On Gravitational Corrections to the Electroweak Vacuum Decay

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Mainly based on

- Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (JHEP) arXiv:1307.3536
- Giudice, Isidori, Salvio, Strumia (JHEP) arXiv:1412.2769
- Salvio, Strumia, Tetradis, Urbano (JHEP) arXiv:1608.02555

Testing the Standard Model (SM) at ultrahigh energies

Two important goals of the LHC:

- testing the SM
- discovering new physics (NP)

But one can also complementary test the SM at even higher energies:
e.g. the stability bound

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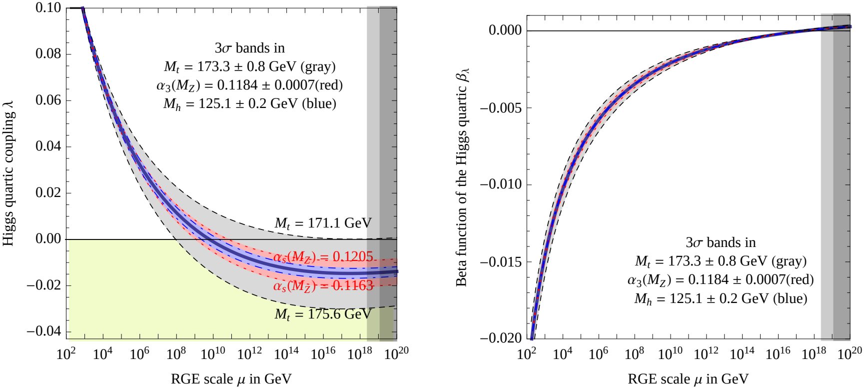
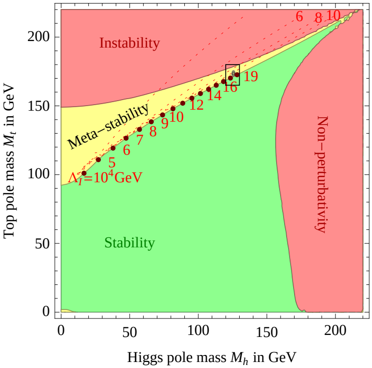
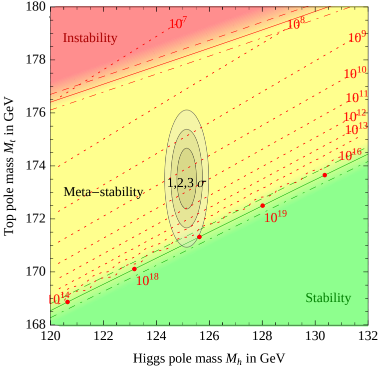
Precise "running" of λ and its β-function $\left(\beta_\lambda \equiv \dfrac{d\lambda}{d\ln\mu}\right)$



Result for the stability of the electroweak (EW) vacuum

Phase diagram of the SM:





[Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (2014)]
The stability of the electroweak vacuum is violated at the $\sim 3\sigma$ level

We see the main uncertainty is due to the top mass, M_t

Result for the stability bound

$$M_h > 129.6\,\mathrm{GeV} + 2.0(M_t - 173.34\,\mathrm{GeV}) - 0.5\,\mathrm{GeV}\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007} \pm 0.3_{\mathrm{th}}\,\mathrm{GeV}$$

The stability bound is violated at the $\sim 3\sigma$ level

Since the experimental error on the Higgs mass is small it is better to express the bound in terms of the pole top mass:

$$M_t < (171.53 \pm 0.15 \pm 0.23_{\alpha_3} \pm 0.15_{M_h})\,\mathrm{GeV} = (171.53 \pm 0.42)\,\mathrm{GeV}.$$

[Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (2014)]

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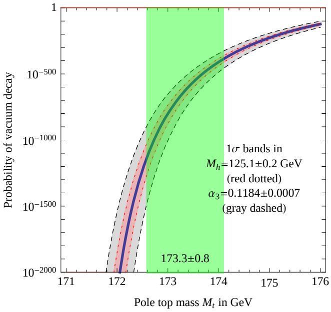
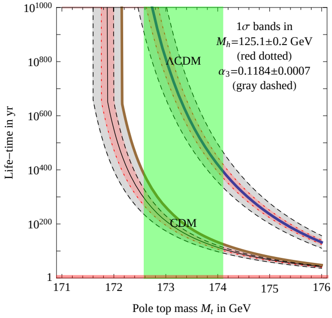
Flat space analysis:





Left: *Probability of EW vacuum decay.*

Right: The life-time of the EW vacuum, with 2 different assumptions for future cosmology: universes dominated by the cosmological constant (ΛCDM) or by the dark matter (CDM).

[Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (2014)]

Details on the calculation of the probability of vacuum decay

The probability $d\mathcal{P}/dV\,dt$ per unit time and volume of creating a bubble of true vacuum within a space volume dV and time interval dt is

$$d\mathcal{P} = dt\,dV\;\Lambda_B^4\,e^{-S_B}$$

S_B is the action of the bounce of size $R \equiv \Lambda_B^{-1}$: the bounce h is an SO(4) symmetric Euclidean solution

$$h'' + \frac{3}{r}h' = \frac{dV}{dh}, \quad \text{with boundary conditions} \quad h'(0) = 0, \quad h(\infty) = h_{\rm EW}$$

[Coleman (1977); Coleman, Callan (1977)]

Gravitational corrections

We are looking at extremely high energies, sometimes reaching the Planck mass, $\bar{M}_{\rm Pl}$. Does gravity play a role?

One can address this question in Einstein gravity (compatible with all experiments)

$$\mathscr{L} = \mathscr{L}_{\rm Einstein} + \mathscr{L}_{\rm SM} - \xi |H|^2 R$$

However, Einstein gravity is an effective theory with a cutoff $\sim \bar{M}_{\rm Pl}$
$\rightarrow$ consider an expansion in $E/\bar{M}_{\rm Pl}$ (it is not restrictive: for $E > \bar{M}_{\rm Pl}$ the theory breaks down)

Some details on the inclusion of gravity

(First down in *[Coleman, de Luccia (1980)]*)

The bounce equation becomes a Higgs-gravity system of equations

$$h'' + 3\frac{\rho'}{\rho}h' = \frac{dV}{dh} - \xi h \mathcal{R}, \qquad \rho'^2 = 1 + \frac{\rho^2/\bar{M}_{\rm Pl}^2}{3(1+\xi h^2/\bar{M}_{\rm Pl}^2)}\left(\frac{h'^2}{2} - V - 6\frac{\rho'}{\rho}\xi h h'\right)$$

where $\mathcal{R}$ is the Ricci scalar for the metric

$$ds^2 = dr^2 + \rho(r)^2 d\Omega^2$$

($d\Omega$ is the volume element of the unit 3-sphere)

[Salvio, Strumia, Tetradis, Urbano (2016)]

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We developed a perturbation theory in $1/R\bar{M}_{\rm Pl}$
which is adequate to describe the gravitational corrections within Einstein gravity.

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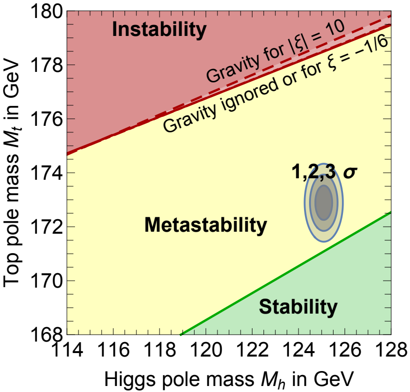
We developed a perturbation theory in $1/R\bar{M}_{\rm Pl}$ **(weak gravity expansion)** which is adequate to describe the gravitational corrections within Einstein gravity.

[Salvio, Strumia, Tetradis, Urbano (2016)]

Impact of Einstein gravity on the phase diagram of the SM



This updates the plot in *[Salvio, Strumia, Tetradis, Urbano (2016)]* by using more recent measurements of M_t.

Unnaturalness of the SM + Einstein gravity

Recall naturalness:

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- when $g \ll 1$ and $M_{NP} \gg$ TeV

A problem:

gravity introduces a large scale $M_{\rm Pl} \gg$TeV

Naturalness and gravity

We do not know if G_N simply describes a coupling constant
or signals the presence of new degrees of freedom with mass $\bar{M}_{\rm Pl} = 1/\sqrt{8\pi G_N}$

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Idea (*softened gravity*): consider theories where the power-law increase of the gravitational coupling stops at $\Lambda_G \ll \bar{M}_{\rm Pl}$.

The gravitational contribution to the Higgs mass is then

$$\delta M_h^2 \approx \frac{G_N \Lambda_G^4}{(4\pi)^2}$$

Requiring naturalness $\rightarrow \Lambda_G \lesssim 10^{11}$ GeV

[Giudice, Isidori, Salvio, Strumia (2014)]

Softened gravity and the stability of the EW vacuum

Given that gravity becomes soft at high energies it negligibly affect the stability issue

(checked in a concrete realization of softened gravity)

However, other UV completion of Einstein gravity, such as string theory *can* affect these results

But, Planck-scale physics cannot suppress sub-Planckian contributions to SM vacuum decay, which can only be affected by new physics at lower energies.

Conclusions

- In the pure SM the vacuum stability is excluded at roughly 3σ level
- These calculations involve the extrapolation of the SM potential up to Planckian energies so one may wonder if gravity changes the result
- We included Einstein gravity within its regime of validity and found that the corrections are small, even including ξ
- We *assumed* a desert between the EW and the Planck scale. What about naturalness? We discussed that a modification of gravity which softened the strength of gravity at high energy leads to negligible modifications

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Disclaimer: *New physics below $\bar{M}_{\rm Pl}$ may or may not change completely the results*. So these calculations are useful as tests of the SM hypothesis and are possible means to find further evidences for new physics.

Thank you very much for your attention