Non-universal gaugino mass, Higgs mass and muon g-2

Keisuke Harigaya (ICRR)

Harigaya, Yanagida and Yokozaki (arXiv:1501.07447)
Harigaya, Ibe and Suzuki (arXiv: 1505.05024)
Plan of talk

• Motivation of supersymmetry
• In compatibility of universal gaugino mass with low-energy SUSY
• Higgs mass and muon g-2 with non-universal gaugino mass
Supersymmetry
Less divergences

Only wave functions are renormalized

\[ \mathcal{L} = Z (H^\dagger \partial^2 H + i \tilde{H}^\dagger \sigma \partial \tilde{H}) + m^2 |H|^2 + m \tilde{H} \tilde{H} \]

No large radiative corrections to Higgs mass!

\[ \delta m^2 \sim M_{\text{PL}}^2, M_{\text{GUT}}^2 \]
EWSB by dimensional transmutation

In minimal SUSY standard model (MSSM),

\[ V_{\text{SUSY}} = |\mu|^2 (|H_u|^2 + |H_d|^2) + \cdots \]

\[ \Delta V = -m^2_{\text{SUSY}} |H_u|^2 + \cdots \]

SUSY by gauge dynamics \(\rightarrow\) dynamical origin of EWSB
## Dark matter Candidate

Assume R parity

<table>
<thead>
<tr>
<th></th>
<th>Boson</th>
<th>Fermion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q, \bar{u}, \bar{d}, L, \bar{e}$</td>
<td>—</td>
<td>+</td>
</tr>
<tr>
<td>$H_u, H_d$</td>
<td>+</td>
<td>—</td>
</tr>
<tr>
<td>Gauge</td>
<td>+</td>
<td>—</td>
</tr>
</tbody>
</table>

Higgsino, Bino, Wino can be dark matter
In MSSM, gauge coupling constants unify around $10^{16}$ GeV

Consistent with SU(5) GUT

Considered to be the motivation of SUSY

We often assume universal gaugino mass
GUT and low energy SUSY

How natural non-universal gaugino mass is
R symmetry

The only symmetry to control the negative potential

\[ V = |F_{\text{SUSY}}|^2 - 3|W_0|^2 \]

If it is largely broken, low energy SUSY is hopeless

ex. minimal SU(5)

\[ W = m_{24}^2 + \lambda_{24}^3 \]

\[ m_{3/2} \sim \frac{M_{\text{GUT}}^3}{M_{\text{pl}}^2} \sim 10^{12}\text{GeV} \]
R symmetry and GUT

In GUT model with universal gaugino mass, R symmetry breaking is mandatory!

Goodmann, Witten (1986)
Fallbasher, Ratz, Vaudrevange (2011)
Harigaya, Ibe, Suzuki (2015)

$$SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5) \subset G_{\text{GUT}}$$

$$G_{\text{GUT}} : \text{e.g. } SU(5), SU(5) \times SU(5), SO(10), \ldots$$
R symmetry and GUT

Assume

GUT breaking fields

gauginos

Higgs, quarks, leptons

No mass mixing

In principle mixing may be possible, but requires many/higher representation fields, leads to blow up…
R symmetry and GUT


\[ R - SU(5) - SU(5) = R - SU(3) - SU(3) = R - SU(2) - SU(2) \]

above GUT below GUT

gaugino

6 4

only \( Z_{2R} \) may remain unbroken….
Non-universal gaugino mass

product GUT e.g. $SU(5) \times SU(3) \times U(1)$

$SU(3)_c \subset SU(3)_{\text{in}}$ $SU(5) \times SU(3)$

$SU(2)_L = SU(2)_{\text{in}}$ $SU(5)$

evade the no-go-theorem

Non-universal gaugino mass

Unification of quarks and leptons is maintained
Higgs mass and muon g-2 with non-universal gaugino mass
\[ m_{\text{SM-higgs}} < m_Z \]

\[ m_h^2 = \lambda v^2 \]

\[ \lambda : \text{determined by SUSY} \]

\[ \lambda < \frac{1}{4} (g^2 + g'^2) \]

\[ m_h < m_Z \sim 90 \text{ GeV} \]
Raising $m_h$

Large SUSY breaking raises higgs mass

$m_{\tilde{t}}>\text{few TeV}$

Okada, Yamaguchi, Yanagida (1991)
Ellis, Ridolfi, Zwirner (1991)
Haber, Hempfling (1991)

Hahn, Heinemeyer, Hollik, Rzehak, Weiglein (2013)
Hagiwara, Liao, Martin, Nomura, Teubner (2011)
g-2 in SUSY

\[ \Delta a_\mu \sim \frac{\alpha_{2,Y}}{4\pi} \frac{m_\mu^2}{m_{\text{SUSY}}^2} \tan\beta = O(1-10) \times 10^{-9} \frac{\tan\beta}{10} \left( \frac{100\text{GeV}}{m_{\text{SUSY}}} \right)^2 \]

muon g-2 and higgs mass

\[ m_{\tilde{t}} > \text{few TeV} \]

\[ m_{\text{SUSY, } g-2} > O(100) \text{ GeV} \]

SU(5) relation, flavor-universality

It is difficult to explain g-2
Ways out

- Beyond MSSM (Extra tree $\lambda$, Extra loop corrections)
  - NMSSM: Ellwanger, Hugonie, Teixeira (Review, 2009)

- Light 2nd generation, Heavy 3rd generation
  - Ibe, Yanagida, Yokozaki (2013)

- Departure from SU(5): heavy squark, light slepton
  - Ibe, Matsumoto, Yanagida, Yokozaki (2012)

Non-universal gaugino mass!
Gaugino mediation

Assume

SUSY breaking field $Z$

$\uparrow$

Higher dimensional theory
Structure of Kahler manifold e.g. $\mathbb{CP}^N$
Other possibilities?

$\downarrow$

Gaugino, higgs

quantum correction

Squark, slepton

\textbf{No flavor problem}

Kaplan, Krib, Schmaltz (1999)

Flavor structure of soft mass aligned with Yukawa
Light higgsino case

(Heavy bino raises right-handed slepton mass)

Stau LSP or stop excluded at LHC

Harigaya, Yanagida, Yokozaki (2015)
Light higgsino case

- $M_2 = 600$ GeV, $\mu = 200$ GeV, $m_A = 2000$ GeV, $A_u = -1500$ GeV, $\tan \beta = 25$
- $M_2 = 800$ GeV, $\mu = 150$ GeV, $m_A = 2000$ GeV, $A_u = -1500$ GeV, $\tan \beta = 35$
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\text{gluino}}$</td>
<td>2.4 TeV</td>
<td>$m_{\tilde{q}}$</td>
<td>1.8 TeV</td>
</tr>
<tr>
<td>$m_{\tilde{q}}$</td>
<td>2.1 TeV</td>
<td>$m_{\tilde{f}_{1,2}}$</td>
<td>2.6 TeV</td>
</tr>
<tr>
<td>$m_{\tilde{e}<em>L}(m</em>{\tilde{\mu}_L})$</td>
<td>1.4, 1.8 TeV</td>
<td>$m_{\tilde{e}<em>L}(m</em>{\tilde{\mu}_L})$</td>
<td>1.8, 2.2 TeV</td>
</tr>
<tr>
<td>$m_{\tilde{e}<em>R}(m</em>{\tilde{\mu}_R})$</td>
<td>450 GeV</td>
<td>$m_{\tilde{e}<em>R}(m</em>{\tilde{\mu}_R})$</td>
<td>573 GeV</td>
</tr>
<tr>
<td>$m_{\tilde{f}_1}$</td>
<td>836 GeV</td>
<td>$m_{\tilde{f}_1}$</td>
<td>721 GeV</td>
</tr>
<tr>
<td>$m_{\chi_1^0}$, $m_{\chi_2^0}$</td>
<td>361 GeV</td>
<td>$m_{\chi_1^0}$, $m_{\chi_2^0}$</td>
<td>174 GeV</td>
</tr>
<tr>
<td>$m_{\chi_3^0}$, $m_{\chi_4^0}$</td>
<td>179, 210 GeV</td>
<td>$m_{\chi_3^0}$, $m_{\chi_4^0}$</td>
<td>145, 159 GeV</td>
</tr>
<tr>
<td>$m_{\chi_1^\pm}$, $m_{\chi_2^\pm}$</td>
<td>342, 935 GeV</td>
<td>$m_{\chi_1^\pm}$, $m_{\chi_2^\pm}$</td>
<td>602, 806 GeV</td>
</tr>
<tr>
<td>$m_h$</td>
<td>184, 343 GeV</td>
<td>$m_h$</td>
<td>151, 602 GeV</td>
</tr>
<tr>
<td>$\Delta a_{\mu}$</td>
<td>124.5 GeV</td>
<td>$\Delta a_{\mu}$</td>
<td>125.3 GeV</td>
</tr>
<tr>
<td>$\Delta Br(b \to s\gamma)$</td>
<td>$2.20 \times 10^{-9}$</td>
<td>$\Delta Br(b \to s\gamma)$</td>
<td>$1.97 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>$-2.9 \times 10^{-5}$</td>
<td></td>
<td>$-2.5 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Heavy higgsino case

Negatively large up-type Higgs mass raises stau mass
Heavy higgsino case

\[ M_1 = 300 \text{GeV}, M_3 = 3000 \text{GeV} \]
\[ A_u = -1500 \text{GeV}, m_{H_u} = 0, \tan \beta = 15 \]

\[ M_1 = 300 \text{GeV}, M_3 = 3000 \text{GeV} \]
\[ A_u = -2000 \text{GeV}, m_{H_d} = 0, \tan \beta = 10 \]
## Reference points

<table>
<thead>
<tr>
<th>$m_{\text{gluino}}$</th>
<th>$m_{\tilde{g}}$</th>
<th>$m_{\tilde{f}_{1,2}}$</th>
<th>$m_{\tilde{e}<em>L}(m</em>{\tilde{\mu}_L})$</th>
<th>$m_{\tilde{e}<em>R}(m</em>{\tilde{\mu}_R})$</th>
<th>$m_{\tilde{\tau}_1}$</th>
<th>$m_{\chi^0_1, m_{\chi^0_2}}$</th>
<th>$m_{\chi^\pm_1, m_{\chi^\pm_2}}$</th>
<th>$m_h$</th>
<th>$\Delta a_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8 TeV</td>
<td>2.5 TeV</td>
<td>1.9, 2.2 TeV</td>
<td>471 GeV</td>
<td>212 GeV</td>
<td>120 GeV</td>
<td>118, 609 GeV</td>
<td>609, 2006 GeV</td>
<td>124.3 GeV</td>
<td>$1.40 \times 10^{-9}$</td>
</tr>
<tr>
<td>6.1 TeV</td>
<td>5.2 TeV</td>
<td>4.4, 4.9 TeV</td>
<td>423 GeV</td>
<td>218 GeV</td>
<td>118 GeV</td>
<td>107, 606 GeV</td>
<td>606, 3671 GeV</td>
<td>125.2 GeV</td>
<td>$1.88 \times 10^{-9}$</td>
</tr>
</tbody>
</table>
Summary

• SUSY is attractive
• Non-universal gaugino mass is well-motivated from GUT
• It explains higgs mass & muon g-2

Harigaya, Yanagida and Yokozaki (arXiv:1501.07447)
Harigaya, Ibe and Suzuki (arXiv: 1505.05024)
Backup
Measurement of $g-2$
$g - 2$

$$H = -g \frac{q}{2m} \vec{s} \cdot \vec{B}$$

$$g = 2 + \text{quantum corrections}$$

$$a \equiv \frac{g - 2}{2}$$

$$\mathcal{L}_{g-2} = \frac{q}{4m} a \bar{\psi} \sigma^{\mu\nu} \psi F_{\mu\nu}$$
Measurement of $g-2$

\[ \omega_{\text{mom}} = -\frac{eB}{m} \quad \omega_{\text{spin}} = \frac{g}{2} \frac{eB}{m} \]

\[ \Delta \omega_{\text{spin}} = \frac{g - 2}{2} \frac{eB}{m} \]
Measurement of $g$-2

Muon ($g$-2) collaboration (2006)
Prediction on g-2

\[ a_\mu = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had}} \]

\[ a_\mu^{\text{QED}} = 116584718.08(15) \times 10^{-11} \]

\[ a_\mu^{\text{EW}} = (154 \pm 2) \times 10^{-11} \]

\[ a_\mu^{\text{had,VP,LO}} = 6949(43) \times 10^{-11} \]

\[ a_\mu^{\text{had,VP,HO}} = -98.4(0.7) \times 10^{-11} \]

\[ a_\mu^{\text{had,LbL}} = [(80-140) \pm (10-40)] \times 10^{-11} \]
QED

\[ a_{\mu}^{\text{QED}} = 116584718.08(15) \times 10^{-11} \]

4 - loop!
Electro weak

\[ a^\text{EW}_\mu = (154 \pm 2) \times 10^{-11} \]

2-loop
Hadronic, VP

Vacuum polarization

\[ a_{\mu}^{\text{had, VP, LO}} = \frac{1}{4\pi^3} \int_{m_\pi^2}^{\infty} ds \sigma_{\text{had}}(s) K(s) \]

\[ a_{\mu}^{\text{had, VP, LO}} = 6949(43) \times 10^{-11} \]
Hadronic, VP

Vacuum polarization, higher order

Example:

\[ a_{\mu}^{\text{had,VP,HO}} = -98.4(0.7) \times 10^{-11} \]
Hadronic, LbL

Light-by-Light

Dominate the theoretical error in SM prediction

Using effective field theories of mesons,

\[ \alpha_{\mu}^{\text{had, LbL}} = \left[ (80-140) \pm (10-40) \right] \times 10^{-11} \]
Higgs mass calc.

Feynhiggs2.10.2

Borowka, Hahn, Heinemeyer, Hienrich, Hollik (2014)

• Full one-loop
• Two-loop $O(\alpha_t^2, \alpha_t \alpha_s, \alpha_s^2)$ for zero-momentum
• Two-loop $O(\alpha_t \alpha_s)$ for non-zero-momentum
• Large logs resummed

2-3 GeV error from uncalculated quantum corrections
Other issues

- Flavor violation from SUSY particles
- CP violations from SUSY particles

Especially, the g-2 diagram contributes to electron EDM, by muon $\rightarrow$ electron

\[ \theta_{CP} < 10^{-3} \left( \frac{m_{SUSY}}{300 \text{ GeV}} \right)^2 \frac{10}{\tan \beta} \]

Pokorski, Rosiek, Savoy (1999)
ACME collaboration (2014)
Assume the shift symmetry

\[ Z \rightarrow Z + iC \]

\[ K(Z + Z^\dagger, QQ^\dagger) \quad \text{Real coefficients} \]

\[ W = W_0 + \mu H_u H_d + W_{\text{yukawa}} \]

Made Real by R-rot PQ-rot

\[ kZ W^\alpha W_\alpha \quad \text{Real } k \]

No CP phases beyond yukawa
About renormalization

Gaugino mass, gauge interaction $\rightarrow$ positive scalar masses
Scalar masses, yukawa interaction $\rightarrow$ negative scalar masses

![Graph showing the transition between positive and negative scalar masses with respect to renormalization scale $\mu$.]