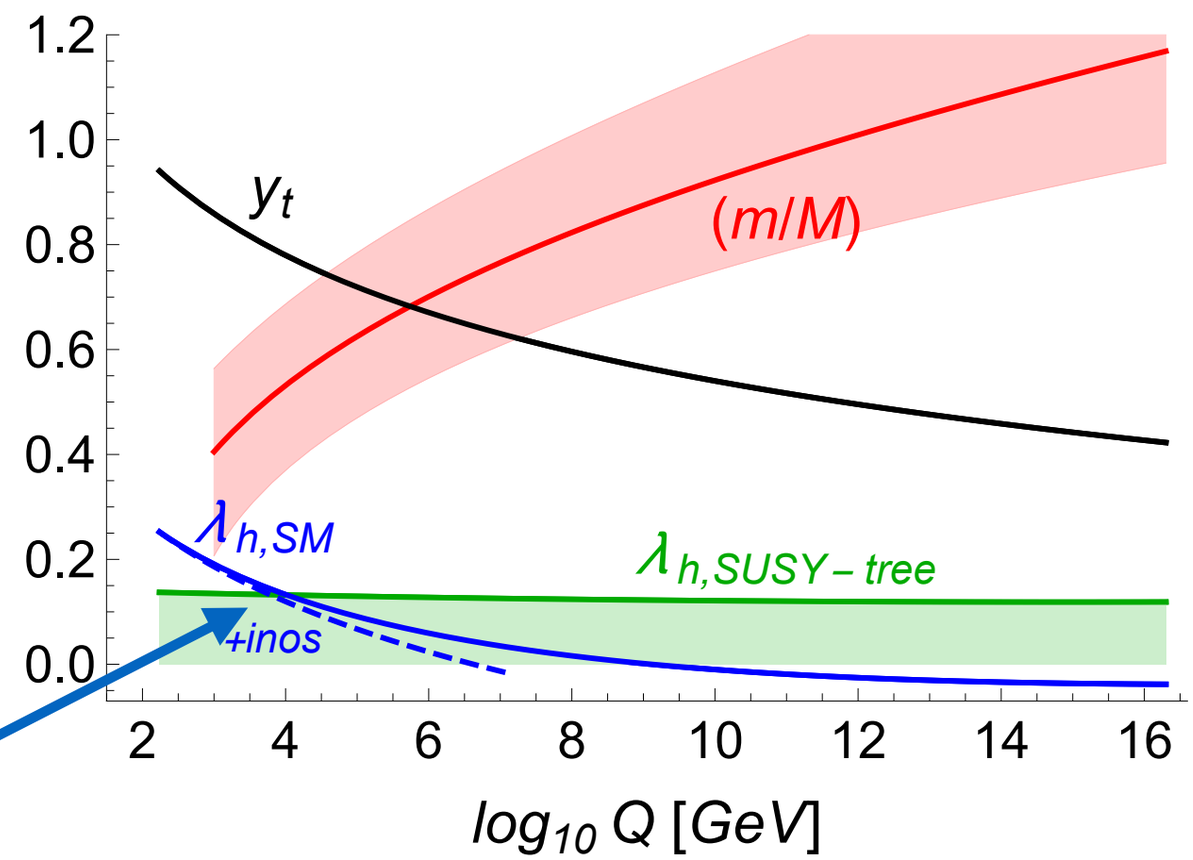
no contribution to $\tilde{m}^2_{H_u}$ is generated from scalar masses

(the same combination of soft masses appears in beta functions of $\tilde{m}^2_q$ and $\tilde{m}^2_{\bar{u}}$)

At O(10 TeV):

- stop masses are generated from mixing with VQ
- all heavy particles are integrated out

Integrating out heavy particles

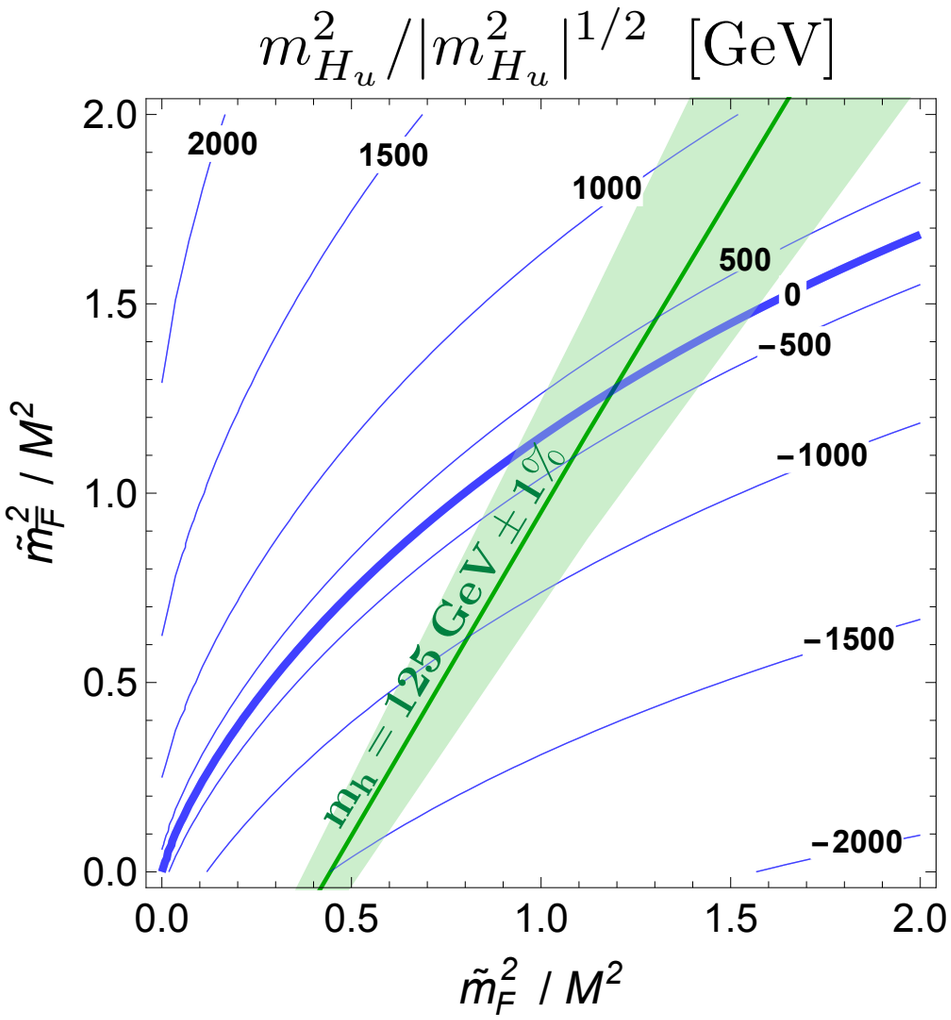


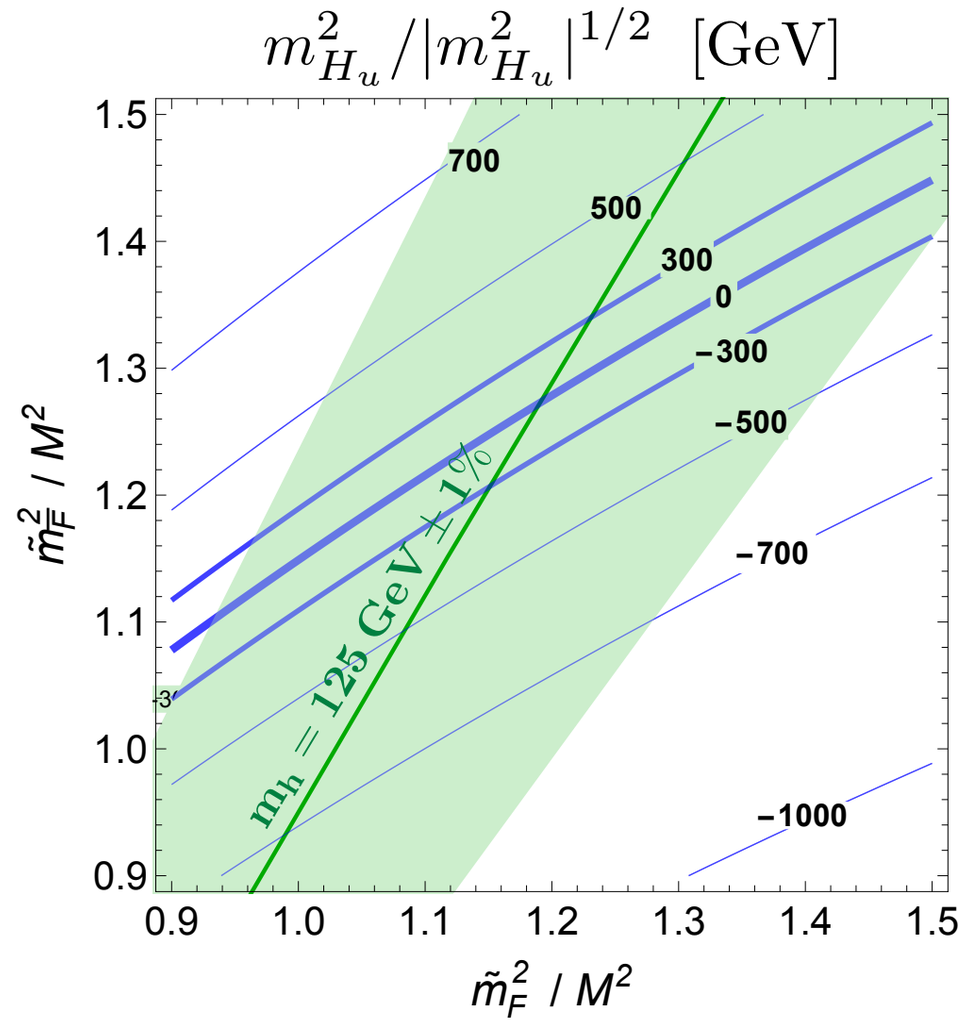
At O(10 TeV):

- stop masses are generated from mixing with VQ
- all heavy particles are integrated out
- threshold corrections to $\tilde{m}^2_{H_u}$ and λ_h are calculated
- the model is matched to SM + inos

Threshold corrections to $\tilde{m}^2_{H_u}$ and λ_h

$M = 23$ TeV:

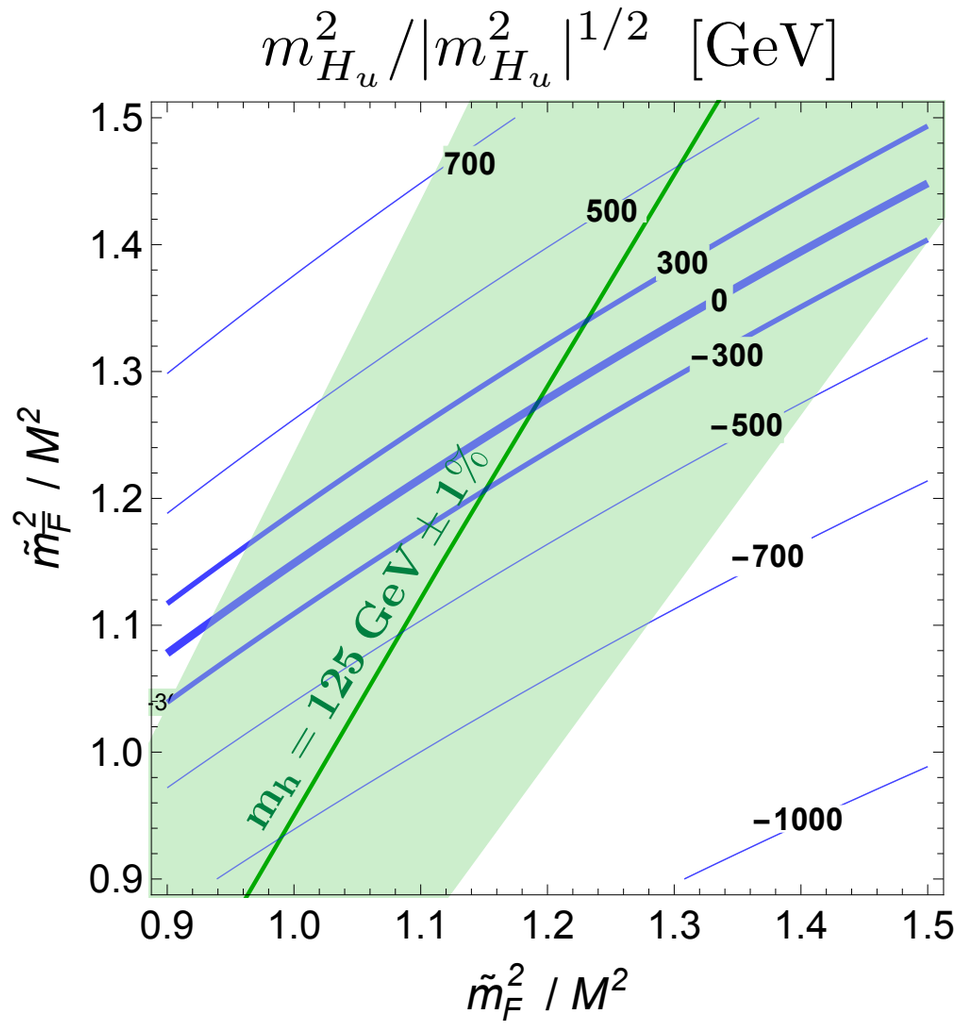




- the matching scale to SM + inos is chosen to be $Q = m_{\tilde{t}_{1,2}}$
- threshold corrections to $\tilde{m}^2_{H_u}$ do not depend on Q

(besides the dependence through couplings)

Threshold corrections to $\tilde{m}^2_{H_u}$

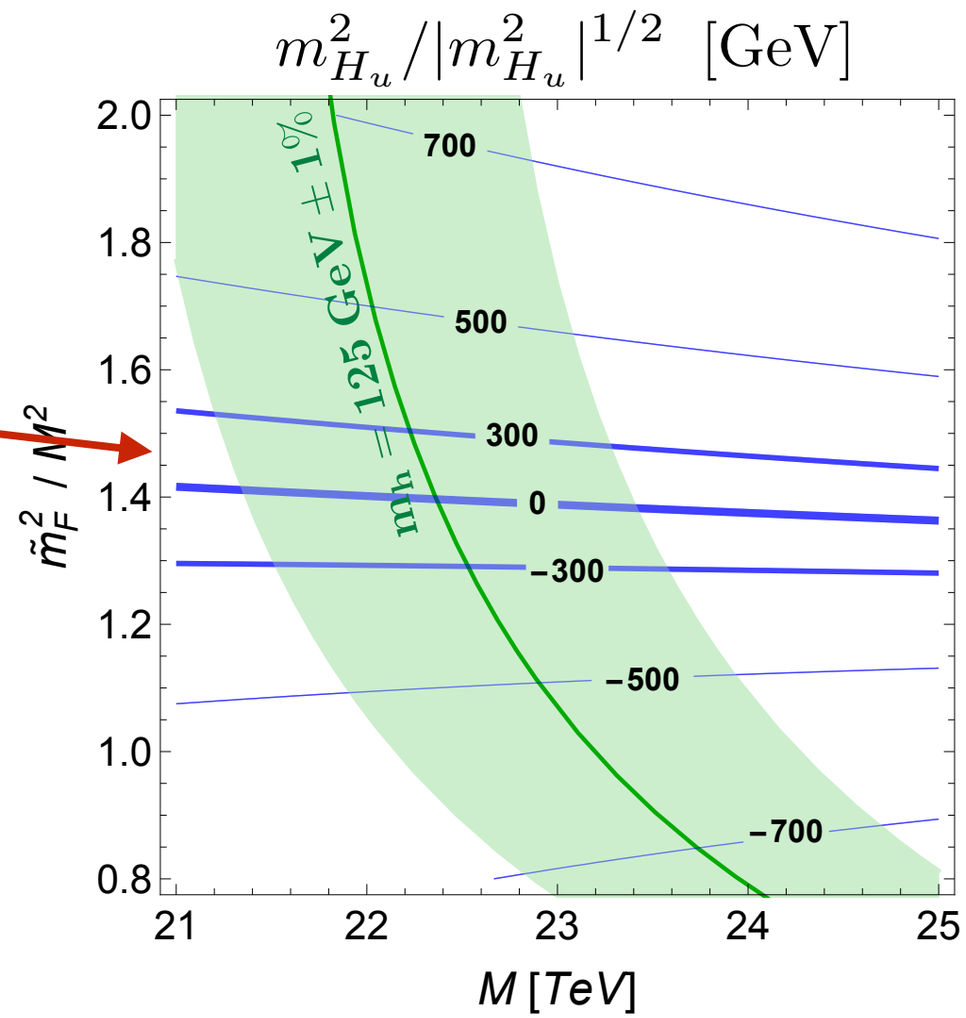


- (for comparable parameters) within 1 TeV
- can be small, + or -, EWSB not preferred by scalar sector
- depend on the origin of soft masses (complete models)

Universal heavy scalar masses

Just two parameters:

~20% range of soft mass squared results in < 300 GeV correction



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Just two parameters:

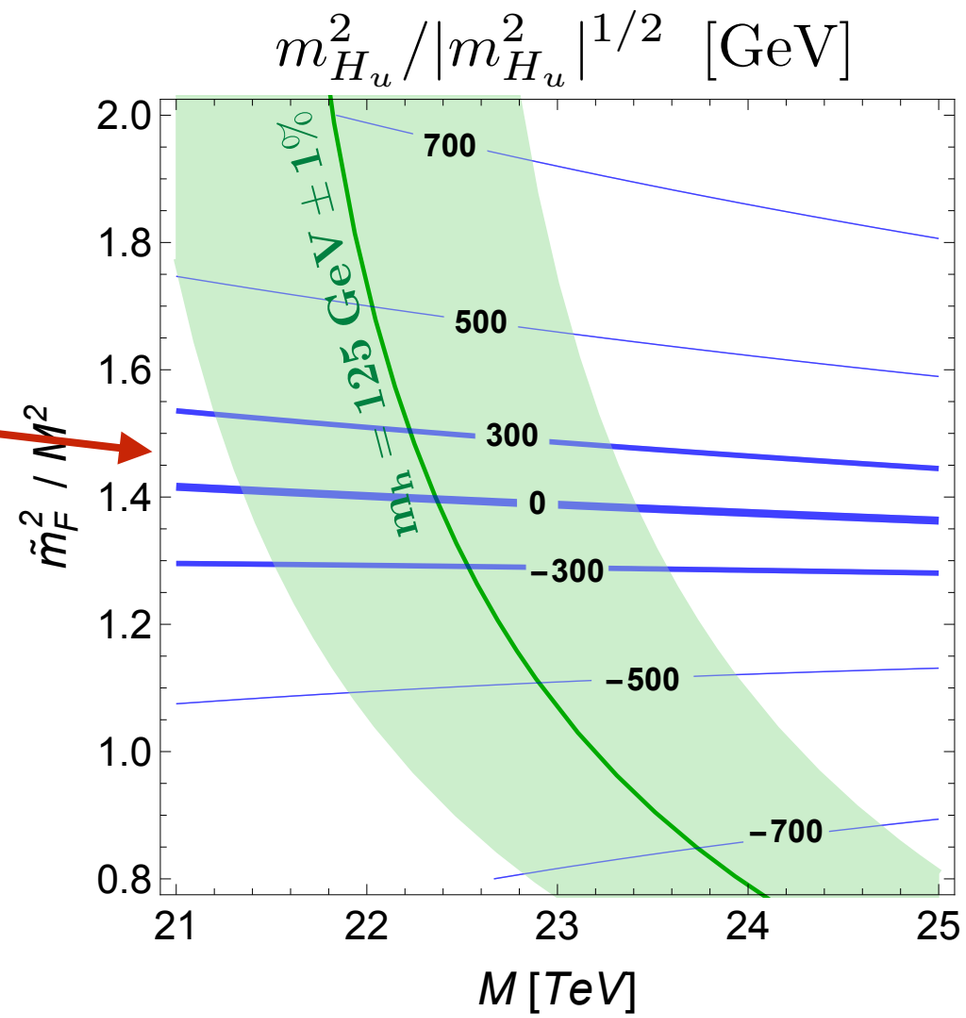
~20% range of soft mass squared results in < 300 GeV correction

explicit masses may originate from vevs of SM singlets:

$$M_{Q,U} = \lambda_{Q,U} \langle S_M \rangle$$

which are related to soft masses by Yukawa couplings

(< 300 GeV correction obtained in ~10% range of Yukawa couplings)



Summary

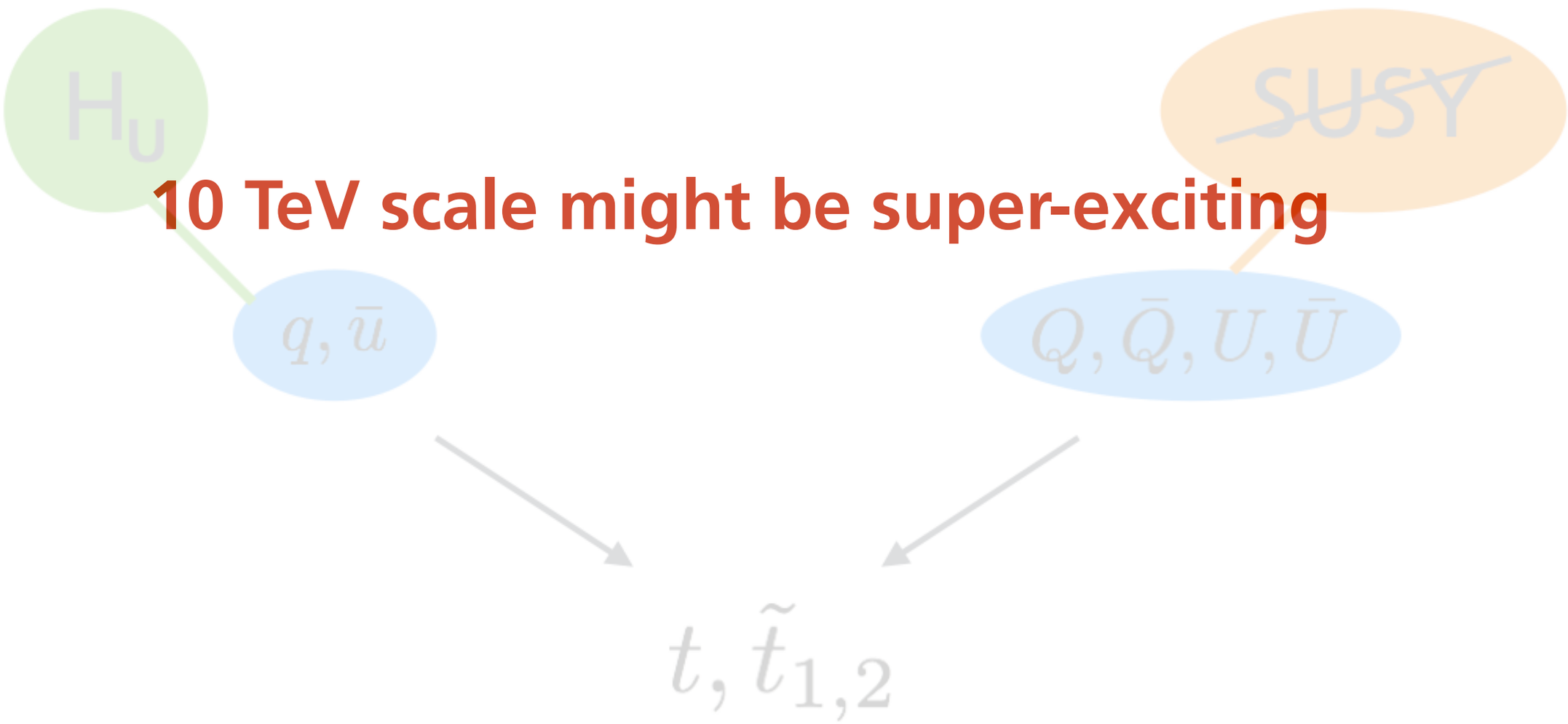
Assumptions about the heavy sector - VQ:

- does not couple to the Higgs
- mixes with “stops”
- feels SUSY breaking stronger than MSSM sector

Results:

- contribution from scalars to $\tilde{m}^2_{H_u}$ from RG running completely eliminated; reduced to threshold corrections
- stop masses (Higgs mass) determined by masses of VQ
- no preference for EWSB **(from scalars)**, it is still driven by gluino
- simple mechanism that can be combined with any model

Conclusions



10 TeV scale might be super-exciting