SUSY Breakdown and Mediation at the Time of the LHC

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IPMU Focus Week on String Cosmology, Oct. (2010)

Outline

1. Motivation and Notation: Supersymmetric extension of the SM
2. SUSY breakdown and it's mediation
   - Generic aspects of mediation mechanism
   - Flavor and CP conserving mediation schemes
     * String dilaton/moduli mediation
     * Gauge mediation
     * Anomaly mediation
     * D-term contribution
   - General mixed mediation suggested by string theory
   - Superparticle mass pattern in general mixed mediation
3. Testing the mediation mechanism at the LHC
   - Collider signatures of SUSY
   - Superparticle mass measurement at the LHC
4. Summary

Some parts of my talk will be based on

- General mixed mediation suggested by string theory:

KC, Falkowski, Nilles, Olechowski, hep-th/0503216
KC, Jeong, Okumura, hep-ph/0504037
KC, Nilles, hep-ph/0702146
KC, Jeong, Nakamura, Okumura, Yamaguchi, arXiv:0901.0052 [hep-ph]
KC, Jeong, Okumura, Shin, Yamaguchi, in preparation

- Superparticle mass measurement at the LHC:

Cho, KC, Kim, Park, arXiv:0709.0288 [hep-ph]; arXiv:0711.4526 [hep-ph]
Barr, Lester, arXiv:1004.2732 [hep-ph]
Brooijmans et. al., arXiv:1005.1229 [hep-ph]

Why SUSY at the TeV scale?

• SUSY at TeV regulates the quadratically divergent Higgs boson mass-square at the correct scale, and thereby solves the hierarchy problem.

• With SUSY at TeV, the strong, weak and electromagnetic gauge couplings are successfully unified at $M_{GUT} \approx 2 \times 10^{16}$ GeV.

• *R*-parity conserving SUSY at TeV can provide an attractive candidate for WIMP dark matter, e.g. the lightest neutralino in the MSSM.

• Compared to other extensions of the SM, it is straightforward to satisfy the constraints from precision electroweak measurements.

$\Longrightarrow$ Supersymmetric extension of the SM is perhaps the most promising candidate, at least among the known scenarios, for new physics beyond the standard model at the TeV scale.

If the idea of weak scale SUSY is correct, superparticles (= SUSY partners of the SM particles) will be copiously produced at the LHC, and we might be able to measure (some of) the superparticle masses.

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

Superparticle masses are described mostly by the soft SUSY breaking lagrangian which is determined by the mediation mechanism of SUSY breaking.

In this talk, I will first discuss generic features of mediation mechanism, and then touch on the following two questions:

- What kind of inputs can string theory provide about the mediation of SUSY breaking?
- Can we test the mediation mechanism at the LHC?

Minimal Supersymmetric Standard Model (MSSM) as an Effective Theory for TeV Scale Physics:

Field contents:

- $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge multiplets:

$$V_a = (A^a_\mu, \lambda_a) = (G_\mu, \tilde{g}),\ (W_\mu, \tilde{W}),\ (B_\mu, \tilde{B})$$

- 3 generations of quark and lepton multiplets:

$$Q_i = (\tilde{q}_i, q_i) = (3,2)_{\frac{1}{6}} \quad (i = 1,2,3)$$
$$U_i^c = (\tilde{u}_i^c, u_i^c) = (\bar{3},1)_{-\frac{2}{3}}, \quad D_i^c = (\tilde{d}_i^c, d_i^c) = (\bar{3},1)_{\frac{1}{3}},$$
$$L_i = (\tilde{\ell}_i, \ell_i) = (1,2)_{-\frac{1}{2}}, \quad E_i^c = (\tilde{e}_i^c, e_i^c) = (1,1)_1$$

- Higgs multiplets:

$$H_u = (h_u, \tilde{h}_u) = (1,2)_{\frac{1}{2}}, \quad H_d = (h_d, \tilde{h}_d) = (1,2)_{-\frac{1}{2}}$$

In the following, the MSSM chiral superfields for quarks, leptons and Higgs bosons will be often denoted collectively by $Q = (\tilde{Q}, \psi_Q)$.

- Superpotential for the Yukawa couplings and the Higgsino mass: (assume R-parity conservation)

$$
\begin{aligned}
W_{\text{MSSM}} &= \frac{1}{6} y_Q QQQ + \mu H_u H_d \\
&= y_{ij}^{(u)} H_u Q_i U_j^c + y_{ij}^{(d)} H_d Q_i D_j^c + y_{ij}^{(\ell)} H_d L_i E_j^c + \mu H_u H_d
\end{aligned}
$$

None of the superpartners is discovered yet, so SUSY has to be broken in order to make all gauginos and squarks/sleptons have a mass at least of the order of the weak scale.

If SUSY still solves the hierarchy problem,
(i) no (or highly suppressed) hard breaking which would regenerate quadratically divergent Higgs boson mass-square,
(ii) dimensionful soft breaking of the weak scale size:

$$m_{\text{soft}} \sim 10^2 - 10^3 \text{ GeV}$$

- Most general gauge-invariant and R-parity conserving soft SUSY breaking lagrangian of the MSSM fields:

$$
\begin{aligned}
\mathcal{L}_{\text{soft}} &= -\left(\frac{1}{2}M_a\lambda^a\lambda^a + \text{c.c.}\right) - m^2_{\tilde{Q}}\tilde{Q}^\dagger\tilde{Q} - \left(\frac{1}{6}A_Q y_Q\tilde{Q}\tilde{Q}\tilde{Q} + \text{c.c.}\right) \\
&\quad - \left(\frac{1}{6}C_Q y_Q\tilde{Q}\tilde{Q}\tilde{Q}^* + \text{c.c.}\right) - \left(\frac{1}{2}B\mu h_u h_d + \text{c.c.}\right) \\
&= -\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B} + \text{c.c.}\right) \\
&\quad - (m^2_{\tilde{q}})_{ij}\tilde{q}^*_i\tilde{q}_j - (m^2_{\tilde{u}})_{ij}\tilde{u}^{c*}_i\tilde{u}^c_j - (m^2_{\tilde{d}})_{ij}\tilde{d}^{c*}_i\tilde{d}^c_j \\
&\quad - (m^2_{\tilde{\ell}})_{ij}\tilde{\ell}^*_i\tilde{\ell}_j - (m^2_{\tilde{e}})_{ij}\tilde{e}^{c*}_i\tilde{e}^c_j - m^2_{h_u}h^*_u h_u - m^2_{h_d}h^*_d h_d \\
&\quad - \left(A^{(u)}_{ij}y^{(u)}_{ij}h_u\tilde{q}_i\tilde{u}^c_j + A^{(d)}_{ij}y^{(d)}_{ij}h_d\tilde{q}_i\tilde{d}^c_j + A^{(\ell)}_{ij}y^{(\ell)}_{ij}h_d\tilde{\ell}_i\tilde{e}^c_j + \text{c.c.}\right) \\
&\quad - \left(C^{(u)}_{ij}y^{(u)}_{ij}h^*_d\tilde{q}_i\tilde{u}^c_j + C^{(d)}_{ij}y^{(d)}_{ij}h^*_u\tilde{q}_i\tilde{d}^c_j + C^{(\ell)}_{ij}y^{(\ell)}_{ij}h^*_u\tilde{\ell}_i\tilde{e}^c_j + \text{c.c.}\right) \\
&\quad - \left(B\mu h_u h_d + \text{c.c.}\right).
\end{aligned}
$$

$$m_{\text{soft}} = \{M_a, m_{\tilde{Q}}, A_Q, C_Q, B\}$$

$\mathcal{L}_{\text{soft}}$ represents the low energy consequence of spontaneous SUSY breaking at higher energy scales.

In such framework, C_Q and hard SUSY breakings through dimensionless couplings are suppressed by more powers of $1/\Lambda_{\text{mess}}$, where the messenger scale Λ_{mess} corresponds to the highest energy scale up to which soft terms appear as local operators.

$\Longrightarrow$ C_Q and possible hard breakings can be ignored.

Still soft terms involve many free parameters: more than 100!

Fortunately, for m_{soft} of the weak scale size, soft terms are severely constrained by the absence any sizable FCNC and CP-violation beyond the SM predictions.

$\Longrightarrow$ Soft masses should be **flavor-blind** and **CP-conserving** in a good approximation.

$$(m^2_{\tilde{Q}})_{ij} \;=\; \hat{m}^2_{\tilde{Q}}\delta_{ij} + (\delta m^2_{\tilde{Q}})_{ij} \qquad (\tilde{Q} \;=\; \tilde{q}, \tilde{u}, \tilde{d}, \tilde{\ell}, \tilde{e})$$

$$(A_Q)_{ij} \times (y_Q)_{ij} = \hat{A}_Q \times (y_Q)_{ij} + (\delta A_Q)_{ij} \times (y_Q)_{ij} \qquad (Q = u, d, \ell)$$

$\Longrightarrow$ **Flavor-blind:** $\quad \dfrac{(\delta m^2_{\tilde{Q}})_{ij}}{\hat{m}^2_{\tilde{Q}}}, \quad \dfrac{(\delta A_Q)_{ij}}{\hat{A}_Q} \;\ll\; 1$

CP-conserving: $\quad \mathrm{Arg}\left(\dfrac{M_a}{M_b}\right), \quad \mathrm{Arg}\left(\dfrac{M_a}{A_Q}\right), \quad \mathrm{Arg}\left(\dfrac{M_a}{B}\right) \;\ll\; 1$

Some bounds from FCNC and CPV:

- K-$\bar{K}$ mass difference and ϵ_K :

$$\sqrt{\Big(\mathrm{Re}, \mathrm{Im}\Big)\left(\frac{(\delta m^2_{\tilde{q}})_{12}(\delta m^2_{\tilde{d}})_{12}}{m^2_{\tilde{q}} m^2_{\tilde{d}}}\right)} \;\leq\; \Big(8 \times 10^{-3},\, 5 \times 10^{-4}\Big)\left(\frac{M_{\tilde{g}}}{1\ \mathrm{TeV}}\right)$$

- $\mu \to e\gamma$:

$$\frac{(\delta A_\ell)_{12}}{m_{\tilde{\ell}}} \leq 2 \times 10^{-2} \left(\frac{m_{\tilde{\ell}}}{100 \text{ GeV}}\right) \left(\frac{M_{\tilde{W}}}{100 \text{ GeV}}\right)$$

- EDMs:

$$\text{Arg}\left(\frac{M_a}{M_b}, \frac{M_a}{A_Q}, \frac{M_a}{B}\right) \leq \left(10^{-2} - 10^{-3}\right) \times \left(\frac{m^2_{\tilde{q},\tilde{\ell}}}{100 \text{ GeV}}\right)^2$$

So any phenomenologically viable mediation of supersymmetry breaking should give (hopefully in a natural manner) flavor and CP conserving soft terms.

Generic features of SUSY breaking and its mediation

In (locally) supersymmetric 4D effective field theory, there can be three type of SUSY-breaking order parameters for spontaneous breakdown of $N = 1$ SUSY.

- Auxiliary F-component of chiral scalar superfield:

$$\Phi = \phi + \sqrt{2}\theta\psi + \theta\theta \mathbf{F}^{\Phi}$$

- Auxiliary D-component of real vector superfield:

$$V_A = -\theta\sigma^\mu\bar{\theta}A_\mu + i\left(\theta\theta\bar{\theta}\bar{\lambda}_A - \bar{\theta}\bar{\theta}\theta\lambda_A\right) + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}\mathbf{g_A^2 D_A}$$

- Auxiliary component of supergravity multiplet:
  (F-components of chiral density and/or compensator superfield)

$$\begin{aligned} 2\mathcal{E} &= \sqrt{-g}\left[\,1 + i\theta\sigma^\mu\bar{\psi}_\mu - \theta\theta\left(\mathbf{M}^* + \bar{\psi}_\mu\sigma^{\mu\nu}\bar{\psi}_\nu\right)\,\right] \\ C &= C_0 + \theta\theta\mathbf{F}^C \end{aligned}$$

In super-Weyl invariant compensator formulation of 4D SUGRA, a combination of M^* and F^C can be gauged away by the super-Weyl gauge transformation:

$$\mathcal{E} \rightarrow e^{-3\theta\theta F^\tau}\mathcal{E}, \quad C \rightarrow e^{\theta\theta F^\tau} C,$$

under which

$$M^* \rightarrow M^* - 3F^\tau, \quad \frac{F^C}{C_0} \rightarrow \frac{F^C}{C_0} + F^\tau.$$

It is convenient to choose the gauge with $M^* = 0$, which allows the SUSY breaking by supergravity multiplet to be described entirely by $C = C_0 + \theta\theta F^C$ within the global SUSY framework.

Then, SUSY breaking in generic 4D SUGRA can be studied with the following form of effective action defined on rigid $N = 1$ superspace:

$$\int d^4\theta\, CC^* \left[-3\exp\left(-\frac{1}{3}K(\Phi,\Phi^\dagger,V_A)\right)\right] + \left(\int d^2\theta\, C^3 W(\Phi) + \text{c.c.}\right)$$

$$\Big(K = \text{Kähler potential}, \quad W = \text{superpotenial}\Big)$$

One can further choose the Einstein frame gauge $C_0 = e^{K/6}$, and find the following on-shell expressions for the auxiliary components:

$$F^\Phi = K^{\Phi\Phi^*}F_{\bar{\Phi}} = -e^{K/2}K^{\Phi\Phi^*}(\partial_\Phi W + W\partial_\Phi K)^*$$

$$\left(K_{\Phi\Phi^*} = \partial_\Phi\partial_{\Phi^*}K,\ K^{\Phi\Phi^*} = (K_{\Phi\Phi^*})^{-1}\right)$$

$$\frac{F^C}{C_0} = m^*_{3/2} + \frac{1}{3}F^\Phi\partial_\Phi K \qquad \left(m_{3/2} = e^{K/2}W\right)$$

$$D_A = -\eta^\Phi\partial_\Phi K = -\frac{\eta^\Phi F_\Phi}{m_{3/2}} \qquad \left(\delta_{U(1)}\Phi = \delta\Lambda\eta^\Phi(\Phi)\right)$$

$$\left(M_{Pl} = \sqrt{1/8\pi G_N} = 2.4\times 10^{18}\ \text{GeV} = 1\right)$$

For a (meta-stable) vacuum with vanishing cosmological constant,

$$K_{\Phi\Phi^*}F^{\Phi}F^{\Phi*} + \frac{1}{2}g_A^2 D_A^2 - 3|m_{3/2}|^2 M_{Pl}^2 \;=\; 0$$

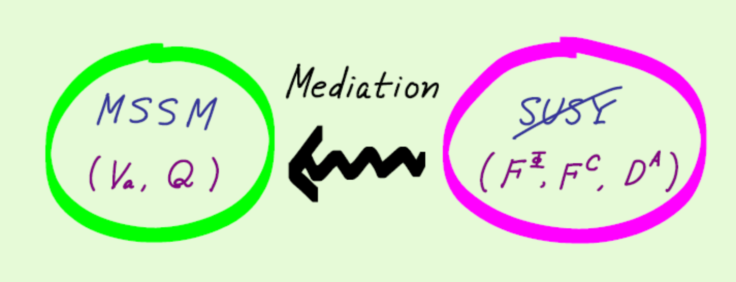
$$\left(\frac{1}{2}M_A^2 + \mathcal{O}(m_{3/2}^2)\right) D_A \;=\; -F^{\Phi}F^{\Phi*}\partial_{\Phi}(\eta^{\Phi'}K_{\Phi'\Phi^*}) + \mathcal{O}(D_A^2)$$

$$\Big(M_A = \text{U(1)-gauge boson mass}\Big)$$

$$\Longrightarrow \qquad F^{\Phi} \;\lesssim\; m_{3/2}M_{Pl}$$

$$D_A \;\sim\; \frac{q_{\Phi}F^{\Phi}F^{\Phi*}}{M_A^2} \quad \text{for} \quad M_A^2 \gg m_{3/2}^2$$

Once some fields $\{\Phi, C, V_A\}$ develop SUSY breaking vacuum values, the MSSM soft terms are determined by **a mediation mechanism** generating local effective interactions between $\{\Phi, C, V_A\}$ and the MSSM superfields $\{V_a, Q\}$ at a mass scale $\Lambda_{\rm mess}$ called the messenger scale:



$\Longrightarrow$ All low energy consequences of the mediation mechanism can be described by an (Wilsonian) effective lagrangian at $\Lambda_{\rm mess}$, which includes the local interactions between MSSM and SUSY-breaking fields.

Wilsonian effective lagrangian at Λ_{mess}:

$$\int d^4\theta\, CC^*\Big[Y_Q(Z,Z^*,V_A)Q^*Q + \Big(X_H(Z,Z^*,V_A)H_uH_d + \text{c.c}\Big)\Big]$$
$$+ \quad \int d^2\theta\left[\frac{1}{4}f_a(Z)W^{a\alpha}W^a_\alpha + C^3\left(\tilde{\mu}(\Phi)H_uH_d + \frac{1}{6}\lambda_Q(\Phi)QQQ\right)\right] + \text{c.c}$$

$$\begin{aligned}
\Phi &= \text{Generic SUSY-breaking chiral scalar superfields}\\
C &= \text{Chiral compensator for SUGRA multiplet,}\\
Z &= \{\Phi, C\}\\
V_A &= \text{SUSY-breaking U(1) vector superfield}\\
W^a_\alpha &= SU(3)_c \times SU(2)_W \times U(1)_Y \text{ gauge superfields}\\
Q &= \text{MSSM matter (quarks and leptons) and Higgs superfields}\\
H_{u,d} &= \text{MSSM Higgs doublets}
\end{aligned}$$

In some cases, soft terms are generated by quantum corrections, and then the renormalization scheme for this Wilsonian action should be specified for unambiguous calculation of the physical (1PI) soft masses.

- For C-independent regularization scheme, Kaplunovsky,Louis

$$f_a(Z) = \tilde{f}_a(\Phi) - \frac{3}{8\pi^2}\left(\mathrm{tr}(T_a^2(\mathrm{adj})) - \sum_Q \mathrm{tr}(T_a^2(Q))\right) \ln C$$

- 1PI gauge coupling superfield at the external momentum $p < \Lambda_{\mathrm{mess}}$:

Novikov,Shifman,Vainshtein,Zakharov; Kaplunovsky,Louis

$$\begin{aligned} \mathcal{F}_a(p^2) &= \mathrm{Re}(f_a(Z)) + \frac{b_a}{16\pi^2} \ln\left(\frac{\Lambda_{\mathrm{mess}}^2}{p^2}\right) \\ &- \frac{1}{8\pi^2} \sum_Q \mathrm{tr}(T_a^2(Q)) \ln(CC^* Y_Q) + \frac{1}{8\pi^2} \mathrm{tr}(T_a^2(\mathrm{adj})) \ln \mathcal{F}_a \end{aligned}$$

$$\left(\text{Lowest component of } \ \mathcal{F}_a|_{C_0 = e^{K/6}} \equiv \text{1PI gauge coupling constant at } p\right)$$

- We can also choose a renormalization convention for which

$$\text{Wilsonian } \ Y_Q \ \text{ at } \ \Lambda_{\mathrm{mess}} = \text{1PI } \ Y_Q \ \text{ at } \ p = \Lambda_{\mathrm{mess}}.$$

- 1PI soft masses at $p = \Lambda_{\rm mess}$:

$$* \; M_a(\Lambda_{\rm mess}) = F^Z \partial_Z \ln \mathcal{F}_a$$

$$* \; m^2_{\tilde{Q}}(\Lambda_{\rm mess}) = -F^Z F^{Z^*} \partial_Z \partial_{Z^*} \ln Y_Q - \frac{1}{2} g_A^2 D_A \frac{\partial}{\partial V_A} \ln Y_Q$$

$$* \; A_Q(\Lambda_{\rm mess}) = -F^Z \partial_Z \ln \left(\frac{\lambda_Q}{Y_Q Y_Q Y_Q} \right)$$

$$* \; \mu(\Lambda_{\rm mess}) = \frac{1}{CC^* Y_{H_u}^{1/2} Y_{H_d}^{1/2}} \left(C^3 \tilde{\mu} + F^{Z^*} \partial_{Z^*} (CC^* X_H) \right)$$

$$\begin{aligned} * \; B\mu(\Lambda_{\rm mess}) = & -\frac{1}{CC^* Y_{H_u}^{1/2} Y_{H_d}^{1/2}} \Big[F^Z \Big(\partial_Z (C^3 \tilde{\mu}) - C^3 \tilde{\mu} \partial_Z \ln (CC^* Y_{H_u} CC^* Y_{H_d}) \Big) \\ & + \; F^Z F^{Z^*} \Big(\partial_Z \partial_{Z^*} (CC^* X_H) - \partial_{Z^*} (CC^* X_H) \partial_I \ln (CC^* Y_{H_u} CC^* Y_{H_d}) \Big) \\ & + \; \frac{1}{2} g_A^2 D_A \frac{\partial}{\partial V_A} (CC^* X_H) \Big] \end{aligned}$$

Observable 1PI soft masses at $p \sim 1$ TeV can be obtained by the 1PI RG running of p from $\Lambda_{\rm mess}$ down to 1 TeV.

Flavor (and CP) conserving mediation schemes

Currently there are four more or less widely discussed mediation schemes, which naturally give flavor-conserving (and CP-conserving besides the Higgs B-parameter) soft masses:

- String dilaton and/or volume modulus mediation
- Gauge mediation
- Anomaly mediation
- D-term mediation

Each of these mediation schemes gives distinctive superparticle spectrum different from each other.

Pure anomaly mediation gives tachyonic slepton, and pure D-term mediation does not provide any gaugino mass.

So anomaly mediation or D-term mediation can not work by alone, but should come with other mediation, e.g. anomaly $+D$-term.

- **String Dilaton and/or Volume Modulus Mediation**

Kaplunovsky,Louis; Brignole,Ibanez,Munoz

Dilaton/modulus mediation is a particular type of gravity mediation, preserving flavor and CP at least at the leading order in small coupling expansion.

Gravity mediation through "generic Planck scale suppressed interactions" does not give flavor and CP conserving soft terms:

$$\int d^4\theta \left(c_{ij} \frac{\Phi\Phi^*}{M_{Pl}^2} + d_{ij} \frac{\Phi}{M_{Pl}} \right) Q_i^* Q_j + \int d^2\theta \frac{\Phi}{M_{Pl}} W^{a\alpha} W_\alpha^a$$

To examine the possibility of flavor and CP conserving gravity mediation, one needs a UV completion of the relevant Planck scale suppressed interactions.

String theory is the only known theory which might allow a systematic calculation of the Planck scale suppressed couplings between Φ and the MSSM fields.

Dilaton and/or volume moduli superfields $\{T\}$ in compactified string theory can provide a flavor and CP conserving gravity mediation.

Kaplunovsky,Louis; Brignole,Ibanez,Munoz

At leading order in the weak string coupling or large volume expansion, the couplings between T and the MSSM matter and gauge fields take the form:

$$\int d^4\theta CC^*(T+T^*)^{n_Q}Q^*Q + \int d^2\theta \frac{1}{4}TW^{a\alpha}W^a_\alpha$$

Typically the modular weights n_Q are flavor-blind rational numbers, and the couplings of T are constrained by the axionic shift symmetry: $T \to T + i\alpha$.

$\Longrightarrow$ Flavor and CP conserving soft masses at $\Lambda_{\rm mess} \sim M_{Pl}$:

$$M_a = \frac{F^T}{T+T^*}, \quad m^2_{\tilde{Q}} = n_Q \frac{|F^T|^2}{(T+T^*)^2},$$

$$A_Q = (n_{Q_i} + n_{Q_j} + n_{Q_k})\frac{F^T}{T+T^*}$$

However, generically there are other moduli which have flavor non-universal couplings to the MSSM matter fields, for instance the complex structure moduli which determine the hierarchical structure of Yukawa couplings.

Flux compactification provides a natural set-up for such flavor non-universal moduli decoupled from SUSY breaking:

KC,Nilles,Falkowski,Olechowski; Conlon,Quevedo,Suruliz

Typically "flavon moduli" ($= U$) and "SUSY-breaking moduli" ($= T$) have different topological origins, e.g. 3-cycle and 4-cycle, so U can get a heavy mass from flux, while T is untouched by flux.

$\Longrightarrow$ Split moduli masses:

$$m_U \gg m_T \;\rightarrow\; F^U \sim \frac{m_T}{m_U} F^T \ll F^T$$

- **(Minimal) Gauge Mediation**

Dine,Fischler,Srednicki; Dimopoulos,Raby; Dine,Nelson,Shirman

Gauge-charged messenger $\Psi + \Psi^c$ with a mass superfield Φ:

$$\int d^2\theta\, \Phi\Psi\Psi^c \qquad \left(\Phi = \Phi_0 + \theta^2 F^\Phi\right)$$

Effective action at $\Lambda_{\rm mess} = \Phi_0$ after $\Psi + \Psi^c$ are integrated out:

$$\int d^4\theta \left(1 - \frac{2}{(16\pi^2)^2} N_\Psi \sum_a g_a^4(\Phi_0) C_a(Q) \left(\ln \frac{\Phi^*\Phi}{|\Phi_0|^2}\right)^2\right) Q^*Q$$

$$+ \int d^2\theta \frac{1}{4}\left(\frac{1}{g_a^2(\Phi_0)} - \frac{1}{8\pi^2} N_\Psi \ln\frac{\Phi}{\Phi_0}\right) W^{a\alpha} W^a_\alpha$$

$$\Longrightarrow \quad M_a(\Phi_0) = -\frac{g_a^2(\Phi_0)}{16\pi^2} N_\Psi \frac{F^\Phi}{\Phi_0}$$

$$m^2_{\tilde Q}(\Phi_0) = \frac{2}{(16\pi^2)^2} N_\Psi \sum_a g_a^4(\Phi_0) C_a(Q) \left|\frac{F^\Phi}{\Phi_0}\right|^2$$

$$A_Q(\Phi_0) = 0$$

Example: Murayama,Nomura

$$\int d^4\theta C C^* \left(X X^* - \frac{(XX^*)^2}{4\Lambda_1^2} \right) + \int d^2\theta\, C^3 \left(\Lambda_2^2 X + (\lambda X + M)\Psi\Psi^c \right)$$

$$\Longrightarrow \quad \Phi \;=\; \lambda X + M \;=\; \Phi_0 + \theta^2 F^{\Phi}$$

$$\left(\Phi_0 = \frac{3\lambda\Lambda_1^2}{\Lambda_2^2} m_{3/2} + M, \quad F^{\Phi} = \lambda F^X = \lambda\Lambda_2^2 \right)$$

$$m_{\rm soft} \sim \frac{g^2}{16\pi^2}\frac{F^{\Phi}}{\Phi_0} \gg m_{3/2}$$

(Minimal) gauge mediation automatically gives flavor and CP conserving soft masses (except for B).

On the other hand, generically the scheme involves more mass scales other than M_{Pl} and the SUSY breaking scale, e.g. Λ_1 and M in this example, and a fully satisfactory model should explain the origin of those mass scales.

- **Anomaly Mediation** Randall,Sundrum; Giudice,Luty,Murayama,Rattazzi

C_0 in $C = C_0 + \theta^2 F^C$ is equivalent to the conformal factor of the spacetime metric.

$\Longrightarrow$ SUSY breaking by F^C appears through the breaking of scale invariance, including the breaking by **scale anomaly**.

$$
\begin{aligned}
M_a(\Lambda_{\rm mess}) &= F^C \partial_C \ln \mathcal{F}_a = \frac{F^C}{C_0} \frac{d \ln g_a^2(p)}{d \ln p^2}\bigg|_{p=\Lambda_{\rm mess}} = \frac{F^C}{C_0} \frac{\beta_a^2}{2 g_a^2}\bigg|_{p=\Lambda_{\rm mess}} \\
A_Q(\Lambda_{\rm mess}) &= -F^C \partial_C \ln \left(\frac{\lambda_Q}{Y_{Q_i} Y_{Q_j} Y_{Q_k}} \right) = -\frac{F^C}{C_0} \frac{d \ln (Y_{Q_i} Y_{Q_j} Y_{Q_k})}{d \ln p^2}\bigg|_{p=\Lambda_{\rm mess}} \\
&= -\frac{1}{2} \frac{F^C}{C_0} \left(\gamma_{Q_i} + \gamma_{Q_j} + \gamma_{Q_k} \right)\Big|_{p=\Lambda_{\rm mess}} \\
m_{\tilde{Q}}^2(\Lambda_{\rm mess}) &= -F^C F^{C*} \partial_C \partial_{C^*} \ln Y_Q = -\left| \frac{F^C}{C_0} \right|^2 \frac{d^2 \ln Y_Q(p)}{d (\ln p^2)^2}\bigg|_{p=\Lambda_{\rm mess}} \\
&= -\left| \frac{F^C}{C_0} \right|^2 \frac{\dot{\gamma}_Q}{4}\bigg|_{p=\Lambda_{\rm mess}}
\end{aligned}
$$

Anomaly mediation also automatically gives flavor and CP conserving soft terms (except for B).

In order for the anomaly mediation to be a dominant source of soft terms, other mediations should be sequestered enough:

$$F^{\Phi}\partial_{\Phi}\ln Y_Q,\; F^{\Phi}\partial_{\Phi}\ln f_a \;\lesssim\; \frac{1}{8\pi^2}\frac{F^C}{C_0} \;\sim\; \frac{m_{3/2}}{8\pi^2}$$

$$\left(\frac{F^C}{C_0} = m^*_{3/2} + \frac{1}{3}F^{\Phi}\partial_{\Phi}K\right)$$

Pure anomaly mediation (within the MSSM) gives tachyonic slepton masses, which should be avoided by introducing other contribution to slepton masses.

- **D-term contribution:**

$$\int d^4\theta\, Q^* e^{-q_Q V_A} Q \quad \Longrightarrow \quad m_{\tilde{Q}}^2 = \frac{1}{2} q_Q g_A^2 D_A$$

Example: Models with anomalous $U(1)_A$

Binetruy,Dudas; Dvali,Pomarol; Arkani−Hamed,Dine,Martin

$$U(1)_A : \; V_A \to V_A - (\Lambda + \Lambda^*), \quad T \to T - \delta_{GS}\Lambda, \quad X \to e^{-\Lambda} X$$

$\left(\delta_{GS} = \mathcal{O}(1/8\pi^2) \text{ for the Green-Schwarz anomaly cancelation}\right)$

$$K \;=\; K_0(T + T^* - \delta_{GS} V_A) + X^* e^{-V_A} X,$$

$$\Longrightarrow \quad g_A^2 D_A \;\sim\; \frac{(\partial_T \partial_{T^*} K_0)^2}{\partial_T K_0 (\partial_T K_0 - \delta_{GS} \partial_T \partial_{T^*} K_0)} \left|F^T\right|^2$$

Depending upon the form of K_0 and also how to stabilize the D-flat direction $\left(\propto T - \delta_{GS} \ln X \right)$, D_A can be a dominant source of soft scalar mass.

General Mixed Mediation in String Theory

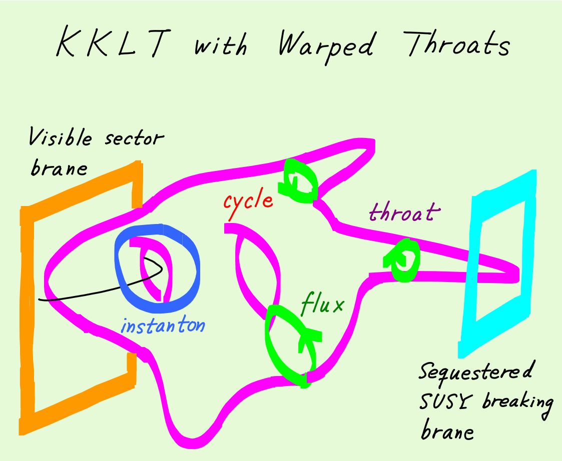
In string-based top-down approach for SUSY breaking, it is quite natural that some or all of "the dilaton/moduli mediation, anomaly mediation, gauge mediation, and D-term mediation" come together, and they give comparable contributions to superparticle masses:

Examples:

- KKLT moduli stabilization
- Combination of KKLT and anomalous $U(1)$

Example 1: KKLT moduli stabilization

- flux stabilization of all moduli except for the Kähler moduli $\{T\}$
- non-perturbative stabilization of $\{T\}$ by instantons
- sequestered SUSY-breaking sector $\{Z\}$ at the tip of throat
  ($\{Z\}$ can be replaced by anti-brane.)



Non-perturbative moduli stabilization + Sequestered SUSY breaking

$\Longrightarrow$ Mixed modulus-anomaly mediation $\left(=\text{mirage mediation}\right)$

KC,Nilles,Falkowski,Olechowski

$$\int d^4\theta CC^* \left[-3e^{-K(T+T^*)/3} + \Omega_{\rm seq}(Z,Z^*)\right]$$
$$+ \quad \left(\int d^2\theta\, C^3\left(W_0 + Ae^{-aT} + W_{\rm seq}(Z)\right) + \text{c.c}\right)$$

(W_0 is required to be small to achieve the weak scale SUSY.

On othe other hand, $\Omega_{\rm seq}$, $W_{\rm seq}$ and K can take a generic form.)

$$m_T \sim \partial_T^2 W = a^2 Ae^{-aT} \sim aW_0 \sim m_{3/2}\ln(M_{Pl}/m_{3/2})$$
$$F^T \sim \frac{m_{3/2}^2}{m_T} \sim \frac{m_{3/2}}{\ln(M_{Pl}/m_{3/2})} \sim \frac{1}{4\pi^2}\frac{F^C}{C_0}$$

$\Longrightarrow$ moduli mediation $\sim$ anomaly mediation

Example 2: Simple generalization of KKLT with anomalous $U(1)$

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

- 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 $U(1)_A$:

$$V_A \to V_A - (\Lambda + \Lambda^*), \quad T \to T - \delta_{GS}\Lambda, \quad X \to e^{-\Lambda}X$$

- Gauge-charged exotic matter $\Psi + \Psi^c$ with a singlet Φ whose VEV determine the mass of $\Psi + \Psi^c$.

- Sequestered SUSY-breaking sector $\{Z\}$.

4D Effective Action:

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

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

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

$$W = W_0 + A e^{-aT} X^n + \lambda \Phi \Psi^c \Psi + \frac{\kappa}{M_{\rm Planck}} \Phi^4$$

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

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

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

$$\Longrightarrow \quad \frac{F^T}{T+T^*} \sim \frac{m_{3/2}^2}{m_T} \sim \frac{m_{3/2}}{\ln(M_{\text{Planck}}/m_{3/2})} \sim \frac{1}{4\pi^2}\frac{F^C}{C_0}$$

- D-flat condition:

$$\sqrt{D_A} \sim \frac{F^T}{T+T^*} \sim \frac{F^X}{X}$$

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

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

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

$$\sim \frac{1}{8\pi^2}\frac{F^C}{C_0}\,(\text{anomaly}) \sim \frac{1}{8\pi^2}\frac{F^\Phi}{\Phi}\,(\text{gauge})$$

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

$$\mathrm{Arg}\left(\frac{F^T}{T+T^*}\right) = \mathrm{Arg}\left(\frac{F^\Phi}{\Phi}\right) = \mathrm{Arg}\left(\frac{F^X}{X}\right) = \mathrm{Arg}\left(\frac{F^C}{C_0}\right)$$

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

$$M_{\text{gaugino}},\, A_{\text{sfermion}} \sim \left[\frac{F^T}{T+T^*}\,(\text{dilaton/modulus}) + \frac{1}{8\pi^2}\frac{F^C}{C_0}\,(\text{anomaly}) + \frac{1}{8\pi^2}\frac{F^\Phi}{\Phi}\,(\text{gauge})\right]$$

$$m_{\text{sfermion}} \sim \left[\frac{F^T}{T+T^*}\,(\text{dilaton/modulus}) + \sqrt{D_A}\,(\text{D-term}) + \frac{1}{8\pi^2}\frac{F^C}{C_0}\,(\text{anomaly}) + \frac{1}{8\pi^2}\frac{F^\Phi}{\Phi}\,(\text{gauge})\right]$$

We are not using any unusual feature of string theory to get a mixed mediation !

- Warped throat for sequestered SUSY breaking is a generic feature of flux compactification.
- Nonperturbative stabilization of dilaton or volume modulus is one of the very few available options.
- Anomalous $U(1)$ gauge symmetry appears very often in potentially realistic string compactification.
- Exotic charged matter is hard to avoid in potentially realistic string compactification.

$\Longrightarrow$ **Mixed mediations emerge naturally in string-based top-down approach for SUSY breaking.**

Superparticle Masses in General Mixed Mediation

The quantities that LHC can measure are the superparticle masses at the weak scale.

Those observable superparticle masses at low energy scale depend not only on the mediation mechanism defined at the high messenger scale $\Lambda_{\rm mess}$, but also on the subsequent renormalization group running and possible threshold corrections at scales below $\Lambda_{\rm mess}$.

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

Assumptions:

- 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 $f_a = k_a T + \ldots$ $(a = 1, 2, 3)$ are universal:

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

  (ii) Exotic gauge-charged matter fields $\Psi + \Psi^c$ form a full $SU(5)$ multiplet.

  (iii) The modular weights and the $U(1)_A$ charges of squarks and sleptons are all $SU(5)$-invariant.

- No hidden dynamics causing a sizable renormalization of soft terms.

Under these assumptions,

- 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.

Let's focus on the gaugino and light generation sfermion masses.

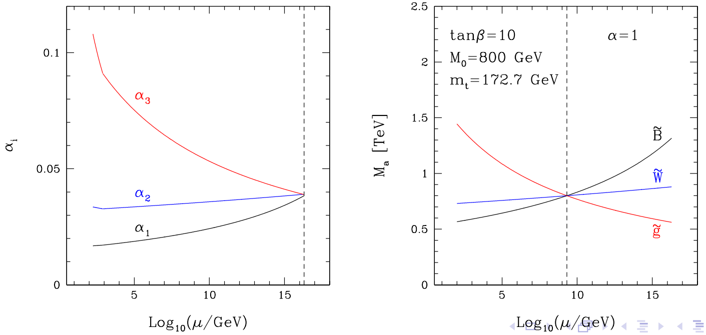
Gaugino Masses KC, Nilles

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

$$\frac{M_a(\mu)}{g_a^2(\mu)} = \left(\frac{1}{2}F^T - \frac{N_\Psi}{16\pi^2}\frac{F^X}{X}\right) + \frac{b_a}{16\pi^2}\frac{F^C}{C_0}$$

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

$$\left(\frac{M_{\rm mirage}}{M_{GUT}} = \exp\left[-\frac{\frac{F^C}{C_0}}{F^T - \frac{N_\Psi}{8\pi^2}\frac{F^X}{X}}\right]\right)$$



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:

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

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

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

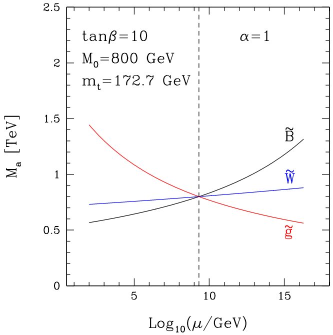
$=$ Contribution from gauge mediation

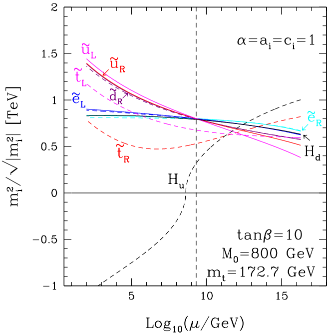
$$R = \frac{g^2_{GUT}}{g_0^2}\left(\frac{F^T}{F^T - \frac{N_\Psi}{8\pi^2}\frac{F^X}{X}}\right), \quad \frac{1}{g_0^2} = \frac{1}{g^2_{GUT}} + \frac{N_\Psi}{8\pi^2}\ln\left(\frac{M_{GUT}}{M_\Psi}\right) \approx \frac{1}{2}$$

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

$\Longrightarrow$ 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:

$$
\begin{aligned}
m^2_{\tilde{q}_L} &= m^2_{\rm eff}(10) + M^2_{\rm eff}(5.0 - 3.48\alpha + 0.48\alpha^2) + \Delta m^2_{\tilde{q}_L} \\
m^2_{\tilde{u}_R} &= m^2_{\rm eff}(10) + M^2_{\rm eff}(4.6 - 3.29\alpha + 0.49\alpha^2) + \Delta m^2_{\tilde{u}_R} \\
m^2_{\tilde{e}_R} &= m^2_{\rm eff}(10) + M^2_{\rm eff}(0.15 - 0.045\alpha - 0.015\alpha^2) + \Delta m^2_{\tilde{e}_R} \\
m^2_{\tilde{d}_R} &= m^2_{\rm eff}(\bar{5}) + M^2_{\rm eff}(4.5 - 3.27\alpha + 0.49\alpha^2) + \Delta m^2_{\tilde{d}_R} \\
m^2_{\tilde{\ell}_L} &= m^2_{\rm eff}(\bar{5}) + M^2_{\rm eff}(0.5 - 0.22\alpha - 0.014\alpha^2) + \Delta m^2_{\tilde{\ell}_L}
\end{aligned}
$$

$$\Big(m_{\rm eff}(10) \; = \; m_{\rm eff}(\bar{5}) \;\; \text{for} \;\; SO(10) \Big)$$

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

- Measure the gaugino masses and determine the gaugino mass unification scale:

  $$M_a(M_{\rm mirage}) = M_{\rm eff}$$

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

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

- Measure squark and slepton masses and examine the deviation from the (mirage) unification:

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

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

Testing the Mediation Mechanism at the LHC

To study SUSY phenomenology, it is important to identify the lightest supersymmetric particle.

Lightest supersymmetric particle (LSP):

- MSSM neutralino:

  Most interesting possibility as it might be detected by dark matter search experiment

- Gravitino:

  In principle, gravitino can be the LSP in any mediation scheme except for the case that anomaly mediation gives a sizable contribution to soft masses.

  In particular, gauge mediation can give a very light gravitino.

- Axino (= fermion partner of the axion solving the strong CP problem):

  In many cases, axino can mimic well a light gravitino.

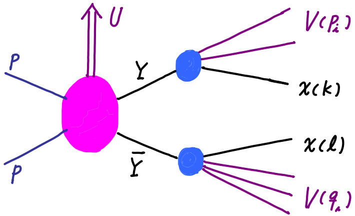
SUSY signatures at the LHC

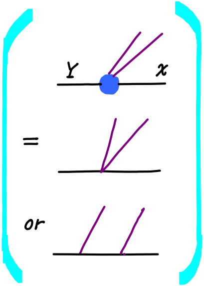
A. Missing Energy Events:

Pair production of (colored) superparticles $(Y + \bar{Y})$ and subsequent prompt decays into visible SM particles (V) and invisible LSP (χ) $\big(\chi =$ neutralino (or gravitino with $m_{3/2} \lesssim 10$ eV)$\big)$

$$pp \;\to\; U + Y + \bar{Y} \;\;\to\;\; U + \sum V(p_i) + \chi(k) + \sum V(q_j) + \chi(l)$$

$\Longrightarrow$ Multi-jets, possibly with isolated leptons and/or isolated photons, with large missing transverse momentum.





Other type of SUSY signatures:

B. Displaced vertex due to a relatively long-lived "next lightest supersymmetric particle" $\big($NLSP: neutralino χ or slepton $\tilde{\ell}$ $\big)$ decaying into the LSP gravitino (or axino) still inside the detector:

$$\chi \to \psi_\mu (\text{or } \tilde{a}) + \gamma,\ \psi_\mu + Z,\ \psi_\mu + h \quad \text{or} \quad \tilde{\ell} \to \psi_\mu + \ell.$$

C. Track of a charged NLSP $\big($slepton$\big)$ which is stable inside the detector.

In the following, I will focus on the missing energy events producing invisible LSPs inside the detector, i.e. the events of type **A** and **B**, and discuss the possibility of superparticle mass measurement with those missing energy events.

$\Big($Mass determination for the events of type **C** is rather straightforward because they do not involve any missing particle.$\Big)$

Superparticle mass measurement at the LHC is quite challenging.

- Missing information on the initial state:
  Initial parton momenta in the beam-direction are unknown.
- Missing information on the final state:
  Each event involves two invisible LSPs.

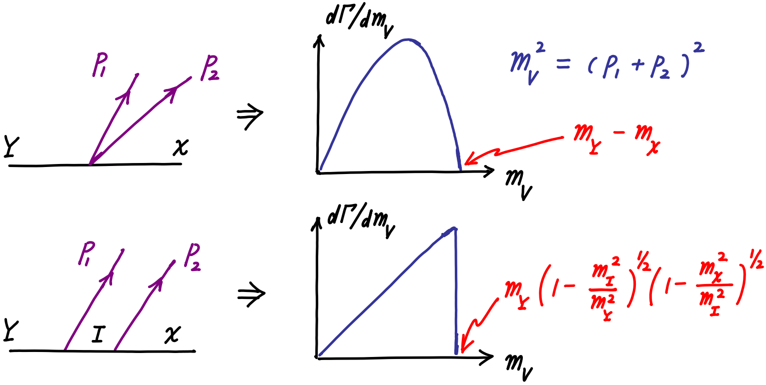
There are few model-independent kinematic methods to overcome these difficulties:

- Endpoint Method
- M_{T2}-Kink Method

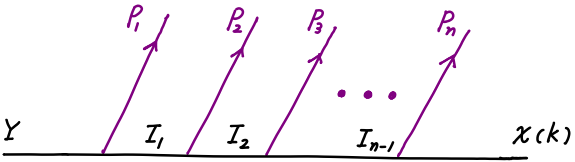
Endpoint Method

Hinchliffe,Paige,Shapiro,Soderqvist,Yao; Bachacou,Hinchliffe,Paige

Endpoint value of the invariant mass distribution of the visible (SM) decay products depend on superparticle masses.



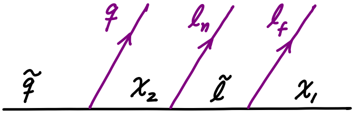
n-step cascade decay:



Number of measurable invariant mass distributions: $2^n - (n+1)$
Number of unknown sparticle masses: $n+1$.

$\Longrightarrow$ For $n \geq 3$, there can be enough number of independent endpoint values to determine all superparticle masses involved in the process.

3-step squark cascade decay ($m_{\tilde{q}} > m_{\chi 2} > m_{\tilde{\ell}_R} > m_{\chi 1}$)

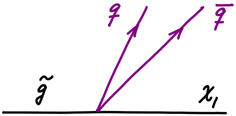


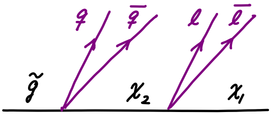
$$
\begin{aligned}
m_{\ell\ell}^{\max} &= m_{\chi 2}\sqrt{(1 - m_{\tilde{\ell}}^2/m_{\chi 2}^2)(1 - m_{\chi 1}^2/m_{\tilde{\ell}}^2)} \\
m_{q\ell\ell}^{\max} &= m_{\tilde{q}}\sqrt{(1 - m_{\chi 2}^2/m_{\tilde{q}}^2)(1 - m_{\chi 1}^2/m_{\chi 2}^2)} \\
m_{q\ell(\mathrm{high})}^{\max} &= m_{\tilde{q}}\sqrt{(1 - m_{\tilde{\chi}_2}^2/m_{\tilde{q}}^2)(1 - m_{\chi 1}^2/m_{\tilde{\ell}}^2)} \\
m_{q\ell(\mathrm{low})}^{\max} &= m_{\tilde{q}}\sqrt{(1 - m_{\chi 2}^2/m_{\tilde{q}}^2)(1 - m_{\tilde{\ell}}^2/m_{\chi 2}^2)} \\
\Big(m_{q\ell(\mathrm{high})} &\equiv \max(m_{q\ell_n}, m_{q\ell_f}), \quad m_{q\ell(\mathrm{low})} \equiv \min(m_{q\ell_n}, m_{q\ell_f}) \Big)
\end{aligned}
$$

In the absence of long decay chain $(n \geq 3)$, endpoint method can not determine the overall mass scale, although it might provide constraints to determine the mass differences.

However, there are many cases (including many of the popular mediation scenarios) that such a long decay chain is not available.

Example: SUSY with $m_{\tilde{Q}}$ significantly heavier than M_a :





• Endpoint method determines only the gaugino mass differences:

$$M_{\tilde{g}} - M_{\chi_1}, \quad M_{\chi_2} - M_{\chi_1}$$

• Recently a new method $(M_{T2}$-kink method$)$ has been proposed, which can determine the overall mass scale even when a long decay chain is not available.

$\mathbf{M_{T2}}$-Kink Method Cho,KC,Kim,Park; Barr,Gripaios,Lester

M_{T2} is a generalization of the transverse mass to an event producing two invisible particles with the same mass.

Transverse mass of $Y \to V(p) + \chi(k)$**:**

$$M_T^2 = m_V^2 + m_\chi^2 + 2\sqrt{m_V^2 + |\mathbf{p}_T|^2}\sqrt{m_\chi^2 + |\mathbf{k}_T|^2} - 2\mathbf{p}_T \cdot \mathbf{k}_T$$

$$M_T(m_\chi = m_\chi^{\text{true}}) \leq m_Y^{\text{true}}$$

$\mathbf{M_{T2}}$ **of** $Y + \bar{Y} \to V_1(p) + \chi(k) + V_2(q) + \chi(l)$ Lester, Summers

$$M_{T2}(\text{event}; m_\chi) \quad \Big(\{\text{event}\} = \{m_{V_1}, \mathbf{p}_T, m_{V_2}, \mathbf{q}_T, \not{p}_T\}\Big)$$

$$= \min_{\mathbf{k}_T + \mathbf{l}_T = \not{p}_T} \Big[\max\Big(M_T(\mathbf{p}_T, m_{V_1}, \mathbf{k}_T, m_\chi), M_T(\mathbf{q}_T, m_{V_2}, \mathbf{l}_T, m_\chi) \Big) \Big]$$

- For each event, M_{T2} is an increasing function of m_χ with slope depending on m_{V_1,V_2} and $\mathbf{p}_T(Y + \bar{Y})$.
- For all events, $M_{T2}(m_\chi = m_\chi^{\text{true}}) \leq m_Y^{\text{true}}$.

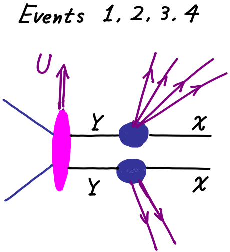
$\mathbf{M_{T2}}$-Kink Cho,KC,Kim,Park

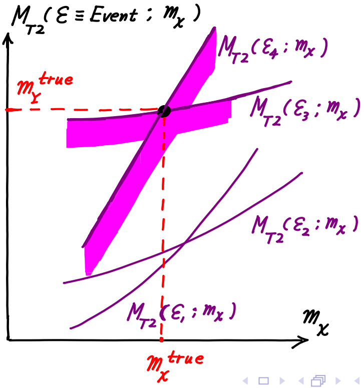
The endpoint value of M_{T2} as a function of the trial LSP mass m_χ,

$$M_{T2}^{\max}(m_\chi) = \max_{\{\text{all events}\}} \Big[M_{T2}(\text{event}; m_\chi) \Big],$$

has a kink-structure at $m_\chi = m_\chi^{\text{true}}$ with $M_{T2}^{\max}(m_\chi = m_\chi^{\text{true}}) = m_Y^{\text{true}}$.

($m_\chi = m_\chi^{\text{true}}$ is a point of enhanced symmetry under the variation of m_V and the transverse boost of $Y + \bar{Y}$.)





In reality, these methods of mass measurements suffer from

- SM and SUSY backgrounds
- Combinatoric ambiguities to identify the location of each particle in the event
- Uncertainties in the detector resolution, e.t.c.

We definitely need further studies to see if these methods can work with real data.

Summary

- Weak scale SUSY is perhaps the leading candidate for new physics beyond the SM at the TeV scale.
- If the idea of weak scale SUSY is correct, LHC will discover (some of) the predicted superparticles whose mass spectrum is determined by the mediation mechanism of SUSY breaking.
- The mediation mechanism of SUSY breaking might involve many varieties of high scale physics, even the physics at grand unification scale and/or string compactification scale.
- In string-based top-down approach for SUSY breaking, it is quite natural that some or all of the “dilaton/moduli, gauge, anomaly and D-term mediations” come together, and give comparable contributions to superparticle masses.

- Such general mixed mediation can accommodate most of the known popular mediation scenarios as a special limit, and might be useful for the interpretation of experimentally measured superparticle masses.
- There are few methods proposed so far to determine the superparticle masses with missing energy events at the LHC, however we still need further studies to see if those methods can work with real data.

Let's hope that SUSY is discovered at the LHC, and we can explore new fundamental physics with real data, not with theoretical speculation alone.