Corfu lectures on SUSY and BSM physics

G.G.Ross, Corfu, September 2012

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Outline:

I Introduction
Building SUSY extensions of the Standard Model

II SUSY searches at the LHC.

CMSSM, Gauge mediated models, GNMSSM, Non-universal gaugino mass

III LHC & BSM

Xtra-dimensions (c.f. Dudas), Composite Higgs, Little Higgs, SUSY Higgs

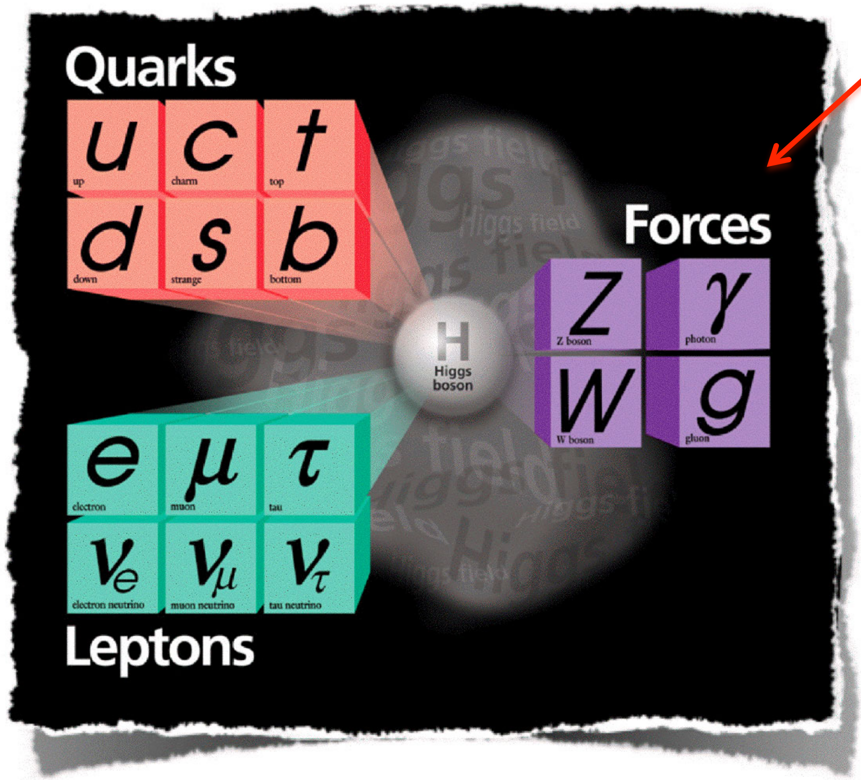
IV Implications of 125 GeV Higgs (c.f. Hebecker)

Vacuum stability, Higgs inflation, SUSY, Just the Standard Model

The Standard Model

$SU(3)\times SU(2)\times U(1)$

$J=\frac{1}{2}$

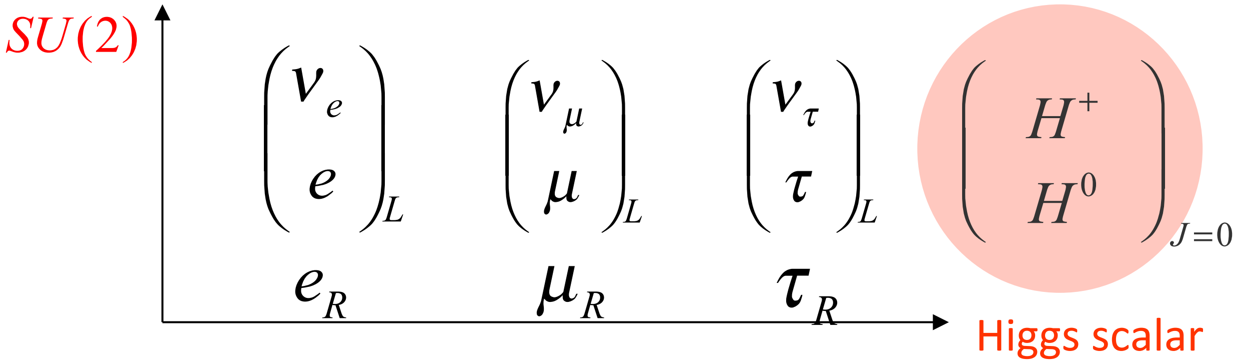


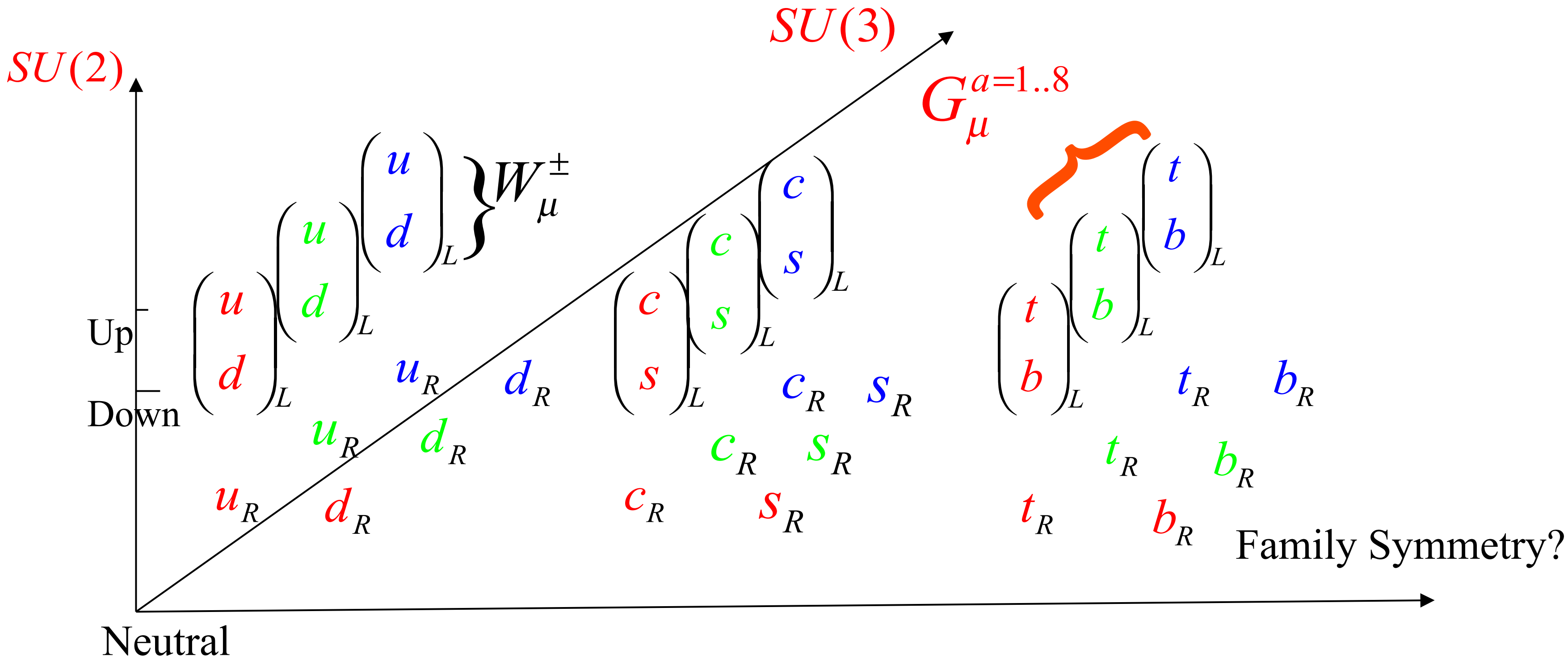
$J=1$

$J=0$

...a renormalisable, spontaneously broken, local gauge quantum field theory of the strong, electromagnetic and weak interactions

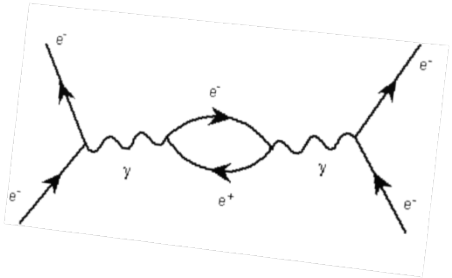
Multiplet structure –'chiral'





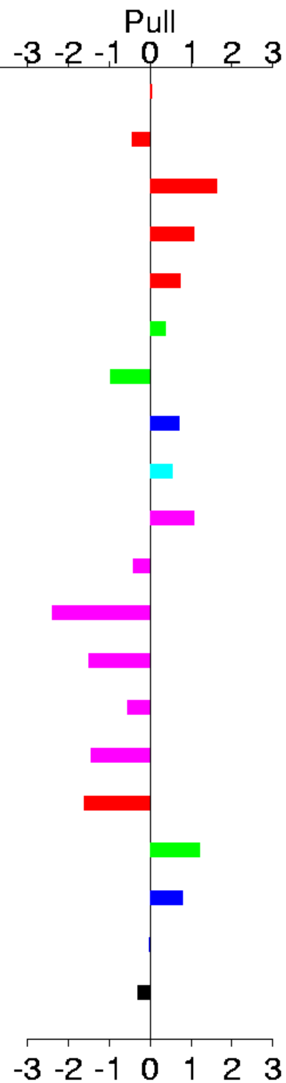
Precision tests of the Standard Model

Gauge interactions detemined by multiplet structures



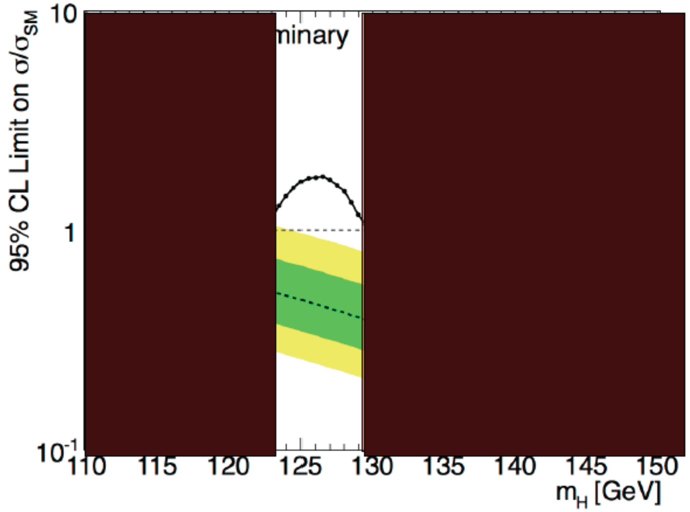
Sensitive to quantum corrections

	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.05
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.07
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.75
A_e	0.1498 ± 0.0048	.38
A_τ	0.1439 ± 0.0042	-.97
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.70
m_W [GeV]	80.427 ± 0.046	.55
R_b	0.21653 ± 0.00069	1.09
R_c	0.1709 ± 0.0034	-.40
$A^{0,b}_{fb}$	0.0990 ± 0.0020	-2.38
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.51
A_b	0.922 ± 0.023	-.55
A_c	0.631 ± 0.026	-1.43
$\sin^2\theta^{lept}_{eff}$	0.23098 ± 0.00026	-1.61
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.81
m_t [GeV]	174.3 ± 5.1	-.01
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.29



Higgs discovery and exclusion – LHC July 2012

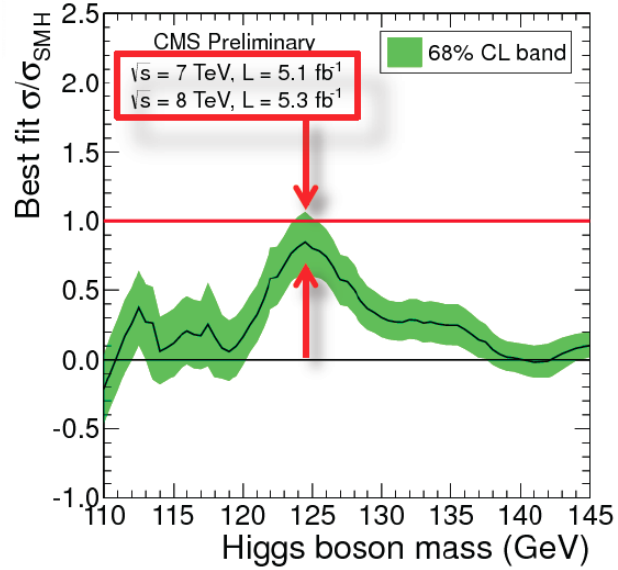
Atlas



Excluded at 95% CL

110-122.7 129-557 GeV

CMS




Stop repeating what I said!
5σ and 5σ

"You're a nice guy and all that,
but I'm looking for somebody
more *symmetrical*."

Beyond the Standard Model

Grand Unification

$SO(10) \supset SU(5) \supset SU(3) \otimes SU(2) \otimes U(1)$

$$(\bar{5})_L : \begin{array}{l} \left.\begin{array}{c} d^c \\ d^c \\ d^c \end{array}\right\} SU(3) \\ \left.\begin{array}{c} e \\ \nu_e \end{array}\right\} SU(2) \end{array}$$

$$3Q_{d^c} + Q_{e^-} = 0$$

$$Q_{d^c} = 1/3$$

LH states SU(2) doublets

$$(10)_L : \begin{array}{cccc} & & \multicolumn{2}{c}{\overbrace{\hphantom{u \quad d}}} \\ u^c & -u^c & u & d \\ & u^c & u & d \\ & & u & d \\ & & & e^c \end{array}$$

$$\nu_{e,L}{}^{c} \equiv \nu_{e,R}$$

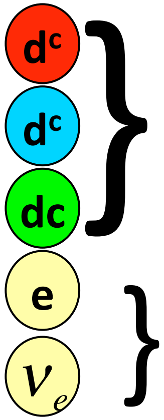
$$(16)_L = (10)_L + (\bar{5})_L + (1)_L$$

Grand unification

$$SO(10) \supset SU(5) \supset SU(3) \otimes SU(2) \otimes U(1)$$

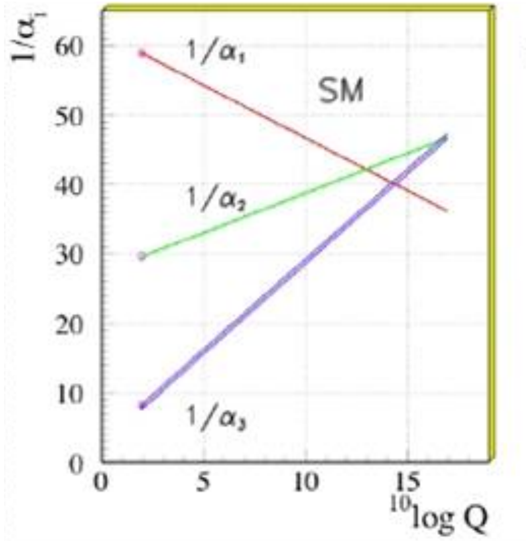
$$g_5 \qquad g_3 \qquad g_2 \qquad g_1$$

$(\bar{5})_L$:

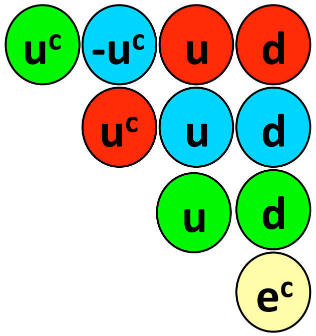


$SU(3)$

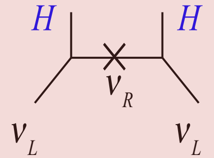
$SU(2)$



$(10)_L$:



Neutrino masses via seesaw



$$M_{\nu_L} = \frac{<H>^2}{M_{\nu_R}}$$

$$(16)_L = (10)_L + (\bar{5})_L + (1)_L$$

The Standard model as an effective field theory…

A renormalisable, spontaneously broken, local gauge quantum field theory

$$\boxed{L_{eff}\left(\phi_{light},\psi_{heavy},M,E\right)\xrightarrow{E\ll M}L_{eff}\left(\phi_{light},E\right)+O\left(\frac{1}{M}\right)}$$

- Renormalisable $\quad D\leq 4+O(1/M)\quad$ ✔

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- Renormalisable $\quad D\leq 4+O(1/M)$ ✔

- $L^{SM}_{effective}\supset \cancel{M_A A_\mu A^\mu}+\cancel{m_f \bar{f}_L f_R}$

$$\boxed{M_A, m_f \ll M_X, M_{Planck}}$$

Fermions chiral ✔

Vector gauge bosons ✔

(Massless - vectorlike couplings; massive – chiral couplings)

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  Fermions chiral ✔

  Vector gauge bosons ✔

  (Massless - vectorlike couplings; massive - chiral couplings)
- Light Higgs ? $L_{effective}^{SM}\supset M_H^2\left|H\right|^2$

The Standard model as an effective field theory...

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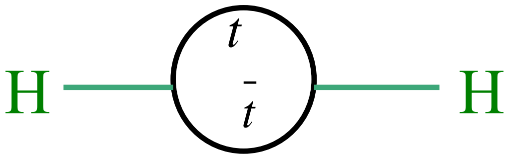
  Fermions chiral ✔

  Vector gauge bosons ✔

- Light Higgs ✗ The Hierarchy problem $\Lambda\le 1TeV$??



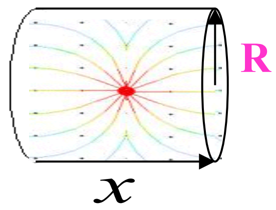
$$\delta^t M_H^2 \simeq -\frac{h_t^2}{8\pi^2}\int_0^{\Lambda^2}dk^2=\frac{h_t^2}{8\pi^2}\Lambda^2+O\left(m_t^2\ln\left(\frac{m_t}{\Lambda}\right)\right)$$

Solutions to the hierarchy problem

$\Lambda \leq 1TeV$??

- Composite: e.g. technicolour,

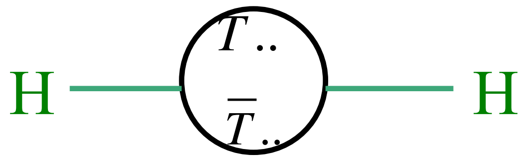
- $\Lambda_{fundamental} \simeq 1TeV$! Xtra dimensions



$$V(r) = \frac{1}{M_*^{2+d} R^d} \frac{m_1 m_2}{r}, \quad D = 4 + d, \quad r \ll R \qquad \boxed{M_{Planck}^2 = M_*^2 \left(M_* R\right)^d}$$

(or warped extra dimensions)

- Symmetry protection Nambu - Goldstone



e.g. $SU(3) \rightarrow SU(2)$ $8 \rightarrow 3$ 5 Goldstone modes

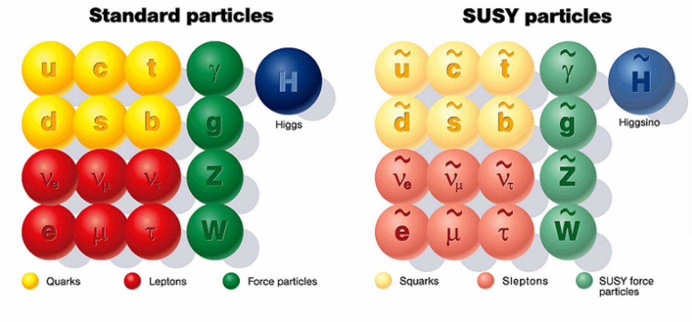
$$\begin{pmatrix} . & . & H^{*+} \\ . & . & H^{*0} \\ H^- & H^0 & . \end{pmatrix}$$

Symmetry broken by gauge interactions – pseudo Goldstone bosons

...addresses little hierarchy problem only

....little Higgs

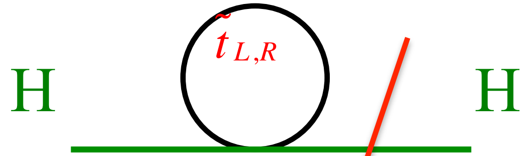
Supersymmetry



$$\psi_H = \begin{pmatrix} \tilde{H} \\ H \end{pmatrix} \qquad \cancel{\mu}\,\bar{\psi}_H \psi_H, \quad \text{chiral symmetry}$$

$m_{\tilde{t}} \leq 1 TeV$

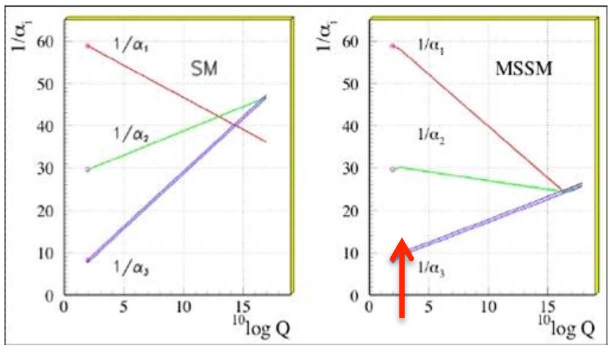
Radiative corrections



$$\delta^{\tilde{t}} M_H^2 \simeq \frac{\lambda_s}{8\pi^2}\left(\Lambda^2 - m_{\tilde{t}}^2 \ln\left(\frac{\Lambda^2}{m_{\tilde{t}}^2}\right) \right)$$

$$\boxed{\delta^{t+\tilde{t}} M_H^2 = \frac{h_t^2}{8\pi^2}\left(m_t^2 \ln\left(\frac{\Lambda^2}{m_t^2}\right) - m_{\tilde{t}}^2 \ln\left(\frac{\Lambda^2}{m_{\tilde{t}}^2}\right) \right)}$$

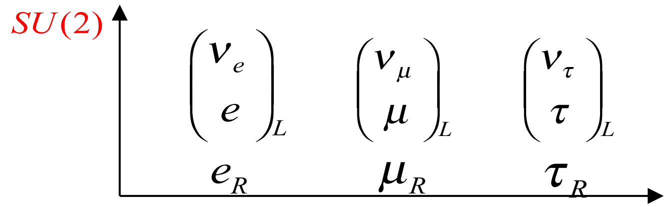
Unification



$M_{SUSY} \sim TeV$

Supersymmetric extensions of the SM (N=1)

Supersymmetry (N=1)

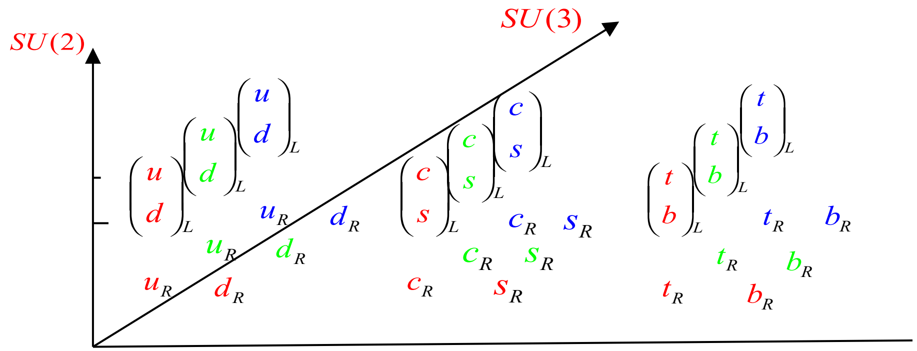


Matter – chiral supermultiplets

$$\begin{pmatrix} \psi \\ \phi \end{pmatrix}$$

J=1/2 quarks and leptons

J=0 squarks and sleptons



Higgs – chiral supermultiplets

$$H_u = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}, H_d = \begin{pmatrix} \overline{H}^0 \\ H^- \end{pmatrix}$$

Anomaly free

Gauge bosons – vector supermultiplets

$$\begin{pmatrix} V_\mu \\ \lambda \end{pmatrix}$$

J=1 gauge bosons

J=1/2 gauginos

$g^{a=1..8}$	Gluons, gluinos
$W^{a=1..3}$	W-bosons, Winos
B	B-boson, Bino

Yukawa interactions - superpotential

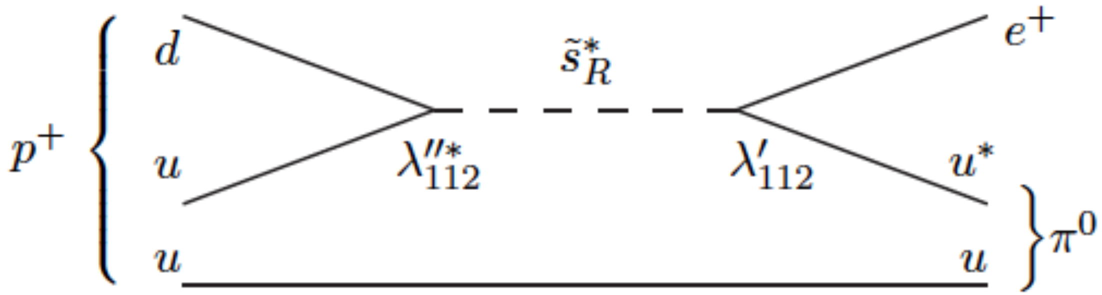
Renormalisable terms allowed by gauge symmetries

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$

$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$

$\Delta L = 1$ $\qquad\qquad$ $\Delta B = 1$

Proton decay



$$\tau / \tau_{\text{exp limit}} \approx \frac{1}{\lambda''^2 \lambda'^2} \left(\frac{10^{16}\, GeV}{m_{\tilde{s}}} \right)^4$$

Discrete symmetries

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$

$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$

$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E}H_d + LLH_uH_u\right)^{\dagger}$$

R-parity: Z_2 $\quad H_u, H_d \; +1$ $\quad$ SUSY states odd

$L, \overline{E}, Q, \overline{D}, \overline{U}, \quad \theta \quad -1$

Weinberg, Sakai

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Weinberg, Sakai

$\dagger$

$$\boxed{\text{but} \quad M > 10^{25}\,GeV = 10^{7}\,M_{Planck}\,!}$$

Discrete symmetries

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$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + L L H_u H_u \right)$$

R-parity: Z_2

SUSY states odd

Weinberg, Sakai

Baryon "parity": Z_3

$$\begin{array}{ll} Q & 1 \\ \overline{D}, H_u & \alpha \\ L, \overline{E}, \overline{U}, H_d & \alpha^2 \end{array}$$

LSP unstable

Discrete gauge symmetry
-anomaly free

Ibanez, GGR

Discrete symmetries

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$
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R-parity: Z_2

SUSY states odd

Baryon "parity": Z_3

LSP unstable

Proton hexality: $Z_6 = Z_2^R \times Z_3^B$

LSP stable

$\frac{1}{M} LLH_u H_u$

Dreiner, Luhn, Thormeier

Discrete symmetries

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$
$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$
$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + LLH_uH_u \right)$$

$\boxed{\text{μ term, GUTs?}}$

R-parity: Z_2 — SUSY states odd

Baryon "parity": Z_3 — LSP unstable

Proton hexality: $Z_6 = Z_2^R \times Z_3^B$ — LSP stable

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R-parity: Z_2 SUSY states odd

Baryon "parity": Z_3 LSP unstable

Proton hexality: $Z_6 = Z_2^R \times Z_3^B$ LSP stable

Z_N^R R-symmetry N=4,6,8,12,24 LSP stable

$\frac{1}{M} LLH_u H_u$

Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange
Babu, Gogoladze, Wang

R-symmetry

$$\mathcal{L}_W = \int d^2\theta\, W(\Phi_i) + \text{h.c.} \qquad \mathcal{L}_K = \int d^4\theta K$$

$$\boxed{\theta \to e^{-i\alpha}\theta, \quad W \to e^{2i\alpha}W}$$

$$\Phi(y^\mu) = \varphi(y^\mu) + \sqrt{2}\theta\eta(y^\mu) + \theta^2 F(y^\mu)$$

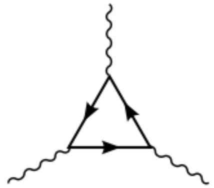
$$\boxed{\varphi \to e^{i\beta}\varphi, \quad \eta \to e^{i(\alpha+\beta)}\eta, \quad F \to e^{i(2\alpha+\beta)}F}$$

A unique solution : Z_4^R discrete R symmetry

MSSM spectrum
No perturbative μ term
Commutes with SO(10)
Anomaly cancellation

N	q_{10}	$q_{\bar{5}}$	q_{H_u}	q_{H_d}	q_N
4	1	1	0	0	2

Green Schwarz term †



$$A_{G-G-Z_N} = \delta_{GS} \quad \mathrm{mod}\ \eta \qquad\qquad \eta = \begin{cases} N/2 & N \text{ even} \\ N & N \text{ odd} \end{cases}$$

$$A_{\mathrm{SU}(3)-\mathrm{SU}(3)-\mathbb{Z}_N} = \frac{1}{2}\sum_i \left[3 \cdot q_{10_i} + q_{\overline{5}_i} - 4R\right] + 3R$$

$$A_{\mathrm{SU}(2)-\mathrm{SU}(2)-\mathbb{Z}_N} = \frac{1}{2}\sum_i^3 \left[3 \cdot q_{10_i} + q_{\overline{5}_i} - 4R\right] + 2R + \frac{1}{2}\left(q_H + q_{\bar{H}} - 2R\right)$$

$$A_{\mathrm{U}(1)_Y\text{-}\mathrm{U}(1)_Y\text{-}\mathbb{Z}_N^R} = \frac{1}{2}\sum_{g=1}^{3}\left(3q_{10}^g + q_{\overline{5}}^g\right) + \frac{3}{5}\left[\frac{1}{2}\left(q_{H_u} + q_{H_d}\right) - 11\right] \qquad (R=1)$$

$$\Rightarrow N = 3, 4, 6, 8, 12, 24$$

Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange

† $\phi(x)\sum_i F_i^2 + i\eta(x)\sum_i F_i\tilde{F}_i, \qquad \eta(x) \to \eta(x) - \theta(x)\delta_{GS}$

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No perturbative μ term
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N	q_{10}	$q_{\bar{5}}$	q_{H_u}	q_{H_d}	q_N
4	1	1	0	0	2

D=5 operators

up and down Yukawas allowed

$$3q_{10} + q_{\bar{5}} + q_{H_u} + q_{H_d} = 4 \quad \text{Mod N} \quad \Rightarrow \quad 3q_{10} + q_{\bar{5}} = 0 \quad \text{Mod N} \quad \Rightarrow \quad \cancel{\frac{1}{M} QQQL} \quad \frac{1}{M} LLH_u H_u$$

Weinberg operator

SUSY breaking

$\langle W \rangle, \langle \lambda\lambda \rangle$ R=2 non=perturbative breaking

$Z_{4R} \rightarrow Z_2^R \quad R - parity$

Domain walls and tadpoles safe Abel

$\mu \sim m_{3/2}, \quad O(\frac{m_{3/2}}{M^2} QQQL)$

$M_{higgs} \approx M_{SUSY}$

$\mu, \cancel{B}, \cancel{L}$

SUSY breaking

$$\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = 2\sigma^\mu_{\alpha\dot\alpha} P_\mu,$$

$$\{Q_\alpha, Q_\beta\} = 0, \qquad \{Q^\dagger_{\dot\alpha}, Q^\dagger_{\dot\beta}\} = 0$$

Global supersymmetry

$$H = P^0 = \frac{1}{4}(Q_1 Q_1^\dagger + Q_1^\dagger Q_1 + Q_2 Q_2^\dagger + Q_2^\dagger Q_2)$$

$$\boxed{V(\phi, \phi^*) = F^{*i} F_i + \frac{1}{2}\sum_a D^a D^a = W_i^* W^i + \frac{1}{2}\sum_a g_a^2 (\phi^* T^a \phi)^2}$$

Local supersymmetry

c.f. Martin, Shirman reviews

$$\boxed{V = [M^2 e^{-G/2} G^j + f^j \frac{\lambda\lambda}{4M}](G^{-1})^k_j [M^2 e^{-G/2} G^k + f^k \frac{\lambda\lambda}{4M}]^* - 3M^4 e^{-G}}$$

e.g. $G(\phi_i, \phi^{*i}) = -\phi_i \phi^{*i} - \log|W(\phi_i)|^2$

$$V = e^{|\eta_i|^2}\left[\left|\frac{\partial W}{\partial \phi_i} + \frac{\phi^{*i}}{M^2} W\right|^2 - \frac{3|W|^2}{M^2}\right]$$

Gaugino condensation:

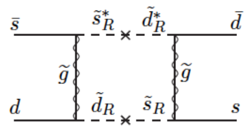
$\langle \lambda\lambda \rangle \propto \Lambda^3, \quad \Lambda^2 = \Lambda^2_{Compactification} e^{-\mathrm{Re}\, S/b_0}$

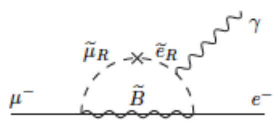
Nilles

$$
\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} \;=\; & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
& -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\
& - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + \text{c.c.})\,.
\end{aligned}
$$

"Gravity" mediation (Planck scale messengers) (mSUGRA)

$$
\boxed{
\begin{aligned}
& M_3 = M_2 = M_1 = m_{1/2}, \\
& \mathbf{m^2_Q} = \mathbf{m^2_{\overline{u}}} = \mathbf{m^2_{\overline{d}}} = \mathbf{m^2_L} = \mathbf{m^2_{\overline{e}}} = m_0^2\,\mathbf{1}, \qquad m^2_{H_u} = m^2_{H_d} = m_0^2, \\
& \mathbf{a_u} = A_0\mathbf{y_u}, \qquad \mathbf{a_d} = A_0\mathbf{y_d}, \qquad \mathbf{a_e} = A_0\mathbf{y_e}, \\
& b = B_0\mu,
\end{aligned}
}
$$





$$
m_{1/2} = f\frac{\langle F\rangle}{M_{\text{P}}}, \qquad m_0^2 = k\frac{|\langle F\rangle|^2}{M_{\text{P}}^2}, \qquad A_0 = \alpha\frac{\langle F\rangle}{M_{\text{P}}}, \qquad B_0 = \beta\frac{\langle F\rangle}{M_{\text{P}}}.
$$

RG running

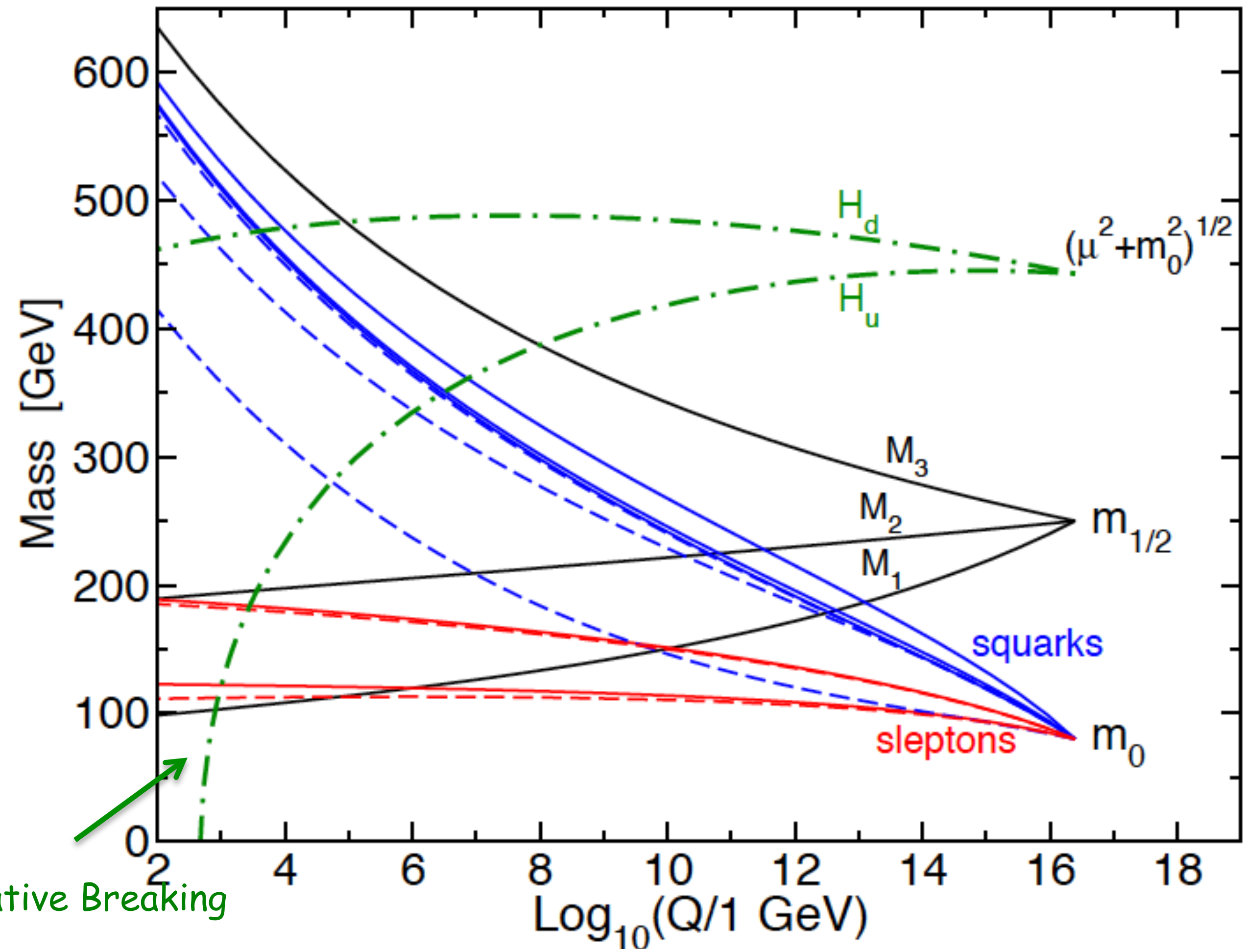
$$2\,|y_t|^2\,(m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}_3}^2) + 2\,|a_t|^2$$

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3X_t - 6g_2^2\,|M_2|^2 - \frac{6}{5} g_1^2\,|M_1|^2$$

$$16\pi^2 \frac{d}{dt} m_{Q_3}^2 = X_t + X_b - \frac{32}{3} g_3^2\,|M_3|^2 - 6g_2^2\,|M_2|^2 - \frac{2}{15} g_1^2\,|M_1|^2$$

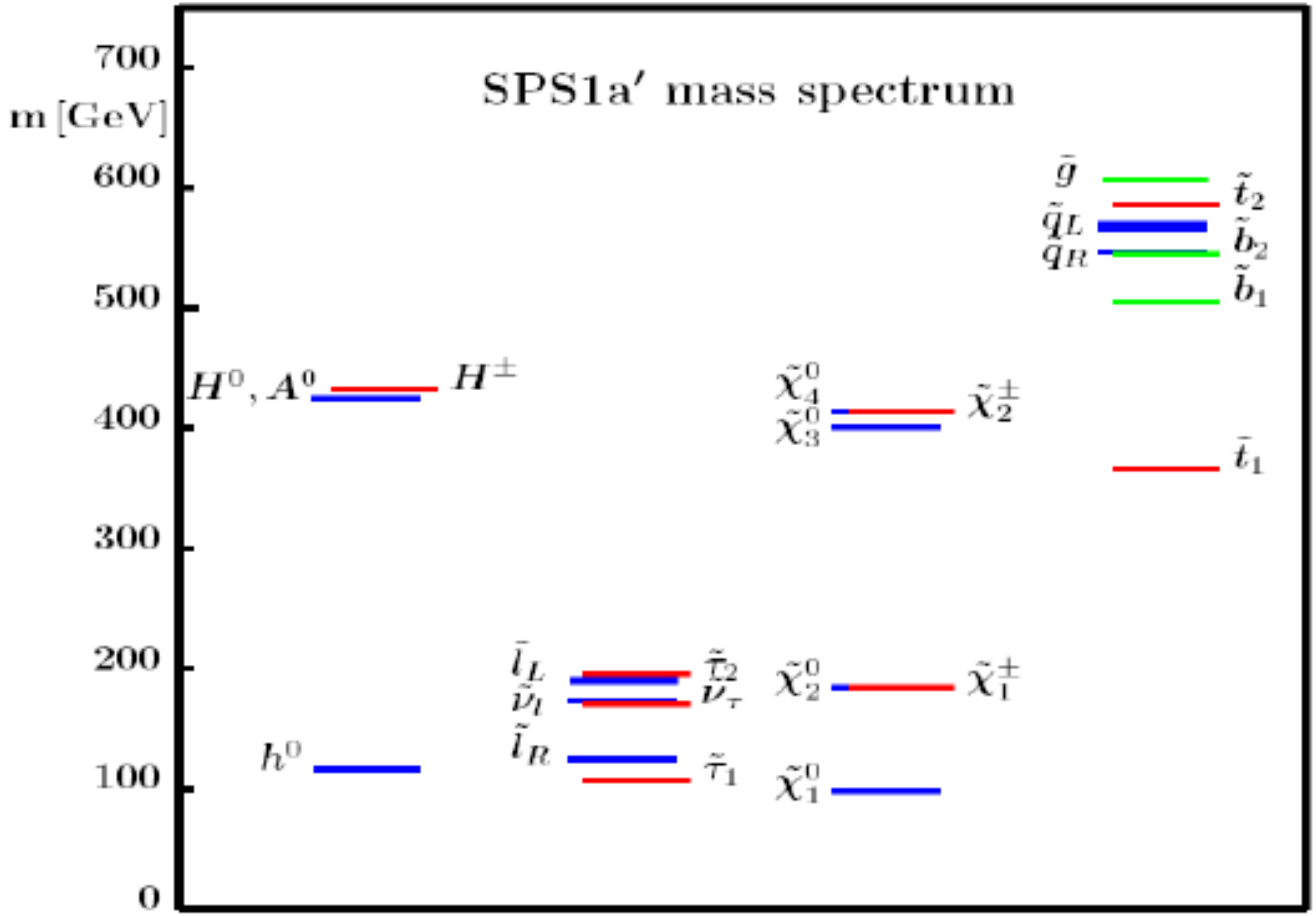
$$16\pi^2 \frac{d}{dt} m_{\bar{u}_3}^2 = 2X_t - \frac{32}{3} g_3^2\,|M_3|^2 - \frac{32}{15} g_1^2\,|M_1|^2$$

...



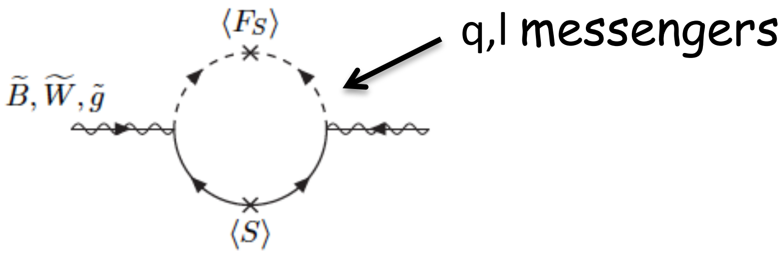
Radiative Breaking

Ibanez, GGR



$$\mathrm{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix} \begin{pmatrix} \widetilde{B} \\ \widetilde{W}^0 \\ \widetilde{H}_d^0 \\ \widetilde{H}_u^0 \end{pmatrix}$$

"Gauge" mediation



$$\boxed{M_a = \frac{\alpha_a}{4\pi}\Lambda,}$$

+...

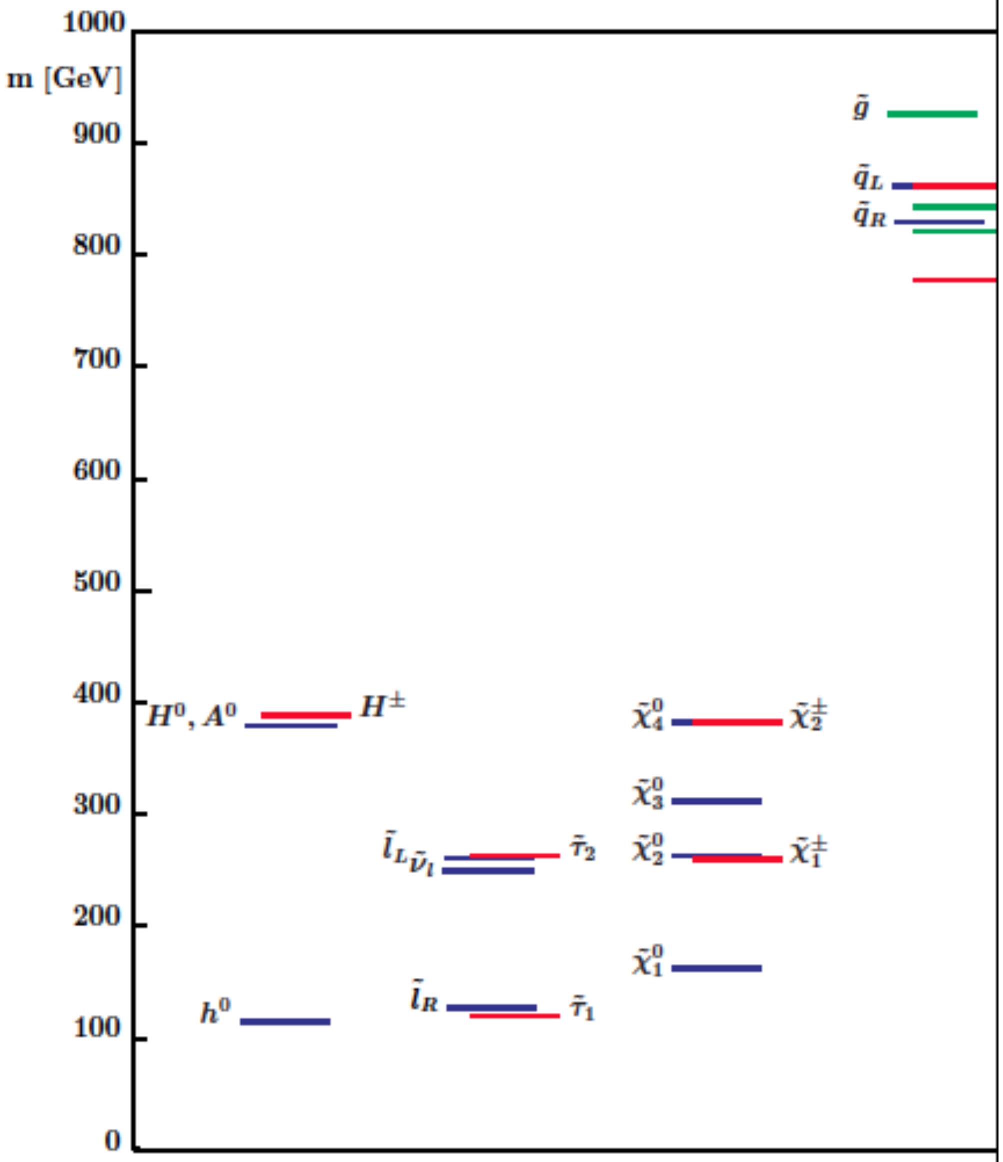
$$\boxed{m_{\phi_i}^2 = 2\Lambda^2\left[\left(\frac{\alpha_3}{4\pi}\right)^2 C_3(i) + \left(\frac{\alpha_2}{4\pi}\right)^2 C_2(i) + \left(\frac{\alpha_1}{4\pi}\right)^2 C_1(i)\right]}$$

GMSB scenario with $\tilde{\tau}$ NLSP

(SPS 7 benchmark scenario):

Typical hierarchy bertween strongly/weakly interacting particles:

$$\alpha_3 : \alpha_2 : \alpha_1$$



Anomaly mediated supersymmetry breaking

….anomalous violation of classical conformal (scale) invariance

$$
\begin{aligned}
M_1 &= \frac{F_\phi}{16\pi^2}\frac{33}{5}g_1^2 \\
M_2 &= \frac{F_\phi}{16\pi^2}g_2^2 \\
M_3 &= -\frac{F_\phi}{16\pi^2}3g_3^2 \\
m_{\tilde{q}}^2 &= \frac{|F_\phi|^2}{(16\pi^2)^2}\left(8g_3^4+\ldots\right), \\
m_{\tilde{e}_L}^2 &= -\frac{|F_\phi|^2}{(16\pi^2)^2}\left(\frac{3}{2}g_2^4+\frac{99}{50}g_1^4\right) \\
m_{\tilde{e}_R}^2 &= -\frac{|F_\phi|^2}{(16\pi^2)^2}\frac{198}{25}g_1^4
\end{aligned}
$$

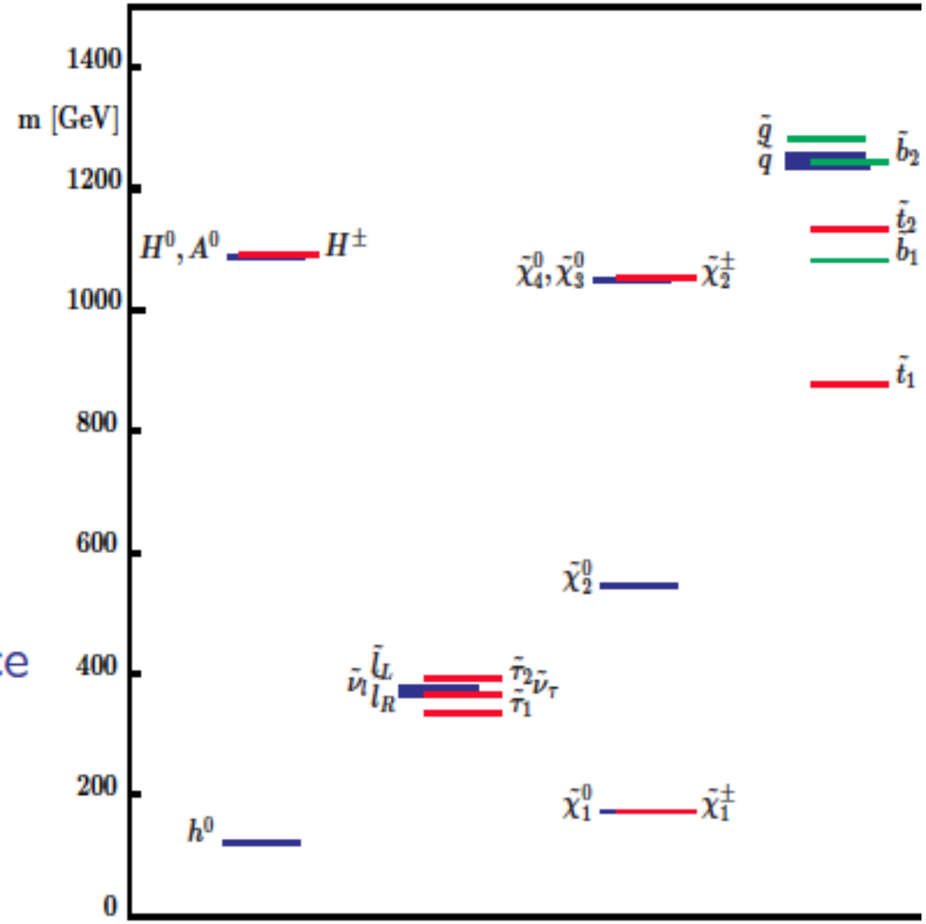
AMSB scenario characterized by

$$m_{\mathsf{aux}}, m_0, \tan\beta, \mathrm{sign}(\mu)$$

m_{aux}: overall scale of SUSY particle masses

m_0: phenomenological parameter: universal scalar mass term

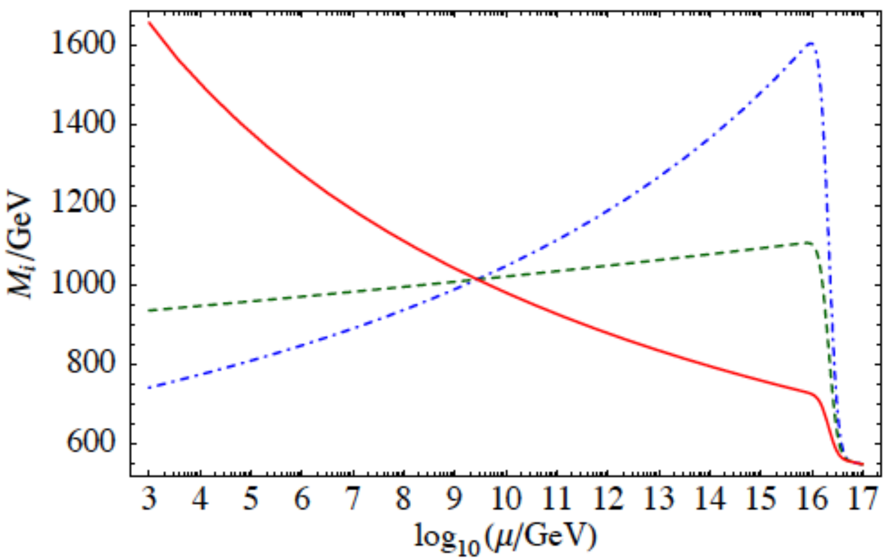
AMSB spectrum (SPS 9):



typical feature: very small neutralino–chargino mass difference

Mixed gravity (modulus) – anomaly mediation (Mirage mediation)

$$
\begin{aligned}
M_a &= M_s\,\left[\alpha + b_a\, g_a^2\right]\;, \\
m_i^2 &= M_s^2\,\left[\alpha^2 - \dot{\gamma}_i + 2\alpha\,(T+\bar{T})\,\partial_T\gamma_i\right]\;, \\
A_{ijk} &= M_s\,\left[3\alpha - \gamma_i - \gamma_j - \gamma_k\right]\;.
\end{aligned}
$$



Nilles et al