New physics beyond the standard model of particle physics and parallel universes

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Abstract

It is shown that if - and only if - “parallel universes” exist, an electroweak vacuum that is expected to have decayed since the big bang with a high probability might exist. It would neither necessarily render our existence unlikely nor could it be observed. In this special case the observation of certain combinations of Higgs-boson and top-quark masses - for which the standard model predicts such a decay - cannot be interpreted as evidence for new physics at low energy scales. The question of whether parallel universes exist is of interest to our understanding of the standard model of particle physics.

Key words: Electroweak vacuum: decay, Higgs-boson and top-quark masses: limits, Foundations of quantum mechanics and cosmology: parallel universes
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1 Introduction

A central question of particle physics is whether there is new physics beyond the standard-model of particle physics[1] (SM) at energy scales that can be experimentally reached at the Tevatron or the next generation Large-Hadron collider. There is no completely compelling argument that would rule out that the standard model is valid up to extremely high energy scales such as the GUT unification or even the Planck scale.

One of the best arguments in favour of new physics at moderate energy scales are experimental indications for a light SM Higgs boson. When the LEP-2 accelerator at CERN closed down finally on November 3, 2000, it had produced

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slightly more events that are compatible with being due to the decay of Higgs bosons with a rest mass of

\[ m_H = 115^{+0.7}_{-0.5} \text{ GeV} \]  

(1)

than expected from background processes[2,3]. If the Higgs boson mass, \( m_H \) and the top quark mass \( m_t \) do not satisfy the approximate relationship

\[ m_t < 0.43 \, m_H + 120.2 \, \text{GeV} \]  

(2)

and if the SM is correct up to the Planck scale then the electroweak vacuum is expected to have decayed from the presently observed “false” state into a “true” state since the beginning of the universe[4]\(^1\). This transition increases all particle masses by many orders of magnitude and releases a tremendous amount of energy. These effects make life as we know it impossible in the true vacuum. Therefore the following conclusion “C” is usually drawn: *If the SM is correct up to the Planck scale, we conclude from our very existence, that combinations of \( m_t \) and \( M_H \) that violate eq.(2) are empirically ruled out.*

The current “world average” for the mass of the top quark is[5]:

\[ m_t = 178.0 \pm 4.3 \, \text{GeV}. \]  

(3)

Eqs.(1,3) are incompatible with eq.(2) on the 1.9-\( \sigma \) level\(^2\). This disagreement is not compelling statistically. Moreover, the assumption that the early universe went through a very hot phase, used by Espinosa & Quirós to derive eq.(2), is not completely certain[7]. Still, it has been convincingly argued by Ellis et al.[8], that the fact that observations favour particle masses that are ruled out by conclusion C is an argument to give up its assumption: the validity of the SM up to very high energies. New physics, most likely supersymmetry, could then stabilize the electroweak vacuum at energies below \( 10^6 \) GeV even for the central values of eqs.(1,3). This argument is of momentous importance for high-energy physics and deserves to be scrutinized from various angles.

Here I argue, that conclusion C might be avoided in a completely different way than the one proposed by Ellis et al.. It might fail because parallel universes exist. As a preparation, the next section 2 reviews the concept of parallel universes. Section 3 explains why their existence allows to reconcile a vacuum that decayed with a high probability with our experience that it didn’t. Section 4 concludes.

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\(^1\) Eq.(2) approximates an exact calculation given by Espinosa & Quirós[4] within its errors for a strong-interaction constant \( \alpha_S = 0.118 \).

\(^2\) A recent preliminary update found 172.7 ± 2.9 GeV[6], which corresponds to a 1.1-\( \sigma \) discrepancy.
My purpose is only to delineate a special circumstance under which an important argument about the SM’s limits of validity ceases to hold. No anthropic arguments of any sort are intended.

2 Parallel universes

“Parallel universes” are an infinity of distinct universes that are completely identical to ours until a random decision makes subsets of them different in the random-decision results. They might exist as a consequence of various physical theories. One possibility is that the universe is spatially infinite and homogeneous on large scales and contains infinitely many Hubble-distance sized regions with an identical structure because the chance for their formation is finite (parallel universes separated in Minkowski space)[9]. Another option is that the basic postulates of quantum mechanics can be literally extrapolated to human observers, thus leading to different components after each quantum-mechanical measurement, each representing a universe with a different measurement result (parallel universes separated in Hilbert space)[10,11,12]. Both possibilities are speculative. However, there is general agreement that both are fully compatible with the current “concordance model” of cosmology and standard quantum mechanics, respectively. They are no arbitrary additions to these theories but might be natural consequences of them. For demonstration purposes I will usually assume the latter possibility in the rest of this paper - Everett’s many worlds interpretation of quantum mechanics - without claiming that this is the only possibility. Other parallel universes do not have any direct influence on ours, either because they are located far beyond our cosmological horizon or because rapid decoherence ensures the absence of any measurable interference effects between macroscopic universes[13].

3 Parallel universes and vacuum decay

3.1 Existence after vacuum decay?

Formally standard quantum theory yields the following state of the quantum-mechanical system: “unstable vacuum and quantum fields” at the beginning of the universe:\footnote{The present discussion greatly simplifies what possibly was a complex dynamical process involving many different vacuum states.}:
\[ |\Psi_{\text{initial}}\rangle = |\text{false vacuum}\rangle \otimes |\text{quantum fields}\rangle \tag{4} \]

Here \(|\text{false vacuum}\rangle\) represents the usual quantum-mechanical false-vacuum state, and \(|\text{quantum fields}\rangle\) represent the quantum fields in nature, like the quark, electron and photon fields. If the vacuum is unstable, unitary evolution due to a standard-model operator \(U_{SM}\) has evolved this state within the 13.6 billion years since the origin of the universe into

\[ |\Psi_{\text{current}}\rangle = U_{SM} |\Psi_{\text{initial}}\rangle = \sqrt{1 - P_{\text{decay}}} |\text{false vacuum}\rangle \otimes |\text{quantum fields}; \sim \rangle + \sqrt{P_{\text{decay}}} |\text{true vacuum}\rangle \otimes |\text{quantum fields}; \times \rangle \tag{5} \]

\(|\text{true vacuum}\rangle\) is the new true-vacuum state into which the false-vacuum state decays. \(|\text{quantum fields}; \sim \rangle\) symbolizes the state of the quantum fields entangled with a false vacuum that now form (besides many other things) our humanity. \(|\text{quantum fields}; \times \rangle\) represent quantum fields entangled with a true vacuum, \(|\times \rangle\) symbolizes that these fields cannot form a living humanity. \(P_{\text{decay}}\) is the probability that vacuum decay has occurred up to to a given moment in time. If the vacuum decays, \(P_{\text{decay}}\) increases with time and can be extremely near to 1 today. However, the decay remains exponentially suppressed, i.e. \(1 - P_{\text{decay}}\) remains finite for all reasonable parameters of the SM. E.g. for the central mass values in eqs.(1,3) one obtains a decay probability\(^5\) up to the present time of \(P_{\text{decay}} \approx 1 - e^{-75}\) but the decay is still exponentially suppressed by the tiny factor of \(e^{-404}\).

It is conventional wisdom that only one of the two components in eq.(5) exists with a probability given by the Born rule (e.g. because one of them vanishes in a “collapse of the wave function”). This assumption predicts that with a probability \(P_{\text{decay}}\) the present state of the “vacuum-humanity” system is:

\[ |\Psi_{\text{current}}\rangle = |\text{true vacuum}\rangle \otimes |\text{quantum fields}; \times \rangle \tag{6} \]

Because \(P_{\text{decay}}\) is very near 1 if the vacuum is unstable, it is usually concluded that the vacuum must be at least meta-stable (i.e. stable on time scale longer than the age of the universe, so that \(P_{\text{decay}} \ll 1\) today). Conclusion C then follows as a corollary.

Alternatively - if parallel worlds exist e.g. in Everett’s many worlds interpretation - both components of eq.(5) continue to coexist (thus forming parallel

\(^4\) Relative-phase angles between components of a state are unimportant for the present purpose. They have been set to 0 throughout this paper.

\(^5\) The following numbers are taken from the work of Isidori, Ridolfi & Strumia[7] who calculated the decay probability under the conservative assumption that the universe was always at zero temperature. The effect of higher temperatures in the early universe is to push \(1-P_{\text{decay}}\) even closer to 0.
universes), so its first component “|false vacuum⟩ ⊗ |quantum fields⟩ ⊗ |false vacuum⟩” continues to exist with probability=1, no matter how small 1-\(P_{\text{decay}}\) becomes. In other words: because the overall quantum-mechanical amplitude of our universe is not measurable for us, all we can safely conclude from the empirical fact of our existence is that this first component did not completely vanish up to now. Human consciousness is not fully understood, yet, so it might remain controversial if the state described by eq.(5) is really compatible with human experience if \((1-P_{\text{decay}}) \ll 1\). However, all that is needed to draw this paper’s conclusion is the undeniable fact that such a compatibility cannot be ruled out, presently. The proposition of compatibility can be formulated as the following complement to the Born rule:

1 If parallel universes do exist the Born rule must be applied only to those state components that contain observers that continue to exist after the measurement.

3.2 Detecting vacuum decay?

If \(P_{\text{decay}}\) is near one, with a very high probability many transition events from the false to the true electroweak vacuum have taken place on the future light cone of a given observer. Should the observer notice anything of these events? Vacuum-transition events proceed via nucleation of a bubble that expands and eventually converts the whole universe into the true-vacuum phase. While the probability \(P_{\text{decay}}\) for bubble formation does not depend strongly on the uncertain depth and properties of the “true-vacuum”, the propagation speed of the “bubble wall” does. In the likely case that the transition proceeds as a detonation wave through the false vacuum, the bubble wall moves with a speed \(v=(1-k)c\) where \(k \approx 0.1/\alpha\) for \(\alpha \gg 1\). \(\alpha\) is the ratio of the energy density in the true vacuum to the much smaller one of the false vacuum[14]. In the standard model the true vacuum is unbounded from below (i.e. \(\alpha = \infty\)), so the propagation proceeds formally with exactly \(c\). If the effective potential receives a large positive contribution from quantum gravity near the Planck-energy scale, \(k \approx 10^{-121}\) [4], i.e. the bubble wall still moves with a speed that is extremely close to one of light. This makes each transition unobservable for a human being. Relativistic causality prevents observers within the same component of the state function as the nucleation event to see any signal from the transition earlier than \(\Delta t = d \times k/c\). The time scale \(\Delta t\) is much shorter than the one of human consciousness \(\Delta t_{hc} \approx \text{msec}\), even for transitions that took place at the farthest possible distance \(d\) of about \(10^{10}\) light years. After the detonation front has passed such observers no longer exist. This makes it impossible for a human to consciously register any of the transitions. Observers on a different component of the state function are also not affected by the transition: the “peaceful coexistence” of vacua implied by eq.(5) in
the many-worlds interpretation is compatible with experience because rapid decoherence ensures the absence of any measurable interference effects between the components[13]. The very fact that parallel universes different from ours do not directly influence us, ensures that they can even be in the dreaded “true vacuum” state.

Summarizing, if parallel universes exist we cannot rule out with certainty that we live in a vacuum that decays on a short time scale. No definite conclusions based on vacuum stability about the validity of the SM can then be drawn.

4 Conclusion

The question whether parallel universes exist has been shown to be of interest to our understanding of the standard model of particle physics. If its answer is affirmative a light Higgs boson leading to a rapidly decaying electroweak vacuum might be compatible with experience. On the one hand this possibility might be interpreted as a slight damper to our hope to find experimental evidence for new physics at LHC or even the Tevatron. On the other hand, the prospect that we live in a rapidly decaying electroweak vacuum seems worthy of further investigation.

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