Sweet Spot Supersymmetry and LHC

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Feb.11th, 2008

Based on works with
Ryuichiro Kitano (LANL)

hep-ph/0611111
0705.3686 [hep-ph]
0711.3300 [hep-ph]

Introduction

- LHC is coming soon.

The MSSM is one of the most motivated candidates for the beyond the SM.

To list "well-motivated" models with simple parametrization is still important.

If the model predicts distinctive features, so much the better.

Sweet Spot Supersymmetry

Gauge Mediation Model for Gaugino + Matter

+

Direct couplings between Higgs and Hidden Sectors

(μ-term + Higgs soft masses)

- No μ-problem, No SUSY CP-problem
- MSSM is determined by three parameters
- Distinctive Spectrum
- Consistent gravitino DM scenario

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SUSY Breaking & Mediation Mechanisms

- 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)

SUSY Breaking & Mediation Mechanisms

- 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;

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

$$W = m^2 S$$

Higher oder terms

Tadpole term for
SUSY breaking

Λ is the mass scale of
the massive fields.

SUSY Breaking & Mediation Mechanisms

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

- 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 Λ, with this effective theory with only two parameters $(m_{3/2}, \Lambda)$.

SUSY Breaking & Mediation Mechanisms

- The origin of Gaugino masses are classified by how S couples to gauge supermultiplets

$$W \ni f(S)\mathcal{W}^\alpha \mathcal{W}_\alpha$$

- Gravity Mediation

$$f(S) \simeq \frac{S}{M_P} \quad \longrightarrow \quad m_{\text{gaugino}} \simeq \frac{\langle F_S \rangle}{M_P} = O(m_{3/2})$$

This choice of $f(S)$ suggests that S cannot carry any charge. $\longrightarrow$ Polonyi/Gravitino Problem

Gravity mediation scenario also suffers from FCNC problem and CP problem.

SUSY Breaking & Mediation Mechanisms

- The origin of Gaugino masses are classified by how S couples to gauge supermultiplets

$$W \ni f(S)\mathcal{W}^{\alpha}\mathcal{W}_{\alpha}$$

- Gauge Mediation
  (after integrating out the messenger particles)

$$f(S) = \frac{g^2 N_{\mathrm{mess}}}{(4\pi)^2}\log S$$

$$\longrightarrow \quad m_{\mathrm{gaugino}} \simeq \frac{g^2}{(4\pi)^2}\frac{\langle F_S\rangle}{\langle s\rangle} = \frac{g^2}{(4\pi)^2}\frac{M_P}{\langle s\rangle}O(m_{3/2})$$

S can be charged field $\longrightarrow$ No Polonyi Problem

Gauge mediation scenario also solves FCNC problem.

SUSY Breaking & Mediation Mechanisms

- What's wrong with Gauge Mediated Model?

$\mu/B\mu$-Problem

Supersymmetric Higgs mixing term

$W \ni \mu H_u H_d$

SUSY breaking Higgs mixing term

$\mathcal{L} \ni B\mu H_u H_d$

From naturalness of EWSB, both two parameters are required to be comparable to or less than the weak scale.

SUSY Breaking & Mediation Mechanisms

- What's wrong with Gauge Mediated Model?

$\mu/B\mu$-Problem

- Why $\mu = O(m_{\mathrm{gaugino}})$?

- Many attempts end up with too large B-term.

ex)

$$K \ni \frac{1}{(4\pi)^2}\frac{S^\dagger}{S}H_u H_d$$

$$\mu = \frac{1}{(4\pi)^2}\frac{\langle F_S\rangle}{\langle s\rangle} = O(m_{\mathrm{gaugino}})$$

$$\frac{B\mu}{\mu} = \frac{\langle F_S\rangle}{\langle S\rangle} = (4\pi)^2 O(m_{\mathrm{gaugino}})$$

Sweet Spot Supersymmetry

Gauge Mediated ~~SUSY~~ masses to Gaugino + Matter

+

Direct couplings between Higgs and Hidden Sectors

(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

Sweet Spot Supersymmetry

In terms of S, SSS is given by;

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$
$$+ \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$
$$+ \left(1 - \frac{4g^4}{(4\pi)^4} C_2 (\log |S|)^2 \right) \Phi^\dagger \Phi$$
$$W = W_{\text{Yukawa}} + m^2 S + w_0$$
$$+ \frac{1}{2} \left(\frac{1}{g^2} - \frac{2}{(4\pi)^2} \log S \right) \mathcal{W}^\alpha \mathcal{W}_\alpha$$
$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P} + \langle F_S \rangle \theta^2$$

Sweet Spot Supersymmetry

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SUSY breaking sector

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

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$$+\frac{1}{2}\left(\frac{1}{g^2} - \frac{2}{(4\pi)^2}\log S\right)$$

R-symmetry is broken by the cosmological constant!

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

$$V(s) \simeq m_S^2 |s|^2 \underline{-2m^2 |w_0| s}$$

supergravity

$$m_S^2 = 4\frac{m^4}{\Lambda^2}$$

$$|w_0| \simeq m^2 M_{\text{Pl}}/\sqrt{3},$$

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

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

['06 R.Kitano]

Sweet Spot Supersymmetry

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← SUSY breaking sector

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$$\boxed{\langle s \rangle \simeq \frac{\sqrt{3}}{6}\frac{\Lambda^2}{M_P}}$$

['06 R.Kitano]

Supersymmetry

SS is given by;

Messenger particle (5,5*)

$$W = kS\Psi\bar{\Psi}$$

Messenger Mass

$$M_{\mathrm{mess}} = k\langle s\rangle$$

mass splitting of messenger bosons

$$\begin{pmatrix} k^2|\langle s\rangle|^2 & kF \\ kF^* & k^2|\langle s\rangle|^2 \end{pmatrix} \longrightarrow |k\langle s\rangle|^2 \pm |kF|$$

Gauge Mediated SUSY Breaking

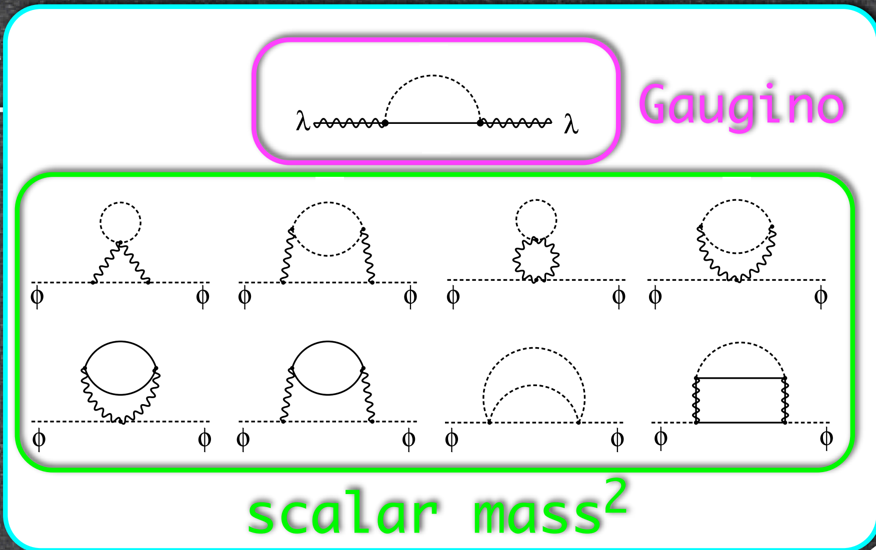
$$- \frac{c_H S^\dagger S(H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

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

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

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

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



Supersymmetry

SS is given by;

Gauge Mediated SUSY Breaking

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

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

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Sweet Spot Supersymmetry

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Gauge Mediated SUSY Breaking

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

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

$$\frac{\langle F_S \rangle}{\langle s \rangle} = \frac{2\sqrt{3} m^2 M_P}{\Lambda^2} = 6 m_{3/2} \left(\frac{M_P}{\Lambda} \right)^2$$

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direct coupling between SUSY breaking and Higgs sector (Giudice-Masiero Mechanism)

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

$$B = O(m_{3/2})$$

→ small CP-phase

$$m^2_{H_{u,d}} = c_H \left|\frac{\langle F_S \rangle}{\Lambda}\right|^2 \sim m^2_{3/2}\left(\frac{M_P}{\Lambda}\right)^2$$

Approximate PQ-symmetry

$$S : +2 \quad H_u : +1 \quad H_d : +1$$

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

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

$$B = O(m_{3/2}) \longrightarrow \text{No CP-problem}$$

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

$$m_{\text{gaugino}} \sim \mu \longrightarrow \Lambda \sim \frac{g^2}{(4\pi)^2} M_P \longrightarrow \boxed{\Lambda \sim M_{\text{GUT}}}$$

$$m_{\text{gaugino}} = O(100)\,\text{GeV} \longrightarrow \boxed{m_{3/2} = O(1)\,\text{GeV}}$$

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

$$\langle s \rangle \simeq 10^{14}\,\text{GeV}$$
$$\sqrt{F_S} \simeq 10^9\,\text{GeV}$$

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

Free Parameters

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

Sweet Spot Supersymmetry

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Free Parameters

$$m_{\tilde{g}} \quad \mu \quad m^2_{H_{u,d}} \quad m_{3/2} \quad M_{\text{mess}}$$

Sweet Spot Supersymmetry

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

$$\rightarrow \boxed{\begin{aligned} \langle s \rangle &\simeq 10^{14}\,\text{GeV} \\ \sqrt{F_S} &\simeq 10^9\,\text{GeV} \end{aligned}}$$

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

Free Parameters (EWSB)

$m_{\tilde{g}}$ μ $\cancel{m^2_{H_{u,d}}}$ $m_{3/2}$ M_{mess}

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

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

$B = O(m_{3/2}) \longrightarrow$ **No CP-problem**

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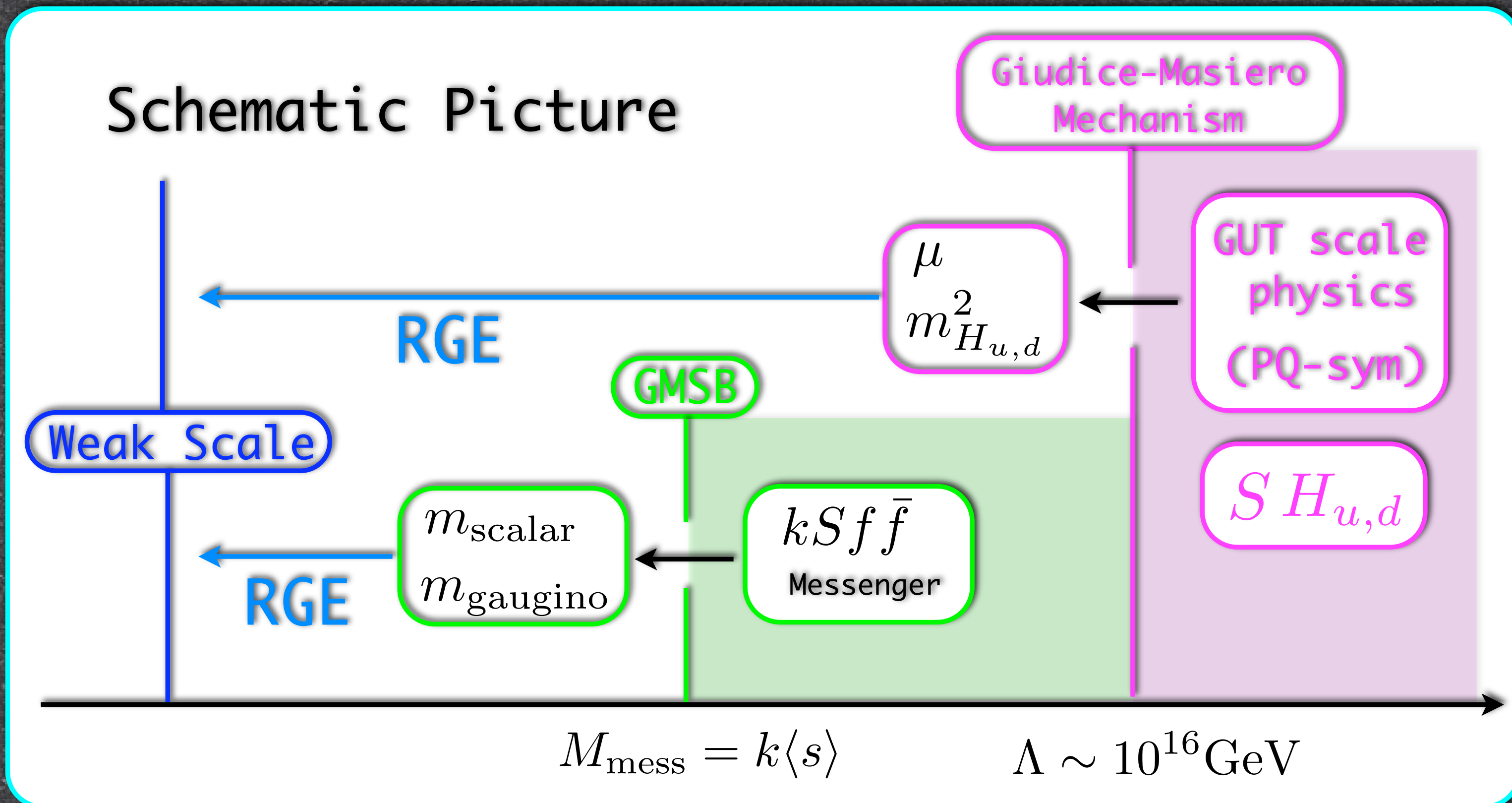
Low energy phenomenology

Cosmology

Free Parameters (EWSB)

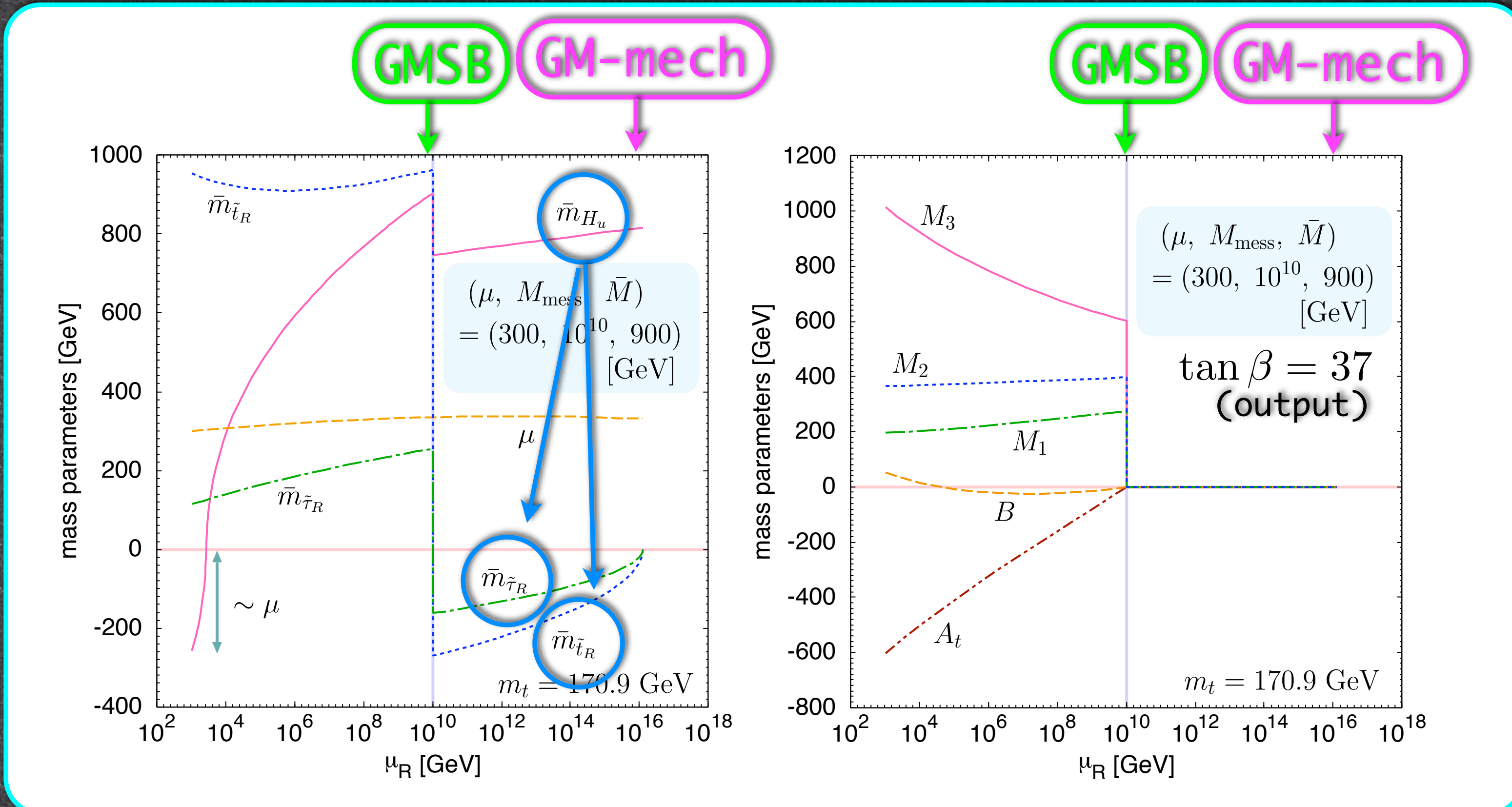
$$m_{\tilde{g}} \qquad \mu \qquad \cancel{m^2_{H_{u,d}}} \qquad m_{3/2} \qquad M_{\text{mess}}$$

Sweet Spot Supersymmetry



Two mediation scale $\longrightarrow$ Peculiar spectrum

Sweet Spot Supersymmetry



$m^2_{H_{u,d}}$ affect other scalar masses between Λ and $M_{\rm mess}$

$\longrightarrow$ SSS predicts light stau $(m^2_{H_{d,u}} > 0)$

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)

$$W_S = m^2 S + \frac{\kappa}{2} S X^2 + M_{XY} X Y \ ,$$ O'Raifeartaigh Model

$$W_{\text{Higgs}} = h H_u \bar{q} X + \bar{h} H_d q X + M_q q \bar{q} \ ,$$ (PQ-sym)

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

$$\longrightarrow M_{XY} \sim M_q \sim M_{\text{GUT}} \simeq 10^{16}\text{GeV}$$

Sweet Spot Supersymmetry

An example of UV-model

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

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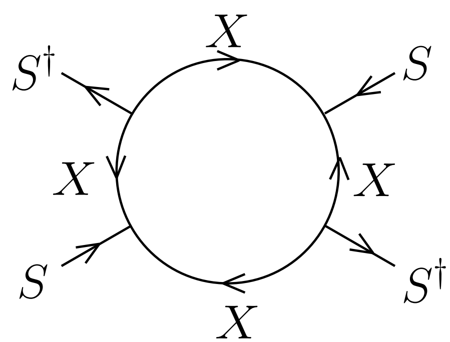

Sweet Spot Supersymmetry

An example of UV-model

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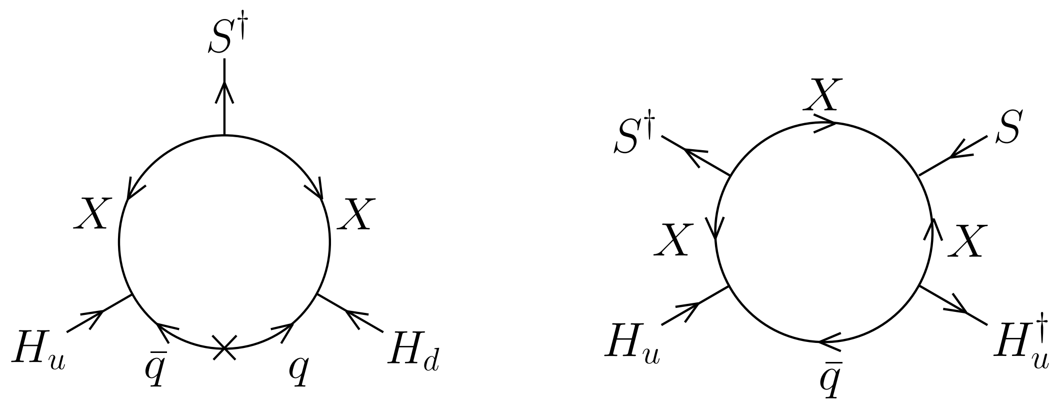


$$W_{\text{Higgs}} = hH_u\bar{q}X + \bar{h}H_d qX + M_q q\bar{q} \ ,$$

Sweet Spot Supersymmetry

An example of UV-model

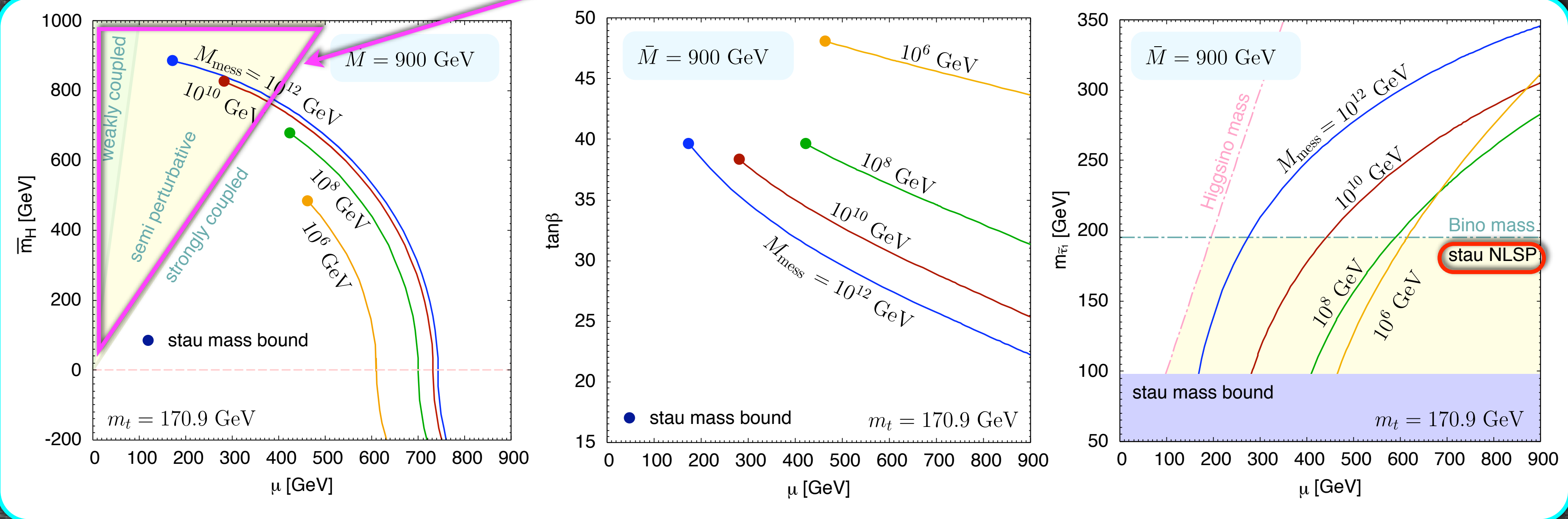
$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} + \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.}\right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

Perturbative example

$$\left\{\begin{array}{l} m_{H_{u,d}}^2 > 0 \xrightarrow{\text{(RGE)}} \text{Light Stau} \\ m_{H_{u,d}}^2 \sim \text{(1-loop)}, \quad \mu \sim \text{(1-loop)} \\ \longrightarrow \mu / m_{H_{u,d}} \sim \text{(1-loop)}^{1/2} \end{array}\right.$$

Sweet Spot Supersymmetry

Prediction of (perturbative) SSS



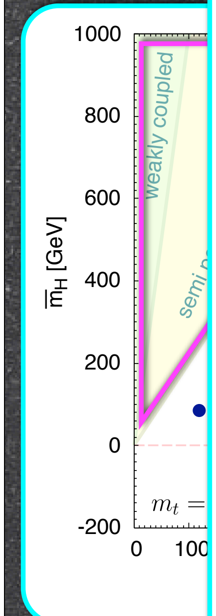
Light Stau (Stau NLSP can be easily realized)

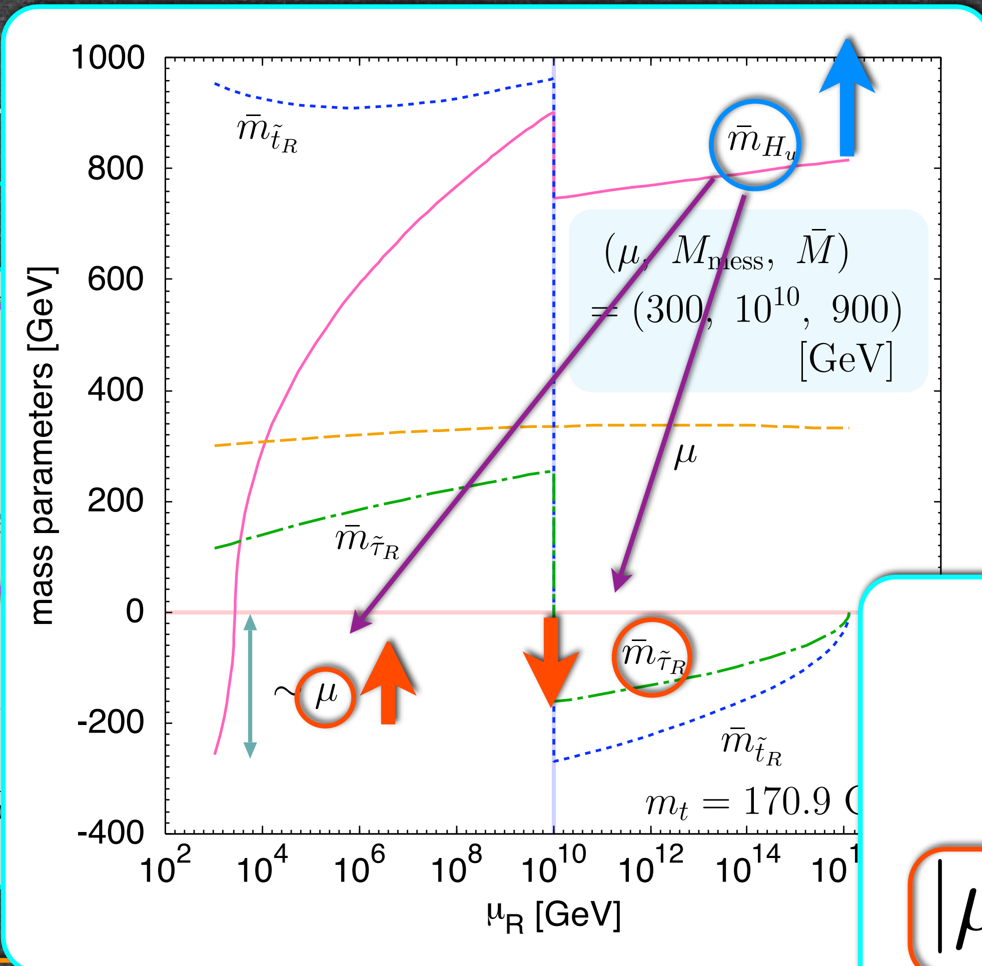
Light Higgsino

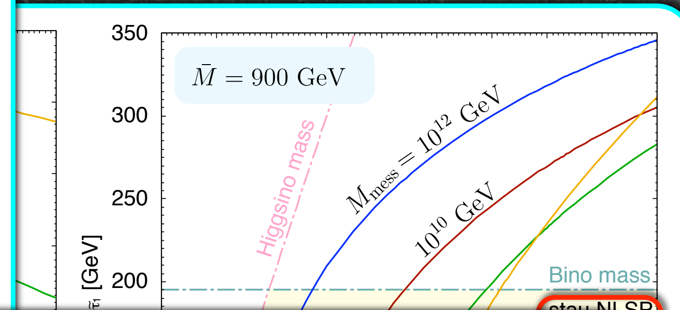
Large tanβ

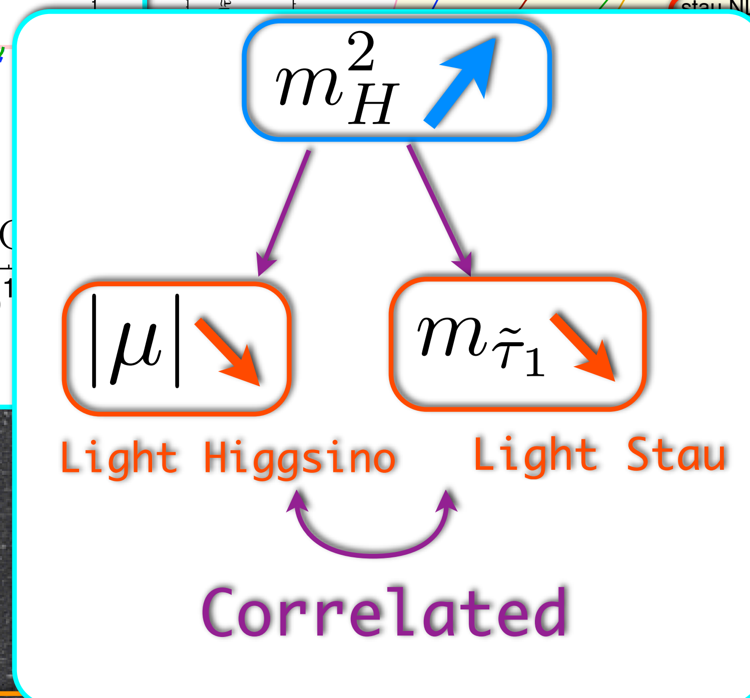
ymmetry

Pred









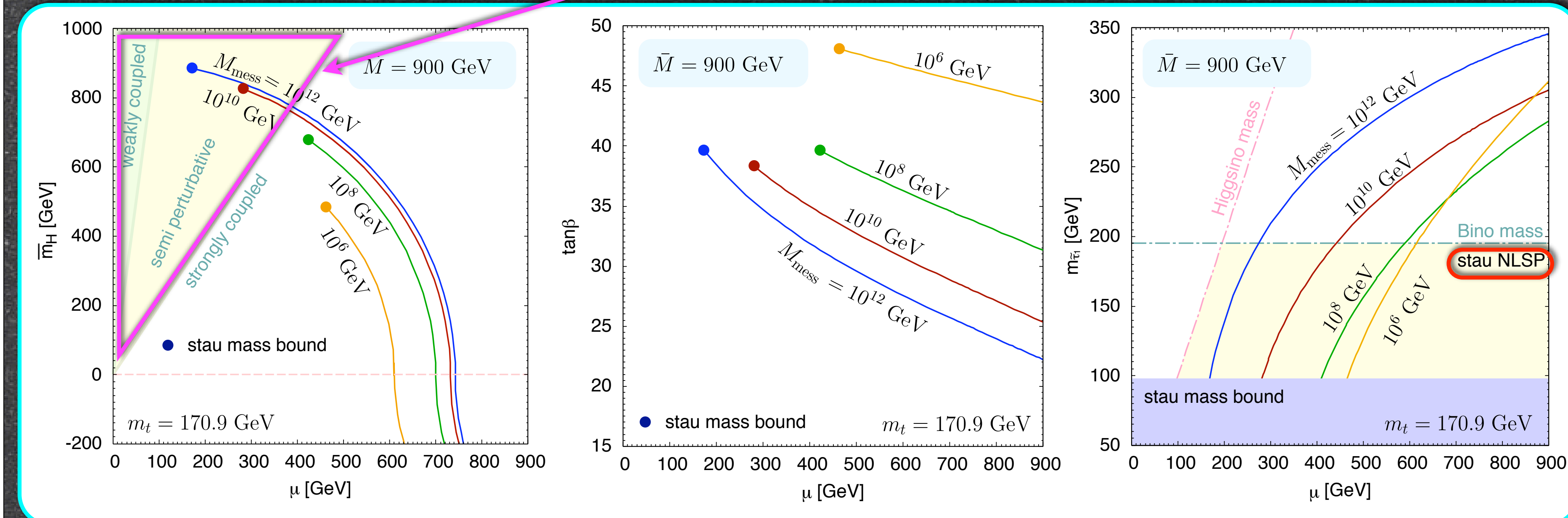
Light Stau (Stau NLSP can

Light Higgsino

Large tanβ

Sweet Spot Supersymmetry

Prediction of (perturbative) SSS



Light Stau (Stau NLSP can be easily realized)

Light Higgsino

Large tanβ

Sweet Spot Supersymmetry

Three low energy parameters $(\mu, M_{\text{mess}}, \bar{M})$

$$m_{\text{gaugino}} = g^2 \bar{M}$$

We can reconstruct model parameters by measuring three masses.

LHC Signatures

Benchmark Point

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

→ Stau NLSP(116GeV)
(lifetime O(10000)sec.)

→ χ_1^0 χ_2^0 χ_3^0 χ_4^0

Bino Higgsino Wino

→ gluinos, squarks ~ 1TeV

$$\boxed{\sigma(pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}) \simeq 1.4\,\text{pb}}$$

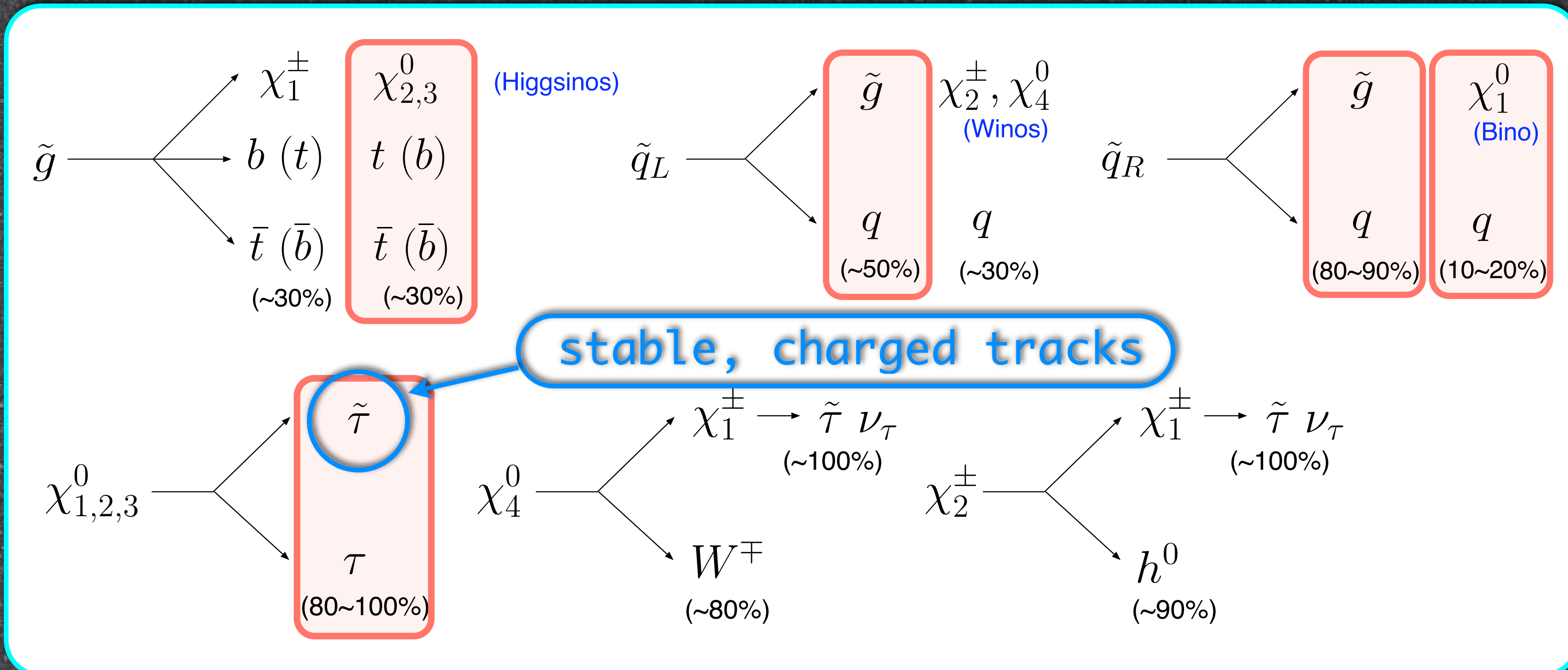
Spectrum

$\tilde{g}$	1013	$\tilde{\nu}_L$	543
$\chi_1^\pm$	270	$\tilde{t}_1$	955
$\chi_2^\pm$	404	$\tilde{t}_2$	1177
χ_1^0	187	$\tilde{b}_1$	1128
χ_2^0	276	$\tilde{b}_2$	1170
χ_3^0	307	$\tilde{\tau}_1$	116
χ_4^0	404	$\tilde{\tau}_2$	510
$\tilde{u}_L$	1352	$\tilde{\nu}_\tau$	502
$\tilde{u}_R$	1263	h^0	115
$\tilde{d}_L$	1354	H^0	770
$\tilde{d}_R$	1251	A^0	765
$\tilde{e}_L$	549	$H^\pm$	775
$\tilde{e}_R$	317	$\tilde{G}$	0.5

$\tan\beta = 37$
(output)

LHC Signatures

Decay modes



Typical Event at LHC

Many b/τ-jets + low-velocity 2 charged tracks

difficult to analyze...

LHC Signatures

Stau Mass Measurement

$$\boxed{m_{\tilde{\tau}_1} = \frac{p_{\tilde{\tau}_1}}{\beta\gamma}}$$

measured from charged track

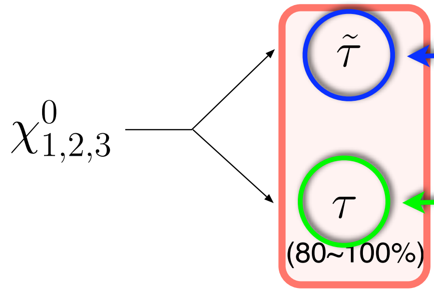
time of flight measurement

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

For $m_{\tilde{\tau}_1} \simeq$ 100GeV stau mass can be measured with an accuracy of 100MeV.

LHC Signatures

Reconstruction of neutralino masses



charged track

We use hadronic decay mode of τ
['98 Hinchiliffe & Paige]

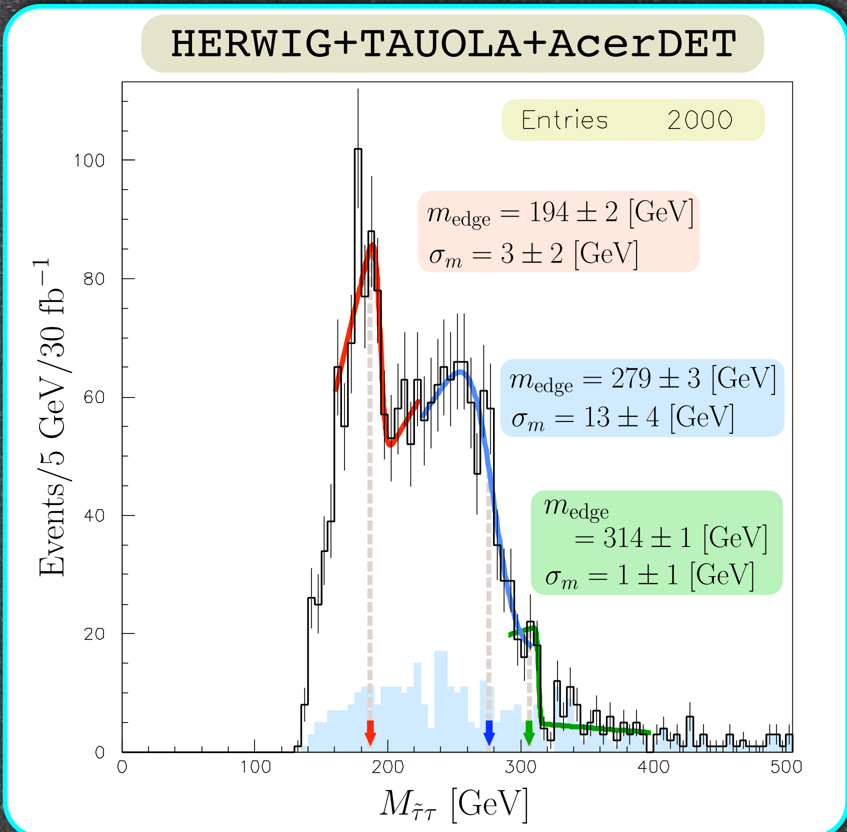
cf.The analysis with leptonic modes discussed in
['06 Ellis,Raklev,Oye] is difficult in our case.

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

Select events with 1 tau-jet candidate.

(within the triggered events with the condition in ATLAS TDL)

LHC Signatures



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

After triggering and selection

2000 event candidates

Main background

Wrong combination of tau-stau

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

Miss-tagging of non-tau-jet

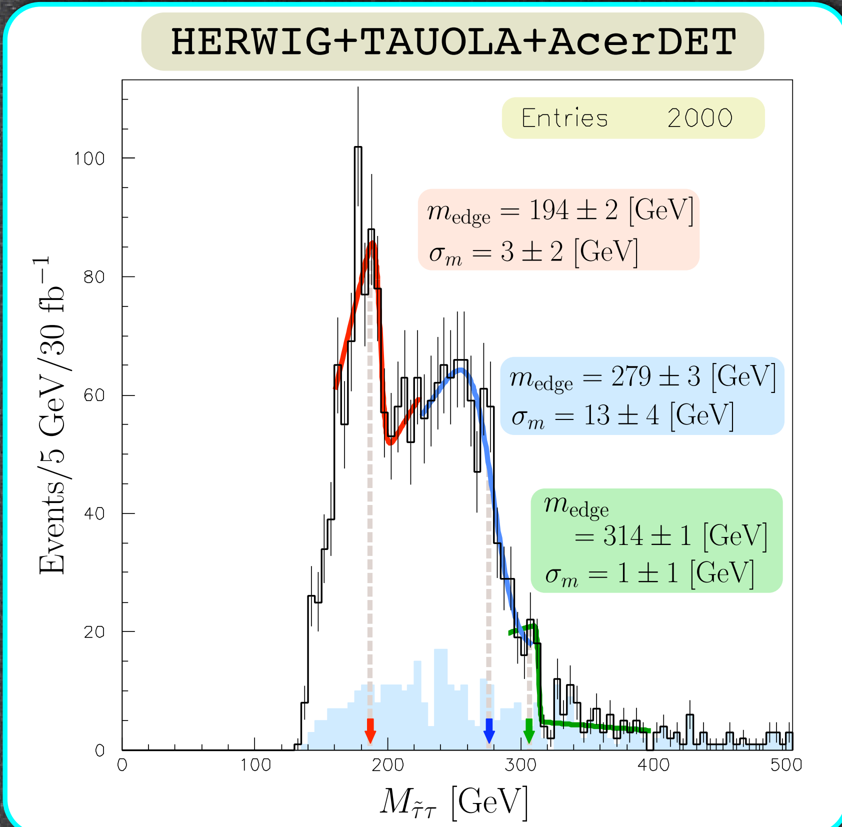
tau-tag efficiency 50%

mis-tag probability 1%

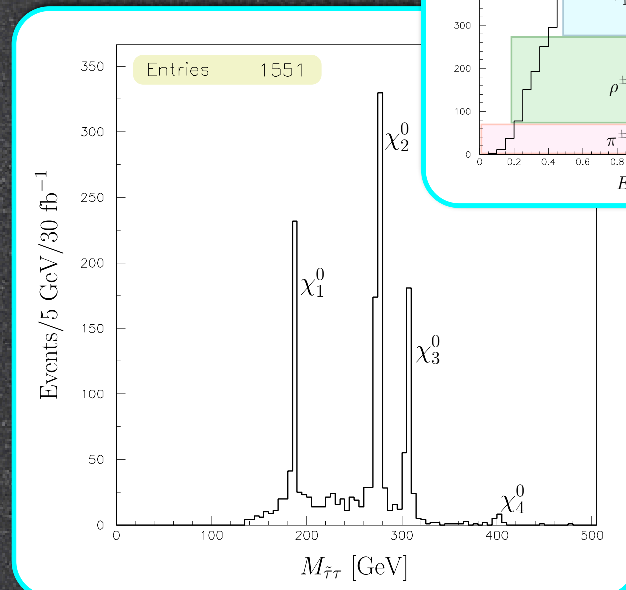
(437 events are mis-tagged events)

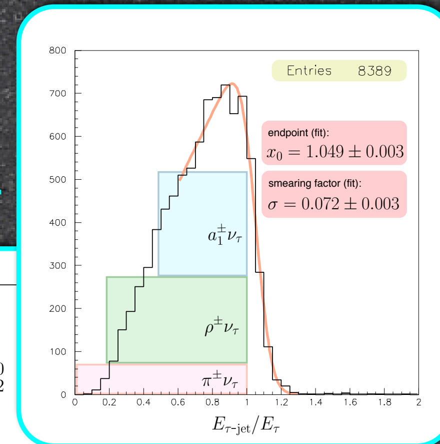
We can determine masses of χ_1^0, χ_2^0 with an accuracy of O(5)%.

LHC Signatures



Neutrinos carry away part of energy.





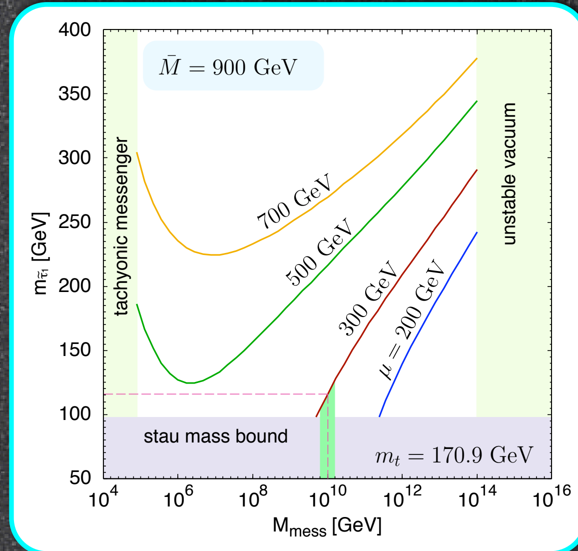
We can determine masses of χ_1^0, χ_2^0 with an accuracy of O(5)%.

LHC Signatures

Parameter Reconstruction

$$\boxed{m_{\chi^0_{1,2}} \longrightarrow \mu,\ \bar{M}}$$

$$\boxed{m_{\tilde{\tau}_1} \longrightarrow M_{\rm mess}}$$



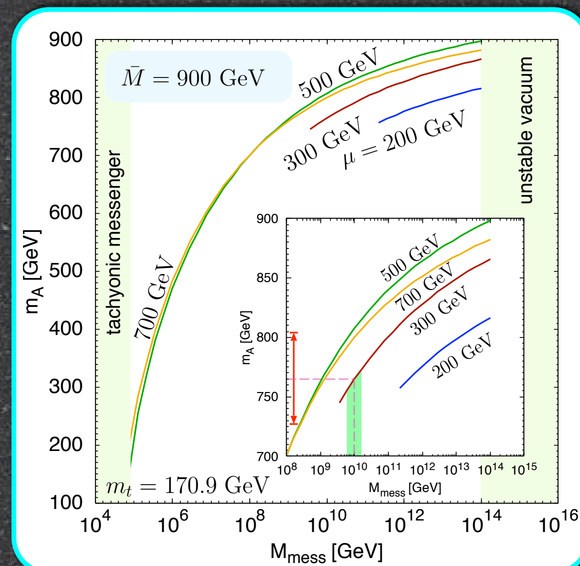
$$\Delta\mu \sim 20\,\mathrm{GeV} \quad \Delta\bar{M} \sim 50\,\mathrm{GeV}$$

$$\Delta \log_{10} M_{\rm mess} \sim 0.2$$

Consistency Check

Prediction of M_A

$$\boxed{M_A = 745 \pm 40\,\mathrm{GeV}}$$



We can perform non-trivial check!

Natural Gravitino Dark Matter

Thermally produced gravitino

$$\Omega_{3/2}h^2 \simeq 0.2 \times \left(\frac{T_R}{10^8\ \mathrm{GeV}}\right)\left(\frac{1\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\mathrm{gluino}}}{1\mathrm{TeV}}\right)^2$$

We need to choose reheating temperature to obtain the observed DM density.

In our model, the scalar component of the SUSY breaking multiplet provides the gravitino.

↓

Gravitino Dark Matter density is determined by low-energy parameters

Natural Gravitino Dark Matter

Scenario

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

$$m_S^4 = 4\frac{m^4}{\Lambda^2}$$
$$|w_0| \simeq m^2 M_{\rm Pl}/\sqrt{3},$$

$$m_S \simeq \ 400\,\mathrm{GeV}\left(\frac{\mathrm{m_{bino}}}{200\,\mathrm{GeV}}\right)^{1/2}\left(\frac{\mathrm{m}_{3/2}}{500\,\mathrm{MeV}}\right)^{1/2}$$

1. During Inflation $|s| \to O(\Lambda \simeq M_{\rm GUT})$
2. $H < m_S$ s starts oscillating about its vev

   s dominates the energy density of the universe
3. s decays into MSSM particles and gravitinos

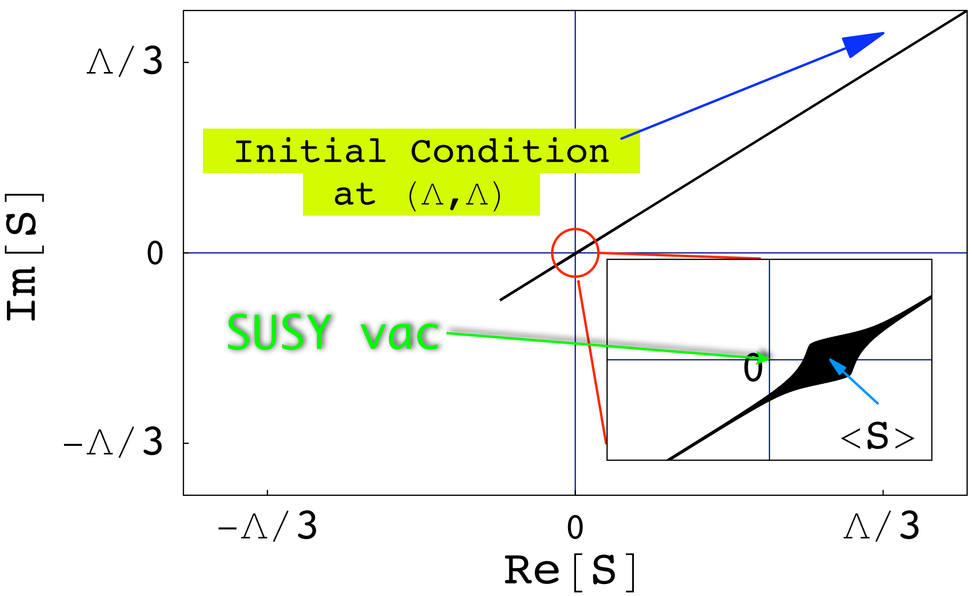
   DM density is only determined by branching ratios

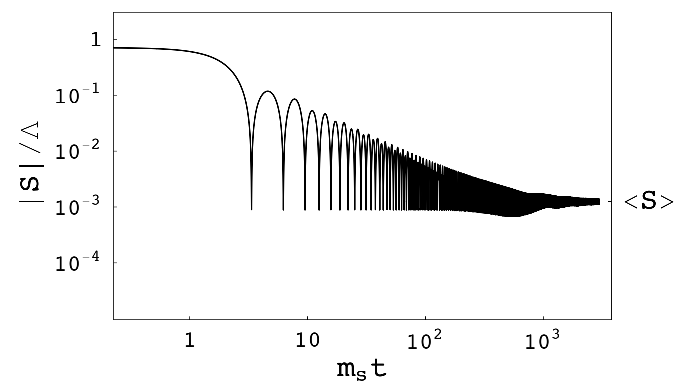
Natural Gravitino Dark Matter

Scenario

V

m





1.

2. $H < m_S$ s starts oscillating about its vev

s dominates the energy density of the universe

3. s decays into MSSM particles and gravitinos

DM density is only determined by branching ratios

Natural Gravitino Dark Matter

Branching ratio

Higgs modes

$$\mathcal{L}_{\tilde f} = \frac{m_{\tilde f}^2}{\langle S \rangle} S \tilde f^\dagger \tilde f + \mathrm{h.c.} \quad (\tilde f \to h)$$

GMSB effects

$$\Gamma_H = \frac{x_H^2 N^2}{1536\pi} \frac{m_S^3}{M_{\rm Pl}^2} \left(\frac{m_S}{m_{3/2}}\right)^8$$

$$x_H = \frac{g_2^4}{(4\pi)^4} \cdot \frac{3}{4} + \frac{g_Y^4}{(4\pi)^4} \cdot \frac{5}{3} \cdot \frac{1}{4} \simeq 6 \times 10^{-6}$$

$$\tau_S = 5 \times 10^{-5}\ \mathrm{sec} \times N^{-2} \left(\frac{m_S}{400\ \mathrm{GeV}}\right)^{-11} \left(\frac{m_{3/2}}{500\ \mathrm{MeV}}\right)^8$$

Gravitino modes

$$\Gamma_{3/2} = \frac{1}{96\pi} \frac{m_S^3}{M_{\rm Pl}^2} \left(\frac{m_S}{m_{3/2}}\right)^2$$

Natural Gravitino Dark Matter

Gravitino abundance

yield of the gravitino

$$\frac{n_{3/2}}{s} = \frac{3}{4}\frac{T_d}{m_S} B_{3/2} \times 2 \ , \quad T_d \simeq 0.5 \times \sqrt{\Gamma_H M_{\rm Pl}} \ , B_{3/2} = \Gamma_{3/2}/\Gamma_H$$

mass density parameter of gravitino

$$\boxed{\Omega_{3/2} h^2 = 0.09 \times \left(\frac{m_S}{400 \ \mathrm{GeV}}\right)^{-3/2} \left(\frac{m_{3/2}}{500 \ \mathrm{MeV}}\right)^3}$$

$$\Omega_{\rm CDM} h^2 = 0.10 \pm 0.02$$

Natural Gravitino Dark Matter

Gravitino abundance

yield of the gravitino

$$\frac{n_{3/2}}{s} = \frac{3}{4}\frac{T_d}{m_S}B_{3/2} \times 2\ , \quad T_d \simeq 0.5 \times \sqrt{\Gamma_H M_{\rm Pl}}\ , B_{3/2} = \Gamma_{3/2}/\Gamma_H$$

mass density parameter of gravitino

$$\boxed{\Omega_{3/2}h^2 = 0.1 \times \left(\frac{m_{3/2}}{500\ \mathrm{MeV}}\right)^{3/2}\left(\frac{\Lambda}{1 \times 10^{16}\ \mathrm{GeV}}\right)^{3/2}}$$

$$\Omega_{\rm CDM}h^2 \ = \ 0.10 \pm 0.02$$

Natural Gravitino Dark Matter

Sweet Spot (again)

gravitino Dark Matter

$$\Omega_{3/2}h^2 = 0.1 \times \left(\frac{m_{3/2}}{500\ \mathrm{MeV}}\right)^{3/2} \left(\frac{\Lambda}{1 \times 10^{16}\ \mathrm{GeV}}\right)^{3/2}$$

Gauge Mediated masses

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

Giudice-Masiero mechanism + PQ-symmetry

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

Natural Gravitino Dark Matter

Sweet Spot (again)

gravitino Dark Matter

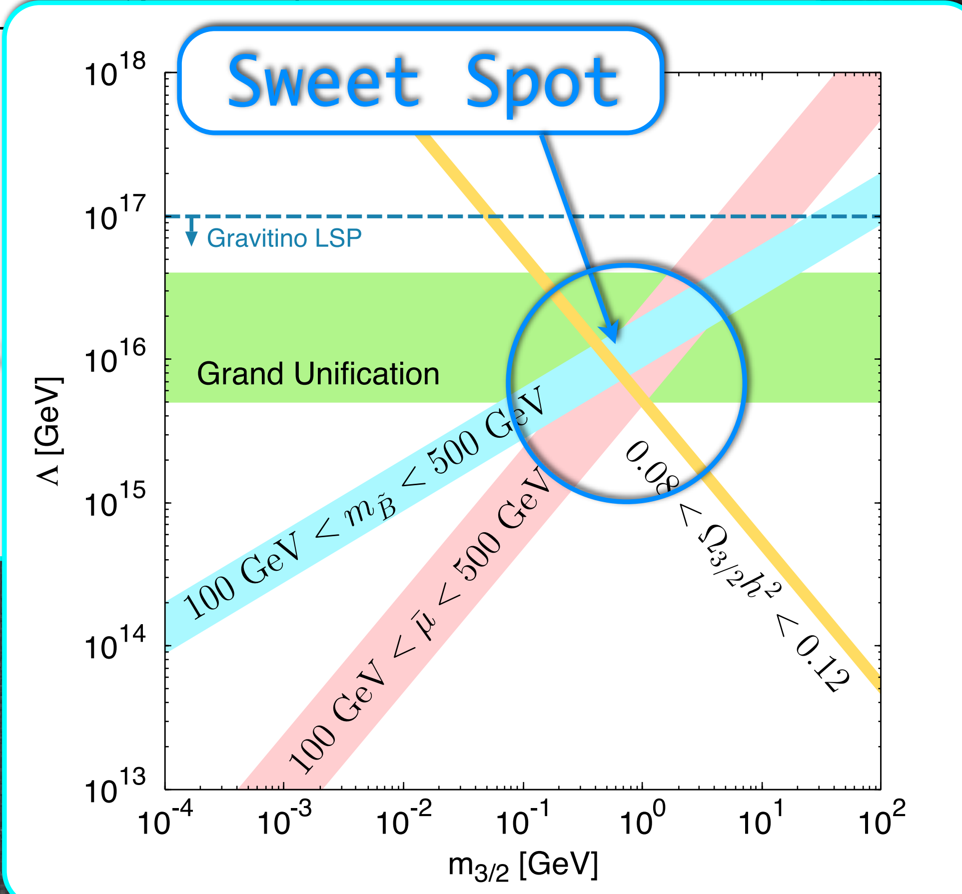
$$\Omega_{3/2}h^2 = 0.1 \times \left(\frac{m_{3/2}}{500\ \mathrm{MeV}}\right)^{3/2} \left(\cdots \Lambda \cdots \right)^{3/2}$$

Gauge Mediated masses

$$m_{\rm gaugino} \simeq m_{\rm scalar} \simeq \frac{g^2}{(4\pi)^2} m_3 \cdots$$

Giudice-Masiero mechanis

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



Summary

Sweet Spot Supersymmetry

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

- No μ-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.
- Successful gravitino dark matter

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 τ-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 Collabolation]

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)

$$\beta' - 0.05 < \beta_{\mathrm{meas}} < \beta' + 0.05 \ ,$$
$$\beta' = \sqrt{p^2_{\mathrm{meas}}/(p^2_{\mathrm{meas}} + m^2_{\tilde{\tau}_1})}$$

Both have pT>40GeV, β/γ>0.4

One of the stau candidates must have βγ<2.2

M_{eff} >800GeV → SM background negligible

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

One tau-jet candidate

pT>40GeV

tau-tag efficiency 50%
mis-tag probability 1%

Simple Gauge Mediation

Messenger particle (5,5*)

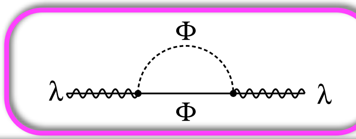
$$W = kX\Phi\bar{\Phi},$$

Spurion (SUSY-, ~~SUSY~~-mass)

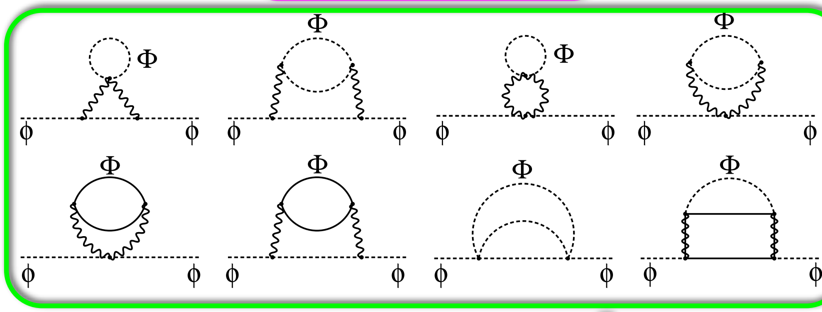
$$\langle X \rangle = M + \theta^2 F,$$

mass splitting of messenger bosons

$$\begin{pmatrix} k^2|M|^2 & kF \\ kF^* & k^2|M|^2 \end{pmatrix} \longrightarrow |kM|^2 \pm |kF|$$



Gaugino



scalar mass^2

At the messenger scale $(M_{\text{mess}} = kM, M \gg \sqrt{F/k})$

$$m_{\text{gaugino}} \simeq \frac{\alpha}{4\pi}\frac{F}{M}$$

$$m^2_{\text{scalar}} \simeq 2C_2 \left(\frac{\alpha}{4\pi}\right)^2 \left|\frac{F}{M}\right|^2$$

Simple Gauge Mediation

Effective operator Method ['97 Giudice & Rattazzi]

After integrating out the messengers

$$\mathcal{L} \ni f(X) W^\alpha W_\alpha, \qquad Z(X, X^\dagger) Q^\dagger Q$$

$$m_{\text{gaugino}} = \frac{1}{2} \frac{\partial \ln f(X)}{\partial \ln X} \frac{\langle F \rangle}{\langle X \rangle}$$

$$m^2_{\text{scalar}} = -\frac{\partial \ln Z(X, X^\dagger)}{\partial \ln X \partial \ln X^\dagger} \left| \frac{\langle F \rangle}{\langle X \rangle} \right|^2$$

The solution of f and Z at the 1-loop level

$$f(X) = \frac{1}{\alpha(M_*)} + \frac{b_H}{2\pi} \ln \frac{X}{M_*} + b_L \ln \frac{\mu_R}{X}$$

$$Z(X, X^\dagger) = \left(\frac{\alpha(M_*)}{\alpha(\sqrt{X X^\dagger})} \right)^{\frac{C_2}{b_H}} \left(\frac{\alpha(\sqrt{X X^\dagger})}{\alpha(\mu_R)} \right)^{\frac{C_2}{b_L}}$$

Simple Gauge Mediation

Effective operator Method ['97 Giudice & Rattazzi]

After integrating out the messengers

$$\mathcal{L} \ni f(X) W^\alpha W_\alpha, \qquad Z(X, X^\dagger) Q^\dagger Q$$

Around the Messenger scale,
relevant effective terms are;

$$f(X) \sim \frac{1}{2g^2} - \frac{1}{(4\pi)^2} \ln X \quad \tilde{Z}(X, X) \sim 1 - \frac{g^4}{(4\pi)^4} C_2 (\ln X X^\dagger)^2$$

Again, the soft terms are;

$$m_{\text{gaugino}} \simeq \frac{\alpha}{4\pi} \frac{F}{M} \qquad m^2_{\text{scalar}} \simeq 2 C_2 \left(\frac{\alpha}{4\pi} \right)^2 \left| \frac{F}{M} \right|^2$$

Neutrino Mass

We can assign the PQ-charge up to B-L symmetry

$$PQ(Q) = PQ(\bar{U}) = PQ(\bar{D}) = PQ(L) = PQ(\bar{E}) = -1/2$$

or

$$PQ(Q) = -1/3 \quad PQ(\bar{U}) = PQ(\bar{D}) = -2/3$$

$$PQ(L) = -1 \qquad PQ(\bar{E}) = 0$$

By using the later assignment, the Majorana neutrino mass can be write down

$$W = \frac{LH_u LH_u}{M_N}$$

see saw ['79 T.Yanagida]

Electric Dipole Moment

$$\theta_{\rm CP} = {\rm Arg}(\mu(B\mu)^* m_{1/2}, m_{1/2}A^*) = O(m_{3/2}/m_{1/2}) = O(10^{-2})$$

$$\mathcal{L}_{\rm EDM} = \frac{i}{2} d_e \bar{e} \sigma^{\alpha\beta}\gamma_5 e F_{\alpha\beta}$$

$$d_e^{\rm SUSY} \sim \sin\theta_{\rm CP} \frac{g_2^2 M_2 m_e \mu \tan\beta}{32\pi^2 m_{\tilde{e}}^4}$$

$$|d_e| < 0.7 \times 10^{-26} cm \simeq 0.4 \times 10^{-12} {\rm GeV}^{-1}$$

['96 Gabbiani et.al.]

The constraint is satisfied for

$$m_{\rm susy} > 300\,{\rm GeV}$$
$$m_{3/2} < 1\,{\rm GeV}$$

Upper bound on the Messenger Mass

The introduction of the messenger interactions results in the radiative corrections to S direction.

$$W = kSf\bar{f}$$

$$V(S) = m^4\left(\frac{4}{\Lambda^2}|S|^2 + \frac{k^2N}{(4\pi)^2}\log\left(\frac{k^2|S|^2}{\Lambda^2}\right)\right) - (2m_{3/2}m^2S + \mathrm{h.c.})\ .$$

In order the radiative correction not to destabilize the SUSY breaking vacuum, we need to require,

$$k < 3\times 10^{-3}\left(\frac{N}{25}\right)^{-1/2}\left(\frac{\Lambda}{1\times 10^{16}\ \mathrm{GeV}}\right)\ .$$

$$M_{\mathrm{mess}} < 4\times 10^{10}\ \mathrm{GeV}\left(\frac{N}{25}\right)^{-1/2}\left(\frac{\Lambda}{1\times 10^{16}\ \mathrm{GeV}}\right)^3$$

Entropy Production from S-decay

The pre-existent quantities such as gravitino abundance or the baryon asymmetry is diluted by a factor

$$\Delta^{-1} \simeq \frac{T_d}{T_{\rm dom}} \simeq \begin{cases} \dfrac{T_d}{T_R}\left(\dfrac{|S_0|}{\sqrt{3}M_{\rm Pl}}\right)^{-2}, & (T_R < T_{\rm osc}), \\ \dfrac{T_d}{T_{\rm osc}}\left(\dfrac{|S_0|}{\sqrt{3}M_{\rm Pl}}\right)^{-2}, & (T_R > T_{\rm osc}). \end{cases}$$

$|S_0|$:Initial amplitude

$$T_{\rm osc} \simeq 0.3 \times \sqrt{M_{\rm Pl} m_S} \simeq 8 \times 10^9\,{\rm GeV} \times \left(\frac{m_S}{400\,{\rm GeV}}\right)^{1/2}$$

the temperature when S starts oscillating

$$T_{\rm dom} = \min[T_R, T_{\rm osc}] \times \left(\frac{|S_0|}{\sqrt{3}M_{\rm PL}}\right)^2$$

the temperature when S osci. dominates the universe

Entropy Production from S-decay

The pre-existent quantities such as gravitino abundance or the baryon asymmetry is diluted by a factor

$$\Delta^{-1} \simeq \frac{T_d}{T_{\rm dom}} \simeq \begin{cases} \dfrac{T_d}{T_R}\left(\dfrac{|S_0|}{\sqrt{3}M_{\rm Pl}}\right)^{-2}, & (T_R < T_{\rm osc}), \\ \dfrac{T_d}{T_{\rm osc}}\left(\dfrac{|S_0|}{\sqrt{3}M_{\rm Pl}}\right)^{-2}, & (T_R > T_{\rm osc}). \end{cases}$$

$T_R < T_{\rm osc}$ $\quad |S_0| = O(M_{\rm GUT})$

$$\Delta^{-1} \simeq 10^{-4}\left(\frac{T_R}{10^8\,{\rm GeV}}\right)^{-1}$$

Entropy Production from S-decay

The dilution factor of the NLSP is given by

$$\Delta^{-1} \simeq \mathrm{Max}[(T_d/T_f)^3,\, T_d/(T_{\mathrm{dom}}T_f)^{1/2}]$$

$$T_f \simeq m_{\mathrm{NLSP}}/20$$

$T_R < 10^{10}\mathrm{GeV}$ $|S_0| = O(M_{\mathrm{GUT}})$

$$\Delta^{-1} \simeq 0.3 \times 10^{-3} \left(\frac{10^8}{T_R}\right)^{1/2}$$

SUSY Breaking & Mediation Mechanisms

- The origin of Gaugino masses are classified by how S couples to gauge supermultiplets

$$W \ni f(S)\mathcal{W}^{\alpha}\mathcal{W}_{\alpha}$$

- Anomaly Mediation

$f(S) = 0 \longrightarrow$ Gaugino mass is dominated by Anomaly Mediated effects

$$\longrightarrow \quad m_{\text{gaugino}} = \frac{g^2 b}{(4\pi)^2} m_{3/2}$$

S can be charged field $\longrightarrow$ No Polonyi Problem
Anomaly mediation scenario suffers from tachyonic slepton problem.

UV completion and Grand Unification

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)

$$W_S = m^2 S + \frac{\kappa}{2} S X^2 + M_{XY} XY \ ,$$ O'Raifeartaigh Model

$$W_{\text{Higgs}} = h H_u \bar{q} X + \bar{h} H_d q X + M_q q \bar{q} \ ,$$ (PQ-sym)

Can we make a model which is consistent with GUT?

UV completion and Grand Unification

An example of a GUT consistent UV-model

'06 Kitano SU(5)XSO(6) Product group GUT model

(similar to '96 Hotta,Izawa,Yanagida)

	$SU(5)_{\rm GUT}$	$SO(6)_H$	$U(1)_{\rm PQ}$
S	$\mathbf{1}$	$\mathbf{1}$	2
M	$\mathbf{1}+\mathbf{24}$	$\mathbf{1}$	0
X	$\mathbf{1}$	$\mathbf{6}$	-1
$q,\ \bar{q}$	$\mathbf{5},\ \bar{\mathbf{5}}$	$\mathbf{6}$	0
$H,\ \bar{H}$	$\mathbf{5},\ \bar{\mathbf{5}}$	$\mathbf{1}$	1

$$W = m^2 S + m_{\rm GUT}^2 Tr[M] - m_{\rm GUT} Tr[MM] + \cdots$$
$$+ S X^i X^i + \bar{q}^i M q^i + \bar{q}^i H X^i + q^i \bar{H} X^i$$

UV completion and Grand Unification

An example of a GUT consistent UV-model

$$\langle M \rangle = \underbrace{\begin{pmatrix} 0 & & & & \\ & 0 & & & \\ & & 0 & & \\ & & & v & \\ & & & & v \end{pmatrix}}_{\text{SU(5)}} \quad \langle q \rangle = \underbrace{\begin{pmatrix} v & & & iv & & \\ & v & & & iv & \\ & & v & & & iv \\ & & & & & \end{pmatrix}}_{\text{SO(6)}} \quad \langle \bar{q} \rangle = \underbrace{\begin{pmatrix} v & & & -iv & & \\ & v & & & -iv & \\ & & v & & & -iv \\ & & & & & \end{pmatrix}}_{\text{SO(6)}}$$

$$v = O(M_{\text{GUT}})$$

GUT: SU(5)XSO(6)

MSSM: SU(3)XSU(2)XU(1)

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Doublet-Triplet Splitting

$$X^i \langle q^i \rangle \bar{H} = (X^1 X^2 X^3 X^4 X^5 X^6) \begin{pmatrix} v & & & iv & & \\ & v & & & iv & \\ & & v & & & iv \\ & & & & & \\ & & & & & \end{pmatrix} \begin{pmatrix} \bar{H}_c^1 \\ \bar{H}_c^2 \\ \bar{H}_c^3 \\ \bar{H}_d^1 \\ \bar{H}_d^2 \end{pmatrix}$$

$$= M_{XY} X_c \bar{Y} \qquad X_c = X^i + iX^{i+3} (i = 1, 2, 3)$$

$$\bar{Y} = \bar{H}_c$$

$\downarrow$ O'Raifeartaigh Model

$$W = m^2 S + S X_c \bar{X}_c + M_{XY}(X_c \bar{Y} + \bar{X}_c Y)$$

$$+(X_c \bar{q}_c + \bar{X}_c q_c)\bar{H} + (X_c \bar{q}_{\bar{c}} + \bar{X}_c q_{\bar{c}})H + M_q(q_c \bar{q}_{\bar{c}} + \bar{q}_c q_{\bar{c}})$$

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$$+(X_c \bar{q}_c + \bar{X}_c q_c)\bar{H} + (X_c \bar{q}_{\bar{c}} + \bar{X}_c q_{\bar{c}})H + M_q(q_c \bar{q}_{\bar{c}} + \bar{q}_c q_{\bar{c}})$$

$\downarrow$ One-loop effects

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

The sign of the Higgs mass^2

- S is a singlet.
- There is no interaction like XH_uH_d .

(If there is such term, we can have a mass term of S, which spoils the supersymmetry breaking model.)

$\longrightarrow$ The term $S^\dagger S H^\dagger H$ comes from the wave function renormalization of Higgses.

- If there is no GUT-scale breaking of the PQ-symmetry, the masses in the Hidden sector gets larger for the larger |S|.

(The mass spectrum is given by not |MGUT + S|^2 but by|MGUT|^2 + |S|^2.)

$\longrightarrow$ The coefficient of the term $S^\dagger S H^\dagger H$ corresponds to the one of the anomalous dimension of the Yukawa-type interactions whose sign is always positive.