Quantum-gravity effects on a Higgs-Yukawa model

Astrid Eichhorn
University of Heidelberg

with Aaron Held
and Jan Pawlowski

September 22, 2016
ERG 2016, ICTP, Trieste
Motivation:
Observational tests of quantum gravity
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No “smoking-gun” signal for any particular QG model, but: could rule out models this way!

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- must reduce to GR in classical limit

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- must accommodate all observed matter degrees of freedom
  example: chiral (i.e., light) fermions

asymptotic safety ✓
(in truncation) [A.E., Gies ’11; Meibohm, Pawlowski ‘15]

LQG ✓
[Gambini, Pullin ‘15]

causal sets: fermions ???
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minimally coupled SM matter fields compatible with asymptotic safety in simple truncation ✓
[Dona, A.E., Percacci ‘13]
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  (charges, interaction strengths, masses….)

→ Higgs discovery: Standard Model consistent up to high scales
Implications of the Higgs discovery

\[ V[H] = \lambda H^4 \]

only for narrow window of values of Higgs masses can we reach high scales without requiring new physics

\[ M_H = \lambda \cdot 246 \text{ GeV} \]

[Ellis et al. '09]
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→ Does gravity provide UV completion for the SM?
A window into Planck-scale physics at the electroweak scale

1. Extrapolating the SM to Very High Scales and the Higgs Potential Instability

The main result of the first run of the LHC was the discovery of the Higgs boson, with mass $M_H = 126$ GeV, which further study has shown to be compatible with the properties expected for a Standard Model (SM) Higgs, although there is still room for some deviation in its properties. Besides this great success, no trace of physics beyond the SM (BSM) has been found, and this typically translates into bounds on the mass scale of different BSM scenarios, supersymmetric or otherwise, of order the TeV. If one is willing to hold on to the paradigm of naturalness, the hierarchy problem that afflicts the breaking of the electroweak (EW) symmetry would imply that BSM physics should be around the corner, probably on the reach of the LHC. In this talk I take a different attitude: I disregard naturalness as a requisite for the physics associated to the breaking of the EW symmetry and I explore the possibility that the scale of new physics, $L$, could be as large as the Planck scale, $M_{Pl}$.

From that perspective, we have now in our hands a quantum field theory, the SM, that should then describe physics in the huge range from $M_W$ to $M_{Pl}$. All the model parameters have been determined experimentally, the last of them being the Higgs quartic coupling, fixed in this model by our knowledge of the Higgs mass. Figure 1, left plot, shows the running of the most important SM couplings extrapolated to very high energy scales using renormalization group (RG) techniques. It shows the three $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge couplings getting closer in the ultraviolet (UV) but failing to unify precisely. It also shows how the top Yukawa coupling gets weaker in the UV (due to $a_s$ effects, see below). The Higgs quartic coupling is also shown: it starts small at the EW but grows at higher scales, reaching a value of order unity at the Planck scale.

Figure 1:

- Left: Evolution of SM couplings from the EW scale to $M_{Pl}$.
- Right: Zoom on the evolution of the Higgs quartic, $\lambda$, for $M_h = 125.7$ GeV, with uncertainties in the top mass, $a_s$, and $M_h$ as indicated. (Plots taken from [9]).

[Butazzo et al. ’13]

low-energy data: viscosity of honey: matched by model A

It's about 1/3 glucose, 1/3 fructose and 1/3 water

It's about 1/2 fructose and 1/2 water

low-energy data: viscosity of honey: matched by model A

A

B
Higgs sector & quantum gravity

\[ \Gamma_k = \ldots + m_h^2 H^2 + \lambda H^4 + \sum_q y_q H \bar{q} q_L + \ldots \]

\[
y_t(M_{Pl}) \approx 0.4 \rightarrow M_{\text{top}} \approx 173 \text{ GeV}
\]

\[
y_b(M_{Pl}) \approx 0 \rightarrow M_{\text{bottom}} \approx 4 \text{ GeV}
\]

[Buttazzo et al. ‘13]
Higgs sector & quantum gravity

Assume:

No new physics below $M_{\text{Planck}}$

$\rightarrow$ Quantum gravity must allow

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$g_2$: UV- attractive (relevant):
any value can be reached in IR

$g_1$: UV- repulsive (irrelevant):
IR-value fixed

$\rightarrow$ Irrelevant couplings in the Higgs sector could allow predictions:

[Buttazzo et al. ‘13]
Yukawa coupling in quantum gravity
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Toy model of the Higgs-Yukawa sector coupled to gravity:

\[ \Gamma_k = \frac{Z_\phi}{2} \int d^4x \sqrt{g} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + i Z_\psi \int d^4x \sqrt{g} \bar{\psi} \mathcal{D} \psi + i y \int d^4x \sqrt{g} \phi \bar{\psi} \psi \]

\[ - \frac{1}{16\pi G_N} \int d^4x \sqrt{g} (R - 2\lambda) + S_{gf} \]
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$$- \frac{1}{16\pi G_N} \int d^4x \sqrt{g} (R - 2\lambda) + S_{gf}$$

Quantum-gravity effects on Yukawa coupling

(Functional Renormalization Group)

See also

Zanusso, Zambelli, Vacca, Percacci, '09
Oda, Yamada '15
Yukawa coupling in quantum gravity

\[ \alpha = 1, \beta = 1 \]

\[ \beta_y = \left( \eta_\phi / 2 + \eta_\psi \right) y + \frac{60 - 5\eta_\phi - 6\eta_\psi}{480\pi^2} y^3 + G y \frac{32 + \eta_\psi}{10\pi} \]

\[ \beta_G = 2G - G^2 \frac{43}{6\pi} + \ldots \]
Yukawa coupling in quantum gravity

for $\alpha = 1, \beta = 1$

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$\rightarrow$ fixed point at $y = 0$, $G > 0$
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UV repulsive

UV attractive

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Prediction (within toy model): $$y(M_{Pl}) \approx 0$$
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gauge dependence: 
\[ F_\mu = \bar{D}_\nu h_\mu - \frac{1 + \beta}{4} \bar{D}_\mu h \]

UV repulsive

UV attractive

\[ \text{w. graviton "mass" parameter from fluctuation calc.} \]
Yukawa coupling in quantum gravity

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Beyond canonical power counting

\[ \Gamma_k = \frac{Z_\phi}{2} \int d^4x \sqrt{g} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + i Z_\psi \int d^4x \sqrt{g} \bar{\psi} \nabla \psi + i y \int d^4x \sqrt{g} \phi \bar{\psi} \psi \]

Can canonical interaction terms capture the full dynamics of matter in quantum gravity?
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matter-gravity interaction vertices from kinetic term

generate new momentum-dependent matter self-interactions

A.E., H. Gies '11  A.E. '12
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vertices depend on momenta of the matter fields:

\[ \frac{\chi_{-1}}{k^4} \int_x \sqrt{g} \left[ (\bar{\psi} \gamma^\mu \nabla_\nu \psi - (\nabla_\nu \bar{\psi}) \gamma^\mu \psi) \partial_\mu \phi \partial_\nu \phi \right] + \frac{\chi_{-2}}{k^4} \int_x \sqrt{g} \left[ (\bar{\psi} \gamma^\mu \nabla_\mu \psi - (\nabla_\mu \bar{\psi}) \gamma^\mu \psi) \partial_\nu \phi \partial_\nu \phi \right] \]

A.E., A. Held, J. Pawlowski '16
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strong gravity fluctuations appear incompatible with existence of fixed point in matter sector
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strong gravity fluctuations appear incompatible with existence of fixed point in matter sector but: critical interaction strength not exceeded (within truncation) → joint fixed point
Conclusions

• properties of the matter sector offer observational consistency tests for quantum gravity

• microscopic model must admit all observed properties of matter (values of masses etc)

• toy model of Higgs sector coupled to asymptotically safe quantum gravity:
  \[ y(M_{Pl}) \approx 0 \]
  \[ \rightarrow \text{gravity does not exceed critical strength for fixed-point annihilation in Yukawa sector} \]
  \[ \rightarrow \text{momentum-dependent scalar-fermion interactions} \]

Outlook: Realistic Yukawa sector (top-bottom asymmetry)