Gauge Mediation: Review and Updates

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MSSM

- Matter and vector fields become supersymmetric

$$\text{Matter} \Rightarrow \text{ Chiral superfields } (\phi, \psi)$$

$$\text{Vector} \Rightarrow \text{Vector superfields } (\lambda, A^{\mu})$$

- Two Higgs chiral superfields

$$h \Rightarrow H_u, H_d$$

- Interaction Superpotential

$$\mathcal{L} = \int d^2\theta W, \qquad W = y_u \bar{u} Q H_u - y_d \bar{d} Q H_d - y_e \bar{e} L H_d + \mu H_u H_d$$

- Special ultraviolet finiteness properties (no quadratic divergencies)
- Address the hierarchy problem $M_{planck} \gg\gg M_{\text{weak}}$
- Better GUT unification
- Included in unification theories
  - Local supersymmetry includes gravity (Supergravity)
  - Superstring theory

SUPERSYMMETRY BREAKING

- Supersymmetry not realized at low energies

SUSY MUST BE BROKEN!!

- Soft susy breaking $\equiv$ No quadratic divergencies

SUPERSYMMETRY MUST BE BROKEN SOFTLY

$$\mathcal{L} = \mathcal{L}_{MSSM} + \mathcal{L}_{soft}$$

- $\mathcal{L}_{soft}$ = Soft terms

$$m_\lambda \lambda_\alpha \lambda^\alpha \qquad \text{Gaugino mass}$$
$$m_{sf}^2 \phi^\dagger \phi \qquad \text{Scalar mass}$$
$$A\phi^3 \,, \qquad \text{A - term}$$
$$\vdots$$

- Superpartners get masses
- Non supersymmetric interactions

?? Predictions for pattern of soft terms ??

SUSY BREAKING AND THE SSM

- Supersymmetry must be broken softly around the weak scale !!!
- Soft terms include masses for unobserved sparticles (λ, ϕ)

STANDARD PARADIGM: MEDIATION OF SUSY BREAKING

- Hidden sector with spontaneous (dynamical) susy breaking (scale $\Lambda_{susy} \equiv \sqrt{F}$)
- Visible sector SSM with gauge group G_{SM}
- Interactions lead to soft terms in the SSM, e.g. mass m_{soft} to sparticles
- SSB $\Rightarrow$ Gravitino with mass $m_{3/2} \simeq \frac{\Lambda_{susy}^2}{M_{Planck}}$

GRAVITY MEDIATION

- Soft terms as Planck suppressed operators
- $m_{soft} \sim \frac{\Lambda_{susy}^2}{M_{Pl}}$
- $\Lambda_{susy} \sim 10^{10-11} GeV$
- $m_{3/2} \simeq m_{soft}$
- Issues with FCNC

GAUGE MEDIATION

- Typically messengers field charged under G_{SM} and with mass M
- Soft terms via loops of SM gauge fields and messenger fields
- $\Rightarrow m_{soft} \sim \frac{g^2}{16\pi^2} \frac{\Lambda_{susy}^2}{M}$
- (Generically M is a supersymmetric scale s.t.: $\Lambda_{weak} \ll M \ll M_{Pl}$)
- Typically $10^4 GeV < \Lambda_{susy} < 10^9 GeV$
- $m_{3/2} \ll m_{soft}$
- Calculable model, Flavour blind
- μ/B_μ problem, ...

General Gauge Mediation

- Parametrize susy breaking sector in a model independent way
- Gauge mediation definition

$$\lim g_v \to 0 \qquad \text{No susy breaking in visible sector}$$

- 6 independent parameters: (gaugino, scalars) $\times$ $U(1), SU(2), SU(3)$
- $\Rightarrow$ Soft masses in GGM (at the messenger scale M_{mess})

$$m_{\lambda_i} = \frac{g_i^2}{(4\pi)^2}\Lambda_{G_i} \qquad i = 1, \ldots 3$$

$$m_{sc}^2 = 2\sum_{i=1}^{3} C_i k_i \frac{g_i^4}{(4\pi)^4}\Lambda_{S_i}^2 \; ; \qquad C_i = \text{Casimir} \qquad k_i = (3/5, 1, 1)$$

- A terms are loop suppressed
- Sum rules for sfermion masses $\mathrm{Tr} Y m^2 = 0$, $\mathrm{Tr}(B-L)m^2 = 0$

Covers all possible models of gauge mediation
(also strongly coupled hidden sectors)

??? Higgs sector (μ, B_μ) ???

Higgs potential and Gauge Mediation

- Higgs Potential in MSSM

$$V = (\mu^2 + m_{h_u}^2) h_u h_u^\dagger + (\mu^2 + m_{h_d}^2) h_d h_d^\dagger + B_\mu (h_u h_d + \text{h.c.}) + \frac{1}{8}(g_2^2 + g_1^2)(|h_u|^2 - |h_d|^2)^2$$

- In Gauge Mediation, m_{h_u} and m_{h_d} naturally radiatively generated at M_{mess}

$$m_{h_u}^2 = m_{h_d}^2 = m_{E_L}^2$$

- In pure Gauge Mediation B_μ loop suppressed at M_{mess}
- μ supersymmetric term in the superpotential
  - μ would be naturally of order UV scale $\mu \sim \Lambda_{GUT}$

Instead: we need μ and B_μ of the order of the EW scale

- To generate μ and B_μ, depart from GGM definition
- $\Rightarrow$ couple Higgs to hidden sector operators, e.g.

$$\Delta W = \lambda_u H_u \mathcal{O}_d + \lambda_d H_d \mathcal{O}_u$$

μ/B_μ PROBLEM

DVALI GIUDICE POMAROL '96

- Minimization conditions for EWSB

$$\sin(2\beta) = \frac{2B_\mu}{m_{h_u}^2 + m_{h_d}^2 + 2\mu^2} \qquad m_Z^2 = 2\frac{m_{h_d}^2 - \tan(\beta)^2 m_{h_u}^2}{\tan(\beta)^2 - 1} - 2\mu^2$$

- We need both μ and B_μ of the order of the EW scale
- Simple attempt: Couple Higgs to messengers $(\Phi_i, \bar{\Phi}_i)$ of SUSY breaking

$$\Delta W_{Higgs} = \lambda_u H_u \Phi_1 \Phi_2 + \lambda_d H_d \bar{\Phi}_1 \bar{\Phi}_2$$

- μ and B_μ generated at one loop

$$\mu \simeq \frac{\lambda_u \lambda_d}{16\pi^2} \frac{F_X}{M_{mess}} \qquad B_\mu = \frac{\lambda_u \lambda_d}{16\pi^2} \left(\frac{F_X}{M_{mess}}\right)^2$$

- $\Rightarrow B_\mu \gg \mu^2$

Generic problem in gauge mediation !!!

125 GeV Higgs in the MSSM

? Is this possible within the MSSM ?

- One loop corrections to the Higgs mass

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right)$$

  where

$$v^2 = v_u^2 + v_d^2 \qquad \tan\beta = \frac{v_u}{v_d} \qquad X_t = A_t - \mu\cot\beta$$

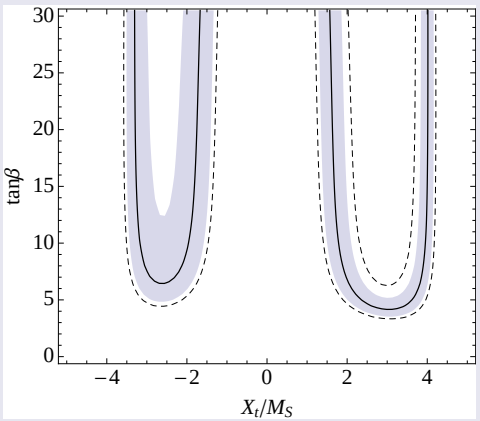
- To reach 125 GeV loop corrections should be relevant
- Free parameters are $\left(\tan\beta,\ X_t,\ m_{\tilde{t}_1} m_{\tilde{t}_2} \equiv M_S\right)$

125 GeV Higgs in the MSSM

Draper, Meade, Reece, Shih: arXiv:1112.3068

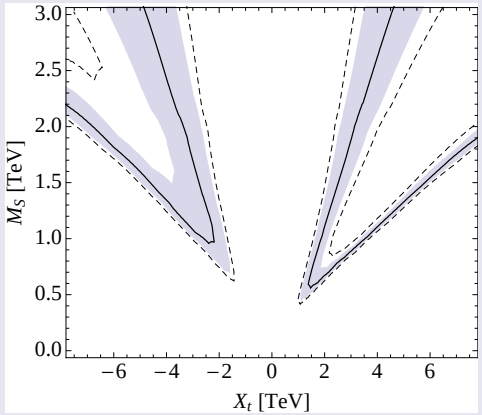
- Consider $m_{\tilde{t}_1}, m_{\tilde{t}_2} < 5$ TeV, within LHC reach
- Contour Plots of Higgs mass as a function of $\tan\beta, M_S, X_t$

Fixing $m_{\tilde{t}_1}, m_{\tilde{t}_2} \sim 2$ TeV



Decreasing $\tan\beta$ always decrease Higgs mass

Fixing $\tan\beta = 30$



Smallest scales

$|X_t| \geq 1000$ TeV

$m_{\tilde{t}_1}, m_{\tilde{t}_2} \geq (500GeV)^2$

- If $m_{\tilde{t}_1}, m_{\tilde{t}_2} < 5$ TeV $\Rightarrow$ Need large A-terms

PROBLEM: A-terms ~ 0 in Gauge Mediation

Gauge Mediation & Higgs sector

Model independent features of pure GMSB

- Quite predictive in the mass spectrum
- No flavour problem
- Sum rules for scalar soft masses: $\mathrm{Tr} Y m^2 = 0$, $\mathrm{Tr}(B-L)m^2 = 0$
- Gravitino LSP
- A-terms are suppressed (loops order)
- Soft terms RG run from M_{mess} to EW scale

Higgs sector in GMSB

- μ and μ/B_μ problem
- Hard to explain 125 in gauge mediated MSSM. Possibilites
  1. Very large stop mass (naturalness issue)
  2. Very large M_{mess}, i.e. very long RG run, to generate A-terms
  3. New interactions of Higgs sector with hidden sector

Conservative possibility

- Small A-terms at M_{mess}
- Long RG run or large stop mass to obtain 125 Higgs mass

? What are still the possible scenarios in GGM ?

Classifying NLSP in GGM with 125 Higgs

- In restricted area of paramater space

$$\Lambda_{G_1} = \Lambda_{G_2} = \Lambda_{G_3} \qquad \neq \qquad \Lambda^2_{S_1} = \Lambda^2_{S_2} = \Lambda^2_{S_3}$$

- $\Rightarrow$ Only standard NLSP (stau, neutralino)

- Scanning the full 6-dim parameter space (plus $\tan\beta$ and Higgs sector parameters)
- $\Rightarrow$ No squarks NLSP
- $\Rightarrow$ Other exotic NLSP are still possible

Work in progress with P. Grajek and D. Redigolo

Extension of GGM: generic features

We need

1. Generate large A-terms by adding new interactions in the Higgs sector
2. Modify MSSM scalar Higgs potential

Challenges and consequences

- Combining them with possible solution of $\mu\, B_\mu$ problem
- Embedding in strong dynamics to address the hierarchy problem
- They can modify Higgs couplings to SM particles

Surviving GMSB features

- Low energy supersymmetry breaking
- $\Rightarrow$ Gravitino LSP
- Address flavour problem

Extension of GGM: examples

NMSSM

- Add Singlet N coupling to Higgs: $W = \lambda N H_u H_d + W(N)$
- Can explain μ and B_μ term
- Can increase the Higgs mass for sufficiently large λ

Direct coupling of Higgs to messengers

- Can generate one-loop sizeable A-terms

Modifying Higgs quartic couplings

- Hidden sector contributions to Higgs quartic couplings
  - Contribution from charged hidden sector particles
  - Contribution from extra heavy gauge fields

Conclusions

Susy as BSM and Gauge Mediation

- Susy still promising
- Gauge Mediation interesting possibility
- Solve flavour problem
- $\Rightarrow$ Provide precise and computable predictions

Higgs at 125 GeV

- 125 is a challenge in gauge mediated MSSM
- However Gauge Mediation not strongly constrain Higgs potential
- $\Rightarrow$ Need new ingredients in Higgs sector
  - Modification of Higgs couplings
  - Mixing of Higgs with hidden sector particles