Subnuclear Physics: Past, Present and Future
Pontifical Academy of Sciences, Scripta Varia 119, Vatican City 2014
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NEW PHYSICS WITHOUT NEW ENERGY SCALE

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Abstract

I will discuss the so-called "nightmare scenario" for particle physics in which the LHC finds the Higgs boson with the mass $m_{\min} < m_H < m_{\max}$ and nothing else. The boundary values of the Higgs mass are given, with several GeV uncertainties, by $m_{\min} \simeq 130$ GeV and $m_{\max} \simeq 174$ GeV. In this case the Standard Model is a valid effective field theory all the way up to the Planck scale, and no new physics between the Fermi and Planck scales is required for its consistency. I will review a proposal in which the new physics responsible for neutrino masses and oscillations, dark matter and baryon asymmetry of the Universe is associated with three new Majorana leptons with masses *below* the Fermi scale and inflation is driven by the Higgs boson of the SM.

Introduction

The mass M_H of the Higgs boson in the Standard Model (SM) is an important indicator of the presence of new energy scales in particle physics. It is well known that if $M_H < m_{\min}$, the SM ground state is unstable against decay into a deeper vacuum with the Higgs vacuum expectation value below the Planck mass (Krasnikov, 1978; Hung, 1979; Politzer & Wolfram, 1979). If $M_H > m_{\max}$ the Landau pole in the scalar self-coupling appears at energies below the Planck scale $M_P = 2.44 \times 10^{18}$ GeV (Maiani, Parisi, & Petronzio, 1978; Cabibbo, Maiani, Parisi, & Petronzio, 1979; Lindner, 1986). In other words, if the Higgs mass is too large or too small, the Standard Model is inconsistent below M_P and there *must* be a new energy scale between the Fermi $M_F \sim 100$ GeV and the Planck scales. On the contrary, in the mass interval $M_H \in [m_{\min}, m_{\max}]$, no new physics between M_F and M_P is needed, if only the self-consistency of the SM all the way up to M_P is considered. Note that M_H coinciding with m_{min} is a *prediction* of the asymptotically safe Standard Model, see (Shaposhnikov & Wetterich, 2010). Also, $m_{\min}$ is just few hundred MeV higher than the lower mass bound coming from the Higgs inflation (Bezrukov & Shaposhnikov, 2009).

So, the discovery of the Higgs boson at the LHC within this mass interval, and no any other physics beyond the SM, may lead to a pessimistic conclusion that there will be no new physics accessible for future particle experiments (that's why "nightmare scenario"). The aim of this talk is to argue that this is not the case – new physics responsible for neutrino masses and oscillations, dark matter and baryon asymmetry of the Universe may be associated with new particles with masses *below* the Fermi scale, which can be searched for with existing accelerators, whereas inflation can be driven by the Higgs boson of the SM.

The paper is organized as follows. First, we will discuss the value of $m_{\min}$ and compare it with the LHC bounds. Then we will overview the observational problems of the SM and describe how the νMSM (Neutrino Minimal Standard Model) solves them. The last section presents the conclusions.

Higgs mass bounds and the LHC

The numerical values of $m_{\min}$ and m_{max} can be computed in the SM with a standard technique, involving fixing the coupling constants of the SM at the Fermi scales through the physical parameters, and then running them to high energy scale with the use of renormalisation group equations (Altarelli & Isidori, 1994; Casas, Espinosa, & Quiros, 1995, 1996; Hambye & Riesselmann, 1997; Espinosa, Giudice, & Riotto, 2008).

With a good accuracy of the order of $\mathcal{O}(100)$ MeV in the Higgs mass, the value of $m_{\min}$ can be determined as follows. Take the standard $\overline{MS}$ definition of all coupling constants of the SM, fix all of them at the Fermi scale given the experimentally known parameters such as the mass of top quark, QCD coupling, etc, and consider the running Higgs self-coupling $\lambda(\mu)$ depending on the standard t'Hooft-Veltman parameter μ. Then $m_{\min}$ is found the from solution of two equations:

$$\lambda(\mu_0) = 0, \quad \beta_\lambda(\lambda(\mu_0)) = 0 \ , \tag{1}$$

which also determine the normalisation point μ_0, coinciding with the position of the second minimum of the effective potential, $\phi \simeq \mu_0$.

The values of $m_{\min}$ below are taken from (Bezrukov & Shaposhnikov, 2009) (see also (Ellis, Espinosa, Giudice, Hoecker, & Riotto, 2009)) [1],

$$m_{\min} = \left[126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5\right] \text{ GeV} \ , \ m_{\max} \simeq 175 \text{ GeV} \ . \tag{2}$$

With experimental value of the top quark mass $m_t = 172.9 \pm 0.6(\text{stat}) \pm 0.9(\text{syst})$ GeV ((Particle Data Group), 2010 and 2011 partial update for the 2012 edition) (all experimental errors are 1σ) and the value of the strong coupling constant $\alpha_s = 0.1184 \pm 0.0007$ one gets

$$m_{\min} = [129.6 \pm 1.2(\text{stat, t} - \text{quark}) \pm 0.5(\text{stat, } \alpha_s) \pm 1.75(\text{syst})] \text{ GeV} \ . \tag{3}$$

The contributions from higher loops can change this value by 2.2 GeV (if uncertainties are added quadratically) or by 5 GeV (if they are summed up linearly), see (Bezrukov & Shaposhnikov, 2009) for a detailed discussion. In summary, given the present theoretical and experimental uncertainties, the value of $m_{\min}$ can be as small as, say, 123 GeV or as large as, say, 135 GeV (in getting these numbers we took 2.2 GeV as an estimate of the theoretical error and added it linearly to 2σ experimental error).

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[1] They correspond to the so-called "one-loop-matching-two-loop running" procedure.

The Atlas and CMS evidence for existence of the Higgs boson with the mass $124-126$ GeV is thus within the interval of allowed values for $m_{\min}$. In other words, we are not in position yet to conclude with confidence whether there is a necessity of a new energy scale between the Fermi and the Planck scales. On the theory side, the most urgent theoretical computations would be to go one step above the current "one-loop-matching-two-loop running" computation. It should account for 2-loop strong and electroweak corrections to low energy $\overline{MS}$-pole matching and 3-loop running up to the Planck scale. This would allow to push down the theoretical error to ~ 0.4 GeV (Bezrukov & Shaposhnikov, 2009). These computations, together with reducing the experimental errors in the Higgs boson and top quark mass, are decisive for setting up the question about the *necessity* of new energy scale besides the two already known - the Fermi and the Planck.

Observational evidence of new physics

Even if the Higgs boson will be found with the mass within interval $M_H \in [m_{\min}, m_{\max}]$, there are no doubts that the SM is not a final theory. Indeed, it fails to explain a number of *observed* phenomena in particle physics, astrophysics and cosmology. These phenomena *beyond the SM* (BSM) are:
(i) *Neutrino oscillations* (transition between neutrinos of different flavours).
(ii) *Dark matter* (some 80% of all matter in the Universe consists of unknown particles).
(iii) *Baryon asymmetry* (excess of matter over anti-matter in the Universe).
(iv) *Inflation* (a period of the rapid accelerated expansion in the early Universe).
(v) *Dark energy* (late time accelerated expansion of the Universe).
This list of *well-established observational* drawbacks of the SM is complete at present time. All the other BSM problems are those of theoretical fine-tuning: the "gauge hierarchy problem", strong CP-problem, etc. There are several anomalies in particle physics experiments, such as discrepancy between experiment and theory prediction of anomalous magnetic moment of muon, LSND anomaly, evidence of the neutrinoless double decay presented by a part of the Heidelberg group, etc. However, none of these anomalies has been confirmed by other experiments.

Once the SM is not a fundamental theory, one has to ask oneself: "At what energies the SM should be superseded by some other, more fundamental theory?" The existence of gravity with the coupling related to the Planck scale $M_{Pl} = G_N^{-1/2} = 1.2 \times 10^{19}$ GeV (G_N is the Newtonian gravitational constant) implies that this certainly happens at energies $\sim M_{Pl}$. However, whether there exists any new intermediate energy scale between the Fermi and Planck scales remains unclear. I will describe below a proposal of solution of above mentioned problems (i-iv), which does not require any new energy scale, which is based on a minimal extension of the SM by three new particles. As for the problem (v), in no-new-scale proposal it may be solved if the theory is scale-invariant on the quantum level and gravity is unimodular (Shaposhnikov & Zenhausern, 2009b, 2009a; Blas, Shaposhnikov, & Zenhausern, 2011; Garcia-Bellido, Rubio, Shaposhnikov, & Zenhausern, 2011). This will not be discussed in this talk due to the lack of time.

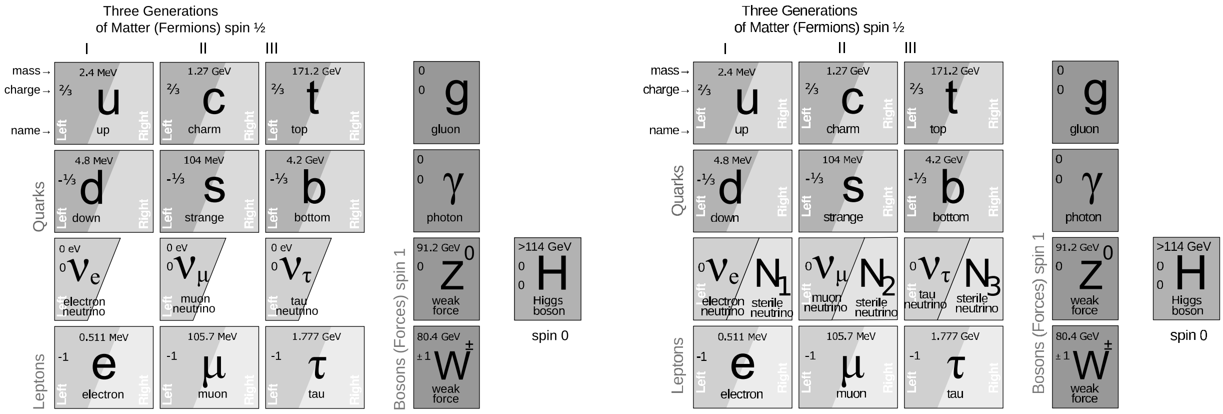

Figure 1. Particle content of the SM and its intension in neutrino sector.

The νMSM

Let us start from the problem (i) of the SM. The success of relativistic quantum field theory, associated with the fact that the SM agrees with most experiments, strongly indicates that the origin of neutrino masses is the existence of new unseen particles and that the complete theory should be a renormalizable extension of the Standard Model. From the SM quantum numbers of active neutrinos one can identify several possible sources for neutrino masses. If no new fermionic degrees of freedom are introduced, one needs to have a Higgs triplet with weak hypercharge 2. Another option is an introduction of singlet (with respect to the SM gauge group) Majorana fermions N_I (other names for them are sterile neutrinos or heavy neutral leptons). We choose the second possibility. Since N_I are SU(3)$\times$SU(2)$\times$U(1) singlets, Majorana mass terms for them are consistent with the symmetries of the SM. The number of singlet fermions cannot be deduced from symmetry principles; the minimal number is 2, to get 2 different mass square differences in active neutrino sector. We take it to be 3 in analogy with the number of generations of quarks and leptons. The new particles complement nicely the fermionic content of the SM, making it left-right symmetric in neutrino sector as well, see Fig. 1.

This extension of the SM is associated with the Lagrangian

$$L = L_{\rm SM} + \bar N_I i\partial_\mu\gamma^\mu N_I - F_{\alpha I}\,\bar L_\alpha N_I\tilde\phi - \frac{M_I}{2}\,\bar N_I^c N_I + h.c., \qquad (4)$$

where $L_{\rm SM}$ is the Lagrangian of the SM. This Lagrangian is usually used for the explanation of the small values of neutrino masses via the see-saw mechanism (Minkowski, 1977; Yanagida, 1980; Gell-Mann, Ramond, & Slansky, 1979; Mohapatra & Senjanovic, 1980), which *assumes* that the Yukawa coupling constants $F_{\alpha I}$ of the singlet fermions are of the order of the similar couplings of the charged leptons or quarks. We are not going to make such an assumption.

In comparison with the SM, this theory contains 18 new parameters: 3 Majorana masses of new neutral fermions N_I, and 15 new Yukawa couplings in the leptonic sector, corresponding to 3 Dirac neutrino masses, 6 mixing angles and 6 CP-violating phases. The number of parameters is almost doubled in comparison with the SM; none of them can be determined theoretically within this model, in complete analogy with the SM parameters (which are all taken from experiment).

The new parameters can be divided in two different groups. The first one is the new mass scale - a generic value of the Majorana neutrino mass (denoted by M), and the second one is the typical amplitude of the Yukawa coupling constants Y, which may be defined as $Y^2 = Trace[F^\dagger F]$. We know very little about the actual values of Y and M. Basically, M can have any value between zero (corresponding to Dirac neutrinos) to 10^{16} GeV, whereas Y can vary from 10^{-13} (Dirac neutrino case) to 1 (the onset of the strong coupling). The admitted region is shown in Fig. 2 (left panel).

The requirement of the absence of new energy scale tells that M should be of the order of the Planck scale, or smaller than the Fermi scale. The first possibility is phenomenological unacceptable - the active neutrino masses following from the see-saw mechanism are too small in comparison with observed values. Therefore we choose the second option, in which the masses of new fermions are similar to those of ordinary quarks or charged leptons. Quite amazingly, in this case these three new Majorana leptons can explain simultaneously neutrino masses and oscillations, Dark Matter, and baryon asymmetry of the Universe, i.e the problems (i-iii) of section (for reviews see (Shaposhnikov, 2007; Boyarsky, Ruchayskiy, & Shaposhnikov, 2009)).

Dark matter

Though the νMSM does not have any extra stable particle in comparison with the SM, the lightest singlet fermion, N_1, may have a life-time τ_{N_1} greatly exceeding the age of the Universe and thus play a role of a dark matter particle (Dodelson & Widrow, 1994; Shi & Fuller, 1999; Dolgov & Hansen, 2002; Abazajian, Fuller, & Patel, 2001). The following considerations determine the range of masses and couplings of the DM sterile neutrino:
(i) Cosmological production. N_1 are created in the early Universe in reactions $l\bar{l} \rightarrow \nu N_1$, $q\bar{q} \rightarrow \nu N_1$, etc. We should get the correct DM abundance.
(ii) Structure formation. If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars and structure of dwarf galaxies.
(iii) X-rays. N_1 decays radiatively, $N_1 \rightarrow \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton). This line has not been seen yet.

The summary of these constrains (see (Boyarsky, Ruchayskiy, & Iakubovskyi, 2008; Gorbunov, Khmelnitsky, & Rubakov, 2008; Boyarsky, Ruchayskiy, & Shaposhnikov, 2009; Boyarsky, Lesgourgues, Ruchayskiy, & Viel, 2009) for more details) is presented in Fig. 2 where the mixing angle θ is the ratio of the Dirac and Majorana masses,

$$\theta = \frac{m_D}{M_1} \ . \tag{5}$$

The interactions of N_1 with particles of the SM is weaker than the weak interactions by a factor θ (in the amplitude). So, they fall into the SuperWIMP category of the DM particle physics candidates. It is important that the DM sterile neutrino production requires the presence of large, $\Delta L/L > 2 \times 10^{-3}$ lepton asymmetry at temperature $T \sim 100$ MeV. It can only be produced in the νMSM (Shaposhnikov, 2008).

The constraints shown in Fig. 2 (right panel) allow to make a number of predictions for neutrino physics (Asaka, Blanchet, & Shaposhnikov, 2005; Boyarsky, Neronov, Ruchayskiy,

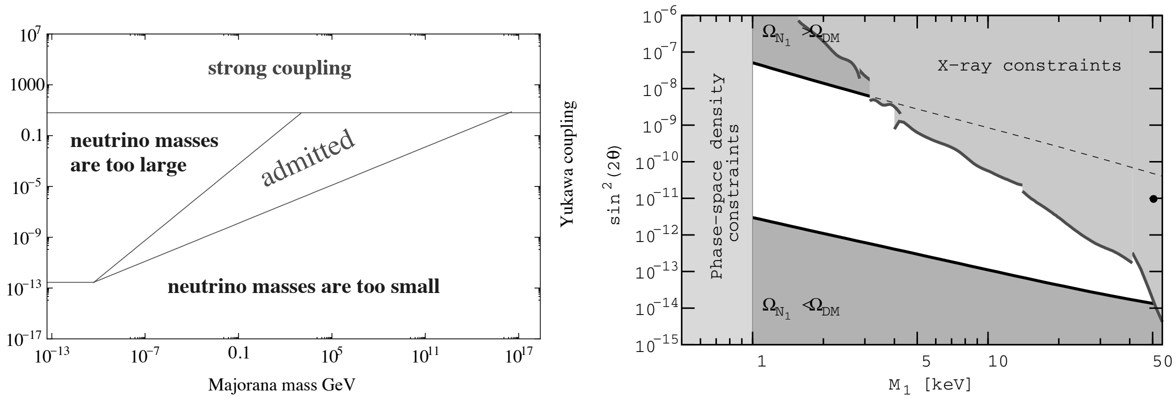

Figure 2. **Left panel.** The admitted values of the Yukawa couplings as a function of the Majorana fermion mass. **Right panel.** The allowed region of parameters for dark matter sterile neutrinos produced via mixing with active neutrinos (unshaded region). The two thick black lines bounding this region represent production curves for zero lepton asymmetry (upper line) and for the maximal lepton asymmetry attainable in the νMSM. The red shaded region in the upper right corner represents X-ray constraints. The region below 1 keV is ruled out according to the phase-space density arguments . The Lyman-α constraints are in general stronger but depend essentially on lepton asymmetry. For zero lepton asymmetry the lower bound on M_1 is around 8 keV, while for large asymmetries it is as small as 2 keV.

& Shaposhnikov, 2006). The minimal number of sterile neutrinos, which can explain the dark matter in the Universe and neutrino oscillations, is $\mathcal{N} = 3$. Only one sterile neutrino can be the dark matter. Moreover, it practically decouples and does not contribute to active neutrino masses. Also, the absolute neutrino mass scale is fixed: the mass of the lightest active neutrino is bounded from above by $m_1 \leq 2 \cdot 10^{-3}$ eV. This leads to the following values of the masses of other active neutrinos: $m_2 = [9.05^{+0.2}_{-0.1}] \cdot 10^{-3}\text{eV} \simeq \sqrt{\Delta m^2_{solar}}$, $m_3 = [4.8^{+0.6}_{-0.5}]{\cdot}10^{-2}\text{eV} \simeq \sqrt{\Delta m^2_{atm}}$ (normal hierarchy), or $m_{2,3} = [4.7^{+0.6}_{-0.5}]{\cdot}10^{-2}$ eV (inverted hierarchy). Yet another prediction is the effective Majorana mass $m_{\beta\beta}$ for neutrinoless double β decay (Bezrukov, 2005): 1.3 meV $< m_{\beta\beta} <$ 3.4 meV (normal hierarchy) and 13 meV $< m_{\beta\beta} <$ 50 meV (inverted hierarchy). Moreover, knowing $m_{\beta\beta}$ experimentally will allow to fix Majorana CP-violating phases in neutrino mass matrix, provided θ_{13} and Dirac phase δ are known.

The strategy for search of DM sterile neutrino was discussed in a number of papers, for a review see (Boyarsky, Ruchayskiy, & Shaposhnikov, 2009). In short, one should use the X-ray telescopes (such as Chandra and XMM Newton) to look for a narrow γ line against astrophysical background. The astrophysical objects leading to the best signal to background ratio are the dwarf satellite galaxies and the Milky Way.

Baryon asymmetry

In addition to DM sterile neutrino the νMSM contains a pair of more heavier singlet fermions, N_2 and N_3. The parameters of these particles can be constrained from the following conditions:
(i) BAU generation via singlet fermion oscillations (Akhmedov, Rubakov, & Smirnov, 1998;

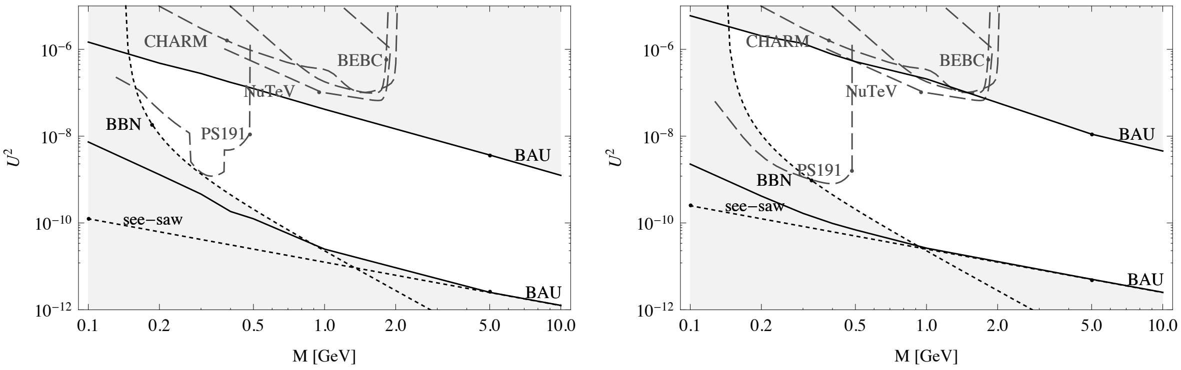

Figure 3. Constraints on U^2 coming from the baryon asymmetry of the Universe (solid lines), from the see-saw formula (dotted line) and from the big bang nucleosynthesis (dotted line). Experimental searched regions are in red - dashed lines. Left panel - normal hierarchy, right panel - inverted hierarchy.

Asaka & Shaposhnikov, 2005) requires out of equilibrium: mixing angle of $N_{2,3}$ to active neutrinos cannot be too large. In addition, due to the smallness of the Yukawa couplings, the asymmetry generation must have a resonant character, leading to the requirement that $N_{2,3}$ must be almost degenerate.
(ii) Neutrino masses: mixing angle of $N_{2,3}$ to active neutrinos cannot be too small.
(iii) BBN: decays of $N_{2,3}$ must not spoil Big Bang Nucleosynthesis.
(iv) Experiment: $N_{2,3}$ have not been seen yet.

The summary of constrains derived in (Canetti & Shaposhnikov, 2010). is presented in Fig. 3 where the mixing angle U^2 is defined in full analogy with (5).

Experimental searches of $N_{2,3}$

It is an experimental challenge to detect Majorana leptons $N_{2,3}$. Indeed, the constraint from baryon asymmetry tells that these particles must interact very weakly, $U^2 \lesssim 5 \times 10^{-7} \left(\frac{\mathrm{GeV}}{M}\right)$.

Several distinct strategies can be used for the experimental search of $N_{2,3}$ (Gorbunov & Shaposhnikov, 2007). The first one is related to their production (U^2 effect). The singlet fermions participate in all the reactions the ordinary neutrinos do with a probability suppressed roughly by a factor U^2. Since they are massive, the kinematics of, say, two body decays $K^\pm \to \mu^\pm N$, $K^\pm \to e^\pm N$ or three-body decays $K_{L,S} \to \pi^\pm + e^\mp + N_{2,3}$ changes when $N_{2,3}$ is replaced by an ordinary neutrino. Therefore, the study of *kinematics* of rare K, D, and B meson decays can constrain the strength of the coupling of heavy leptons. This strategy has been used in a number of experiments for the search of neutral leptons in the past (Yamazaki et al., n.d.; Daum et al., 2000), where the spectrum of electrons or muons originating in decays π and K mesons has been studied. The precise study of kinematics of rare meson decays is possible in Φ (like KLOE), charm, and B factories, or in experiments with kaons where their initial 4-momentum is well known.

The second strategy is to use the proton beam dump (U^4 effect). As a first step, the proton beam heating the fixed target creates K, D or B mesons, which decay and produce

$N_{2,3}$. The second step is a search for decays of N in a near detector, looking for the processes "nothing" → leptons and hadrons (Bernardi et al., 1986, 1988; Vaitaitis et al., 1999; Astier et al., 2001). To this end, quite a number of already existing or planned neutrino facilities (related, e.g., to CERN SPS, MiniBooNE, MINOS or J-PARC), complemented by a near *dedicated* detector, can be used. Finally, these two strategies can be unified, so that the production and the decay occurs inside the same detector (Achard et al., 2001).

For the mass interval $M_N < M_K$, both strategies can be used. According to the estimates, an upgrade of NA62 experiment at CERN would allow the finding or exclusion of singlet fermions with the mass below that of the kaon. If $m_K < M_{2,3} < m_D$, the search for the missing energy signal, potentially possible at beauty, charm, and τ factories, is unlikely to gain the necessary statistics. Thus, the search for decays of neutral fermions is the most effective opportunity. The dedicated experiments on the basis of the SPS proton beam at CERN can touch a very interesting parameter range for $M_N < 1.8$ GeV. The sensitivity is proportional to total delivered protons on target (PoT); for 2.5×10^{20} PoT the constraints shown in Fig. 3 can be improved by one order of magnitude (without accounting for improvement of experimental technique). An upgrade of the LHCb experiment, allowing to use the combination of two strategies, could potentially enter in a cosmologically interesting region for masses and mixing angles of singlet fermions. Going above D-meson but still below B-meson thresholds is very hard if not impossible with the present or planned proton machines or B-factories. To enter into a cosmologically interesting parameter space would require the increase in the present intensity of, say, CERN SPS beam by two orders of magnitude or to produce and study the kinematics of more than 10^{10} B-mesons.

Standard Model Higgs boson as inflaton

Let us turn now to the problem (iv) of section . Our Universe is flat, homogeneous and isotropic, and contains structures that were produced from initial perturbations with almost scale invariant spectrum. An elegant explanation of these facts is associated with cosmological inflation (Starobinsky, 1979, 1980; Mukhanov & Chibisov, 1981; Guth, 1981; Linde, 1982; Albrecht & Steinhardt, 1982). In inflationary cosmology (for a recent review see (Linde, 2008)) the early evolution of the Universe can be roughly divided into three parts. During the first stage, the Universe expands exponentially and becomes nearly flat. At this stage matter perturbations, leading to structure formation, are generated. During the second, reheating stage, the energy stored in the inflaton field is transferred to the fields of the Standard Model. The third stage is the radiation dominated Universe in nearly thermal equilibrium for most of the SM particles. The starting moment of this stage t_r corresponds to a maximal temperature of the Universe $T_{\max}$, and this is the onset of the standard hot Big Bang.

In (Bezrukov & Shaposhnikov, 2008) it was proposed that the Higgs boson of the SM can play the role of the inflaton and make the Universe flat, homogeneous and isotropic, produce the primordial fluctuations, necessary for structure formation, and heat up the Universe making the Big Bang. In other words, no new special particle is needed for inflation.

To describe the main idea of SM Higgs-inflation, let us consider Lagrangian of the

SM *non-minimally* coupled to gravity,

$$L_{\rm tot} = L_{\rm SM} - \frac{M^2}{2} R - \xi H^\dagger H R\,, \tag{6}$$

where $L_{\rm SM}$ is the SM part, M is some mass parameter, R is the scalar curvature, H is the Higgs field, and ξ is an extra constant, characterizing the strength of coupling of the Higgs field to gravity. The third term in (6) is in fact required by the renormalization properties of the scalar field in a curved space-time background (Birrell & Davies, 1982). If $\xi = 0$, the coupling of the Higgs field to gravity is said to be "minimal". Then M can be identified with the reduced Planck scale M_P related to the Newton's constant as $M_P = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18}$ GeV. The parameter ξ cannot be fixed within the theory (6), it will be determined from the requirement of successful inflation.

For large Higgs backgrounds $\xi h^2 \gtrsim M_P^2$ (here $h^2 = 2H^\dagger H$) the masses of all the SM particles *and* the induced Planck mass $[M_P^{\rm eff}]^2 = M_P^2 + \xi h^2$ are proportional to one and the same parameter, leading to independence of physical effects on the magnitude of h. In other words, the Higgs potential in the large-field region is effectively flat and can result in successful inflation. This is not the case for the theory with the minimal coupling, when $\xi = 0$.

Let us discuss the predictions of the Higgs inflation. The basic inflationary parameters, which can be extracted from the analysis of anisotropies of cosmic microwave background are:
(i) The amplitude of the temperature fluctuation $\delta T/T$ at the WMAP normalization scale ~ 500 Mpc.
(ii) The value of spectral index n_s of scalar density perturbations

$$\left\langle \frac{\delta T(x)}{T} \frac{\delta T(y)}{T} \right\rangle \propto \int \frac{d^3k}{k^3} e^{ik(x-y)} k^{n_s - 1}\ . \tag{7}$$

(iii) The amplitude of tensor perturbations $r = \frac{\delta\rho_t}{\delta\rho_s}$.
Since in the Higgs inflation we have got one new parameter ξ, we can fix it from (i) and make predictions of n_s and r.

The analysis can be performed in standard way using the slow-roll approximation (for a review see (Lyth & Riotto, 1999)). The condition (i) leads to the relation between the Higgs mass and the parameter ξ,

$$\xi \simeq 47000\sqrt{\lambda}\ . \tag{8}$$

Since the Higgs self-coupling constant is of the order of one, ξ must be large enough. As anticipated, the Higgs-inflation predicts the specific values for spectral indexes describing scalar (n_s) and tensor (r) perturbations. They are in accordance with the WMAP-5 observations, see Fig. 4 (left panel).

If tree approximation is used for computations, nothing can be said about the Higgs mass: change λ and ξ^2 in such a way that the ratio λ/ξ^2 stays constant - cosmological predictions do not change (see eq. (8)). This is not true any longer if quantum effects are taken into account. In particular, the Higgs self-coupling constant λ is not a constant as it depends on energy through renormalisation group equations. Since the typical inflationary energy scale is $M_P/\sqrt{\xi}$, for Higgs inflation to work, the SM must be a valid quantum

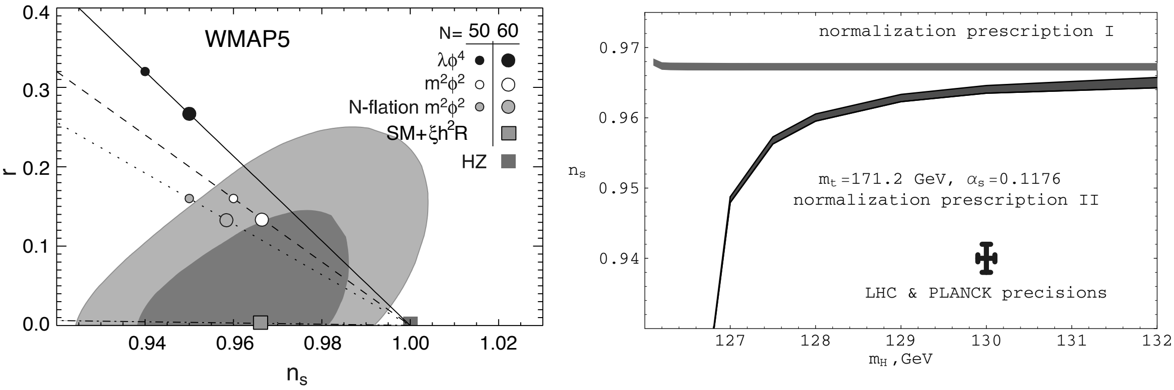

Figure 4. **Left.** The allowed WMAP region for inflationary parameters (r, n_s). The green box is the prediction for Higgs inflation. Black and white dots are predictions of usual chaotic inflation with $\lambda\phi^4$ and $m^2\phi^2$ potentials, HZ is the Harrison-Zeldovich spectrum. **Right.** Dependence of the spectral index of scalar perturbations on the Higgs mass in two different renormalisation prescriptions, related to the computations in the Jordan and Einstein frames. The cross indicates the accuracy to be achieved in the measurements of the Higgs mass at the LHC and of the spectral index n_s with the Planck satellite.

field theory up to the inflation scale. The analysis of radiative corrections carried out in (Bezrukov, Magnin, & Shaposhnikov, 2009; Bezrukov & Shaposhnikov, 2009) (see also (De Simone, Hertzberg, & Wilczek, 2009; Barvinsky, Kamenshchik, Kiefer, Starobinsky, & Steinwachs, 2009; A. Barvinsky, Kamenshchik, Kiefer, Starobinsky, & Steinwachs, 2009)) lead to the conclusion that Higgs inflation works works for sufficiently large Higgs masses, $M_H > m_{\min} - \Delta M$, where ΔM is typically few hundreds of MeV, slightly depending on the mass of the top quark. The inflationary range of Higgs masses lies within the region allowed the direct LEP and LHC searches for the Higgs boson. The combination of the future Planck measurements of n_s and r with the coming LHC data on the Higgs boson would allow to test the predictions of the Higgs inflation.

Remarkably, the Higgs inflation automatically solves the problem of the graceful exit from inflation. Roughly, for the Higgs fields $h > \frac{M_P}{\sqrt{\xi}}$ the Universe is inflating, for $\frac{M_P}{\xi} < h < \frac{M_P}{\sqrt{\xi}}$ it is in the matter dominated phase (the role of matter is played by the oscillating Higgs field), and at $h < \frac{M_P}{\xi}$ it enters into the radiation dominated phase. At $h \simeq \frac{M_P}{\xi}$ the energy stored in the Higgs field is transferred rapidly to other fields of the SM, leading to the Big Bang. The detailed discussion of these processes can be found in (Bezrukov, Gorbunov, & Shaposhnikov, 2009; Garcia-Bellido, Figueroa, & Rubio, 2009).)

Conclusions

The so-called "nightmare scenario" for particle physics (discovery of the Higgs boson in a specific mass interval and nothing else at the LHC) would indicate that there is no need in new scale between the Fermi and Planck energies. Quoting Hermann Nicolai, the absence of an intermediate scale will provide then a possibility to have an unobstructed view of Planck physics, otherwise impossible. The accuracy of theoretical computations and of the experimental measurements of the top and the Higgs masses does not allow yet to conclude with confidence whether there is a necessity of a new energy scale between the Fermi and the Planck scales. However, the nearly coincidence of $m_{\rm min}$ and of the experimental number $124 - 126$ GeV reported recently at CERN puts a strong argument in favour of the absence of new energy scale. The following argument (quite well known, but not widely appreciated) adds an extra evidence to this conjecture.

There is a remarkable numerical coincidence of the energy scale μ_0, defined from equations (1) with the Planck mass. This coincidence is highly non-trivial, because these equations are formulated with the use of the SM only, without inclusion of gravity. The fact that $\mu_0 \simeq M_P$ suggests that the electroweak symmetry breaking is likely to be associated with gravity. A generic new physics between the Fermi and Planck scales would remove this coincidence unless some conspiracy is taking place.

The "nightmare scenario" does not mean that no new physics can be found in future experiments: it may be very well that it exists below the electroweak scale. The fact that the universe contains different structures, but is flat, homogeneous and isotropic at large distances, may find its explanation in a non-minimal coupling of the Higgs field to gravity. Yet other problems of the SM, related to the cosmological constant puzzle, to the existence of Dark Energy (late Universe acceleration), and to the problem of stability of the Higgs mass against radiative corrections may be related to quantum scale invariance (Shaposhnikov & Zenhausern, 2009b, 2009a) and not to the existence of any intermediate energy scales between the Fermi and Planck scales. New physics, responsible for neutrino masses and mixings, for dark matter, and for baryon asymmetry of the Universe may hide itself *below* the EW scale. This possibility is offered by the νMSM - a minimal model, explaining simultaneously a number of well-established observational drawbacks of the SM.

There are many experimental applications of no-new-scale proposal. Higgs inflation is only possible in a specific interval of the Higgs boson masses, discussed above. Moreover, the inflationary spectral indices have definite values in the Higgs inflation, what can be tested by the Planck satellite. A pair of new neutral leptons, creating the baryon asymmetry of the Universe can be searched for in dedicated experiments with the use of existing intensive proton beams at CERN, FNAL and neutrino facilities in Japan (J-PARC). To search for DM sterile neutrino in the Universe one needs an X-ray spectrometer in Space with good energy resolution $\delta E/E \sim 10^{-3} - 10^{-4}$ getting signals from our Galaxy and its dwarf satellites. The laboratory search for this particle would require an extremely challenging detailed analysis of kinematics of β-decays of different isotopes (Bezrukov & Shaposhnikov, 2007).

An indirect evidence in favour of our proposal will be given by LHC, if it discovers the Higgs boson within the mass interval discussed above and nothing else. Moreover, the νMSM gives a hint on how and where to search for new physics in this case. It tells, in particular, that in order to uncover new phenomena in particle physics one should go towards high intensity proton beams or very high intensity charm or B-factories. At the same time, to pin down the value of $m_{\rm min}$, which can provide a non-trivial relationship between the electroweak and Planck scales making a "window" to Planck physics, one would need, besides higher order theoretical computations, a precise determination of the top quark mass. The required accuracy can hardly be reached at the LHC - an electron-positron accelerator (top-Higgs factory) would be needed.

Acknowledgements

I am grateful to the organizers of the International Symposium on Subnuclear Physics: Past, Present and Future, held at the Pontifical Academy of Sciences in the Vatican from 30 Oct. - 2 Nov. 2011 for the invitation to this outstanding meeting. This work was supported in part by the Swiss National Science Foundation.

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