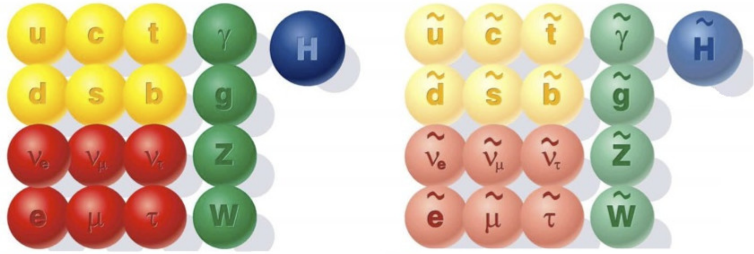
Resummation of large-logarithms in MSSM Higgs-boson mass calculations

Henning Bahl

IMPRS Young Scientist Workshop
at Ringberg castle
8.6.2016

Minimal **S**upersymmetric **S**tandard **M**odel:

- one of the most common models of BSM physics
- Supersymmetry relates bosons to fermions
- each SM particle gets a superpartner (e.g. stops $\leftrightarrow$ top)
- able to address:
  hierarchy problem, DM, gauge coupling unification,...

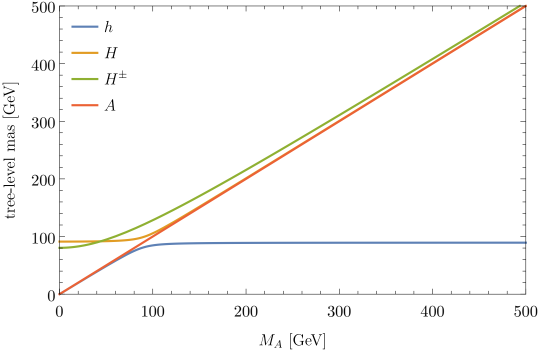


- Holomorphicity of superpotential and anomaly cancellation
  $\Rightarrow$ need to introduce second Higgs doublet
- corresponds to type II THDM (remember Stephan's talk)
- five physical Higgses: h, H (CP-even); A (CP-odd); $H^{\pm}$
- SUSY restricts masses, couplings
- tree-level Higgs sector determined by 2 parameters:
  M_A, $\tan\beta = v_2/v_1$
  (7 free parameters in general THDM models)

Distinct feature of the MSSM

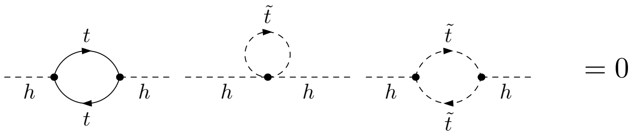
Mass of lightest Higgs boson is calculable in terms of model parameters.

- measured M_h can be used as a precision observable to constrain parameter space of the model ($\rightarrow$ Stephan's talk)
- at tree-level: $M_h^2 \leq M_Z^2 \cos(2\beta)^2 \leq M_Z^2$



What's about quantum correction?

- exact SUSY $\rightarrow$ all quantum corrections cancel



Reasons?

- exact SUSY forces sparticles to have the same mass as the corresponding SM particle ($m_t = m_{\tilde{t}_1} = m_{\tilde{t}_2}$)
- SUSY forces sparticles to have the same couplings as the corresponding SM particle
- fermion (scalar) loop has opposite sign as scalar (fermion) loop

But M_h was measured to be ~ 125 GeV ($> M_Z \sim 90$ GeV)!

And no SUSY particles have been found yet!

$\Rightarrow$ **SUSY must be broken**

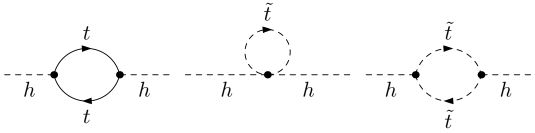
- We don't know breaking mechanism
- Parametrize our ignorance by adding addtional mass terms for sparticles to Lagrangian (soft-breaking terms)

$$m_{\tilde{t}_1}^2 = m_t^2 + \Delta m_1^2$$
$$m_{\tilde{t}_2}^2 = m_t^2 + \Delta m_2^2$$

- We don't change couplings ($\rightarrow$ no quadratic divergences)

SUSY broken

Loop corrections contribute to Higgs mass



$\neq 0$

but

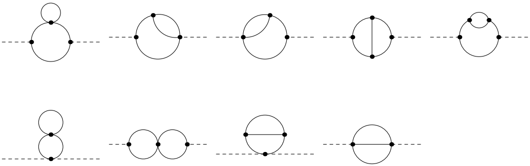
$$M_h^2 = M_Z^2 \cos(2\beta)^2 + \frac{3}{4\pi^2} m_t^2 h_t^2 \ln\left(\frac{M_S^2}{m_t^2}\right) + (\text{non logarithmic terms})$$

with $M_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$.

- 1-loop correction can raise tree-level mass by more than $\sim$80%

$\Rightarrow$ **Higher order corrections necessary to obtain accurate result!**

$\rightarrow$ 2-loop calculation (already quite complicated, but doable):



- calculation yields terms $\propto \ln^2\left(\frac{M_S^2}{m_t^2}\right)$
- for $M_S \gg m_t$ (heavy stops $\leftarrow$ LHC stop searches):

logarithms get large spoiling convergence of perturbative expansion

$\rightarrow$ 3-loop calculation ???

Not feasible, but large logarithmic terms ($\ln^3(..)$) expected!!

$$\Downarrow$$

Alternative method needed to control large logarithms!

Origin of the problem

Huge hierarchy between scales m_t and M_S

$$\Downarrow$$

We need to seperate the effects of high- and low-energy physics!

$$\Downarrow$$

Effective **F**ield **T**heory

$$\begin{aligned}\mathcal{L}_{\text{toy}} =& \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi - m^2\phi^2 - M^2\Phi^2 - V(\phi,\Phi)\\ V(\phi,\Phi) =& \lambda_1\phi^4 + \lambda_2\phi^2\Phi^2 + \lambda_3\Phi^4\end{aligned}$$

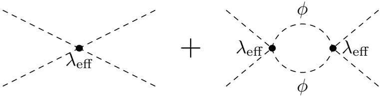
Effective Langragian for energies $Q \sim m \ll M$:

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - m^2\phi^2 - \frac{\lambda_{\text{eff}}}{4!}\phi^4$$

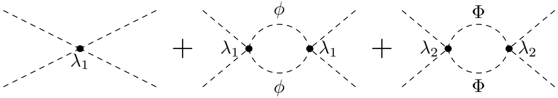
$\rightarrow$ 'high-energy physics' encoded in λ_{eff}

Determine λ_{eff} by matching with full theory at $Q \sim M$ via $\phi\phi \to \phi\phi$ scattering:

EFT result =



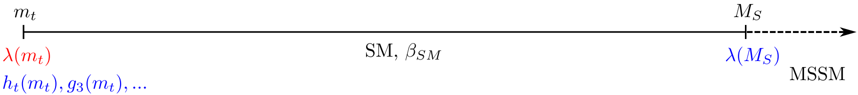
full theory result =



$$\textbf{EFT result} \stackrel{!}{=} \textbf{full theory result}$$

Regard SM as EFT

$M_h^2 = 2\lambda(Q = m_t)v^2$ (λ: SM Higgs self-coupling, v: SM vev)



- Match SM to MSSM at $Q = M_S$: $\lambda(M_S)$ fixed in MSSM

Calculate Higgs mass in SM:

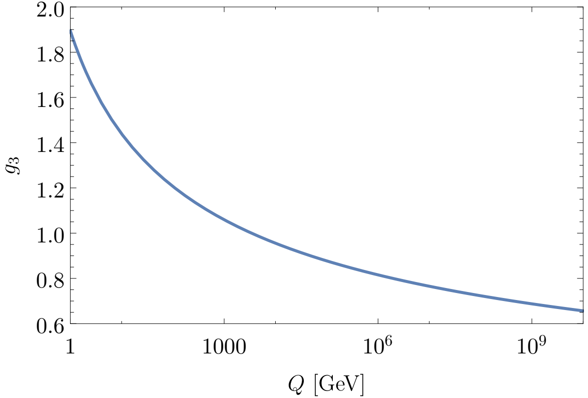
- In EFT (SM) all SUSY-particles are integrated out
  $\rightarrow$ no large logarithms
- All effects of SUSY-particles are absorbed into $\lambda(m_t)$

How to get $\lambda(m_t)$? We only have $\lambda(M_S)$.

- Higgs self-coupling is a running parameter
  $\rightarrow$ changes value depending on the scale (energy) of process
- running is governed by renormalization group equations (RGEs)

- typical example: running gauge coupling of QCD:

$$\frac{dg_3}{d\ln Q^2} = -\frac{7}{2}kg_3^3 \text{ with } (k = 1/(4\pi)^2)$$



$$\frac{d\lambda}{d\ln Q^2} = 6k\left(\lambda^2 + \lambda h_t^2 - h_t^4\right)$$

Solve iteratively:

$$\lambda(m_t) \approx \lambda(M_S) + \int_{Q=M_S}^{Q=m_t} \frac{d\lambda}{d\ln Q^2} d\ln Q^2 \approx$$

$$\approx \lambda(M_S) - 6k\left(\lambda^2(M_S) + \lambda(M_S)h_t^2(m_t) - h_t^4(m_t)\right)\ln\left(\frac{M_S^2}{m_t^2}\right) \approx$$

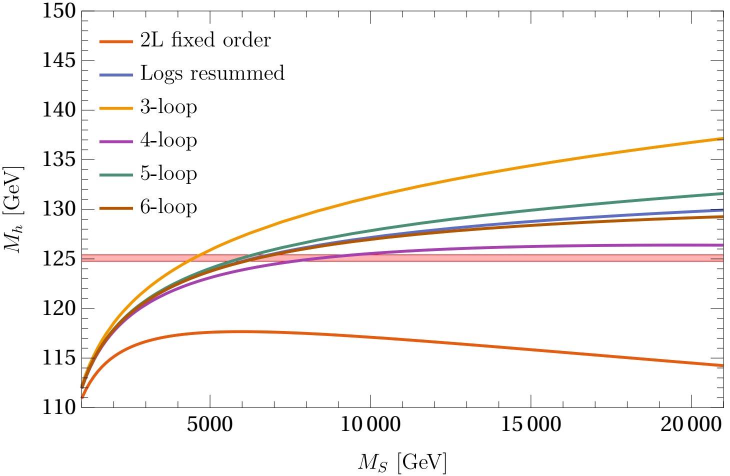
$$\approx 6kh_t^4(m_t)\ln\left(\frac{M_S^2}{m_t^2}\right)$$

Multiply by $2v^2 \rightarrow$ 1-loop large logarithm reproduced ($h_t v = m_t$)

$\Rightarrow$ **large logarithms originate from RGE running**

Solve system of RGEs ($dg_i/d\ln Q^2 = \ldots$) **numerically**:

⇒ **Resummation of large logarithms up to all orders**



- In the MSSM lightest, the Higgs mass M_h is calculable in terms of model parameters
- M_h can be used as a precision observable to constrain parameter space
- Calculation suffers from large logarithmic contributions spoiling the convergence of the perturbative expansion
- Effective field theory techniques provide tools to resum these contributions up to all orders