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CP VIOLATIONS (AND MORE) AFTER THE FIRST TWO YEARS OF LHCB

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Abstract. The most interesting cosmological open problems, baryon asymmetry, dark matter, inflation and dark energy, are not explained by the standard model of particle physics (SM). The final goal of the Large Hadron Collider an experimental verification of the SM in the Higgs sector, and also a search for evidence of new physics beyond it. In this paper we will report some of the results obtained in 2010 and 2011, from the LHCb experiment dedicated to the study of CP violations and rare decays of heavy quarks.

1. Introduction

The Standard Model (SM) of particle physics is at present the most advanced and comprehensive phenomenological theory of all the elementary particles and forces known, with the exclusion of gravity [1]. The SM is already a very successful theory because it can predict very accurately the particle properties and their interactions [2], but it needs to be completed in the Higgs sector[1]. With data taking at the Large Hadron Collider (LHC) at $\sqrt{s} = 8\,\mathrm{TeV}$ in progress, the SM (if completely confirmed) will be the best candidate description for the physics of the Universe in the time span from $\sim 10^{-10}\,\mathrm{s}$ to 13.7 Gy after the Big Bang (see Fig. 1). However the progress of observative cosmology made in last decades, specially from space, has radically reshaped our vision of the Universe, in a way that seems to contradict the completeness of the SM. The following is a time ordered list of problems in cosmology, that do not appear compatible with the SM, at least in its minimal version.

- **Baryon asymmetry:** Since the discovery of the existence of antimatter in the early 1940's, the predominance of matter over antimatter in the whole visible Universe has been a puzzle [5]. In the late 1960's, Sakharov [6] showed that the puzzle could be solved by the recently discovered Charge and Parity violation (CPV) in the decay of K^0 mesons. A few years later, Kobayashi & Maskawa found that the extension of Cabibbo mixing [8] to three families could easily explain CPV if one of the elements of the 3×3 quarks mixing matrix was complex [9] (see following §2).
- **Dark Matter:** Constitutes $(23 \pm 2)\,\%$ of the mass of the Universe in the ΛCDM model, while baryons account only for the $(4.6 \pm 0.2)\,\%$ [10]. The formation of large scale structures in the Universe gives a clue to the nature of this matter, which is currently understood as formed by Weakly Interacting Massive Particles (WIMPs) relic from the Big Bang (see e.g. [11] and references therein). An ideal candidate for WIMPs is the lightest SuperSymmetric Particle (LSP) of the supersymmetric theories (SUSY), stable if R-parity is conserved [12]. LHC is expected to be able either to prove the validity of SUSY, or to exclude its realization in specific models [13, 14] (see §4).
- **Inflation:** The prototype for the *"inflaton"* [15] for Alan Guth was originally the Higgs field. However it was realized very soon [16] that in order to have the required shape the self-coupling of the Higgs should be of the order of $\lambda \lesssim 10^{-13}$, too small to be compatible with EW physics. However the SM Higgs itself could provide the inflationary potential if its coupling to gravity is non-minimal [17]. In this case the observation of the Cosmic Microwave Background (CMB) fluctuations set limits to the Higgs mass in the range $120 \div 140\,\mathrm{GeV}/c^2$, compatible with the present limits of the TEVATRON and LHC experiments (see e.g. [18]).
- **Dark Energy:** About fifteen years ago, two independent groups tracking the expansion of the Universe with Type Ia SuperNovae (SNIa) with the Hubble Space Telescope discovered that the expansion was accelerating [20]. The present understanding is that about 73 % of the mass-energy content of the universe is in the form of a vacuum energy very similar to the famous *"cosmological constant"* Λ_0, introduced by Einstein [21]. From the point of view of HEP, the problem with Λ_0 is its smallness, compared to the huge energy density of quantum fluctuations in the vacuum of SM, which can be estimated to about 128 orders of magnitude larger than the critical density [22]. Perfect symmetry between boson and fermion, or in other words

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[1] During the preparation of this manuscript, CERN announced officially that a significant excess of events for $m_{\mathrm{H}} = 125.5 \pm 0.6\,\mathrm{GeV/c^2}$ has been observed in the data by both ATLAS [3] and CMS [4].

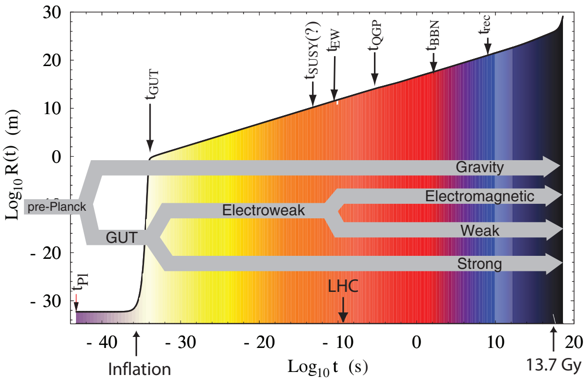

FIGURE 1. A schematic view of the expansion of the Universe.

an unbroken SUSY, offers a perfect cancellation of this energy density, because the contribution of bosons to the vacuum energy has an opposite sign to that of fermions (see e.g. §5.1 of Ref. [21]). Since SUSY is broken at present, the discrepancy is not eliminated but only mitigated by SUSY to the level of about 60 order of magnitudes. This situation indicates a serious unsolved problem for particle physics theory [23].

Finally, it should be emphasized that all these problems are more or less directly related to our present lack of knowledge of the Higgs sector of the SM. In fact while the fermion sector of the SM includes at least three families of quarks and leptons, and four gauge bosons, its Higgs structure consists only of a single doublet. In the coming years, the LHC experiments will be certainly able to set constraints to the various possible alternative theories that have been proposed.

2. THE SAKHAROV MECHANISM FOR BARYON ASYMMETRY

In his seminal paper, Sakharov [6] pointed out that even if the initial Universe was matter–antimatter symmetrical, the observed present asymmetry could be originated if at a certain point of the evolution of the Universe:

(1.) the baryon number is violated;

(2.) charge and parity is violated;

(3.) there is an exit from thermodynamical equilibrium.

In fact, condition (1.) is obviously needed to go from the initial $B = 0$ to $B \neq 0$, with $B = \frac{1}{3}\sum_q \left(n_q - n_{\overline{q}}\right)$; condition (2.) produces asymmetry because the decay rates of particles are different from those of antiparticles (see e.g. Fig. 3), finally condition (3.) is needed because otherwise annihilation reactions $q\overline{q} \leftrightarrows \gamma\gamma$ would keep $B = 0$ in force of the CPT theorem. These conditions could be present at different stages of the evolution of the Universe [24].

In the SM, there is a possibility that baryon asymmetry could be produced at the electroweak phase transition (EWPT) [25], which is the transition induced at a temperature $T_{\mathrm{EW}} \sim 200\,\mathrm{GeV}$ [26] by Spontaneous Symmetry Breaking (SSB) from the full $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ symmetry of the early Universe, to the present time, in which fermions and boson get mass interacting with the Higgs field. For $T \gg T_{\mathrm{EW}}$, the early Universe was in the state of the vacuum expectation value (VEV) of the Higgs field $\langle\phi\rangle = 0$, while at $T \ll T_{\mathrm{EW}}$ the Higgs field has the present value $\langle\phi\rangle = v_0 = 246\,\mathrm{GeV}$. In this transition vector bosons and fermions acquired masses. The first Sakharov condition can be realized in the SM because only the difference $B - L$, where $L = \sum_\ell \left(n_\ell - n_{\overline{\ell}}\right)$ is strictly conserved. Anomalous processes that changes both B and L, keeping $\Delta B = \Delta L$, are possible as tunneling through the Higgs field potential barrier. In the present state of the Universe these processes are strongly suppressed, but this is not true when $T \geq T_{\mathrm{EW}}$.

In the SM, CPV occurs only via the CKM-mechanism [8, 9], which arise from quark mixing. This mechanism with 3 families can operate if and only if there is a complex phase δ_{CP} in the mixing matrix with $\sin\delta_{\mathrm{CP}} \neq 0$, and if the masses of quarks with equal electric charge but a different flavor are not degenerated, namely should $m_{\mathrm{u}} \neq m_{\mathrm{s}} \neq m_{\mathrm{t}}$ and $m_{\mathrm{d}} \neq m_{\mathrm{c}} \neq m_{\mathrm{b}}$. It is evident that the CKM mechanism will be switched off in the symmetric phase of the primordial plasma at $T > T_{\mathrm{EW}}$, when all fermions and bosons were mass less. In the minimal SM, a sizable baryon asymmetry can therefore be generated at the EWPT only if the SSB proceeds through a strong first order transition [27, 28]. In this case the VEV of the Higgs field changes non-adiabatically at $T \approx T_{\mathrm{EW}}$ by nucleation of bubbles with $\langle\phi\rangle = v_{T_{\mathrm{EW}}}(T_{\mathrm{EW}}) \neq 0$ inside the supercooled bulk with null VEV. In fact, CPV will be active inside the bubbles and can produce baryon asymmetry. A first order transition occurs only if the effective potential of the Higgs field $V_{\mathrm{eff}}(\phi, T)$ [29] has a pronounced second local minimum with $\xi = v_{T_{\mathrm{EW}}}(T_{\mathrm{EW}})/T_{\mathrm{EW}} > 1$. Recent calculations [30] of V_{eff} in the minimal SM show that this is possible if the Higgs mass is $m_{\mathrm{h}} \lesssim 114\,\mathrm{GeV}/c^2$, already excluded by the combined TEVATRON limits [31].

SUSY completely changes this scenario, for two reasons: 1) EWPT can be strong even with a mass of the Higgs compatible with the LHC experiments [30, 32] and 2) CPV is not switched off for $T \approx T_{\mathrm{EW}}$. The Minimal SUSY extension of the SM (MSSM) [33] includes two Higgs complex doublets of opposite hypercharge:

$$\Phi_{\mathrm{u}} = \begin{pmatrix} \Phi_{\mathrm{u}}^{+} \\ \Phi_{\mathrm{u}}^{0} \end{pmatrix} \quad \text{and} \quad \Phi_{\mathrm{d}} = \begin{pmatrix} \Phi_{\mathrm{d}}^{0} \\ \Phi_{\mathrm{d}}^{-} \end{pmatrix}, \tag{1}$$

a combination of eight real degrees fields that couples separately to heavier u, c, t and lighter d, s, b quarks (and leptons). The expectation values of the two neutral fields will be respectively the heavier $\left\langle\Phi_{\mathrm{u}}^{0}\right\rangle = \frac{v_{\mathrm{u}}}{\sqrt{2}}$

and the lighter $\langle \Phi^0_{\mathrm{d}} \rangle = \frac{v_{\mathrm{d}}\,\mathrm{e}^{\mathrm{i}\theta}}{\sqrt{2}}$ that originate *"spontaneous"* CP violating phases in the mixing matrix [34]. In order to conserve the strength of SM weak interactions the VEV of the two fields must obviously be

$$v_{\mathrm{u}}^2 + v_{\mathrm{d}}^2 = v_0^2 = (246\,\mathrm{GeV})^2 \qquad (2)$$

$\tan\beta = v_{\mathrm{u}}/v_{\mathrm{d}} \gg 1$ being a free parameter of the theory. In the physical realization of this theory the eight degrees of freedom correspond to three massless Goldstone bosons and five massive Higgs fields: a CP-odd neutral scalar A^0, two charged scalar $\mathrm{H}^{\pm}$ and two CP-even neutral scalars h^0, H^0, the first being identical to the SM one. If the mass of the heavier Higgs is $m_{\mathrm{H}} \lesssim$ few TeV, it will be possible to detect the existence of this new type of CPV as small deviations from the prediction of the CKM *ansatz*, generically indicated as *"New Physics"* (NP), using precision measurements on the B meson physics by LHCb and the other LHC experiments, as we will discuss in the following Section §3.

More recently a different way of establishing baryon asymmetry has been proposed [35]. As we said before, in the SM only the difference $B - L$ is conserved, while both baryon number B and lepton number L can change with the constraint $\Delta B = \Delta L$. Leptonic asymmetry can easily be generated from the CP violating decay of right handed massive neutrinos N at $T \gg M_{\mathrm{N}} \gg T_{\mathrm{EW}}$. When $M_{\mathrm{N}} \leq T \leq T_{\mathrm{EW}}$, the difference $B - L \neq 0$ would be enforced by baryon number violating interactions of the SM. The existence of heavy Majorana neutrinos can explain the mass of the ordinary light neutrinos [36]. In Section §4 we will give the results of indirect searches for SUSY and majorana neutrinos in B meson rare decays.

3. CPV after the first two years of LHCb

The LHCb detector, located at intersection point 8 of the LHC, is a single arm spectrometer covering the very forward cone $30 \leq \theta \leq 300\,\mathrm{mrad}$ optimized for the reconstruction of heavy mesons decay [37]. As shown in Fig. 2, LHCb does not look like a regular collider experiment (e.g. compare with the ATLAS or CMS layout shown in Ref. [18]). The core of the detector is the vertex locator (VELO), a high resolution silicon tracker with cylindrical geometry, which allows the reconstruction of the position of the decay vertices with a resolution of $\sim 10\,\mathrm{\mu m}$. Two Ring Cerenkov Detectors (RICH1 & RICH2) allow the identification of charged particles, whose momentum is determined by the magnet deflection measured by the downstream (TT) and upstream tracking stations (T1, T2, T3). Energy measurements are performed by the electromagnetic (ECAL) and the hadronic (HCAL) calorimeters. Finally, energetic muon are identified by the muon detector chambers (M1–M5) interleaved into the 4 m iron filter.

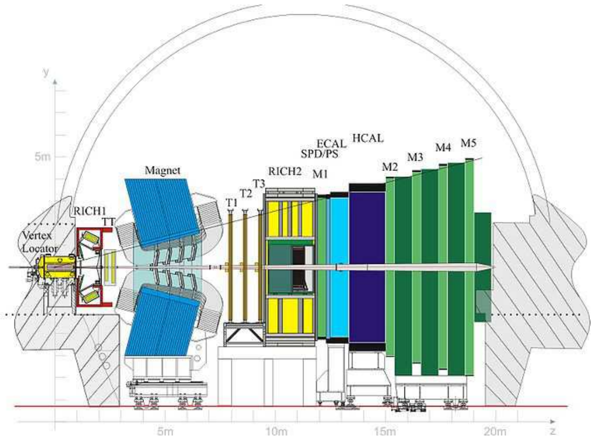

Figure 2. Layout of the LHCb detector at the intersection point 8 of LHC [37].

The LHCb detector ran at $\sqrt{s} = 7\,\mathrm{TeV}$ from April 2010 to September 2011, collecting integrated luminosity for about $1\,\mathrm{fb}^{-1}$ (corresponding to $\approx 10^{14}$ pp collisions and $\approx 8 \times 10^{10}$ $\mathrm{b\bar{b}}$ inclusive pair produced in the LHCb acceptance [38]). Among the many interesting results obtained by the LHCb collaboration, it is worth mentioning.

- **Direct CPV in the $\mathbf{B^0_{s,d}}$ system:** The CKM mechanism manifests itself in two ways in neutral meson decays: time dependent *"indirect"* CPV, which take place during $\mathrm{B}^0_{\mathrm{s,d}} \leftrightarrow \overline{\mathrm{B}}^0_{\mathrm{s,d}}$ oscillations and *"direct"* CPV which gives the different decay rate of the $\mathrm{B}^0_{\mathrm{s,d}}$ from $\overline{\mathrm{B}}^0_{\mathrm{s,d}}$ that could originate baryon asymmetry. LHCb has given the first evidence of direct CPV in the charmless two body decay $\mathrm{B}^0_{\mathrm{s}} \to \mathrm{K}^-\pi^+$ at 3.3σ [39]. Figure 3 makes a direct comparison of the distribution of the invariant mass of $\mathrm{K}^-\pi^+$ pairs (on the left) with that of $\mathrm{K}^+\pi^-$.
- **Mixing and indirect CPV in the charmed mesons:** Evidence for indirect CPV in D mesons has been reported for the first time by LHCb [40]. Evidence for the mixing $\mathrm{D}^0 \leftrightarrow \overline{\mathrm{D}}^0$ has been observed at the B-factories. Belle has published the mixing parameters derived from the 3-body decay $\mathrm{D}^0 \to \mathrm{K}^0_{\mathrm{s}}\pi^+\pi^-$, obtaining a CP violation phase -0.2 ± 0.3 consistent with no CPV. LHCb has investigated the decay of D^0 and $\overline{\mathrm{D}}^0$ into a pair of charged hadrons using data taken in 2010. LHCb obtaining $y_{\mathrm{CP}}^{\mathrm{LHCb}} = [5.5 \pm 6.3\,(\mathrm{stat}) \pm 4.1\,(\mathrm{syst})] \times 10^{-3}$, a value still compatible with no CPV. A significant improvements in sensitivity and systematic uncertainty is expected from an improved treatment of background events, which will be possible for the data taken in 2011 [41].

An important test of the SM is the check for unitarity of the CKM matrix V_{CKM} extracted from measurements [42]. In the complex plane $(\overline{\rho}, \overline{\eta})$, where $\overline{\eta}$ is related to the CPV phase, the unitarity condition is represented by a closed triangle (see §12.3 of Ref. [2]). Figure 4 shows the various constraints used for the fit

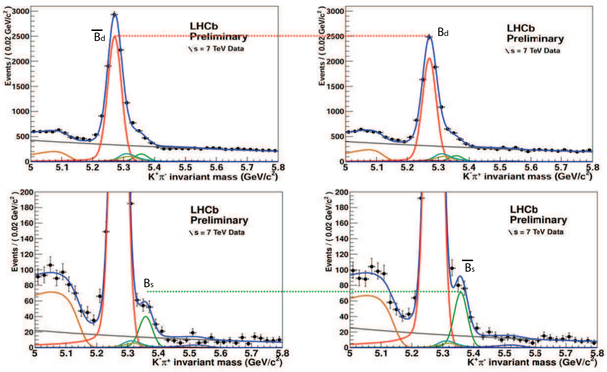

Figure 3. Visual illustration of direct CPV in the b-meson system [39]. Top and bottom plots show the same data, only the vertical scale of the bottom is multiplied ×15.

of the unitary triangle, together with the uncertainty over the closure of the triangle.

A detailed study of the parameters of the oscillations $B_s^0 \leftrightarrow \bar{B}_s^0$ has been proposed in the past as a sensitive test of deviations from the predictions of the SM that could be explained by NP (see e.g. [43] and references therein). Particularly

- **$\mathbf{B_s}$ anomaly:** the CPV phase ϕ_s of the $|\Delta F| = 2$ transitions, predicted to be $\phi_s^{SM} = -0.036 \pm 0.002$ rad in the SM. Previous measurements of this phase at TEVATRON gave values only marginally compatible with the SM [44, 45]. LHCb has significantly improved the study of the decay $\overline{B}_s^0 \to J/\psi\varphi$ followed by $\varphi \to K^+K^-$ [46]. Using 0.37 fb^{-1} of data taken during 2011 at $\sqrt{s} = 7$ TeV, the LHCb collaboration has obtained

$$\phi_s^{J/\psi\varphi} = 0.15 \pm 0.18\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})\,, \qquad (3)$$

only 1σ larger than the SM. Hopefully the collection of larger amount of data expected at $\sqrt{s} = 8$ TeV in the 2012 runs of LHC can reduce the statistical error to an acceptable level suitable for understanding the situation. In case of the very similar decay $\overline{B}_s^0 \to J/\psi f_0\,(980)$ with $f_0 \to \pi^+\pi^-$ [47], LHCb derived a value

$$\phi_s^{comb} = -0.44 \pm 0.44\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})\,. \qquad (4)$$

This value is compatible with the SM, but leaving still room for NP deviations. A statistical study using both $B_s^0 \leftrightarrow \bar{B}_s^0$ and $B_d^0 \leftrightarrow \bar{B}_d^0$ LHCb data [48] concludes that the the SM predictions have only ≈ 0.7 % C.L.

4. The search for New Physics in rare B decays

- **Search for the decay $\mathbf{B^0_{d,s} \to \mu^+\mu^-}$:** This is the golden channel in the search for NP, because in the SM this decay is possible only through the transition b → u, c or t shown by the graph in Fig. 5, which allows precise calculation of the branching ratio [49], being $\mathrm{Br}\left(B_d^0 \to \mu^+\mu^-\right)_{SM} = (1.0 \pm 0.1) \times 10^{-10}$ and $\mathrm{Br}\left(B_s^0 \to \mu^+\mu^-\right)_{SM} = (3.2 \pm 0.2) \times 10^{-9}$. The best experimental limits obtained until now are set by LHCbr [50] using 1.0 fb^{-1} integrated luminosity, which are respectively $\mathrm{Br}\left(B_d^0 \to \mu^+\mu^-\right)_{LHCb} \leq 1.0 \times 10^{-9}$ and $\mathrm{Br}\left(B_s^0 \to \mu^+\mu^-\right)_{LHCb} \leq 4.5 \times 10^{-9}$ at 95 % C.L. In theories beyond the SM, with an extended Higgs sector, additional graphs are expected to contribute to these decays. An example is the graph shown in Fig. 5 where this essential role is played by the neutralino, supposed to be a good candidate for dark matter [51]. The enhancement of the branching ratio with respect to the SM is

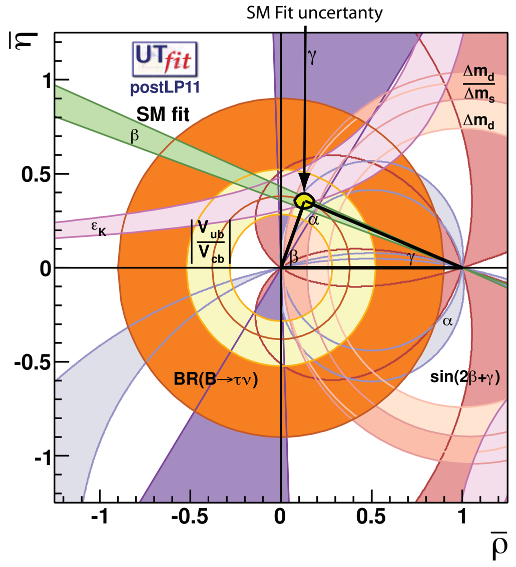

Figure 4. The present status of the fit to the unitary triangle. Yellow color indicates 95 % C.L. contour of the SM fit (adapted from Ref. [42]).

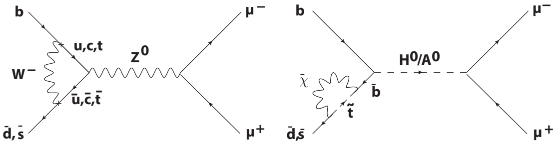

Figure 5. Left: SM, right: MSSM.

$$\mathrm{R_s} = \frac{\mathrm{Br}\left(B_s^0 \to \mu^+\mu^-\right)_{LHCb}}{\overline{\mathrm{Br}}\left(B_s^0 \to \mu^+\mu^-\right)_{SM}} \leq 1.2 \quad \text{at } 95\,\%\ \text{C.L.} \qquad (5)$$

where $\overline{\mathrm{Br}}$ is the time averaged theoretical branching ratio [52]. The complete MSSM has about 100 free parameters, making any comparison with experimental results practically impossible. Some indications can be obtained from the *"constrained"* MSSM (CMSSM), in which all the masses of scalar partners of fermions (squarks, sleptons, etc.) are assumed to have the same mass m_0 while all the fermionic partners of gauge bosons (gauginos) are

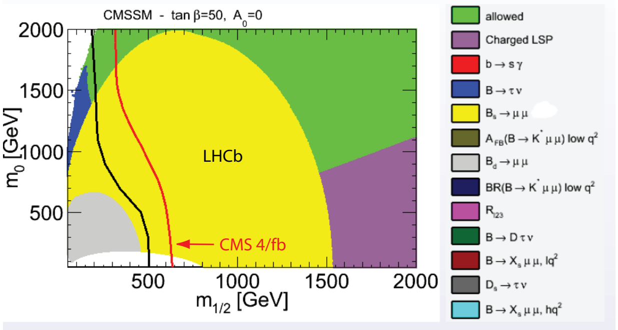

Figure 6. Exclusion region for the two CMSSM mass parameters, derived from the LHCb upper limits on $\mathrm{B_s} \to \mu^+\mu^-$ for $\tan\beta = 50$. Solid lines indicate the direct limits from CMS (adapted from Ref. [54]).

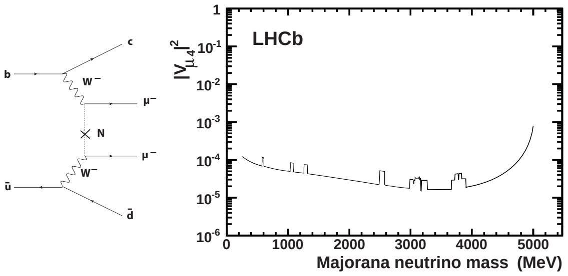

Figure 7.

assumed to have mass $m_{1/2}$. In the CMSSM it is possible to make predictions about the amplitude of NP deviations from the SM, for example in the rare decays of B meson. In the CMSSM it is expected [53]:

$$\mathrm{Br}\left(\mathrm{B_s^0} \to \mu^+\mu^-\right)_{\mathrm{MSSM}} \propto \frac{m_\mathrm{b} m_\mu}{m_\mathrm{A}^4} \tan^6\beta. \qquad (6)$$

Therefore the limit on $\mathrm{R_s}$ from LHCb can already exclude a substantial fraction of the CMSSM parameter space, as shown in Fig. 6.

- **Search for Heavy Majorana neutrinos:** The decay $\mathrm{B}^- \to \mathrm{D}^+\mu^-\mu^-$ (if it exists) violates the conservation of the lepton number [55]. Its graph, shown schematically in Fig. 7, is equivalent to the nuclear neutrinoless double beta decay [56]. The limit on the branching ratio is $\leq 10^{-8}$. Figure 7 shows the limit to the coupling of the majorana neutrino with the muon for $M_\mathrm{N} \leq 5\,\mathrm{GeV}/c^2$.

- **Lepton number violation:** More recently LHCb has also searched for the decay $\tau^- \to \mu^+\mu^+\mu^-$, which violates the lepton number conservation, expected in the SM with an extremely small branching ratio $\mathrm{Br}\left(\tau^- \to \mu^+\mu^+\mu^-\right)_{\mathrm{SM}} \approx 10^{-40}$ [57]. LHCb has obtained the upper limit $\mathrm{Br}\left(\tau^- \to \mu^+\mu^-\mu^-\right)_{\mathrm{LHCb}} \leq 6.3 \times 10^{-8}$ (90 % C.L.). The sensitivity of this search has been calibrated with the control channel $\mathrm{D_s^-} \to \varphi(\mu^+\mu^-)\pi^-$, for which the branching ratio measured by LHCb is $1.33 \pm 0.8 \times 10^{-5}$ [58].

5. Summary

- All the results obtained up to now exclude a mass of the lighter Higgs particles smaller than $115\,\mathrm{GeV}/c^2$ or greater than $126\,\mathrm{GeV}/c^2$ (up to $\approx 800\,\mathrm{GeV}/c^2$). The ATLAS and CMS data are at present not inconsistent with a SM Higgs mass in the range $115 \leq m_\mathrm{h} \leq 126\,\mathrm{GeV}/c^2$ (see note 1) which is favored by EW precision measurements [2] and is compatible with the CMSSM [59].
- CPV phenomenology is very well established in the transitions of the s and b quarks while only some indirect evidence has finally been found by LHCb for charmed hadrons. In all respects, the CKM mechanism is the dominant way in which CPV is realized, as shown from the most accurate fit of the unitary triangle made possible by LHCb measurements. Some large anomalies in $\mathrm{B_s^0}$ semileptonic decays claimed by past experiments have not been confirmed, even if the situation is still ambiguous.
- Rare decays of B mesons are theoretically well constrained in the SM, e.g. $\mathrm{B_s^0} \to \mu^+\mu^-$, have been shown to be very effective in setting constraints to beyond SM effects. LHCb, increasing the collected integrated luminosity, will soon be able to detect this decay at the level predicted by the SM, earlier if it is enhanced as predicted by CMSSM. At present, both the scalar mass scale m_0 and the gauginos mass $m_{1/2}$ are above $1\,\mathrm{TeV}/c^2$ for the large $\tan\beta$ fit of CMSSM [60].
- The 2012 data taking period of LHC, started last spring, is expected to yield in LHCb an integrated luminosity of at least $5\,\mathrm{fb}^{-1}$, that is very promising for the detection or exclusion of new physics phenomenology.

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