(SP, 29)

<u>Neutrino masses</u> - see saw mechanism.

In SM $\quad m_\nu \equiv 0.$

$$m_\nu LL \rightarrow \text{not gauge invariant.}$$

add a singlet. $N_R \rightarrow \lambda L N_R h^* \rightarrow$ Dirac mass term

$$M_X N_R N_R \rightarrow N_R \text{ majorana mass term.}$$

$$M_\nu = \begin{array}{c c} \nu_L & N_R \\ \end{array}$$
$$\begin{pmatrix} 0 & \lambda v \\ \lambda v & M_X \end{pmatrix}.$$

Eigenvalues $\quad \dfrac{(\lambda v)^2}{M_X} \; ; \quad M_X.$

$$\Rightarrow m_{\nu_L} \sim \frac{m_t^2}{M_X} \quad \text{OR} \quad \frac{m_e^2}{M_X}.$$

$$m_{\nu_L} \sim \frac{(100\ \text{GeV})^2}{10^{15}\ \text{GeV}} \sim \frac{10^4}{10^{15}} \sim 10^{-11}\ \text{GeV}$$

$$\sim 10^{-2}\ \text{eV}$$

m_{ν_L} in good agreement with recent Super K data.

Neutrino sector $\rightarrow$ <u>intensive activity</u>.

another indication for large M_X.

sxsp.30

1/5/01 Running masses.

we have $\lambda_f \bar{5}_f\, 10_f\, \bar{5}_h \rightarrow$ fermion masses.

$$\left[(\bar{3},1)+(1,2)\right]\left[(3,2)+(\bar{3},1)+(1,1)\right]\left[(\bar{3},1)+(1,2)\right] \Rightarrow$$

$$\Big[\underbrace{\underset{d^c_L}{(\bar{3},1)}\,\underset{Q}{(3,2)}\,\underset{h}{(1,2)}}_{m_b} \;+\; \underset{L}{(1,2)}\,\underset{e^c}{(1,1)}\,\underset{h}{(1,2)}\Big].$$

$= m_\tau$ at M_{GUT}.

$\lambda_b = \lambda_\tau$ at M_{GUT} is a consequence of the $SU(5)$ group structure.)

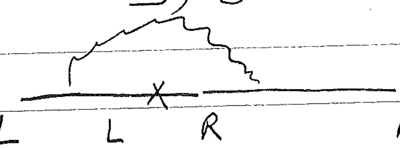
(similar relations for lighter generations).

$m_b = (\lambda_b \cdot v)$ $\qquad m_\tau = \lambda_\tau \cdot v$

$$\Rightarrow \frac{m_b}{m_\tau} = \frac{\lambda_b}{\lambda_\tau}$$

$g, B \rightarrow$ no W_L.

couplings evolve with energy



$$\frac{d}{d\ln\mu^2}\left[\ln\frac{m_b(\mu)}{m_\tau(\mu)}\right] = -\frac{\alpha_3(\mu)}{\pi} + \frac{\alpha_1(\mu)}{4\pi}.$$

solution.
$$\frac{m_b(\mu_1)}{m_\tau(\mu_1)} = \frac{m_b(\mu_2)}{m_\tau(\mu_2)}\left[\frac{\alpha_3(\mu_1)}{\alpha_3(\mu_2)}\right]^{\frac{1}{4\pi^2 b_3}}\left[\frac{\alpha_1(\mu_1)}{\alpha_1(\mu_2)}\right]^{-\frac{1}{16\pi^2}}.$$

$\mu_1 = M_X \longrightarrow \mu_2 \approx 2\, m_b.$

$$\left(\frac{m_b}{m_\tau}\right)_{\mu_1} = 1 \longrightarrow \left(\frac{m_b}{m_\tau}\right)_{\mu_2} \approx 2.5.$$

Ellis, Chanowitz, G.
Buras, Ellis, G., N.

Experimentally: $\left(\frac{m_b}{m_\tau}\right) \sim 2.65$

XSP.31 | symmetry breaking.

$$SU(5) \xrightarrow{\langle H\rangle} SU(3) \times SU(2) \times U(1)_Y \xrightarrow{\langle\phi\rangle} SU(3)\times U(1)$$

$H = 24$ $\qquad \phi = \bar{5}$

$$V(H,\phi) = V(H) + V(\phi) + \lambda_4 (\mathrm{tr}\, H^2)\, \phi^\dagger\phi + \lambda_5\, \phi^\dagger H^2 \phi.$$

with

$$V(H) = -m_1^2\, \mathrm{tr}\, H^2 + \lambda_1 (\mathrm{tr}\, H^2)^2 + \lambda_2 (\mathrm{tr}\, H^4)$$

$$V(\phi) = -m_2^2 (\phi^\dagger\phi) + \lambda_3 (\phi^\dagger\phi)^2$$

minimize the potential. $\lambda_2 > 0 \quad \lambda_1 > -\frac{7}{30}\lambda_2$

$V(H)$, has a extremum at.

$$\langle H\rangle = v_1 \begin{bmatrix} 2 & & & & \\ & 2 & & & \\ & & 2 & & \\ & & & -3 & \\ & & & & -3 \end{bmatrix}.$$

$$v_1^2 = \frac{m_1^2}{60\lambda_1 + 14\lambda_2}.$$

$\langle H\rangle$ commutes with G of $SU(3)\times SU(2)\times U(1)_Y$.

and $M_X = M_Y = \sqrt{\frac{25}{2}}\, g\, v_1$

symmetry breaking $\rightarrow$ cumbersome $\rightarrow$ string theory
$\rightarrow$ simplify.

SP.32/ /01

The hierarchy problem.

First incarnation → GUTS.

two scales M_W ; M_X.

10^2 GeV $\quad 10^{15}$ GeV

Higgs: → $\bar{5} = [(\bar{3},1) + (1,2)]$.

The triplet mediate proton decay from dimension 6 operator $QQQL \sim \frac{1}{M_H^2} QQQL$.

⇒ $M_3 \sim M_X$ but $M_2 \sim M_W$.

⇒ doublet-triplet splitting problem. → solution cumbersome fine tuning of parameter $V(\phi, H)$. large reps.

(strings can help!!!)

without GUTS

Higgs sector: M_W $\quad M_{planck}$
$SU(3)\times SU(2)\times U(1)$; G.

@ "natural aspect": how to generate M_W from M_P without fine tuning.

X Sp. 33
15/01

(b) "technical aspect"

The Higgs sector is an essential component of the Standard Model.

t'hooft - Veltman - Renormalizability of NA Yang - Mills.

The Higgs mass term.

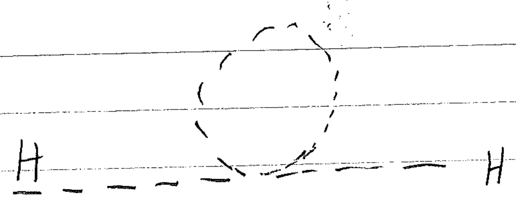
$$\Delta \mathcal{L} = -\mu^2 \phi^\dagger \phi + \lambda^2 (\phi^\dagger \phi)^2$$

Respects all SM symmetries.

why $\mu^2 \sim M_W$ and not M_P.

(b) if we set $\mu^2 = 0$. at tree level.

The Higgs mass squared is corrected by Radiative corrections.



$$-i m^2 = -i \lambda^2 \int \frac{d^4 k}{(2\pi)^4} \frac{1}{k^2} = -i \frac{\lambda^2}{16\pi^2} \Lambda^2$$

where Λ is the cut off scale where the SM breaks down.

$\Rightarrow$ contribution of Radiative correction to the Higgs boson

ᴋ SP. 34
/5/01

mass is non-zero, divergent and positive.

$\Rightarrow$ fine tuning between 1^{st}-order - 2^{nd}-order

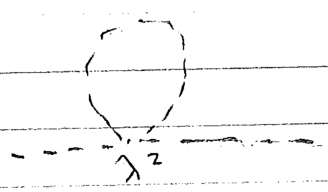
to obtain a negative mass term. !!!

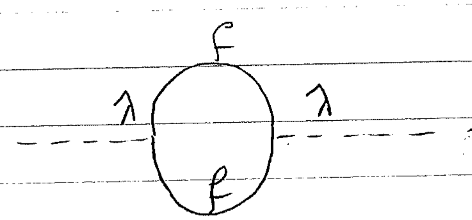
$\Rightarrow$ unnatural fine tuning.

Technicolor: ~~Higgs $\rightarrow$ strong sector at~~ o(1 TeV) / ~~Large extra dimensions~~/R

Supersymmetry : for every spin-0 state -

a a spin ½ - superpartner.





$$\sim \; +\lambda^2 \int \frac{d^4k}{k^2} \qquad\qquad -\lambda^2 \int \frac{d^4k}{k^2}$$

The difference between the fermion and boson loop.

$$\delta m^2 \sim (n_B - n_f)\lambda^2\Lambda^2 \quad + (m_B^2 - m_f^2)$$

supersymmetry $\quad n_B = n_f$

$$\Rightarrow |\delta m^2| \propto |(m_B^2 - m_f^2)| \leqslant 1 \text{ TeV}.$$

corrections are under control.

$\Rightarrow$ set it and forget it.

x SP.35

Additional + of supersymmetry.

1) local => spin 3/2 -> spin 2 => Gravity

2) gauge coupling unification in MSSM. => in good agreement with data.

=> — of supersymmetry.

spectrum is doubled ->

3) electroweak symmetry breaking with large λ_t. $\frac{dm^2}{dt^2} \propto (\lambda_t - \alpha_3)$

Where in the world is supersymmetry.

<u>Essential Supersymmetry.</u>

we won't go into the details of supersymmetry. which will require a dedicated course in it self

Rather we will discuss the aspects that are important from the perspective of Superstring phenomenology.

<u>PRIMARY</u>. 1) mass terms -> superpotential.

2) supersymmetry breaking

end of lecture 4

XSP. 36

global supersymmetry.

So far: two kind of symmetries in particle physics.

1) Poincare group – translation, rotation boost.

2) $X'^{\mu} = \Lambda^{\mu}{}_{\nu} X^{\nu} + a^{\mu}$

10 generators 3+3+4.

2 casimirs : 1) m^2 2) spin → statistics.

all reps are labeled by their masses & spin.

2) internal symmetries G.

Coleman – Mendula theorem. [poincare, G] = 0.

cannot find bigger group that contains both Poincare & G as subgroups.

⇒ internal symmetries cannot relate different spins.

Exceptions: Graded Lie algebras. – generators obey anticommutation relations.

DX SP. 37

1/5/01

$\Rightarrow$ Internal $[T_a, T_b] = i f_{abc} T_c$.

Poincare $[P_\mu, P_\nu] = 0$

$[M_{\mu\nu}, M_{\rho\sigma}] = -i(\eta_{ms} M_{nl} + \cdots \cdots)$.

$[M_{\mu\nu}, P_\rho] = -i g_{\mu\rho} P_\nu + i g_{\nu\rho} P_\mu$

graded Lie algebra: $N=1$

$Q_\alpha |\text{boson}\rangle = |\text{fermion}\rangle$.

$Q_\alpha |\text{fermion}\rangle = |\text{boson}\rangle$.

algebra $[P_\mu, Q_\alpha] = 0 \rightarrow$ translation invariant.

$[M_{\mu\nu}, Q_\alpha] = -(\sigma_{\mu\nu} Q)_\alpha \rightarrow Q$ spinor of P. G.

$\{Q_\alpha, \bar{Q}_{\dot\beta}\} = 2\gamma^\mu_{\alpha\dot\beta} P_\mu$.

$\sigma_{\mu\nu} = \frac{1}{4} i [\gamma_\mu, \gamma_\nu]$

Extended supersymmetry: $i = 2, 3, 4 \cdots N$

$Q^i_\alpha \rightarrow N$ susy generators.

$\{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2\delta^{ij} \sigma^\mu_{\alpha\dot\beta} P_\mu + \varepsilon_{\alpha\beta} Z^{ij}$

(4 component notation).

central charges.