Higgs Boson Mass in Yukawa Unified SUSY SO(10)

Qaisar Shafi
Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
E-mail: shafi@bartol.udel.edu

Abstract. We employ third family Yukawa unification, predicted by simple supersymmetric SO(10) models, to estimate the lightest MSSM Higgs boson mass. For $\mu > 0$ (or $\mu < 0$) and $m_t = 173.1$ GeV, the Higgs mass is estimated to lie close to 123-124 GeV. The theoretical uncertainty in this estimate is $\pm 3$ GeV. We highlight some LHC testable benchmark points which also display the presence of neutralino-stau coannihilation channel.

1. Introduction
Supersymmetric (SUSY) SO(10) grand unified theory (GUT), in contrast to its non-SUSY version, yields third family ($t$-$b$-$\tau$) Yukawa unification via the unique renormalizable Yukawa coupling $16 \cdot 16 \cdot 10$, if the Higgs 10-plet is assumed to contain the two Higgs doublets $H_u$ and $H_d$ of the minimal supersymmetric standard model (MSSM) [1]. The matter 16-plet contains the 15 chiral superfields of MSSM as well as the right handed neutrino superfield. The implications of this Yukawa unification condition at $M_{\text{GUT}} \sim 2 \times 10^{16}$ GeV have been extensively explored over the years [1, 2]. In SO(10) Yukawa unification with $\mu > 0$ and universal gaugino masses, the gluino is the lightest colored sparticle [3, 4], which is now being tested [5] at the Large Hadron Collider (LHC). The squarks and sleptons, especially those from the first two families, turn out to have masses in the multi-TeV range. Moreover, it is argued in [3, 4] that the lightest neutralino is not a viable cold dark matter candidate in SO(10) Yukawa unification with $\mu > 0$ and universal gaugino masses at $M_{\text{GUT}}$.

Spurred by these developments we have investigated $t$-$b$-$\tau$ Yukawa unification [4, 6, 7] in the framework of SUSY $SU(4)_c \times SU(2)_L \times SU(2)_R$ [8] (4-2-2, for short). The 4-2-2 structure allows us to consider non-universal gaugino masses while preserving Yukawa unification. An important conclusion reached in [4, 6] is that with same sign non-universal gaugino soft terms, Yukawa unification in 4-2-2 is compatible with neutralino dark matter and gluino coannihilation [4, 5, 6, 9] being a unique dark matter scenario for $\mu > 0$.

Encouraged by the abundance of solutions and coannihilation channels available in the case of Yukawa unified 4-2-2 with $M_2 < 0$ and $\mu < 0$, it seems natural to explore Yukawa unification in SO(10) GUT (with $M_2 < 0$ and $\mu < 0$). It has been pointed out [10] that non-universal MSSM gaugino masses at $M_{\text{GUT}}$ can arise from non-singlet F-terms, compatible with the underlying GUT symmetry such as SU(5) and SO(10). The SSB gaugino masses in supergravity [11] can arise, say, from the following dimension five operator:

$$F_{a\beta} \lambda^a \lambda^\beta + cc$$

(1)
Here $\lambda^a$ is the two-component gaugino field, $F^{ab}$ denotes the F-component of the field which breaks SUSY, the indices $a, b$ run over the adjoint representation of the gauge group, and $M_P = 2.4 \times 10^{18}$ GeV is the reduced Planck mass. The resulting gaugino mass matrix is $\langle F^{ab} \rangle / M_P$ where the supersymmetry breaking parameter $\langle F^{ab} \rangle$ transforms as a singlet under the MSSM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$. The $F^{ab}$ fields belong to an irreducible representation in the symmetric part of the direct product of the adjoint representation of the unified group.

In SO(10), for example,

$$(45 \times 45)_S = 1 + 54 + 210 + 770$$

If $F$ transforms as a 54 or 210 dimensional representation of SO(10) [10], one obtains the following relation among the MSSM gaugino masses at $M_{\text{GUT}}$:

$$M_3 : M_2 : M_1 = 2 : -3 : -1,$$

where $M_1, M_2, M_3$ denote the gaugino masses of $U(1), SU(2)_L$ and $SU(3)_c$ respectively. The low energy implications of this relation have recently been investigated in [12] without imposing Yukawa unification. To our surprise, we find that this class of $t-b-\tau$ Yukawa unification models make a rather sharp prediction for the mass of the lightest SM-like Higgs boson. In addition, lower mass bounds on the masses of the squarks and gluino are obtained.

2. Phenomenological Constraints and Scanning Procedure

We employ the ISAJET 7.80 package [13] to perform random scans over the fundamental parameter space. In this package, the weak scale values of gauge and third generation Yukawa couplings are evolved to $M_{\text{GUT}}$ via the MSSM renormalization group equations (RGEs) in the $\overline{DR}$ regularization scheme. We do not strictly enforce the unification condition $g_3 = g_1 = g_2$ at $M_{\text{GUT}}$, since a few percent deviation from unification can be assigned to unknown GUT-scale threshold corrections [14]. The deviation between $g_1 = g_2$ and $g_3$ at $M_{\text{GUT}}$ is no worse than $3 - 4\%$. For simplicity we do not include the Dirac neutrino Yukawa coupling in the RGEs, whose contribution is expected to be small.

The various boundary conditions are imposed at $M_{\text{GUT}}$ and all the SSB parameters, along with the gauge and Yukawa couplings, are evolved back to the weak scale $M_Z$. In the evaluation of Yukawa couplings the SUSY threshold corrections [15] are taken into account at the common scale $M_{\text{SUSY}} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$, where $m_{\tilde{t}_L}$ and $m_{\tilde{t}_R}$ are the third generation left and right handed stop quarks. For further details about iteration of the entire parameter set between $M_Z$ and $M_{\text{GUT}}$, see [13].

An important constraint comes from limits on the cosmological abundance of stable charged particles [16]. This excludes regions in the parameter space where charged SUSY particles become the lightest supersymmetric particle (LSP). We accept only those solutions for which one of the neutralinos is the LSP and saturates the WMAP bound on relic dark matter abundance.

The MSSM Higgs doublets reside in the 10 dimensional representation of $SO(10)$ and fermions of the third family belong to the 16 dimensional representation of $SO(10)$, which implies Yukawa coupling unification at $M_{\text{GUT}}$. At low scale, Higgs mass is estimated with the approximate error of $\pm 3\text{GeV}$, which could stem from experimental uncertainties in the values of $m_t$ and $\alpha_s$.

We have performed random scans for the following parameter range:

$$
\begin{align*}
0 \leq & \quad m_{16} \leq 5\text{TeV} \\
0 \leq & \quad m_{10} \leq 5\text{TeV} \\
0 \leq & \quad M_{1/2} \leq 2\text{TeV} \\
35 \leq & \quad \tan \beta \leq 55 \\
-3 \leq & \quad A_0/m_{16} \leq 3
\end{align*}
$$

(4)
Here $m_{16}$ is the universal SSB mass for MSSM sfermions, $m_{10}$ is the universal SSB mass term for up and down MSSM Higgs masses, $M_{1/2}$ is the gaugino mass parameter, $\tan \beta$ is the ratio of the vacuum expectation values (VEVs) of the two MSSM Higgs doublets, $A_0$ is the universal SSB trilinear scalar interaction (with corresponding Yukawa coupling factored out). We use $m_t = 173.1$ GeV [17]. Note that our results are not too sensitive to one or two sigma variation in the value of $m_t$ [18]. We use $m_b(m_Z) = 2.83$ GeV which is hard-coded into ISAJET.

Employing the boundary condition from Eq.(3) one can define the MSSM gaugino masses at $M_{GUT}$ in terms of the mass parameter $M_{1/2}$:

$$M_1 = -M_{1/2}, \quad M_2 = -3M_{1/2}, \quad M_3 = 2M_{1/2}$$

Note that $M_2$ and $M_3$ have opposite signs which, as we show, is important implementing Yukawa coupling unification to a high accuracy.

In order to obtain the correct sign for the desired contribution to $(g - 2)_\mu$, we consider two possible combinations of $SU(2)_L$ gaugino and the sign of $\mu$ term: (a) $\mu < 0$ and $M_2 < 0$, (b) $\mu > 0$ and $M_2 > 0$.

In scanning the parameter space, we employ the Metropolis-Hastings algorithm as described in [19]. The data points collected all satisfy the requirement of REWSB, with the neutralino in each case being the LSP. After collecting the data, we impose the mass bounds on all the particles [16] and use the IsaTools package [20] to implement the various phenomenological constraints. We successively apply the following experimental constraints on the data that we acquire from ISAJET:

\[
\begin{align*}
 m_h \text{ (lightest Higgs mass)} & \geq 114.4 \text{ GeV} \quad [21] \\
 BR(B_s \to \mu^+\mu^-) & < 1.2 \times 10^{-8} \quad [22] \\
 2.85 \times 10^{-4} & \leq BR(b \to s\gamma) \leq 4.24 \times 10^{-4} \ (2\sigma) \quad [23] \\
 0.15 & \leq \frac{BR(B_s \to \tau\nu \tau\nu)_{MSSM}}{BR(B_s \to \tau\nu\tau\nu)_{SM}} \leq 2.41 \ (3\sigma) \quad [23] \\
 \Omega_{CDM}h^2 & = 0.1123 \pm 0.0035 \ (5\sigma) \quad [24] \\
 0 & \leq \Delta(g - 2)_\mu/2 \leq 55.6 \times 10^{-10} \quad [25]
\end{align*}
\]

3. Yukawa Unification, Higgs Boson Mass and Sparticle Spectrum

In order to quantify Yukawa coupling unification, we define the quantity $R$ as,

$$R = \frac{\max(y_t, y_b, y_\tau)}{\min(y_t, y_b, y_\tau)}$$

In Figure 1 we show the results in the $R - m_{16}$, $R - M_{1/2}$, $R - m_{10}$ and $R - \tan \beta$ planes. The left panels correspond to the following choice of parameters: $\mu < 0$, $M_2 < 0$ and $M_3 : M_2 : M_1 = 2 : -3 : -1$. The right panels are for $\mu > 0$, $M_2 > 0$ and $M_3 : M_2 : M_1 = -2 : 3 : 1$. The gray points are consistent with REWSB and neutralino LSP. The green points satisfy the particle mass bounds and constraints $BR(B_s \to \mu^+\mu^-)$,

$BR(b \to s\gamma)$ and $BR(B_s \to \tau\nu\tau\nu)$. In addition, the green points do no worse than the SM in terms of $(g - 2)_\mu$. The brown points belong to a subset of the green points and satisfy the WMAP bounds on neutralino dark matter abundance.

In the $R - m_{16}$ plane of Figure 1 we see that with $\mu > 0$, $M_2 > 0$ and $M_3 < 0$, we can realize perfect Yukawa unification consistent with all constraints mentioned in Section 2. This is possible because we can implement Yukawa unification for relatively small values of $m_{16}$ ($\sim 1$ TeV). This is more than an order of magnitude reduction in the $m_{16}$ values required for Yukawa unification, compared with the case $\mu > 0$ and universal gaugino masses. We also see
that the minimum R values, close to 1.02, can be reached for $m_{16} \simeq 2$ TeV for the case $\mu < 0$, $M_2 < 0$ and $M_3 > 0$. In the $R - M_{1/2}$ plane of Figure 1, we see that employing the boundary conditions for gauginos presented in Eq. (5), perfect $t$-$b$-$\tau$ Yukawa unification prefers heavier (> 1.2 TeV) values for $M_{1/2}$. We can also predict that $\tan \beta \approx 47$. In this case for Yukawa unification up to 5% level, $45 \leq \tan \beta \leq 48$.

In Figure 2 we show the results in the $R - m_h$, $m_{\tilde{g}} - m_{\tilde{q}}$, $m_{\tilde{\tau}} - m_{\tilde{\chi}^0}$ planes. The left and right panels, as in Figure 1, correspond to $\mu < 0$ and $\mu > 0$ respectively, with the sign of $M_2$ suitably chosen. It is most interesting to note that demanding precise $t$-$b$-$\tau$ Yukawa unification for $\mu > 0$ allows us to predict the light CP even Higgs mass in a very narrow interval, 122 GeV.

Figure 1. Plots in $R - m_{16}$, $R - M_{1/2}$ and $R - \tan \beta$ planes. Left side panels correspond to the following choice of parameters: $\mu < 0$, $M_2 < 0$ and $M_3 : M_2 : M_1 = 2 : -3 : -1$. Right side panels are for $\mu > 0$, $M_2 > 0$ and $M_3 : M_2 : M_1 = -2 : 3 : 1$. Gray points are consistent with REWSB and neutralino LSP. Green points satisfy particle mass bounds and constraints from $BR(B_s \to \mu^+\mu^-)$, $BR(b \to s\gamma)$ and $BR(B_u \to \tau\nu_\tau)$. In addition, we require that green points do no worse than the SM in terms of $(g - 2)_\mu$. Brown points belong to a subset of green points and satisfy the WMAP bounds on neutralino dark matter abundance.
For Yukawa unification of up to 5%, it becomes $120 \text{ GeV} < m_h < 125 \text{ GeV}$. We expect a theoretical uncertainty of about 3 GeV in the calculation of the light Higgs mass. Similarly, for $\mu < 0$, the best unification solutions predict a Higgs mass close to 123 GeV ($\pm 3$ GeV).

The $m_{\tilde{q}} - m_{\tilde{g}}$ panel shows that $t$-$b$-$\tau$ Yukawa unification in our scenario predicts masses for the gluino and the first two family squarks which lie somewhat beyond the current ATLAS [26] and CMS [27] bounds.

In the present framework, the WMAP constraint on the relic dark matter abundance is only satisfied by the neutralino-stau coannihilation scenario. From the plot in $m_{\tilde{\tau}} - m_{\tilde{\chi}^0}$ plane, we see that the LSP neutralino mass is greater than or of order 300 GeV.

**Figure 2.** Plots in $R - m_h$, $m_{\tilde{q}} - m_{\tilde{g}}$, $m_{\tilde{\tau}} - m_{\tilde{\chi}^0}$ planes. Left and right panels, as in Figure 1, correspond to two different choices of sign of $\mu$ with suitable choice of sign for $M_2$.

Finally, in Tables 1 we present some benchmark points with $\mu > 0$ (on left side) and $\mu < 0$ (on right side) respectively. All of these benchmark points satisfy the various constraints, except possibly for a small discrepancy with the WMAP bound on relic dark density. Points 1’s on both sides depict solutions corresponding to minimum R and best $\Omega_{CDM}h^2$ values. Each Point 1 predicts the CP-even light Higgs boson mass $\sim 124$ GeV and the relic density abundance is satisfied by the neutralino-stau coannihilation scenario. However, these points predict stau mass about 850 GeV. Point 2’s on both sides display solutions for neutralino-stau coannihilation scenario with relatively lighter stau mass ($< 500$ GeV). The CP-even light Higgs boson mass is about 122 GeV, if $m_{\tilde{\tau}} < 500$ GeV.

4. Conclusion
We have reconsidered $t$-$b$-$\tau$ Yukawa unification within a slightly revised framework in this paper. The main difference from most previous investigations stems from the assumptions.
Table 1. Sparticle and Higgs masses (in GeV). The columns on left are for $\mu > 0$ while those on right for $\mu < 0$. On both sides, Point 1’s depict solutions for the heaviest mass for the CP-even light Higgs boson corresponding to minimum $R$ and best $\Omega_{CDM} h^2$ values. Each Point 1 predicts the CP-even light Higgs boson mass $\sim 124$ GeV and relic dark matter abundance is satisfied by the neutralino-stau coannihilation scenario. For these points stau mass is about 850 GeV. Point2’s on both sides seek for a solution for neutralino-stau coannihilation scenario with relatively lighter stau mass $\sim 500$ GeV. The maximum mass of the CP-even Higgs boson mass is about 122 GeV, if $m_{\tilde{t}} < 500$ GeV.

we make related to the soft supersymmetry breaking parameters. First, we assume that the MSSM gauginos have non-universal masses, which are related to one another at $M_{\text{GUT}}$ by some appropriate SO(10) group theory factors. Second, we set the masses of the two MSSM Higgs doublets to be equal at $M_{\text{GUT}}$. Overall, this means that we effectively have one parameter less than in the standard approach to SO(10) Yukawa unification.

The ramifications of these slightly different assumptions for TeV scale physics turn out to
be quite startling, with the low energy predictions being very different from previous studies. We find, for instance, that $t$-$b$-$\tau$ Yukawa unification solutions at 5\% level or better exist in our model for both $\mu > 0$ and $\mu < 0$.

These solutions, obtained using the ISAJET software, are compatible with all experimental observations, as well as the WMAP dark matter constraint (through stau coannihilation). The masses of the gluino and first two family squarks are found to lie in the 2.7 - 5 TeV range, while the lightest stop (top squark) weighs at least 2 TeV or so. Finally, with 5\% or better Yukawa unification, the lightest Higgs boson is predicted to have a mass of around 120 - 125 GeV mass range, (with an uncertainty of $\pm$3 GeV). The MSSM parameter $\tan \beta$ is around 45 - 47.

Acknowledgments
I would like to thank Professors Yue- Liang Wu and Yu- Feng Zhou and members of the local organizing committee for their warm hospitality.

References

[1] B. Ananthanarayan, G. Lazarides and Q. Shafi, Phys. Rev. D 44, 1613 (1991) and Phys. Lett. B 300, 24 (1993); S. Shafi and B. Ananthanarayan, Trieste HEP Cosmol.1991:233-244.

[2] L. J. Hall, R. Rattazzi and U. Sarid, Phys. Rev. D 50, 7048 (1994); M. Olechowski and S. Pokorski, Phys. Lett. B 214, 393 (1988); T. Banks, Nucl. Phys. B 303, 172 (1988); V. Barger, M. Berger and P. Ohmann, Phys. Rev. D 49, (1994) 4908; M. Carena, M. Olechowski, S. Pokorski and C. Wagner, Nucl. Phys. B 426, 269 (1994); B. Ananthanarayan, Q. Shafi and X. Wang, Phys. Rev. D 50, 5980 (1994); G. Anderson et al. Phys. Rev. D 47, (1993) 3702 and Phys. Rev. D 49, 3660 (1994); R. Rattazzi and U. Sarid, Phys. Rev. D 53, 1553 (1996); T. Blazek, M. Carena, S. Raby and C. Wagner, Phys. Rev. D 56, 6919 (1997); T. Blazek, S. Raby and K. Tobe, Phys. Rev. D 62, 055001 (2000); H. Baer, M. Diaz, J. Ferrandis and X. Tata, Phys. Rev. D 61, 111701 (2000); H. Baer, M. Brhlik, M. Diaz, J. Ferrandis, P. Mercadante, P. Quintana and X. Tata, Phys. Rev. D 63, 015007(2001); C. Balazs and R. Dermisek, JHEP 0306, 024 (2003); C. Pallis, Nucl. Phys. B 678, 398 (2004); U. Chattopadhyay, A. Corsetti and P. Nath, Phys. Rev. D 66 035003, (2002); T. Blazek, R. Dermisek and S. Raby, Phys. Rev. Lett. 88, 111804 (2002) and Phys. Rev. D 65, 115004 (2002); M. Gomez, T. I. Ibrahim, P. Nath and S. Skadhauge, Phys. Rev. D 72, 095008 (2005); K. Tobe and J. D. Wells, Nucl. Phys. B 663, 123 (2003); I. Gogoladze, Y. Mimura, S. Nandi, Phys. Lett. B562, 307 (2003); W. Altmanshofer, D. Guadagnoli, S. Raby and D. M. Straub, Phys. Lett. B 668, 385 (2008); S. Antusch and M. Spinrath, Phys. Rev. D 78, 075020 (2008); H. Baer, S. Kraml and S. Sekmen, JHEP 0909, 005 (2009); S. Antusch and M. Spinrath, Phys. Rev. D 79, 095004 (2009); D. Guadagnoli, S. Raby and D. M. Straub, JHEP 0910, 059 2009; K. Choi, D. Guadagnoli, S. H. Im and C. B. Park, JHEP 1005, 025 (2010); S. Dar, I. Gogoladze, Q. Shafi and C. S. Un, Phys. Rev. D 84, 085015 (2011); N. Karagiannakis, G. Lazarides and C. Pallis, Phys. Lett. B 704, 43 (2011); I. Gogoladze, Q. Shafi and C. S. Un, Phys. Lett. B 704, 201 (2011); M. Badziak, M. Olechowski and S. Pokorski, JHEP 1108, 147 (2011); S. Antusch, L. Calibbi, V. Maurer, M. Monaco and M. Spinrath, arXiv:1111.6547 [hep-ph]; J. S. Gainer, R. Huo and C. E. M. Wagner, arXiv:1111.3639 [hep-ph].

[3] H. Baer, S. Kraml, S. Sekmen and H. Summy, JHEP 0803, 056 (2008); H. Baer, M. Haider, S. Kraml, S. Sekmen and H. Summy, JCAP 0902, 002 (2009).

[4] I. Gogoladze, R. Khalid and Q. Shafi, Phys. Rev. D 79, 115004 (2009).

[5] H. Baer, S. Kraml, A. Lessa and S. Sekmen, JHEP 1002, 055 (2010); D. Feldman, Z. Liu and P. Nath, Phys. Rev. D 80, 015007 (2009); M. A. Ajub, T. Li, Q. Shafi and K. Wang, JHEP 1101, 028 (2011).

[6] I. Gogoladze, R. Khalid and Q. Shafi, Phys. Rev. D 80, 095016 (2009).

[7] I. Gogoladze, R. Khalid, S. Raza and Q. Shafi, JHEP 1012, 055 (2010); arXiv:1008.2765 [hep-ph].

[8] J. C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974).

[9] S. Profumo and C. E. Yaguna, Phys. Rev. D 69, 115009 (2004); D. Feldman, Z. Liu and P. Nath, Phys. Rev. D 80, 015007 (2009).

[10] See, for instance, S. P. Martin, Phys. Rev. D79, 095019 (2009); U. Chattopadhyay, D. Das and D. P. Roy, Phys. Rev. D 79, 095013 (2009); B. Ananthanarayan, P. N. Pandita, Int. J. Mod. Phys. A22, 3229-3259 (2007); S. Bhattacharyya, A. Datta and B. Mukhopadhyaya, JHEP 0710, 080 (2007); A. Corsetti and P. Nath, Phys. Rev. D 64, 125010 (2001) and references therein.

[11] A. Chamseddine, R. Arnowitt and P. Nath, Phys. Rev. Lett. 49 (1982) 970; R. Barbieri, S. Ferrara and C. Savoy, Phys. Lett. B119 (1982) 343; N. Ohta, Prog. Theor. Phys. 70 (1983) 542; L. J. Hall, J. D. Lykken
and S. Weinberg, Phys. Rev. D27 (1983) 2359; for a review see S. Weinberg, The Quantum Theory of Fields: Volume 3, Supersymmetry, Cambridge University Press (2000) 442p.

[12] N. Okada, S. Raza and Q. Shafi, Phys. Rev. D 84, 095018 (2011) [arXiv:1107.0941 [hep-ph]].

[13] F. E. Paige, S. D. Protopopescu, H. Baer and X. Tata, hep-ph/0312045.

[14] J. Hisano, H. Murayama , and T. Yanagida, Nucl. Phys. B402 (1993) 46. Y. Yamada, Z. Phys. C60 (1993) 83; J. L. Chkareuli and I. G. Gogoladze, Phys. Rev. D 58, 055011 (1998).

[15] D. M. Pierce, J. A. Bagger, K. T. Matchev, and R.-j. Zhang, Nucl. Phys. B491 (1997) 3.

[16] K. Nakamura et al. [ Particle Data Group Collaboration ], J. Phys. G G37, 075021 (2010).

[17] [Tevatron Electroweak Working Group and CDF Collaboration and D0 Collab], arXiv:0903.2503 [hep-ex].

[18] I. Gogoladze, R. Khalid, S. Raza and Q. Shafi, JHEP 1106 (2011) 117.

[19] G. Belanger, F. Boudjema, A. Pukhov and R. K. Singh, JHEP 0911, 026 (2009); H. Baer, S. Kraml, S. Sekmen and H. Sumny, JHEP 0803, 056 (2008).

[20] H. Baer, C. Balazs, and A. Belyaev, JHEP 03 (2002) 042; H. Baer, C. Balazs, J. Ferrandis, and X. Tata Phys. Rev. D64 (2001) 035004.

[21] S. Schael et al. Eur. Phys. J. C 47, 547 (2006).

[22] T. Aaltonen et al. [ CDF Collaboration ], Phys. Rev. Lett. 100, 101802 (2008).

[23] E. Barberio et al. [ Heavy Flavor Averaging Group ], arXiv:0808.1297 [hep-ex].

[24] E. Komatsu et al. [ WMAP Collaboration ], Astrophys. J. Suppl. 180, 330 (2009).

[25] G. W. Bennett et al. [ Muon G-2 Collaboration ], Phys. Rev. D 73, 072003 (2006).

[26] G. Aad et al. [ ATLAS Collaboration ], arXiv:1109.6572 [hep-ex].

[27] S. Chatrchyan et al. [ CMS Collaboration ], arXiv:1109.2352 [hep-ex].