Sweet Spot
Supersymmetry

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Based on works with Ryuichiro Kitano (SLAC) hep-ph/0611111 0705.3686 [hep-ph]
LHC is coming soon.

To list “well-motivated” models to be tested is still important.

If the model can be parametrized simply and predicts distinctive features, so much the better.
Introduction

Sweet Spot Supersymmetry

Gauge Mediation Model for Gaugino + Matter

+ Direct Mediation to Higgs Sector

(\(\mu\)-term + Higgs soft masses)

- No \(\mu\)-problem, No CP-problem
- MSSM is determined by three parameters
- Distinctive Spectrum
- Consistent gravitino DM scenario
Introduction

Sweet Spot Supersymmetry

LHC signatures
Let us assume that the SUSY is mainly broken by an F-term of $S = (s, \psi_S, F_S)$. 

- scalar
- Goldstino
- F-term (non vanishing)
Let us assume that the SUSY is mainly broken by an F-term of $S = (s, \psi_S, F_S)$.

In terms of $S$, we can write down an effective theory of SUSY breaking sector;

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} + \cdots$$

$$W = m^2 S$$

Tadpole term for SUSY breaking

$\Lambda$ is the mass scale of the massive fields.

Higher order terms

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\[
K = S^\dagger S - \frac{(S^\dagger \bar{S})^2}{\Lambda^2} + \cdots \\
W = m^2 S
\]

- F-term  \( \langle F_S \rangle = m^2 \)
- Scalar mass  \( m_S = 2 \frac{\langle F_S \rangle}{\Lambda} \)
- Gravitino (Goldstino)  \( m_{3/2} = \frac{\langle F_S \rangle}{\sqrt{3} M_P} \)

We can discuss physics of hidden sector below the scale \( \Lambda \), with this effective theory with only two parameters \( (m_{3/2}, \Lambda) \).
Sweet Spot Supersymmetry

Gauge Mediation Model for Gaugino + Matter
+
Direct Mediation to Higgs Sector
(μ-term + Higgs soft masses)

- No μ-problem, No CP-problem
- MSSM is determined by three parameters
- Distinctive Spectrum
- New production mechanism of gravitino DM
In terms of $S$, SSS is given by:

\[ K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} \]

\[ + \left( \frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S(H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2} \]

\[ + \left( 1 - \frac{4g^4}{(4\pi)^4} C_2(\log |S|)^2 \right) \Phi^\dagger \Phi \]

\[ W = W_{\text{Yukawa}} + m^2 S + w_0 \]

\[ + \frac{1}{2} \left( \frac{1}{g^2} - \frac{2}{(4\pi)^2} \log S \right) \mathcal{W}^\alpha \mathcal{W}_\alpha \]

\[ \langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P} + \langle F_S \rangle \theta^2 \]
Sweet Spot Supersymmetry

In terms of $S$, SSS is given by;

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$

$$+ \left( \frac{c_{ij} S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

$$+ \left( 1 - \frac{4 g_4}{(4\pi)^4} C_2 (\log |S|^2)^2 \right) \Phi^\dagger \Phi.$$

$$W = W_{\text{Yukawa}} + m^2 S + w_0$$

$$+ \frac{1}{2} \left( \frac{1}{g_5} - \frac{1}{(4\pi)^2} \log S \right) W^\alpha W_\alpha$$

$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P} + \langle F_S \rangle \theta^2$$
Sweet Spot Supersymmetry

In terms of S, SSS is given by:

\[ K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} \]

\[ + \left( \frac{c_i S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_i^2 S^\dagger H_u H_d}{\Lambda^2} \]

\[ + \left( 1 - \frac{4g^4}{(4\pi)^4} C_2 (\log |S|^2)^2 \right) \Phi \]

\[ V(s) \simeq m_S^2 |s|^2 - 2m^2 |w_0| s \]

\[ m_S^4 = 4 \frac{m^4}{\Lambda^2} \]

\[ |w_0| \simeq m^2 M_{Pl}/\sqrt{3}, \]

\[ (\langle V \rangle \simeq |m^2|^2 - 3|w_0|^2 \simeq 0) \]

\[ \langle s \rangle \simeq 2 \frac{m^2 |w^0|}{m_S^2} \neq 0 \]

\[ \langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P} + \langle F_s \rangle \theta^2 \]

R-symmetry is broken by the cosmological constant!

[^06 R. Kitano]
Sweet Spot Supersymmetry

In terms of $S$, SSS is given by;

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$

$$W = W_{\text{Yukawa}} + m^2 S + w_0$$

$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P} + \langle F_S \rangle \theta^2$$

Gauge Mediated SUSY Breaking

$$m_{\text{gaugino}} = \frac{g^2}{(4\pi)^2} \frac{\langle F_S \rangle}{\langle s \rangle}$$

$$m_{\text{scalar}}^2 = \left( \frac{g^2}{(4\pi)^2} \right)^2 \cdot 2C_2 \left| \frac{\langle F_S \rangle}{\langle s \rangle} \right|^2$$

$$\frac{\langle F_S \rangle}{\langle s \rangle} = \frac{2\sqrt{3}m^2 M_P}{\Lambda^2} = 6m_{3/2} \left( \frac{M_P}{\Lambda} \right)^2$$
In terms of $S$, SSS is given by;

$$K = S^+ S - \frac{(S^+ S)^2}{\Lambda^2}$$

$$+ \left( \frac{c_\mu S^+ H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^+ S (H^+_u H_u + H^+_d H_d)}{\Lambda^2}$$

**Direct coupling between SUSY breaking and Higgs sector**

(Giudice-Masiero Mechanism)

- **PQ-symmetry**
  - $S: +2$
  - $H_u: +1$
  - $H_d: +1$

$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda}{M_P} + \left| \frac{\langle F_S \rangle}{\Lambda} \right|^2 \theta^2$$

$$\mu = c_\mu \frac{\langle F_S \rangle}{\Lambda} \sim m_{3/2} \left( \frac{M_P}{\Lambda} \right)$$

$$B_\mu = 0$$

No CP-phase

$$m_{H_u,d}^2 = c_H \left| \frac{\langle F_S \rangle}{\Lambda} \right|^2 \sim m_{3/2}^2 \left( \frac{M_P}{\Lambda} \right)^2$$
Gauge Mediated masses

\[ m_{\text{gaugino}} \approx m_{\text{scalar}} \approx \frac{g^2}{(4\pi)^2} m^{3/2} \left( \frac{M_P}{\Lambda} \right)^2 \]

Giudice-Masiero mechanism + PQ-symmetry

\[ \mu \approx |m_{H_u,d}| \sim m_{3/2} \left( \frac{M_P}{\Lambda} \right) \]

\[ B\mu = 0 \quad \Rightarrow \quad \text{No CP-problem} \]

Sweet Spot \((c_\mu = O(1))\)

\[ m_{\text{gaugino}} \sim \mu \quad \Rightarrow \quad \Lambda \sim \frac{g^2}{(4\pi)^2} M_P \quad \Rightarrow \quad \Lambda \sim M_{\text{GUT}} \]

\[ m_{\text{gaugino}} = O(100) \text{ GeV} \quad \Rightarrow \quad m_{3/2} = O(1) \text{ GeV} \]

Free Parameters

\[ \Lambda \quad c_\mu \quad c_H \quad m^2 \quad M_{\text{mess}} \]

These are supported by gravitino DM produced by the decay of “s”.

\[ \langle s \rangle \approx 10^{14} \text{ GeV} \]
Sweet Spot Supersymmetry

**Gauge Mediated masses**

\[ m_{\text{gaugino}} \approx m_{\text{scalar}} \approx \frac{g^2}{(4\pi)^2} m_3/2 \left( \frac{M_P}{\Lambda} \right)^2 \]

**Giudice-Masiero mechanism + PQ-symmetry**

\[ \mu \approx |m_{H_u,d}| \sim m_3/2 \left( \frac{M_P}{\Lambda} \right) \]

\[ B\mu = 0 \quad \rightarrow \quad \text{No CP-problem} \]

**Sweet Spot** \((c_\mu = O(1))\)

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\[ m_{\text{gaugino}} = O(100) \text{ GeV} \quad \rightarrow \quad m_3/2 = O(1) \text{ GeV} \]

**Free Parameters**

\[ m_{\tilde{g}} \quad \mu \quad m^2_{H_{u,d}} \quad m_3/2 \quad M_{\text{mess}} \]

\[ \langle s \rangle \approx 10^{14} \text{ GeV} \]

These are supported by gravitino DM produced by the decay of “s”.

\[ K = S^\dagger S - \left( S^\dagger S \right)^2 \]

\[ + \left( \frac{g_3 S H_u H_d}{\Lambda} + \text{h.c.} \right) - c_R S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d) \]

\[ + \left( 1 - \frac{4g^4}{(4\pi)^2} C_2 (\log |S|) \right) \Phi^\dagger \Phi \]

\[ W = W_{\text{Yukawa}} + (m^2 S + \psi_0) + \frac{1}{2} \left( \frac{g^2}{4\pi} \right)^2 \log S |W^\alpha W_\alpha \rangle \]

\[ \langle s \rangle = \left( \sqrt{\frac{3}{6}} \Lambda^2 \langle F_s \rangle \right)^2 \]
Sweet Spot Supersymmetry

Gauge Mediated masses

\[ m_{\text{gaugino}} \simeq m_{\text{scalar}} \simeq \frac{g^2}{(4\pi)^2} m_{3/2} \left( \frac{M_P}{\Lambda} \right)^2 \]

Giudice-Masiero mechanism + PQ-symmetry

\[ \mu \simeq |m_{H_{u,d}}| \sim m_{3/2} \left( \frac{M_P}{\Lambda} \right) \]

\[ B\mu = 0 \rightarrow \text{No CP-problem} \]

Sweet Spot \((c_\mu = O(1))\)

\[ m_{\text{gaugino}} \sim \mu \rightarrow \Lambda \sim \frac{g^2}{(4\pi)^2} M_P \rightarrow \Lambda \sim M_{\text{GUT}} \]

\[ m_{\text{gaugino}} = O(100) \text{ GeV} \rightarrow m_{3/2} = O(1) \text{ GeV} \]

Free Parameters \((\text{EWSB})\)

\[ m_{\tilde{g}}, \mu, m_{H_{u,d}}^2, m_{3/2}, M_{\text{mess}} \]

\[ \langle s \rangle \simeq 10^{14} \text{ GeV} \]

These are supported by gravitino DM produced by the decay of “s”.
**Sweet Spot Supersymmetry**

**Gauge Mediated masses**

\[
m_{\text{gaugino}} \sim m_{\text{scalar}} \approx \frac{g^2}{(4\pi)^2} m_{3/2} \left(\frac{M_P}{\Lambda}\right)^2
\]

**Giudice-Masiero mechanism + PQ-symmetry**

\[
\mu \sim |m_{H_u,d}| \sim m_{3/2} \left(\frac{M_P}{\Lambda}\right)
\]

\[B\mu = 0 \quad \Rightarrow \quad \text{No CP-problem}
\]

**Sweet Spot** \((c\mu = O(1))\)

\[
m_{\text{gaugino}} \sim \mu \quad \Lambda \sim \frac{g^2}{(4\pi)^2} M_P \quad \Lambda \sim M_{\text{GUT}}
\]

\[
m_{\text{gaugino}} = O(100) \text{ GeV} \quad m_{3/2} = O(1) \text{ GeV}
\]

**Free Parameters (EWSB)**

\[
m_{\tilde{g}}, \quad \mu, \quad m^2_{H_u,d}, \quad m_{3/2} \quad \text{or} \quad M_{\text{mess}}
\]

**Low energy phenomenology**

**Cosmology**

\[
K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}
\]

\[
+ \left( c_R S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d) + \text{h.c.} \right)
\]

\[
+ \left( \frac{i}{2(4\pi)^2} C_2 (\log |S|) \right) \Phi^\dagger \Phi
\]

\[
W = W_{\text{Yukawa}} + \left( m^2 S + \psi_0 \right)
\]

\[
+ \frac{1}{2} \left( \frac{1}{g^2} \right) \frac{2}{(4\pi)^2} \log S \left. W^\alpha W_\alpha \right|
\]

\[
\langle S \rangle = \sqrt{3} \frac{\Lambda^2}{6 M_P} \langle F_S \rangle \theta^2
\]
Schematic Picture

Two mediation scale → Peculiar spectrum

$M_{\text{mess}} = k \langle s \rangle$  \hspace{1cm} $\Lambda \sim 10^{16}\text{GeV}$

$\mu$

$\mu$

$H_{u,d}$

Giudice-Masiero Mechanism

GUT scale physics (PQ-sym)

$m_{\text{scalar}}$

$m_{\text{gaugino}}$

$kSff$ Messenger

Weak Scale

RGE

RGE

GMSB

Peculiar spectrum

Sweet Spot Supersymmetry
Sweet Spot Supersymmetry

$\tan \beta = 37$ (output)

$M_3$

$M_2$

$M_1$

$B$

$A_t$

$m_t = 170.9$ GeV

$m^2_{H_u,d}$ affect other scalar masses between $\Lambda$ and $M_{\text{mess}}$

SSS predicts light stau ($m_{H_{d,u}}^2 > 0$)
Sweet Spot Supersymmetry

An example of UV-model

\[
K = S \dagger S - \frac{(S \dagger S)^2}{\Lambda^2} \\
+ \left( \frac{c_\mu S \dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S \dagger S (H_u \dagger H_u + H_d \dagger H_d)}{\Lambda^2}
\]

(One-loop calculation)

\[
W_S = m^2 S + \frac{\kappa}{2} SX^2 + M_{XY} XY , \quad \text{O'Raifeartaigh Model}
\]

\[
W_{\text{Higgs}} = h H_u \bar{q} X + \bar{h} H_d q X + M_q q \bar{q} , \quad \text{PQ-sym}
\]

colored Higgs

These superpotentials can be embedded into a product group GUT model (S0(9)XSU(5) or S0(6)XSU(5)) [’06 R. Kitano].

\[
M_{XY} \sim M_q \sim M_{\text{GUT}} \sim 10^{16}\text{GeV}
\]

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Sweet Spot Supersymmetry

An example of UV-model

\[ K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} \]
\[ + \left( \frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2} \]

\[ W_S = m^2 S + \frac{\kappa}{2} S X^2 + M_{XY} X Y, \quad \text{O’Raifeartaigh Model} \]
$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$

$+ \left( \frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right)$

$- \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$

$W_{\text{Higgs}} = h H_u \bar{q} X + \bar{h} H_d q X + M q q \bar{q}$,
Sweet Spot Supersymmetry

An example of UV-model

\[ K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} \]

\[ + \left( \frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2} \]

Perturbative example

\[ m_{H_u,d}^2 > 0 \quad \rightarrow \quad \text{Light Stau} \]

\[ m_{H_u,d}^2 \sim (1\text{-loop}), \quad \mu \sim (1\text{-loop}) \]

\[ \mu/m_{H_u,d} \sim (1\text{-loop})^{1/2} \]

\[ \rightarrow \quad \text{Light Higgsino} \]
Light Stau (Stau NLSP can be easily realized)
Light Higgsino
Large tanβ
Sweet Spot Supersymmetry

Three low energy parameters \((\mu, M_{mess}, \tilde{M})\)

We can reconstruct model parameters by measuring three masses.
LHC Signatures

Benchmark Point

$\mu = 300$ GeV, $M_{mess} = 10^{10}$ GeV, $\bar{M} = 900$ GeV.

$\longrightarrow$ Stau NLSP(116GeV)
(lifetime $O(1000)$sec.)

$\longrightarrow$ $\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$

Bino Higgsino Wino

$\longrightarrow$ gluinos, squarks $\sim$ 1TeV

$\sigma(pp \rightarrow \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}) \approx 1.4$ pb

$\tan \beta = 37$

(output)

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LHC Signatures

Decay modes

Typical Event at LHC

Many $b/\tau$-jets + low-velocity 2 charged tracks
difficult to analyze...

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LHC Signatures

Stau Mass Measurement

\[ m_{\tilde{\tau}_1} = \frac{p_{\tilde{\tau}_1}}{\beta \gamma} \]

measured from charged track

time of flight measurement

[’00 Ambrosanio, Mele, Petrarca, Polesello, Rimoldi]

For \( m_{\tilde{\tau}_1} \approx 100 \text{GeV} \) stau mass can be measured with an accuracy of 100MeV.
LHC Signatures

Reconstruction of neutralino masses

\[ \chi_{1,2,3}^0 \]

\[ \tau \]

(80\text{-}100\%)

\[ \tilde{\tau} \]

charged track

We use hadronic decay mode of \( \tau \)
[’98 Hinchcliffe & Paige]

cf. The analysis with leptonic modes discussed in [’06 Ellis, Raklev, Oye] is difficult in our case.

Select events with 2 stau candidates.
(one of them should be slow \( \beta \gamma < 2.2 \))

Select events with 1 tau-jet candidate.

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LHC Signatures

42,900 (30fb\(^{-1}\)) SUSY event

\[
\text{After selection}
\]

2000 event

Main background

Wrong combination of tau-stau

We chose a stau for the smaller invariant mass. (efficiency 70%)

Miss-tagging of non-tau-jet

tau-tag efficiency 50%

mis-tag probability 1%

We can determine masses of \(\chi_1^0, \chi_2^0\) with an accuracy of 0(5)%.
LHC Signatures

Neutrinos carry away part of energy.

We can determine masses of $\chi_1^0, \chi_2^0$ with an accuracy of 0(5)%.
LHC Signatures

Parameter Reconstruction

\[ m_{\chi_{1,2}^0} \rightarrow \mu, \quad M \]
\[ m_{\tilde{\tau}_1} \rightarrow M_{\text{mess}} \]

\[ \Delta \mu \sim 20 \text{ GeV} \quad \Delta M \sim 50 \text{ GeV} \]
\[ \Delta \log_{10} M_{\text{mess}} \sim 0.2 \]

Consistency Check

Prediction of \( M_A \)

\[ M_A = 745 \pm 40 \text{ GeV} \]

We can perform non-trivial check!
Summary

**Sweet Spot Supersymmetry**

Gauge Mediation + Giudice-Masiero Mechanism (+PQ-symmetry)

- No $\mu$-problem, No CP-problem
- Light Stau + Light Higgsino
  - Collider signal can be different from minimal gauge mediation.
- MSSM is determined by three parameters
  - We can perform consistency check of the model at LHC.

What's new?

As far as I know, no one explicitly discussed that we can solve the mu-problem and the CP problem by assuming direct mediation with PQ-symmetry. Besides, the effects of such direct mediated masses to the RGE of other susy masses are an interesting observation. Collider analysis for our nightmare spectrum is also interesting. Although I did not explained, the success of the DM generation is also an important feature of this model.
AcerDET

Isolated Leptons, Photon

Isolated from other clusters by $\Delta R = 0.4$.

Transverse energy deposited in cells in a cone $\Delta R = 0.2$ around the cluster is less than 10GeV.

Jet

A cluster is recognized as a jet by a cone-based algorithm if it has $p_T > 15$ GeV in a cone $\Delta R = 0.4$.

Labeled either as a light jet, b-jet, c-jet or $\tau$-jet, using information of the event generators.

A flavor independent calibration of jet four-momenta optimized to give a proper scale for the di-jet decay of a light Higgs boson.
Event Selection

Triggering ['99 Atlas Collaboration]

one isolated electron with $p_T > 20$ GeV;
one isolated photon with $p_T > 40$ GeV;
two isolated electrons/photons with $p_T > 15$ GeV;
one muon with $p_T > 20$ GeV;
two muons with $p_T > 6$ GeV;
one isolated electron with $p_T > 15$ GeV
+ one isolated muon with $p_T > 6$ GeV;
one jet with $p_T > 180$ GeV;
three jets with $p_T > 75$ GeV;
four jets with $p_T > 55$ GeV.

Isolated electrons/photons, muons and jets
in the central regions of pseudorapidity
$|\eta| < 2.5$, 2.4, and 3.2, respectively.

Staus with $\beta\gamma > 0.9$ as muons in the simulation of
triggering.[’06 Ellis,Raklev,Oye]
Event Selection

Two stau candidates for neutralino reconstruction (consistent with measured stau mass)

\[ \beta' - 0.05 < \beta_{\text{meas}} < \beta' + 0.05 , \]

\[ \beta' = \sqrt{\frac{p^2_{\text{meas}}}{(p^2_{\text{meas}} + m_{\tilde{\tau}_1}^2)}} \]

Both have \( pT > 40\text{GeV} \), \( \beta/\gamma > 0.4 \)

One of the stau candidates must have \( \beta\gamma < 2.2 \)

\[ M_{\text{eff}} > 800\text{GeV} \] \( \rightarrow \) SM background negligible

One tau-jet candidate

- \( pT > 40\text{GeV} \)
- tau-tag efficiency 50%
- mis-tag probability 1%

[’00 Ambrosanio, Mele, Petrarca, Polesello, Rimoldi]