The electroweak hierarchy problem

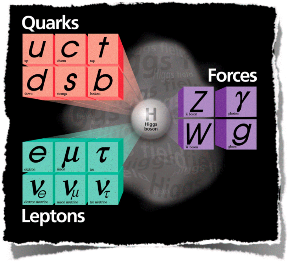
Monika Blanke

The SM – a story of success

The Standard Model of particle physics – a story of success

- all SM particles have been observed in the laboratory
- latest discoveries
  - 1995 top quark
  - 2000 tau neutrino
  - 2012 Higgs boson

  ➢ all of them had previously been postulated based on theoretical arguments



- no particles beyond the SM have been discovered so far

  ➢ mass limits in the $\mathcal{O}(1)$ TeV range (depending on couplings etc.)

Indirect probes of the SM

New particles could also be seen through their quantum contributions to SM observables ➢ **precision tests**

- electroweak observables
- Higgs couplings
- flavour violating decays

➢ few slight tensions ("anomalies"), but overall astonishingly good agreement with SM predictions!

➢ constraints on the New Physics scale of several TeV (even up to 10^5 TeV for neutral kaon mixing!)

Problems of the SM

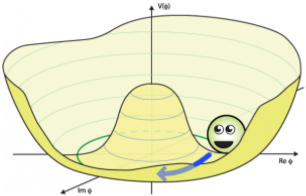
Open questions:

- neutrino masses
- dark matter and dark energy
- baryon asymmetry of the universe
- inclusion of (quantum) gravity
- structure of the SM: gauge group, flavour structure ...
- etc.

➢ **SM not complete – extension needed!**

But at which energy scale?

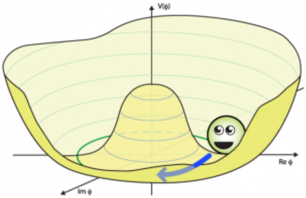
Back to the Higgs potential



classical level: shape of Higgs potential determined by Lagrangian parameters μ^2, λ:

$$V(H) = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

Back to the Higgs potential



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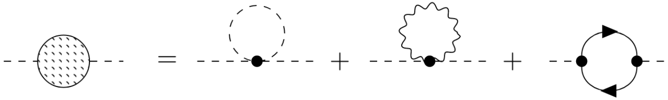
quantum level: radiative corrections



$$\delta\mu^2 = \frac{\Lambda^2}{32\pi^2}\left[6\lambda + \frac{1}{4}(9g^2 + 3g'^2) - 6y_t^2\right] + \cdots$$

Λ : dimensionful regulator, cut-off scale

A closer look at the quadratic divergence

$$\delta\mu^2 = \frac{\Lambda^2}{32\pi^2}\left[6\lambda + \frac{1}{4}(9g^2 + 3g'^2) - 6y_t^2\right] + \cdots$$

- removed in dimensional regularisation, hence unphysical within SM
- appears in the presence of NP, where Λ becomes mass scale M of new particles
  ➢ fine-tuning between tree and loop contributions if $M \gtrsim 1\,$TeV
- Λ could be different for different terms
  ➢ fine-tuned cancellation possible (but ugly)

➢ **electroweak hierarchy problem** – why is $v \ll M_{\text{Planck}}$?

How to avoid fine tuning

Requirements for a natural scale of electroweak symmetry breaking

1. new particles are present at (or below) the TeV scale
2. they do not re-introduce the fine-tuning problem

➢ introduce symmetry that protects the Higgs potential

More exotic explanations (not the focus of this course)

- anthropic explanation, multiverse
- cosmological relaxation
- etc.

Supersymmetry

most popular candidate: supersymmetry (SUSY)

Some SUSY basics

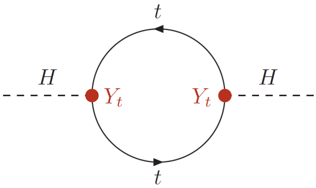
- SUSY is a symmetry connecting bosons and fermions
- for each SM particle a superpartner with opposite spin-statistics is introduced

  spin 1/2 fermions ➢ spin 0 sfermions
  spin 1 gauge bosons ➢ spin 1/2 gauginos
  spin 0 Higgs field ➢ spin 1/2 higgsinos

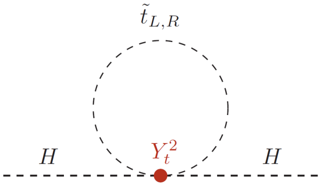
- we also need two Higgs doublets, H_u and H_d
- if SUSY is unbroken, particles and their superpartners have the same masses ➢ **SUSY must be broken**

SUSY's solution to the hierarchy problem

Additional contrbutions to the Higgs potential from superpartners, e. g.



top loop



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Due to the opposite spin-statistics, these diagrams are opposite in sign.

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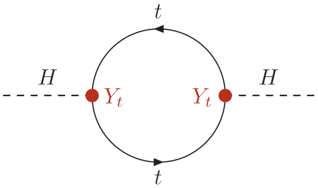

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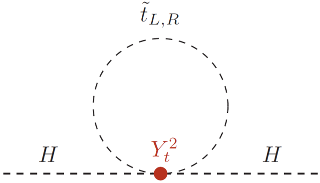

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Due to the opposite spin-statistics, these diagrams are opposite in sign.

If the masses are equal, $m_t = m_{\tilde{t}_{1,2}}$, then the contributions cancel exactly.

➢ **SUSY non-renormalisation theorem**
If SUSY is exact, then the Higgs potential does not receive quantum corrections.

In the presence of SUSY breaking

If $m_t \neq m_{\tilde{t}_{1,2}}$, then the cancellation is not exact anymore:

$$\delta\mu_u^2 = \frac{-3Y_t^2}{8\pi^2}\left[m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 + |A_t|^2\right]\log\frac{\Lambda_{\mathsf{SB}}}{m_t}$$

$m_{\tilde{t}_{1,2}}$: masses of the stop partners
A_t: trilinear coupling between stops and Higgs
Λ_{SB}: scale of SUSY breaking

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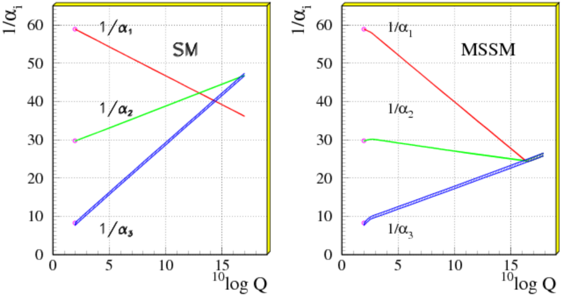
For a natural scale of electroweak symmetry breaking, the stops (scalar top quark partners) should be below the TeV scale.

More about SUSY

The good...

- stabilisation of electroweak scale
- dark matter candidate (assuming R-parity conservation)
  ➢ *lightest neutral gaugino/higgsino, gravitino, sneutrino, ...*
- successful gauge coupling unification



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. . . and the bad

- SUSY would have preferred a lighter Higgs ($m_H < m_Z$ at the classical level)
- no superpartners seen at high energies yet
- no indirect sign of SUSY in precision tests of the SM

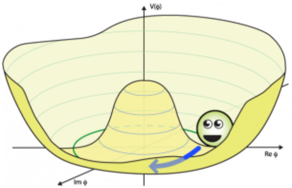
Alternative concepts

- **composite Higgs** – bound state of some new strong interaction, mass scale set by compositeness scale
- **Higgs as pseudo-Goldstone boson** – mass scale protected by Goldstone theorem, parametrically lighter than symmetry breaking scale
- **extra dimensions (large, warped)** – "true" higher-dimensional scale of gravity different from effective 4D one
- **gauge-Higgs unification** – Higgs as extra degree of freedom of gauge field in extra-dimension model, mass protected by gauge symmetry

Summary

Study goal: hierarchy problem

- SM very successful, but requires extension
- large NP scale introduces fine-tuning in Higgs potential
- TeV-scale NP and protective symmetry required to avoid hierarchy problem
- SUSY as popular solution, but under increasing experimental pressure



Reading assignment

- chapter 1 of C. Csaki, S. Lombardo, O. Telem, *TASI Lectures on Non-Supersymmetric BSM Models*, `arXiv:1811.04279`