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Scalar-top masses from SUSY loops with 125 GeV m_h and precise M_W, m_t

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ABSTRACT

We constrain the masses of scalar-tops (stop) by analyzing the new precision Tevatron measurement of the W-boson mass and the LHC/Tevatron indications of a Higgs boson of mass 125.5 ± 1 GeV. Our study adopts Natural SUSY with low fine-tuning, which has multi-TeV first- and second-generation squarks and a light Higgsino mixing parameter $\mu = 150$ GeV. An effective Lagrangian calculation is made of m_h to 3 loops using the H3m program with weak scale SUSY parameters obtained from RGE evolution from the GUT scale in the Natural SUSY scenario. The SUSY radiative corrections to the Higgs mass imply maximal off-diagonal elements of the stop mass matrix and a mass splitting of the two stops larger than 400 GeV.

Supersymmetry (SUSY) is a theoretically attractive extension of the Standard Model (SM) that may explain the hierarchy of the weak scale and the Planck scale. Of the SUSY particles, the lighter scalar-top squark may have a sub-TeV mass and be detectable by LHC experiments. Existence of a light top squark is particularly suggested by the Natural SUSY model [1–21], that has less fine-tuning. The first- and second-generation squarks have multi-TeV masses to mitigate unwanted flavor changing neutral currents (FCNC) and large CP violation. For a third-generation scalar GUT-scale mass $m_0(3) < 1$ TeV, $m_{\tilde{t}_1}$ is less than 400 GeV from the running of the RGE equations [17].

A light top squark can give a significant radiative contribution to the W-boson mass. The precision of M_W has been improved by recent Tevatron measurements; $M_W = 80{,}387 \pm 12(\text{stat.}) \pm 15(\text{syst.})$ MeV by the CDF Collaboration [22] and $M_W = 80{,}367 \pm 13(\text{stat.}) \pm 22(\text{syst.})$ MeV by the D0 Collaboration [23]. Including these measurements, the world average M_W is shifted downward from [24] $M_W^{\text{exp}} = 80{,}399 \pm 26$ MeV to $80{,}385 \pm 15$ MeV. The SM prediction [25,26] of M_W at 2-loop order is

$$M_W^{\text{SM}} = 80{,}361 \pm 7 \text{ MeV} \quad (1)$$

where we have used the numerical formula of Ref. [27] with central values of parameters [28]. The uncertainties of the SM prediction of M_W resulting from the uncertainties of these input parameters are summarized in Table 1.

Table 1
Uncertainty of the SM M_W prediction from the uncertainties of the parameters. Beside these errors, there is another uncertainty due to missing higher order corrections, which is estimated as about 4 MeV [27].

	δM_W
$\delta m_h = 1.0$ GeV	-0.5 MeV
$\delta m_t = 1$ GeV	6.0 MeV
$\delta M_Z = 2.1$ MeV	2.6 MeV
$\delta(\Delta\alpha_{\text{had}}^{(5)}) = 0.6 \times 10^{-4}$	-1.1 MeV
$\delta\alpha_s(M_Z) = 0.0007$	-0.4 MeV

The LHC experiments have reported indications of a Higgs boson at mass $125.3 \pm 0.4_{\text{stat}} \pm 0.5_{\text{syst}}$ GeV in CMS data [29] and at $126.0 \pm 0.4_{\text{stat}} \pm 0.4_{\text{syst}}$ GeV in ATLAS data [30]. Accordingly, we assume a Higgs boson mass of 125.5 ± 1 GeV in our study. Then, the difference of the experimental and SM values of M_W is

$$M_W^{\text{exp}} - M_W^{\text{SM}} = 24 \pm 15 \text{ MeV}. \quad (2)$$

As can be seen in Table 1, the largest source uncertainty in M_W^{SM} (of 6.0 MeV) is from the uncertainty $\delta m_t = 1$ GeV in the top mass measurement. It is significantly smaller than the experimental uncertainty in M_W^{exp} (of 15 MeV), given in Eq. (2).

The contributions of SUSY particles to the 1-loop calculation of M_W [31] along with the W self-energy at the 2-loop level [32] can account for the 1.6σ deviation of the experimental value from the SM prediction [31]. Conversely, the M_W measurement gives a constraint on the squark masses of the third generation, $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, and $m_{\tilde{b}_L}$. We assume no mixing in sbottom sector since that

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off-diagonal element is proportional to m_b; $m_{\tilde{b}_R}$ is irrelevant to δM_W.

The dominant SUSY radiative corrections to m_h are due to loops of $\tilde{t}_1$ and $\tilde{t}_2$. Implications of a 125 GeV Higgs boson for supersymmetric models are investigated in Ref. [33]. If m_h is confirmed with the value of the present Higgs boson signal ~ 125.5 GeV, the values of $m_{\tilde{t}_1}, m_{\tilde{t}_2}$ and the top-squark mixing angle $\theta_{\tilde{t}}$ can be constrained from the measured m_h. We investigate how a Higgs mass $m_h = 125.5 \pm 1.0$ GeV and the new experimental value of M_W constrain the third-generation SUSY scalar-top masses.

1. Constraint from M_W

The M_W prediction is obtained by calculating the muon lifetime [25,26,31]. The SUSY correction Δr to the Fermi constant G_μ is

$$\frac{G_\mu}{\sqrt{2}} = \frac{e^2}{8 s_W^2 M_W^2}(1 + \Delta r) \tag{3}$$

where $s_W = \sin\theta_W$ and θ_W is weak mixing angle which is defined by the experimental values of W/Z pole mass $M_{W/Z}$ as

$$c_W^2 \equiv \cos^2\theta_W = \frac{M_W^2}{M_Z^2}. \tag{4}$$

Δr is calculated [31] in the MSSM, and the corresponding M_W prediction is obtained by iterative solution of the equation

$$M_W^2 = M_Z^2 \times \left\{ \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha}{\sqrt{2} G_\mu M_Z^2}\left[1 + \Delta r(M_W, M_Z, m_t, \ldots)\right]} \right\}. \tag{5}$$

Then, the correction to M_W^2 at 1-loop level is

$$\delta M_W^2 = -M_Z^2 \frac{c_W^2 s_W^2}{c_W^2 - s_W^2} \Delta r. \tag{6}$$

Δr is given by [25,26]

$$\Delta r = \frac{c_W^2}{s_W^2}\left(\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2}\right) + \Delta\alpha + (\Delta r)_{\text{rem.}}. \tag{7}$$

The first term on the left-hand side is the on-shell self-energy correction to gauge boson masses; $\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2} = -\frac{\Sigma^Z(M_Z^2)}{M_Z^2} + \frac{\Sigma^W(M_W^2)}{M_W^2}$. $\Delta\alpha$ is the radiative correction to the fine structure constant α. The remainder term $(\Delta r)_{\text{rem.}}$ includes vertex corrections and box diagrams at 1-loop level which give subleading contributions compared with the first term of Eq. (7) [31].

The main contribution to δM_W is the on-shell gauge boson self-energy, which is well approximated [32,34] with its value at zero momenta as

$$\Delta r \simeq -\frac{c_W^2}{s_W^2}\left(\frac{\Sigma^Z(0)}{M_Z^2} - \frac{\Sigma^W(0)}{M_W^2}\right) = -\frac{c_W^2}{s_W^2}\Delta\rho \tag{8}$$

where $\Delta\rho$ is the deviation of the ρ parameter due to new physics in the EW precision measurements. It is related to the T parameter [35] by

$$\Delta\rho \simeq \alpha(M_Z) T. \tag{9}$$

The squark, slepton, and neutralino/chargino loops contribute to $\Delta\rho$ at 1-loop level, which we denote as $\Delta\rho_0$. The neutralino/chargino contributions are small [36], and the slepton contributions are suppressed relative to squark contributions by color, and thus the squark contributions are dominant. It is well known [37] that the weak $SU(2)_L$ isospin violation from SUSY doublet masses gives non-zero contributions to δM_W. The scalar-top sector is expected to have a large L–R mixing since the off-diagonal elements of the top-squark mass matrix are proportional to m_t. Finally, δM_W is given by [32,34]

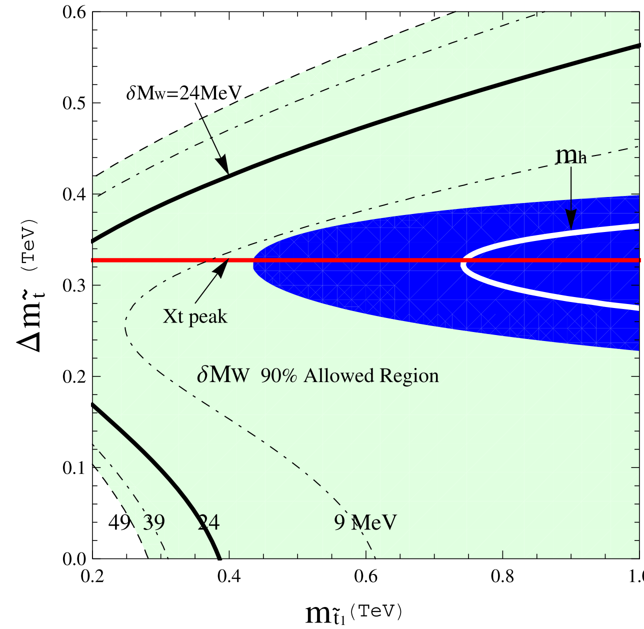

Fig. 1. Allowed regions in the $(m_{\tilde{t}_1}, \Delta m_{\tilde{t}})$ plane for $\theta_{\tilde{t}} = \frac{\pi}{4}$; $\Delta m_{\tilde{t}} = (m_{\tilde{t}_2} - m_{\tilde{t}_1})$. Black (red) solid lines are $\delta M_W = 24$ MeV (maximum m_h with $X_{t\,\text{peak}} = -\sqrt{6} M_{\text{susy}}$). The blue (dark-shaded) region is $m_h = 123.5$ to 127.5 GeV and the white line represents its central value $m_h = 125.5$ GeV. The green (medium-shaded) region is allowed by δM_W at 90% CL, and the dot-dashed lines represent its 1σ deviation, $\delta M_W = 24 \pm 15$ MeV.

$$\delta M_W \simeq \frac{M_W}{2}\frac{c_W^2}{c_W^2 - s_W^2}\Delta\rho_0,$$

$$\Delta\rho_0 = \frac{3 G_F}{8\sqrt{2}\pi^2}\left[-s_{\tilde{t}}^2 c_{\tilde{t}}^2 F_0\left(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2\right) + c_{\tilde{t}}^2 F_0\left(m_{\tilde{t}_1}^2, m_{\tilde{b}_L}^2\right) + s_{\tilde{t}}^2 F_0\left(m_{\tilde{t}_2}^2, m_{\tilde{b}_L}^2\right)\right] \tag{10}$$

where $F_0(a, b) \equiv a + b - \frac{2ab}{a-b}\ln\frac{a}{b}$, $s_{\tilde{t}} = \sin\theta_{\tilde{t}}$, $c_{\tilde{t}} = \cos\theta_{\tilde{t}}$, and $\theta_{\tilde{t}}$ is the top-squark mixing angle. The 2-loop gluon/gluino exchange effects, $\Delta\rho^{\text{SUSY}}_{1,\text{gluon/gluino}}$, are neglected since they are subleading compared with the 1-loop $\Delta\rho$ for $M_{\text{susy}} \gtrsim 300$ GeV [34]. The prediction of M_W in SUSY is then $M_W = M_W^{\text{SM}} + \delta M_W$. From Eq. (10) the δM_W of Eq. (2) corresponds to

$$\Delta\rho = (4.2 \pm 2.7) \times 10^{-4}, \qquad T = 0.054 \pm 0.034. \tag{11}$$

The uncertainty is substantially reduced from that of the previous global electroweak precision analyses: $\Delta\rho = (3.67 \pm 8.82) \times 10^{-4}$ [38], $T = 0.03 \pm 0.11$ [39].

By using Eq. (10) with (2), we can determine the allowed region in the $m_{\tilde{t}_1}, \Delta m_{\tilde{t}}$ plane for a given value of $\theta_{\tilde{t}}$. Here $\Delta m_{\tilde{t}} = (m_{\tilde{t}_2} - m_{\tilde{t}_1})$. The case $\theta_{\tilde{t}} = \frac{\pi}{4}$ is shown in Fig. 1. Note that X_t and $\theta_{\tilde{t}}$ are independent because the soft-SUSY parameters in the diagonal elements are different.

We also note that $m_{\tilde{b}_L}$ in Eq. (10) is given by $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, and $\theta_{\tilde{t}}$

$$m_{\tilde{b}_L}^2 = m_{\tilde{t}_1}^2 \cos^2\theta_{\tilde{t}} + m_{\tilde{t}_2}^2 \sin^2\theta_{\tilde{t}} - m_t^2 + m_b^2 - M_W^2 \cos 2\beta. \tag{12}$$