Universal Landau Pole

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Outline:

- **Do we really need asymptotic freedom?**
  Our understanding of quantum gravity suggests that at the Planck scale the usual geometry loses its meaning. Then grand unification in a large non-abelian group naturally endowed with the property of asymptotic freedom may also lose its motivation.

- **Singular unification:**
  an unification of all fundamental interactions at the Planck scale in the form of a **Universal Landau Pole (ULP)**, at which all gauge couplings diverge.

- **Minimal working model of the Universal Landau Pole.**
  The unification is achieved with the addition of fermions with vector gauge couplings coming in multiplets and with hypercharges identical to those of the Standard Model.

- **Stability of the Higgs Potential.**
  The Higgs quartic coupling diverges while the Yukawa couplings vanish.

DO WE REALLY NEED ASYMPTOTIC FREEDOM?

- Simplicity: the less parameters the better $\rightarrow$ unification.

- Asymptotic freedom (flat space-time): the theory is valid up to infinitely high energies.

- BUT what about gravity?

- At the energies of order of Planck scale $\mathrm{M_{Pl}} \sim 10^{19}$ GeV gravity becomes strongly coupled, concept of weakly interacting point-like fields looses its meaning!

- Simplicity + pointless geometry $\rightarrow$ singular unification.

SINGULAR UNIFICATION: UNIVERSAL LANDAU POLE

- **We propose a singular unification at the Planck scale: one should find such a generalization of the Standard Model, that under the renormalization group flow ALL gauge couplings meet their common Landau pole at the Planck scale.**

$$\boxed{g_{1,2,3}(\mu) \to \infty \text{ at } \mu \to M_{Pl}}$$

- **Kinetic terms of ALL gauge fields vanish and they cannot propagate anymore.**

$$\boxed{\frac{1}{g(\mu)^2} F_{\mu\nu} F^{\mu\nu} \to 0 \text{ at } \mu \to M_{Pl}}$$

- **? UV fixed point and dimensional reduction of gauge fields ?**

$$\boxed{F_{\mu\nu} \left(\frac{1}{g(\mu)^2} + \gamma \frac{\Box}{M_{Pl}^2} + \cdots \right) F^{\mu\nu} \to \gamma F_{\mu\nu} \frac{\Box}{M_{Pl}^2} F^{\mu\nu} \text{ at } \mu \to M_{Pl}}$$

MINIMAL ULP: REQUIREMENTS

- **Simplicity: the gauge group of SM $SU(3) \times SU(2) \times U(1)$.** We add only fermions. Enlarging the gauge group in principle could be motivated by introduction of a GUT group. However it leads to ULP at 10^{16} GeV [see V. A. Rubakov and S. V. Troitsky, hep-ph/0001213, for a review] much smaller than $\mathrm{M_{Pl}}$.

- **Higgs sector: to remain unchanged.** If the new particles are described by 4-component spinors with Dirac masses and vector-like gauge interactions $\rightarrow$ no necessity for any Higgs fields. It fits well the recent LHC bounds on the number of generations [see A. Lenz, Adv. High En. Phys. 2013 (2013) 910275]

- **NO pathological electric charges** $\rightarrow$ restrictions on the representations of new fermions.

- **Stability:** quartic coupling of the Higgs field self interaction λ is always positive under the renormalization group flow. It discriminates a single scenario with four generations.

MINIMAL WORKING ULP: REALIZATION

- We use Dirac mass terms $M\bar{\psi}\psi$ for new fermions and we are looking for a minimal number of them.

- New femions belong to known representations of gauge group

  L-quarkons: SU(3) - triplets, SU(2) - doublets, $Y = \frac{1}{3}$

  R-quarkons: SU(3) - triplets, SU(2) - singlets, $Y = \frac{4}{3},\ -\frac{2}{3}$

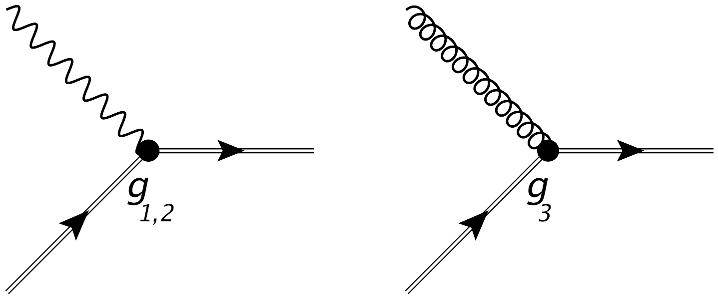
  L-leptos: SU(3) - singlets, SU(2) - doublets, $Y = -1$

  R-leptos: SU(3) - singlets, SU(2) - singlets, $Y = -2,\ 0$

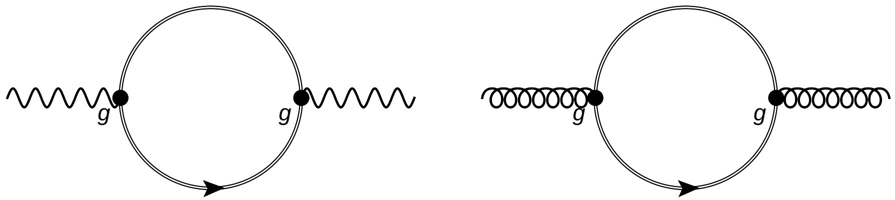
- Remark: L- and R- notations do not imply left and right chiralities! They vector-like relatives.

MINIMAL WORKING ULP: REALIZATION

The only new vertexes appearing in the theory couple Quarkons and Leptos to E-W gauge bosons and gluons.



And at one loop level only beta functions of gauge fields are modified due to presence of these diagramms:

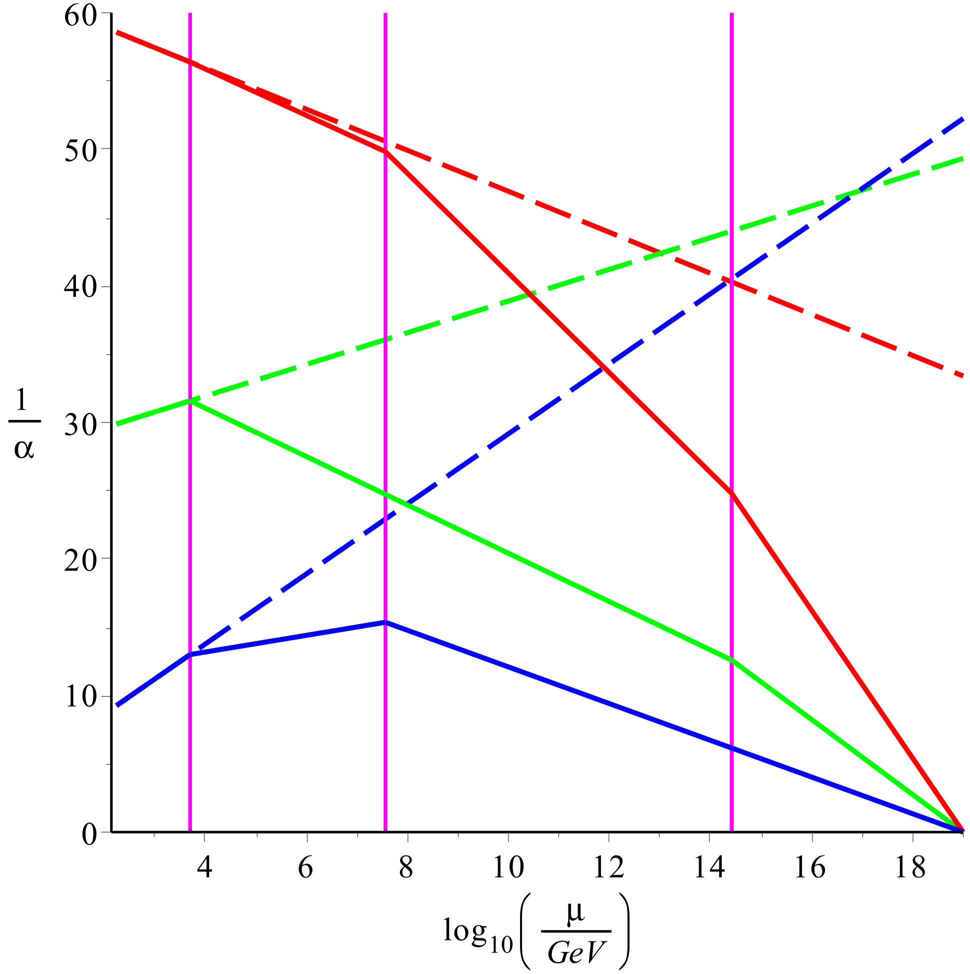


MINIMAL WORKING ULP: THE ANSWER

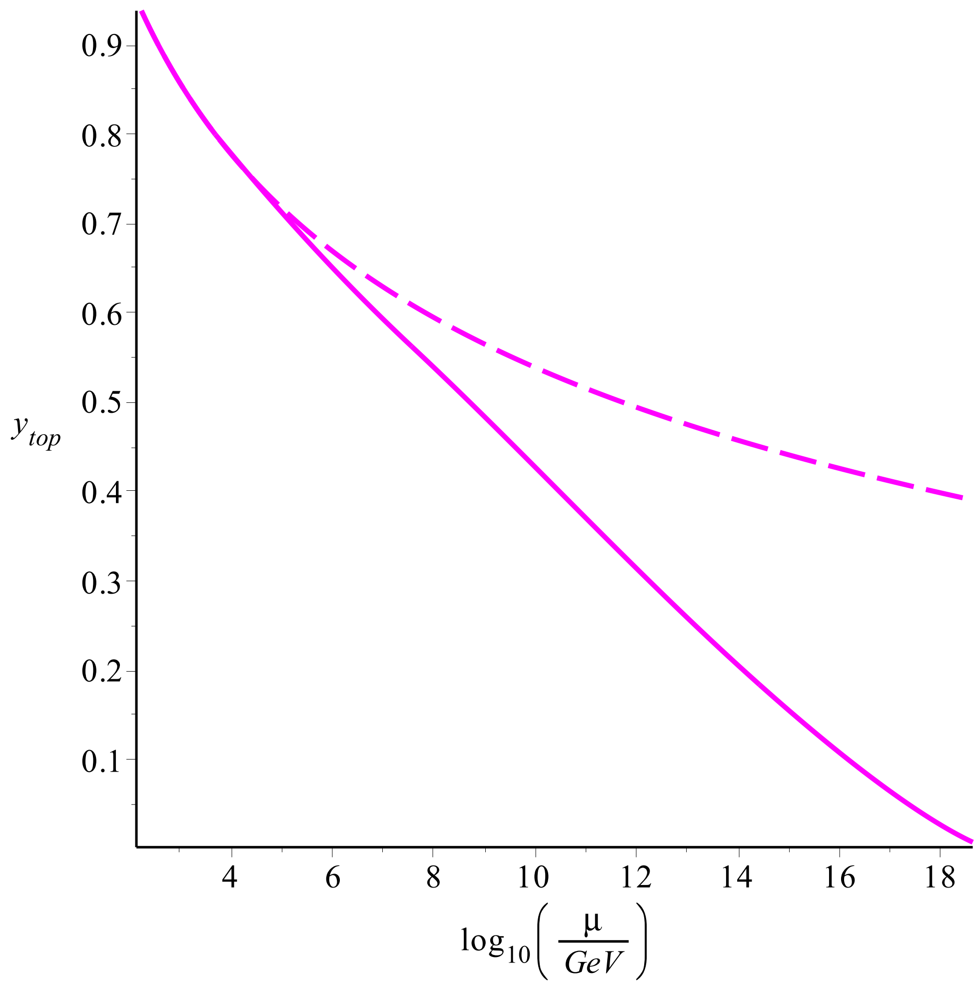
ULP can be rendered within 4 identical "generations" of new vector-like massive fermions with different mass scales:

- **At** $5.0 \cdot 10^3$ **GeV L-quarkons (**$N_{\mathrm{L-quarkon}} = 4$**).**
- **At** $3.7 \cdot 10^7$ **GeV R-quarkons (**$N_{\mathrm{R-quarkon}} = 4$**).**
- **At** $2.6 \cdot 10^{14}$ **GeV L and R-leptos (**$N_{\mathrm{L-leptos}} = N_{\mathrm{R-leptos}} = 4$**).**

One(two)-loop RG running of gauge couplings



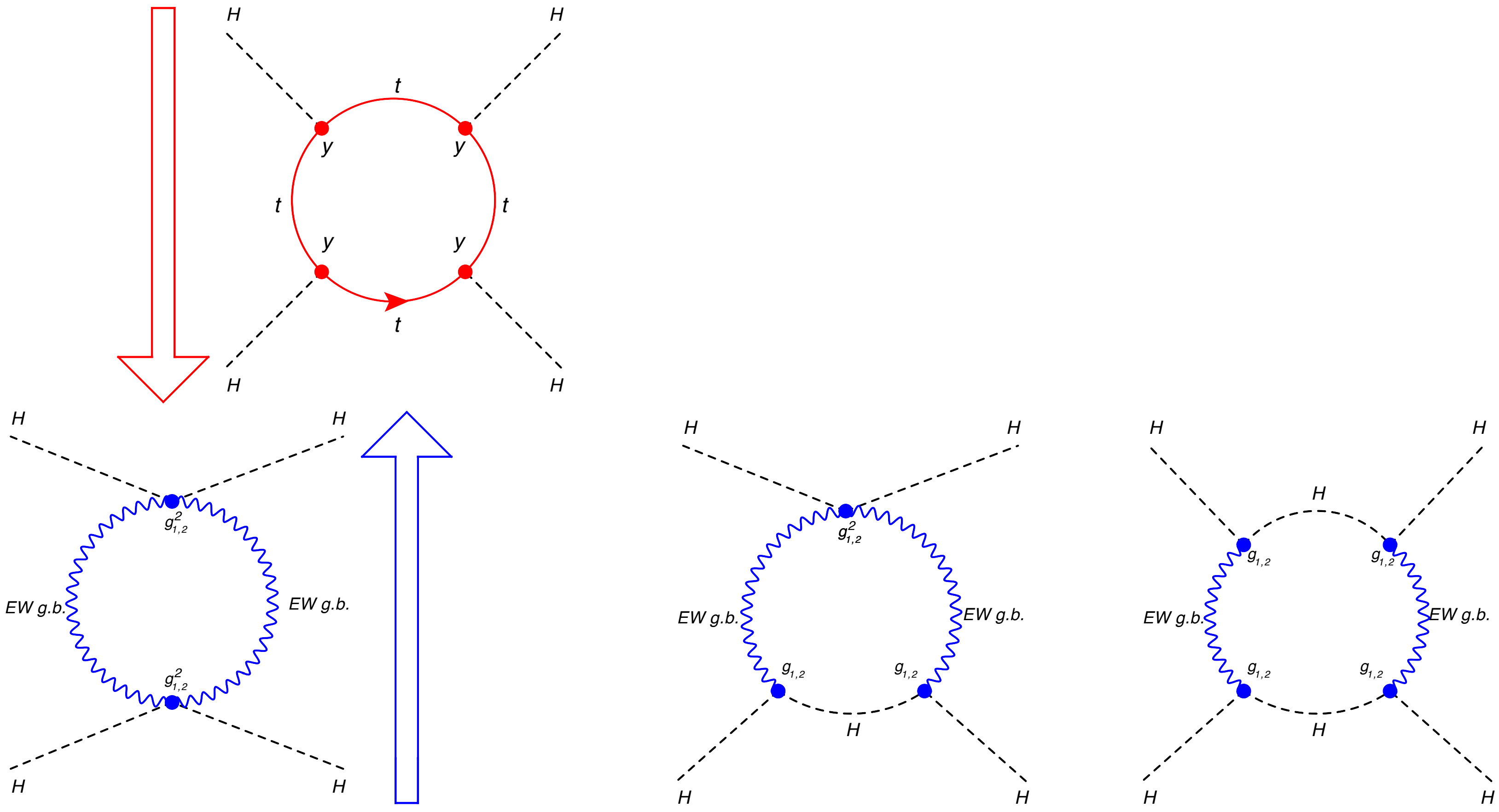
One(two)-loop RG running of top Yukawa coupling



ON THE STABILITY OF THE HIGGS POTENTIAL

Now we clarify how our vector-like fermions save the Universe from instability, i.e. how they don't let RG flow to drive the quartic coupling $\lambda(\mu)$ to negative values.

$$\beta_\lambda^{(1)} = \frac{1}{16\pi^2}\Big(24\,\lambda^2 - 6\,y^4 \underline{+ \frac{3}{4}\,g_2^4 + \frac{3}{8}\,\left({g_2}^2 + {g_1}^2\right)^2} + \left(-9\,{g_2}^2 - 3\,{g_1}^2 + 12\,y^2\right)\lambda\Big)\,.$$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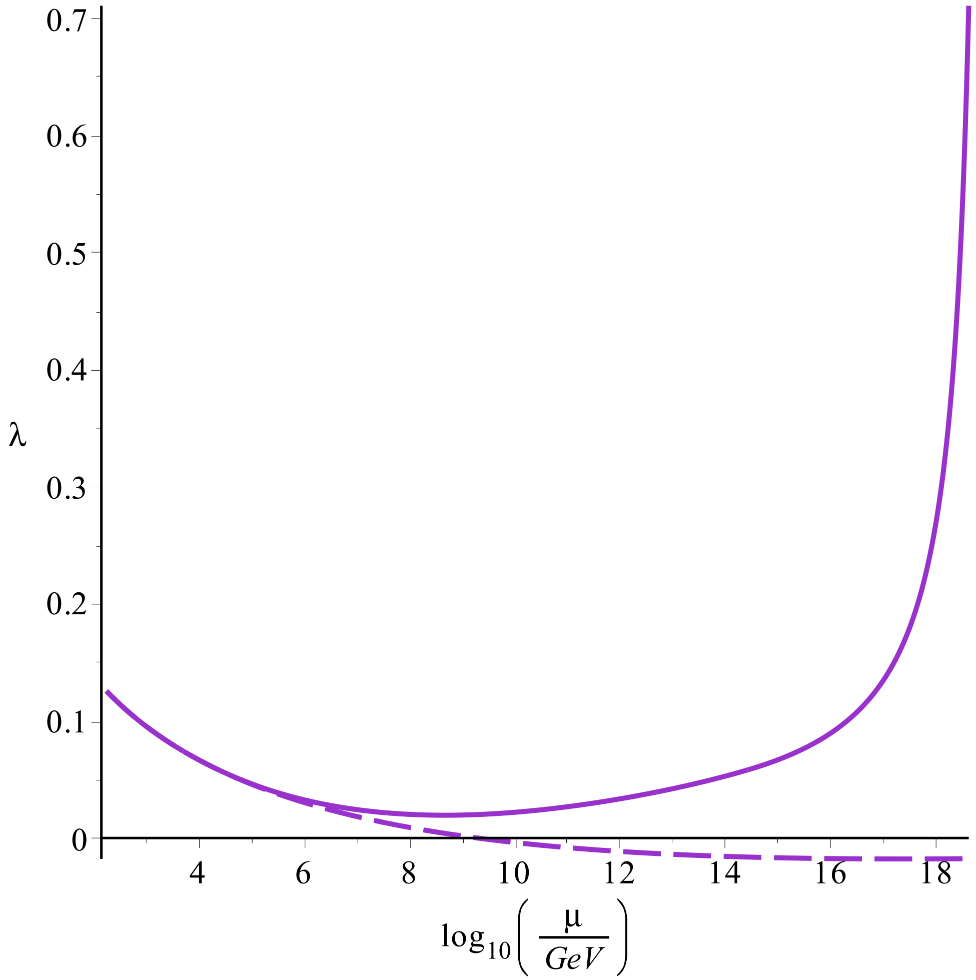
One(two)-loop RG running of Higgs boson quartic coupling



UV completion

It could well be the case that the onset of gravity corrections renders the ULP non-singular. Indeed gravity being non-renormalizable will require higher-dimensional operators with more derivatives to make the theory finite. In particular, we expect dimension six kinetic terms like

$$\boxed{\frac{\gamma}{2M_P^2}\mathbf{tr}\left(D_\mu W^{\mu\nu} D_\mu W^\mu_\nu\right) + \cdots}$$

This would correspond to a renormalization of the gauge coupling induced by gravity of the form

$$\boxed{\frac{1}{g^2(p^2)} \simeq \beta_0 \log \frac{m_P^2}{p^2} + \gamma \frac{p^2}{m_P^2}}$$

Thus gravitational corrections may drive the ULP towards a new fixed point [see, for instance, M. E. Shaposhnikov, Theor. Math. Phys. 170, 229 (2012)].

CONCLUSIONS

- An idea of singular unification of ALL gauge interactions at the Planck scale, can be realized in the form of the Universal Landau Pole (ULP).

- The minimal working model of ULP generalization of the SM is constructed.

- Under the RG flow the top Yukawa coupling eventually goes to zero while the quartic coupling has a concordant singularity at the Planck scale. Such a RG behavior saves the Universe from instability problem.

- Yukawa couplings for quarks and leptons run to zero differently: the latter for leptons are diminishing more slowly (due to lack of gluon contribution). Thereby the ULP unification may give a partial resolution of fermion mass hierarchy problem in the range of strong gauge couplings (AEKL, in progress).

- For this problem the two-loop contribution may be essential (in progress).