

Title: Enhanced Radiative Corrections to Supersymmetric Relations

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Abstract:

# **Enhanced radiative corrections to Supersymmetric relations: The Charginos and Neutralinos**

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P.I. 12/03

Howard Haber and J.M. hep-ph/0711.2890

# Outline

- Introduction/Motivation
- Wrong Higgs/Quark Yukawa interactions
- Wrong Higgs interactions in the Chargino/Neutralino Sector
- Effective operators in the MSSM + Messengers
- Physical Parameters and Supersymmetric relations
- Conclusion

# Introduction/Motivation

## The Standard Model

Local Gauge Invariance  $\rightarrow$  SU(3) SU(2) U(1)

Spin 0	
$H$	1

Three copies (flavors)	
Spin 1/2	
$\psi_Q^*$	$\frac{1}{3}$
$\psi_U^*$	$-\frac{4}{3}$
$\psi_D^*$	$\frac{2}{3}$
$\psi_l$	-1
$\psi_e$	2
Adjoints	
Spin 1	
$G_\mu^a$	0
$A_\mu^a$	0
$B_\mu$	0

# Minimal Supersymmetric Standard Model (MSSM)

$B_\mu$	$\lambda'$
$A_\mu^a$	$\lambda^a$
$G_\mu^a$	$\lambda_g^a$
$\psi_Q^i$	$\bar{Q}^i$
$\psi_D^i$	$\bar{D}^i$
$\psi_U^i$	$\bar{U}^i$
$\psi_l^i$	$\bar{L}^i$
$\psi_e^i$	$\bar{E}^i$
$H_u$	$\psi_{H_u}$
$H_d$	$\psi_{H_d}$

$$\{Q_\alpha, Q^\dagger_{\dot{\beta}}\} = 2P^\mu \sigma_\mu$$

$E > 0 \rightarrow$  Broken SUSY

$$X = x + \theta\psi_x - \theta^2 F_x$$

$F_x \neq 0 \rightarrow$  Broken SUSY

$$W = \epsilon_{ij}(H_u^i Q^j U + H_d^i Q^j D + H_d^i L^j E + \mu H_u^i H_d^j)$$

$$\int d^2y \left[ X^3 \right]$$

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$\psi_e^i$	$\bar{E}^i$
$H_u$	$\psi_{H_u}$
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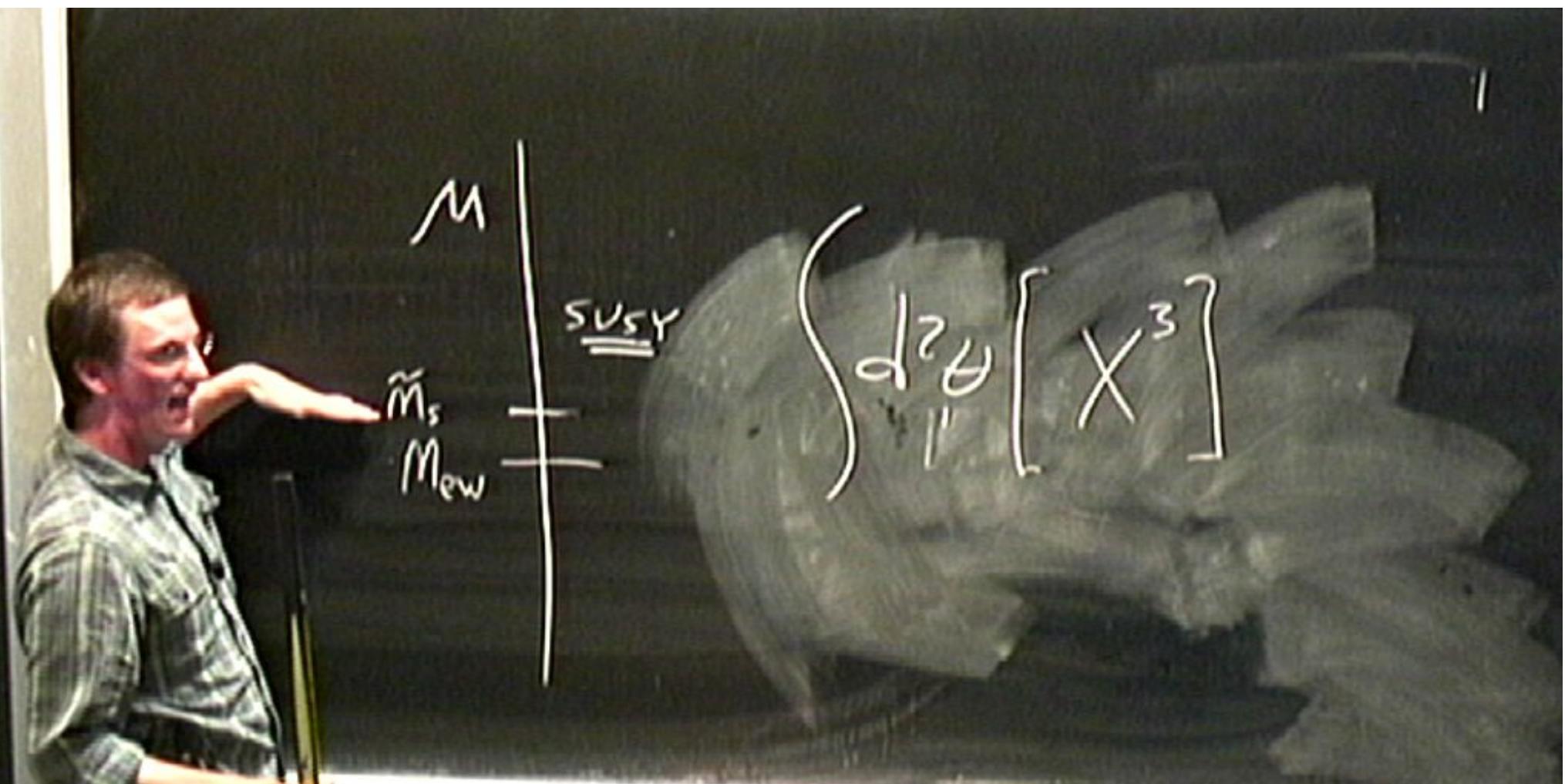
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A man in a plaid shirt stands to the left of a chalkboard, holding a piece of chalk. On the chalkboard, there is a vertical coordinate system with a horizontal axis labeled  $M$  at the top. Two points on the axis are labeled  $\tilde{m}_s$  and  $m_{ew}$ . To the right of the axis, there is a large chalk-drawn integral symbol with the expression  $d^2\theta [x^3]$  written inside it.

$$\int d^2\theta [x^3]$$



$\mathcal{L}^{MSSM}$  has 124 parameters

(known)	18	Standard Model
(unknown)	{ 1 105	Light Higgs Mass New parameters { 62 real parameters 43 CPV phases

All unknown parameters (except  $\mu$ ) come from all gauge invariant relevant SUSY breaking operators

Spontaneous SUSY Breaking (SSB) of a more fundamental theory provides an organizing principle for the parameters of  $\mathcal{L}^{MSSM}$

$$\mathcal{L}^{SSB} \xrightarrow{\hspace{1cm}} \mathcal{L}^{MSSM} + \text{special relations between 124 MSSM parameters}$$

Special relations among parameters determined by mechanism of SSB  
Mediation

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$M$

$\tilde{m}_s$   
 $M_{ew}$

SUSY

$$\underline{F_X \neq 0}$$

$$\int d^2\psi [X^3]$$

$M$

$\tilde{m}_s$

$M_{ew}$

SUSY

$\bar{F}_\lambda \neq 0$

$d\varphi$

$[X^3]$

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# A Variety of ways to mediate SUSY Breaking

## Gauge/Gravity/Anomaly/etc...

### Focus on Gauge Mediation

$$Z = \langle Z \rangle - \theta^2 F_z$$

1-loop

$$m_\lambda \sim \frac{g^2}{16\pi^2} \frac{F}{\langle Z \rangle}$$

$$W = Z \bar{M} M$$

2-loops

$$m_s^2 \sim \left( \frac{g^2}{16\pi^2} \right)^2 \frac{FF^\dagger}{\langle Z \rangle^2}$$

$$\frac{F}{\langle Z \rangle} \sim 10 - 100 \text{TeV}$$

$\langle Z \rangle$  Sets the Messenger mass scale

$$\frac{F}{\langle Z \rangle^2} \sim 1 \quad \xrightarrow{\hspace{1cm}} \quad$$

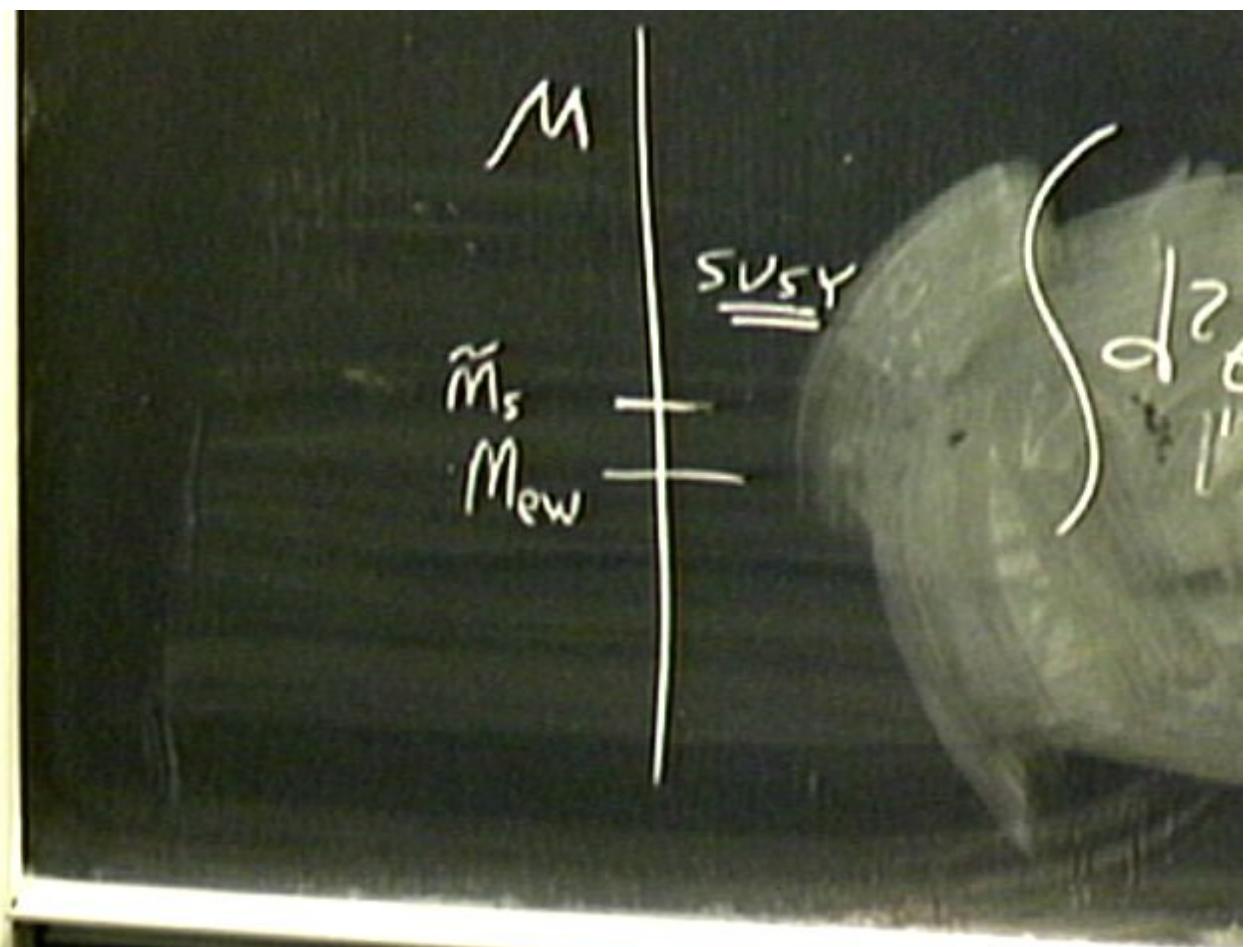
means lighter messengers

$$\left[ \text{often } \frac{F}{\langle Z \rangle^2} \ll 1 \right]$$

High or Low scale Messengers?

Is there a more complicated structure in the Messenger interactions?

Solution to the  $\mu, B$  problems?



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$$\frac{F}{\langle Z \rangle^2} \sim 1 \quad \xrightarrow{\text{blue arrow}} \quad \text{means lighter messengers}$$

[ often  $\frac{F}{\langle Z \rangle^2} \ll 1$  ]

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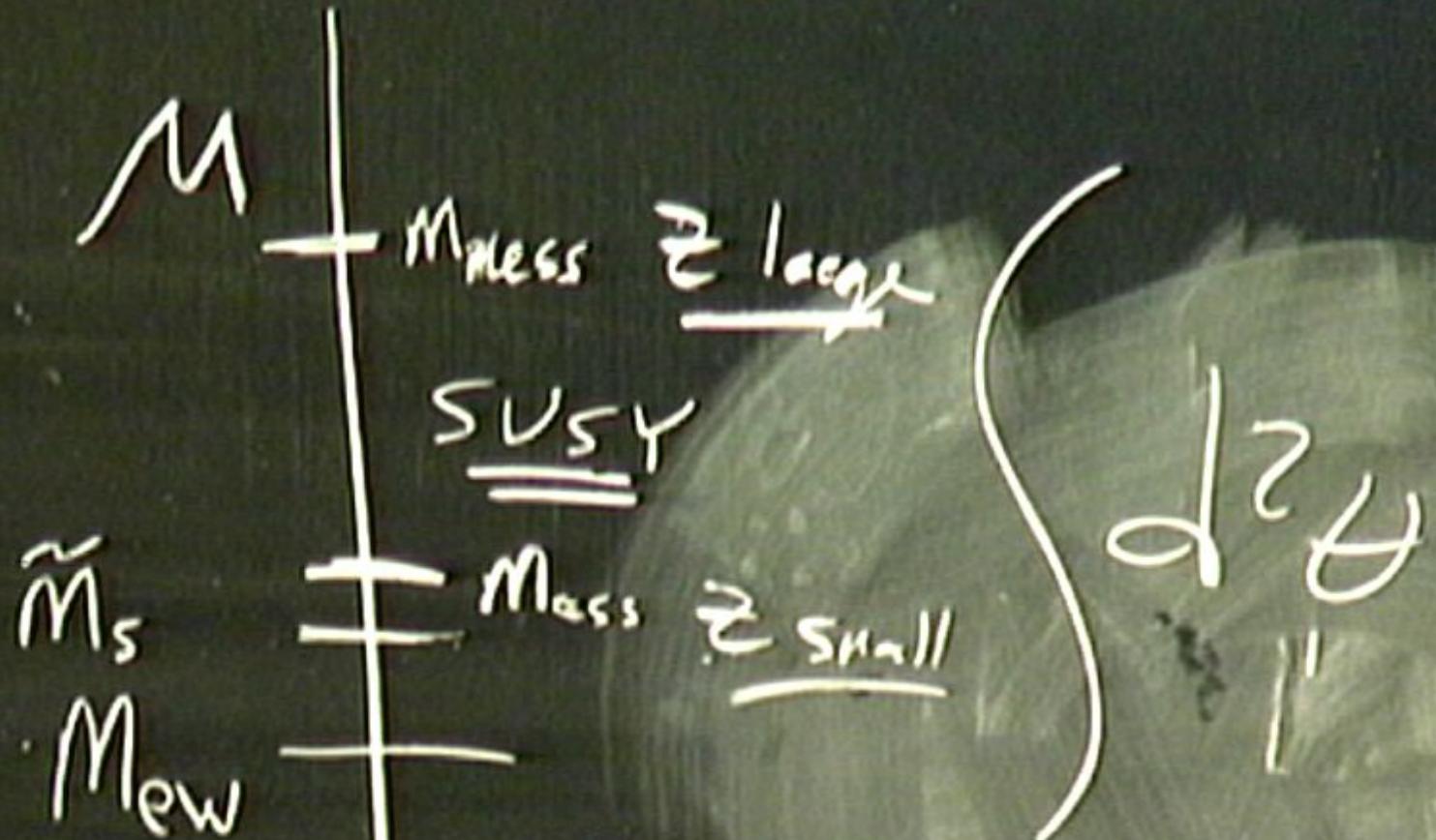
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### Focus on Gauge Mediation

$$Z = \langle Z \rangle - \theta^2 F_z \quad \text{1-loop} \quad m_\lambda \sim \frac{g^2}{16\pi^2} \frac{F}{\langle Z \rangle}$$

$$W = Z \bar{M} M \quad \text{2-loops} \quad m_s^2 \sim \left( \frac{g^2}{16\pi^2} \right)^2 \frac{FF^\dagger}{\langle Z \rangle^2}$$

$$\frac{F}{\langle Z \rangle} \sim 10 - 100 \text{TeV} \quad \langle Z \rangle \text{ Sets the Messenger mass scale}$$

$$\frac{F}{\langle Z \rangle^2} \sim 1 \quad \xrightarrow{\hspace{1cm}} \quad \text{means lighter messengers} \quad \left[ \text{often } \frac{F}{\langle Z \rangle^2} \ll 1 \right]$$

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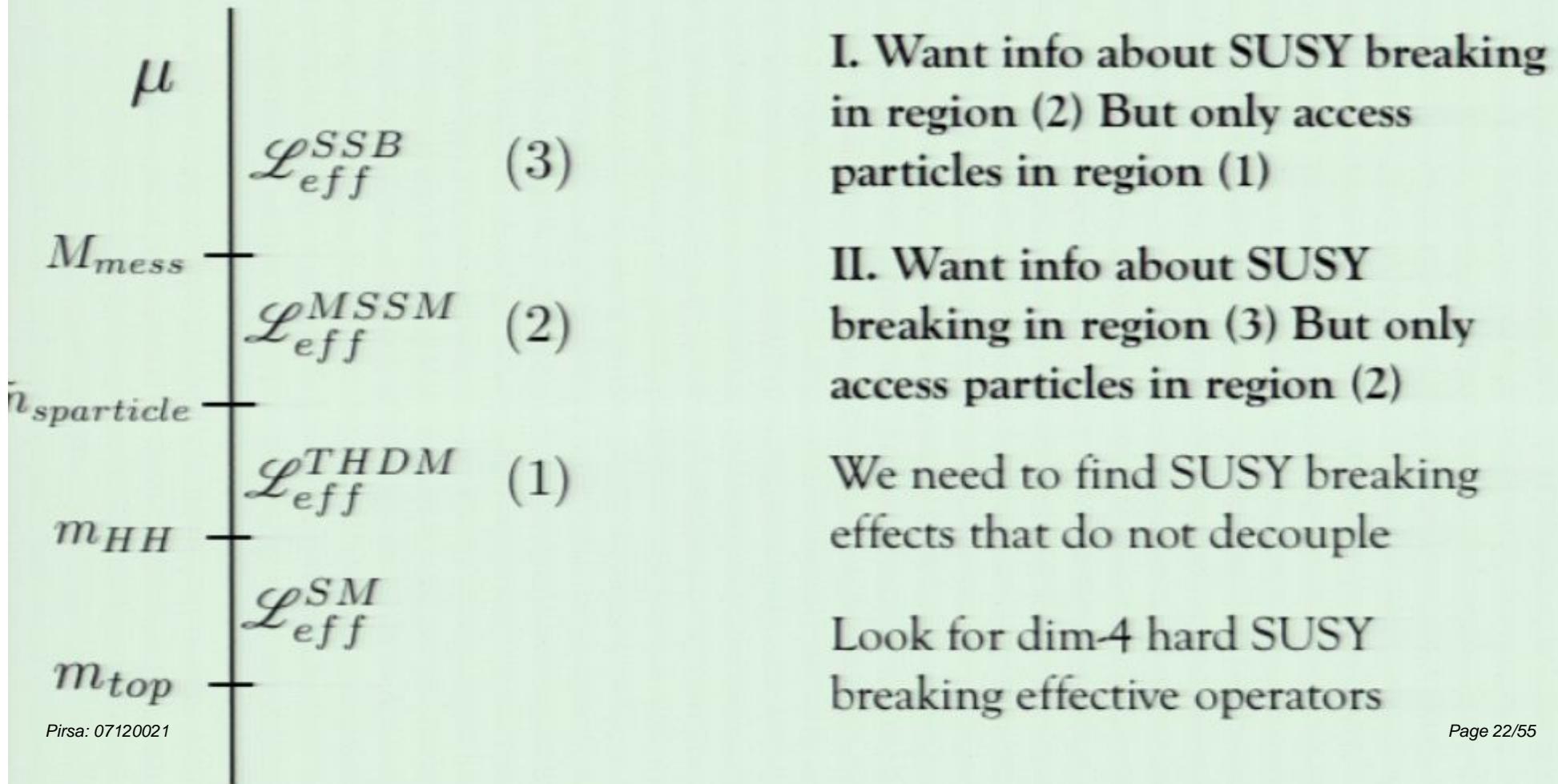
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Solution to the  $\mu, B$  problems?

# Questions about the Messenger Sector are questions about heavy physics ( $> 10$ TeV).

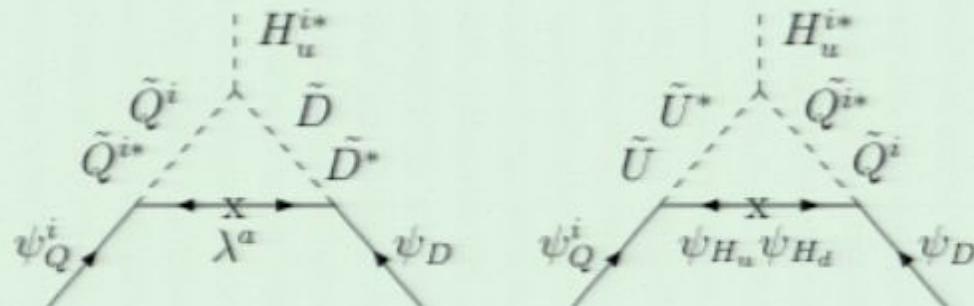
We want to utilize an effective Lagrangian description of the MSSM to isolate and then extract information about Messengers. Focus on special effects of SUSY breaking.



# The Effective Two Higgs Doublet Model (THDM)

$$\mathcal{L}_{yuk}^{tree} = -\epsilon_{ij} h_d H_d^i \psi_Q^j \psi_D + \epsilon_{ij} h_u H_u^i \psi_Q^j \psi_U$$

Decouple all superpartners, include thresholds and get new (dim-4) SUSY breaking operators



$$\Delta h_b = h_b \left[ \frac{2\alpha_s}{3\pi} \mu M_g \mathcal{I}(M_{b1}^2, M_{b2}^2, M_g^2) + \frac{h_t}{16\pi^2} \mu A_t \mathcal{I}(M_{t1}^2, M_{t2}^2, \mu^2) \right]$$

$$(a^2, b^2, c^2) = \frac{a^2 b^2 \ln(a^2/b^2) + b^2 c^2 \ln(b^2/c^2) + c^2 a^2 \ln(c^2/a^2)}{(a^2 - b^2)(b^2 - c^2)(a^2 - c^2)} \quad \Delta h_b \sim h_b \frac{2\alpha_s}{3\pi} \frac{\mu M_{\tilde{g}}}{m_{sq}^2}$$

$$\mathcal{L}_{yuk}^{eff} = -\epsilon_{ij}(h_b + \delta h_b)\psi_b H_d^i \psi_Q^j + \Delta h_b \psi_b H_u^{k*} \psi_Q^k$$

Carena, Mrenna, Wagner '98

Carena, Haber '03

- New interaction called “Wrong Higgs” interactions
- It is a dim-4 hard breaking operator
- No counterterm required

Replace Higgs doublets with mass eigenstates

$$\mathcal{L}_{yuk}^{eff} = -\epsilon_{ij}(h_b + \delta h_b)\psi_b H_d^i \psi_Q^j + \Delta h_b \psi_b H_u^{k*} \psi_Q^k \quad \left\{ \begin{array}{l} H_d^1 = \frac{v \cos \beta}{\sqrt{2}} + \frac{1}{\sqrt{2}}(H^0 \cos \alpha - h^0 \sin \alpha + iA^0 \sin \beta) \\ H_u^2 = \frac{v \sin \beta}{\sqrt{2}} + \frac{1}{\sqrt{2}}(H^0 \sin \alpha + h^0 \cos \alpha + iA^0 \cos \beta) \end{array} \right.$$

## $\tan \beta$ enhanced radiative correction to a SUSY relation

corrected SUSYc relation

$$\frac{\sqrt{2}m_b}{h_b v \cos \beta} = 1 + \Delta_b$$

- Loops effects are enhanced ( can be 20% corrections or more )
- Modified relations reflect information about heavy physics
- Since  $\Delta_\tau \ll \Delta_b$  the effects of  $\Delta_b$  can be determined from  $\frac{g_{h\bar{b}b}}{g_{h\bar{\tau}\tau}}$

# Wrong Higgs Interactions for Gauginos

The Softly Broken MSSM Gaugino Sector

$$\begin{aligned}\mathcal{L}^{gaugino} = & \frac{ig_u}{\sqrt{2}} \lambda^a \tau_{ij}^a \psi_{H_u}^j H_u^{*i} + \frac{ig_d}{\sqrt{2}} \lambda^a \tau_{ij}^a \psi_{H_d}^j H_d^{*i} + \frac{ig'_u}{\sqrt{2}} \lambda' \psi_{H_u}^i H_u^{*i} \\ & - \frac{ig'_d}{\sqrt{2}} \lambda' \psi_{H_d}^i H_d^{*i} - M \lambda^a \lambda^a - M' \lambda' \lambda' - \mu \epsilon_{ij} \psi_{H_u}^i \psi_{H_d}^j + h.c.\end{aligned}$$

- $g_u = g_d = g \quad g'_u = g'_d = g'$  at tree-level
- Deviations from these SUSY relations at 1-loop Randall / Feng
- These are dim-4 hard SUSY breaking effects

$M$  $\tilde{M}_5$  $M_{ew}$  $m_{Kerr} \gtrsim l_{\text{reg}} \lambda$  $\underline{\underline{SUSY}}$  $m_{Kerr} \gtrsim l_{\text{small}}$  $T_X \neq 0$ 

$$d^2\varphi [X^3]$$

$$\int d^4\varphi \bar{\Psi}^+ e^{2gV} \Psi$$

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## Wrong Higgs interactions

$$ik_1 \lambda^a \tau_{ij}^a \psi_{H_u}^j \epsilon_{ki} H_d^k$$

- dim-4 hard SUSY breaking

$$ik_2 \lambda' \psi_{H_u}^k \epsilon_{ki} H_d^i$$

- Zero at tree-level

$$ik_3 \lambda^a \tau_{ij}^a \psi_{H_d}^j \epsilon_{ki} H_u^k$$

- generated at 1-loop

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- RG effects at 2-loop

- R-charge = 2 Operators

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Look for effects that can generate these interactions... locally.

## Messenger Sector revisited

Dvali, Giudice, Pomarol

Roy, Schmaltz

Murayama, Nomura, Poland

$$W = \gamma_1 \epsilon_{ij} Z M_1^i \bar{M}_1^j + \gamma_2 Z M_2 \bar{M}_2 + \alpha \epsilon_{ij} H_u^i M_1^j M_2 + \beta \epsilon_{ij} H_d^i \bar{M}_1^j \bar{M}_2$$

$$\bar{M}_1 \sim (1, 2)_1 \quad M_1 \sim (1, 2)_{-1}$$

$$\bar{M}_2 \sim (1, 1)_{-2} \quad M_2 \sim (1, 1)_2$$

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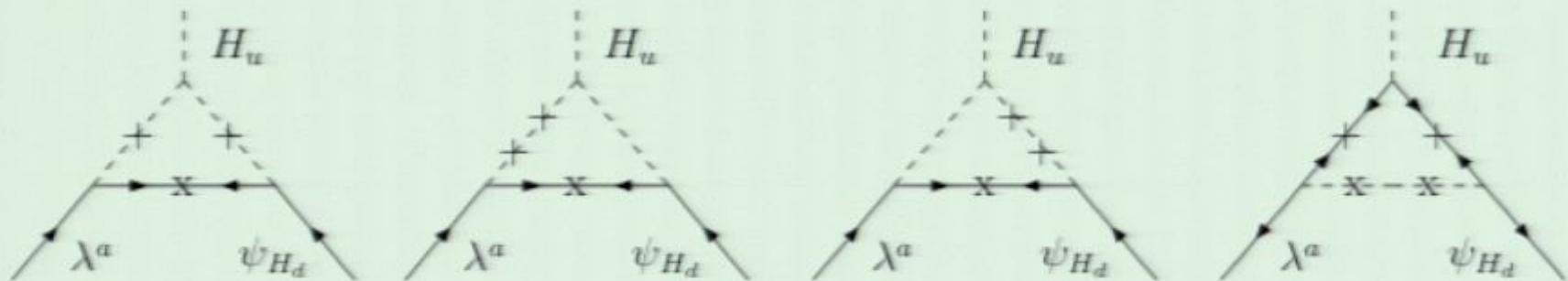
Murayama, Nomura, Poland

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$$\bar{M}_1 \sim (1, 2)_1 \quad M_1 \sim (1, 2)_{-1}$$

$$\bar{M}_2 \sim (1, 1)_{-2} \quad M_2 \sim (1, 1)_2$$

focus on  $ik_3\lambda^a\tau_{ij}^a\psi_{H_d}^j\epsilon_{ki}H_u^k$  employ a mass insertion technique



$$k_3 \sim g\alpha\beta(\gamma_2^2 + \gamma_1\gamma_2) \frac{1}{16\pi^2} \left( \frac{F_z}{\langle Z \rangle^2} \right)^2$$

for  $\frac{F_z}{\langle Z \rangle^2} \ll 1$  (heavy messengers) effect decouples.

for  $\frac{F_z}{\langle Z \rangle^2} \sim 1$  (lighter messengers) can still integrate out messengers and the effective operator does not decouple.

However, you must work with Messenger mass eigenstates for the correct threshold expression.

Define:

$$\gamma_1 = \gamma_2 = \gamma \quad \langle Z \rangle \equiv z$$

$$M_{\pm} \equiv (\gamma^2 z^2 \pm \gamma F_z)^{\frac{1}{2}}$$

Rotate to mass eigenstates:

$$\begin{aligned}\epsilon_{ki} M_{1i}^+ &= \frac{1}{\sqrt{2}}(\epsilon_{ki} M_{1i} - \bar{M}_{1k}) & M_2^+ &= \frac{1}{\sqrt{2}}(M_2 + \bar{M}_2) \\ \epsilon_{ki} M_{1i}^- &= \frac{1}{\sqrt{2}}(\epsilon_{ki} M_{1i} + \bar{M}_{1k}) & M_2^- &= \frac{1}{\sqrt{2}}(M_2 - \bar{M}_2)\end{aligned}$$

$$\frac{k_3}{g} = \frac{\sqrt{2}\alpha\beta\gamma^2 z^2}{32\pi^2} (\mathcal{I}(\gamma z, M_+, M_+) + \mathcal{I}(\gamma z, M_-, M_-) - \mathcal{I}(\gamma z, \gamma z, M_+) - \mathcal{I}(\gamma z, \gamma z, M_-))$$

$$\mathcal{I}(a, a, b) = \frac{a^2(a^2 - b^2) + a^2 b^2 \ln \frac{b^2}{a^2}}{a^2(a^2 - b^2)^2}$$

And the result is...

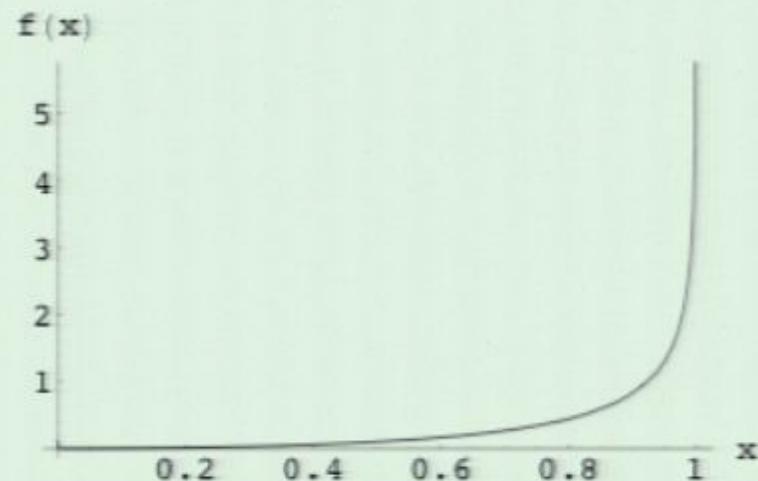
$$\frac{k_3}{g} = \frac{\sqrt{2}\alpha\beta}{32\pi^2} f(x) \quad x = \frac{F}{\gamma \langle Z \rangle^2}$$

$$f(x) = \frac{-(2+x)\ln(1+x) + (-2+x)\ln(1-x)}{x^2}$$

- Small x expansion matches expectations.
- $\gamma_1 \neq \gamma_2$  a little more work

$$f(x) = \frac{x^2}{3} + \frac{4x^4}{15} + \mathcal{O}(x^6) + \dots$$

How large can  $f(x)$  get?



$$\frac{k_3}{g} \sim \frac{(1 - 0.1)}{16\pi^2}$$

for  $10 \text{ TeV} \leq M_- \leq 50 \text{ TeV}$

## 4 sample points

$$\langle Z \rangle = 100\text{TeV} \quad \tan \beta = 50 \quad \alpha = \beta = 1$$

$\gamma_1$	$\gamma_2$	$F_Z$	$M_-$	$16\pi^2 k_3/g$
1	1	$(99 \text{ TeV})^2$	1.41 TeV	4.55
0.9	1	$(94 \text{ TeV})^2$	12.1 TeV	0.81
1	1	$(84 \text{ TeV})^2$	54.8 TeV	0.19
0.75	1	$(70 \text{ TeV})^2$	44.2 TeV	0.10

## Effects on the Chargino Sector

$$\begin{aligned}\mathcal{L}_{gaugino}^{eff} = & \frac{ig_u}{\sqrt{2}}\lambda^a\tau_{ij}^a\psi_{H_u}^j H_u^{*i} + \frac{ig_d}{\sqrt{2}}\lambda^a\tau_{ij}^a\psi_{H_d}^j H_d^{*i} + \frac{ig'_u}{\sqrt{2}}\lambda'\psi_{H_u}^i H_u^{*i} - \frac{ig'_d}{\sqrt{2}}\lambda'\psi_{H_d}^i H_d^{*i} \\ & - M\lambda^a\lambda^a - M'\lambda'\lambda' - \mu\epsilon_{ij}\psi_{H_u}^i\psi_{H_d}^j + \\ & ik_1\lambda^a\tau_{ij}^a\psi_{H_u}^j\epsilon_{ki}H_d^k + ik_2\lambda'\psi_{H_u}^k\epsilon_{ki}H_d^i + ik_3\lambda^a\tau_{ij}^a\psi_{H_d}^j\epsilon_{ki}H_u^k + ik_4\lambda'\psi_{H_d}^i\epsilon_{ki}H_u^k\end{aligned}$$

Plug in Higgs VEVs:

$$H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix} \quad H_d = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix} \quad \Rightarrow \quad \mathcal{L}_{mass} = -\frac{1}{2} \begin{pmatrix} \psi^+ & \psi^- \end{pmatrix} \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix} \begin{pmatrix} \psi^+ \\ \psi^- \end{pmatrix} + h.c.$$

$$\psi_i^+ = \begin{pmatrix} -i\lambda^+ \\ \psi_{H_u}^1 \end{pmatrix} \quad \psi_i^- = \begin{pmatrix} -i\lambda^- \\ \psi_{H_d}^2 \end{pmatrix} \quad X = \begin{pmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{pmatrix}$$

Recall that without k's:

$$X^{SUSY} = \begin{pmatrix} M & \sqrt{2}m_W \sin \beta \\ \sqrt{2}m_W \cos \beta & \mu \end{pmatrix} \quad \text{Only 2 new parameters}$$

Look at effective mass matrix:

$$\begin{pmatrix} X_{11}^{eff} & X_{12}^{eff} \\ X_{21}^{eff} & X_{22}^{eff} \end{pmatrix}$$

$$= \begin{pmatrix} M & (g + \delta g_u) v \sin \beta (1 - \sqrt{2} \frac{k_1}{g + \delta g_u} \cot \beta) \\ (g + \delta g_d) v \cos \beta (1 + \sqrt{2} \frac{k_3}{g + \delta g_d} \tan \beta) & \mu \end{pmatrix}$$

enhanced corrections  
to SUSY relations

$$\boxed{\frac{X_{21}^{eff}}{X_{21}^{SUSY}} = 1 + \sqrt{2} \frac{k_3}{g} \tan \beta = 1 + \delta_{21}}$$

Now we need to isolate  $X_{21}^{eff}$  in terms of physical parameters in the Chargino Sector. Assume no SUSY relations between the parameters of the Charginos.

## Effects on the Chargino Sector

$$\begin{aligned}\mathcal{L}_{gaugino}^{eff} = & \frac{ig_u}{\sqrt{2}}\lambda^a\tau_{ij}^a\psi_{H_u}^j H_u^{*i} + \frac{ig_d}{\sqrt{2}}\lambda^a\tau_{ij}^a\psi_{H_d}^j H_d^{*i} + \frac{ig'_u}{\sqrt{2}}\lambda'\psi_{H_u}^i H_u^{*i} - \frac{ig'_d}{\sqrt{2}}\lambda'\psi_{H_d}^i H_d^{*i} \\ & - M\lambda^a\lambda^a - M'\lambda'\lambda' - \mu\epsilon_{ij}\psi_{H_u}^i\psi_{H_d}^j + \\ & ik_1\lambda^a\tau_{ij}^a\psi_{H_u}^j\epsilon_{ki}H_d^k + ik_2\lambda'\psi_{H_u}^k\epsilon_{ki}H_d^i + ik_3\lambda^a\tau_{ij}^a\psi_{H_d}^j\epsilon_{ki}H_u^k + ik_4\lambda'\psi_{H_d}^i\epsilon_{ki}H_u^k\end{aligned}$$

Plug in Higgs VEVs:

$$H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix} \quad H_d = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix} \quad \Rightarrow \quad \mathcal{L}_{mass} = -\frac{1}{2} \begin{pmatrix} \psi^+ & \psi^- \end{pmatrix} \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix} \begin{pmatrix} \psi^+ \\ \psi^- \end{pmatrix} + h.c.$$

$$\psi_i^+ = \begin{pmatrix} -i\lambda^+ \\ \psi_{H_u}^1 \end{pmatrix} \quad \psi_i^- = \begin{pmatrix} -i\lambda^- \\ \psi_{H_d}^2 \end{pmatrix} \quad X = \begin{pmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{pmatrix}$$

Recall that without k's:

$$X^{SUSY} = \begin{pmatrix} M & \sqrt{2}m_W \sin \beta \\ \sqrt{2}m_W \cos \beta & \mu \end{pmatrix} \quad \text{Only 2 new parameters}$$

Look at effective mass matrix:  $\begin{pmatrix} X_{11}^{eff} & X_{12}^{eff} \\ X_{21}^{eff} & X_{22}^{eff} \end{pmatrix}$

$$= \begin{pmatrix} M & (g + \delta g_u)v \sin \beta (1 - \sqrt{2} \frac{k_1}{g + \delta g_u} \cot \beta) \\ (g + \delta g_d)v \cos \beta (1 + \sqrt{2} \frac{k_3}{g + \delta g_d} \tan \beta) & \mu \end{pmatrix}$$

enhanced corrections  
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$$\boxed{\frac{X_{21}^{eff}}{X_{21}^{SUSY}} = 1 + \sqrt{2} \frac{k_3}{g} \tan \beta = 1 + \delta_{21}}$$

Now we need to isolate  $X_{21}^{eff}$  in terms of physical parameters in the Chargino Sector. Assume no SUSY relations between the parameters of the Charginos.

Chargino Mass matrices are diagonalized by two Unitary matrices U and V.

$$VX^\dagger XV^{-1} = U^* XX^\dagger U^T = \begin{pmatrix} m_{\chi_1^+}^2 & 0 \\ 0 & m_{\chi_2^+}^2 \end{pmatrix}$$

$$U^* XV^{-1} = \begin{pmatrix} m_{\chi_1^+} & 0 \\ 0 & m_{\chi_2^+} \end{pmatrix}$$

This works for any matrix X: Most General U and V are parameterized as

$$U^* = \begin{pmatrix} \cos \theta_L & e^{i\beta_L} \sin \theta_L \\ -e^{-i\beta_L} \sin \theta_L & \cos \theta_L \end{pmatrix} \quad \text{and} \quad V = \begin{pmatrix} e^{i\gamma_1} & 0 \\ 0 & e^{i\gamma_2} \end{pmatrix} \begin{pmatrix} \cos \theta_R & e^{-i\beta_R} \sin \theta_R \\ -e^{i\beta_R} \sin \theta_R & \cos \theta_R \end{pmatrix}$$

$$(X_{11}, X_{22}, X_{12}, X_{21}) \rightarrow (m_{\chi_1^+}, m_{\chi_2^+}, \theta_R, \theta_L, \beta_R, \beta_L, \gamma_1, \gamma_2)$$

This parameterization does not assume SUSY relations between elements of the Chargino Mass matrix.

Look at effective mass matrix:  $\begin{pmatrix} X_{11}^{eff} & X_{12}^{eff} \\ X_{21}^{eff} & X_{22}^{eff} \end{pmatrix}$

$$= \begin{pmatrix} M & (g + \delta g_u)v \sin \beta (1 - \sqrt{2} \frac{k_1}{g + \delta g_u} \cot \beta) \\ (g + \delta g_d)v \cos \beta (1 + \sqrt{2} \frac{k_3}{g + \delta g_d} \tan \beta) & \mu \end{pmatrix}$$

enhanced corrections  
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$$(X_{11}, X_{22}, X_{12}, X_{21}) \rightarrow (m_{\chi_1^+}, m_{\chi_2^+}, \theta_R, \theta_L, \beta_R, \beta_L, \gamma_1, \gamma_2)$$

This parameterization does not assume SUSY relations between elements of the Chargino Mass matrix.

$X_{12}$  and  $X_{21}$  can be complex

For simplicity assume CP conservation

$$(M, |\mu|, X_{12}, X_{21}) \rightarrow (m_{\chi_1^+}, m_{\chi_2^+}, \theta_R, \theta_L)$$

Polarized or unpolarized  $e^+e^-$  collisions can be used to extract  $(m_{\chi_1^+}, m_{\chi_2^+}, \theta_{R,L})$

(Choi, Djouadi, Guchait, Kalinowski, Song, Zerwas)

$$\Delta = \left( (M^2 + |\mu|^2 + (X_{12}^2 + X_{21}^2))^2 - 4(M^2|\mu|^2 + X_{12}^2X_{21}^2 - 2M|\mu|X_{12}X_{21}\cos\Phi) \right)^{\frac{1}{2}}$$

$$m_{\chi_{1,2}^\pm}^2 = \frac{1}{2} \left( M^2 + |\mu|^2 + X_{12}^2 + X_{21}^2 \mp \Delta \right)$$

$$\cos 2\theta_{L,R} = -\frac{M^2 - |\mu|^2 \pm (X_{12}^2 - X_{21}^2)}{\Delta}$$

## 4 Equations

$$C_{RL}^+(m_{\chi_2^\pm}^2 - m_{\chi_1^\pm}^2) = 2(M^2 - \mu^2)$$

$$C_{RL}^-(m_{\chi_2^\pm}^2 - m_{\chi_1^\pm}^2) = 2(X_{12}^2 - X_{21}^2)$$

$$m_{\chi_2^\pm}^2 + m_{\chi_1^\pm}^2 = M^2 + \mu^2 + X_{12}^2 + X_{21}^2$$

$$\Delta = m_{\chi_2^\pm}^2 - m_{\chi_1^\pm}^2$$

where:  $C_{RL}^+ = -(\cos 2\theta_R + \cos 2\theta_L)$        $C_{RL}^- = \cos 2\theta_R - \cos 2\theta_L$

### Perturb SUSY relations

$$X_{12} = \sqrt{2}m_W \sin \beta (1 + \delta_{12})$$

$$X_{21} = \sqrt{2}m_W \cos \beta (1 + \delta_{21})$$

$$2f^{\frac{1}{2}}(m_{\chi_2^\pm}^2 - m_{\chi_1^\pm}^2 - f^{\frac{1}{2}}) = g\delta_{21} + h\delta_{12}$$

$f$ ,  $g$ , and  $h$  are complicated functions of the physical parameters

After some algebra ...

---

$$\delta_{21} = \frac{2s_\beta^2 f^{1/2}(\Delta - f^{1/2}) - \frac{1}{2}h \left[ c_{2\beta} + \frac{C_{RL}^{-} (m_{\chi_2^\pm}^2 - m_{\chi_2^\pm}^1)}{4m_W^2} \right]}{hc_\beta^2 + gs_\beta^2}$$

---

where  $\delta_{21} = \sqrt{2} \frac{k_3}{g} \tan \beta$   $\delta_{21} = (0.2 \sim 0.02)$

for 3 earlier points:  $\delta_{21} = (0.027, 0.074, 0.22)$

Look at effective mass matrix:  $\begin{pmatrix} X_{11}^{eff} & X_{12}^{eff} \\ X_{21}^{eff} & X_{22}^{eff} \end{pmatrix}$

$$= \begin{pmatrix} M & (g + \delta g_u)v \sin \beta (1 - \sqrt{2} \frac{k_1}{g + \delta g_u} \cot \beta) \\ (g + \delta g_d)v \cos \beta (1 + \sqrt{2} \frac{k_3}{g + \delta g_d} \tan \beta) & \mu \end{pmatrix}$$

enhanced corrections  
to SUSY relations

$$\boxed{\frac{X_{21}^{eff}}{X_{21}^{SUSY}} = 1 + \sqrt{2} \frac{k_3}{g} \tan \beta = 1 + \delta_{21}}$$

Now we need to isolate  $X_{21}^{eff}$  in terms of physical parameters in the Chargino Sector. Assume no SUSY relations between the parameters of the Charginos.

After some algebra ...

---

$$\delta_{21} = \frac{2s_\beta^2 f^{1/2}(\Delta - f^{1/2}) - \frac{1}{2}h \left[ c_{2\beta} + \frac{C_{RL}^{-}(m_{\chi_2^\pm}^2 - m_{\chi_2^0}^1)}{4m_W^2} \right]}{hc_\beta^2 + gs_\beta^2}$$

---

where  $\delta_{21} = \sqrt{2} \frac{k_3}{g} \tan \beta$   $\delta_{21} = (0.2 \sim 0.02)$

for 3 earlier points:  $\delta_{21} = (0.027, 0.074, 0.22)$

Are these local operators the dominate contribution to  $\delta_{21}$  ?

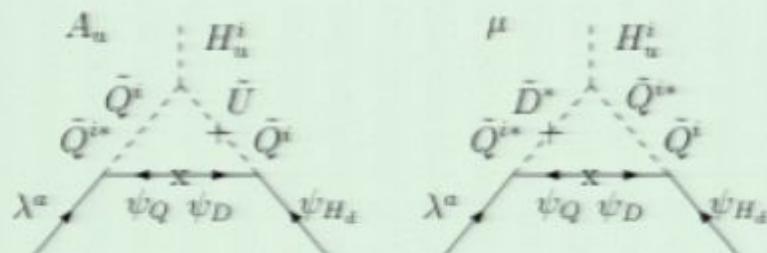
Squarks (large Yukawa couplings for 3rd Gen)

Recall that in Gauge Mediation:

$$\frac{m_{\tilde{t}, \tilde{b}}}{m_{\tilde{e}_R}} \sim \frac{g_3^2}{g_1^2}$$

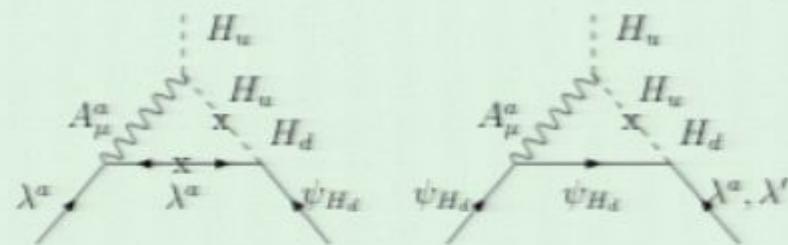
$$m_{\tilde{e}_R} > 73 \text{ GeV} \rightarrow m_{squark} > 850 \text{ GeV}$$

Integrate out squarks



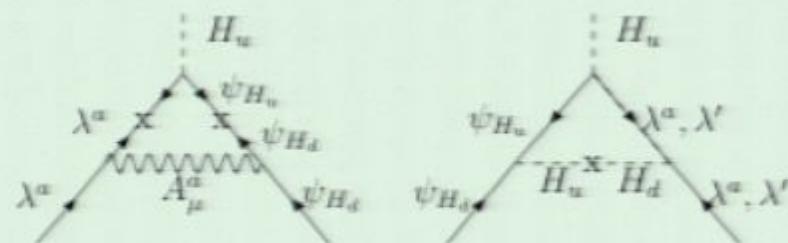
$$\sim \frac{m_b v}{m_{sq}^2} \quad (\text{Effects suppressed})$$

## Higgs/Neutralinos/Charginos/Gauge Bosons



(a)

(b)



(c)

(d)

$$\sim g^3$$

## Sleptons



$$\sim gh_l^2$$

$$\delta_{21} = \frac{2s_\beta^2 f^{1/2}(\Delta - f^{1/2}) - \frac{1}{2}h \left[ c_{2\beta} + \frac{C_{RL}^{-}(m_{\chi_2^\pm}^2 - m_{\chi_2^\pm}^1)}{4m_W^2} \right]}{hc_\beta^2 + gs_\beta^2}$$

Corrections to this relation from light particle effects are at most

$$\sim \frac{g^2}{16\pi^2} \tan \beta f(m_i^2) \quad \begin{aligned} m_i &= \text{light mass} \\ f(m_i^2) &\sim O(1) \end{aligned}$$

parametrically smaller than Messenger effects for large Messenger Yukawas

$$\sim \frac{\alpha\beta}{16\pi^2} \tan \beta$$

These local effects can be dominant if  $\alpha\beta > g^2$ .

## Conclusion

- SUSY predicts dim-4 “wrong” Higgs interactions in the Chargino/Neutralino Sector are zero at tree-level.
- Low scale Gauge Mediation with Messenger/Higgs interactions generate these new operators at 1-loop.
- New interactions can induce leading large corrections to Supersymmetric relations at large  $\tan \beta$
- The physical parameters of the Chargino sector can be used in combination with the parameters of the Electroweak sector to isolate the corrections to the SUSY relations.
- Similar effects exist in the Neutralino sector, these are presently under study along with CP violation