UV completion of the Standard Model

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IMPRS

PTFS

Outline

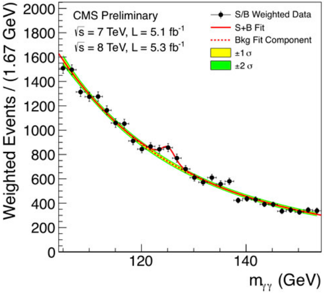
1. Introduction
   - Limits of the Standard Model
   - Stability of the Higgs-potential
   - Idea of Asymptotic Safety

2. Asymptotic Safety in Quantum Gravity
   - Non-perturbative method: The Functional Renormalisation Group
   - Results

- 2012 at LHC: Discovery of Higgs-Boson

$$M_H \approx 125 \text{ GeV}$$

- Last missing piece of the SM
- So far: no signs for physics beyond the Standard Model at the LHC
- Do we need new degrees of freedom? (Where?)



CMS Collaboration (2012)

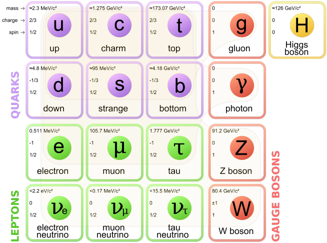


Image: Wikipedia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Joghurt
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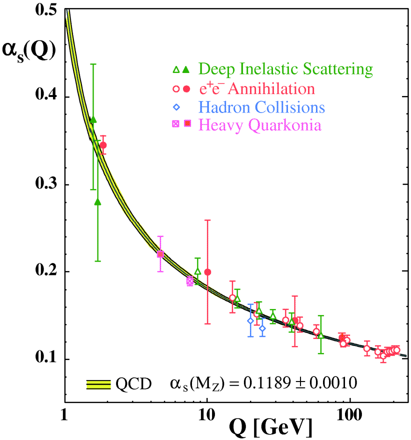
RG running of the Standard Model

- The Standard Model parameters are measured at low energies
- The interaction strength depends on the scale
- Running of the coupling is described with β-function
- Physical picture: Wilsonian block spinning / integrating out of momentum modes



Bethke (2006)

Scale dependence of the Standard Model

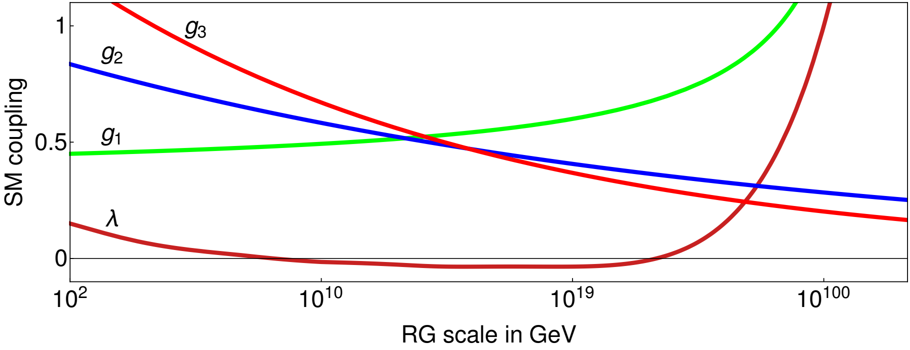
$\lambda = \phi^4$-Higgs-coupling

$g_1 =$ gauge-coupling of $U(1)$

$g_2 =$ gauge-coupling of $SU(2)$

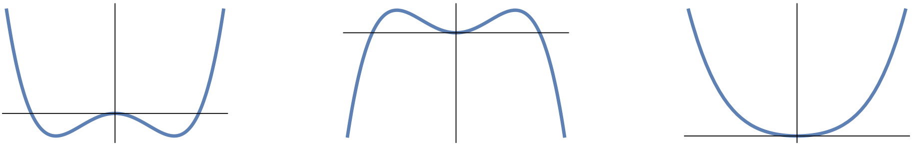
$g_3 =$ gauge-coupling of $SU(3)$

Yukawa-couplings are missing in the plot

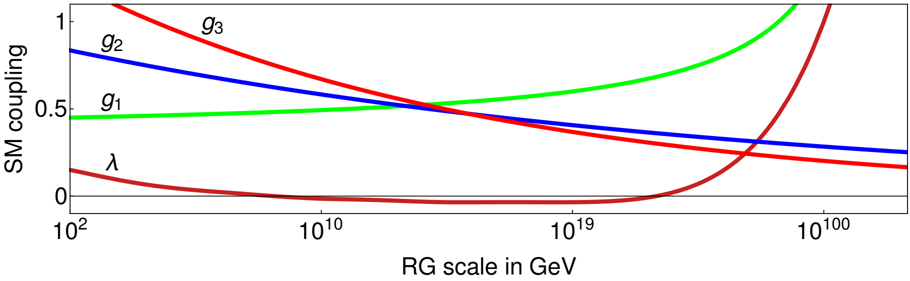


Scale dependence of the Standard Model

Higgs-potentials at different scales: $V_k(H) = \frac{\mu(k)^2}{2} H^2 + \frac{\lambda(k)}{4} H^4$



Vacuum instability at $\approx 10^{10}$ GeV?



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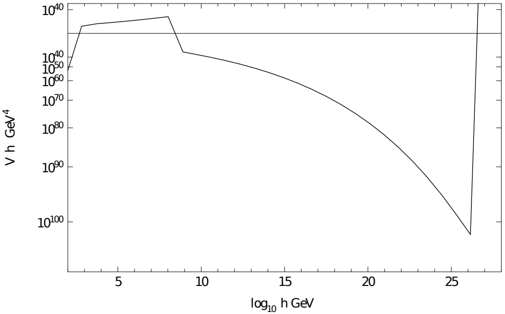

Gabrielli et al. (2014)

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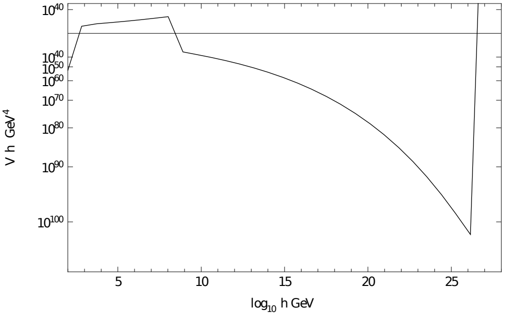
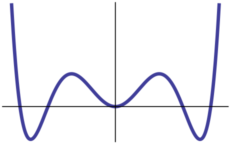


Gabrielli et al. (2014)

- Non-perturbative effects of higher dimensional operators

$$V_{\text{eff}}(k;H) = \frac{\mu(k)^2}{2} H^2 + \frac{\lambda_4(k)}{4} H^4 + \frac{\lambda_6(k)}{8k^2} H^6 + \dots$$

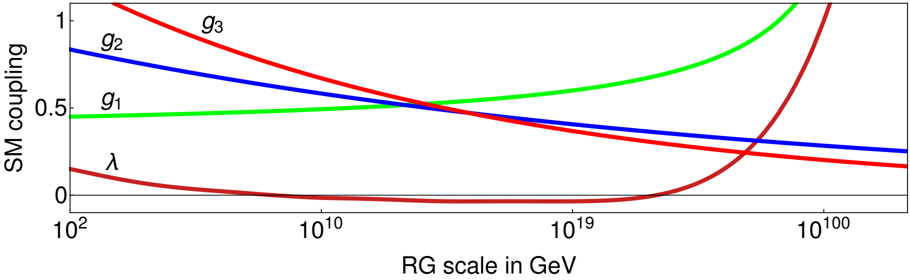
Branchina, Messina (2013); Eichhorn, Gies, Jaeckel, Plehn, Scherer, Sondenheimer (2015)



Scale dependence of the Standard Model

Beyond $M_{\text{Planck}} \approx 10^{19}$ GeV:

- Gravity effects are not taken into account
- Occurrence of Landau poles



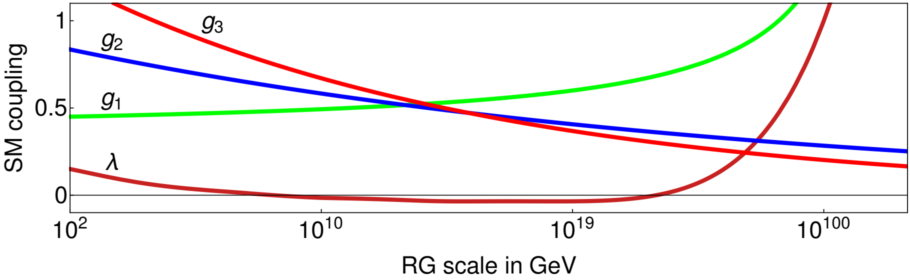
Scale dependence of the Standard Model

For RG-scale $\to \infty$ so far realised in the Standard Model:

- Coupling $\to 0$ (asymptotic freedom)
- Coupling $\to \infty$ (Landau pole)

Generalisation:

- Coupling $\to$ const. (asymptotic safety)



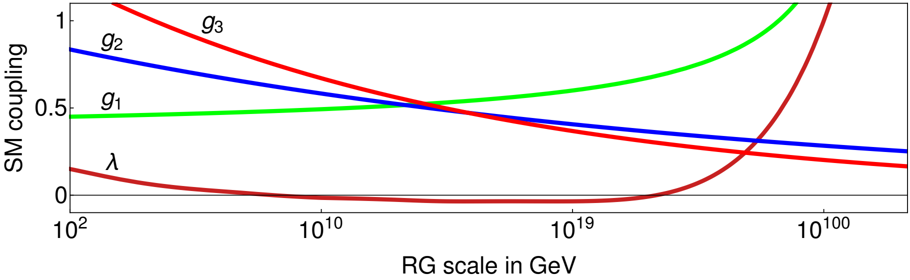
Summary: Limits of the Standard Model

Limits:

- Issues of vacuum stability of the Higgs potential at $\approx 10^{10}$ GeV
- Landau pole of g_1 and λ at scales $\gg M_{\text{Pl}}$

Missing items:

- Gravity at $M_{\text{Pl}} \approx 10^{19}$ GeV
- Dark matter (unknown scale)
- ...



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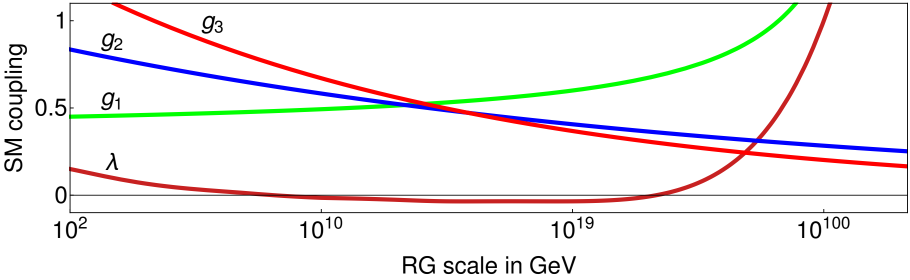


Outline

What is the Asymptotic Safety Scenario?

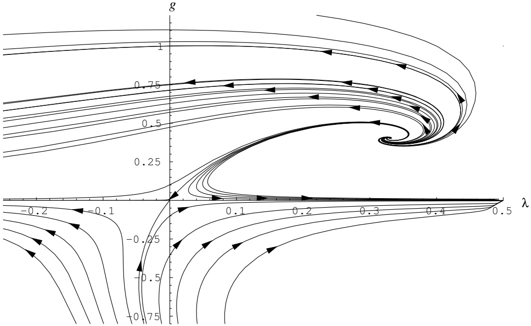
Weinberg's proposal (1976)

Non-trivial UV fixed point of the renormalisation group flow

$$S_{\mathrm{EH}} = \frac{1}{16\pi G_N} \int_x \sqrt{g}(2\Lambda - R)$$

$$\dot{g} \equiv \beta_g \xrightarrow{k\to\infty} 0$$

$$\dot{\lambda} \equiv \beta_\lambda \xrightarrow{k\to\infty} 0$$



Reuter, Saueressig (2001)

Codello, Percacci, Rahmede (2008); Benedetti, Machado, Saueressig (2009); Eichhorn, Gies (2010); Benedetti, Caravelli (2012); Donkin, Pawlowski (2012); Falls, Litim, Nikolakopoulos (2013); Dietz, Morris (2013); Codello, D'Odorico, Pagani (2013); ...

The Functional Renormalisation Group

General problem: Gravity is perturbatively non-renormalisable

$$[G_N] = -2$$

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$$\partial_t \Gamma_k = \frac{1}{2} \mathrm{STr} \left[(\Gamma_k^{(2)} + R_k)^{-1} \partial_t R_k \right]$$

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- Exact one-loop equation
- β functions in non-perturbative regime

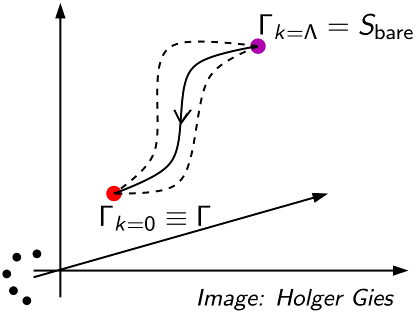

Image: Holger Gies

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- Exact one-loop equation
- β functions in non-perturbative regime
- The resulting theory is fundamental

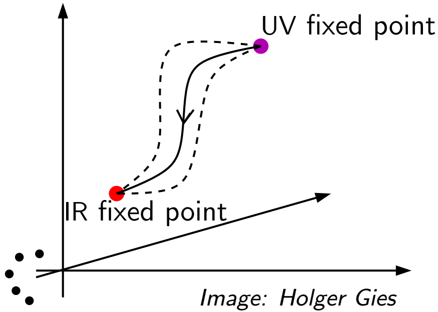

Image: Holger Gies

Our computation

Einstein-Hilbert ansatz

$$S_{\mathrm{EH}} = \frac{1}{16\pi G_N} \int \mathrm{d}^4 x \sqrt{g} (2\Lambda - R) + S_{\mathrm{gf}} + S_{\mathrm{gh}}$$

Linear metric split

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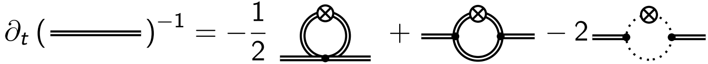
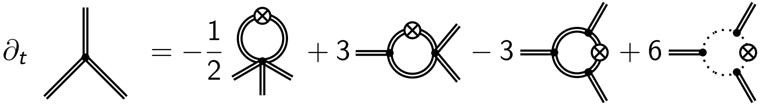
Vertex expansion to compute dynamical n-point correlation functions, e.g.

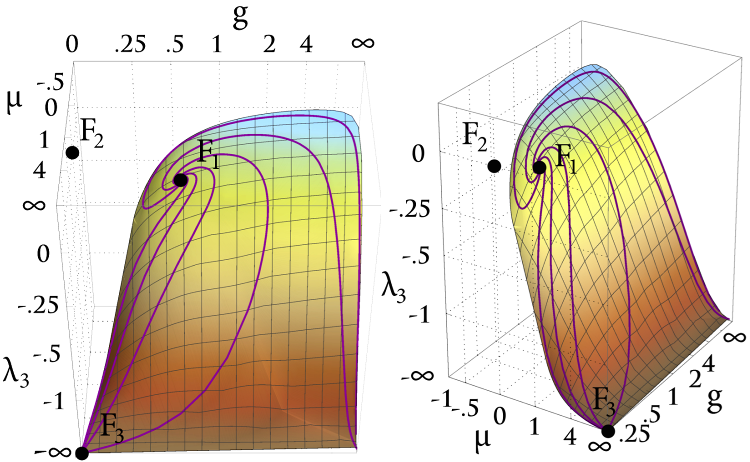
Graviton two-point function: (Flow of μ and $Z_h(p^2)$)



Graviton three-point function: (Flow of g and λ_3)



Phase diagram



F_1: UV fixed point $\quad$ F_2: Gaußian fixed point $\quad$ F_3: IR fixed point

N. Christiansen, B. Knorr, J. Meibohm, J. Pawlowski, MR (2015)

Inclusion of matter

Is the UV fixed point stable under inclusion of matter?

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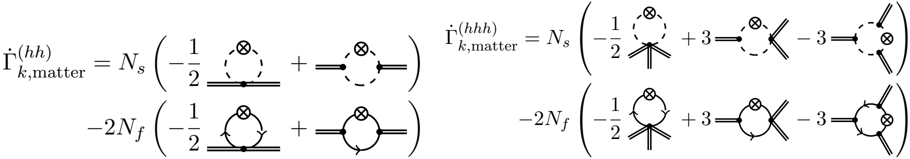
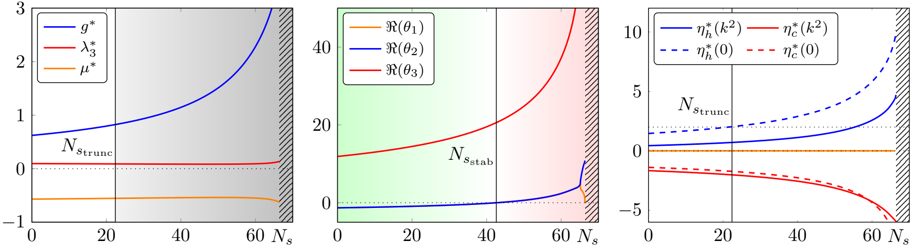
Generating action: (with N_s scalars and N_f fermions)

$$S = S_{\mathsf{EH}} + \int \mathrm{d}^4x\sqrt{g}\,\bar{\psi}_i \not{\nabla}\psi_i + \frac{1}{2}\int \mathrm{d}^4x\sqrt{g}\,g_{\mu\nu}\partial^\mu\varphi_j\partial^\nu\varphi_j$$

with $\quad i = 1, \ldots, N_f \quad$ and $\quad j = 1, \ldots, N_s$



Inclusion of scalars



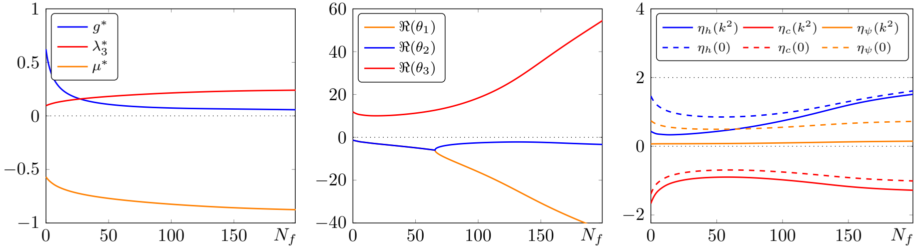
Reliability bound on truncation $N_{s_{\mathrm{trunc}}} \approx 21.5$

Loss of an attractive UV fixed point $N_{s_{\mathrm{stab}}} \approx 42.6$

Complete loss of the UV fixed point $N_{s_{\mathrm{max}}} \approx 66.4$

J. Meibohm, J. Pawlowski, MR (2015)

Inclusion of fermions



Reliable attractive UV fixed point for all N_f

J. Meibohm, J. Pawlowski, MR (2015)

Summary and Outlook

Working hypothesis:

The Standard Model + gravity is valid up to arbitrary high energy scales

- Asymptotic safety is a promising route towards a UV completion of the Standard Model
- Many indications that asymptotic safety works in gravity coupled to simple matter systems

Further research

- Investigation of the stability of the Higgs potential
- Coupling the whole Standard Model to gravity