



# A first-order electroweak phase transition from varying Yukawas

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## ABSTRACT

We show that the dynamics responsible for the variation of the Yukawa couplings of the Standard Model fermions generically leads to a very strong first-order electroweak phase transition, assuming that the Yukawa couplings are large and of order 1 before the electroweak phase transition and reach their present value afterwards. There are good motivations to consider that the flavour structure could emerge during electroweak symmetry breaking, for example if the Froggatt–Nielsen field dynamics were linked to the Higgs field. In this paper, we do not need to assume any particular theory of flavour and show in a model-independent way how the nature of the electroweak phase transition is completely changed when the Standard Model Yukawas vary at the same time as the Higgs is acquiring its vacuum expectation value. The thermal contribution of the fermions creates a barrier between the symmetric and broken phase minima of the effective potential, leading to a first-order phase transition. This offers new routes for generating the baryon asymmetry at the electroweak scale, strongly tied to flavour models.

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## 1. Introduction

While the Higgs sector has started to be well measured at the LHC, the nature of the electroweak phase transition (EWPT) still remains very poorly constrained. In fact, it depends only weakly on the value of the Higgs mass which solely provides information about the Higgs potential in the vicinity of its broken-electroweak-symmetry minimum and not on its global properties. In the Standard Model (SM), the EWPT is a rapid crossover [1] but minimal extensions of the SM can make it first-order. By further constraining the Higgs couplings, the next run of the LHC will provide new probes of models leading to first-order EWPT, which would have major implications for EW baryogenesis and therefore our understanding of the origin of the matter antimatter asymmetry of the universe [2]. The EW baryogenesis framework relies on the existence of a strongly first-order EW phase transition [3,4]. The baryon asymmetry is produced in the vicinity of the EW symmetry breaking bubble walls [5] where all three Sakharov conditions [6] are at work. Particle distributions depart from thermal equilibrium and CP-violating currents are converted into baryons by sphalerons [7,8].

A variety of mechanisms leading to a first-order EWPT have been proposed. Extensions of the Standard Model (SM) where the

barrier separating the symmetric and broken phase minima is thermally generated due to loops of new bosonic modes in the Higgs effective potential, e.g. in the supersymmetric extension of the SM [9], have been severely constrained by Higgs measurements. In contrast, a model where the Higgs potential is modified at tree level due to the couplings of the Higgs to an additional singlet, leading to potentially a 2-step EWPT is a very simple scenario which remains difficult to test, e.g. [10,11]. Finally, models where EW symmetry breaking is induced by a dilaton [12–14], with couplings similar to the Higgs, although relatively suppressed, are another interesting and testable possibility.

We present a different path here. We show that if the Yukawa couplings  $y_{ij}$  in the interactions between the SM fermions and the Higgs boson,  $y_{ij} \bar{f}_L^i \Phi^{(c)} f_R^j$ , vary during the EWPT, from a value of order 1 at the beginning of the EWPT to their present value at the end of the EWPT when  $\langle \Phi \rangle = v/\sqrt{2}$ , this can lead naturally to a very strong first-order PT.

## 2. Emerging flavour during EW symmetry breaking

A variation of the Yukawa couplings during the EWPT is actually well-motivated when considering how the flavour structure and fermion mass hierarchy of the SM may emerge. There are three main mechanisms to describe fermion masses  $m_f = y_f v/\sqrt{2}$ : spontaneously broken abelian flavour symmetries as originally pro-

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posed by Froggatt and Nielsen [15] (FN), localisation of the profiles of the fermionic zero modes in extra dimensions [16] and partial fermion compositeness in composite Higgs models [17]. The last two scenarios may be related by holography [18,19]. The scale  $M$  at which the flavour structure emerges is not a-priori constrained. In FN constructions, the Yukawa couplings are controlled by the breaking parameter of a flavour symmetry. A scalar field  $\chi$  carrying a negative unit of the abelian charge develops a vacuum expectation value (VEV) and

$$y_{ij} \sim (\langle \chi \rangle / M)^{-q_i + q_j + q_H}, \quad (1)$$

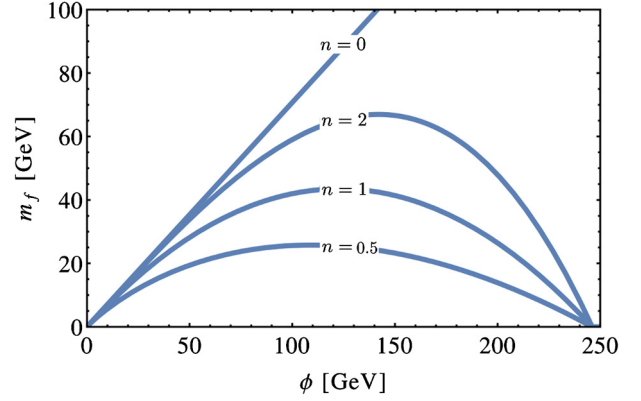
where the  $q$ 's are the flavor charges of the fermions and the Higgs. For an appropriate choice of flavour charges and with  $\langle \chi \rangle / M \sim 0.22$ , measured masses and mixings can be well described. In most FN constructions, the prejudice is that the scale  $M$  is very high, close to the GUT or Planck scale. However, it could be lower, and even close to the EW scale [20–29].

While there is a huge literature on models advocated to explain the fermion masses [30], until recently there was no study on the associated cosmology. On the other hand, in all flavour models, Yukawa couplings are controlled by the VEV of some scalar fields (the so-called “flavons”) and it is natural to wonder about their cosmological dynamics. Our working assumption is that the flavon couples to the Higgs and therefore the flavon and the Higgs VEV dynamics are intertwined, motivating the possibility that the Yukawas vary during the EWPT. The various implications of this framework for electroweak baryogenesis are presented in a series of papers (reviewed in [31]). In particular, the CKM matrix as the unique CP-violating source is discussed in [32]. Specific models of varying Yukawas have been studied: Froggatt–Nielsen [33,34], Randall–Sundrum [35] and composite Higgs [36,37].

In this letter, the key point we want to make is that even before specifying the dynamics responsible for the evolution of the Yukawas, we can derive important implications for the nature of the EWPT. The fact that the Yukawas of the SM were large during the EWPT is enough to change the nature of the EWPT, even when ignoring the flavon dynamics and only considering the SM degrees of freedom (dof) in the first place. We refer to the above references for specific realisations and the associated experimental constraints.

### 3. Effect of fermionic masses on the EWPT

The physics of the effect of varying Yukawas is related to the contribution of effective relativistic dof  $g_*$  to the effective potential  $V_{\text{eff}} \supset -g_* \pi^2 T^4 / 90$ . Regions in Higgs space in which species are massive correspond to a decrease in  $g_*$  and hence an increase in  $V_{\text{eff}}$ . The effect of species coupled to the Higgs is therefore to delay and hence strengthen the phase transition. In the usually assumed case where the Yukawas have the same values during the EWPT as today, all Yukawas except the one of the top quark are small and therefore almost all fermions are light even in the broken phase during the EWPT. Therefore there is no significant change in  $g_*$  during the EWPT and the effect of the light fermions is negligible. Crucially, the contribution of bosonic species to the finite- $T$  effective potential also includes a term cubic in the mass and hence bosonic dof not only delay the phase transition but also create a barrier between the two minima. However, the effect of the SM bosons is insufficient to provide a strong first-order phase transition [1]. Thus, the common lore consists of adding additional bosonic degrees of freedom to strengthen the phase transition. As mentioned in the introduction, this has been severely constrained at the LHC.



**Fig. 1.** The mass of a fermionic species as a function of  $\phi$  for a constant Yukawa coupling,  $n = 0$ , and varying Yukawas. In the constant Yukawa case we take  $y(\phi) = 1$ . For the varying Yukawa cases we take  $y_1 = 1$  and  $y_0 = 0$  (see Eq. 2).

On the other hand, it was shown in [38] that adding new strongly-coupled fermions with *constant* Yukawa couplings can also help to strengthen the EWPT. Though these do not create a thermal barrier on their own, they can lead to a decrease in  $g_*$  between the symmetric and broken phases and hence delay and strengthen the phase transition. However, these models suffer from a vacuum instability near the EW scale due to the strong coupling of the new fermions and new bosons are also needed to cure this instability.

In our approach of varying Yukawas, these problems are alleviated. We are interested in models where the variation of the Yukawa couplings is due to the VEV of a flavon field, coupled to the Higgs, whose VEV therefore also varies during the EWPT. If the Yukawa couplings decrease with the Higgs background value  $\phi$ , the SM fermions can be massless both in the symmetric phase, at  $\phi = 0$ , as well as at  $\phi \sim v$  due to the falling couplings, but be massive somewhere in between, i.e. in the region  $0 < \phi < v$ . This raises the potential in this area and can therefore create a barrier. The quantitative size of this effect is encoded in the effective potential which we shall study below.

We stress that this does not mean that the Yukawa couplings are controlled solely by the Higgs field, i.e. the Higgs need not itself be the flavon (such a scenario is strongly constrained by various Higgs and flavour measurements, see [20,21,26,27]). The variation of the Yukawas is related to the variation of the Higgs VEV during the EWPT (during which the flavon VEV may also change) but the Yukawas today do not depend on the Higgs VEV  $v = 246$  GeV nor are the Higgs-fermion couplings sizeably affected. Model-dependent implementations are presented elsewhere [31, 33–37].

The aim of this letter is to stress the model-independent features of the physics of Yukawa variation. We will therefore present results using the following ansatz for the variation of the Yukawa related to the variation of the Higgs VEV itself (once the path is known in the  $(\phi, \chi)$  plane, we can eliminate the flavon VEV via the relation  $\chi(\phi)$ ):

$$y(\phi) = \begin{cases} y_1 \left(1 - \left[\frac{\phi}{v}\right]^n\right) + y_0 & \text{for } \phi \leq v, \\ y_0 & \text{for } \phi \geq v. \end{cases} \quad (2)$$

The mass of the fermion species is given by

$$m_f = \frac{y(\phi)\phi}{\sqrt{2}}, \quad (3)$$

and we illustrate the dependence of  $m_f$  on  $\phi$  in Fig. 1. Equation (2) just expresses the fact that before the EWPT, the Yukawas take val-

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