The Standard model as an effective field theory…

A renormalisable, spontaneously broken, local gauge quantum field theory

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

- Renormalisable ✔

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- Renormalisable ✔
- Vectors gauge bosons ✔ $A_\mu \to A_\mu + \partial_\mu \theta$
- Fermions chiral ✔ $f_L \to e^{i\alpha_L . \sigma} f_L, \quad f_R \to f_R$
- Massless gauge bosons - vectorlike couplings ✔
- Massive gauge bosons - chiral couplings ✔

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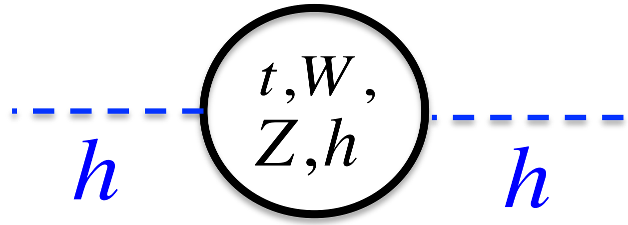
- Light Higgs ✗ The hierarchy problem

Hierarchy problem?



$$\delta m_h^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 = \left(\frac{\Lambda}{500GeV}\right)^2$$

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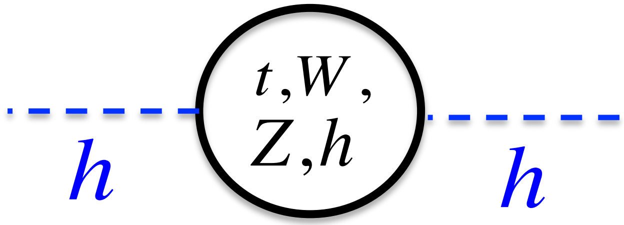

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Field theory: δm^2 not measureable

…only $m^2 = m_0^2 + \delta m^2$ "physical"

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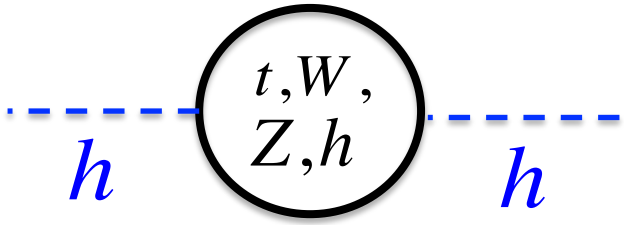

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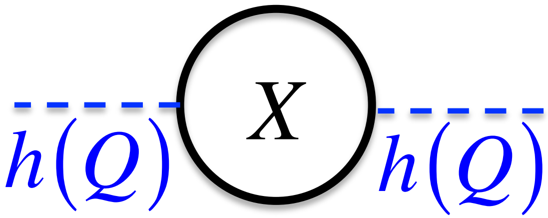
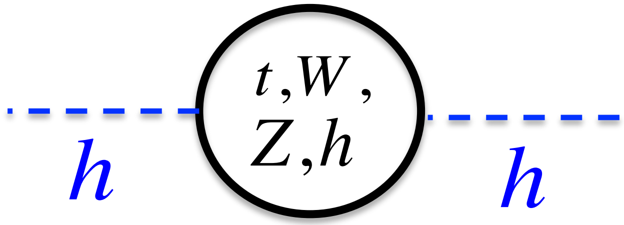
GUTS:

$$\delta m_h^2 \propto M_X^2 \ln\left(\frac{Q^2 + M_X^2}{\Lambda^2}\right)$$



- "real hierarchy problem"

Hierarchy problem?



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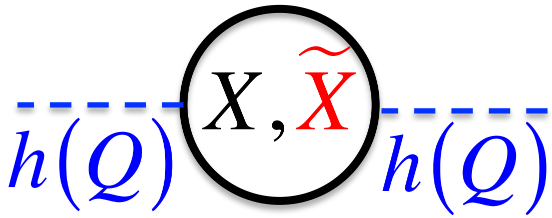
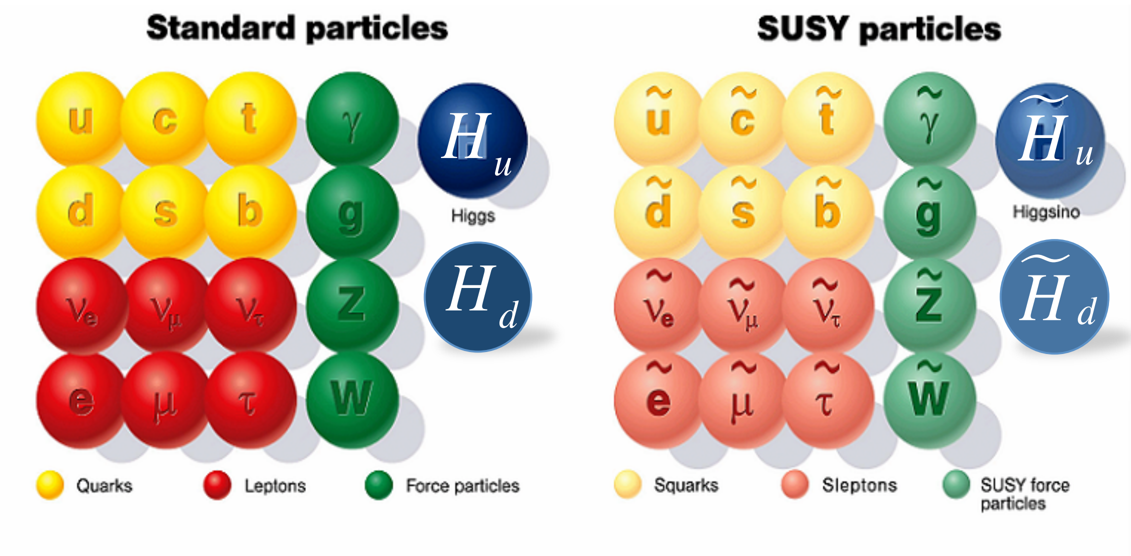


- "real hierarchy problem"

GUTS $\Longrightarrow$ SUSYGUTS

$$\delta m_h^2 \propto \left(M_{\tilde{X}}^2 - M_X^2\right)$$

III. SUSY GUTS



$$\underbrace{\qquad}$$

$$G_{GUT} \times G_{Flavour} \times \left(N = 1\,\mathrm{SUSY}\right)$$

Supermultiplets

SO(10): V_{45} Vector +3 φ_{16} chiral + H_{10} chiral +...

SUSY gauge coupling unification

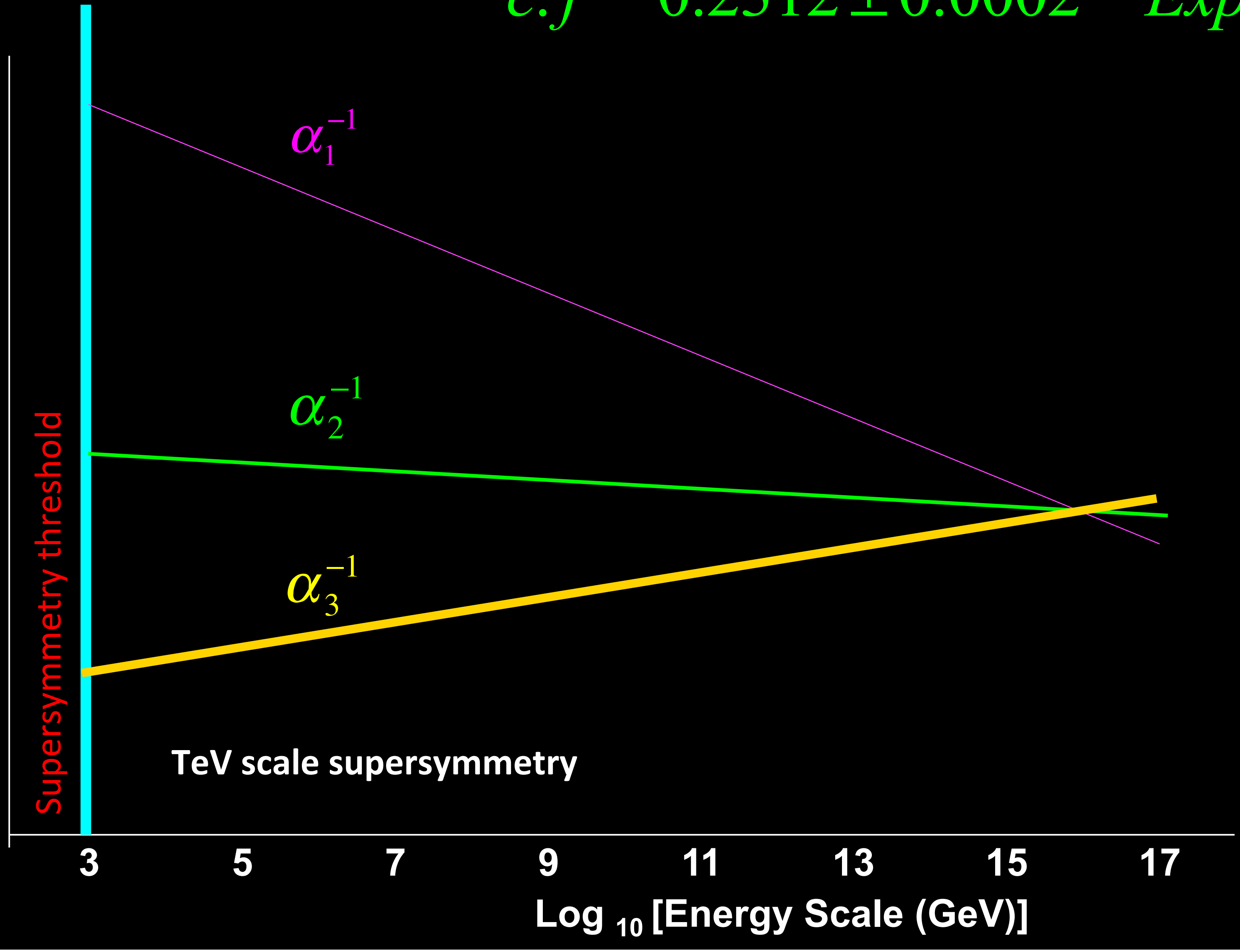
$$\alpha_i^{-1}(\mu)=\alpha^{-1}(M_X)+\frac{1}{2\pi}b_i\ln\left(\frac{M_X}{\mu}\right)+..$$

$$b_i^{SM}=\begin{pmatrix}0\\-\frac{22}{3}\\-11\end{pmatrix}+N_g\begin{pmatrix}\frac{4}{3}\\\frac{4}{3}\\\frac{4}{3}\end{pmatrix}+H\begin{pmatrix}\frac{1}{10}\\\frac{1}{6}\\0\end{pmatrix}$$

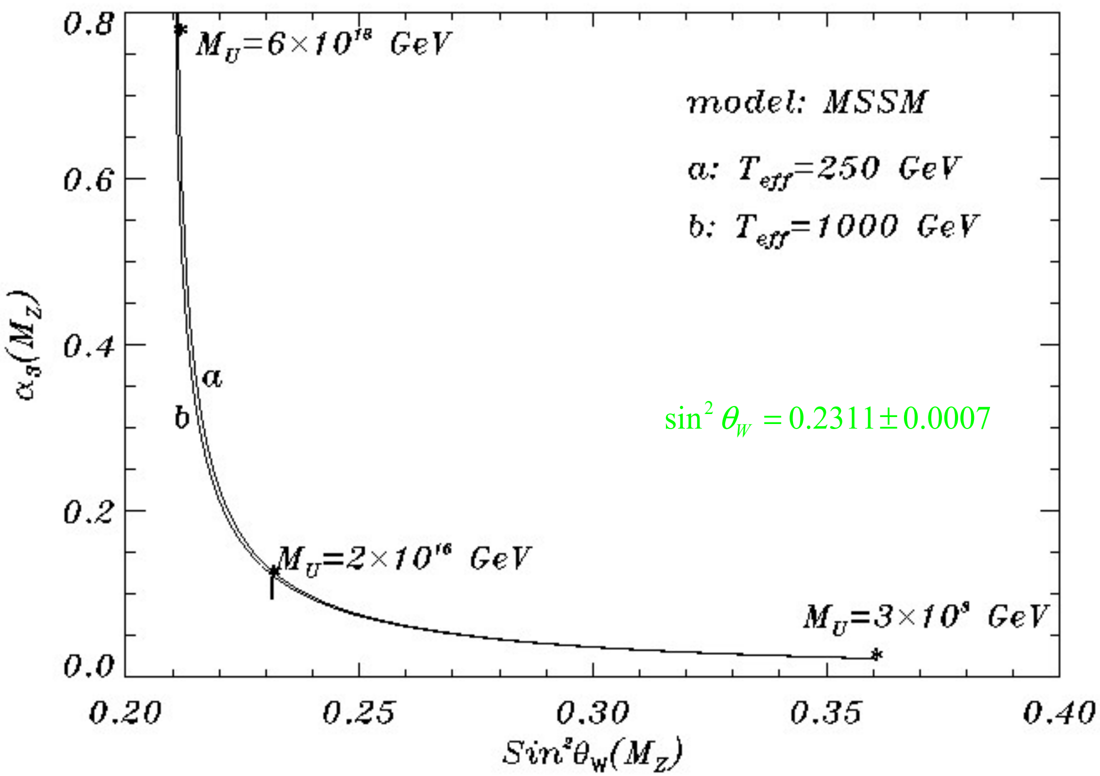
$$b_i^{MSSM}=\begin{pmatrix}0\\-6\\-9\end{pmatrix}+N_g\begin{pmatrix}2\\2\\2\end{pmatrix}+H\begin{pmatrix}\frac{3}{10}\\\frac{1}{2}\\0\end{pmatrix}$$

$$\sin^2\theta_W = 0.2337 \pm 0.0015$$

$$c.f \quad 0.2312 \pm 0.0002 \quad Expt$$



SUSY gauge coupling unification

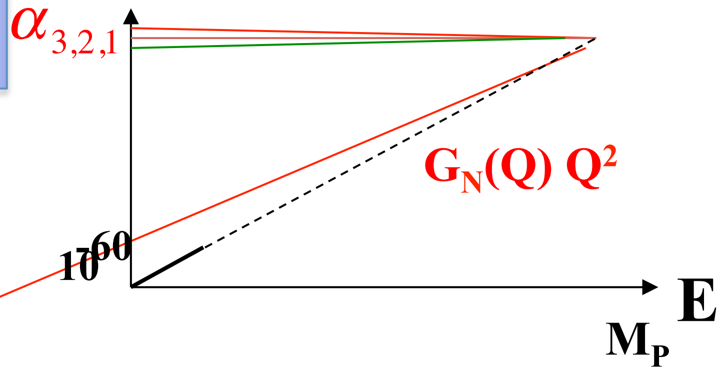


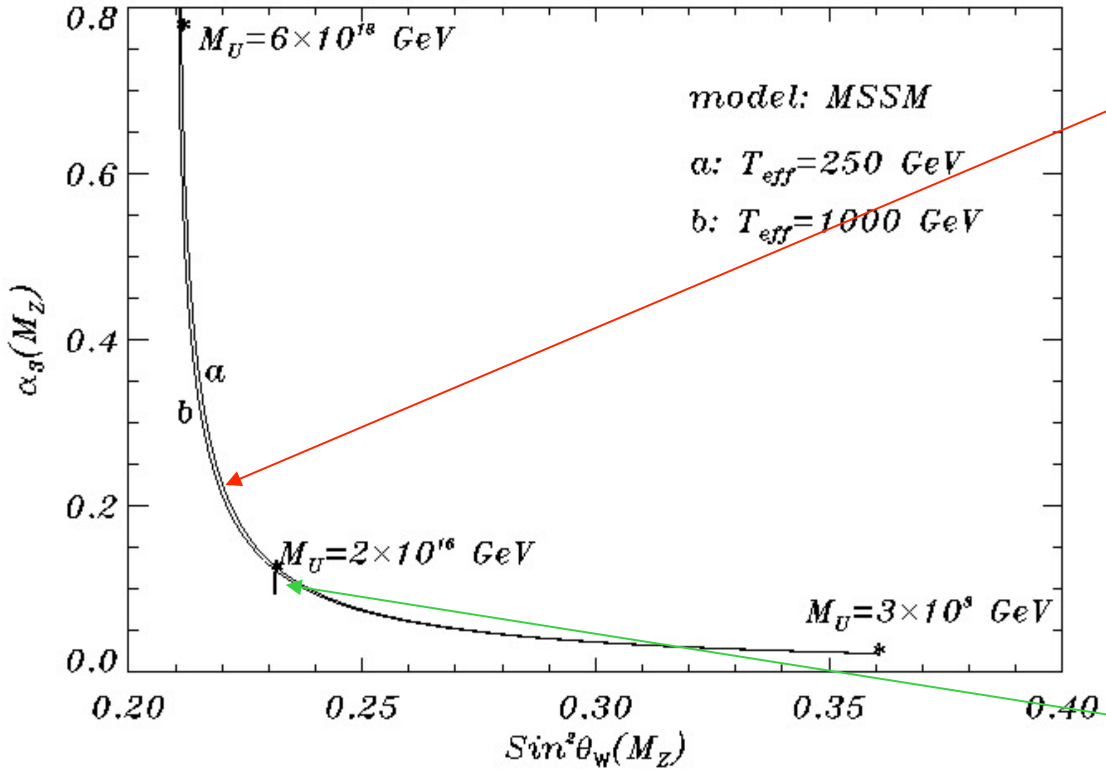
$$\sin^2\theta_W = 0.2334 \pm 0.0025 - 0.25(\alpha_s - 0.119) \quad = 0.2311 \pm 0.0007 \quad (Expt)$$

$$\alpha_s = 0.134 \pm 0.01 - 4(\sin^2\theta_W - 0.2334) \quad = 0.119 \pm 0.01 \quad (Expt)$$

SUSY gauge coupling unification

Unification with gravity?





$$M_U = (2.6 \pm 2).10^{16}\, GeV$$

$$\sin^2\theta_W = 0.23116(12) \quad (Expt)$$

$$\alpha_s = 0.134 \pm 0.01 - 4(\sin^2\theta_W - 0.23116) \qquad c.f. \quad 0.1184(7) \quad (Expt)$$

Gauge unification - Heterotic String

$$L_{eff}^{HS} = \int d^{10}x \sqrt{g} e^{-\phi} \left(\frac{4}{\alpha'^4} R + \frac{k_i}{\alpha'^3} Tr F_i^2 + \ldots \right)$$

$$\int d^4x \, V \qquad \alpha_{10}^{-1} \qquad \alpha' = 1/M_{string}^2 \text{ only scale}$$

$$G_N = \frac{\alpha_{10}\alpha'^4}{64\pi V}, \quad \alpha_{String} = \frac{\alpha_{10}\alpha'^3}{16\pi V} \quad \Rightarrow \quad G_N = \frac{\alpha_{String}\alpha'}{4}$$

$$\frac{1}{g_i^2(M_Z)} = \frac{k_i}{g_{string}^2} + b_i \ln\left(\frac{M_{string}}{M_Z}\right) + \Delta_i$$

$$M_{string} = g_{string} . M_{Planck} = 3.6 \times 10^{17} GeV \qquad c.f. M_U^{"expt"} = (2.6 \pm 2).10^{16} GeV$$

Gauge unification - Heterotic String

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$M_{string} = g_{string}.M_{Planck} = 3.6\times 10^{17}\, GeV$ ....close...but not close enough!

..string threshold corrections, Δ_i?

Spontaneous symmetry breaking

$$SU(5) \xrightarrow[\Sigma_{24}]{M_X} SU(3) \times SU(2) \times U(1) \xrightarrow[H_{\bar{5}}]{M_W} SU(3) \times U(1)$$

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$$P = \frac{\beta_2}{2} M \, Tr\left(\Sigma^2\right) + \frac{\beta_3}{3} Tr\left(\Sigma^3\right)$$

superpotential

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$$P = \frac{\beta_2}{2} M\, Tr\left(\Sigma^2\right) + \frac{\beta_3}{3} Tr\left(\Sigma^3\right)$$ superpotential

$$V(\Sigma) = \sum_a \left| \frac{\partial P}{\partial \Sigma^a} \right|^2 = Tr\left| \beta_3 \Sigma^2 + \beta_2 M \Sigma - I \frac{\beta_3}{5} Tr\left(\Sigma^2\right) \right|^2$$

$$\left(\frac{\partial P}{\partial \Sigma^a} \to \frac{\partial P}{\partial \Sigma^i_j} - \frac{1}{N} \delta^i_j Tr\left(\frac{\partial P}{\partial \Sigma}\right), \quad i,j = 1..5, \quad a = 1..24 \right)$$

$$\langle \Sigma \rangle = 0$$
$$\langle \Sigma \rangle = \mathrm{v}_4 \mathrm{Diagonal}(1,1,1,1,-4)$$
$$\langle \Sigma \rangle = \mathrm{v}_3 \mathrm{Diagonal}(2,2,2,-3,-3)$$

} Degenerate → SUGRA
→ Radiative corrections

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$$P_{5_M} = -\frac{1}{\sqrt{2}} M_{ij}^{d} \psi_{i\alpha} \chi_j^{\alpha\beta} H_{d\beta} - \frac{1}{4} M_{ij}^{u} \varepsilon_{\alpha\beta\gamma\delta\rho} \chi_i^{\alpha\beta} \chi_j^{\gamma\delta} H_u^{\rho}$$

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$$P_{Higgs} = \mu H_u H_d + \lambda H_u \Sigma H_d$$

$$V = \left(\left| \mu H_u + \lambda H_u \Sigma \right|^2 + \left| \mu H_d + \lambda \Sigma H_d \right|^2 \right) + \left| H_u H_d - \frac{1}{5} \left(H_u H_d \right) \right|^2$$

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Must forbid these terms by symmetry

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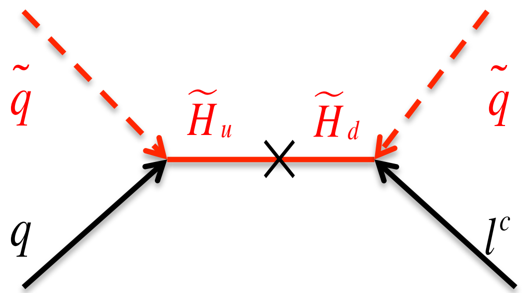
Must forbid these terms by symmetry

+ doublet- triplet splitting



D=5 proton decay amplitude

Doublet -triplet splitting

Missing doublet mechanism

No (1,2) component

$$\Theta_{50} = (8,2) + (6,3) + \left(\bar{6},1\right) + (3,2) + \left(\bar{3},1\right) + (1,1)$$

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$$\Theta_{50} = (8,2) + (6,3) + (\bar{6},1) + (3,2) + (\bar{3},1) + (1,1)$$

$$P_{MD} = b\,\Theta\Sigma_{75}H_u + b'\,\overline{\Theta}\Sigma_{75}H_d + \widetilde{M}\,\overline{\Theta}\Theta$$

$\langle \Sigma_{75} \rangle \propto M$ breaks SU(5) to SM

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$$P_{MD} \supset bM\,\Theta_3 H_{uT} + b'M\,\overline{\Theta}_3 H_{dT} + \widetilde{M}\,\overline{\Theta}_3\Theta_3$$

Triplets get mass $\frac{M^2}{\widetilde{M}}$ (Still need to drive SSB - later)

Doublet -triplet splitting

Higher dimensions (String unification)

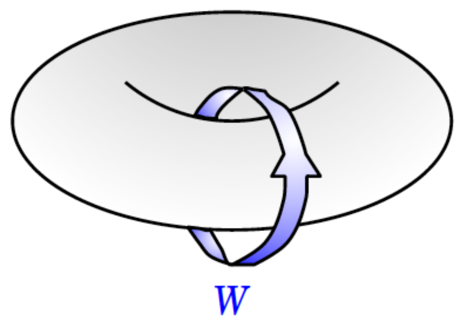
Compactification: $K = K_0 / H$

freely acting discrete group

Wilson line breaking: $W : \ \overline{H} \subset G$

embedding of H into gauge group G

Massless states: $H \otimes \overline{H}$ singlets



$$W = P \exp\left(-i \int_{\gamma} T^a A_m^a \, dx^m \right)$$

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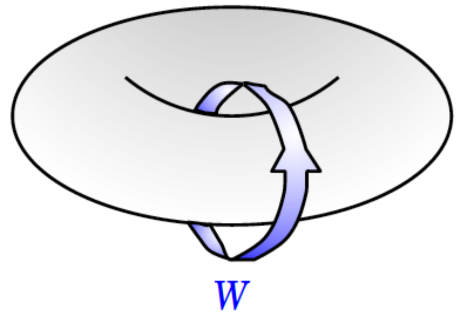

$$W = P\exp\left(-i\int_{\gamma} T^a A_m^a \, dx^m\right)$$

Breit, Ovrut, Segre

$$e.g. \quad SU(5): \quad H = Z_3, \quad \overline{H} = Diag(\alpha,\alpha,\alpha,1,1), \quad \alpha = e^{2i\pi/3}$$

$$\left(R\otimes\overline{R}\right): \quad (1\otimes\overline{5}) \rightarrow \begin{pmatrix} H^- \\ \overline{H}^0 \end{pmatrix}_1, \quad \left(3,\overline{5}\right) \rightarrow \begin{pmatrix} e \\ \nu_e \end{pmatrix}_1 \oplus \begin{pmatrix} d^c \\ d^c \\ d^c \end{pmatrix}_{\alpha^2}, \quad \text{Matter} \quad \rightarrow \quad \left(3,\overline{5}+10\right)$$

SUSY GUTS - Nucleon decay

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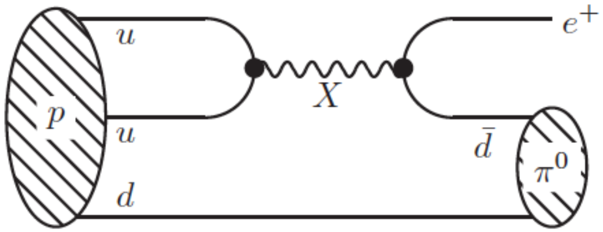
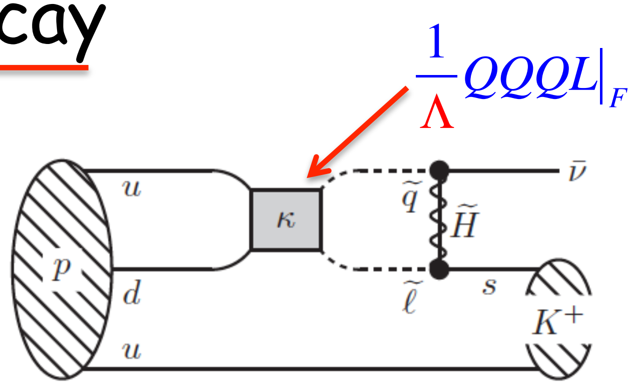


(a) Dimension 6.



(b) Dimension 5.

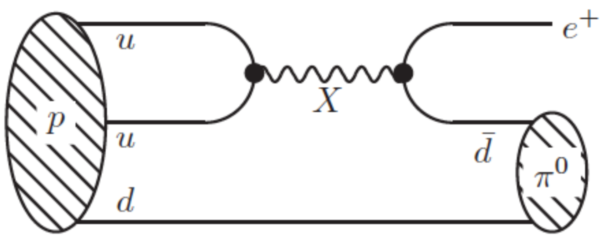
$$p \to \pi^0 + e^+$$

$$\tau_{p \to e^+ \pi^0} > 1 \times 10^{34} \text{ yrs}, \; M_X > 10^{16}\, GeV$$

$$p \to K^+ + \bar{\nu}$$

$$\tau_{p \to K^+ \bar{\nu}} > 3.3 \times 10^{33}\, yrs$$

SUSY GUTS - Nucleon decay



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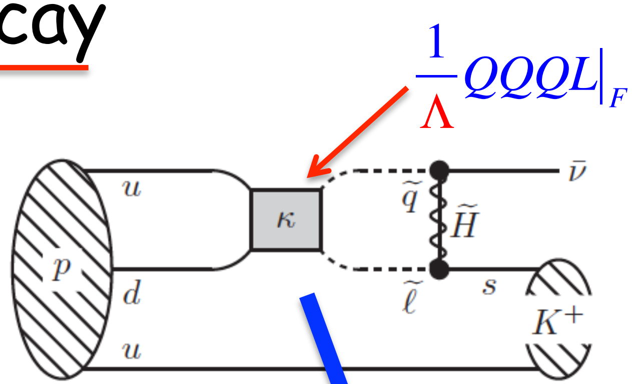

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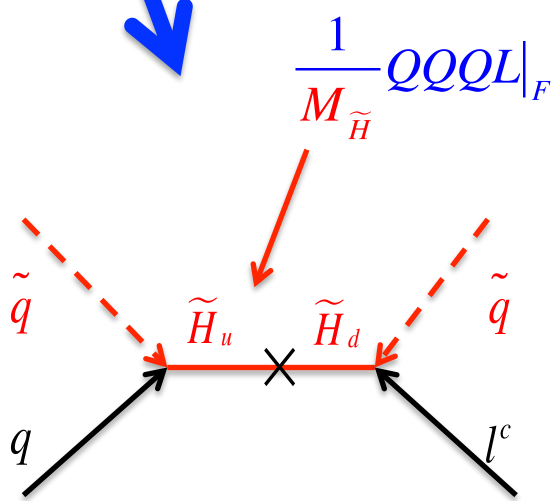
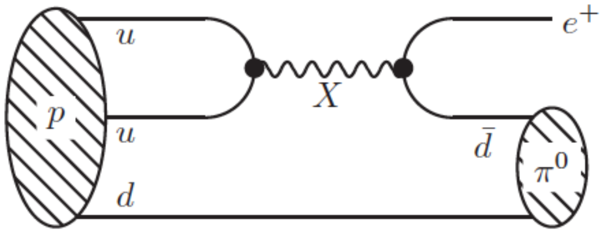


D=5 proton decay amplitude

SUSY GUTS - Nucleon decay



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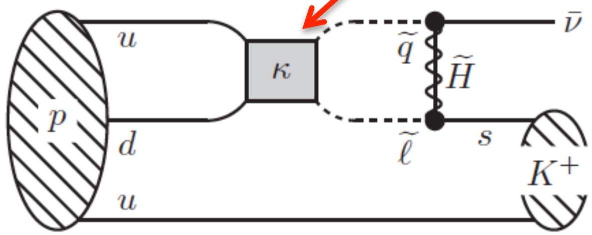
$$\frac{1}{\Lambda} QQQL\big|_F$$



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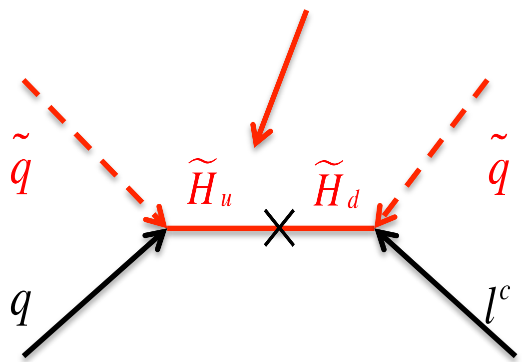
$$\Delta(B-L) = 0$$

$$\frac{1}{M_{\tilde{H}}} QQQL\big|_F$$



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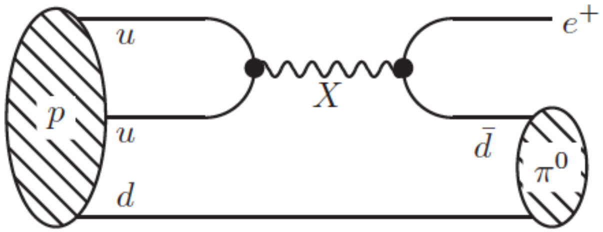

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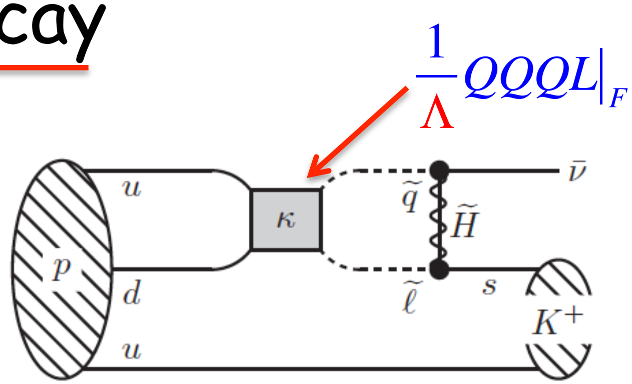

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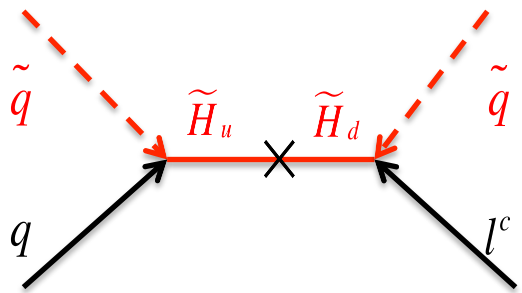
$\Lambda > 10^{27}\, GeV,\ 10^{9} M_{Planck}$???

$\Delta(B-L)=0$



D=5 proton decay amplitude

SUSY extensions of the Standard Model

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$
$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$
$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + \ldots (\not{L}) \right)$$

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

$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E}H_d + \ldots(\not{L})\right)$$

$e.g. \left(LH_u\right)^2$

SUSY extensions of the Standard Model

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

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

$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + \ldots (\not{L}) \right)$$

R-parity: Z_2 $\quad H_u, H_d \ +1$ $\quad L, \overline{E}, Q, \overline{D}, \overline{U}, \ \theta \ \ -1$

SUSY states odd

Weinberg, Sakai

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SUSY states odd

Weinberg, Sakai

Baryon "parity": Z_3

$Q \quad 1$

$\overline{D}, H_u \quad \alpha$

$L, \overline{E}, \overline{U}, H_d \quad \alpha^2$

LSP unstable

Discrete gauge symmetry
-anomaly free

Ibanez, GGR

SUSY extensions of the Standard Model

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LSP unstable

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

LSP stable

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

Dreiner, Luhn, Thormeier

	R_2	R_3L_3	R_3	L_3	$R_3^2L_3$	$R_6^5L_6^2$	R_6	$R_6^3L_6^2$	$R_6L_6^2$	all $\boldsymbol{Z}_9$ & $\boldsymbol{Z}_{18}$
H_dH_u	✓	✓	✓	✓	✓	✓	✓	✓	✓	
LH_u		✓								
$LL\bar{E}$		✓								
$LQ\bar{D}$		✓								
$\bar{U}\bar{D}\bar{D}$				✓						
$QQQL$	✓		✓				✓			
$\bar{U}\bar{U}\bar{D}\bar{E}$	✓		✓				✓			
$QQQH_d$				✓						
$Q\bar{U}\bar{E}H_d$		✓								
LH_uLH_u	✓	✓				✓				
$LH_uH_dH_u$		✓								
$\bar{U}\bar{D}^*\bar{E}$		✓								
$H_u{}^*H_d\bar{E}$		✓								
$Q\bar{U}L^*$		✓								
$QQ\bar{D}^*$				✓						

SUSY extensions of the Standard Model

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

$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E}H_d + \ldots(\not{L})\right)$$

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

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

Dreiner, Luhn, Thormeier

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

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

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

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

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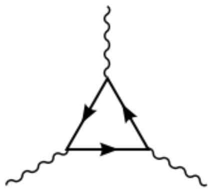
4	1	1	0	0	2

Green Schwarz term

$$A_{G-G-\mathbb{Z}_N} = \rho \mod \eta \quad \begin{cases} N \\ N/2 \end{cases}$$



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

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

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

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

A unique solution : Z_4^R discrete R symmetry

MSSM spectrum
No perturbative μ term
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Anomaly cancellation

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

D=5 operators

$\frac{1}{M}QQQL$ (crossed out) $\frac{1}{M}LLH_uH_u$

Weinberg operator

SUSY breaking

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

Domain walls safe

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

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

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

$\mu, \not{B}, \not{L}$

Nucleon decay outlook

- Nucleon decay D=6 operators

Operator renormalisation

$$\tau(p \to \pi^0 e^+) = \left(\frac{M_{\rm GUT}}{10^{16}\ {\rm GeV}}\right)^4 \left(\frac{1/35}{\alpha_{\rm GUT}}\right)^2 \left(\frac{0.015\ {\rm GeV}^3}{\alpha_N}\right)^2 \left(\frac{5}{A_L}\right)^2 4.4\times 10^{34}\ {\rm yr}.$$

Hadronic matrix element

$$\tau^{SuperK}_{p\to e^+\pi^0} > 1\times 10^{34}\,\mathrm{yrs}$$

Giudice, Romanino

$$M_{\rm GUT} > \left(\frac{\alpha_{\rm GUT}}{1/35}\right)^{1/2} \left(\frac{\alpha_N}{0.015\ {\rm GeV}^3}\right)^{1/2} \left(\frac{A_L}{5}\right)^{1/2} 6\times 10^{15}\ {\rm GeV}$$

$$c.f.\ M_U = (2.5 \pm 2).10^{16}\,GeV$$