Loop suppressed EWSB

and naturally heavy superpartners

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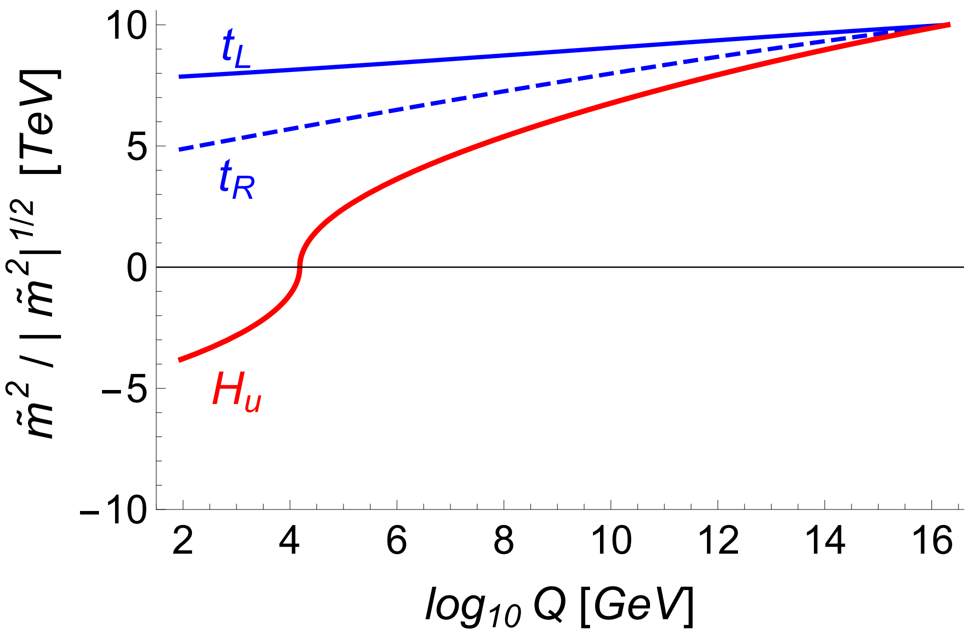
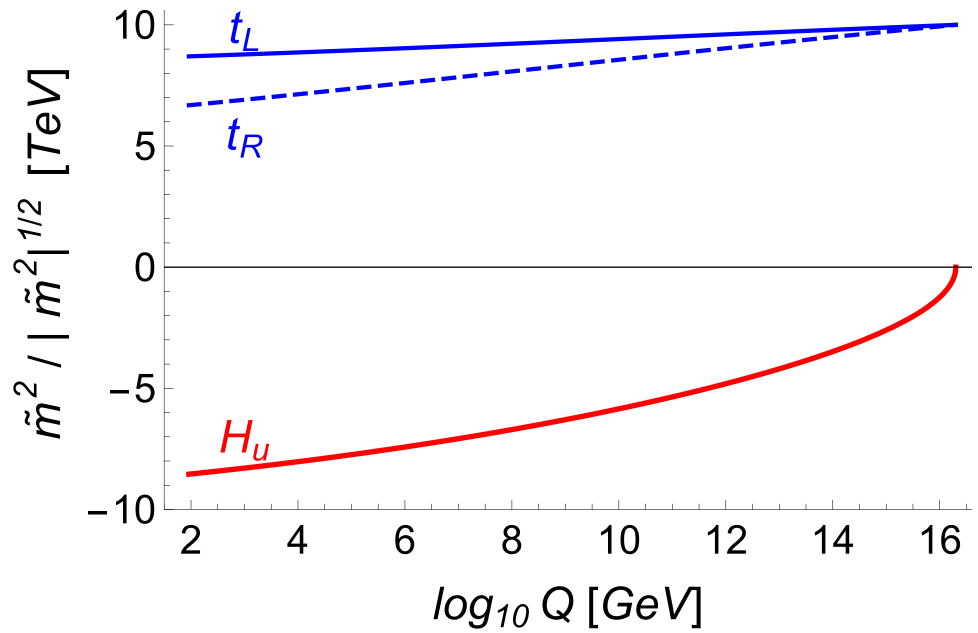
Elegant EWSB in SUSY

Radiatively driven EWSB:





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

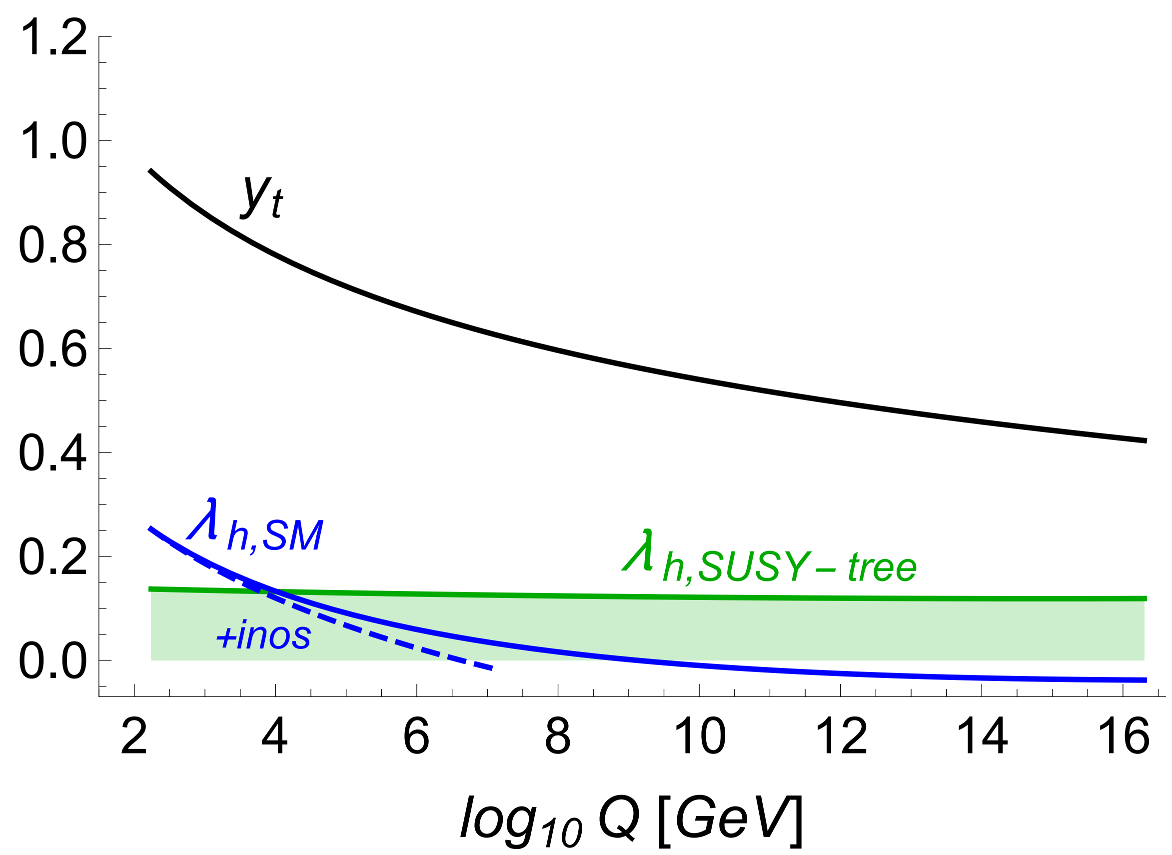
$$\tilde{m}^2_{H_u} \simeq -m^2_{\tilde{t}_{1,2}}$$

preference for EW symmetry to be broken

but EW scale seems to be highly fine tuned!

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 O(10 TeV)

Fine tuning (for generic SUSY models)

EW scale related to soft masses: $\frac{1}{2}M_Z^2 \simeq -\mu^2(M_Z) - \tilde{m}_{H_u}^2(M_Z)$

example for MSSM with boundary conditions at GUT scale: $\tan\beta = 10$

$$M_Z^2 \simeq -1.9\mu^2 + 5.9M_3^2 - 1.2\tilde{m}_{H_u}^2 + 1.5\tilde{m}_t^2 - 0.8A_tM_3 + 0.2A_t^2 + \ldots$$

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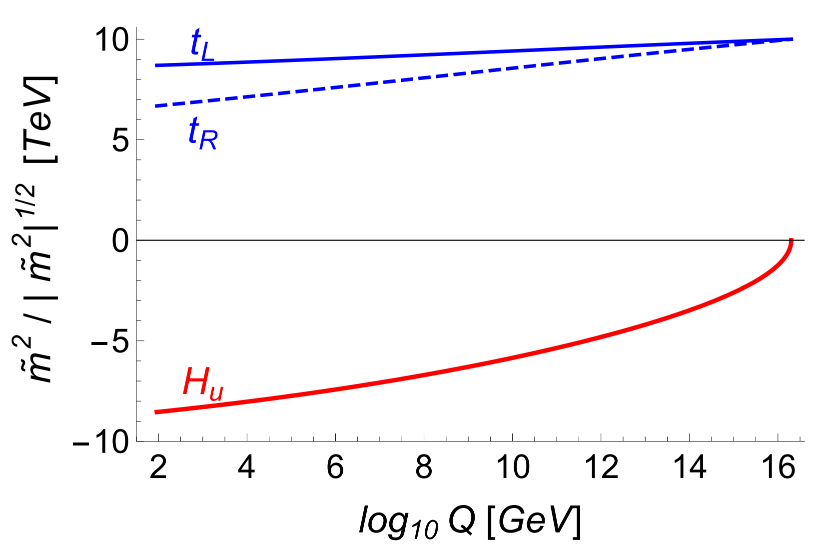
Ignoring (many) possible relations between parameters:

- **tuning from stops**

  O(10 TeV) required from the Higgs mass

  ~0.01% tuning for high scale mediation

  ~0.1% tuning from 1 decade of RG running



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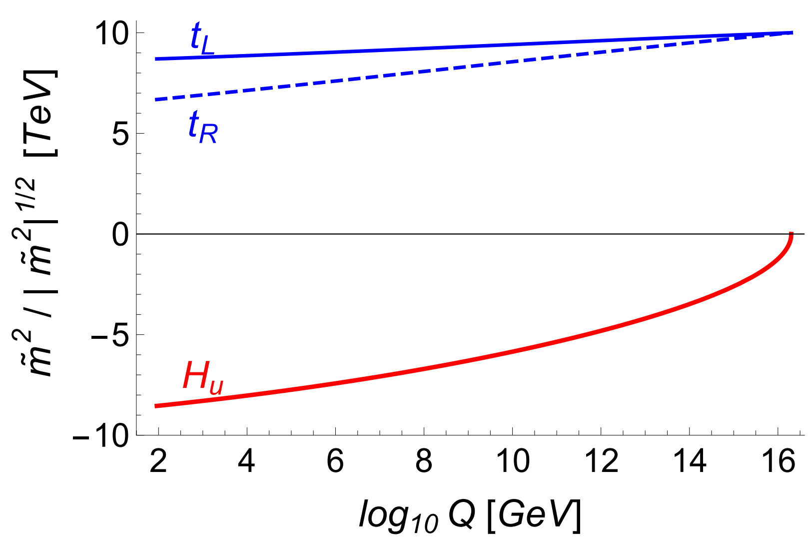

- **tuning from gluino**

  O(1 TeV) required by experiments

  ~1% tuning for high scale mediation

  ~10% tuning allows ~3 decades of RG running

Summary and Outline

Problem of generic SUSY models:

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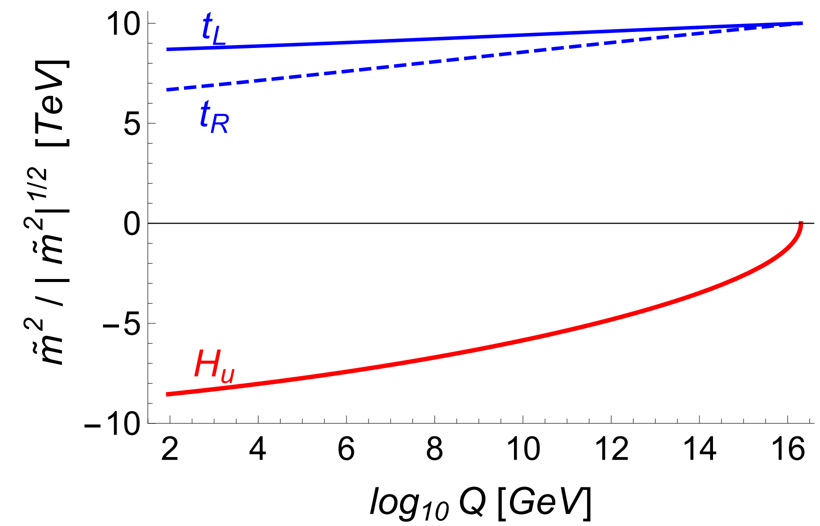

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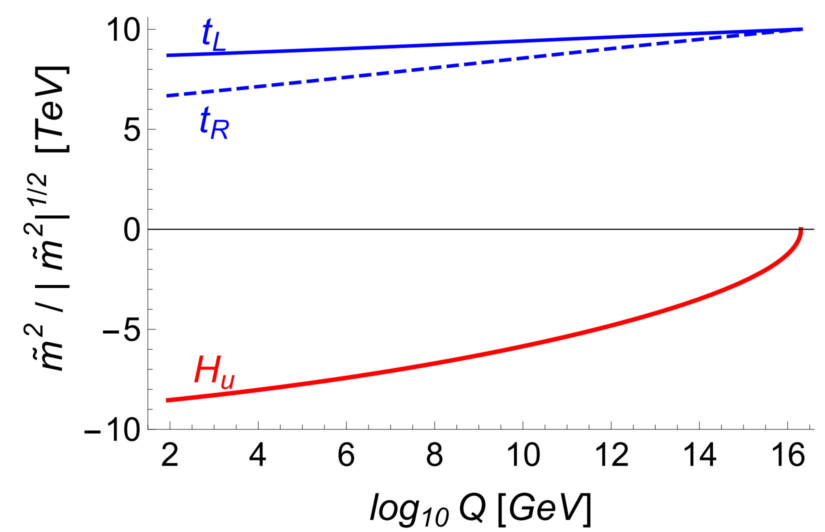

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I will discuss a model which, without any specific relations between parameters, completely removes the contribution from stops in the RG evolution from arbitrary scale.

MSSM with vectorlike quarks

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 top 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:

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

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

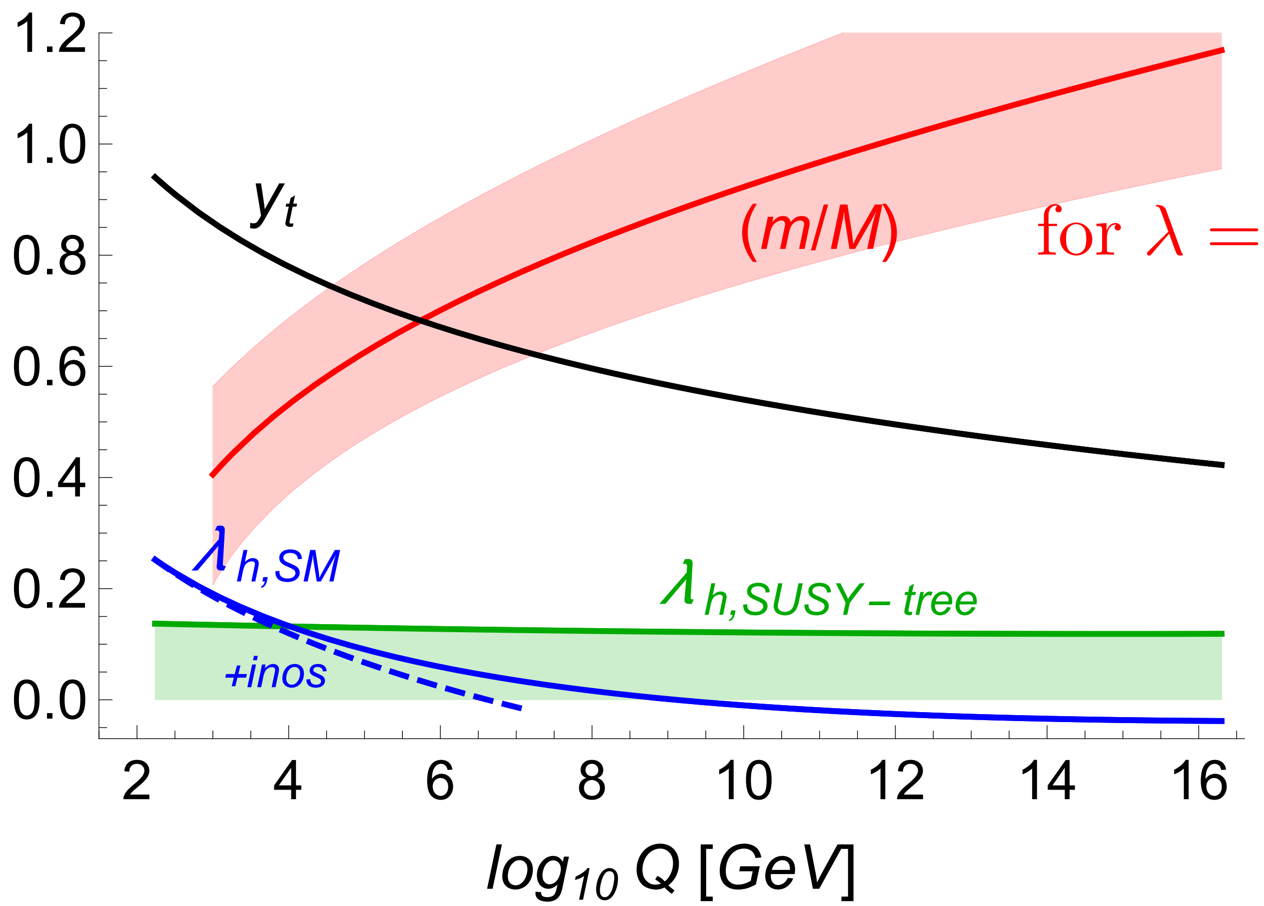
Simplification:

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

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:

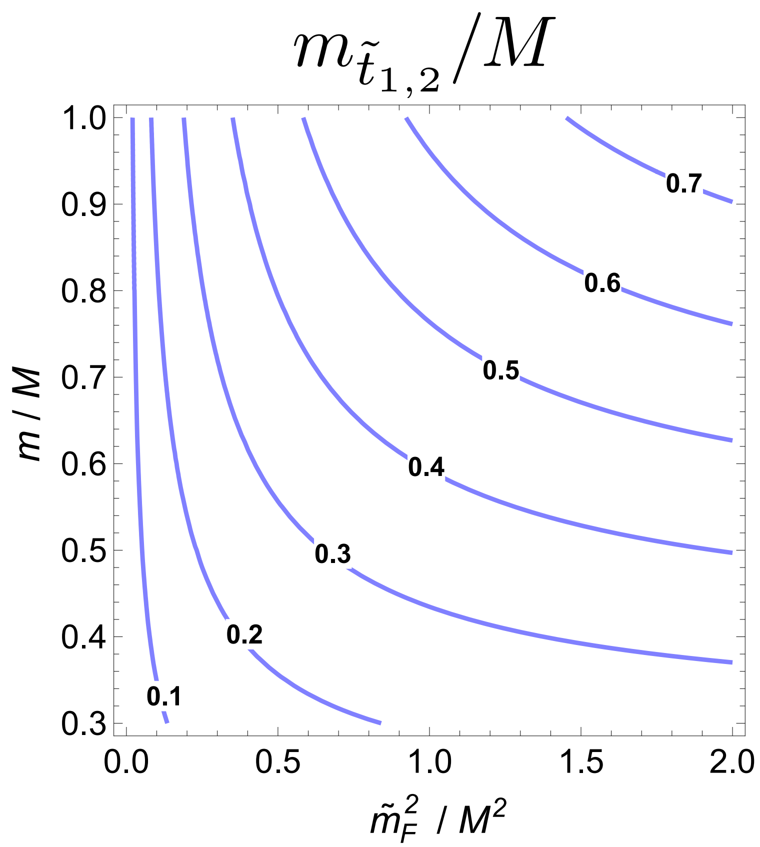
$$\tilde{m}_q^2 = \tilde{m}_{\bar{u}}^2 \equiv \tilde{m}_f^2$$

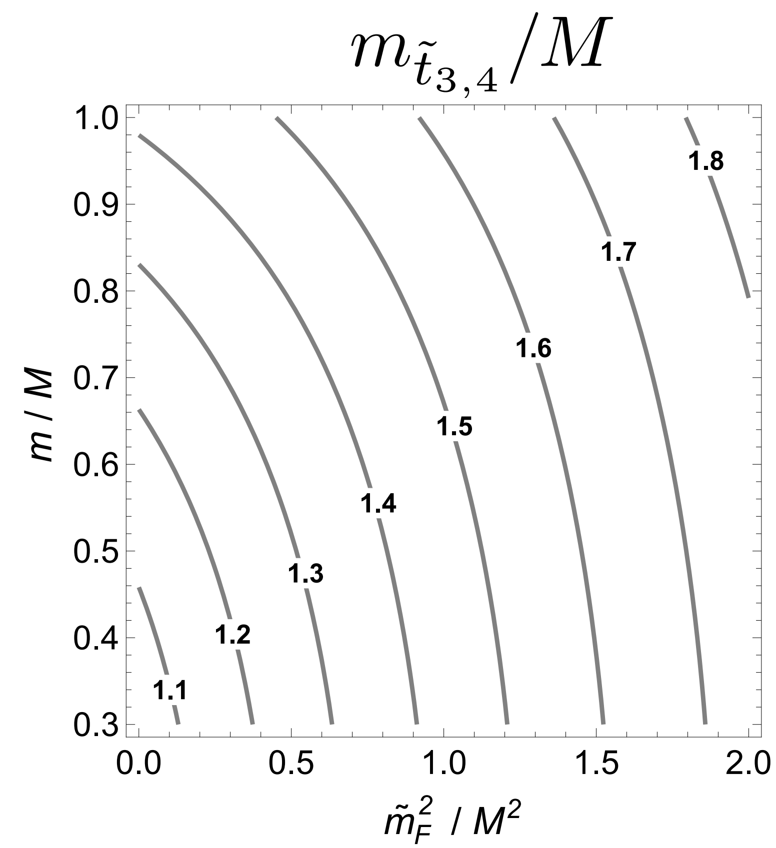
$$\tilde{m}_Q^2 = \tilde{m}_{\bar{U}}^2 \equiv \tilde{m}_F^2$$

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

Stops and stop partners

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





Eigenvalues:

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Simplification:

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

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

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!

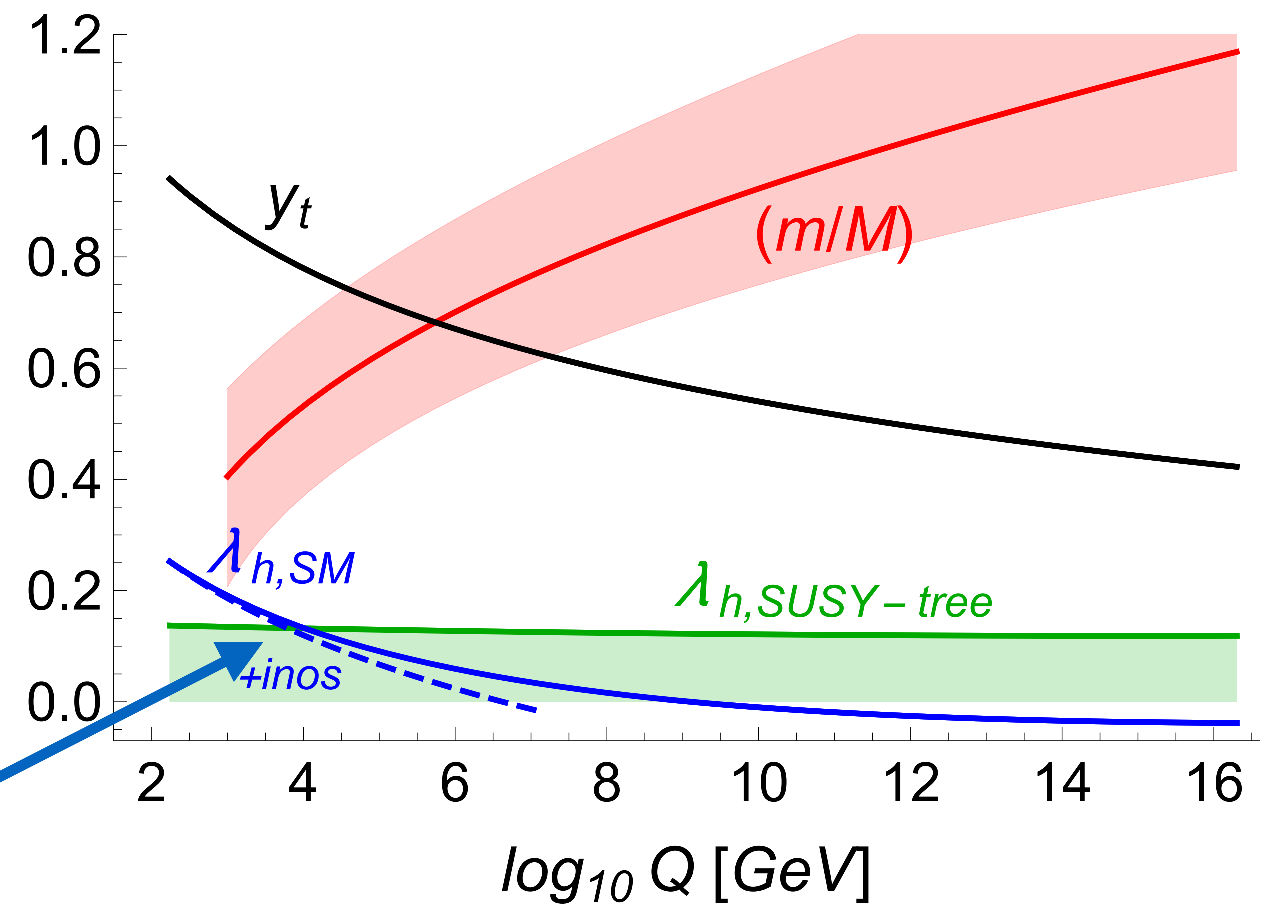
from scalar masses for $\tilde{m}^2_{H_u} = \tilde{m}^2_f = 0$ boundary conditions

(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

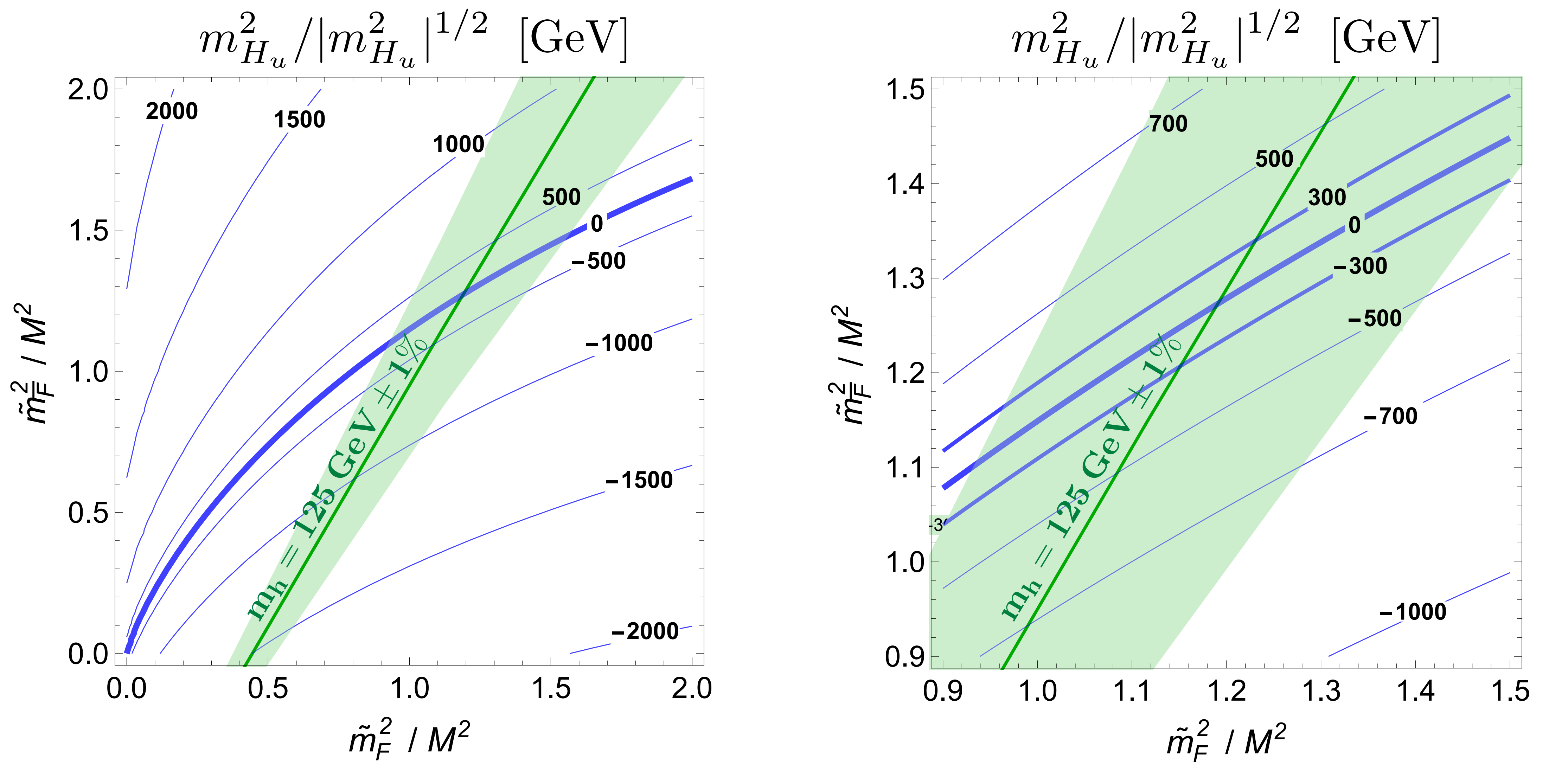


At O(10 TeV):

- 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:

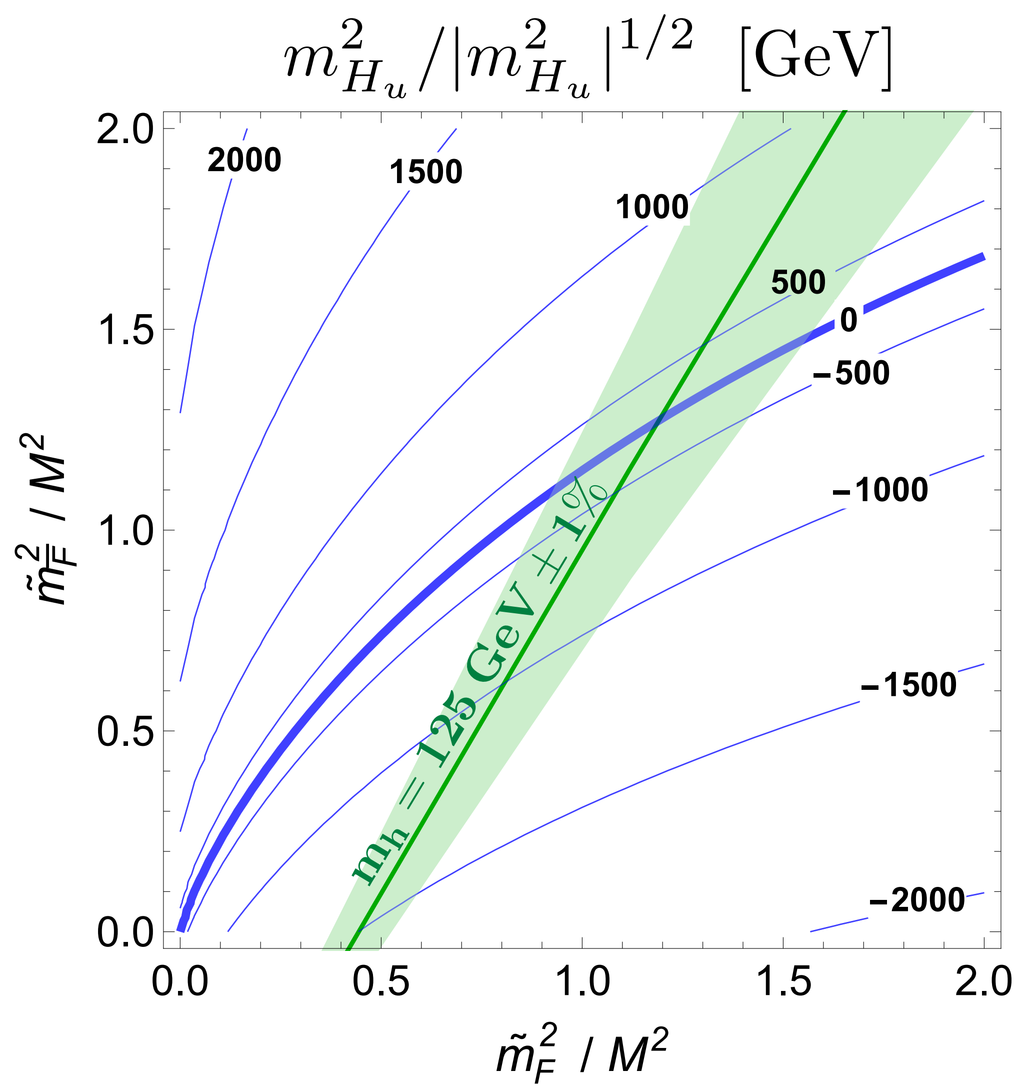


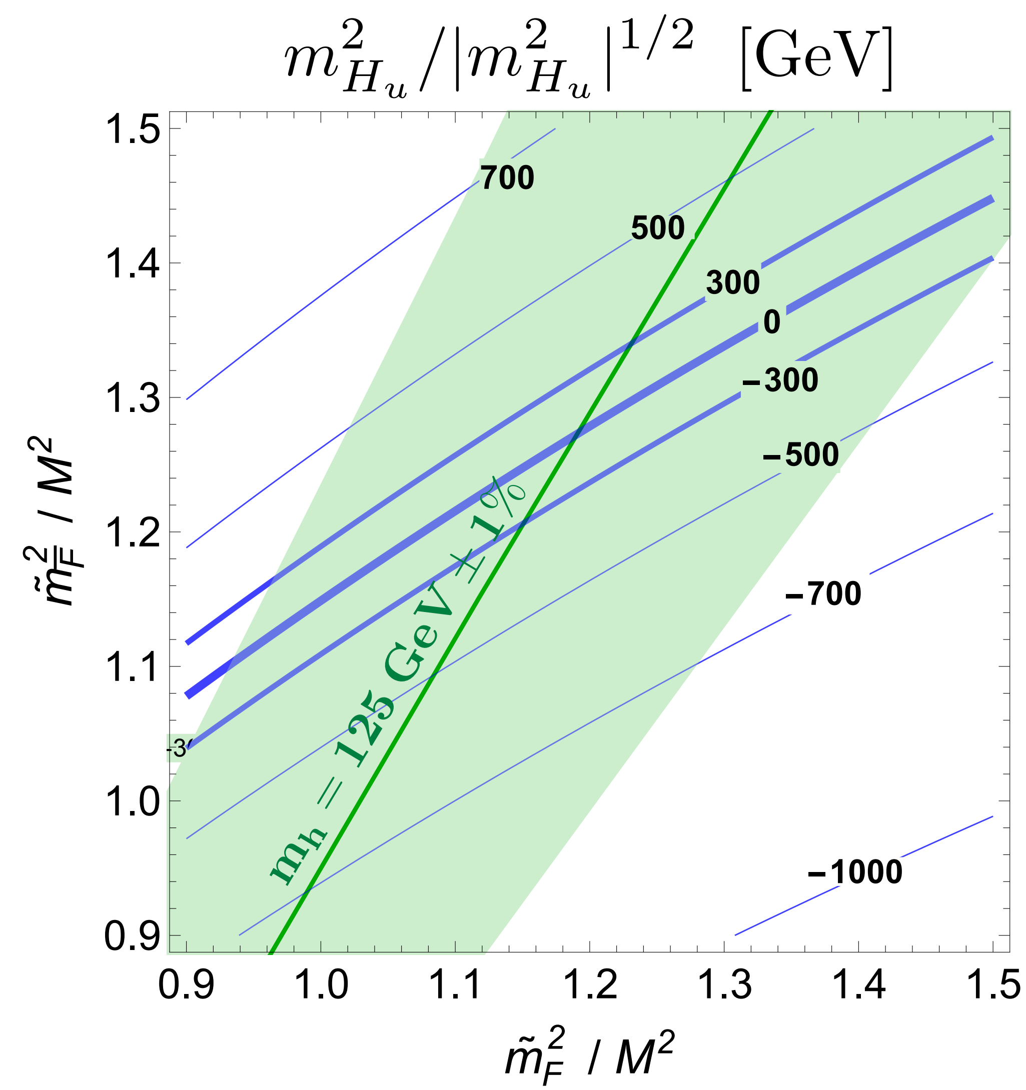
- the matching scale to SM + inos is chosen to be $Q = m_{\tilde{t}_{1,2}}$
- threshold corrections to $\tilde{m}^2_{H_u}$ do not depend on Q

(besides the dependence through couplings)

Back to fine tuning

Fine tuning in EWSB





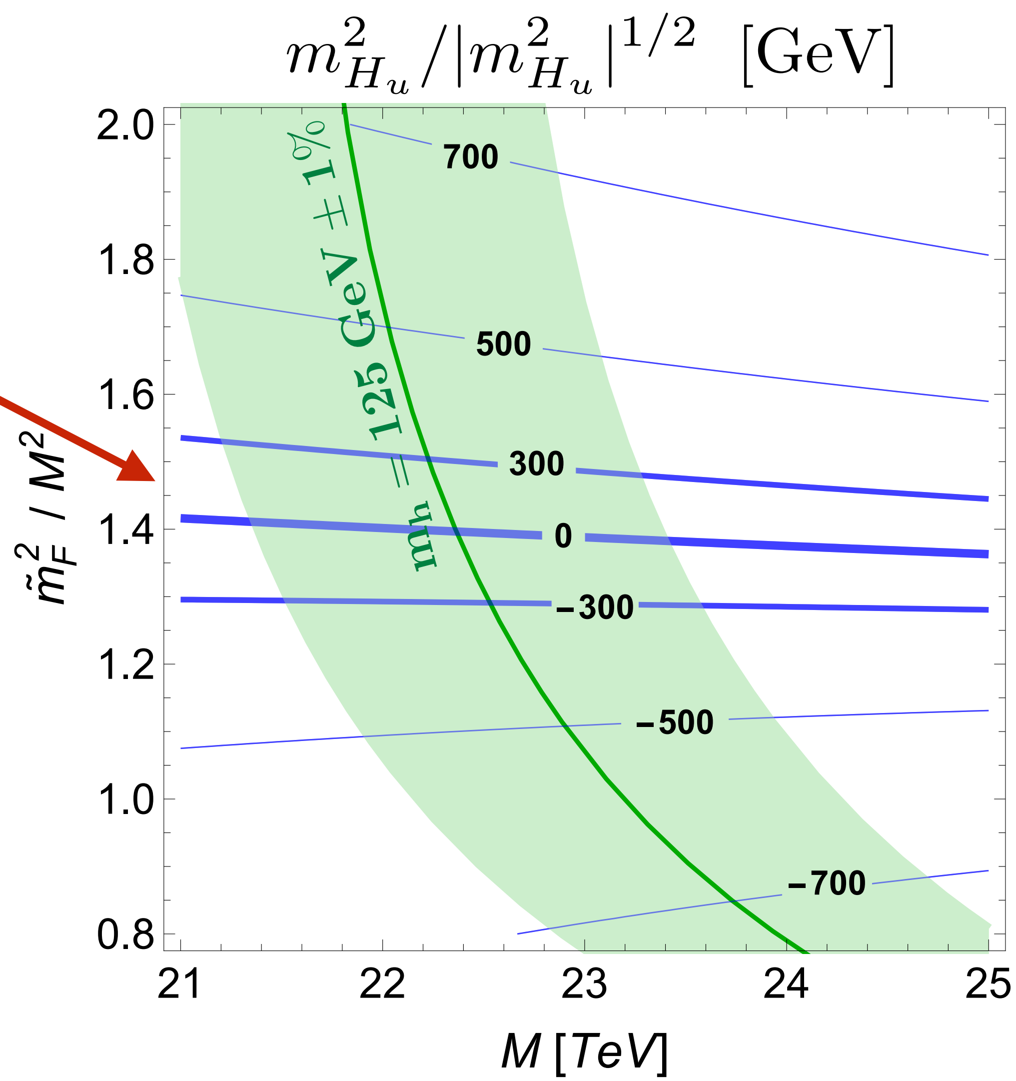
- typical tuning for random unrelated parameters ~1%

  factor of 100 improvement compared to MSSM
- depends on the origin of soft masses (relations)

Universal heavy scalar masses

Just two parameters:

~10% range of soft mass squared results in < 300 GeV correction



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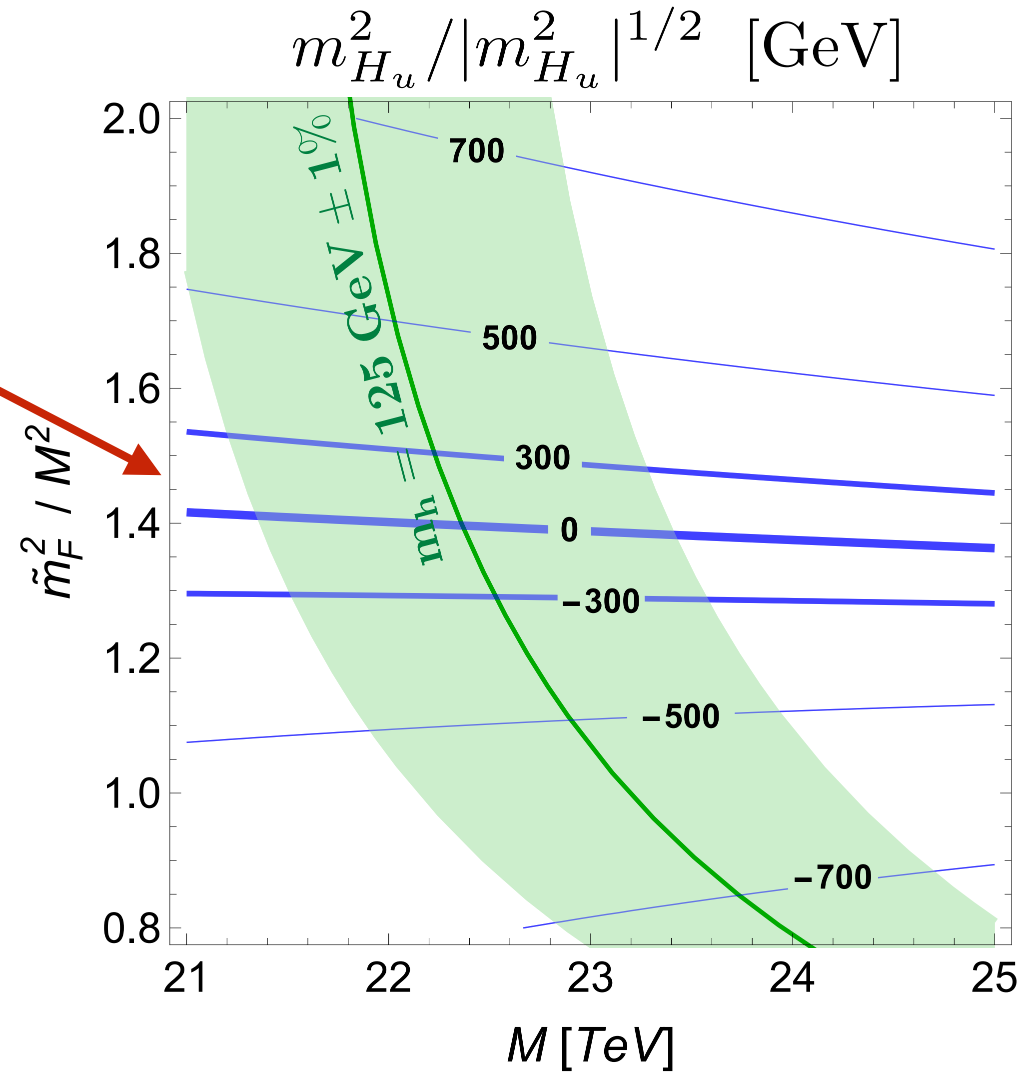
explicit masses may originate from vevs of SM singlets:

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

which are related to soft masses by Yukawa couplings



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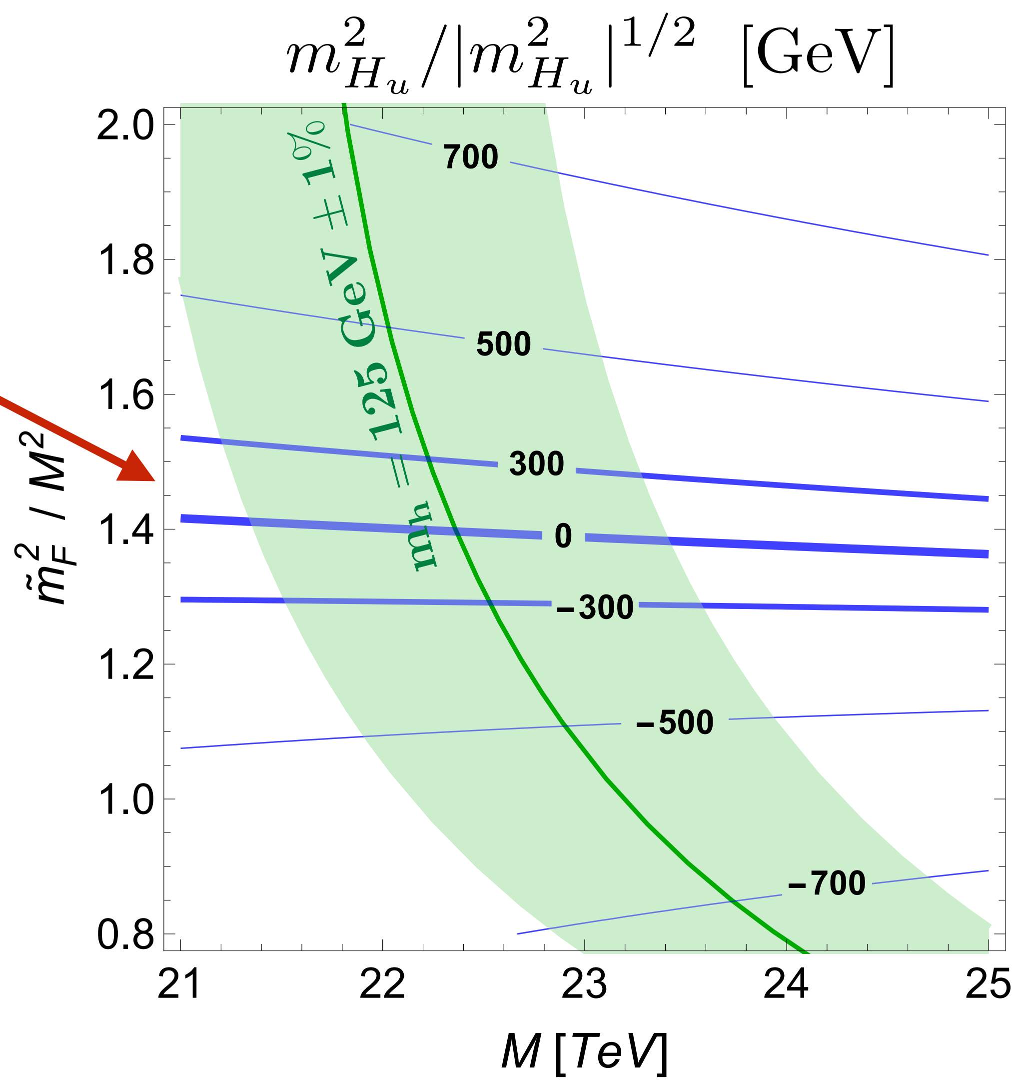

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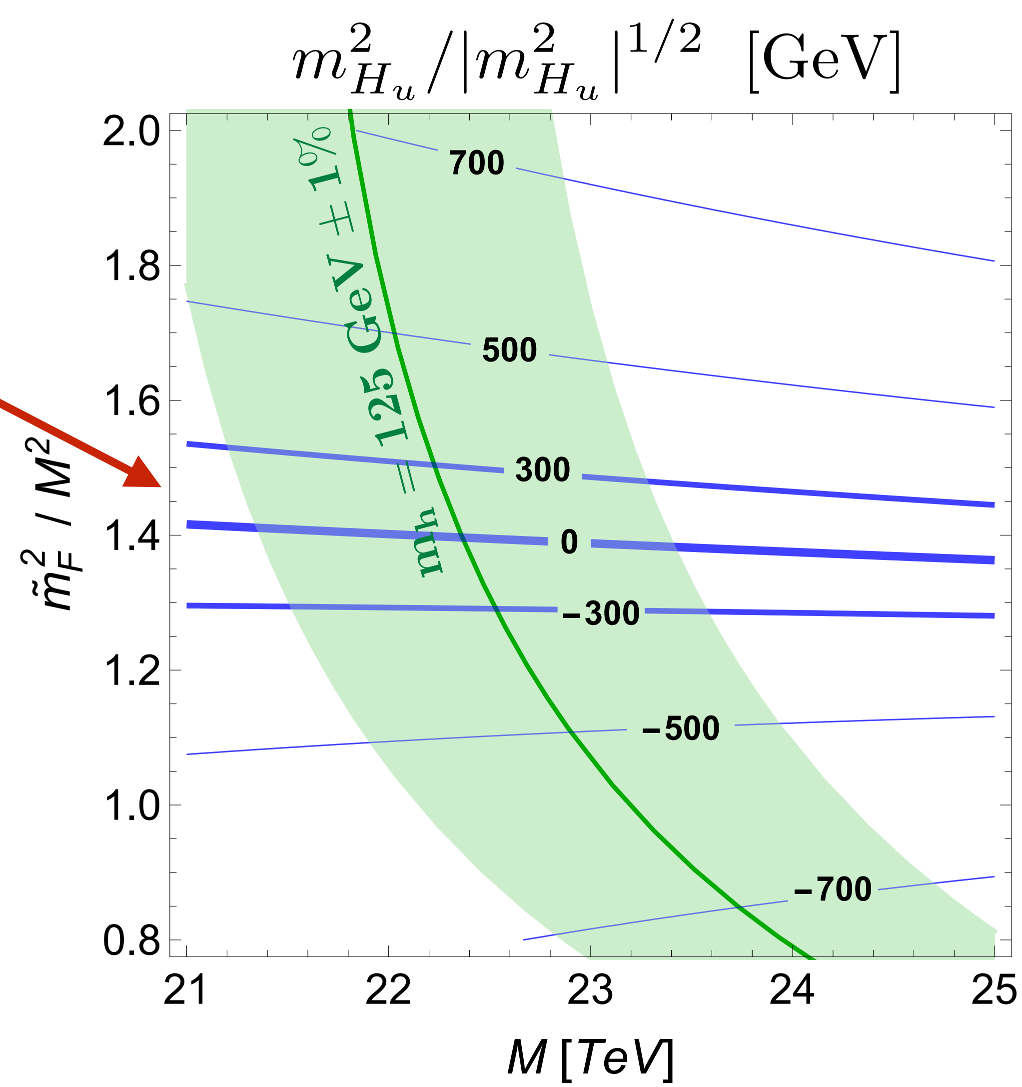

chance to build models with O(10%) tuning!

Conclusions

Stop masses, O(10 TeV), originating from mixing with VQ:

- **remove the contribution to $\tilde{m}^2_{H_u}$ from RG evolution**
- **generic threshold corrections result in ~1% tuning in EWSB**

  compared to ~0.01% tuning from O(10 TeV) stops in generic MSSM
- **tuning may be further reduced in specific models**
- **can be combined with other scenarios that increase m_h**
- **predicts existence of top partners (fermions and scalars)**