Supersymmetry Breaking and the Pattern of Sparticle Masses at the LHC

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Outline

1. Motivation

   A Map of (Flavor and CP-conserving) Mediations of SUSY Breaking:

   How closely can we identify the underlying mediation scheme with the LHC data?

2. General Mixed "Gravity(Dilaton/Moduli)-Anomaly-Gauge -*D* Term" Mediation

   A theoretically well-motivated framework to incorporate many of the proposed mediation schemes, which might be useful for the interpretation of the sparticle masses measured at the LHC.

3. Sparticle Mass Pattern in General Mixed Mediation

4. Conclusion

Weak scale SUSY is perhaps the leading candidate for physics beyond the SM at the TeV scale:

- solves the hierarchy problem
- unification friendly
- straightforward to satisfy the EW precision test
- provides an attractive DM candidate: neutralino LSP

If the idea of weak scale SUSY is correct, sparticles will be produced copiously at the LHC, and we might be able to measure (some of) the SUSY parameters, particularly "the sparticle masses".

Then the next utmost question will be "what is the underlying physics for the observed pattern of sparticle masses?"

Most of the unknown SUSY parameters ($\ni$ sparticle masses) reside in soft SUSY-breaking terms:

$$\mathcal{L}_{\rm soft} = \left(\frac{1}{2}M_a\lambda^a\lambda^a + {\rm c.c.}\right) - m^2_{\tilde{Q}}\tilde{Q}^\dagger\tilde{Q} - \left(\frac{1}{6}A_Q y_Q \tilde{Q}\tilde{Q}\tilde{Q} + {\rm c.c.}\right)$$

and these soft terms are determined by "the mediation mechanism of SUSY breaking".

At the moment, the most severe constraints on soft terms come from the absence any sizable FCNC and CP-violation beyond the SM predictions.

$\Longrightarrow$ Soft terms should preserve the flavor and CP in a rather good approximation.

Flavor (and CP) conserving mediation schemes

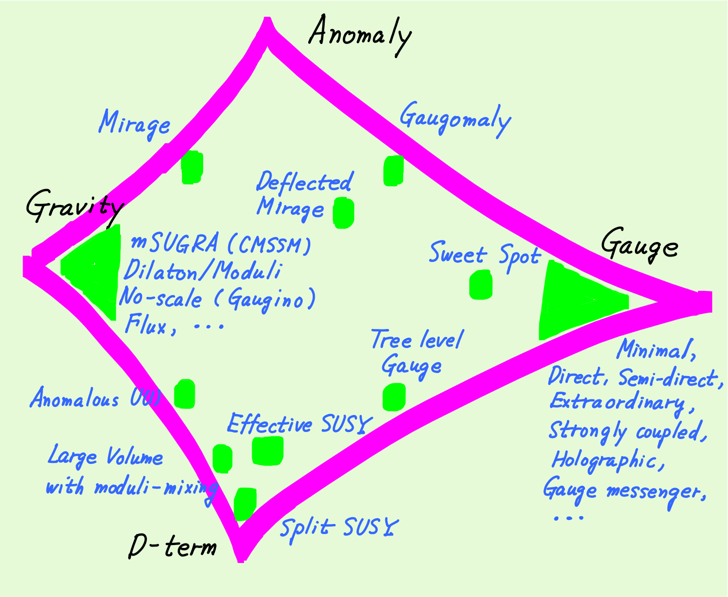
Even under the constraints of flavor and CP conservation, there can be many varieties of viable mediation mechanism of SUSY breaking.

Currently there are at least four widely discussed mediation schemes which are known to naturally give flavor-conserving (and CP-conserving besides the Higgs B-parameter) soft masses:

- Particular type of gravity mediation by the F-components of dilaton and/or volume-modulus superfields in string theory
- Gauge mediation by the loops of massive charged messengers
- Anomaly mediation by the auxiliary component of SUGRA multiplet
- D-term mediation by the D-component of massive vector superfields

Besides these four basic building blocks of mediation, there can be some variants and also many different mixtures of them.

A Map of Flavor (and CP) Conserving Mediations



So we have a proliferation of possible models, although it is not as severe as that of the string theory vacua.

Most of these models have quite different UV structures at high scales ($\gg$ TeV) where the mediation mechanism starts to operate, however this can not be tested in any foreseeable future.

On the other hand, quite often different models give similar LHC signatures, making it difficult to distinguish them with the LHC data.

(R_p-conserving) SUSY signatures at the LHC

- Missing E_T carried away by WIMP-like LSP which is stable inside the detector
- Displaced vertex with γ (or charged-lepton ℓ) which might arise from late-decaying NLSP $\rightarrow$ gravitino (or axino) $+\gamma$ (or ℓ)
- Tracks of massive charged and/or R-hadronic NLSP which is stable inside the detector

If the 2nd or 3rd type of events are discovered, one might interpret it as an evidence for light gravitino, and so of gauge mediation since a light gravitino is one of the most distinct features of gauge mediation.

However in many cases, light gravitino can be mimicked well by another well-motivated particle, "the axino", which can have a light mass in almost all mediation schemes. Chun, Kim, Nilles; Talk by L.Covi

$$\mathcal{L}_{\text{gravitino}} = \frac{1}{\sqrt{3}M_{\text{Planck}}m_{3/2}}\left[m_\phi^2\phi^*\psi\tilde{G} + \frac{M_a}{4\sqrt{2}}\lambda^a\sigma^{\mu\nu}\tilde{G}F^a_{\mu\nu}\right]$$

$$\mathcal{L}_{\text{axino}} = \frac{1}{F_a}\left[c_\psi m_\psi\phi^*\psi\tilde{a} + \frac{c_a}{32\pi^2\sqrt{2}}\lambda^a\sigma^{\mu\nu}\tilde{a}F^a_{\mu\nu}\right]$$

$\Longrightarrow$ With $c_\psi, c_a = \mathcal{O}(1)$, similar phenomenology when

$$F_a \sim 10^8\left(\frac{m_{3/2}}{100\text{ eV}}\right)\text{ GeV} \quad \left(m_{\text{NLSP}} \sim 100\text{ GeV}\right)$$

(It might be possible to distinguish the hadronic axino ($c_\psi = 0$) from gravitino.) Brandenburg, Covi, Hamaguchi, Roszkowski, Steffen

Best scenario:

If the nature chooses a simple and already known mediation scheme described by just few parameters, then it might be relatively easy to identify the underlying mediation scheme as there could be many testable predictions.

- mSUGRA (CMSSM) with $m_0 = M_{1/2}$:

$$\begin{array}{ccccccccccccccccc} & M_{\tilde{B}} & : & M_{\tilde{W}} & : & M_{\tilde{g}} & : & m_{\tilde{q}_L} & : & m_{\tilde{u}_R} & : & m_{\tilde{d}_R} & : & m_{\tilde{\ell}_L} & : & m_{\tilde{e}_R} \\ \approx & 1 & : & 2 & : & 6 & : & 5.7 & : & 5.4 & : & 5.4 & : & 2.9 & : & 2.5 \end{array}$$

- Minimal Gauge Mediation with $N_{\rm mess} = 1$, $M_{\rm mess} \sim 10^6$ GeV:

$$\begin{array}{ccccccccccccccccc} & M_{\tilde{B}} & : & M_{\tilde{W}} & : & M_{\tilde{g}} & : & m_{\tilde{q}_L} & : & m_{\tilde{u}_R} & : & m_{\tilde{d}_R} & : & m_{\tilde{\ell}_L} & : & m_{\tilde{e}_R} \\ \approx & 1 & : & 2 & : & 6 & : & 8.6 & : & 8.1 & : & 8.0 & : & 2.7 & : & 1.3 \end{array}$$

Although in principle possible, in view of the currently available map of mediation schemes, this might be a too much optimistic hope.

It is particularly true for the top-down approach based on string theory:

- Dilaton/moduli are always there, so we need to take care of the dilaton/moduli mediation.
- In any potentially realistic string compactification, it is difficult to avoid exotic gauge charged matters which can be the messenger of gauge mediation.
- An anomalous $U(1)$ gauge symmetry appears quite often, and then it can give a sizable D-term contribution.
- String theory involves the gravity, so anomaly mediation is always there, although its importance is model-dependent.

$\Longrightarrow$ Mixtures of different mediations are a quite natural possibility:

- mirage mediation: KC, Nilles, Falkowski, Olechowski, Pokorski

  dilaton/modulus $\sim$ anomaly

- deflected mirage mediation: Everett, Kim, Ouyang, Zurek

  dilaton/modulus $\sim$ anomaly $\sim$ gauge

Simple Example of General Mixed Mediation in which

dilaton/modulus $\sim$ anomaly $\sim$ gauge $\sim$ D-term.

Models (a kind of simple generalization of KKLT) with

- Nonperturbative stabilization of the gauge coupling modulus T:

$$\langle T \rangle = \frac{1}{g_{\rm SM}^2} + \frac{i}{8\pi^2}\theta_{\rm SM}$$

- Anomalous $U(1)_A$:

$$V_A \to V_A + \Lambda + \Lambda^*, \quad T \to T - \delta_{GS}\Lambda, \quad Y \to e^{\Lambda} Y$$
$$\Big(Y \; = \; U(1)_A\text{-charged, but MSSM-singlet} \Big)$$

- Gauge-charged exotic matters $\Psi + \Psi^c$ with a singlet X whose VEV determine the masses of $\Psi + \Psi^c$.

- Uplifting sector $\{Z\}$ for de-Sitter vacuum.

4D Effective Action:

$$\int d^4\theta \left[-3e^{-K/3} + \Omega_{\rm uplift}(Z,Z^*)\right] + \left(\int d^2\theta \left(W + W_{\rm uplift}(Z)\right) + {\rm c.c.}\right)$$

$$K = -n_0 \ln(t) + Z_X(t) X^* X + Z_Y(t) Y^* e^{-V_A} Y + Z_\Psi(t) \Psi^* e^{-q_\Psi V_A} \Psi$$

$$\left(t = T + T^* - \delta_{GS} V_A\right)$$

$$W = w_0 + A e^{-nT/\delta_{GS}} Y^n + \lambda X \Psi^c \Psi + \frac{\kappa}{M_{\rm Planck}} X^4$$

* $\Omega_{\rm uplift}$, $W_{\rm uplift}$: generic sequestered uplifting sector.

* Relative importance of the D-term mediation depends on the form of the moduli Käher potenitial: Arkani−Hamed, Dine, Martin; KC, Jeong

$$\Delta K = -n_0 \ln(T + T^* - \delta_{GS} V_A).$$

Under the condition of vanishing cosmological constant, the model involves just two mass scales: M_{Planck} and $m_{3/2}$

- Non-perturbative stabilization of the gauge-coupling modulus:

$$m_T \sim m_{3/2} \ln\left(1/\text{NP effect}\right) \sim m_{3/2} \ln\left(M_{\text{Planck}}/m_{3/2}\right)$$

$$\Longrightarrow \quad \frac{F^T}{T+T^*} \sim \frac{m_{3/2}^2}{m_T} \sim \frac{m_{3/2}}{\ln(M_{\text{Planck}}/m_{3/2})} \sim \frac{m_{3/2}}{4\pi^2}$$

- D-flat condition:

$$\sqrt{D_A} \sim \frac{F^T}{T+T^*} \sim \frac{F^Y}{Y} \quad \left(T,\ Y : U(1)_A \text{ charged}\right)$$

- X is stabilized by the tree level potential involving M_{Planck} and $m_{3/2}$:

$$\frac{F^X}{X} \sim m_{3/2}$$

$$\Longrightarrow \quad \frac{F^T}{T+T^*}\,(\text{dilaton/modulus}) \sim \sqrt{D_A}\,(\text{D-term})$$

$$\sim \frac{m_{3/2}}{8\pi^2}\,(\text{anomaly}) \sim \frac{1}{8\pi^2}\frac{F^X}{X}\,(\text{gauge})$$

- Dynamical relaxation of the relative phases by $\mathrm{Im}(T)$, $\mathrm{Arg}(X)$ and $\mathrm{Arg}(Y)$:

$$\mathrm{Arg}\left(\frac{F^T}{T+T^*}\right) = \mathrm{Arg}\left(\frac{F^X}{X}\right) = \mathrm{Arg}\left(\frac{F^Y}{Y}\right) = \mathrm{Arg}\left(m_{3/2}\right)$$

$\Longrightarrow$ **Flavor and CP conserving general mixed mediation:**

$$M_{\rm gaugino},\, A_{\rm sfermion} \sim \left[\frac{F^T}{T+T^*}\,(\text{dilaton/modulus}) + \frac{m_{3/2}}{8\pi^2}\,(\text{anomaly}) + \frac{1}{8\pi^2}\frac{F^X}{X}\,(\text{gauge})\right]$$

$$m_{\rm sfermion} \sim \left[\frac{F^T}{T+T^*}\,(\text{dilaton/modulus}) + \sqrt{D_A}\,(\text{D-term}) + \frac{m_{3/2}}{8\pi^2}\,(\text{anomaly}) + \frac{1}{8\pi^2}\frac{F^X}{X}\,(\text{gauge})\right]$$

So mixed mediations emerge naturally in string-based top-down approaches.

We can easily modify the model to make some mediations more important than the others.

Previous studies show that different mixed mediations often give quite different patterns of sparticle masses, implying that we might need a framework which can accommodate all possible mixtures of the four mediation schemes in order to interpret the LHC data.

KC, Jeong, Okumura; Everett, Kim, Ouyang, Zurek

Such general mixed mediation will be useful by itself as it can cover many of the proposed models that appear in the map of mediation.

Sparticle Masses in General Mixed Mediation

In addition to the dependence on the mediation mechanism defined at the messenger scale $\Lambda_{\rm mess}$, the observable sparticle masses at the weak scale are affected also by the subsequent renormalization group running and possible threshold corrections at scales below $\Lambda_{\rm mess}$.

Kane, Kumar, Morrissey, Toharia; Carena, Draper, Shah, Wagner;...

This would give an additional model-dependence, e.g. on the extra fields and/or extra interactions that might exist at scales $\lesssim \Lambda_{\rm mess}$.

With such many varieties of possible UV physics, we need certain assumptions to make any (quantitative) prediction on the sparticle masses testable at the LHC:

Conflict between genericity and predictability

Assumptions (perhaps the most reasonable at the moment)

Gauge coupling unification is not an accident, but a consequence of the following $SU(5)$-invariant (or $SO(10)$) structure of the underlying theory:

(i) For a dilaton or modulus T whose F-component gives a substantial contribution to gaugino masses, the real (quantized) coefficients k_a in $f_a = k_a T + ...$ $(a = 1, 2, 3)$ are universal:

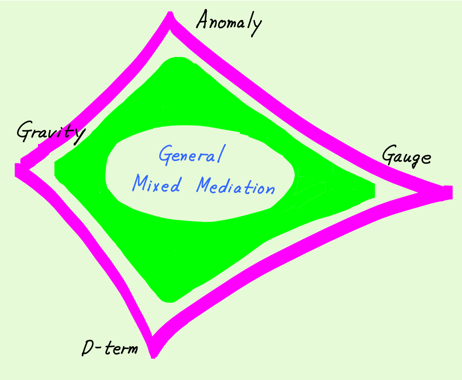
$$\langle \mathrm{Re}(f_a) \rangle = \frac{1}{g_a^2(M_{GUT})}$$

(ii) If exist, exotic gauge-charged matter fields below M_{GUT} (including the gauge mediation messengers $\Psi + \Psi^c$) form a full $SU(5)$ multiplet.

(iii) The couplings with T and the $U(1)_A$ charges (in case with an anomalous $U(1)_A$) of the squarks/sleptons are all $SU(5)$-invariant.

General mixed mediation under these unification assumptions can be useful:

- It can cover many of the mediation schemes in the map.
  (But not for non-minimal gauge mediations.)



- Gaugino masses still take a simple pattern.
- The 1st and 2nd generation sfermion masses also take a manageable form as much of the model-dependence can be efficiently parameterized.
- The 3rd generation sfermions and the Higgs bosons are the most model-dependent and difficult to analyze. Particularly they can depend on the mechanism to generate the μ-term, which will not be discussed here.

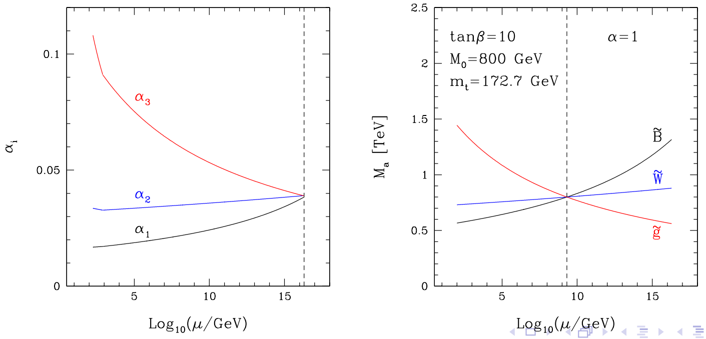
Gaugino Masses KC, Nilles

Just with the assumptions (i) and (ii), at one-loop approximation,

$$\frac{M_a(\mu)}{g_a^2(\mu)} = \left(\frac{1}{2}F^T - \frac{N_\Psi}{16\pi^2}\frac{F^X}{X}\right) + \frac{b_a}{16\pi^2}m_{3/2}$$

$\Longrightarrow$ Mirage unification of gaugino masses at $M_{\rm mirage}$:

$$\left(\frac{M_{\rm mirage}}{M_{GUT}} = \exp\left[-\frac{m_{3/2}}{F^T - \frac{N_\Psi}{8\pi^2}\frac{F^X}{X}}\right]\right)$$



The difference between the gaugino mass unification scale M_{mirage} and the gauge coupling unification scale M_{GUT} represents the contribution from anomaly mediation.

Gaugino masses at the weak scale:

$$\begin{aligned} M_1 &= M_{\text{eff}}(0.43 + 0.29\alpha) \\ M_2 &= M_{\text{eff}}(0.83 + 0.084\alpha) \\ M_3 &= M_{\text{eff}}(2.5 - 0.74\alpha) \end{aligned}$$

$$\begin{aligned} \alpha &= \frac{2\ln(M_{\text{mirage}}/M_{\text{GUT}})}{\ln(m_{3/2}/M_{Pl})} = \frac{\text{anomaly}}{\text{modulus} + \text{gauge}} \\ M_{\text{eff}} &= \frac{g_{GUT}^2}{2}\left(F^T - \frac{N_\Psi}{8\pi^2}\frac{F^X}{X}\right) = \text{universal} \end{aligned}$$

Sfermion Masses (1st and 2nd generation)

KC, Jeong, Nakamura, Okumura, Yamaguchi

$$m^2_{\tilde{Q}}(\mu) \;=\; m^2_{\rm eff} \;-\; \sum_a \frac{2C_a(Q)}{b_a}\left(M_a^2(\mu) - M^2_{\rm eff}\right) \;+\; \Delta m^2_{\tilde{Q}}$$

(1) $m^2_{\rm eff} \;=\; SU(5)$-invariant dilaton/modulus mediation at M_{GUT}

$+ \; SU(5)$-invariant D-term contribution from anomalous $U(1)_A$

(2) Second term represents the MSSM RG running and anomaly mediation.

(3)
$$\Delta m^2_{\tilde{Q}}(R, \ln M_\Psi, N_\Psi) \;=\; 2(R-1)^2 M^2_{\rm eff} \sum_a C_a(Q)\left[\frac{1}{N_\Psi}\frac{g_a^4(M_\Psi)}{g_0^4} + \frac{g_a^2(M_\Psi)}{8\pi^2}\left(\frac{R+1}{R-1} - \frac{g_a^2(M_\Psi)}{g_0^2}\right)\ln\left(\frac{M_{GUT}}{M_\Psi}\right)\right]$$

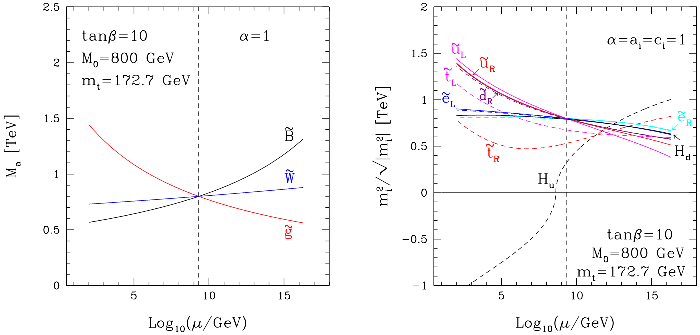
$$= \;\text{Contribution from gauge mediation}$$

$$R \;=\; \frac{g^2_{GUT}}{g_0^2}\left(\frac{F^T}{F^T - \frac{N_\Psi}{8\pi^2}\frac{F^X}{X}}\right), \qquad \frac{1}{g_0^2} = \frac{1}{g^2_{GUT}} + \frac{N_\Psi}{8\pi^2}\ln\left(\frac{M_{GUT}}{M_\Psi}\right) \approx \frac{1}{2}$$

$$m^2_{\tilde{Q}}(\mu) \;=\; m^2_{\rm eff} \;-\; \sum_a \frac{2C_a(Q)}{b_a}\left(M_a^2(\mu) - M^2_{\rm eff}\right) \;+\; \Delta m^2_{\tilde{Q}}$$

$\Longrightarrow$ In the absence of gauge mediation, sfermion masses are unified at the same mirage scale $M_{\rm mirage}$:

$$m^2_{\tilde{Q}}(M_{\rm mirage}) \;=\; m^2_{\rm eff} \quad \text{for} \;\; \Delta m^2_{\tilde{Q}} \;=\; 0$$



Sfermion masses at the weak scale:

$$\begin{aligned}
m^2_{\tilde{q}_L} &= m^2_{\rm eff} + M^2_{\rm eff}(5.0 - 3.48\alpha + 0.48\alpha^2) + \Delta m^2_{\tilde{q}_L} \\
m^2_{\tilde{u}_R} &= m^2_{\rm eff} + M^2_{\rm eff}(4.6 - 3.29\alpha + 0.49\alpha^2) + \Delta m^2_{\tilde{u}_R} \\
m^2_{\tilde{e}_R} &= m^2_{\rm eff} + M^2_{\rm eff}(0.15 - 0.045\alpha - 0.015\alpha^2) + \Delta m^2_{\tilde{e}_R} \\
m^2_{\tilde{d}_R} &= m^2_{\rm eff} + M^2_{\rm eff}(4.5 - 3.27\alpha + 0.49\alpha^2) + \Delta m^2_{\tilde{d}_R} \\
m^2_{\tilde{\ell}_L} &= m^2_{\rm eff} + M^2_{\rm eff}(0.5 - 0.22\alpha - 0.014\alpha^2) + \Delta m^2_{\tilde{\ell}_L}
\end{aligned}$$

$$\Big(m_{\rm eff} \;=\; \text{universal for } SO(10) \Big)$$

In typical string-inspired models of general mixed mediation, $\Delta m^2_{\tilde{Q}}$ are not numerically significant if $\Lambda_{\rm mess}(\text{gauge}) \geq 10^{10}$ GeV and $N_{\rm mess}(\text{gauge}) \lesssim 5$.

Some interesting limits:

- Pure dilaton/modulus mediation (mSUGRA):

$$\alpha = 0, \;\; R = 1 \;\; (\Delta m^2_{\tilde{Q}} = 0)$$

- Pure (minimal) gauge mediation:

$$\alpha = m^2_{\rm eff} = 0, \;\; R = 0$$

- Anomaly mediation with D-term contribution to avoid tachyonic slepton:

$$\alpha = \infty, \;\; \alpha M_{\rm eff} = \text{finite}$$

- Mirage mediation with dilaton/modulus $\sim$ anomaly:

$$\alpha = \mathcal{O}(1), \;\; R = 1 \;\; (\Delta m^2_{\tilde{Q}} = 0)$$

- Deflected mirage mediation with dilaton/modulus $\sim$ anomaly $\sim$ gauge:

$$\alpha = \mathcal{O}(1), \;\; 1 - R = \mathcal{O}(1)$$

A strategy to probe the mediation mechanism with sparticle mass measurement:

- With the LHC data, we might be able to determine many of the SUSY parameters:

  * Kinematic methods: edge, kink, cusp, ...

  * Global likelyhood fit: Fittino, SFitter, ...

- From the measured gaugino masses, check the gaugino mass unification and determine its scale: $M_a(M_{\rm mirage}) =$ universal.

  Sizable value of $\frac{1}{4\pi^2} \ln \left(M_{GUT}/M_{\rm mirage}\right)$ indicates a sizable anomaly mediation contribution.

$\left(M_{GUT} = \text{Scale of gauge coupling unification} \approx 2 \times 10^{16}\,\text{GeV}\right)$

- Unless sfermions are too heavy to be produced at the LHC, one can measure some of the squark and slepton masses to examine the deviation from the (mirage) unification structure:

$$m^2_{\tilde{Q}}(M_{\rm mirage}) = m^2_{\rm eff} + \Delta m^2_{\tilde{Q}}.$$

  Deviation from the (mirage) unification indicates the gauge mediation contribution.

This strategy might be implemented with an experimental determination of relatively smaller number of sparticle masses:

$$m_{\chi_1},\, m_{\chi_2},\, m_{\tilde{g}},\, m_{\tilde{q}_L},\, m_{\tilde{e}_R}$$

Conclusion

- Even under the constraint of flavor and CP conservation, there can be many varieties of possible mediation mechanism of SUSY breaking: gravity(dilaton/modulus), anomaly, gauge, D-term and their mixtures

- In the top-down approaches based on string theory, it is quite plausible that some or all of gravity, gauge, anomaly and D-term mediations give comparable contribution to the MSSM soft masses.

- The sparticle masses at the weak scale might involve additional model-dependence arising from the RG running and threshold corrections below the messenger scale of SUSY breaking.

- Generic mixed mediation is general enough to incorporate much of these varieties of unknown high scale physics, while providing a manageable framework to interpret experimentally measured sparticle masses.
- Test of the mirage unification of sparticle masses might provide a crucial information on the mediation mechanism of SUSY breaking.