

Moduli stabilization,
Pattern of sparticle spectra &
the Gluino transverse mass

Kiwoon Choi @ BSM Workshop

Based on

K.C. & H.P. Nilles, JHEP 04 (2007) 006 [hep-ph/0702146]

W. Cho, K.C., Y. Kim & C. Park, arXiv:0709.0288 [hep-ph]

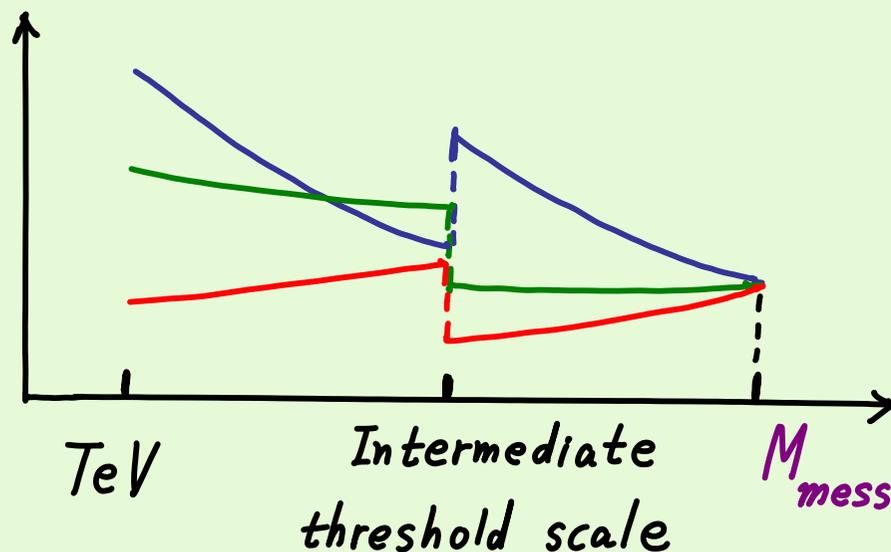
◆ Stabilization of gauge coupling modulus
and the gaugino (sfermion) mass pattern

◆ Gluino transverse mass (M_{T2}) which can
determine $m_{\tilde{g}}$ & m_{χ_1} separately and
provide information on $m_{\tilde{g}}$

LHC might discover weak scale SUSY, and provide information on superparticle spectra at TeV.

Superparticle masses at TeV are determined by

- soft parameters induced at high messenger scale M_{mess}
- RG running below M_{mess}
- Intermediate scale threshold effects



Generically, RG running & intermediate thresholds depend on the details of physics at scales between M_{mess} & TeV, e.g. extra matter or gauge interaction.

Unlike *sfermion masses*, RG running & possible intermediate thresholds for *gaugino masses* are highly constrained by gauge coupling unification.

* At one-loop, M_a / g_a^2 do not run, while the RG runnings of g_a^2 are constrained by the measured values at TeV and the unification at $M_{\text{GUT}} \approx 2 \times 10^{16}$ GeV.

* Intermediate threshold corrections to M_a/g_a^2 have a direct connection to the RG evolution of g_a^2 , thus are constrained also by the gauge coupling unification.

• Sensitivity to unknown physics at $\text{TeV} < E < M_{\text{mess}}$

gauginos $<$ 1st & 2nd generations $<$ 3rd generation & Higgs

\Rightarrow Gaugino mass pattern is a good 1st step to reveal the nature of the transmission of SUSY breaking at high messenger scale.

KC & Nilles

◆ Gaugino masses in generic SUSY breaking scenario

Assumptions {

- i) high scale gauge coupling unification
- ii) $\frac{1}{g_{GUT}^2} = \langle T \rangle$ ↙ gauge coupling modulus

↙ small thresholds $\langle \Delta f_a \rangle \sim 1$

$$\Rightarrow f_a = T + \frac{1}{8\pi^2} \Delta f_a \quad (a = SU(3), SU(2), U(1))$$

$$\left(\frac{M_a}{g_a^2} \right)_{TeV} = \frac{1}{2} F^T + \left(\text{loop thresholds at scales from } \underline{M_{Pl} = 1 \text{ or } M_{GUT} \text{ to TeV}} \right)$$

If $F^T \sim m_{3/2}$, gravity-mediated loop thresholds of $\mathcal{O}\left(\frac{m_{3/2}}{8\pi^2}\right)$ can be ignored, and then the conventional gravity mediation

with universal M_a/g_a^2 can be realized while giving a

vanishing C.C : $V \approx K_{T\bar{T}} |F^T|^2 - 3 m_{3/2}^2 \approx 0$.

However most of known moduli stabilization schemes give rise to $|F^T| \ll m_{3/2}$.

* Racetrack in heterotic string Krasnikov; Casas, Lalak, Munoz, Ross

$$f_a = S, \quad W = A_1 e^{-a_1 S} + A_2 e^{-a_2 S}$$

$$\Rightarrow F^S = 0$$

* KKLT Kachru, Kallosh, Linde, Trivedi

$$f_a = T, \quad W = W_{\text{flux}} + A e^{-a T},$$

Sequestered SUSY breaking yielding $\int d^4\theta e^{4\tilde{A}} \theta^2 \bar{\theta}^2$
(Warped sequestering: $g_{\mu\nu} = e^{2\tilde{A}} \eta_{\mu\nu}$)

KC, Falkowski, Nilles, Olechowski

$$\Rightarrow F^T \sim \frac{m_{3/2}}{\ln(M_{\text{pl}}/m_{3/2})} \sim \frac{m_{3/2}}{4\pi^2}$$

* Race track in G_2 -compactification of M-theory

Acharya, Bobkov, Kane, Kumar, Sho

• $f_a = \sum_i k_i T_i$
 \uparrow 3-cycle moduli of G_2 -compactification

• $K = - \sum_i n_i \ln(T_i + T_i^*) + \sum_\phi \phi^* \phi$
 \uparrow composite meson

$$W = \underbrace{A_1 \phi^2 e^{-a_1 (\sum_i \tilde{k}_i T_i)}}_{\text{ADS superpotential}} + A_2 e^{-a_2 (\sum_i \tilde{k}_i T_i)}$$

$$\Rightarrow F^{T_i} \sim \frac{m_{3/2}}{\ln(M_{\text{pl}}/m_{3/2})}, \quad F^\phi \sim m_{3/2}$$

If $|F^T| \ll m_{3/2}$, we need other source of SUSY breaking

$F^X \sim m_{3/2}$ (uplifting sector) to get vanishing C.C.,

and then loop threshold effects associated with F^X (even gravity-mediated ones) can be important.

• Gaugino masses with loop thresholds from F^X

Kaplunovsky, Louis; Randall, Sundrum;

Giudice, Luty, Murayama, Rattazzi; Bagger, Moroi, Poppitz

$$\left(\frac{M_a}{g_a^2}\right)_{\text{TeV}} = \frac{1}{2} F^T + \frac{b_a(\text{TeV})}{16\pi^2} F^{\text{SUGRA}}$$

$\uparrow m_{3/2} + \frac{1}{3} F^T \partial_x K$

$$- \frac{1}{8\pi^2} F^X \left[\sum_{\Xi} \frac{C_a(\Xi)}{X} + \sum_Q C_a(Q) \partial_x \ln(Y_Q) + \sum_R C_a(R) \partial_x \ln\left(\frac{Y_R}{|M_R|}\right) \right]$$

\rightarrow from $\frac{1}{M_{\text{pl}}}$ - suppressed couplings between X & $\{Q, R\}$

$$\int d^4\theta \left[-3e^{-K_0/3} + Y_Q Q^\dagger Q + Y_\Xi \Xi^\dagger \Xi + Y_R R^\dagger R \right] + \int d^2\theta (X \Xi \Xi + M_R R R)$$

$Q \equiv$ light chiral matters at TeV

$\Xi \equiv$ intermediate scale messengers which have renormalizable couplings with X : $\int d^2\theta X \Xi \Xi$

$R \equiv$ superheavy **regulator** fields ($M_R \sim$ cut-off scale)

$K_0(T, T^\dagger, X, X^\dagger) \equiv$ Kähler potential of X & T

$Y_I \equiv e^{-K_0/3} Z_I$ ($Z_I(T, T^\dagger, X, X^\dagger) \equiv$ Kähler metric of Ξ_I)

$$\left(\frac{M_a}{g_a^2}\right)_{\text{TeV}} = \frac{1}{2} F^T + \frac{b_a(\text{TeV})}{16\pi^2} F^{\text{SUGRA}} - \frac{1}{8\pi^2} F^X \left[\sum_{\Phi} \frac{C_a(\Phi)}{X} + \sum_Q C_a(Q) \partial_X \ln(Y_Q) + \sum_R C_a(R) \partial_X \ln\left(\frac{Y_R}{|M_R|}\right) \right]$$

The regularization scheme dependent threshold correction

$$\Delta_{\text{UV}}\left(\frac{M_a}{g_a^2}\right) = -\frac{1}{8\pi^2} F^X \sum_R C_a(R) \partial_X \ln\left(\frac{e^{-K_0/3} Z_R}{|M_R|}\right)$$

can be interpreted as the UV thresholds of $\mathcal{O}\left(\frac{m_{3/2}}{8\pi^2}\right)$ due to the Planck scale suppressed couplings between X and heavy stringy, KK & GUT modes for Λ_{cutoff} chosen to be just below M_{GUT} , and generically non-universal.

Scenario A

Such UV sensitive thresholds are negligible if

$$F^T \sim m_{3/2} \quad (\text{conventional gravity mediation})$$

or there exist intermediate scale gauge thresholds :

$$\frac{1}{8\pi^2} F^X \sum_{\mathbb{I}} \frac{C_a(\mathbb{I})}{X} \gg m_{3/2} \quad (\text{gauge mediation}).$$

\Rightarrow mSUGRA pattern

$$\left(\frac{M_a}{g_a^2} \right) = \text{Universal} \quad \frac{1}{2} F^T \quad \text{or} \quad \frac{1}{8\pi^2} F^X \sum_{\mathbb{I}} \frac{C_a(\mathbb{I})}{X}$$

$$\Rightarrow M_{\tilde{B}} : M_{\tilde{W}} : M_{\tilde{g}} \simeq g_1^2 : g_2^2 : g_3^2 \simeq 1 : 2 : 6 \quad \text{at TeV}$$

$$\left(\frac{M_a}{g_a^2}\right)_{\text{TeV}} = \frac{1}{2} F^T + \frac{b_a(\text{TeV})}{16\pi^2} F^{\text{SUGRA}} - \frac{1}{8\pi^2} F^X \left[\sum_{\Xi} \frac{C_a(\Xi)}{X} + \sum_Q C_a(Q) \partial_X \ln(Y_Q) + \sum_R C_a(R) \partial_X \ln\left(\frac{Y_R}{|M_R|}\right) \right]$$

However if $|F^T| \ll m_{3/2}$ as non-perturbative (or flux) stabilization of T suggests & there is no gauge mediation at scales below $\Lambda_{\text{cutoff}} \sim M_{\text{GUT}}$, one needs to know

$$\Delta_{\text{UV}}\left(\frac{M_a}{g_a^2}\right) = \mathcal{O}\left(\frac{m_{3/2}}{8\pi^2}\right) \text{ to make a reliable prediction for}$$

gaugino mass pattern, which requires information on

the UV completion of 4D effective SUGRA at Λ_{cutoff} .

Scenario B

X is sequestered from the visible gauge sector :

$$\int d^4\theta \left[\Omega_1(\Phi_I, \Phi_I^\dagger) + \Omega_0(X, X^\dagger) \right] + \int d^3\theta \left[W_1(\Phi_I) + W_0(X) \right]$$

\uparrow $\{Q, R\}$

$$\Rightarrow \partial_X Y_Q = \partial_X Y_R = \partial_X M_R = 0 \quad \left(\rightarrow \Delta_{uv} \left(\frac{M_a}{g_a^2} \right) = 0 \right)$$

$$\Rightarrow \underline{\left(\frac{M_a}{g_a^2} \right)} = \frac{1}{2} F^T + \frac{1}{16\pi^2} b_a m_{3/2}$$

* Non-perturbative stabilization of T

$$F^T \sim \frac{m_{3/2}}{\ln(M_{\text{pl}}/m_{3/2})} \sim \frac{m_{3/2}}{8\pi^2} \Rightarrow \underline{\text{Mirage pattern}}$$

* Flux stabilization of T

$$F^T \ll \frac{m_{3/2}}{8\pi^2} \Rightarrow \underline{\text{Anomaly pattern}}$$

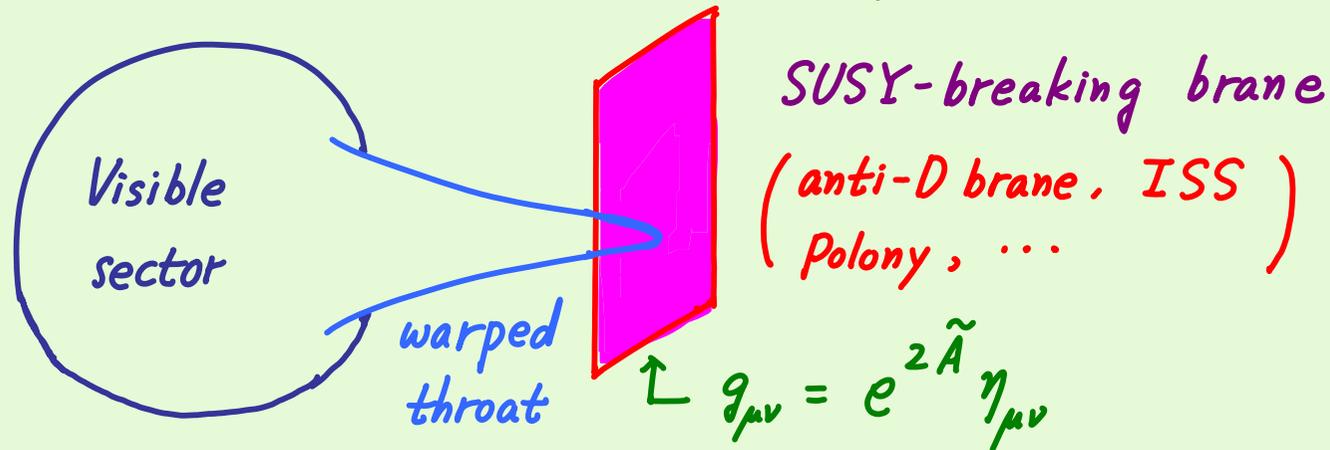
Warped sequestering

5D context : Randall, Sundrum ; Luty, Sundrum ;

Gregoire, Rattazzi, Scrucra, Strumia, Trincherini

(cf : Anisimov, Dine, Graesser, Thomas)

KKLT context : KC, Jeong ; Kachru, McAllister, Sundrum



- 9 Flux compactification generically produces warped throat
- 9 Any SUSY-breaking brane introduced into warped geometry is stabilized at the IR end of throat.
- 9 SUSY breaking in visible sector at the UV end is totally independent of the nature of SUSY-breaking brane.
- 9 Anti-brane at the tip of throat provides perfectly controllable SUSY breaking at UV end : $F_{\text{Goldstino}} \sim e^{2\tilde{A}} (M_{Pl} = 1)$

* Nonperturbative stabilization \Rightarrow Mirage pattern

$$M_{\tilde{B}} : M_{\tilde{W}} : M_{\tilde{g}} = (1 + 0.66\alpha) : (2 + 0.2\alpha) : (6 - 1.8\alpha)$$

$$= \begin{cases} 1 : 1.6 : 3.8 & (\alpha = 0.5) \\ 1 : 1.3 : 2.5 & (\alpha = 1) \\ 1 : 1.2 : 1.7 & (\alpha = 1.5) \end{cases}$$

$$\alpha = \frac{g_{\text{hidden}}^2}{g_{\text{GUT}}^2} \propto \frac{m_{3/2}}{F^T \ln(M_{\text{pl}}/m_{3/2})} \rightarrow 1 \text{ in dilute flux limit}$$

(Another scheme : Deflected anomaly mediation
Pomarol, Rattazzi)

$$\frac{M_a}{g_a^2} = \frac{1}{8\pi^2} \frac{F^X}{X} \sum_{\mathbb{I}} C_a(\mathbb{I}) + \frac{b_a}{16\pi^2} m_{3/2} \quad \left(\frac{F^X}{X} \sim m_{3/2} \right)$$

* Flux stabilization of $T \Rightarrow$ Anomaly pattern

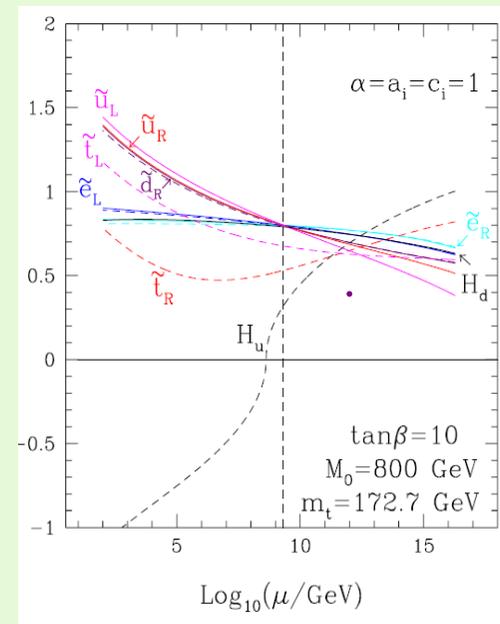
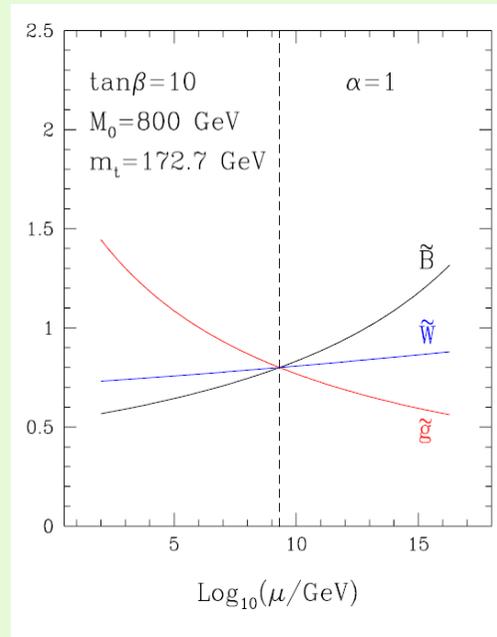
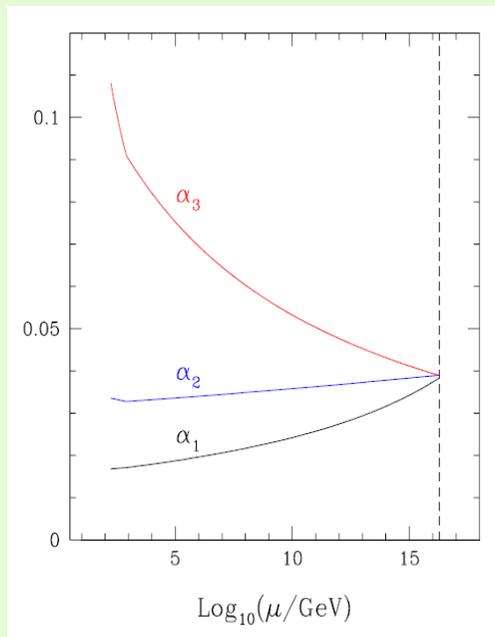
$$M_{\tilde{B}} : M_{\tilde{W}} : M_{\tilde{g}} \approx 3.3 : 1 : 9$$

Mirage unification of sparticle masses

KC, Jeong, Okumura

$$M_a(\mu) = M_0 \left[1 - \frac{b_a}{8\pi^2} g_a^2(\mu) \ln \left(\frac{M_{\text{mirage}}}{\mu} \right) \right]$$

$$m_i^2(\mu) = m_0^2 + M_0^2 \left\{ \nu_i(\mu) - \frac{j_i(\mu)}{16\pi^2} \ln \left(\frac{M_{\text{mirage}}}{\mu} \right) \right\} \frac{\ln \left(\frac{M_{\text{mirage}}}{\mu} \right)}{4\pi^2}$$



$$M_{\text{mirage}} = M_{\text{GUT}} \left(\frac{m_{3/2}}{M_{\text{pl}}} \right)^{\frac{\alpha}{2}} \quad \left(\alpha = \frac{g_{\text{hidden}}^2}{g_{\text{GUT}}^2} \right)$$

Scenario C

$|F^T| \ll m_{3/2}$, and $F^X \sim m_{3/2}$ is not sequestered.

• $\frac{M_a}{g_a^2} = \mathcal{O}\left(\frac{m_{3/2}}{8\pi^2}\right)$ are highly *UV sensitive*

* generically non-universal

* can be mirage or anomaly pattern in some special case

• $m_{\tilde{q}, \tilde{\ell}} \sim F^X = \mathcal{O}(8\pi^2 M_a)$: *Loop split SUSY Wells*

Nonperturbative stabilization of T & unsequestered

F -term uplifting scenario generically leads to such

pattern of sparticle masses.

*Gomez-Reino, Scrucra ; Lebedev, Nilles, Ratz ; Dudas, Papineau, Pokorski
Abe, Higaki, Kobayashi, Omura ; Acharya, Bobkov, Kane, Kumar, Shao*

Summary

- *mSUGRA* pattern : dilaton/modulus domination scenario, gauge mediation, gaugino mediation, ...

$$M_{\tilde{B}} : M_{\tilde{W}} : M_{\tilde{g}} \simeq 1 : 2 : 6 \Rightarrow \frac{m_{\tilde{g}}}{m_{\chi_1}} \gtrsim 6$$

- mirage pattern : nonperturbative stabilization of T with sequestered uplifting

$$M_{\tilde{B}} : M_{\tilde{W}} : M_{\tilde{g}} \simeq 1 : 1.3 : 2.5 \Rightarrow \text{compressed spectra (in dilute flux limit)}$$

- anomaly pattern : flux stabilization of T with sequestered uplifting

$$M_{\tilde{B}} : M_{\tilde{W}} : M_{\tilde{g}} \simeq 3.3 : 1 : 9 \Rightarrow \frac{m_{\tilde{g}}}{m_{\chi_1}} \gtrsim 9$$

- UV sensitive pattern : nonperturbative or flux stabilization of T with unsequestered uplifting

Highly UV sensitive gaugino mass ratios & $M_a \sim \frac{m_{\tilde{g}, \tilde{e}}}{8\pi^2}$

◆ Gluino transverse mass (M_{T2}) which can determine $m_{\tilde{g}}$, m_{χ_1} & $m_{\tilde{f}}$

• Transverse mass

$W \rightarrow \ell(p) \nu(\not{p})$ ↓ missing momentum

$$p^\mu = (E_T \cosh \eta, \vec{P}_T, E_T \sinh \eta)$$

$$\eta = \frac{1}{2} \ln \left(\frac{E + P_z}{E - P_z} \right), \quad E_T = \sqrt{|\vec{P}_T|^2 + m^2}$$

$$m_T^2 = m_\ell^2 + m_\nu^2 + 2(E_T \cancel{E}_T - \vec{P}_T \cdot \vec{P}_T)$$

$$m_W^2 = m_\ell^2 + m_\nu^2 + 2(E_T \cancel{E}_T \cosh \Delta\eta - \vec{P}_T \cdot \vec{P}_T) \geq m_T^2$$

⇒ $m_T^{\max} = \underset{\text{all data}}{\text{Maximum over}} [m_T(\vec{P}_T)] = m_W$ can be determined as we know m_ν

- Squark M_{T2} Lester, Summers ; Barr, Lester, Stephens

$$\tilde{q} \tilde{q} \rightarrow q(p_1) \chi(p'_1) \bar{q}(p_2) \chi(p'_2)$$

We don't know m_x yet, so consider the transverse mass of \tilde{q} for a trial LSP mass \tilde{m}_x :

$$m_T^2(\vec{P}_T, \vec{P}'_T; \tilde{m}_x) = m_{\tilde{q}}^2 + \tilde{m}_x^2 + 2(E_T \cancel{E}'_T - \vec{P}_T \cdot \vec{P}'_T)$$

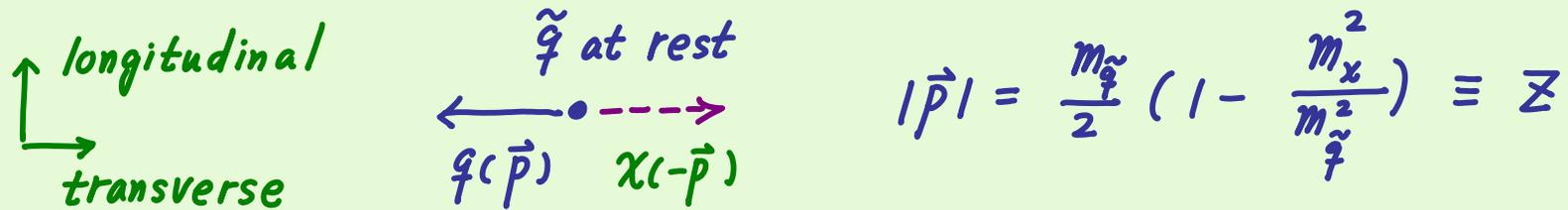
$$(\cancel{E}'_T = \sqrt{|\vec{P}'_T|^2 + \tilde{m}_x^2})$$

$$m_{T2}^2(\vec{P}_{1T}, \vec{P}_{2T}; \tilde{m}_x) = \underset{\vec{P}_{1T} + \vec{P}_{2T} = \vec{P}_T}{\text{Minimum over}} \left[\max \left(m_T^2(\vec{P}_{1T}, \vec{P}'_{1T}; \tilde{m}_x), m_T^2(\vec{P}_{2T}, \vec{P}'_{2T}; \tilde{m}_x) \right) \right]$$

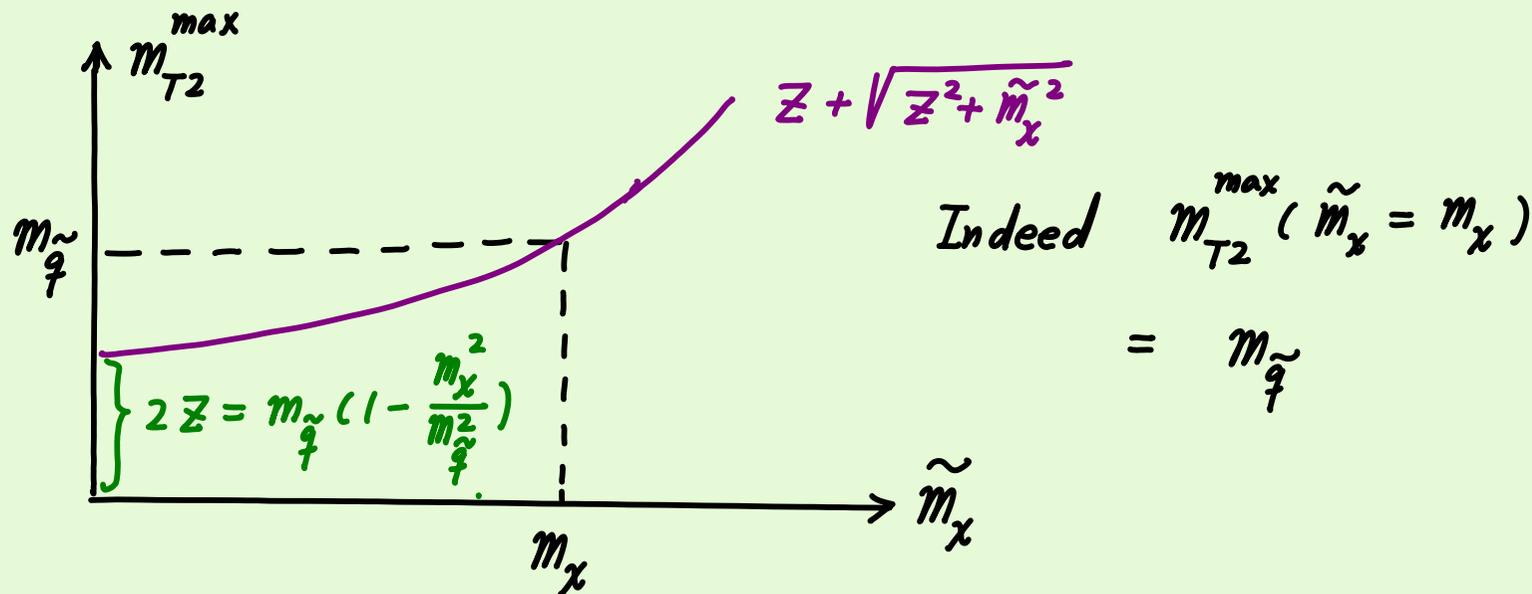
$$m_{T2}^{\max}(\tilde{m}_x) = \underset{\text{all events}}{\text{Maximum over}} \left[m_{T2}(\vec{P}_{1T}, \vec{P}_{2T}; \tilde{m}_x) \right]$$

$$= m_{\tilde{q}} \quad \text{for} \quad \tilde{m}_x = m_x$$

Behavior of squark transverse mass (m_{T2}^{\max}) as a function of trial LSP mass \tilde{m}_χ provides a relation between $m_{\tilde{q}}$ & m_χ :



$$m_T(\vec{P}_T, \vec{P}_T; \tilde{m}_\chi) = Z + \sqrt{Z^2 + \tilde{m}_\chi^2} = m_{T2}^{\max}(\tilde{m}_\chi)$$



- Gluino M_{T2} (stransverse mass)

$$\tilde{g}\tilde{g} \rightarrow q(p_1) q(p_2) \chi(p_1) q(p_3) q(p_4) \chi(p_2)$$

$$* m_T^2(\vec{P}_{1T}, \vec{P}_{2T}, \vec{P}_1) = 2m_q^2 + \tilde{m}_\chi^2 + 2(E_{1T}E_{2T} - \vec{P}_{1T} \cdot \vec{P}_{2T})$$

$$+ 2[(E_{1T} + E_{2T})E_{1T} - (\vec{P}_{1T} + \vec{P}_{2T}) \cdot \vec{P}_{1T}]$$

$$(E_{1T} = \sqrt{|\vec{P}_{1T}|^2 + \tilde{m}_\chi^2})$$

$$* m_{T2}^2(\vec{P}_{1T}, \vec{P}_{2T}, \vec{P}_{3T}, \vec{P}_{4T}; \tilde{m}_\chi)$$

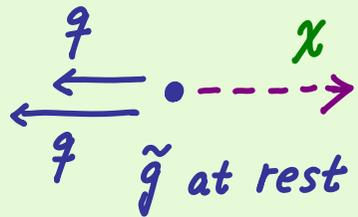
$$= \underset{\substack{\text{Minimum} \\ \text{over} \\ \vec{P}_{1T} + \vec{P}_{2T} = \vec{P}_T}}{\text{Minimum}} \left[\max \left(m_T^2(\vec{P}_{1T}, \vec{P}_{2T}, \vec{P}_1), m_T^2(\vec{P}_{3T}, \vec{P}_{4T}, \vec{P}_2) \right) \right]$$

$$* m_{T2}^{\max}(\tilde{m}_\chi) = \underset{\text{all events}}{\text{Maximum}} \left[m_{T2}(\vec{P}_{1T}, \vec{P}_{2T}, \vec{P}_{3T}, \vec{P}_{4T}; \tilde{m}_\chi) \right]$$

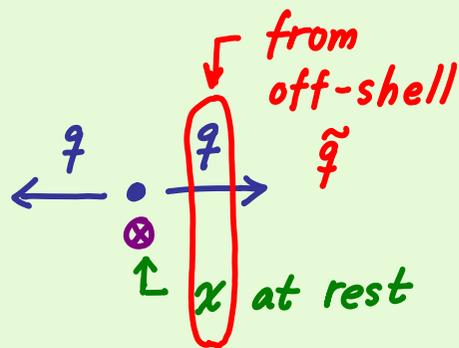
$$= m_{\tilde{g}} \text{ for } \tilde{m}_\chi = m_\chi$$

Gluino transverse ($m_{T2}^{\max}(\tilde{m}_x)$ for $\tilde{g}\tilde{g} \rightarrow q\bar{q} \chi q\bar{q} \chi$)

has a richer structure ! Cho, KC, Kim, Park

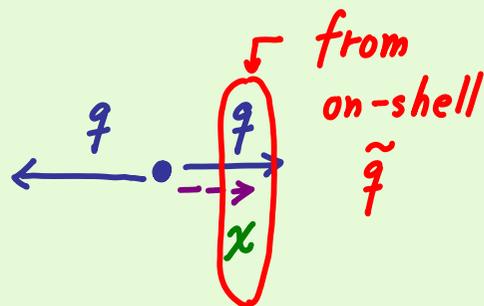

 $\Rightarrow m_{T2}^{\max}(\tilde{m}_x) = Z_0 + \sqrt{Z_0^2 + \tilde{m}_x^2}$

$$\left(Z_0 = \frac{m_{\tilde{g}}}{2} \left(1 - \frac{m_x^2}{m_{\tilde{g}}^2} \right) \right)$$



$$\Rightarrow m_{T2}^{\max}(\tilde{m}_x) = Z_1 + \tilde{m}_x$$

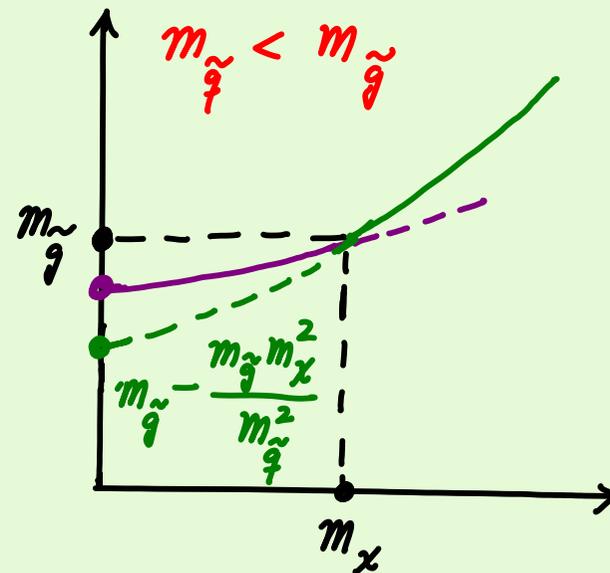
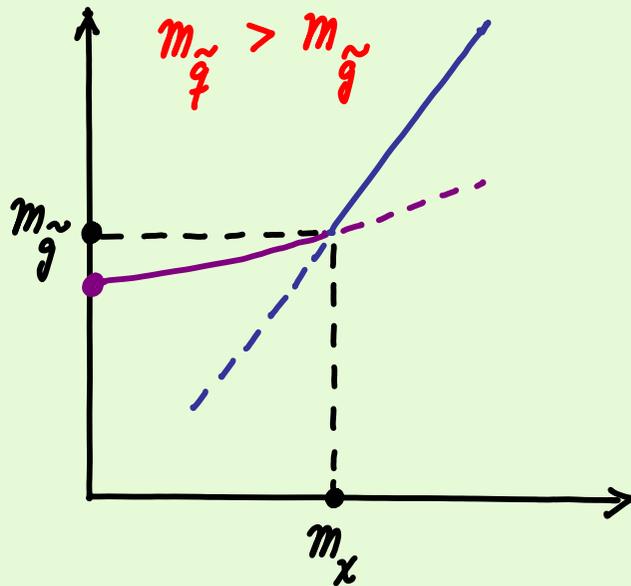
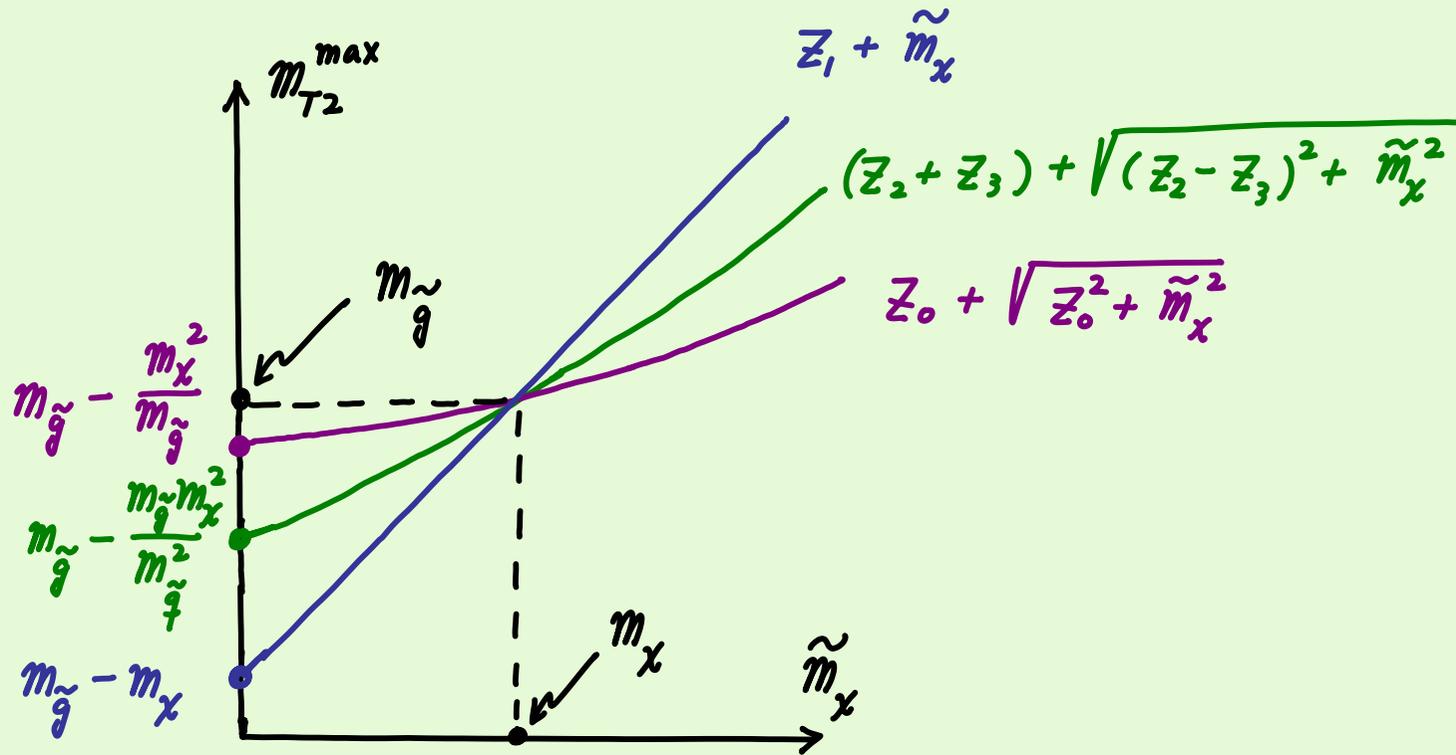
for $m_{\tilde{q}} > m_{\tilde{g}}$ ($Z_1 = m_{\tilde{g}} - m_x$)



$$\Rightarrow m_{T2}^{\max}(\tilde{m}_x) = (Z_2 + Z_3) + \sqrt{(Z_2 - Z_3)^2 + \tilde{m}_x^2}$$

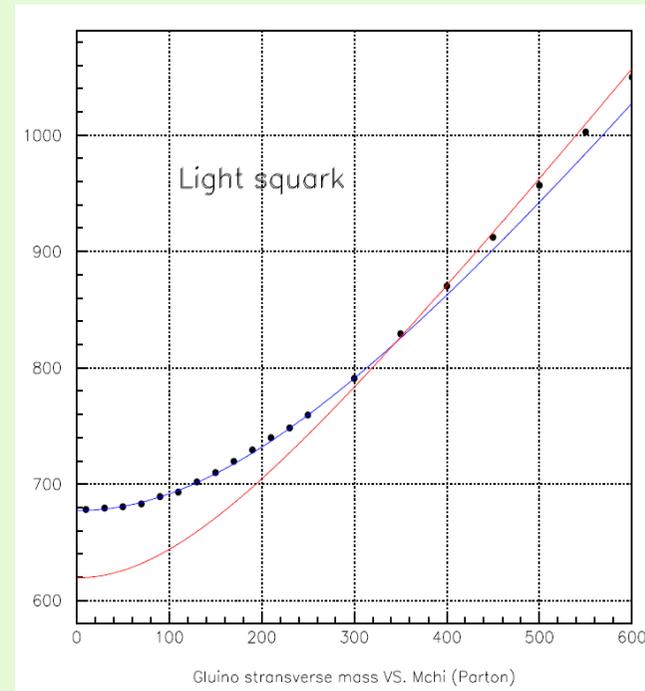
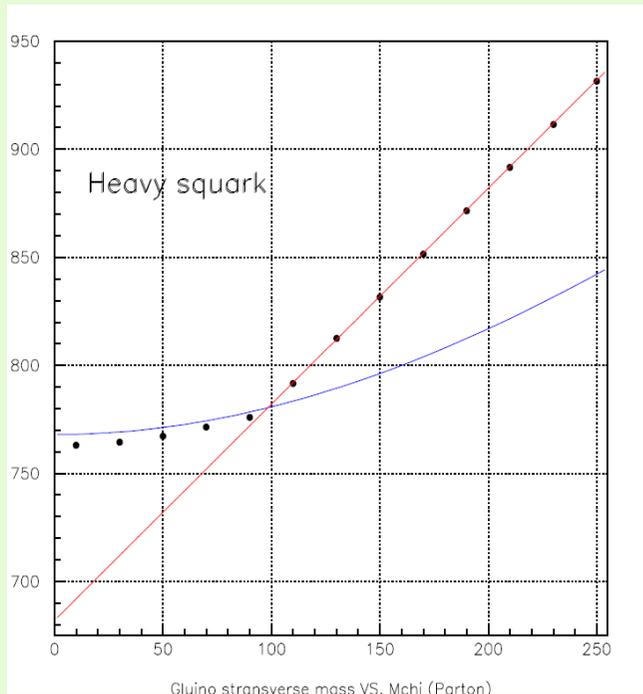
for $m_{\tilde{q}} < m_{\tilde{g}}$

$$\left(Z_2 = \frac{m_{\tilde{g}}}{2} \left(1 - \frac{m_x^2}{m_{\tilde{g}}^2} \right), Z_3 = \frac{m_{\tilde{q}}}{2} \left(1 - \frac{m_{\tilde{q}}^2}{m_{\tilde{g}}^2} \right) \right)$$



Gluino M_{T2} as a function of \tilde{m}_x can in principle
 determine $m_{\tilde{g}}$ & m_x (and $m_{\tilde{q}}$ also if $m_{\tilde{q}} < m_{\tilde{g}}$)
seperately!

SUSY events generated by PYTHIA :



Can we construct $m_{T2}^{\max}(\tilde{m}_x)$ from real LHC data ?

Various backgrounds, hadronization & detector effects might spoil the edge structure of m_{T2} , which would make it difficult to obtain a reliable functional form of $m_{T2}^{\max}(\tilde{m}_x)$.

Include SM backgrounds & proceed with PGS

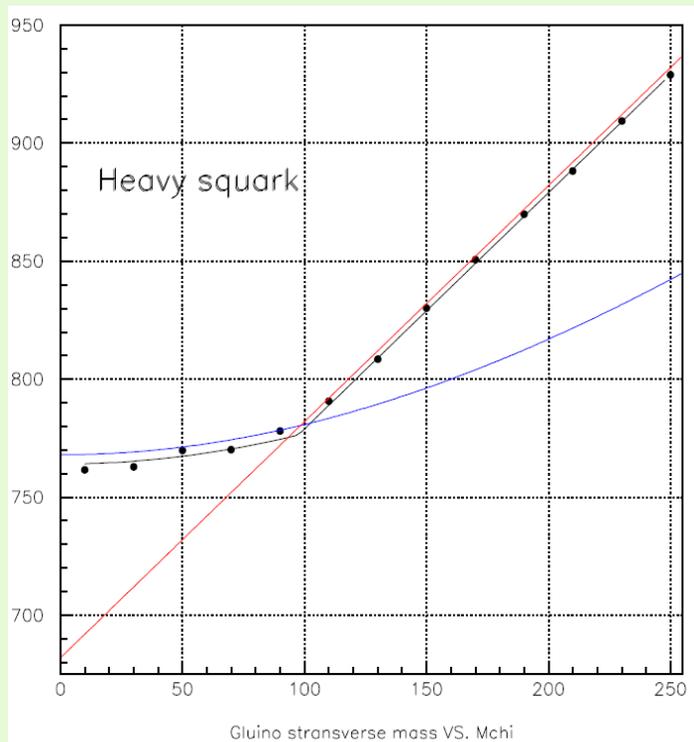
Event selection cuts :

* At least 4 jets with $P_T > 200, 150, 100, 50$ GeV

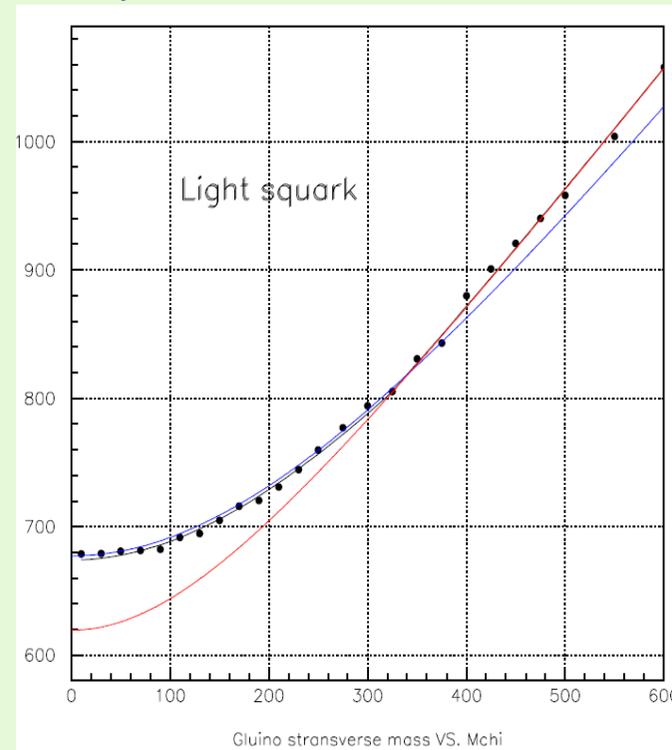
* $\cancel{E}_T > 250$ GeV, $S_T > 0.25$, no b-jets & no-leptons

* (P_1, P_2) & (P_3, P_4) : $P_1 =$ highest momentum,

$P_3 =$ largest $|P| \sqrt{\Delta\phi^2 + \Delta\eta^2}$ w.r.t P_1



$$\mathcal{L} = 300 \text{ fb}^{-1}$$



$$\mathcal{L} = 100 \text{ fb}^{-1}$$

Conclusion

- ◆ One can classify the patterns of sparticle masses based on possible schemes of moduli stabilization.

Known schemes of moduli stabilization suggest that non-universal M_a/g_a^2 are plausible possibility.

- ◆ Experimental measurement of $R = \frac{m_{\tilde{g}}}{m_{\chi_1}}$ will be useful for discriminating different SUSY-breaking schemes:

mSUGRA pattern $\rightarrow R \gtrsim 6$

anomaly pattern $\rightarrow R \gtrsim 9$

mirage pattern $\rightarrow R$ can be significantly smaller

- ◆ Gluino transverse mass might be able to determine $m_{\tilde{g}}$ & m_{χ_1} separately ($m_{\tilde{g}}$ also if $m_{\tilde{g}} < m_{\tilde{g}}$).