5. MSSM and SUSY Breaking

5.1 MSSM

5.1.1 SUSY ~~[illegible]~~ Part

as ~~[illegible]~~ ~~[illegible]~~ SQED / SQCD : 4-spinor $= \begin{pmatrix} u_{L\alpha} \\ \bar{u}_R^{\dot\alpha} \end{pmatrix}$ etc

$\tilde{u}_L, u_L \to$ chir. SF

~~$\tilde{u}_R^*, \bar{u}_R \to$ antich. SF~~

~~$\tilde{u}_R^\dagger, u_R \to$ chir. SF~~

fields: SM + 2nd H-doublet

superfield	SM	sparticle	$Y = Q - T^3$	T_s^a	T^a
Q	$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\tilde{q}_L = \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$\frac{1}{6}$	$\frac{\lambda_a}{2}$	$\frac{\sigma_a}{2}$
U	u_R	$\tilde{u}_R^\dagger$	$-\frac{2}{3}$	$-\frac{\lambda_a^*}{2}$	0
D	d_R	$\tilde{d}_R^\dagger$	$\frac{1}{3}$	"	0
L	$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\tilde{l}_L = \begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$	$-\frac{1}{2}$	0	$\frac{\sigma^a}{2}$
E	e_R	$\tilde{e}_R^\dagger$	1	0	0
H_d	$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\tilde{H}_d$	$-\frac{1}{2}$	0	$\frac{\sigma^a}{2}$
H_u	$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\tilde{H}_u$	$\frac{1}{2}$	0	$\frac{\sigma^a}{2}$
V'	B^μ	λ'			
V^a	$W^{a\mu}$	λ^a			
V_s^a	$G^{a\mu}$	λ_s^a			

$\Rightarrow$ unique Superpotential:

$$W = y_u H_u Q U + y_d H_d Q D + y_e H_d L E - \mu H_d H_u$$

$\Rightarrow$ unique full Lagrangian according to 4.4

5.1.2 R-Parity

"Miracle of SM": $\nexists$ gauge-inv. and dim ≤ 4 term which violates baryon/lepton number

MSSM however: L, H_d : <u>identical</u> gauge quantum numbers!

$\Rightarrow$ LQD, LLE, LH_u

gauge inv. but L, B violating

also UUD " "

$\Rightarrow$ $\boxed{\text{B-, L- could be strongly violated in MSSM!}}$

Problem!

<u>Solution: impose additional symmetry:</u>

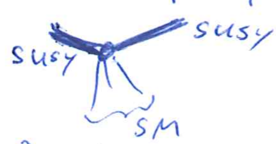
e.g. "R-parity" (multiplicative qu. number)

R(SM-field) = +1, R(sparticle) = −1

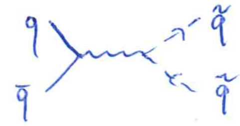
$\Rightarrow$ all terms above violate R-parity
but all terms in 5.1.1. conserve R-parity

<u>Implication:</u>

- each vertex/term in $\mathcal{L}$:
  <u>even</u> number of sparticles, any number of SM-p.



- sparticle prod. only in <u>pairs</u> eg.



- Lightest sparticle (LSP) cannot decay $\rightarrow$ <u>stable</u>

$\Rightarrow$ if electr. neutral and R-par. exact $\Rightarrow$ contributes to dark matter
- must not exceed $\Omega_{D.M.}$
- must be neutral

$\Longrightarrow$ neutral $\tilde{W}^0$, $\tilde{B}$, $\tilde{H}^0$

5.13 Highlights of dim = 4 - properties

Higgs sector: 2 doublets, H_d couples to U, H_u to L, D $\Rightarrow$ 2HDM type II

quartic terms in V_{Higgs} : F - terms $\left|\frac{\partial W}{\partial A_i}\right|^2$ → at most two powers of H_i

D - terms $D^a = - H_i^\dagger g_w \frac{\sigma^a}{2} H_i$

$D' = - H_i^\dagger g_Y Y_{H_i} H_i$

$\sim D^a D^a + D' D' \sim H^4 g^2_{w,Y}$

$\Rightarrow$ all quartic terms in V_{Higgs} governed by $g^2_{w,Y}$

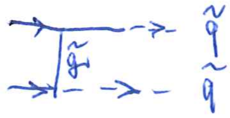
$$\boxed{\begin{array}{l} \Rightarrow \text{MSSM} = \text{special case of 2HDM type II} \\ \quad \lambda_{1\ldots7} \sim g^2_{w,Y} \\ \Rightarrow M_h \text{ related to } M_Z \,! \end{array}}$$

$\Longrightarrow$ Precision (multi-loop) calculations of M_h important!

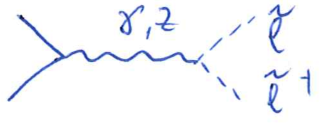
MSSM predicts $M_h \sim 120 \ldots 130$ for $m_{\tilde{t}} \sim$ few TeV

Processes:

,



$\tilde{q}\tilde{q}$, $\tilde{q}\tilde{q}^\dagger$-production $\sim \alpha_s$



slepton production $\sim \alpha$

chargino/neutralino prod. $\sim \alpha$

contrib. to flavour changes

$(g-2)_\mu$

Running Couplings

gauge couplings $\alpha_i = \frac{g_i^2}{4\pi}$, ~~$g_1, \ldots, g_3$~~.

in $\overline{MS}$-scheme: running coupling $\alpha_i(\mu) \hat{=}$ effective coupling for processes at $E \approx \mu$.

β-functions at 1-loop

$$\beta_i := \frac{d\alpha_i}{d\ln\mu} \hat{=} \text{divergent part of } \delta\alpha_i \text{ renorm. constant}$$

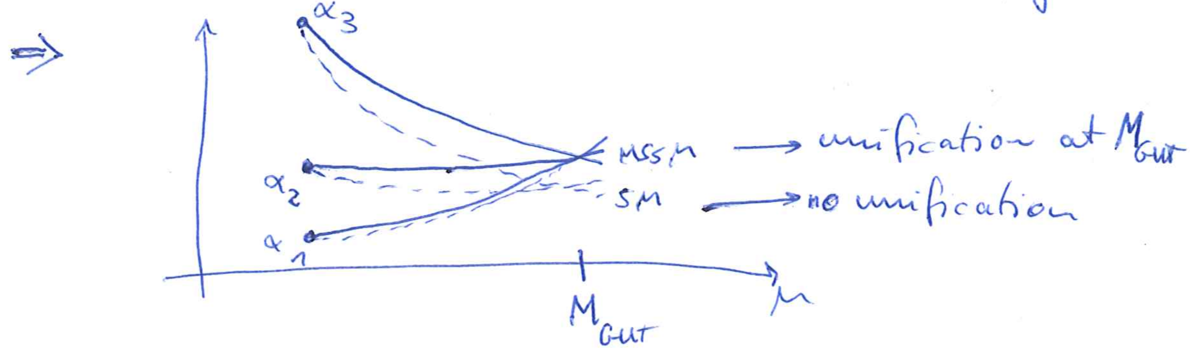
~~SM~~ →

main contrib. from V_i^μ

SM: α_Y (q, ℓ, H) , α_2 ($q, \ell, H, W^\pm$) , α_3 (q, g)

MSSM also: $\tilde{q}, \tilde{\ell}, \tilde{H}$ and $\tilde{W}^\pm$ $\tilde{q}, \tilde{g}$

⇒



- unification at $M_{GUT} \sim 10^{16}$ GeV
- supports idea of GUT + SUSY at $M_{SUSY} \sim 1$ TeV

[Note: MSSM is not the unique theory with gauge coupling unification]

5.1.4 SUSY Breaking

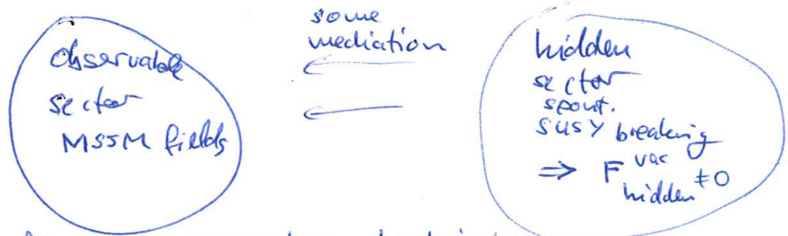
Idea: unbroken SUSY $\Rightarrow m_{SM} = m_{susy\text{-}partner} \Rightarrow$ excluded

spontaneous SUSY breaking in MSSM $\Rightarrow$ ~~pless~~ mass relations such as at least one $m_{\tilde{e}} < m_e \Rightarrow$ excluded

$\Rightarrow$ need explicit breaking terms

Ansatz:

- field content, dim = 4 - interactions = SUSY
- explicit breaking terms have structure that could originate from spontaneous SUSY breaking in hidden sector



- first parametrize breaking terms, then try to derive them from theory

Girardello Grisaru terms: General class of possible arising "Soft SUSY breaking" terms:

can be written as SUSY interactions with chiral SF η where $\eta = \theta\theta f_0$, $f_0 = \text{const.}$

$\dim(\eta) = 0$, $\dim(f_0) = 1$

η could be remnant of spont. SUSY Breaking

a) $\int d^4\theta \; \Phi^\dagger e^{2gV} \Phi \; \eta^\dagger \eta \quad = A^\dagger A \cdot |f_0|^2$

$\rightarrow$ scalar mass term

b) $\int d^2\theta \; W^\alpha_a W_{a\alpha} \; \eta \quad = \lambda^\alpha_a \lambda_{a\alpha} \cdot f_0$

$\rightarrow$ gaugino mass term

c) $\int d^2\theta \left(m_{ij} \Phi_i \Phi_j + g_{ijk} \Phi_i \Phi_j \Phi_k \right) \eta \quad = f_0 m_{ij} A_i A_j + f_0 g_{ijk} A_i A_j A_k$

$\rightarrow$ holomorphic scalar bi/trilinear terms, copying superpotential terms

Soft breaking terms in MSSM:

a) $$\mathcal{L}_{soft,a} = -M_Q^2 \, \tilde{q}_L^\dagger q_L - M_u^2 \, \tilde{u}_R^\dagger \tilde{u}_R - (\text{sim. for } \tilde{d}_R, \tilde{l}_L, \tilde{e}_R)$$
$$- m_{H_u}^2 |H_u|^2 - m_{H_d}^2 |H_d|^2$$

(actually $(M_Q^2)_{IJ} \, \tilde{q}_L^{I\dagger} \tilde{q}_L^J \leftarrow$ gener. index)

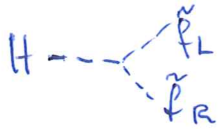
- scalar mass terms
- $m_{H_{u,d}}^2 \rightarrow$ Higgs potential, at least $m_{H_u}^2 < 0 \Rightarrow$ 
- expect $M_i \sim \mathcal{O}(\text{TeV})$, often: theory $\Rightarrow M_{Q,U,D} \gg M_{L,E}$
  $\uparrow$ strong interact.
- $(M_Q^2)_{IJ}$ induces flavour changes beyond CKM
  $\Rightarrow$ strongly constrained.

b) $$\mathcal{L}_{soft,b} = \frac{1}{2} \left(M_1 \lambda' \lambda' + M_2 \lambda_a \lambda_a + M_3 \lambda_{sa} \lambda_{sa} + h.c. \right)$$

- gaugino mass terms
- can be complex $\Rightarrow$ induces CP violation
  without flavour change/CKM
  $\Rightarrow$ strongly constrained
- often: theory $\Rightarrow M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3 \approx 1:2:6$

c) $$\mathcal{L}_{soft,c}^{(\text{R-parity invariant})} = -A_u y_u H_u \tilde{q}_L \tilde{u}_R^\dagger + (\text{sim. for } d,e) - B\mu H_d H_u + h.c.$$

- $B\mu \rightarrow$ Higgs potential
- $A_{u,d,e} \rightarrow$ actually 3×3 matrices in gen. space
  $\Rightarrow$ CP and flavour violation



interactions and mass terms

$\mathcal{L} \rightarrow \ldots -(A_u y_u v_u) \tilde{q}_L^\dagger \tilde{u}_R$

Comments:

- all soft breaking terms : dim 2 or dim = 3
- not all dim = 3 - terms are "soft", e.g. $H_d^c \tilde{q}_L \tilde{u}_R^\dagger$ "wrong Higgs" (gauge inv. but non-holomorphic)
- soft breaking does not modify dim = 4 - interactions:
  - couplings to gauge bos./gauginos
  - H - self couplings
  - Yukawa couplings Higgs(ino) — (s)fermion

Non-Standard Soft Breaking: Beyond Girardello Grisaru:

$*$ $\int d^4\theta\, \Phi^\dagger e^{2gV} \Phi\, \Phi\, \eta^\dagger \eta \rightarrow A^\dagger A A$ non-holomorphic

$*$ $\int d^2\theta\, W^\alpha_a \Phi_a (\theta^\alpha D_\alpha)\eta$ VEV in D-component, $\rightarrow \lambda^a \psi_a \Rightarrow \Phi_a$ in adjoint rep. → gaugino Dirac mass

Problems for potential theories generating $\mathcal{L}_{soft}$:

- SUSY Flavour/CP Problem:

  ~~Why~~ How to suppress flavour/CP viol. contrib.?

  (either $(M_Q^2)_{IJ}$, A_u^{IJ} etc : almost diagonal/real
  or sparticle masses very large)
  or additional symmetry

- Mass pattern needed: evade LHC constraints
  ($\Rightarrow$ sparticles heavier than limits)

  predict $m_h \approx 125\,\text{GeV}$
  ($\Rightarrow$ $m_{\tilde{t}}$ needs specific value)

  describe $(g-2)_\mu$, dark matter, ...
  ($\Rightarrow$ sleptons, gauginos, higgsinos : light/specific values)

- μ - problem:

  susy parameter but should be similar to M_{soft}
  → how/why?

5.2 Remarks on SUSY Breaking

5.2.1 How to Break SUSY spontaneously (at tree-level)

consider only chiral S.F. - theory contains Φ_i $(i=1\dots n)$

$$\Rightarrow \boxed{\begin{array}{l} \text{scalar potential} \quad V = |F_i|^2 = \left|-\frac{\partial W(A)}{\partial A_i}\right|^2 \\ \text{spont. SUSY breaking} \Leftrightarrow \nexists \text{ value } A_i^{vac}: \left.\frac{\partial W(A)}{\partial A_i}\right|_{A_i^{vac}} = 0 \; \forall i \end{array}}$$

discussion: n eqs. for n unknowns
$\Rightarrow$ solution exists, SUSY unbroken, unless very special form of W

possible class: chiral SFs $\{X_a\}$ $(a=1\dots n_X)$
$\{Y_i\}$ $(i=1\dots n_Y)$

W = linear in Y's:

$$\boxed{W = \sum f_i(X)\cdot Y_i \quad , \text{ where } n_Y > n_X}$$

e.g. O'Raifeartaigh:

$$W^{OR} = (1 + g \underbrace{X_1^2}_{\Phi_1^2}) \underbrace{Y_1}_{\Phi_0} + m X_1 \underbrace{Y_2}_{\Phi_2}$$

then: $0 = \frac{\partial W}{\partial x_a} = \sum_i \frac{\partial f_i(x)}{\partial x_a} \cdot Y_i$ easy to fulfil

scalar comp.

$$0 = \frac{\partial W}{\partial Y_i} = f_i(x)$$

$\hookrightarrow$ n_Y eqs. for n_X unknowns
$\Rightarrow$ in general no solution if $n_Y > n_X$!

Minimize V:

$$V = \sum_a \underbrace{\left| \frac{\partial f_i(x)}{\partial x_a} \cdot y_i \right|^2}_{\text{can}} + \underbrace{\sum_i |f_i(x)|^2}_{\substack{\text{minimize first} \\ \rightarrow \text{ result } x_a^{vac}}}$$

define $y_i^{(a)} := \left. \frac{\partial f_i(x)}{\partial x_a} \right|_{x^{vac}}$ = n_x vectors in y-space

$\Rightarrow$ ~~there are at least $(n_y - n_x)$ vectors~~

~~any vector Y_i with $Y_i \, y_i^{(a)} = 0 \;\; \forall a$~~

~~minimizes V~~

~~(there are at least $n_y - n_x$ such vectors)~~

$\Rightarrow$

$$\boxed{\begin{array}{l} V \text{ is minimized for } (x_a^{vac}, Y_i^{vac}) \\ \text{where } Y_i^{vac} \cdot y_i^{(a)} = 0 \;\; \forall a \;\; \text{(the space of such } Y_i^{vac} \\ \text{is at least } (n_y - n_x)\text{-dimensional)} \end{array}}$$

"flat directions" in potential

O'Raifeartaigh: minimum for $A_1 \equiv x_1 = 0$, $A_2 \equiv Y_2 = 0$,
$A_0 \equiv Y_1$ = arbitrary

5.2.2 Spontaneous SUSY Breaking

(at tree-level, only chiral S.F.)

assume:

Potential $$V = \sum_i \left| \frac{\partial W(A)}{\partial A_i} \right|^2 \qquad (1)$$

minimized for A_i^{vac} : $$\frac{\partial V}{\partial A_j}\Big|_{A^{vac}} = 0 \quad \forall j \qquad (2)$$

SUSY broken: $$V\Big|_{A^{vac}} \neq 0 \qquad (3)$$

Parametrize around vacuum:

$$A_i = A_i^{vac} + a_i$$

$$W(A) = W(A^{vac}) + \frac{\partial W(A)}{\partial A_i}\Big|_{A^{vac}} \cdot a_i + \dots$$

$$=: W(A^{vac}) + w_i\, a_i + \frac{1}{2} w_{ij}\, a_i\, a_j + \frac{1}{6} w_{ijk}\, a_i a_j a_k \dots$$

$$(3) \Rightarrow \sum_i |w_i|^2 \neq 0 \Rightarrow (w_1, \dots, w_n) \neq (0, \dots, 0)$$

$$(2) \Rightarrow \sum_i w_i^* w_{ij} = 0 \Rightarrow (w_{ij}) \text{ is matrix with Eigenvalue} = 0$$

fermion masses:

$$\mathcal{L}_{superpot} = \dots - \frac{1}{2} \psi_i \psi_j \frac{\partial^2 W}{\partial A_i \partial A_j}$$

$$\overset{A \to A^{vac}}{=} \dots - \frac{1}{2} \psi_i \psi_j\, w_{ij}$$

$\Rightarrow$ (w_{ij}) is fermion mass matrix and has EV $= 0$

$\Rightarrow$ there is (at least) one massless fermion (Goldstino)

(note: in local SUSY $\to$ Sugra: Goldstino eaten by Gravitino)

$\Rightarrow$ massive Gravitino

scalar masses

$$V\Big|_{\text{bilinear}} = \sum_i \left| w_i + w_{ij} a_j + \tfrac{1}{2} w_{ijk} a_j a_k \right|^2 \Big|_{\text{bilinear}}$$

$$= \sum_i |w_i|^2 + 2\,\mathrm{Re}\Big(\underbrace{w_i^* \tfrac{1}{2} w_{ijk}}_{=:B_{jk}} a_j a_k \Big) + a_k^\dagger \underbrace{w_{ki}^* w_{ij}}_{=:\mathcal{M}^2_{kj}} a_j$$

write $a_i = \varphi_i + i\chi_i$

$$\leadsto V_{bil} = (B_{jk} + B^*_{jk})(\varphi_j \varphi_k - \chi_j \chi_k) + (iB_{jk} - iB^*_{jk})(\varphi_j \chi_k + \chi_j \varphi_k)$$
$$+ \mathcal{M}^2_{jk} (\varphi_j \varphi_k + \chi_j \chi_k)$$

~~Scalar~~ mass matrices:

scalars, basis $(\varphi_1 \dots \varphi_n, \chi_1 \dots \chi_n)$: $\begin{pmatrix} \mathcal{M}^2 + 2\mathrm{Re}B & iB - iB^* \\ iB - iB^* & \mathcal{M}^2 - 2\mathrm{Re}B \end{pmatrix}$

fermions, basis $(\psi_1 \dots \psi_n)$: (w_{ij})

$\Rightarrow$ $\sum$ (scalar mass^2 eigenvalues) $= \mathrm{Tr}(\dots) = 2\,\mathrm{Tr}(\mathcal{M}^2)$
$= 2\,\mathrm{Tr}(w^\dagger w)$

$\sum$ (fermion mass^2 eigenvalues) $= \mathrm{Tr}(w^\dagger w) = \mathrm{Tr}(\mathcal{M}^2)$

$\Rightarrow$ mass relation between sums of EVs

$\rightarrow$ This is why spont. susy breaking in MSSM not enough

scales:

- susy breaking scale: $V|_{vac} = \sum |w_i|^2 =: \Lambda^4_{susy}$
  o'R. : $\Lambda^2_{susy} = \lambda$
- overall mass scale, fermions: $\mathcal{M}^2$ o'R.: m^2
- mass splitting : B o'R : $g\lambda$

$\Rightarrow$ three indep. scales

T-12

5.3 Fundamental SUSY Models

Ansatz:

~~obs. se~~ hidden sector
spont. SUSY
$\Rightarrow F^{vac} \neq 0$

$\xrightarrow{\text{mediation}}$

obs. sector,
MSSM,
effective
soft ~~SUSY~~

no tree-level, renormalizable couplings
$\Rightarrow$ evade mass relations of 5.2.2

"gravity mediation", "gauge mediation", "gaugino m.", "anomaly m."

5.3.1 Minimal, concrete model

- gauge mediation, minimal version

hidden sector
O'Raifeartaigh

$\longrightarrow$
SU(5)
multiplets $\Phi_{L/R}$

MSSM

ansatz: simplest model with spont. ~~SUSY~~ $\to$ O'R.

$$W^{\text{hidden}} = (\lambda_{mid} + g X^2) Y_1 + m' X Y_2$$

$\Rightarrow$ vacuum: $F^{vac}_{Y_1} = \lambda_{mid} \neq 0$

Y_1 = arbitrary

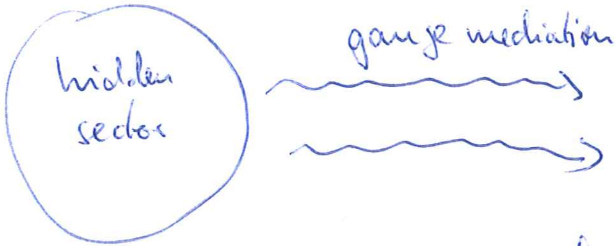
$\Rightarrow$ rename $Y_1 = S$

5-14

<u>output</u> : singlet (gauge invariant) S.F. S with

$$\boxed{F_s^{vac} \neq 0 \,, \quad s^{vac} \neq 0}$$

→ can be generalized to more complicated hidden sectors with many fields, $s_n^{vac}, F_n^{vac} \neq 0$



<u>gauge mediators - minimal ansatz</u>

- two sets of ch. SF : Φ_{Li}, Φ_{Ri} such that

$$\Phi_{Li} \Phi_{Ri} \quad \text{is gauge invariant}$$

(like SQED, SQCD mass term)

- $$\boxed{W_{med.} = \lambda \, S \, \Phi_{Li} \Phi_{Ri}}$$

(g. inv., renorm. coupling to hidden sector)

<u>mediator masses</u>

spinors: $\mathcal{L}_{superpot} = \ldots - \frac{1}{2} \psi_i \psi_j \frac{\partial W}{\partial A_i \partial A_j} + h.c.$

$$\stackrel{!}{=} -\left(\lambda s^{vac}\right) \cdot \psi_{Li} \psi_{Ri} + h.c.$$

Dirac masses $\quad m_\psi = \lambda s^{vac}$

(5 ~ 15)

scalars : $\mathcal{L}_{superpot} = \dots - |F_i|^2 = \dots - |F_{L_i}|^2 - |F_{R_i}|^2 - |F_S|^2$ $\quad = F_S + \dots$

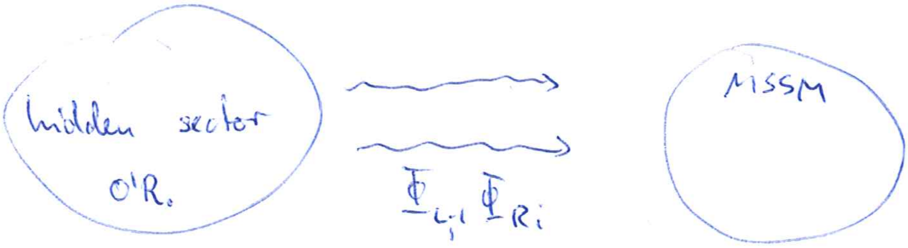
$$= -\left\{ m_\psi^2 |A_{L_i}|^2 + m_\psi^2 |A_{R_i}|^2 + 2\,\mathrm{Re}\,\lambda F_S^{vac} A_{L_i} A_{R_i} \right\}$$

$$\frac{\partial W_{hid}}{\partial A_S} + \frac{\partial W_{med}}{\partial A_S} = F_S^{vac} + \lambda A_{L_i} A_{R_i}$$

$$\boxed{\begin{array}{l} \text{fermion Dirac mass : } m_\psi = \lambda s^{vac} \\ \text{mass matrix for scalars : } \\ (A_L^\dagger, A_R) \begin{pmatrix} |\lambda s^{vac}|^2 & \lambda^* F_S^{vac*} \\ \lambda^* F_S^{vac*} & |\lambda s^{vac}|^2 \end{pmatrix} \begin{pmatrix} A_L \\ A_R^\dagger \end{pmatrix} \end{array}}$$

→ scalar masses split around fermion mass, split $\Delta m^2 \sim \sqrt{\lambda F_S^{vac\dagger}} \equiv M_{LR}^2$

→ overall mass scale $\sim \lambda s^{vac}$



ansatz :

Φ_{i_L}, Φ_{i_R} form complete SU(5) multiplets in 5, 5^* representations.

Digression:

SU(5) generators in fund. repres. :

T^a = traceless, hermitian ~~5n~~ 5×5 - matrices

basis with $Tr(T^a T^b) = \frac{1}{2}\delta^{ab}$:

$$T^a = \begin{pmatrix} \lambda^a/2 & 0 \\ 0 & 0 \end{pmatrix} \qquad (a = 1 \dots 8)$$

$$T^a = \begin{pmatrix} 0 & 0 \\ 0 & \sigma^a/2 \end{pmatrix} \qquad (a = 9, 10, 11)$$

$$\cancel{T^{12} = \sqrt{\tfrac{3}{5}}\,(-1/3 \dots)}$$

$$T^{12} = \sqrt{\frac{3}{5}} \left(\begin{array}{ccc|cc} -1/3 & & & & \\ & -1/3 & & & 0 \\ & & -1/3 & & \\ \hline & & & 1/2 & \\ & 0 & & & 1/2 \end{array}\right)$$

$$T^{13 \ldots \cancel{24}} = \ldots\ldots$$

$\Rightarrow$ can interpret T^{12} as $\sqrt{\frac{3}{5}}$ * hypercharge!

[$\Rightarrow$ in $SU(5)$ GUT: identify $g_5 \cdot T^a = \begin{cases} g_s T^a_s & (a = 1 \ldots 8) \\ g_W T^a & (a = 9, 10, 11) \\ \underbrace{g_Y}_{=: g_1 \cdot \sqrt{\frac{3}{5}}} Y & (a = 12) \end{cases}$

at M_{GUT}: $g_s(M_{GUT}) \approx g_W(M_{GUT}) \approx \underbrace{g_Y(M_{GUT}) \sqrt{\frac{5}{3}}}_{g_1}$]

$\phantom{at M_{GUT}:} = g_3 \approx g_2 \approx g_1$

example of such $SU(5)$ multiplet:

$$\begin{pmatrix} d_R^1 \\ d_R^2 \\ d_R^3 \\ e_L^c \\ -\nu_L^c \end{pmatrix} = \begin{pmatrix} d_R^i \\ \cdots \\ L^c \end{pmatrix}$$

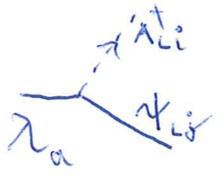
here: $\Phi_L \Rightarrow$ ~~colour~~ $\begin{pmatrix} \Phi_{L1} \\ \Phi_{L2} \\ \Phi_{L3} \\ \Phi_{L4} \\ \Phi_{L5} \end{pmatrix}$ $\begin{array}{l} \left.\begin{array}{l} \\ \\ \\ \end{array}\right\} \text{colour triplet, } Y = -1/3, \; SU(2) \text{ singlet} \\ \left.\begin{array}{l} \\ \\ \end{array}\right\} \text{colour singlet, } Y = 1/2, \; SU(2) \text{ doublet} \end{array}$

$\Phi_R \rightarrow$ complex conj. rep.

$\Rightarrow$ couplings to all gauge bosons!

$$\mathcal{L} = \int d^4\theta \; \Phi_L^\dagger e^{2gV} \Phi_L + \Phi_R^\dagger e^{2gV} \Phi_R + \text{rest of MSSM}$$

$\Rightarrow$ $\boxed{\text{gaugino interactions}}$

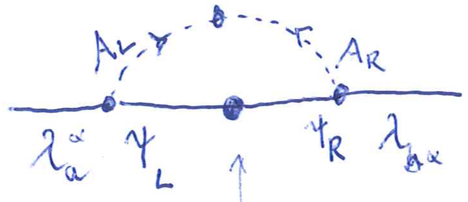


$= -\sqrt{2}\, i g_a T^a_{ij}$ etc

5.3.2 Resulting MSSM masses

Gauginos: $\mathcal{L}^{\text{eff}}_{\text{gaugino}} = -M(-i\lambda_a^{\alpha})(-i\lambda_{a\alpha}) + h.c.$

generated by loops



fake mass term $\begin{pmatrix} \psi_L \psi_R, \\ A_L^* A_R^* \end{pmatrix}$ as interaction

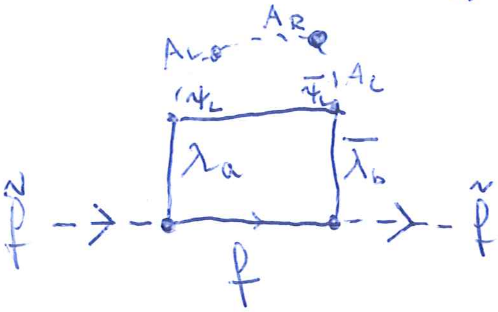
$$\sim \frac{1}{16\pi^2} \underbrace{g_a^2}_{g^2_{1,2,3}} \underbrace{T^a_{ij} T^b_{ji}}_{\frac{\delta^{ab}}{2}} \cdot m_\psi \cdot m_{LR}^2 \times f\left(\underbrace{M_{\text{overall}}}_{\approx m_\psi}\right)$$

$\Rightarrow$ effective mass term

$$\boxed{M_a \sim \frac{g_a^2}{16\pi^2} \underbrace{\frac{m_{LR}^2}{m_\psi}}_{\frac{F_s^{\text{vac}}}{s^{\text{vac}}}} \cdot \underbrace{\mathcal{O}(1)}_{\text{dim.-less loop function}}}$$

- $M_a \sim \alpha_i \quad (i = 1,2,3)$, $\quad M_{\text{Bino}} \approx \frac{1}{2} M_{\text{Wino}} \approx \frac{1}{6} M_{\text{gluino}}$
- result $= \mathcal{O}(\text{TeV})$ if $\frac{F_s^{\text{vac}}}{s^{\text{vac}}} \sim 1000\,\text{TeV}$

Sfermions & Higgs $\quad \mathcal{L}^{eff}_{\text{sfermions, Higgs}} = -m_Q^{2IJ}\, Q_I^\dagger Q_J + (U, D, L, E) + (H_{u,d})$



$$\sim \frac{g_a^2\, g_b^2}{(16\pi^2)^2}\, m_{LR}^2 \cdot f(m_{overall}) \underbrace{*\mathrm{Tr}(T^a T^b)}_{\approx \delta ab!}\, T_f^b T_f^a$$

$$= \frac{(g_a)^4}{(16\pi^2)^2}\, \underbrace{(T^a T^a)_f}\, \cdot \left(\frac{F_s^{vac}}{s^{vac}}\right)^2 \cdot \mathcal{O}(1)$$

~~for squarks;~~ depends on scalars

scalar $(\text{mass})^2$ terms

$$m_{\tilde{f}}^2 \sim \left(\frac{g_a^2}{16\pi^2}\, \frac{F_s^{vac}}{s^{vac}}\, \mathcal{O}(1)\right)^2 \cdot (T^a T^a)_{\tilde{f}}$$

$m^2_{\text{squark}} \sim m^2_{\text{gluino}}$
$m^2_{\text{slepton-L}} \sim m^2_{\text{wino}}$
$m^2_{\text{slepton-R}} \sim m^2_{\text{Bino}}$
$m^2_{\text{Higgs}} \sim m^2_{\text{wino}}$

} dominant terms, up to group factors

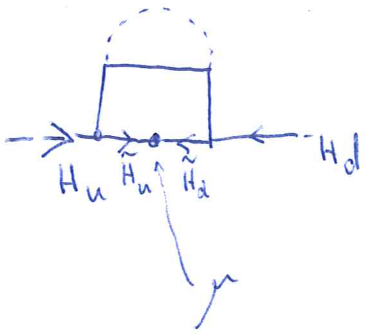
- hierarchy; similar to gaugino masses
- <u>diagonal</u> in flavour! <u>No FCNC</u>!

Big advantage of gauge mediation!

example result: $m_{\tilde{q}} : m_{\tilde{g}} : m_{\tilde{L}} : m_{\tilde{W}} : m_{\tilde{E}} : m_{\tilde{B}}$
$\approx 9.3 : 6.4 : 2.6 : 1.9 : 1.3 : 1$ (Weinberg III p.229)

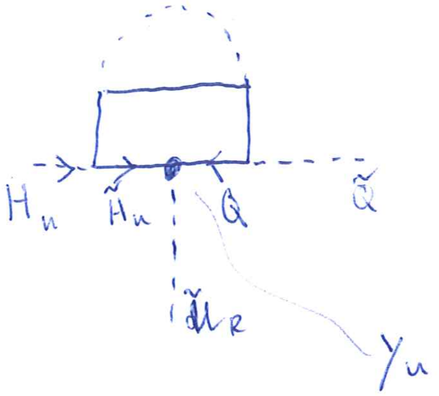
holomorphic A, $B\mu$ - parameters:

$B\mu \;\hat{=}$



$\sim \mu \dfrac{g^4}{(16\pi^2)^2} \dfrac{F_s}{s}$

$A_u y_u \;\hat{=}$



$\sim y_u \dfrac{g^4}{(16\pi^2)^2} \dfrac{F_s}{s}$

$\Rightarrow \quad B\mu \sim \mu * 2\text{-loop}$

$\quad\quad A\, y \sim y * 2\text{-loop}$

$\Rightarrow$ mass scales $\ll$ $m_{\text{gaugino, scalars}}$

- small A-terms $\rightarrow$ nice, simpler pheno, no FCNC
- " $B\mu$ $\rightarrow$ problem

$\rightsquigarrow$ how to generate acceptable μ, $B\mu$ values in gauge-mediated SUSY?

(5-20)

Gravitino mass: SUSY + gravity $\Rightarrow$ graviton (spin 2)
gravitino (spin 3/2)

$\cancel{SUSY}$ $\sim F^{vac}$ $\Rightarrow$ gravitino "eats" goldstino

$\Rightarrow$ $\boxed{m_{gravitino} \sim \frac{F^{vac}}{M_{Planck}}}$

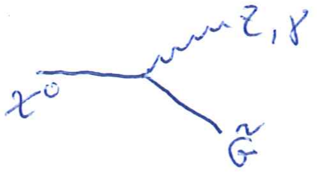
Scales:

		e.g.	
$\cancel{SUSY}$ scale	$\sqrt{F^{vac}}$	1000 TeV	10[illegible] GeV
Gravitino	$\frac{F^{vac}}{M_{Planck}}$	$\sim$eV	$10^{-2\ldots 6}$ GeV
$m_{soft,\,gaugino,\,scalar}$	$\frac{\alpha}{4\pi}\cdot\frac{F^{vac}}{S^{vac}}$	TeV	TeV
mass scale of messengers:	λS^{vac}	1000 TeV	$10^{10..18}$ GeV

Typical:

Gravitino = LSP, much lighter than other sparticles

$\Rightarrow$ cannot ignore!

decays 

possible,

"normal LSP" is unstable

$\rightarrow$ affects LHC signals if χ^0 lifetime short

$\rightarrow$ affects dark matter

5.3.3 Outlook

~~gra~~	gravity mediation	gauge mediation
expected scales	~~$F \sim M_{Pl}^2$~~	$\sqrt{F} \gtrsim 1000\,\text{TeV} \ldots$
	$m_{\text{Gravitino}} \sim m_{\text{soft}}$	$m_{\text{mediator}} \gtrsim 1000\,\text{TeV} \ldots$
	$m_{\text{soft}} \sim \frac{M_S^2}{M_{Pl}}, \frac{M_S^3}{M_{Pl}^2}$	$m_{\text{soft}} \sim \frac{\alpha}{4\pi} \frac{\langle F \rangle}{\langle S \rangle}$
	$M_S \sim 10^{10 \ldots 13}\,\text{GeV}$	$m_{\text{grav.}} \lesssim \text{GeV}$
FCNC	problem	✓
$\mu, B\mu$	ok	problem

Minimal versions → - simple, predict characteristic mass patterns
- specific problems

Generalizations → - more complicated setups, solutions for $\mu / B\mu$ problems
- can lead to different phenomenology

$\Longrightarrow$ - there is no single, most appealing scenario
- need experimental guidance and/or novel theor.- ideas