Tree Level Gauge Mediation

Andrea Romanino SISSA

with Nardecchia, Ziegler arXiv:0909.3058 (JHEP) arXiv:0912.5482 (JHEP) and Monaco (in progress)

A wide class of models of supersymmetry breaking

[Polchinski Susskind, Dine Fischler, Dimopoulos Raby, Barbieri Ferrara Nanopoulos]



$$\int d^4\theta \, \frac{Z^{\dagger} Z \, Q^{\dagger} Q}{M^2} \quad \to m^2 \tilde{Q}^{\dagger} \tilde{Q}, \quad m = \frac{F}{M}$$

Tree level gauge mediation





heavy vector superfield
 SM singlet
 non-anomalous
assumed to part of a GUT (⇒ Z is charged under G_{GUT})

"D-term", non-anomalous, mediation

Anomalous case: e.g. Barbieri Ferrara Nanopoulos Dvali Pomarol



What about...

- Supersymmetry breaking masses (Z*ZQ*Q) are obtained at the tree level from spontaneous SUSY breaking in a renormalizable theory
- Two arguments seem to prevent this possibility
 - 1. the supertrace formula

 $\begin{array}{l} 0 = (\operatorname{Str} M^2)_{\mathrm{f,tot}} = (\operatorname{Str} M^2)_{\mathrm{f,MSSM}} + (\operatorname{Str} M^2)_{\mathrm{f,extra}} \\ & > 0 & < 0 \\ & \left(\tilde{m}_{\mathrm{lightest} \; "\mathrm{squark"}}^2 \leq m_d^2 \; \mathrm{or} \; m_u^2 \; \mathrm{if no \; additional \; U(1)'s} \right) \end{array}$

2. small gaugino masses [Arkani-Hamed Dimopoulos Giudice R]

$$\tilde{m}_f \sim 100 M_2 \gtrsim 10 \,\mathrm{TeV}$$
 \longrightarrow $\tilde{m}_f \sim 10 M_2 \cdot \eta \gtrsim 1 \,\mathrm{TeV} \cdot \eta$

A concrete example

- \odot V associated to the SU(5)-invariant generator "X"



 The (usual) embedding of a MSSM family in a single 16 does not work (whatever the sign of X_z)



Does not require any effort! (SO(10) reps with d < 120)</p>

SO(10) breaking needs 16 + $\overline{16}$ with <16> = < $\overline{16}$ > = $M \approx M_{GUT}$ h_{ij} 16_i 10_j 16 \rightarrow M_{ij} 5_i $\overline{5}_j$ when 16 \rightarrow <16>

(Reinforces the theoretical consistency)

• SUSY breaking: Z must be the singlet of a 16' (gauge invariance: $16' \neq 16$)

$$\tilde{m}_Q^2 = \frac{X_Q}{2X_Z} \frac{F^2}{M^2}$$

• Then
$$\tilde{m}_q^2 = \tilde{m}_{u^c}^2 = \tilde{m}_{e^c}^2 = \tilde{m}_{10}^2 = \frac{1}{10} m^2$$
, $\tilde{m}_l^2 = \tilde{m}_{d^c}^2 = \tilde{m}_{\bar{5}}^2 = \frac{1}{5} m^2$, $m = \frac{F}{M}$

- In particular
 - all sfermion masses are positive
 - sfermion masses are flavour universal, thus solving the supersymmetric flavour problem
 - sfermion masses are determined by a single parameter as in the CMSSM, but for a reason

$$\circ ~~ { ilde m}^2_{q,u^c,e^c} = rac{1}{2} { ilde m}^2_{l,d^c}$$
 (at M)

How general are the predictions?

• They assume:

Minimal GUT implementation (SO(10))

Only SO(10) reps with d < 120</p>

Pure embeddings of SM multiplets in 1 type of SO(10) reps (guarantees the solution of the SUSY flavour problem), or no matter mass terms

Gaugino masses

Arise at one-loop because of a built-in ordinary gauge mediation structure



O(100) hierarchy → O(10): $\tilde{m}_t > O(1 \text{ TeV}) \times \text{model dep factor } \lambda$

Miscellaneous

- A new D=3 solution of the μ problem
 D=4 (NMSSM) and D=5 (Giudice-Masiero) can also work
- Sugra contamination smaller than in loop gauge mediation (M_{GUT} OK)
- SP is the gravitino
- Higgs soft terms bounded in predicted interval
- Op and down Yukawas decoupled despite SO(10)
- Neutrino masses through type-I, type-II, or hard susy breaking operators

[Arkani-Hamed Hall Murayama Tucker-Smith Weiner Dermir Everett Langacker Abel Dedes Tamvakis]

Predictive type-II leptogenesis possible

[Frigerio Hosteins Lavignac R Calibbi Frigerio Lavignac R]

A new solution to the μ -problem

- The phenomenological window O(100 GeV) < μ < O(1 TeV) turns out to coincide with the window of supersymmetry breaking sfermion masses m̃: is it an accident or is there a connection between μ and m̃?</p>
- \odot The well known solutions of the μ -problem can be implemented

• D=5: Giudice-Masiero $\int d^4\theta \ a \frac{Z^{\dagger}}{M} h_u h_d \rightarrow \mu = a \frac{F}{M}$ can arise at looplevel; $\mu \approx M_g \approx 100$ GeV, $B\mu \approx m \approx \text{TeV}$ (because of $\mu/B\mu$ connection)

• D=4: NMSSM $\int d^2\theta \ \lambda Sh_u h_d \rightarrow \mu = \lambda \langle S \rangle \sim \lambda \tilde{m}$ S can have negative soft mass (unlike in ordinary gauge mediation) but should take care of quartic coupling

D=3: an intrinsic TGM solution

- The D=3 solution of the μ-problem in TGM: μ and m̃ arise from the same mass term in the superpotential
- Reminder: we need

 $\odot 16 = \overline{5} + 10 + 1$ $\overline{16} = 5 + \overline{10} + \overline{1}$ $\langle 1 \rangle = \langle \overline{1} \rangle = M \approx M_{GUT}$

 $\odot 16' = \overline{5}' + 10' + Z$ $\overline{16}' = 5' + \overline{10}' + \overline{Z}$ $\langle Z \rangle = F \theta^2$

- The easiest way to get a susy-breaking <16'> is through
 W = m 16' 16 [+ Y (16 16 M²) + X 16' 16]
 then F = m M (so that m = F/M)
- Because of SO(10), m is also the mass term of the doublet components of 16' 16, which can contain a Higgs component: 16' = $\alpha' h_d + ..., 16 = \alpha h_u + ...$ so that $\mu = \alpha \alpha' m = \alpha \alpha' (F/M)$

Sugra contributions to sfermion masses

Add to the tree level gauge mediated contribution and may induce FCNCs

Their size is less important than in loop gauge mediation (because no loop suppression here). As a consequence, a messenger scale as large as M_{GUT} does not represent a potential problem for FCNCs

Assuming the gravity contribution to a generic entry of the sfermion mass matrix is (m²)_{sugra} = (F/M_{Pl})² (M_{Pl} = 2.4 10¹⁸ GeV) we obtain

(m²)_{sugra} < 2 10⁻³ (m²)_{stop} iff M < 3 10¹⁶ GeV (guarantees FCNC effects from flavour-anarchical sugra contribution are under control)

Cosmology

LSP is the gravitino (in the regime in which sugra FCNC effects are under control), as in loop gauge mediation

$$m_{3/2} = \frac{F}{\sqrt{3}M_{\rm P}} \approx 15 \,\mathrm{GeV}\left(\frac{\tilde{m}_{10}}{\mathrm{TeV}} \frac{M}{2 \cdot 10^{16} \,\mathrm{GeV}}\right)$$

- Stable gravitino: a dilution mechanism is necessary not to overclose the universe, T_R < 2 10⁹ GeV
- NLSP decay can spoil BBN
 - If the NLSP is a neutralino (typical case) a decay channel much faster than the Goldstino one is needed in order not to spoil BBN (e.g. a tiny amount of R_P-violation; consistent with thermal leptogenesis and gravitino DM)

[Buchmuller, Covi, Hamaguchi, Ibarra, Yanagida, hep-ph/0702184 (JHEP)]

If the NLSP is a stau (the other possibility) BBN not a problem but the peculiar predictions of TGM are hidden by large loop gauge mediation contributions
[Pospelov Pradler Steffen arXiv:0807.4287 (JCAP)]

[Pospelov Pradler Steffen arXiv:0807.4287 (JCAP) Olechowski Pokorski Turzynski Wells arXiv:0908.2502 (JHEP)]

(work in progress)

Higgs doublets: only possible embeddings are into 16, 10 (h_d), 16, 10 (h_u)

The Let $\cos^2\theta_{u,d}$ be the size of the components of $h_{u,d}$ in 10's

• Then
$$m_{h_u}^2 = \frac{-2c_u^2 + 3s_u^2}{5}m^2$$
 $m_{h_d}^2 = \frac{2c_d^2 - 3s_d^2}{5}m^2$
 $-\frac{2}{5}m^2 < m_{h_u}^2 < \frac{3}{5}m^2$ $-\frac{3}{5}m^2 < m_{h_d}^2 < \frac{2}{5}m^2$

SM Yukawas

Down quark and charged lepton Yukawas:

IO_i 5_j 5_H (in SU(5) language) → h_{ij} 16_i 10_j 16_H (where possibly 16_H = 16)

• Up quarks:

IO_i 1O_j 5_H (in SU(5) language) → y_{ij} 16_i 16_j 10_H

Note: down and up quarks described by two independent Yukawa matrices (room to explain their different structure despite the SO(10) constraints)

An example of spectrum

Higgs:	m_{h^0}	114	
	m_{H^0}	1543	
	m_A	1543	
	$m_{H^{\pm}}$	1545	
Gluinos:	$M_{\tilde{g}}$	448	
Neutralinos:	$m_{\chi_{1}^{0}}$	62	
	$m_{\chi^0_2}$	124	
	$m_{\chi^0_3}$	1414	
	$m_{\chi_{4}^{0}}$	1415	
Charginos:	$m_{\chi_1^{\pm}}$	124	
	$m_{\chi_2^{\pm}}$	1416	
Squarks:	$m_{\tilde{u}_L}$	1092	
	$m_{\tilde{u}_R}$	1027	
	$m_{\tilde{d}_L}$	1095	
	$m_{\tilde{d}_R}$	1494	
	$m_{\tilde{t}_1}$	1007	
	$m_{\tilde{t}_2}$	1038	
	$m_{\tilde{b}_1}$	1069	
	$m_{\tilde{b}_2}$	1435	
Sleptons:	$m_{\tilde{e}_L}$	1420	
	$m_{\tilde{e}_R}$	1091	
	$m_{\tilde{\tau}_1}$	992	
	$m_{\tilde{\tau}_2}$	1387	
	$m_{\tilde{\nu_e}}$	1418	
	$m_{\tilde{ u_{ au}}}$	1382	

GeV 4							
1500 -	- <u>–</u> H	$\frac{H^{\pm}}{f^0 A^0}$	$\underline{\tilde{N}_3 \ \tilde{N}_4}$	\tilde{C}_2	$\frac{\tilde{d}_L}{\tilde{e}_L}$	$\frac{R}{\tilde{\nu}_e}$	$\frac{\tilde{b}_2}{\bar{\nu}_\tau \tilde{\tau}_2}$
1000 -	-				$\tilde{e}_R \frac{\tilde{d}_L \tilde{u}}{\tilde{u}_L}$	$\frac{\tilde{\mu}_L}{R}$	$\frac{\tilde{t}_2}{\overline{\tilde{t}_1\tilde{\tau}_1}}\tilde{b}_1$
500 -	-				ĝ		
100 -		h^0	$\frac{\tilde{N}_2}{\tilde{N}_1}$	\tilde{C}_1			

Figure 2: An example of spectrum, corresponding to m = 3.2 TeV, $M_{1/2} = 150 \text{ GeV}$, $\theta_d = \pi/6$, $\tan \beta = 30$ and $\operatorname{sign}(\mu) = +$, A = 0, $\eta = 1$. All the masses are in GeV, the first two families have an approximately equal mass.

How general are the sfermion mass predictions?

- They assume:
 - Minimal GUT implementation (SO(10))
 - Only SO(10) reps with d < 120</p>
 - Pure embeddings of SM multiplets in 1 type of SO(10) reps (guarantees the solution of the SUSY flavour problem), or no matter mass terms
- Non minimal GUTs?
 - \odot A natural option is E_6
 - \odot 27_i = 16_i + 10_i + 1_i under SO(10)

TGM in E₆

- To be general: G rank 6 such that $G_{SM} ⊂ G ⊆ E_6$
- Still, only two relevant cases (sfermion mass predictions)
 - Reminder:
 - Turns out:

Candidate messengers: $V_5 V_{10} V'_+ V'_- = V', V'_3 V'_+ V'_- (U(1)' \times SU(2)')$

- Then either
 - The messengers are V₅ V₁₀ (G ⊇ SU(2)') or
 - The messengers are V₅ V₁₀ V'₊ V'_− (G ⊇ SU(2)')

$V_5 + V_{10}$

3 + conj. sources of
G & SUSY breaking
(2 needed to break G
1 to break SUSY)

E ₆			2	7			
SO(10)		16		1	0	1	
SU(5)	<u>5</u>	10	1	<u>5</u>	5	1	
T ₁₀	1	1	1	-2	-2	4	
T ₅	-3	1	5	2	-2	0	(

E ₆		78									
SO(10)	45				16			<u>16</u>			1
SU(5)	24	10	<u>10</u>	1	<u>5</u>	10	1	5	<u>10</u>	1	1
T ₁₀	0	0	0	0	-3	-3	-3	3	3	3	0
T ₅	0	-4	4	0	-3	1	5	3	-1	-5	0

(X)

(+ 27)

E ₆	E ₅	E4	m̃²
	16	<u>5</u>	$-3m_5^2 + m_{10}^2$
~~~		10	$m_5^2 + m_{10}^2$
		1	$5 m_5^2 + m_{10}^2$
21	10	<u>5</u>	$2m_5^2-2m_{10}^2$
		5	$-2m_5^2-2m_{10}^2$
	1	1	$4m_{10}^2$

$$m_5^2 = \frac{f_x(4y+3z) + f_y(3z-x) - f_z(x+4y)}{20(xy+xz+yz)}$$
$$m_{10}^2 = \frac{f_xz + f_y(x+z) + f_zx}{4(xy+xz+yz)}$$

$x \equiv  1_{16}^{27} ^2 +  1_{\overline{16}}^{\overline{27}} ^2$	$f_x \equiv  F(1_{16}^{27}) ^2 -  F(1_{\overline{16}}^{27}) ^2$
$y \equiv  1_1^{27} ^2 +  1_{\overline{1}}^{\overline{27}} ^2$	$f_y \equiv  F(1_1^{27}) ^2 -  F(1_{\overline{1}}^{27}) ^2$
$z \equiv  1_{16}^{78} ^2 +  1_{\overline{16}}^{\overline{78}} ^2$	$f_z \equiv  F(1_{16}^{78}) ^2 -  F(1_{\overline{16}}^{78}) ^2$

- Sfermion masses depend on 2 real parameters and on the embedding in 27
- (pure embedding)
- Specific limits
  - SO(10) limit:  $y \gg x, y = m_{10} \ll m_5$
  - I f ≠ 0 (e.g. f_x), pure embedding, G-breaking from 27:  $\tilde{m}_5^2 = 2 \, \tilde{m}_{10}^2$

#### F-theory?

- Oppring Dynamics of gauge theory decouples from gravity  $\rightarrow$  natural to address in SUSY-breaking in the gauge theory (but usually dominantly through LGM)
- Tree-level contributions with `wrong' sign have been shown to arise in Heckman Vafa 0809.1098 associated to  $U(1) = U(1)_{10}$

$$\mathcal{L} = -g_{\mathrm{U}(1)}^2 \frac{e_Z e_Q}{M_{\mathrm{U}(1)}^2} \int d^4\theta \, Z^{\dagger} Z Q^{\dagger} Q$$

- This forces the tree-level contribution to be subdominant wrt the loop one:  $M_{U(1)} \approx 10^{15-16}$  GeV,  $M_{mess} \approx 10^{12}$  GeV
- No fundamental reason for the `wrong' sign but the mechanism used to generate the µ-term, which forces  $e_z e_Q < 0$



Simple(st)

 Sfermion masses are flavour universal, thus solving the supersymmetric flavour problem

 SO(10): sfermion masses determined in terms of a single parameter (as in the CMSSM, but for a reason)

 $\odot$  SO(10): peculiar, testable prediction:

$$\left[\tilde{m}_{q,u^c,e^c}^2 = \frac{1}{2}\tilde{m}_{l,d^c}^2\right]$$

Different possible realizations