Constraints on non-universal gaugino mass scenario using the latest LHC data

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little hierarchy problem

Higgs mass and SUSY search indicate high-scale SUSY

hierarchy between SUSY scale and EW scale

minimization condition of the Higgs potential

\[ m_Z^2 \approx -2 |\mu|^2 + 2|m_{h_u}^2| \]

EW scale \quad SUSY scale

✓ fine-tuning is required if \( m_Z \ll \mu, m_{h_u} \)

✓ at least \( \mu(m_Z) \) must be small since it’s unique SUSY parameter

✓ small \( \mu(m_Z) \) means small \( m_{H_u}(m_Z) \)
Higgs mass vs little hierarchy

little hierarchy problem relates to the Higgs mass

RGE of $m_{h_u}$

$$16\pi^2 \frac{d m_{h_u}^2}{dt} \approx 6 y_t^2 (m_{h_u}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2) - 6 g_2^2 |M_2|^2 - \frac{6}{5} g_1^2 |M_1|^2$$

- top squark parameters $m_{\tilde{t}_L}^2, m_{\tilde{t}_R}^2, A_t$ appear
- heavier top squark leads severer fine-tuning
- top squark mass is crucial for the Higgs mass

✔ 10 TeV top squark forces $10^{-3}$ % tuning
maximal mixing

- MSSM Higgs boson mass

\[ m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{8\pi^2 v_u^2} \left[ \log \frac{M_{\text{stop}}^2}{m_t^2} + \frac{2A_t^2}{M_{\text{stop}}^2} \left( 1 - \frac{A_t^2}{12M_{\text{stop}}^2} \right) \right] \]

- \( M_{\text{stop}} \approx 10 \text{ TeV} \) if \( A_t/M_{\text{stop}} \ll 1 \)

- Higgs mass requires severer bound than direct SUSY search

- maximal mixing scenario

  the last term is maximized at

  \[ \frac{2A_t^2}{M_{\text{stop}}^2} \left( 1 - \frac{A_t^2}{12M_{\text{stop}}^2} \right) \]

  \( A_t/M_{\text{stop}} \sim \sqrt{6} \)

  “maximal mixing”
Higgs boson mass in NUGM

we assume universal soft masses $m_0$ and A-term $A_0$ at the GUT scale

- top squark parameters

  $m_{\tilde{t}_L}^2 (m_Z) \approx +0.38M_2^2 + 5.63M_3^2 + 0.58m_0^2$

  $m_{\tilde{t}_R}^2 (m_Z) \approx -0.21M_2^2 + 4.61M_3^2 + 0.19m_0^2$

  $A_t (m_Z) \approx -0.21M_2 - 1.90M_3 + 0.18A_0$

- universal gaugino masses

  $M_2 = M_3 \gg m_0 \quad \Rightarrow \quad \frac{A_t}{M_{stop}} \approx \frac{2.11^2 \times M_3^2}{\sqrt{6.01 \times 4.40 \times M_3^2}} \approx 0.87$

  $125 \text{ GeV Higgs boson requires heavy top squark } \gtrsim \text{ sub TeV}$
Higgs boson mass in NUGM

- top squark parameters

\[ m_{\tilde{t}_L}^2 (m_Z) \approx +0.38M_2^2 + 5.63M_3^2 + 0.58m_0^2 \]
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- Non-Universal Gaugino Masses (NUGM)

- \( m_{\tilde{t}_R} (m_Z) \) decreases, \( |A_t (m_Z)| \) increases as \( M_2 \) increases

\[ A_t / M_{stop} \lesssim \sqrt{6} \]

- upper bound is \( M_2 / M_3 \lesssim 5 \) for \( m_{\tilde{t}_R}^2 (m_Z) > 0 \)

- In other words, \( A_t / M_{stop} \) is maximized at \( M_2 / M_3 \sim 5 \)
brief summary

✓ large wino mass enhances the Higgs boson mass

✓ $A_t/M_{stop}$ is maximized at $M_2/M_3 \approx 5$

What happen for naturalness?
naturalness in NUGM

- RG-running of $m_{H_u}$

$$m_{h_u}^2 (m_Z) \simeq +0.17M_2^2 - 0.20M_2M_3 - 3.09M_3^2 - 0.23m_0^2$$

GUT scale

$\rightarrow M_2 \simeq 5 \times M_3 \rightarrow m_{h_u}^2 (m_Z) \simeq 0$

- $\mu$-parameter is minimized at $M_2/M_3 \simeq 5$

- Higgs mass is also maximized at $M_2/M_3 \simeq 5$ !

suitably large wino reconcile the Higgs mass and naturalness
our tuning measure

□ our tuning measure (BG-type)

\[ \Delta_\mu \equiv \left| \frac{d \ln m_Z^2}{d \ln \mu (\Lambda_{GUT})^2} \right| \]

□ minimization condition of the Higgs potential

\[ m_Z^2 \simeq -2 |\mu|^2 + 2|m_{h_u}^2| \]

✓ we focus on tuning between \( \mu \)-parameter and SUSY breaking parameters

✓ \( \mu \)-parameter is unique SUSY dimensionful parameter in MSSM

✓ we expect some relations (e.g. gaugino mass ratio) among SUSY breaking parameters since these have same origin i.e. SUSY breaking mediation
NUGM from SUSY breaking mediation

- possibilities of NUGM (large wino)
  
  - mixed moduli/anomaly mediation (mirage mediation)
    
    $$M_a = \frac{F^T}{T + \overline{T}} + \frac{g_0^2}{16\pi^2} b_a \frac{F^C}{C}$$
    
    where, 
    $$b_a = \left( \frac{33}{5}, 1, -3 \right)$$
    $$a = U(1)_Y, SU(2)_L, SU(3)_C$$

  - moduli-mixing gauge kinetic function
    
    $$\mathcal{L} \ni \int d^2 \theta \ f_a(T) W^a W^a \ni f_a(T) F^{a\mu\nu} F_{\mu\nu}$$
    
    $$f_a(T) = k^i_a T_i \quad \rightarrow \quad M_a = k^i_a \frac{F^{Ti}}{T_i + \overline{T_i}}$$
the Higgs boson mass and degree of tuning

\[ M_3 = 385\text{GeV} \]
\[ A_0 = -400\text{GeV} \]
\[ (m_0)_{3\text{rd}} = 200\text{GeV} \]
brief summary

✓ large wino mass enhances the Higgs boson mass

✓ $A_t/M_{stop}$ is maximized at $M_2/M_3 \approx 5$

✓ $\mu$-parameter is also minimized at $M_2/M_3 \approx 5$

✓ Higgs mass can reach 125 GeV even when $\Delta_\mu \lesssim 10$

✓ SUSY particles can be lighter than TeV scale

How to probe NUGM ?
typical mass spectrum

- higgsinos are light
- right-handed stop can be lighter than others
- most of sparticles are heavy
  - these are determined by gluino mass $M_3$
  - as a result of large wino mass
- higgsinos are light
decays of higgsinos

- higgsinos are light and degenerate \( \Delta m_{\tilde{\chi}} \lesssim 2.0 \text{ GeV} \)

  - decay products are too soft to be reconstructed
  - no charged tracks unlike pure wino

higgsino searches are not efficient
typical mass spectrum

- Higgsinos are light, but degenerate.
  - Right-handed stop is lighter than others.
  - Most of sparticles are heavy:
    - These are determined by gluino mass $M_3$.

- Stop / gluino searches are important.
top squark decays

- right-handed top squark is light in NUGM

\[ W_{\text{MSSM}} \ni y_t (t_L \tilde{h}_u^0 - b_L \tilde{h}_u^+) \tilde{t}_R \]

- top squark decays to \( t + \tilde{\chi}_{1,2}^0 \) or \( b + \tilde{\chi}_1^\pm \)

- right-handed top squark couples to quark/higgsinos universally

- \[ \text{Br}(\tilde{t}_1 \to b \tilde{\chi}_1^\pm) = 1 - \text{Br}(\tilde{t}_1 \to t \tilde{\chi}_{1,2}^0) \approx 0.5 \text{ unless } m_{\tilde{t}_1} \approx m_{\tilde{\chi}_1}^\pm \]
top squark search

- signals are $\text{tt} (25\%) / \text{tb} (50\%) / \text{bb} (25\%) + \text{MET}$
- $\text{bb+MET}$ channel gives the severer bound than $\text{tt+MET}$ in run-1 result [1]
- 13TeV data [2] has already given the severest bound

\[
\begin{align*}
\tan\beta &= 15 \\
\mu &= M_3 = 1 \text{ TeV}
\end{align*}
\]

softsusy+sdecay+MG5+
pythia6+delphes3

gluino search

- gluino decays to top and stop: $\tilde{g} \rightarrow t \tilde{t}_1 \rightarrow t + t\tilde{\chi}_{1,2}^0 / b \tilde{\chi}_1^\pm$

- signals are characterized by 4 bottoms and large MET

- **13TeV data** [3] has already given the severest bound

\[
\begin{align*}
\tan\beta &= 15 \\
m_0 &= 1 \text{ TeV} \\
M_1 &= 12 \text{ TeV}
\end{align*}
\]

softsusy+sdecay+MG5 +pythia6+delphes3

bounds on boundary conditions

✓ right-handed sbottom can also be light for large $\tan\beta$

✓ sbottom pair production gives same signal as stop

✓ stop tends to be tachyonic for small $M_1$ and $M_3$

$tan\beta = 15$

$tan\beta = 50$

$m_0 = 1$ TeV
$\mu = 150$ GeV

softsusy+sdecay+MG5
+pythia6+delphes3
conclusion

- NUGM can realize 125 GeV Higgs and small $\mu$-parameter
- right-handed top squark tends to be light
- stop/gluino search are important for NUGM scenario
- $m_{\tilde{t}_1} \lesssim 700$ GeV, $m_{\tilde{g}} \lesssim 1.6$ TeV is excluded by the latest data

thank you for your attention
backups
boundary conditions

- universal soft mass $m_0 = 1 \text{ TeV}$, $\tan\beta = 15, 50$
- wino mass $M_2$, universal A-term $A_0$ are tuned to realize $\mu = 150 \text{ GeV}$ and $125.5 \leq m_h < 126.1 \text{ GeV}$
- Higgs mass is slightly heavier than the latest LHC result, but it will not affect to our results of stop/gluino search
degenerate higgsinos

- higgsinos are light and degenerate

heavy bino, wino $M_{1,2} \gg \mu$ leads $\Delta m_{\tilde{\chi}} = O(1\,\text{GeV})$

\[
\Delta m_{\tilde{\chi}} \equiv m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \approx \frac{m_Z^2}{M_2(m_Z)}
\]

$M_{1,2} \approx 2 - 4 \, \text{TeV}$

$\Rightarrow \Delta m_{\tilde{\chi}} \lesssim 2.0 \, \text{GeV}$

$m_0 = 1 \, \text{TeV}$
\[\tan \beta = 15\]
\[\mu = 150 \, \text{GeV}\]
\[125.5 \leq m_h \leq 125.8 \, \text{GeV}\]
\[M_2, A_t: \text{tuned}\]
Higgs boson mass in NUGM

\[ r_a \equiv \frac{A_t}{M_{st}} \]

\[ M_{stop} / m_{\tilde{t}_L} \]

\[ M_3 = 385 \text{GeV} \]
\[ A_0 = -400 \text{GeV} \]
\[ (m_0)_{3\text{rd}} = 200 \text{GeV} \]