Towards a complete theory of gauge mediation

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Tomer Volansky
(Institute for Advanced Study, Princeton)

Base on:
C. Csaki, A. Falkowski, Y. Nomura, TV, [arXiv:0809.4492]
C. Csaki, A. Falkowski, Y. Nomura, TV, in writing.
N. Seiberg, TV, B. Wecht, [arXiv:0809.4437]
TV, B. Wecht, work in progress.

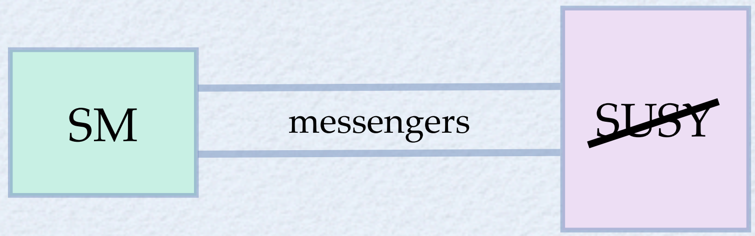
Motivation

WHY?

- Thanks to the "spilled helium" incident, we can all relax again and continue guessing what we'll be found at the LHC..
- One of the favorite candidates for the LHC is SUSY.
- Nevertheless, we are still far from finding a completely satisfactory model.
- Among the open questions:
  - Mechanism of SUSY breaking.
  - Mechanism of mediation.
  - Spectrum.
- The SUSY-flavor problem points towards gauge mediation.

Gauge Mediation

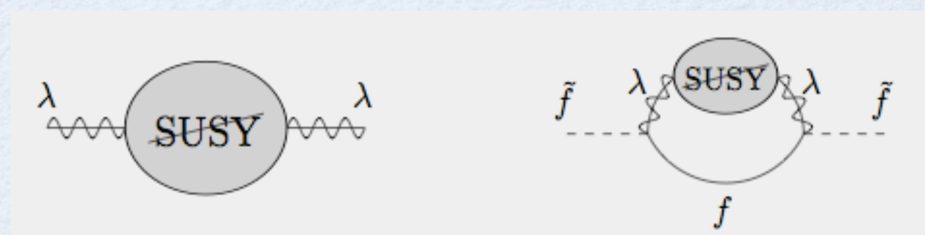
- Idea: SUSY-breaking is mediated through gauge interactions.



[Dine, Fischler, Nappi, Ovrut, Alvarez-Gaume, Claudson, Wise..]

- Theory is very predictive, especially in the minimal form.

- Soft masses take the form:



$$M_a \approx g_a^2 \frac{N}{16\pi^2}\Lambda, \quad m_I^2 \approx \sum_{a=1,2,3} \frac{g_a^4 C_I^a}{8\pi^2}\frac{N}{16\pi^2}\Lambda^2.$$

- Λ is the effective SUSY breaking scale. In perturbative theory: $\Lambda = F/M$.

Gauge Mediation

Still GMSB suffers from various problems:

- Little hierarchy.
- μ-B_μ.
- SUSY-CP.
- A complete model is typically complicated - not found yet.

In this talk we take a new approach to resolve many if not all of these issues.

OUTLINE

- The $\mu - B_\mu$ Problem
- A New Approach to $\mu - B_\mu$
- Flavor and CP
- Phenomenology
- Realizations:
  - 5D RS model
  - 4D Semi-direct Gauge Mediation
- Outlook and Summary

THE $\mu - B_\mu$ PROBLEM

The μ Problem in the MSSM

- The vacuum solution in MSSM is determined by the parameters of the Higgs sector: μ, B_μ, m_{H_u} , m_{H_d}.

- Minimization of tree-level potential:

$$
\begin{aligned}
\frac{m_Z^2}{2} &= -|\mu|^2 - \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{\tan^2\beta - 1}, \\
\sin 2\beta &= \frac{2B_\mu}{2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2}.
\end{aligned}
$$

- The first eq. demonstrates the μ-problem: The SUSY preserving μ parameter must be related to the SUSY-breaking soft masses. In the absence of tuning $\Rightarrow \mu \sim \mathcal{O}(m_Z)$

- In the limit $\mu \to 0$, MSSM has an enhanced PQ symmetry.

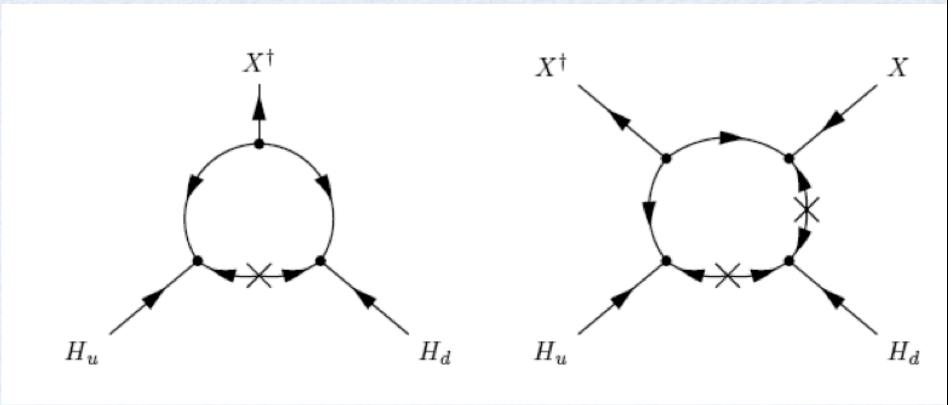
- If SUSY breaking breaks PQ, a μ parameter is generated.

The μ problem in GMSB

- The above solution works well in gravity mediation but not in GMSB.
- Reason: Gauge interactions do not break PQ.
- The Higgs fields must be directly coupled to SUSY breaking sector.
- Such couplings typically generate μ and B_μ at one loop.

$$\int d^4\theta \frac{X^\dagger}{M} H_u H_d \quad \rightarrow \quad \int d^2\theta \mu H_u H_d$$

$$\int d^4\theta \frac{X^\dagger X}{M^2} H_u H_d \quad \rightarrow \quad B_\mu H_u H_d$$



The μ problem in GMSB

- Thus in GMSB: $B_\mu \sim 16\pi^2\mu^2 \gg \mu^2$.

$$\begin{aligned} \frac{m_Z^2}{2} &= -|\mu|^2 - \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{\tan^2\beta - 1} && (1) \\ \sin 2\beta &= \frac{2B_\mu}{2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2} && (2) \end{aligned}$$

- Two possibilities:
  - $m_{H_u}^2 \sim m_{H_d}^2 \sim \mu^2 \Rightarrow$ (2) has no solution.
  - $m_{H_u}^2 \sim m_{H_d}^2 \sim B_\mu \Rightarrow$ Fine tuning since $\mu \gtrsim m_Z$.

This is the $\mu - B_\mu$ problem.

[Dvali, Giudice, Pomarol, 1996]

A NEW APPROACH TO μ-B_μ

Basic Idea

- The common lore: Solution must reduce hierarchy, $\mu^2 \sim B_\mu$, through non-trivial dynamics.
- This is not necessary. It is sufficient that $2B_\mu < m^2_{H_u} + m^2_{H_d} + 2|\mu|^2$.
- This suggests the solution:

$$m^2_{H_d} \gg B_\mu \gg m^2_{H_u} \sim \mu^2$$

- Consider mass parameters:

$$\mu \approx \epsilon \Lambda_H \qquad B_\mu \approx \epsilon \Lambda_H^2$$

$$m^2_{H_u} \approx \epsilon^2 \Lambda_H^2 \qquad m^2_{H_d} \approx \Lambda_H^2$$

- For EWSB, two conditions must be fulfilled:

$$2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2 > 2B_\mu \quad (1)$$

$$(B_\mu)^2 > (|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_d}^2) \quad (2)$$

- (1) is fulfilled due to $m_{H_d}^2 \gg B_\mu$. One finds,

$$\tan\beta \approx \frac{m_{H_d}^2}{B_\mu} \approx \frac{1}{\epsilon}.$$

- (2) usually requires negative $m_{H_u}^2$. Typically generated through running with large $\tilde{m}_t$.

- In this case there is no need for RGEs to trigger EWSB:

EWSB is triggered by (possibly strong) dynamics that generate μ and B_μ.

- Naively, m_Z^2 is naturally obtained without fine tuning:

$$m_Z^2 \simeq -\mu^2 - m_{H_u}^2 + \frac{m_{H_d}^2}{\tan^2\beta} \sim \epsilon^2 \Lambda_H^2$$

- The situation is more complicated. As we show, to eliminate all fine tuning from this sector, H_d needs to be strongly coupled.

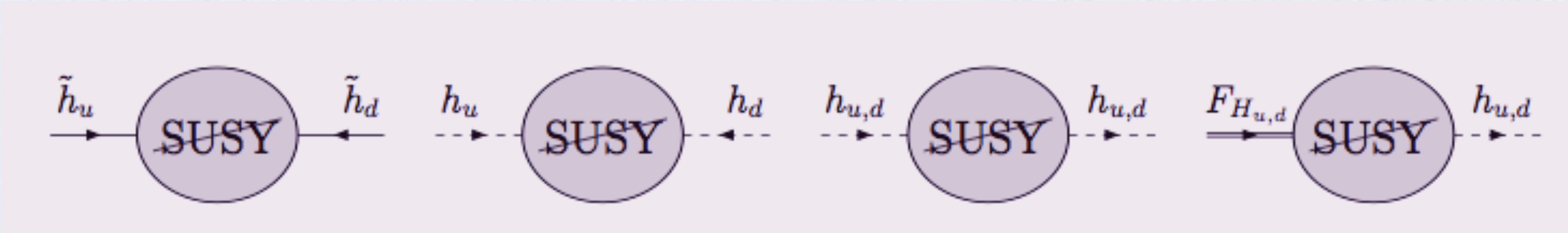
- LEP-II bound on $m_h \gtrsim 114$ GeV suggests some fine tuning. Without resolving this little hierarchy, there is no compelling reason to eliminate fine tuning in μ-B_μ.

Implementation

- The above solution to the μ-B_μ requires dynamics to naturally generate the pattern.
- For that we couple $H_{u,d}$ directly to supersymmetry breaking sector. At scale M where supersymmetry breaking effects are mediated to SSM:

$$\boxed{\mathcal{L} = \int d^2\theta \, (\lambda_u H_u \mathcal{O}_u + \lambda_d H_d \mathcal{O}_d) + \text{h.c.}}$$

- $\mathcal{O}_{u,d}$ operators consisting of fields in supersymmetry breaking sector (for example, messenger fields).
- We use convention where $\lambda_{u,d}$ are dimensionless.



- Integrating out the SUSY-breaking sector at M:

$$\delta\mathcal{L} = \int d^4\theta \left[\langle \mathcal{O}_u^\dagger \mathcal{O}_u\rangle |\lambda_u H_u|^2 + \langle \mathcal{O}_d^\dagger \mathcal{O}_d\rangle |\lambda_d H_d|^2 + (\lambda_u \lambda_d \langle \mathcal{O}_u \mathcal{O}_d\rangle H_u H_d + \text{h.c.})\right]$$

- The correlators are parametrized as

$$\begin{aligned}
\langle \mathcal{O}_u^\dagger \mathcal{O}_u\rangle &= \hat{Z}_u + (\theta^2\, \mathcal{C}_{A_u} + \bar{\theta}^2\, \mathcal{C}^*_{A_u})\Lambda_H + \theta^2\bar{\theta}^2\, \mathcal{C}_{m_u}\Lambda_H^2 \\
\langle \mathcal{O}_d^\dagger \mathcal{O}_d\rangle &= \hat{Z}_d + (\theta^2\, \mathcal{C}_{A_d} + \bar{\theta}^2\, \mathcal{C}^*_{A_d})\Lambda_H + \theta^2\bar{\theta}^2\, \mathcal{C}_{m_d}\Lambda_H^2 \\
\langle \mathcal{O}_u \mathcal{O}_d\rangle &= \hat{Z}_{ud} + (\theta^2\, \mathcal{C}_{\bar{\mu}} + \bar{\theta}^2\, \mathcal{C}_{\mu})\Lambda_H + \theta^2\bar{\theta}^2\, \mathcal{C}_{B_\mu}\Lambda_H^2
\end{aligned}$$

- Λ_H is the effective SUSY-breaking scale in the Higgs sector.
  $\Lambda_H \simeq \Lambda$ (normal gauge-mediation scale) up to order one coefficients.

- If SUSY sector is perturbative, $\Lambda_H = F/M$.

- Diagrams generate (ignoring A-terms for the moment):

$$\mu \approx \lambda_u \lambda_d \mathcal{C}_\mu \Lambda_H \qquad\qquad m^2_{H_u} \approx |\lambda_u|^2 \mathcal{C}_{m_u} \Lambda_H^2$$
$$B\mu \approx \lambda_u \lambda_d \mathcal{C}_{B\mu} \Lambda_H^2 \qquad\qquad m^2_{H_d} \approx |\lambda_d|^2 \mathcal{C}_{m_d} \Lambda_H^2$$

- The usual solution assumes some dynamics such that $C_{B_\mu} \lesssim C_\mu^2$.
  - In perturbative case, C_{B_μ} arises at two loop.
  - In strongly coupled case this is due to renormalization in the hidden sector.

- For our solution we assume no special structure. Through NDA:

$$\mathcal{C}_{A_{u,d}} \approx \mathcal{C}_{m_{u,d}} \approx \mathcal{C}_\mu \approx \mathcal{C}_{\bar{\mu}} \approx \mathcal{C}_{B\mu} \approx \frac{N_H}{16\pi^2}.$$

  N_H is the effective number of messengers in Higgs sector.

- If we further take $\lambda_u \sim \lambda_d$,

$$B \equiv \frac{B\mu}{\mu} \approx \Lambda_H \approx O(10 - 100) \text{ TeV}$$

  implying that all the Higgs sector parameters cannot be of order m_Z. This is the μ-B_μ problem.

- We therefore have,

$$\mu \approx \lambda_u \lambda_d \frac{N_H}{16\pi^2} \Lambda_H \qquad B_\mu \approx \lambda_u \lambda_d \frac{N_H}{16\pi^2} \Lambda_H^2 \qquad m_{H_{u,d}}^2 \approx \lambda_{u,d}^2 \frac{N_H}{16\pi^2} \Lambda_H^2$$

- To generate the hierarchy we take

$$\lambda_u \ll \lambda_d \qquad \Longrightarrow \qquad \mu^2 \sim m_{H_u}^2 \ll B_\mu \ll m_{H_d}^2$$

- The hierarchy depends on physics above the scale M and is completely calculable.

- Ignoring for a moment quantum corrections, we can substitute the solution into m_Z^2:

$$m_Z^2 \sim |\lambda_u|^2 \frac{N_H}{16\pi^2} \left[-|\lambda_d|^2 \frac{N_H}{16\pi^2} + \epsilon_{FT} \right] \Lambda_H^2$$

- To have no fine tuning, this suggests a strongly coupled H_d:

$$\lambda_d \simeq \frac{4\pi}{\sqrt{N_H}} \qquad \epsilon \equiv \frac{\lambda_u}{\lambda_d}.$$

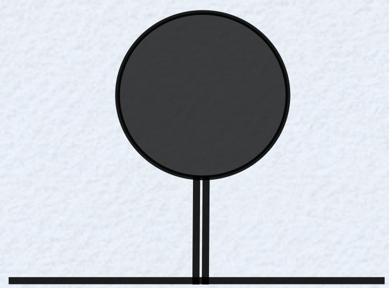
- For smaller values of λ_d, cancellation of order ϵ_{FT} is required.

- Quantum corrections may (for a heavy stop) reintroduce the tuning. Without resolving this "irreducible" fine tuning, there is no need to consider large λ_d.

- Constraints on λ_d:

  1. SUSY breaking sector must be strongly coupled otherwise λ_d hits a Landau pole.
  2. Large λ_d violates "messenger parity" and may therefore lead to large FI for $U(1)_Y$.

- Large FI terms generate masses of order $\delta m^2 \sim g_1^2 Y \xi$ through the diagram:



- Messenger parity ensures no FI term through the symmetry:

$$V_Y \leftrightarrow -V_Y \qquad\qquad \eta \leftrightarrow \bar{\eta}$$

- Even without messenger parity, the above is solved if λ_d is slightly smaller than $4\pi/\sqrt{N_H}$.

High energy behavior of $\lambda_{u,d}$

- How do we obtain the hierarchy $\lambda_u \ll \lambda_d$?
- Consider the couplings at some high scale $M_* \gg M$ (e.g. GUT or $M_{\rm Pl}$):

$$\mathcal{L} = \int d^2\theta \, (\tilde{\lambda}_u H_u \mathcal{O}_u + \tilde{\lambda}_d H_d \mathcal{O}_d) + \text{h.c.},$$

- $\lambda_{u,d}$ are obtained by evolving $\tilde{\lambda}_{u,d}$ from M_* down to M and multiplying by appropriate powers of M.
- If theory is weakly coupled above M:

$$\dim(\mathcal{O}_{u,d}) \simeq 2 \qquad \tilde{\lambda}_u(M_*) \ll \tilde{\lambda}_d(M_*)$$

This is completely natural for dimensionless couplings.

HIGH ENERGY BEHAVIOR OF $\lambda_{u,d}$

- If theory is strongly coupled above M, large anomalous dimensions can generate the hierarchy,

$$\lambda_{u,d} \sim \left(\frac{M}{M_*}\right)^{\dim(\mathcal{O}_{u,d})-2}$$

- As opposed to strongly coupled theories that generate $C_{B_\mu} \ll C_\mu$, such solution is calculable.
- This has a dual Randall-Sundrum description which we discuss later.

FLAVOR AND CP

The SUSY Flavor Problem

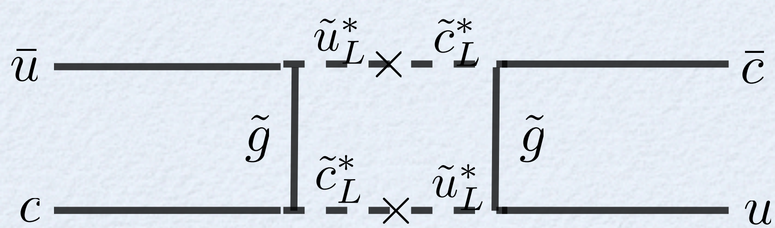
- SUSY breaking parameters are generated by gauge mediation and direct higgs couplings. They are therefore flavor universal.
- No flavor problem if:
    1. No additional sources for SSM SUSY breaking parameters.
    2. Low energy radiative corrections do not induce large flavor violation.
- Direct couplings between SUSY sector and SSM at the scale M, are typically forbidden with the use of discrete symmetries.
- Couplings to SSM are possible through non-renormalizable interactions (e.g. if hidden sector is strongly coupled), but those are highly suppressed.

The SUSY Flavor Problem

- Both $m^2_{H_d}$ and $\tan\beta$ are enhanced $\Rightarrow$ could lead to dangerous flavor violation through radiative corrections:

$$(m^2_Q)_{ij} \simeq \frac{1}{2}(m^2_D)^\dagger_{ij} \simeq -\frac{(y_d^\dagger y_d)_{ij}}{8\pi^2}\left(m^2_{H_d} + |A_{H_d}|^2\right)\ln\frac{M}{m_{H_d}},$$

- $A_{H_d} \simeq \lambda_d^2 \frac{N_H}{16\pi^2}\Lambda_H$ are only important if $\lambda_d \sim 4\pi/\sqrt{N_H}$.
- In the super-CKM basis ($y_{u,d}$ are diagonal), the enhanced contribution to non-diagonal masses appear only in left-handed up-type squarks.
- The only mass insertion contributing to FCNCs is δ^u_{LL}.
- Largest constraint is still weak: $(\delta^u_{LL})_{12} \lesssim (10^{-2} - 10^{-1})$



SUSY CP problem

- Flavor diagonal phases may in principle exist:

$$\phi_{A,a} = \arg(A_f M_a^*) \qquad \phi_{B,a} = \arg(B M_a^*)$$

- For TeV scale soft masses, the latter are constrained through EDMs to be $\phi_{A,B} \lesssim 10^{-2}$.

This is the SUSY-CP problem.

SUSY CP Problem

- Our framework allows for simple solution.
- Assume the SUSY-breaking sector preserves CP.
- Then the phases in $\lambda_{u,d}$ can be rotated away through a redefinition of $H_{u,d}$.

$$\phi_{A,a} = \phi_{B,a} = 0$$

- Phases are reabsorbed in Yukawa couplings and have no physical effects.
- Possible example for CP preserving sector is the 3-2 model with extra messenger fields.
- This solution is special for the linear couplings. Typically, imposing CP on hidden sector is not enough (e.g. Giudice-Masiero).

BASIC PHENOMENOLOGY

- Our framework leads to several distinct phenomenological consequences.
- The hierarchy $\mu^2 \sim m_{H_u}^2 \ll B_\mu \ll m_{H_d}^2$ implies heavy CP-odd neutral Higgs:
$$m_{A^0}^2 = m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2 \gg m_Z^2$$
- This is the decoupling limit of the MSSM - one Higgs doublet at low energy. [Gunion, Huber, 2003]
- The Higginos are light (of order μ) $\Rightarrow$ light charginos and neutralino is Higgssino-like for $\mu < M_1$.
- Large m_{H_d} induces large corrections through RGEs:
(I). Large negative corrections to third generation down squarks:
$$m_{\tilde{q}_3}^2 \simeq \frac{1}{2} m_{\tilde{b}}^2 \simeq \frac{y_b^2}{8\pi^2}(m_{H_d}^2 + |A_{H_d}|^2) \ln \frac{M}{m_{H_d}}$$
This sets an upper bound on $\tan\beta$.

(II) Large $m_{H_d}^2$ induces large FI D-term for $U(1)_Y$: $\mathrm{Tr}Y m^2$.

- This contributes to soft masses through RGEs:

$$\delta m_I^2 \simeq Y_I \frac{3g_1^2}{40\pi^2} m_{H_d}^2 \ln \frac{M}{m_{H_d}}$$

- Typically in gauge mediation this contribution vanishes and two sum-rules result:

$$\mathrm{Tr}Y m^2 = \mathrm{Tr}(B-L)m^2 = 0.$$

[Meade, Seiberg, Shih, 2008]

(Trace over one generation).

- In our case, $\mathrm{Tr}Y m^2 - \frac{5}{4}\mathrm{Tr}(B-L)m^2 = 0$ is approximately RG invariant for first two generations. Thus,

$$6m_Q^2 + 3m_U^2 - 9m_D^2 - 6m_L^2 + m_E^2 = 0$$

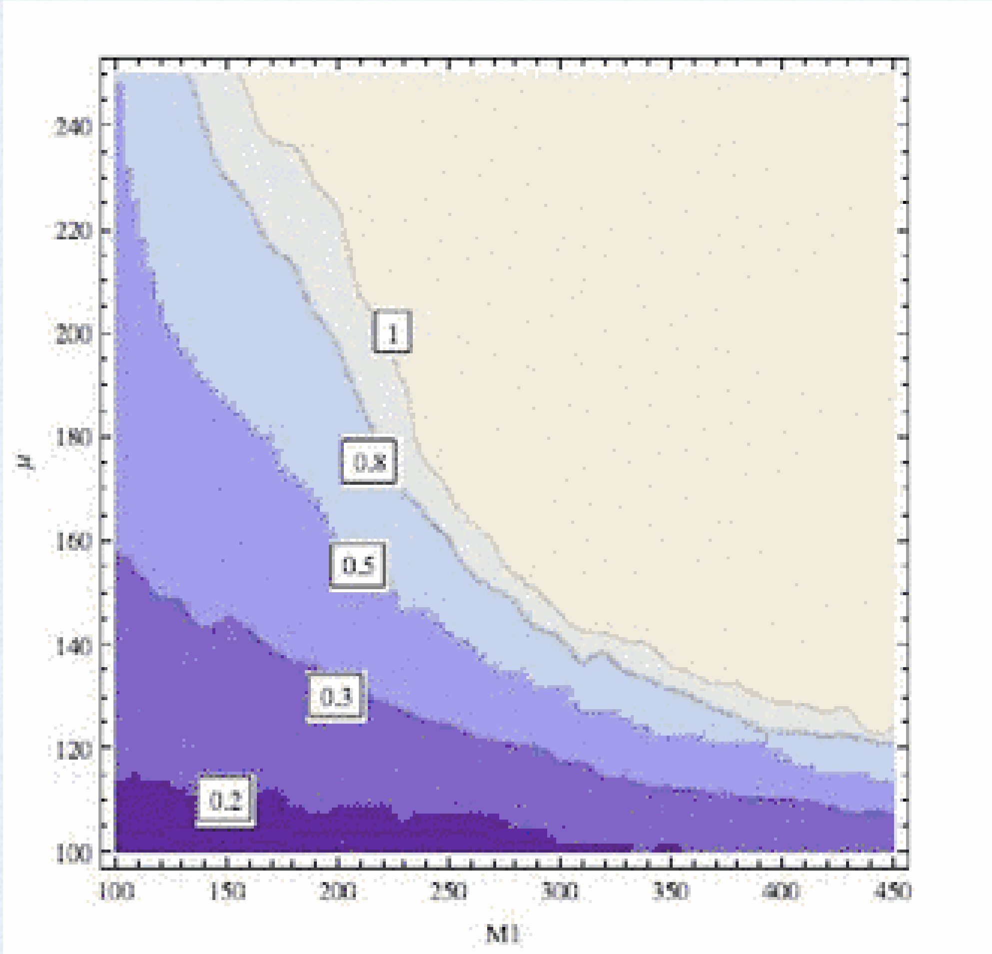
while the traditional sum-rule becomes:

$$\mathrm{Tr}Y m^2 \simeq \frac{g_1^2}{4\pi^2} m_{H_d}^2 \ln \frac{M}{m_{H_d}}$$

- Such measurement would point towards large $m_{H_d}^2$ and therefore this scenario.

- GMSB is typically more constrained due to the characteristic $2\gamma + \not{E}_T$ signature from $\tilde{\chi}_1^0 \to \tilde{G} + \gamma$.

- Tevatron searches constrains $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^+}$ which translates into bound on $\mu - M_1$ plane (applies if NLSP decays in detector).



[Reece, Talk at KITP, 2008]

EXAMPLES

	Λ		Λ_H	λ_u	λ_d	$\tan\beta$	$m^2_{H_u}$	μ	m_{h^0}	m_{A^0}	$m_{\tilde{\chi}^0_1}$	$m_{\tilde{\chi}^+_1}$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{\tau}_1}$
M1	60		18	0.50	2.795	8.01	$(521)^2$	160	115	4030	150	159	1360	1516	353
M2	40		25	0.22	1.66	10.71	$(303)^2$	164	113	3330	140	158	923	1038	190
M3	19	35	10	0.28	3.05	8.47	$(251)^2$	160	106	2470	119	148	450	576	195
M4	19	35	10	0.27	3.93	9.35	$(280)^2$	209	106	3150	140	193	438	577	137

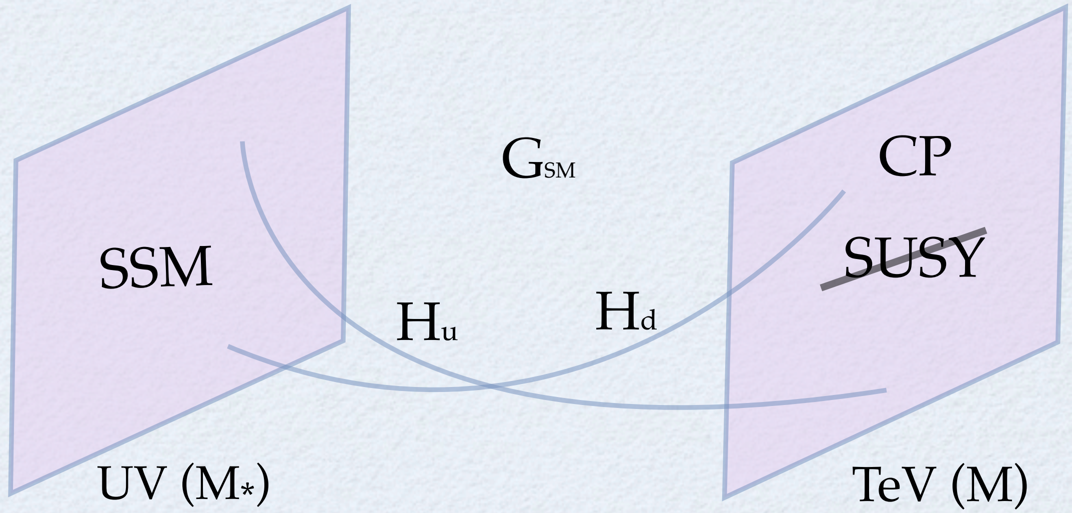
M1: Conservative. Minimal GMSB with heavy stop. Higgs sufficiently heavy, but theory suffers from usual ('irreducible') fine tuning.

M2: Minimal GMSB. Stop is lighter, but (possibly) small new contributions to Higgs quartic is required.

M3,M4: Squashed spectrum by assuming different $\Lambda_{1,2,3} = (F/M)_{1,2,3}$. Stop mass is lowered (fine tuning of 10%). Sizable extra contribution to quartic is required.

- In all cases, $m^2_{H_u}$ is positive at low energy, μ is small, m_{A^0} is above TeV.

5D Realization



- Dual to a spontaneously broken SCFT at scale M.
- SM fields are elementary and reside on UV brane.
  Higgs and gauge fields are in the bulk and interact with strongly coupled sector.
- The profiles of $H_{u,d}$ generate the hierarchy $\lambda_u \ll \lambda_d$.
- Soft masses are induced by bulk gauge/gaugino loops. One finds,

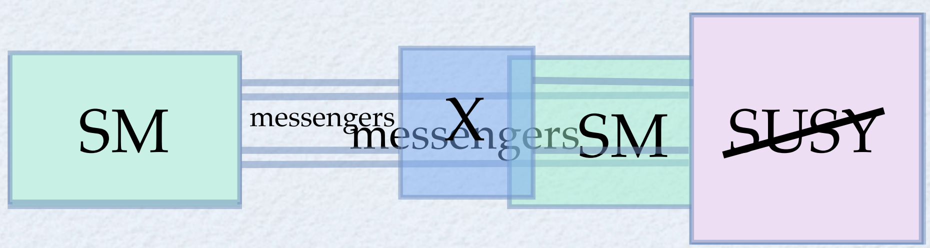
$$m_{\tilde{f}}^2 = \sum_a \frac{C_2^a}{16\pi^2} {m_{1/2}^a}^2 g_*^2,$$

[Nomura, Tucker-Smith, 2003]

- Result is precisely that of gauge mediation through the AdS/CFT.

Semi-direct gauge mediation

- The scenario above still requires a full 4D description that incorporates the sector that breaks supersymmetry.
- To date, there is no simple and fully working model of gauge mediation.
- The two main approaches are minimal and direct gauge mediation.
  - Direct gauge mediation typically suffers from Landau pole problem.
  - No completely satisfactory MGM - models are complicated and singlets acquire large tadpoles.
- A new approach is to have something in between minimal and direct.
- Messengers are directly coupled to SUSY-breaking gauge group, but do not participate in the breaking dynamics.



Model

- The model is the 3-2 model with extra messengers. $G_{\text{hidden}} = SU(3) \times SU(2)$ with matter content:

	$SU(3)$	$SU(2)$
Q^r_A	$\square$	$\square$
$\tilde{u}_r$	$\overline{\square}$	$\mathbf{1}$
$\tilde{d}_r$	$\overline{\square}$	$\mathbf{1}$
L^A	$\mathbf{1}$	$\square$
ℓ^{Ai}	$\mathbf{1}$	$\square$

and an $Sp(N_f) \times U(1) \times U(1)_R$ invariant superpotential:

$$W_{eff} = \boxed{hQ\tilde{d}L} + \frac{\Lambda_3^7}{Q^2\tilde{u}\tilde{d}} + \frac{m}{2}\mathcal{J}_{ij}\ell^{Ai}\ell^{Bj}\epsilon_{AB}$$

- The minimum of the theory is not influenced by the presence of the heavy messengers and is calculable for $h \ll g_2 \ll g_3$.

- h controls SUSY-breaking:

$$\langle\Phi\rangle \propto h^{-1/7} \qquad F_\Phi \propto h^{5/7}$$

Messenger spectrum

- The goal is to compute the SUSY-breaking spectrum of the messengers, l^{Ai} which in turn transmit the breaking to the SSM.

- The analysis is conveniently done in a specific Unitary gauge around a point on the moduli space $\phi_0 \in \mathcal{M}$ which satisfies $\phi^\dagger_{(0)} T^I \phi_{(0)} = 0$:

$$\phi^\dagger_{(0)} T^I \Phi = 0 \, .$$

- Upon integration out of the vector bosons one obtains a non-canonical Kahler potential at tree-level:

$$K_{\text{eff}} = \Phi^\dagger \Phi - \frac{1}{2} (\delta\Phi^\dagger T^I \delta\Phi) \, \lambda^{-1}_{IJ} \, (\delta\Phi^\dagger T^J \delta\Phi) + (\delta\Phi^5) \qquad\qquad \Phi = \phi_{(0)} + \delta\Phi$$

Messenger Spectrum

- The non-trivial metric corresponds to non-vanishing D-terms even though the minimum lies on the moduli space,

$$D_I \sim \frac{F^\dagger T^I F}{|\phi_{(0)}|^2} \propto h^{12/7}$$

- This induces soft diagonal messenger masses, $m_d^2 l^\dagger l$, which are independent of g and m.

- Off-diagonal mass terms of the form $m_{od} l^2$ (as in minimal gauge mediation) are generated at one loop:

$$m_{od} \sim \alpha_2 m \frac{F_\Phi}{\phi_{(0)}} \propto m h^{6/12}$$

Messenger Spectrum

- The messenger mass squared matrix is therefore:

$$\tilde{m}^2 \simeq \begin{pmatrix} m^2 + \frac{F_\Phi^2}{\phi_{(0)}^2} & \alpha_2 m \frac{F_\Phi}{\phi_{(0)}} \\ \alpha_2 m \frac{F_\Phi}{\phi_{(0)}} & m^2 + \frac{F_\Phi^2}{\phi_{(0)}^2} \end{pmatrix}$$

Compare to usual minimal gauge mediation:

$$\tilde{m}^2_{MGM} \simeq \begin{pmatrix} M^2 & F \\ F & M^2 \end{pmatrix}$$

- Therefore m interpolates between D-term breaking and F-term breaking.

Phenomenology

- No Landau poles
- Messenger parity automatically exist. It will be broken once $\lambda_{u,d}$ are turned on to couple l to $H_{u,d}$. Large FI D-terms can probably still be prevented rather simply (work in progress).
- Sector is CP even.
- R-symmetry is broken.
- Problem - gaugino masses vanish to leading order in F/M. This can probably be solved by considering $F/M \sim 1$ which is still calculable (work in progress).

Summary and Outlook

Summary & Outlook

- Gauge mediation is still the most attractive framework around.
- It suffers from several problems, e.g. $\mu - B_\mu$, SUSY-CP, fine tuning etc.
- The μ-B_μ problem calls for a new approach which allows for EWSB and minimal fine tuning.
- The hierarchy $\mu^2 \ll B_\mu$ is not required to be solved.
- This approach can naturally solve the SUSY-CP and allow for gauge coupling unification.

Summary & outlook

- The scenario predicts unique phenomenology:
  - Decoupled second Higgs doublet.
  - Light Higgsinos,
  - Large violation of traditional sum-rule.
  - Large corrections to sbottom and stau.
- A 5D toy model is simple to construct.
- 4D model is expected to naturally be realized in Semi-direct gauge mediation.

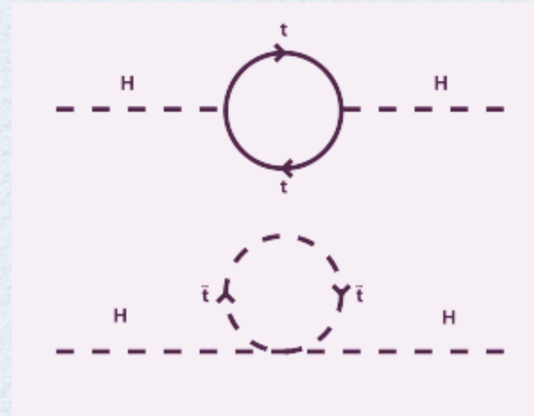
EXTRAS

EWSB and Fine Tuning

- RGEs change this picture. Two large contributions arise from

$$\delta m_{H_u}^2 = -\frac{3}{4\pi^2} y_t^2 m_{\tilde{t}}^2 \ln \frac{M}{m_{\tilde{t}}} \quad < 0$$

$$\delta m_{H_u}^2 = \frac{3}{80\pi^2} g_1^2 m_{H_d}^2 \ln \frac{M}{m_{H_d}} > 0$$



- LEP-II constrains $m_h \gtrsim 114$ GeV. For small A_t, this amounts to $m_{\tilde{t}} \gtrsim 1$ TeV.

- Thus,

$$\delta m_{H_u}^2 \gtrsim (500 \text{ GeV})^2$$

- This is an 'irreducible' amount of fine tuning of order 3%. Without a solution there is no motivation to insist on large λ_d.

- The 'irreducible' fine-tuning can be removed by additional sources to Higgs quartic.
- Quartics arising from direct coupling to SUSY-breaking sector become significant for $\lambda_u \gtrsim 0.8$.
- Further contribution can arise with extra singlets (e.g. NMSSM).

If stop is heavy:

- Typically stop-top loop is cancelled by $|\mu|^2$ term.
- In this scenario μ is always small, and top-stop contribution must be cancelled by contribution from direct coupling at M:

$$m_{H_u}^2 \simeq \lambda_u^2 \frac{N_H}{16\pi^2} \Lambda_H^2$$

or FI contribution, depending on $\tan\beta$.

Contribution to quartic

- Strong dynamics generate couplings of the form,

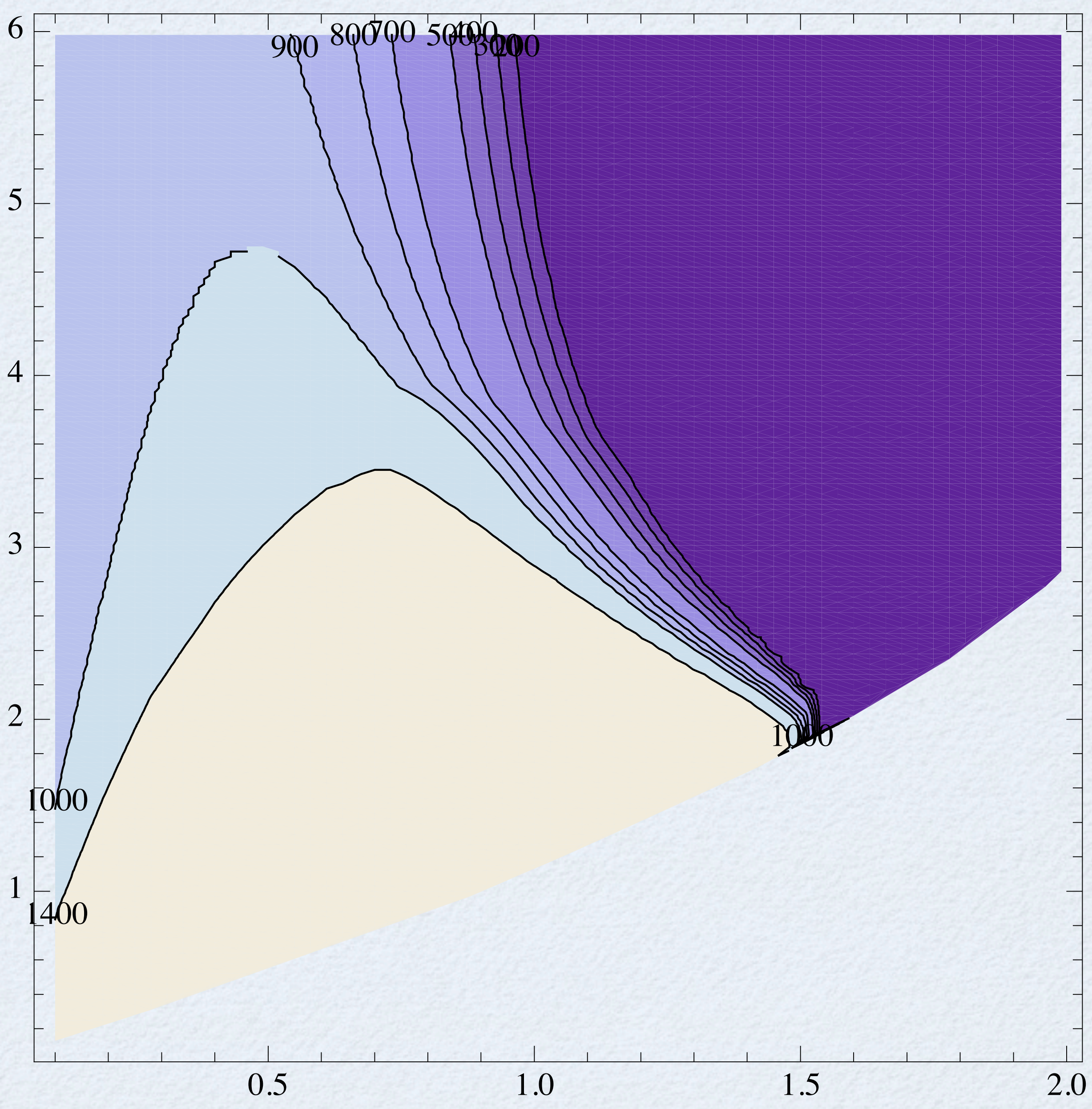
$$\frac{1}{4}\int d^4x\left[g_u|H_u|^4 + 2g_{ud}|H_u|^2|H_d|^2 + g_d|H_d|^4\right].$$

- Using NDA,

$$g_{u,d} \simeq |\lambda_{u,d}|^4\frac{N_H}{16\pi^2}, \qquad g_{ud} \simeq |\lambda_u\lambda_d|^2\frac{N_H}{16\pi^2}.$$

- Ignoring for simplicity order coefficients one finds to leading order,

$$(\Delta m_h^2)_{\text{strong}} = 2\frac{|\lambda_u|^4}{g'^2+g^2}\frac{N_H}{16\pi^2}m_Z^2\tan^2\beta\left[\frac{(m_Z^2 - {}^2)\cos^2(2\beta)}{\sqrt{({}^2 - m_Z^2)^2 + 4{}^2 m_Z^2\sin^2(2\beta)}} + 1\right].$$



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