Is there a new physics between electroweak and Planck scales? *

Mikhail Shaposhnikov

I. INSTITUTE DE THÉORIE DES PHÉNOMÈNES PHYSIQUES, ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE, CH-1015 Lausanne, Switzerland

(Dated: February 1, 2008)

We argue that there may be no intermediate particle physics energy scale between the Planck mass $M_{Pl} \sim 10^{19} \text{ GeV}$ and the electroweak scale $M_W \sim 100 \text{ GeV}$. At the same time, the number of problems of the Standard Model (neutrino masses and oscillations, dark matter, baryon asymmetry of the Universe, strong CP-problem, gauge coupling unification, inflation) could find their solution at $M_{Pl}$ or $M_W$. The crucial experimental predictions of this point of view are outlined.

PACS numbers: 14.60.Pq, 98.80.Cq, 95.35.+d

I. INTRODUCTION

In this paper we describe a (hopefully) consistent scenario for physics beyond the Standard Model (SM) that does not require introduction of any new energy scale besides already known, namely the electroweak and the Planck scales, but can handle different problems of the SM mentioned in the abstract. This point of view, supplemented by a requirement of simplicity, has a number of experimental predictions which can be tested, at least partially, with the use of existing accelerators and the LHC and with current and future X-ray/γ-ray telescopes. Most of the arguments in favour of the absence of an intermediate energy scale presented in this work have already appeared in scattered form in refs. [1]-[5]; here they are collected together with some extra views added.

The paper is organised as follows. In Section II we will review different arguments telling that the SM model cannot be a viable effective field theory all the way up to the Planck scale. In Section III we will discuss different arguments in favour of existence of the intermediate energy scale and their weaknesses. In Section IV we discuss a proposal for the physics beyond the SM based on an extension of the SM which we called the νMSM. Section V is devoted to the discussion of crucial tests and experiments that can confirm or rule out this scenario.

II. NECESSITY OF EXTENSION OF THE STANDARD MODEL

The content of this section is fairly standard, we need it to fix the starting point for the discussion that will follow later.

There are no doubts that the Standard Model defined as a renormalisable field theory based on SU(3)×SU(2)×U(1) gauge group and containing three fermionic families with left-handed particles being the SU(2) doublets, right-handed ones being the SU(2) singlets (no right-handed neutrinos) and one Higgs doublet is not a final theory. On field-theoretical grounds, it is not consistent as it contains the U(1) gauge interaction and a self-coupling for the Higgs field, both suffering from the triviality, or Landau-pole problem [6, 7, 8]. Though the position of this pole may correspond to experimental predictions of this point of view are outlined.

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\* Talks given at the Workshop on Astroparticle Physics: Current Issues (APCI07), Budapest, Hungary, June 21-25, 2007 and at the 11th Paris Cosmology Colloquium 2007, Paris, France, August 16-18, 2007.

† Electronic address: Mikhail.Shaposhnikov@epfl.ch

In fact, the scale of quantum gravity may happen to be much smaller than $M_{Pl}$. An example is given by theories with large extra dimensions [9, 10]. We are not going to consider this possibility here.
on the Higgs mass, depending on the value of the cutoff \( \Lambda \), which we take to be \( \Lambda = M_{Pl} \). The computations of this bound done in [20, 21, 22] lead to \( M_H > 134 \pm 5 \) GeV, consistent with the result of [14] \( M_H > 140.7 \pm 10 \) GeV. So, a conservative lower limit on the Higgs mass from these considerations is \( M_H > 129 \) GeV.

To summarize: theoretically it is possible to think that the SM is valid all the way up to the Planck scale\(^2\), and some complete theory takes over above it, though this is only feasible if the Higgs mass lies in the interval

\[
M_H \in [129, 189] \text{ GeV}.
\]

This region expands at both lower and upper bounds if the scale of quantum gravity is smaller than the Planck mass.

Let us see now if this point of view can survive when confronted with different experiments and observations. Since the SM is not a fundamental theory, the low energy Lagrangian can contain all sorts of higher-dimensional \( SU(3) \times SU(2) \times U(1) \) invariant operators, suppressed by the Planck scale:

\[
L = L_{SM} + \sum_{n=5}^{\infty} \frac{O_n}{M_{Pl}^{4n}}.
\]

These operators lead to a number of physical effects that cannot be described by the SM, such as neutrino masses and mixings, proton decay, etc. For example, the lowest order five-dimensional operator

\[
O_5 = A_{\alpha\beta} \left( \bar{\nu}_\alpha \tilde{\phi} \right) \left( \phi^\dagger L_\beta \right)
\]

leads to Majorana neutrino masses of the order \( m_\nu \sim v^2/M_{Pl} \simeq 10^{-6} \) eV (here \( L_\alpha \) and \( \phi \) are the left-handed leptonic doublets and the Higgs field, \( c \) is the sign of charge conjugation, \( \tilde{\phi} = \epsilon_{ij} \phi^*_j \) and \( v = 175 \) GeV is the vacuum expectation value of the Higgs field). The six-dimensional operators like \( O_6 \propto QQQL \) (\( Q \) is the quark doublet) lead to the proton decay with a lifetime exceeding \( \tau_p \simeq M_{Pl}^4/m_\pi^4 \simeq 10^{36} \) years (\( m_\pi \) is the proton mass).

The fact that \( m_\nu \) following from this Lagrangian is so small in comparison with the lower bound on neutrino mass coming from the observations of neutrino oscillations \( m_\nu > \sqrt{\Delta m_{atm}^2} = m_{atm} \simeq 0.05 \) eV (\( \Delta m_{atm}^2 \) is the atmospheric neutrino mass difference, for a review see [23]) rules out the conjecture that the SM is a viable effective field theory up to the Planck scale. Though it is enough to kill a theory just by one observation, let us discuss another three, though not so solid ones as they related to cosmological observations rather than particle physics experiments.

(i) Since the SM has no candidate for the Dark Matter (DM) particle\(^3\) and the theory [2] does not contain any new degrees of freedom, a hope to get the DM may be associated with the primordial black holes (BH) (for a review see [27]). However, those BH which were formed at temperatures above \( \sim 10^9 \) GeV should have been evaporated by now [28] (see, however, [29] and references therein for discussion of the possibility that BH of Planck mass could be stable). The production of BH at later times could be enhanced due to the first order electroweak or QCD phase transitions [30]. However, both of these transitions are in fact smooth crossovers (see [31] for the EW case and [32] for QCD) and the number of produced BH is far too small to play a role of DM. So, unless a complete theory provides the stable states such as non-evaporating BH or some particles with the Planck mass, the theory [2] fails to describe the dark matter in the Universe.

(ii) The theory [2] does not contain any scalar field that could play a role of the inflaton and thus the inflation should occur due to some Planck scale physics as was proposed already in [33, 34]. However, the vacuum energy density \( V \) during inflation is limited from above [35] by (non) observation of tensor fluctuations of the cosmic microwave background radiation, with the current limit being much smaller than the Planck scale, \( V_{inflation} \lesssim (10^{-2}M_{Pl})^4 \) [36]. This difference seems to make the pure gravitational origin of inflation unlikely and so for the theory [2]. Interestingly, a possible alternative to inflation, the pre Big-Bang scenario of [37, 38], besides the pure gravitational degrees of freedom contains a new field — dilaton, which may be light and is essential for realisation of the scenario.

(iii) Though the SM has all the ingredients [39] to produce the baryon asymmetry of the Universe [40], it fails to do so since there is no first order EW phase transition with experimentally allowed Higgs boson masses [31]. In addition, it is a challenge to use CP-violation in Cabibbo–Kobayashi–Maskawa mixing of quarks for net baryon production. The higher dimensional operators can only contribute to baryogenesis provided the temperature is of the order of the Planck scale, whereas the maximum reheating temperature after inflation from the argument above is at most \( 10^9 \) GeV. Thus, the Lagrangian [2] has to be modified.

In addition to experimental and observational drawbacks of the SM one usually adds to the list of its problems different naturalness issues, such as: “Why the EW

\(^2\) Note that the SM is not a consistent field theory up to \( M_{Pl} \) if the fourth chiral family of fermions is introduced [12].
scale is so much smaller than the Planck scale?”, “Why the cosmological constant is so small but non-zero?”, “Why CP is conserved in strong interactions?” etc., making the necessity of physics beyond the SM even more appealing.

III. ARGUMENTS IN FAVOUR OF INTERMEDIATE ENERGY SCALE AND WHY THEY COULD BE IRRELEVANT

There is the dominating point of view that we must have some new particle physics between the electroweak scale and the Planck mass. Let us go through these arguments and try to see whether they are really convincing.

GUT and SUSY scales. We start with gauge coupling unification [41]. If one uses the particle content of the SM and considers the running of the three gauge couplings one finds that they intersect with each other at three points scattered between $10^{13}$ and $10^{17}$ GeV (for a recent review see [42]). This is considered as an indication that strong, weak and electromagnetic interactions are the parts of the gauge forces of some Grand Unified Theory (GUT) based on a simple group like SU(5) or SO(10) which is spontaneously broken at energies $M_{GUT} \sim 10^{16}$ GeV which is close, but still much smaller than the Planck scale. The fact that the constants do not meet at the same point is argued to be an indication that there must exist one more intermediate threshold for new physics between the GUT scale and the electroweak scale, chosen in such a way that all the three constants do intersect at the same point. The most popular proposal for the new physics below the GUT scale is the low energy supersymmetry (SUSY). Indeed, it is amazing that the gauge coupling unification is almost perfect in the Minimal Supersymmetric Standard Model (MSSM) [43] or in the models based on split SUSY [44, 45]. So, these considerations lead to the prediction of two intermediate energy scales between $M_W$ and $M_{Pl}$: one in the potential reach of the LHC whereas the other can only be revealed experimentally by the search of proton decay or other processes with baryon number non-conservation.

The arguments presented above are the standard ones. Before discussing an alternative let us go through the problem of gauge hierarchy which exists in the GUT scenario (why and how achieve “naturally” $M_H \ll M_{GUT}$) in some more details.

Usually the problem of gauge hierarchies is identified with the problem of quadratic divergences which appear if quantum field theory is regularized with the use of a scheme that depends explicitly on some mass parameter $\Lambda$ (this could be, for example, the UV cutoff, or Pauli-Villars, or lattice regularizations). One can hear often that since the quantum corrections to the Higgs scale diverge quadratically, one must introduce new physics which cancels these divergences, and that new physics should appear close to the scale under consideration (EW in our case). This argument, if applied to other (quartically) divergent quantity of the SM, the vacuum energy $\epsilon_{vac}$ (cosmological constant), would lead to necessity of new physics at energies larger than $\epsilon_{vac}^{1/4} \sim 10^{-3}$ eV. Since this is not observed, we should either conclude that the case of quartic divergences is very much different from the case of quadratic divergences, or accept that this type of logic can be wrong. And, in fact, besides the problem of Landau pole, the EW theory itself is known to be a perfectly valid theory without any new physics [46].

In GUTS, the SM is an effective field theory below $M_{GUT}$, having a field theory UV completion above $M_{GUT}$. This makes the cutoff scale to be a physical parameter (so it must not be sent to infinity); and to achieve that the physical Higgs mass is much smaller than the GUT scale one has to choose carefully counter-terms up to $N \sim \log(M_{GUT}^2/M_W^2)/\log(\pi/\alpha_W) \sim 13$ loop level in non-supersymmetric GUTS [47], which is considered to be an enormous fine-tuning (and one has to do it 13 times!) and as an argument for existing of new physics right above the EW scale. The low energy SUSY extensions of the SM ease the problem: it is sufficient to make a fine tuning just once, at the tree level, and all loop corrections will cancel away automatically, which is believed to be an advantage of the MSSM with respect to the SM.

In fact, the structure of divergences does depend on the regularisation scheme. One can use also the scale-independent regularisation, such as the dimensional regularisation of ’t Hooft and Veltman [48]. In this scheme the renormalization of parameters is the multiplicative one and thus there is no difference in removing the divergences from dimensionless parameters such as gauge coupling or dimensionfull parameters such as the mass of the Higgs boson. However, inspite of these specific features of the dimensional regularisation the conclusion about fine tunings remains intact [49]; even in this scheme to have a field theory GUT with two or more well separated scales one has to tune a number (varying from 1 in SUSY GUTs to 14 in non-SUSY GUTs) of terms to achieve the hierarchy of masses.

Is there an alternative to this logic which removes the necessity of introduction of these intermediate scales? Perhaps, a simplest possibility is to say that there is no Grand Unification and the fact that the gauge couplings nearly meet at high energy scale is a pure coincidence. Then the “stand alone” EW theory contains just one energy scale, the Higgs mass, which does not require any fine-tuning if one uses the minimal subtraction scheme of [48]. True, the theory is not mathematically consistent because of the Landau pole, but hiding this pole and the
vacuum instability above the Planck scale leaves the solution for a complete theory of gravity. Moreover, it is quite possible that the Planck mass cannot be considered as a field-theoretical cutoff (or as a mass of some particle in the dimensional regularisation) as we still do not know what happens at the Planck scale.

Of course, it is a pity to give up the Grand Unification. In addition to gauge coupling unification, GUTs provide an explanation of charge quantization \[52\] and give some non-trivial relations between quark and lepton masses \[53\]. An alternative is to have gauge coupling unification at the Planck scale. It is known \[54, 55\] that this possibility can be easily realised in GUTs, if higher order non-renormalisable operators are included in the analysis,

\[ L = L_{\text{GUT}} + \sum_{n=5}^{\infty} \frac{O_n}{M_{\text{Pl}}^n}, \tag{4} \]

Indeed, if \( F_{\mu\nu} \) is the GUT gauge field strength and \( \Phi \) is the scalar field in adjoint representation which is used to break spontaneously the GUT group down to the SM, the operators like

\[ O_{4+n} = \text{Tr}[F_{\mu\nu}\Phi^kF^{\mu\nu}\Phi^{n-k}], \quad 0 \leq k < n, \quad n > 0 \tag{5} \]

will rescale the SM gauge couplings with large effect if \( \langle \Phi \rangle \sim M_{\text{Pl}} \). It was shown in \[56, 57\] that it is sufficient to add dimension 5 and 6 operators to the minimal SU(5) theory to bring the unification scale up to the Planck one. In this case the corrections due to higher order operators are reasonably small and within 10%. Note that the fact of charge quantization in GUTs does not depend on the unification scale, while the breaking of the minimal SU(5) GUT predictions for lightest fermion masses is in fact welcome.

To summarize: it is appealing to think that there is no new field-theoretical scale between \( M_W \) and \( M_{\text{Pl}} \) and that the gauge couplings meet at \( M_{\text{Pl}} \) ensuring that \textit{all four interactions} get unified at one and the same scale. This is only self-consistent if the Higgs mass lies in the interval \[1\]. The experimental fact that \( M_H < M_{\text{Pl}} \) gets unexplained, but the absence of any field-theoretical cutoff below the Planck mass makes this hierarchy stable, at least in the minimal subtraction renormalization scheme.

\textbf{Inflation.} The energy density of the Universe at the exit from inflation \( V_{\text{inf}} \) (for a review and historical account of inflationary cosmology see \[58\]) is not known and may vary from \((2 \times 10^{16} \text{ GeV})^4\) on the high end (limit is coming from the CMBR observations) down to \((\text{few MeV})^4\) (otherwise the predictions of Big Bang Nucleosynthesis will be spoiled). At the same time, there are the “naturalness” arguments telling that \( V_{\text{inf}} \) should better be large (for a review see \[59\]), as otherwise it is difficult to reconcile the necessary number of e-foldings with the amplitude of scalar perturbations. The simplest quadratic potential

\[ V(\chi) = \frac{1}{2} m_\chi^2 \chi^2 \tag{6} \]

fits well the data \[58\] with \( m_\chi \sim 10^{13} \text{ GeV} \). This fact, and also the closeness of this number to the GUT scale is often considered as an extra argument in favour of existence of the high energy scale between \( M_W \) and \( M_{\text{Pl}} \).

It is well known, however, that the CBM constraints the inflaton potential (say, in the single field chaotic inflation) only for the inflaton field of the order of the Planck scale and tells nothing about the structure of \( V(\chi) \) near its minimum (for a recent discussion see \[60\]). In other words, the inflaton may be very light whereas the requisite large \( V_{\text{inf}} \) may come from its self-interactions. For example, even a pure \( 3 \chi^4 \) potential (\textit{massless inflaton}) provides a reasonable fit to the WMAP data with just \( 3 \sigma \) off the central values for inflationary parameters \[58\], which can be corrected by a slight modification of the potential at \( \chi \sim M_{\text{Pl}} \) by higher dimensional operators or by allowing non-minimal coupling of the inflaton to gravity \[61, 62\]. We will discuss a concrete proposal for light inflaton interactions later in Section \textbf{IV}.

\textbf{Strong CP-problem.} One of the fine-tuning problems of the SM is related to complicated vacuum structure of QCD leading to the existence of the vacuum \( \theta \) angle \[63, 64\] leading to CP-non-conservation in strong interactions. A most popular solution to the problem is related to Peccei-Quinn symmetry \[65\] which brings \( \theta \) to zero in a dynamical way; a degree of freedom which is responsible for this is a new hypothetical (pseudo) scalar particle - axion \[66, 67\] or invisible axion \[68, 69, 70\]. Axion has never been seen yet, and the strong limits on its mass and couplings are coming from direct experiments \[71\] and from cosmology and astrophysics \[72\]. They lead to an admitted “window” for the Peccei-Quinn scale \( 10^8 \text{ GeV} \leq M_{PQ} \leq 10^{12} \text{ GeV} \) where the lower and upper bound depend on the type of axion and different cosmological assumptions. So, it looks like an intermediate scale appears again!

In fact, the axion solution to the strong CP-problem is not the unique one. As an example we will discuss shortly a proposal for a solution of the strong CP-problem which uses extra dimensions\[6\] \[73, 74\] and does not require the presence of any new scale between \( M_W \) and \( M_{\text{Pl}} \) and does not contradict to any observation. Other extra-dimensional solutions have been suggested in \[75, 76\].

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\[5\] In fact, in the SM with \textit{one} fermionic generation the structure of U(1) hypercharges of all particles can be fixed by the requirement of absence of gauge and mixed gauge-gravitational anomalies. The anomaly free solution leads automatically to charge quantisation \[60\]. This is not the case for the SM with 3 families, where the choice of hypercharges may be unequal for different generations \[51\].

\[6\] Higher spacial dimensions appear, for instance, in string theory and in Kaluza-Klein or brane models.
The mere existence of the strong CP problem is based on the assumption that the number of dimensions of the space-time is four. Indeed, the existence of \( \theta \) vacua is related to topology: the mapping of the three-dimensional sphere, representing our space, to the gauge group \( SU(3) \) of QCD is non-trivial, \( \pi_3(S_3) = \mathbb{Z} \). This leads to the existence of classical vacua with different topological numbers, and the quantum tunneling between these states forms a continuum of stable vacua characterized by \( \theta \in (0, 2\pi) \). Clearly, these considerations are only valid if the space is 3-dimensional. Thus, in higher dimensional theories, where the 3-dimensional character of the space is just a low-energy approximation, the strong CP-problem has to be reanalyzed.

If the topology of the higher-dimensional space is such that the mapping of it to the gauge group is trivial, strong CP-problem disappears. Concrete examples were given \([73, 74]\) for 4 + 1 dimensional space-time, where the space is a 4-sphere \( S_4 \). It was shown there that the only remnant from extra dimensions which should be added to the low energy effective theory is a quantum-mechanical degree of freedom - “global axion” \( a(t) \) which depends on time but does not depend on the spacial coordinates and thus does not represent any new particle degree of freedom. The global axion couples to the ordinary fields in a way the standard axion does and thus relaxes the effective vacuum \( \theta \) angle to zero. Still, the solution of the \( U(1) \) problem in QCD is unaffected \([77]\). None of the astrophysical bounds can be applied to the global axion, simply because there is no particle to emit or absorb, while it is impossible to excite the \( a(t) \) by any local process. As for the “over-closure of the Universe” constraint, it depends strongly on the cosmological scenario of dynamics of the compactification which may happen at the Planck scale.

We see therefore that the strong CP-problem, if fact, does not point to the existence of an intermediate scale.

**Neutrino masses.** A popular argument in favour of existence of the very large mass scale is related to neutrino masses \([78]\). Indeed, let us add to the Lagrangian of the Standard Model a dimension five operator \([80]\) suppressed by an (unknown a-priory) mass parameter \( \Lambda \) and find it then from the requirement that this term gives the correct active neutrino masses. One gets immediately that

\[
\Lambda \simeq \frac{v^2}{m_{\text{atm}}} \simeq 6 \times 10^{14} \text{ GeV} ,
\]

which is amazingly close to the GUT scale.

In fact, eq. \([74]\) provides an upper bound on the scale of new physics beyond the SM rather than an estimate of this scale. This will be discussed in more detail in Section IV.

**Baryogenesis.** One of the key points of any baryogenesis scenario is departure from thermal equilibrium \([89]\). One of the popular mechanisms is called thermal leptogenesis \([73]\). In this scenario heavy Majorana neutrinos \( N \) with the mass \( M_N \) decay with non-conservation of lepton number and CP and produce lepton asymmetry of the Universe which is then converted to baryon asymmetry in rapid EW anomalous processes with fermion number non-conservation \([10]\). A very quick (and missing many details) estimate shows that \( M_N \) should be better close to the GUT scale. Indeed, the temperature at which \( N \) decay should be smaller than their mass (out of equilibrium condition) but larger than the EW scale (sphalerons must be active), \( M_N < T_{\text{decay}} < M_N \). This leads to the following constraint on the typical Yukawa coupling of \( N \) to the leptons and the SM Higgs (the decay rate of \( N \) is roughly \( \Gamma_{\text{tot}} \simeq f^2 M_N \)):

\[
\frac{M_N^2}{M_N M_0} < f^2 < \frac{M_N}{M_0} ,
\]

where \( M_0 \simeq 10^{18} \text{ GeV} \), and the Hubble constant-temperature relation is \( H = T^2/M_0 \). CP-violating effects appear from loop corrections to the decay amplitudes, and without extra fine-tunings one gets an estimate for baryon-to-entropy ratio

\[
\frac{n_B}{s} \sim 10^{-3} f^2 .
\]

A correct prediction is obtained for \( f^2 \sim 10^{-7} \), leading to the requirement \( M_N > f^2 M_0 \simeq 10^{11} \text{ GeV} \). At the same time, since temperature after inflation cannot exceed \( 10^{16} \text{ GeV} \), the leptogenesis with Planck mass Majorana leptons does not seem to be possible \([7] \).

Electroweak baryogenesis, in which the only source for baryon number non-conservation is the electroweak anomaly, requires strongly first order phase transition \([81, 82]\). As this phase transition is absent in the SM \([31]\), the use of EW anomaly for baryogenesis calls for modification of the scalar sector of the EW theory by introducing new scalar singlets or doublets and thus to a new physics in the vicinity of the EW scale.

Though both of these arguments are certainly true for specific mechanisms of baryogenesis, they are not universal. We will discuss in more detail in Section IV how they are avoided in the \( \nu \)MSM.

**Dark matter.** A particle physics candidate for dark matter must be a long-lived or stable particle. The most popular candidates are related to supersymmetry (neutralino etc.) or to the axion, which we have already discussed. The scenario for WIMPs assumes that initially these particles were in thermal equilibrium and then annihilated into the particles of the SM. Quite amazingly, if the cross-section of the annihilation is of the order of the typical weak cross-section (for a review see \([83]\)) one gets roughly correct abundance of dark matter, suggesting that the mass of DM particles is likely to be of the

\[7\] Even stronger constraints exist in supergravity theories coming from the copious gravitino production, see \([84]\) for a recent discussion.
order of the EW scale, as it happens, for example, in the MSSM, and thus to a new physics nearby.

This argument is based on the specific processes by which the dark matter can be created and destroyed and thus is not valid in general. In the next section we will discuss the \( \nu \)MSM dark matter candidate with completely different properties.

IV. THE \( \nu \)MSM AS AN ALTERNATIVE

In Section II we reviewed the arguments that the SM must necessarily be extended while in Section III we argued that the solutions to the problem of gauge coupling unification and strong CP problem can be shifted up to the Planck scale. This cannot be done with neutrino masses, and unlikely to be possible with other problems we have discussed, namely with dark matter, baryon asymmetry of the Universe and inflation. In this section we review how a minimal extension of the SM, the \( \nu \)MSM, can solve all of them.

Let us add to the SM three\(^8\) right-handed fermions \( N_I, I = 1, 2, 3 \) (they can be called singlet leptons, right-handed leptons or Majorana neutrinos) and write the most general renormalisable interaction between these particles and fields of the SM:

\[
L_{\nu \text{MSM}} = L_{\text{SM}} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{aI} \bar{L}_a N_I \phi - \frac{M_I}{2} \bar{N}_I^I N_I + \text{h.c.} . \tag{10}
\]

Here \( L_{\text{SM}} \) is the Lagrangian of the SM, \( \alpha = e, \mu, \tau \), and both Dirac \( (M^D = F_{aI} \langle \phi \rangle) \) and Majorana \( (M_I) \) masses for singlet fermions are introduced. This Lagrangian contains 18 new parameters in comparison with the SM.

Why is this Lagrangian? Since we even do not know where the SM itself is coming from, the answer to this question can only be very vague. Here is an argument in its favour. The particle content of the SM has an asymmetry between quarks and leptons: every left quark and its counterpart - right quark or right-handed lepton, while the right-handed counterpart for charged lepton has its counterpart - right quark or right-handed lepton. Interestingly, the requirement of gauge and gravity anomaly cancellation, applied to this theory, leads to quantization of electric charges for three fermionic generations [51], which was not the case for the SM, because of new relations coming from Yukawa couplings and Majorana masses.

Besides fixing the Lagrangian, one should specify the masses and couplings of singlet fermions. The see-saw [78] logic picks up the Yukawa term in [10] and tells that it is “natural” to have Yukawa coupling constants of new leptons of the same order of magnitude as Yukawa couplings of quarks or charged leptons. Then the mass parameters for singlet fermions must be large, \( M \sim 10^8 \sim 10^{14} \text{ GeV} \), to give the correct order of magnitude for active neutrino masses. This leads to an intermediate energy scale already discussed above. Yet another proposal is to fix the masses of singlet fermions in the eV region [84] to explain the LSND anomaly [85]. Note that the oscillation explanation of the LSND result is disfavoured by the MiniBooNE experiment [86].

The \( \nu \)MSM logic picks up the mass term in [10] and assumes that it is “natural” to have it roughly of the order of another mass term in the EW Lagrangian, namely that of the Higgs boson \( \nu \). This does not lead to any intermediate scale but requires smaller Yukawa couplings. To get a more precise idea about the values of Majorana masses, a phenomenological input, discussed below, is needed.

Neutrino masses and oscillations. The Lagrangian [10] can explain any pattern of active neutrino masses and their mixing angles for arbitrary (and, in particular, below the EW scale) choice of the Majorana neutrino masses. This is a simple consequence of the parameter counting: the active neutrino mass matrix can be completely described by 9 parameters whereas [10] contains 18 arbitrary masses and couplings.

Dark matter. The dark matter candidate of the \( \nu \)MSM is the long-lived lightest singlet fermion. The mass of this particle is not fixed by theoretical considerations. However, there are some cosmological and astrophysical arguments giving a preference to the keV region. In particular, the keV scale is favoured by the cosmological considerations of the production of dark matter due to transitions between active and sterile neutrinos [57] and by the structure formation arguments related to the problems of missing satellites and cuspy profiles in the Cold Dark Matter (CDM) cosmological models [88, 89, 90, 91] (see, however, [92]); warm DM may help to solve the problem of galactic angular momentum [93]. At the same time, much larger masses are perfectly allowed [84, 94]; in this case the dark matter sterile neutrino is a CDM candidate. This particle has never been in thermal equilibrium in the early Universe and thus the arguments about the mass scales of the dark matter particle of the previous section do not apply to it. For reviews of different astrophysical constraints on the properties of the sterile neutrino dark matter, and the mechanisms of its cosmological production see [95, 96] and references

\(^8\) Any number of singlet fermions can be added without spoiling the consistence of the theory. However, the number 3 is the minimal one which allows simultaneous explanation of neutrino masses and mixings, dark matter and baryon asymmetry of the Universe, see below. Since the maximal number of fermionic generations in a theory without intermediate energy scale is also 3, it looks reasonable to pick up the same for the singlet fermions.

\(^9\) We say “roughly” since even if the source of the mass is known and unique, as in the SM case, the numerical values of particle masses can be very much different. For example, the electron is lighter than the top quark by 5 orders of magnitude.
Therein. We just mention here that the *simultaneous explanation* of neutrino masses and mixings and dark matter requires that the number of singlet fermions in the νMSM is at least three and that the mass of one of the active neutrinos is very small, \( \lesssim O(10^{-6}) \) eV [1, 97].

**Baryogenesis.** The phase structure of the νMSM is the same as that of the SM: there is no EW phase transition which could lead to large deviations from thermal equilibrium. The masses of singlet fermions are smaller than the electroweak scale, they decay below the sphaleron freezout temperature and thus the thermal leptogenesis of [74] does not work. However, the presence of singlet fermions provides another source of thermal non-equilibrium, simply because these particle, due to their small Yukawa couplings, interact very weakly. The mechanism of baryogenesis in this case is related to coherent resonant oscillations of singlet fermions [2, 98]. To explain simultaneously neutrino masses, dark matter and baryon asymmetry of the Universe at least three singlet fermions are needed, with two of them with the mass preferably in the GeV region [4]. They are required to be almost degenerated [2, 98]. The specific pattern of the singlet lepton masses and couplings leading to phenomenological success of the νMSM can be a consequence of the leptonic U(1) symmetry discussed in [4].

**Inflation.** Adding just new fermions to the SM cannot lead to inflation. The simplest way out is to introduce a singlet scalar field, \( \chi \), with scalar potential

\[
V(\chi) = \frac{1}{2} m_\chi^2 \chi^2 + \lambda_3 \chi^3 + \lambda_4 \chi^4 \tag{11}
\]

and renormalisable couplings to the field of the νMSM. The number of these interactions is in fact not that large, possible terms are those of interaction of \( \chi \) with the Higgs field and singlet fermions,

\[
L_\chi = h_1 \chi^2 \phi^\dagger \phi + h_2 \chi^4 \phi + f_{IJ} N_j^c N_J \chi . \tag{12}
\]

As we have already discussed in Section III, the mass of the inflaton can be small, and taking it to be below the electroweak scale does not contradict to any principles or observations. Note also that [12] for large values of \( \chi \sim M_{Pl} \) can be modified due to Planck scale corrections. It is not difficult to find constraints on the inflaton couplings to the fields of the νMSM which insure that the model with inflaton satisfies experimental, astrophysical, and cosmological constraints [3].

In fact, the number of the parameters in the νMSM with the inflaton field can be reduced greatly without losing its attractive phenomenological features [3] if one requires that the classical Lagrangian obeys an (approximative) dilatation symmetry [99]. A requirement that the complete Lagrangian exhibits dilatation symmetry on classical level puts all dimensional couplings of the theory (mass of the Higgs boson, inflaton, and masses of singlet fermions, and also \( \lambda_3 \) and \( h_2 \)) to zero; in this case the origin of all masses in the νMSM must be related to the vacuum expectation value of the inflaton field \( \chi \). This (Coleman-Weinberg [100]) scenario can only work if \( \chi \) gets a non-trivial potential due to radiative corrections. Though possible for a specific choice of \( \lambda_4 \) and \( f_{IJ} \) [101], the theory obtained cannot accommodate inflation (since \( \lambda_4 \) is required to be of the order of one [101] and thus too large density perturbations are generated) and baryon asymmetry of the Universe (since \( f_{IJ} \) must be of the order of one [101] which leads these particles to thermal equilibrium well above the electroweak scale), and, therefore, the requirement of complete dilatation invariance should be abandoned. A way out is to break it by minimal means, and a possibility is to admit that \( m_\chi^2 \neq 0 \) and negative [3]. For a theory constructed in such a way the condensate of \( \chi \) gives masses to singlet fermions and induces the EW symmetry breaking; the same field gives rise to inflation. Moreover, the mass of \( \chi \) must be smaller than the EW scale: if this is not the case the energy stored in the inflaton field right after inflation will go predominantly to the inflaton field itself rather than to the Higgs field and eventually to other degrees of freedom of the SM. This would change the standard Big Bang scenario right above the EW scale and make baryogenesis impossible. In fact, to keep baryogenesis in place a stronger constraint \( m_\chi < 2 M_N \) must be satisfied [3].

**Fine tunings and hierarchies.** The “stand alone” νMSM or an extension of this model by a light inflaton is a theory with just one energy scale and thus it does not suffer from a fine-tuning problem typical to the field theory models containing two or more very distinct energy scales. Moreover, the masses of the singlet leptons are protected by the lepton number symmetry and thus can “naturally” be small. In addition, due to the smallness of all extra constants of interaction the renormalisation group behaviour of the SM couplings remains practically the same, and the interval [11] does not change. Of course, this theory, as the SM, has a Landau pole problem, but it can presumably be avoided in a more complete theory that includes gravity, if this pole is situated above the Planck scale.

**V. CRUCIAL TESTS AND EXPERIMENTS**

As we argued, none of the arguments in favour of existence of the intermediate energy scale really requires it: gauge coupling unification and solution of the strong CP-problem can both occur at the Planck scale, whereas inflation, neutrino masses, dark matter and baryogenesis can all be explained by the particles with the masses below the electroweak scale.

The point of view that there is no intermediate energy scale between the weak and Planck scales and that the low energy effective theory is the νMSM which explains neutrino oscillations, dark matter and baryon asymmetry of the Universe is rather fragile. It predicts an outcome of a number of experiments, and if any of the predictions is not satisfied, this conjecture will be ruled out. Though most of these predictions were discussed elsewhere, we
present them here for completeness.

**LHC physics.** Nothing but the Higgs with the mass in the window $M_H \in [129, 189]$ GeV in which the νMSM is a consistent theory below the Planck scale.

**ILC physics.** No new physics at the ILC.

**Neutrino physics.** Hierarchical structure of active neutrino masses with one of them smaller than $\mathcal{O}(10^{-5})$ eV\cite{1}. Two other masses are fixed to be $m_3 = [4.8^{+0.6}_{-0.5}] \cdot 10^{-2}$ eV and $m_2 = [9.05^{+0.2}_{-0.1}] \cdot 10^{-3}$eV ($[4.7^{+0.6}_{-0.5}] \cdot 10^{-2}$eV) in the normal (inverted) hierarchy. Majorana mass of electron neutrino is smaller than the atmospheric mass difference, $m_{ee} \leq 0.05$ eV\cite{102}. The νMSM is in conflict with the oscillation hypothesis of the LSND result and with the result of \cite{103} claiming that the neutrinoless double β decay has been observed.

**Dark matter searches.** Negative result for the WIMP and axion searches. The existence of a narrow X-ray line due to two-body decays of the sterile dark matter neutrino. The position and the intensity of this line are quite uncertain, with a possible cosmological preference for a few keV energy range, though higher values are certainly allowed as well. The best choice of astrophysical objects to search for dark matter sterile neutrino is discussed in \cite{104}, and future experimental perspectives in\cite{105}. The laboratory searches of the dark matter sterile neutrino would require a precision study of kinematics of β−decays of tritium or other isotopes\cite{106}.

**B-non-conservation.** No sign of proton decay or neutrion-antineutron oscillations.

**Flavour physics.** Existence of two almost degenerate weakly coupled singlet leptons which can be searched for in rare decays of mesons or τ-lepton and their own decays can be looked for in dedicated experiments discussed in \cite{3}. Though the masses of these particles cannot be precisely fixed, they must certainly be below $M_W$ with a preference for small masses $\lesssim 1$ GeV \cite{4}. Visible lepton number non-conservation in $N$ decays, with CP-breaking that can allow to fix theoretically the sign and magnitude of the baryon asymmetry of the Universe. Possible existence of the light inflaton \cite{3}.

**VI. ACKNOWLEDGEMENTS**

I thank Fedor Bezrukov, Alexey Boyarsky, Sergei Khlebnikov and Oleg Ruchayskiy for many helpful comments. This work was supported in part by the Swiss National Science Foundation.
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