Minimal SUSY standard model

- $G = SU(3) \times SU(2) \times U(1) \qquad Q = T^3 + Y$

- Vector mults for each gauge group : G, W, B

  gauginos = matter? no wrong reps.

$\Rightarrow$

- Chiral multiplets for each ferm

$(3,2)_{1/6}$	Q_i	$i = 1,2,3$
$(\bar{3},1)_{-2/3}$	$\bar{U}_i$	
$(\bar{3},1)_{1/3}$	$\bar{D}_i$	
$(1,2)_{-1/2}$	L_i	
$(1,1)_1$	$\bar{E}_i$	
[$(1,1)_0$	$\bar{N}_i$]	← Not SM but possibly important?

Lagrangian:

$$\mathcal{L}_{\substack{\text{kinetic} \\ +\text{min coup}}} + \mathcal{L}_{\text{superpot}}$$

$\rightsquigarrow$ Yuk. couplings

convention

Leptons: $W_e = \lambda^e_{ij} L_i \bar{E}_j \bar{H}$

↑ Yuk couplings

$\bar{H} = \varphi + \cdots$

↑ usual Higgs

$\rightsquigarrow \quad l_i \bar{e}_j \varphi + \cdots$

$\bar{H} : (1,2)_{-1/2}$, just like in SM

Downs: $W_d = \lambda^d_{ij} Q_i \bar{D}_j \bar{H}$

Ups: $W_u = \lambda^u_{ij} Q_i \bar{U}_j$ ← uh oh:

need $\underline{Y = 1/2}$

$\bar{H}^\dagger$ has $Y = \frac{1}{2}$

but not chiral

⇒ need another chiral superfield

$H : (1,2)_{1/2}$ $\qquad \bar{H} \neq H^\dagger$

extra particles, beyond superpartners

"Baroqueness thm:" all BSM physics is baroque ?

↑

counterexample and win big.

Any economy ? $\bar{H} = (1,2)_{-1/2}$

$L = (1,2)_{-1/2}$

Higgs = sneutrino ??

no 1. Anomalies. Cancel in SM. extra w/ H, need $\bar{H}$.

2. ~~Lepton #~~ :

$$\left.\begin{matrix} Q\bar{d}L \\ L\bar{E}L \end{matrix}\right\} \text{violate badly}$$

General superpot w/ gauge symms:

$$W = \underset{\substack{\cancel{U(1)_L} \\ \text{forbid} \\ \text{how? (more later)}}}{\beta LH} + \underset{\text{Maj mass}}{M\bar{N}\bar{N}} + \mu H\bar{H} + W_e + W_d + W_u + \cdots + \text{higher dim}$$

Problem – superpartner masses

∴ need <u>SUSY breaking</u> ⇝ heavy superpartners

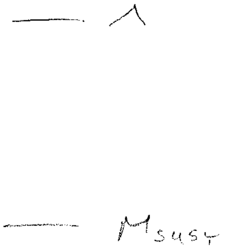
How? general picture

$$\begin{tikzcd} \text{breaking sector} \arrow[r] & \text{MSSM sector} \\ \text{e.g. dynamical breaking, extra dims, } \vdots \arrow[u, squiggly] & \text{gravity, new gauge interactions, } \vdots \arrow[u, squiggly] \end{tikzcd}$$

Many possibilities – possibly more later

6.25

Parametrize ignorance



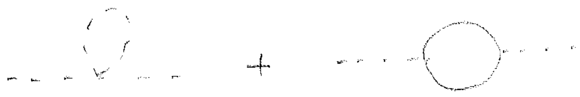
- assume superpartners w/ masses $\gtrsim M_{SUSY}$
- no other phys below $\Lambda \sim M_{Pl}$?

want $M_{Higgs} \lesssim 200$ GeV

general lagrangian $\rightsquigarrow$ $M_{Higgs} \sim \Lambda$

$\Rightarrow$ need "partial SUSY" for $p < \Lambda$

e.g. need to cancel quad divs in



$\Rightarrow$ preserve SUSY at large momentum

but suppose $m_\varphi \neq m_\psi$

 $\propto \int d^4p \, \frac{1}{p^2 + m_\psi^2 + \Delta m^2} = \int d^4p \left[\frac{1}{p^2 + m_\psi^2} - \frac{\Delta m^2}{(p^2 + m_\psi^2)^2} + \cdots \right]$

still cancels ↑ (first term) ↑ $\sim \ln \Lambda$

i.e. hierarchy not spoiled.

"soft SUSY breaking"

<u>Allowed terms</u> - e.g. W.Z model

$$\mathcal{L} = \int d^4\theta \; Z\Phi^\dagger\Phi + \int d^2\theta \left(m\frac{\Phi^2}{2} + \frac{\lambda}{3}\Phi^3 \right)$$

recall can think of $m = \langle m \rangle$

$\lambda = \langle \lambda \rangle$

also Z = real superfield $Z = \langle Z \rangle$

more generally

$$\begin{aligned} m &\to m + \theta^2 F_m \\ \lambda &\to \lambda + \theta^2 F_\lambda \\ Z &\to Z + \underbrace{(\theta^2 B + h.c.) + \theta^2\bar\theta^2 C}_{\substack{\text{break SUSY} \\ \underline{\text{softly}} \\ \text{"spurions"}}} \end{aligned}$$

$\overset{\sim}{\text{(ex)}}$ $$V = V_{susy} + M^2 \phi^* \phi + \left[\frac{1}{2} A_m \Phi^2 + \frac{1}{6} A_\lambda \Phi^3 + h.c. \right]$$

$$M^2 = -C + |B|^2$$

$$A_m = -2(F_m - Bm)$$

$$A_\lambda = -2\left(F_\lambda - \frac{3}{2} B\lambda\right)$$

renormalization: determined by SUSY thy w/ Z, m, λ.

supergraphs or holo + sym + renorm struct

$\Rightarrow$ <u>no quad divs.</u>

Gauge fields:

$$\mathcal{L} = \frac{-i}{8\pi}\int d^2\theta\, \tau\, \mathrm{Tr}(W^\alpha W_\alpha) + \text{h.c.} - \int d^4\theta\, Z\, \Phi^\dagger e^{2gV}\Phi$$

$$\tau \to \tau - \theta^2 \frac{m_\lambda}{g}$$

$$\rightsquigarrow \quad + \frac{m_\lambda}{g^2}\lambda\lambda$$

one other kind: $\int d^4\theta\, \underset{\substack{\uparrow \\ \theta^2\bar\theta^2 C}}{C}\, \Phi^\dagger\Phi^2 \sim C\varphi^*\varphi^2$

soft if no singlets

—2/27/07

∴ general result:

$$\boxed{\text{Soft SUSY terms} = \text{those from higher components of superfield couplings in lagrangian } (+\,C \text{ terms})}$$

MSSM:

scalar only.

$$\begin{aligned}-\mathcal{L}_{SSB} = {} & m^2_{Q\,ij}\, Q_i^* Q_j + m^2_{\bar u\,ij}\, \bar u_i^* \bar u_j + m^2_{\bar d\,ij}\, \bar d_i^* d_j \\ & + m^2_{L\,ij}\, L_i^* L_j + m^2_{\bar e\,ij}\, \bar e_i^* \bar e_j + m_H^2 |H|^2 + m_H^2 |\bar H|^2 \\ & + (m^2_{H\bar H}\, H \bar H + \text{h.c.}) + \underbrace{M_I \lambda_I \lambda_I}_{\text{gauginos}} + 27 \text{ trilinears}\end{aligned}$$

(many parameters, ~100!)

Predicted by theory of SUSY, but challenge to get it all right...

Some issues :

- B & L violation

what about $W_{\not{B}\not{L}} = \bar{U}\bar{D}\bar{D} + QL\bar{D}$?!

violate B & L, at dim 4

in EFT ext. of SM, B & L can be violated,

but <u>higher dim</u> $\Rightarrow$ suppressed.

Resolution : symmetries. global (not great w/ grav)

discrete (can be gauge)

One that works: R-parity. (= R symm w/ discrete phase)

$$\theta \to -\theta$$

$$Q, \bar{U}, \bar{D}, L, \bar{E}, \bar{N} \to \times(-1)$$

$\therefore$ $q, \bar{u}, \cdots$ (ferms) <u>even</u>

$Q, \bar{U}, \cdots$ (bosos) <u>odd</u>

$$H, \bar{H} \to \times 1$$

$\therefore$ $H, \bar{H}$ <u>even</u>

$\psi_H, \psi_{\bar{H}}$ <u>odd</u>

$\Rightarrow$ $W_{\not{B}\not{L}}$ forbidden

also LH

Gauge fields: V even $\Rightarrow$ λ <u>odd</u>
A_μ <u>even</u>

$\therefore$ SM fields even
superpartners odd

Thus lightest supersymmetric part. (LSP) = stable

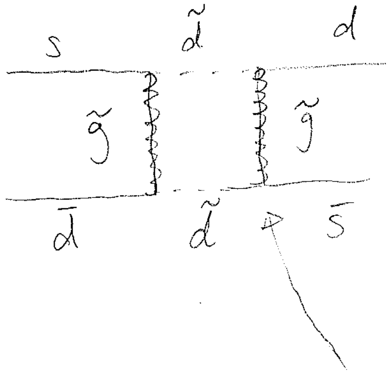
<u>SUSY bonus #1</u> : if $M_{LSP} \sim 1$ TeV, Dark matter candidate (right mass for producing observed abundance)

- <u>Flavor</u>

Recall V_{CKM} ~> no FCNC's <u>GIM</u>

also $\mu \to e\gamma$ not observed, etc.

e.g. K_0-$\bar{K}_0$ mixing



$\rightsquigarrow$ $\Delta m \sim 10^3 \times \Delta m_{SM}$

different mixing matrix.

suggests: A) alignment in mass matrices

or B) universality (~flavor independence)

Should emerge from SUSY.

One simplifying assumption ("minimal SUGRA")
~ complete universality:

$$m_{ij}^2 = m_0^2 \delta_{ij}$$

$$A_{ijk} = A_0 \times (\text{Yukawas of SM})$$

$$M_I = M_0$$ ("GUT relⁿ" - more motivated w/ GUTs)

$$m_{H\bar{H}}^2 = B\mu$$

... many fewer parameters some motivation ...

+ other issues. (& pluses)

turn to something where might see another motivator for SUSY ...