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Lecture II & III

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

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FLAVOR IN SUPERSYMMETRIC THEORIES

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(II) FLAVOR SYMMETRIES.

L. J. Hall.

THE SUPERSYM. FLAVOR/CP "PROBLEM"

SM $\qquad \lambda \longrightarrow 13$ flavor params.

Supersym. $\qquad \lambda, m^2 \longrightarrow 56$ flavor params.

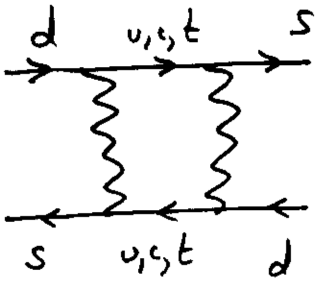
$\boxed{\text{Experiments on FCNC/CP} \Rightarrow \text{many of 42 dimensionless parameters of } m^2 \text{ are necessarily small.}}$

ϵ_K

Gives the most powerful constraints.

Others: $\quad d_{n,e}, \quad \mu \to e, \quad b \to s, \quad \ldots$

S.M. recall GIM



$$\propto \left(V_{2i}^{\dagger} \, \frac{\not{k} + m_i}{k^2 - m_i^2} \, V_{i1} \right)^2$$

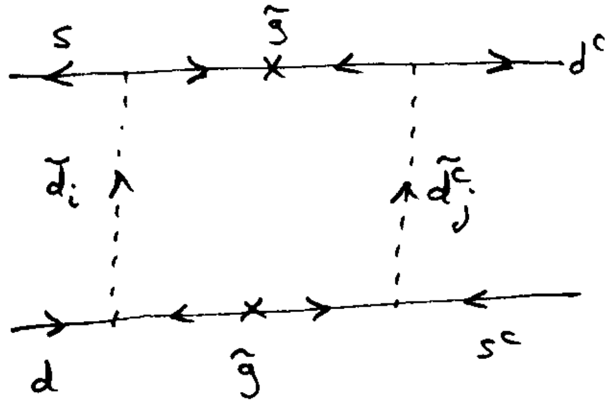
$$\epsilon_K^{SM} \propto G_F^2 m_t^2 \, f\!\left(\frac{m_t}{M_W}\right) \, \mathrm{Im}\left(V_{td} V_{ts}^{*}\right)^2$$

GIM: $\quad$ 12 problem solved by small m_q

$\qquad\quad$ 3 problem solved by small θ_{ij}.

STRONG SUPER-BOX FOR ϵ_K : need SGIM

Consider only 2 gen. theory — cannot argue that this contrib: small due to small W_{31}, W_{32}. LR box has largest matrix element:



$$\propto \left(W^{+}_{2i}\,\frac{1}{k^2-m_i^2}\,W_{i1}\right)\left(W^{c+}_{1j}\,\frac{1}{k^2-m_j^{c\,2}}\,W^c_{j2}\right)$$

In superKM basis each m^2 has 1 phase $\quad m^2 = \begin{pmatrix} m_1'^2 & m_3'^2\alpha \\ m_3'^2\alpha^* & m_2'^2 \end{pmatrix}, \; m^{c\,2} = \dots$

Hence mass basis obtained first by rel. rot. α between d and s phases, & then 2×2 real rotation:

$$W^d = \begin{pmatrix} c & s \\ -s & c \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & \alpha \end{pmatrix}, \qquad W^{d^c} = \begin{pmatrix} c^c & s^c \\ -s^c & c^c \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & \alpha^c \end{pmatrix}$$

$$\epsilon_K^{susy} \propto \operatorname{Im}\left(sc\, s^c c^c\, \alpha^* \alpha^c\right)\frac{m_2^2-m_1^2}{(k^2-m_1^2)(k^2-m_2^2)}\cdot\frac{m_2^{c\,2}-m_1^{c\,2}}{(k^2-m_1^{c\,2})(k^2-m_2^{c\,2})}$$

$$\approx \frac{1}{\bar m^2}\left(c c^c s s^c \operatorname{Im}\alpha^*\alpha^c\right)\frac{\Delta m_{12}^2}{\bar m^2}\,\frac{\Delta m_{12}^{c\,2}}{\bar m^2}$$

Hence we must compare

$$\underbrace{G_F^2 m_t^2 \operatorname{Im}(V_{td}^* V_{ts})^2}_{\lesssim 10^{-7}} \quad \text{to} \quad \underbrace{\frac{1}{\bar m^2}\, c c^c s s^c \operatorname{Im}\alpha^*\alpha^c\,\frac{\Delta m_{12}^2}{\bar m^2}\,\frac{\Delta m_{12}^{c\,2}}{\bar m^2}}_{\lesssim 10^{-6} \text{ for } \bar m = 300\text{ GeV}}$$

THE POSSIBLE DIRECTIONS.

The supersym. FC/CP problem is a useful guide to constructing theories of flavor.

1. $\bar{m} \gg 300$ GeV

Regain fine tuning.
5 TeV OK for "cousins"
but only buys $(15)^2$.

2. $s, s^c \ll s_c$

Apparently outrageous:
$W = \tilde{R}^{+} R \xleftarrow{} \theta_c$.
"Alignment" possibility
$R_d = I$, $R_u = V_{CKM}$.

3. $\mathrm{Im}\,\alpha \ll 1$

Apparently outrageous:
3 gen. level
$W = \tilde{R}^{+} R \xleftarrow{} \bar{J}$
How about Δm_K, $\mu \to e\gamma$, .

4. $\dfrac{\Delta m^{2\,(c)}_{12}}{\bar{m}^2} \ll 1$

Original idea (DG), &
still the best.

$\boxed{\text{WHY DEGENERATE ?}}$

① Gauge Mediation
Flavor signals are sparticle spectrum. W are "trivial". ~~program~~. Does not address q/l masses.

② Flavor Symmetries   These lectures.

FLAVOR SYM. : THE BASIC IDEA.

1. Choose a flavor group $G_f \subset G_{f\,max} = U(3)^5$

2. Write down most general G_f invariant Lag. with all dimensionless couplings of order unity.

3. At this point : light q/l are massless
   $\tilde{q}/\tilde{\ell}$ of 1/2 are degenerate
   small mixing angles, eg V_{cb}, W_{23} are zero.

4. Allow G_f to be broken by a set of dim. params — at least some of which are small

$$G_f \xrightarrow{1} G \xrightarrow{\epsilon} G' \xrightarrow{\epsilon'} \cdots$$

*** $\epsilon, \epsilon', \ldots$ determine $\left\{ \begin{array}{l} \text{light } q/l \text{ masses} \\ \text{small mixing angles} \\ \text{small } \tilde{q}/\tilde{\ell} \text{ mass splittings} \end{array} \right.$

5. Advantages :
   i) few ϵ, ϵ' for many observed small quantities.
   ii) we can construct theories for small SB quantities.
   $\epsilon = \frac{\langle \phi \rangle}{M}$.

$$\underleftrightarrow{G_f = U(3)^5}$$

Hall-Randall 1990^{15}

1. $G_f = U(3)^5$

2. $\lambda, \xi = 0 \quad ; \quad m^2_{Q,U,D,L,E} = m^2_{0\,Q,U,D,L,E}\, I$

3. $m_{q,l} = \theta_i = 0$. $\quad \tilde{q}/\tilde{l}$ degenerate with weak universality

4. Assume: $\epsilon_U(3,3,1,1,1)$, $\epsilon_D(3,1,3,1,1)$, $\epsilon_E(1,1,1,3,3)$

$$\left.\begin{aligned} \lambda_U &= \epsilon_U + \epsilon_D \epsilon_D^+ \epsilon_U + \dots \\ \lambda_D &= \epsilon_D + \epsilon_U \epsilon_U^+ \epsilon_D + \dots \\ \lambda_E &= \epsilon_E + \epsilon_E \epsilon_E^+ \epsilon_E + \dots \\ \xi_{U,D,E} &= \epsilon_{U,D,E} + \dots \end{aligned}\right\} \text{with } O(1) \text{ coeffics understood.}$$

Thus weak universality $\quad \xi_{U,D,E} = A_{U,D,E}\, \lambda_{U,D,E} + \dots$
(except for t)

$$m_Q^2 = I + \epsilon_U^+ \epsilon_U + \epsilon_D^+ \epsilon_D + O(\epsilon^4)$$

Comments.

1. Completely solves supersym. flav/CP problem.
$\frac{\Delta m_{12}^2}{m^2} \approx \lambda_c^2 \approx 10^{-4}$, etc.

2. No progress on understanding q/l masses.

$$\boxed{\text{CAN A SMALLER } G_f \text{ STILL SOLVE FC PROBLEM BUT HAVE FEW ENOUGH SB PARAMS. TO MAKE PROGRESS ON } q/l \text{ MASSES?}}$$

$G_f = SU(2)$ Dine, Leigh, Kagan 1993

$\tilde{d}/\tilde{s}$ degenerate because members of a $SU(2)$ doublet
Why 12 years ?!

$$\begin{pmatrix} q_1 \\ q_2 \end{pmatrix} \quad \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \quad \begin{pmatrix} d_1 \\ d_2 \end{pmatrix} \quad \begin{pmatrix} l_1 \\ l_2 \end{pmatrix} \quad \begin{pmatrix} e_1 \\ e_2 \end{pmatrix} \quad \text{or} \quad \psi_a \quad a=1,2.$$

$$q_3 \quad u_3 \quad d_3 \quad l_3 \quad e_3 \qquad \psi_3$$

Disaster :

$$W \supset q_a d_b \epsilon^{ab} h = (q_1 d_2 - q_2 d_1) h$$

$$\lambda_D \approx \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} + O(\epsilon) \qquad \text{no light } q/l \text{ !!}$$

Lesson : Too ambitious, $SU(2)$ too small for G_f.

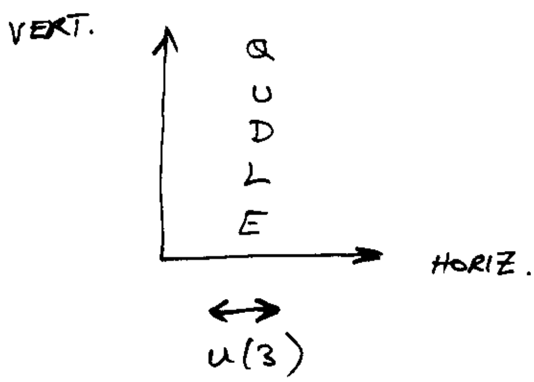
$SU(2)^5$

$q_a, d_a, \ldots$ transform under different $SU(2)$

Too large.

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

Which $U(1)$?



$$U(3) \xrightarrow[\text{top}]{\text{large}} SU(2) \times U(1).$$

$$U(3) \longrightarrow U(2).$$

$$3 \times 3 = \bar{3} + 6$$

$$q_A \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}_{AB} u_B \, h \qquad A, B = 1, 2, 3$$

$$U(3) \left\{ \begin{array}{l} \begin{pmatrix} 1 & & \\ & -1 & \\ & & 0 \end{pmatrix} \longrightarrow \begin{pmatrix} 1 & & \\ & -1 & \\ & & 0 \end{pmatrix} \\ \left. \begin{array}{l} \begin{pmatrix} 1 & & \\ & 1 & \\ & & -2 \end{pmatrix} \\ \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} \end{array} \right\} \longrightarrow \begin{pmatrix} 1 & & \\ & 1 & \\ & & 0 \end{pmatrix} \end{array} \right\} U(2)$$

$$\begin{array}{ccccc} q_a & u_a & d_a & l_a & e_a \\ q_3 & u_3 & d_3 & l_3 & e_3 \end{array}$$

← lower index means charge +1.

b/t, τ/t

$U(3)$ and its breaking cannot explain all of q/l masses.
Small b/t, τ/t may be due to a Higgs effect:

$$W \supset (q\, u) h_u + (q\, d + l\, e) h_d$$

<u>Either</u> i) $v_u \gg v_d$: large $\tan\beta$.

or ii) All couplings to h_d suppressed : Higgs take part in flavor.

THE U(2) THEORY OF FLAVOR

See Barbieri, Hall, Romanino hep-ph/9702315 & ref. cited.

$$\rightarrow \begin{pmatrix} \psi_a \\ \psi_3 \end{pmatrix} \qquad \psi = q, u, d, l, e.$$

Yukawa couplings:

$$\frac{1}{M} \begin{pmatrix} \psi_a & \psi_3 \end{pmatrix} \begin{pmatrix} S^{ab} + A^{ab} & \phi^a \\ \phi^b & 1 \end{pmatrix} \begin{pmatrix} \psi_b \\ \psi_3 \end{pmatrix} h_{u,d} + O\left(\frac{1}{M^2}\right)$$

q/l mass hierarchy suggests:

$$U(2) \xrightarrow{\epsilon} U(1) \xrightarrow{\epsilon'} 0$$

Most general 1st stage is

$$\phi^a = \begin{pmatrix} 0 \\ V \end{pmatrix} \quad , \quad S^{ab} = \begin{pmatrix} 0 & 0 \\ 0 & V \end{pmatrix}$$

with $\frac{V}{M}$ $\cancel{o(\epsilon)}$. $= \epsilon$

Most general 2nd stage is

$$S^{ab} = \begin{pmatrix} V' & V' \\ V' & V \end{pmatrix} \qquad A^{ab} = \begin{pmatrix} 0 & V' \\ -V' & 0 \end{pmatrix}$$

with V'/M $\cancel{o(\epsilon')}$. $= \epsilon'$

Study of alignment of S using a general form of potential shows only A breaks final U(1).

Yukawa couplings:

$$\boxed{\lambda = \begin{pmatrix} 0 & \epsilon' & 0 \\ -\epsilon' & \epsilon & \epsilon \\ 0 & \epsilon & 1 \end{pmatrix}} \text{ ——— } \lambda$$

The ξ matrices have same symm. therefore same form.

The m^2 matrices follow from

$$\left(\tilde{\psi}_a^{+}\ \tilde{\psi}_3^{+}\right)\left(\begin{array}{c:c} 1 + S^{+}S + \phi^{+}\phi + A^{+}A & \phi_a \\ \hdashline \phi^{+b} & 1 \end{array}\right)\begin{pmatrix} \tilde{\psi}_b \\ \tilde{\psi}_3 \end{pmatrix}$$

Relevant terms:

$$\boxed{m^2 = \left(\begin{array}{cc:c} m_1^2 & 0 & 0 \\ 0 & m_1^2(1+\epsilon^2) & \epsilon m_4^{2*} \\ \hdashline 0 & \epsilon m_4^2 & m_3^2 \end{array}\right)} \text{ ——— } m^2$$

flav. param.

$\lambda \longrightarrow m_{q/l}$, V : $13 \longrightarrow 11$

$m^2 \longrightarrow m_{\tilde{q}/\tilde{l}}$, W : $43 \longrightarrow 25$

25:
- 10 scalar masses, 5 R-mass splittings
- 5 θ_{23} for W
- 5 phases for W $\xrightarrow[\text{sector } \nu/c]{\text{Rephase. in lepton}}$ $\tilde{K}_{23}$ ee^c, uu^c, dd^c, ud ($\tilde{K}_{12}, \tilde{J} = 0$!)

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THE HIGGS MYSTERY.

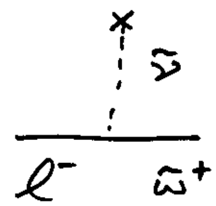
I left out 2 chiral superfields of MSSM : $H_{u,d}$.
They do not fit in, in fact they are vectorlike & should be heavy : $M H_u H_d$.

REMOVE HIGGS SUPERFIELDS !

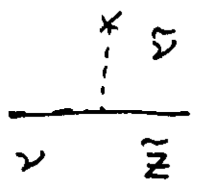
Break EWS via $\langle \tilde{\nu} \rangle$. : supersym. would provide dream of Higgs-matter unific

Problems

(a)



Need 4th generation.



(b) $$W = (\ell \lambda_E E^c)\, \ell_4 + (Q \lambda_D D^c)\, L_4$$

where does m_t come from. This is the killer.

(c) Successful gauge unificⁿ REQUIRES light $H_{u,d}$.

ARE $H_{u,d}$ PART OF FLAVOR?

$$G_{f\,max} = U(3)^5 \times U(1)_{H_u} \times U(1)_{H_d}.$$

Basic problem: there is no 3-2-1 gauge distinction between L and H_d:

$$G_{f\,max} = U(3)^4 \times U(4)_L \times U(1)_{H_u}$$

$$W = QUH_u + QDL + LEL + \mu L H_u$$

where L runs over 4 species.

Disastrous p decay. $\Rightarrow$ need some symmetry X eg R_p.

Important Question

Is X part of G_f that explains small param. of $m, \tilde{m}^2$

(III) THEORIES OF FLAVOR

L. Hall

1.) The origin of small dimensionless params.

2.) The ν see-saw: heavy-light mixing.

3.) The charged fermion see-saw: Froggatt-Nielsen mechanism.

4.) The Dimopoulos-Pomarol effect.

5.) $U(2)$ Froggatt-Nielsen theories.

III ORIGIN OF SMALL FLAVOR SYMM. BREAKING

1) We interpreted $\left\{ \begin{matrix} m_e/m_\mu \ldots \\ V_{cb} \ldots \\ \frac{\Delta m^2_{12}}{m^2} \ldots \end{matrix} \right\}$ as small SB params ϵ.

2) In field theories, with all dimensionless couplings $O(1)$, there are 2 origins for ϵ:

(i) Perturbative loop factors: $1/16\pi^2$.

(ii) Ratio of mass scales: m/M.

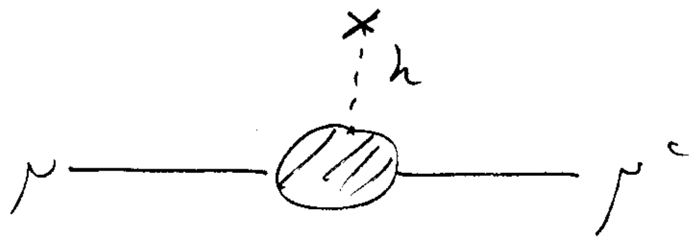
(i) RADIATIVE FERMION MASS HIERARCHIES

are very plausible.

$$m_\tau : m_\mu : m_e = 1 : \frac{1}{16\pi^2} : \frac{1}{(16\pi^2)^2}$$

Any such theory has new exotic particles & interactions:

Generically



Basic problem

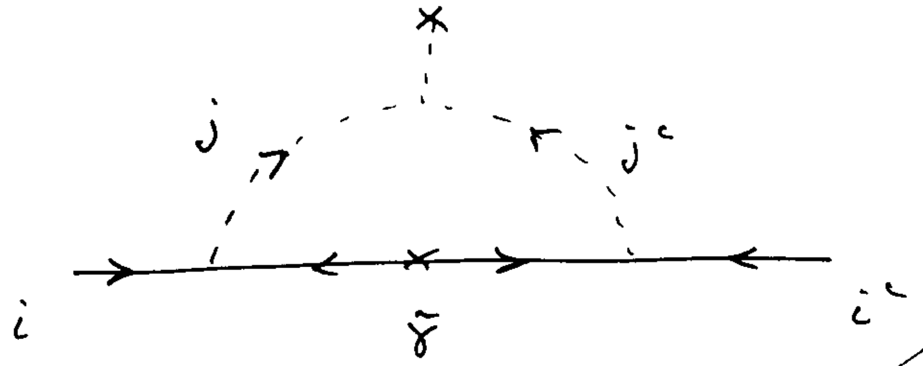
a) Predictive theories have not been constructed.

b) No constraint on mass M in loops.

Supersymmetric theories offer new hope because

b) Superpartners with mass $O(v_{EW})$ in loop.

a) Hope to measure superpartner masses & couplings so that superloops really can be computed.



Could be zero. At scales ≫ v fermion mass info. is in (ξ, m^2)

$$m_i = \frac{e^2}{16\pi^2} \cdot \frac{m_{\tilde{\gamma}}}{\tilde{m}^2} \cdot \left(\xi_{jj^c} + \mu \lambda_{jj^c} \tan\beta \right) v_1 \, W_{ji} \, W^c_{ji}$$

However, these diags are closely related to $j \to i \gamma$.

$\tau \to \mu \gamma$ forbids $\frac{m_\mu}{m_\tau} = O(\alpha)$

$\mu \to e \gamma$ forbids $\frac{m_e}{m_\mu} = O(\alpha)$

$\tau \to e \gamma$ CLEO measurement of 1996 "excludes" $\frac{m_e}{m_\tau} \sim \frac{\alpha}{4\pi}$

$\Rightarrow$ Superpartner loops at weak scale are apparently NOT generating dominant contrib: to light fermion masses. Basic problems a) and b) remain for radiative ferm. masses.

ii) $\epsilon = m/M$.

Where do mass scales come from?

a) Definition of unit: M_{PL}. M could be M_{PL}.

b) Dimensional Transmutation

— QCD

$$\frac{dg}{dt} = \frac{-bg^3}{16\pi^2}, \quad \frac{\Lambda}{M_0} = e^{-8\pi^2/bg_0^2}.$$

In QCD flavour symmetries are broken at Λ.

$\to$ DSB

m^2 runs −ve in supersym.

— $$\frac{dm_1^2}{dt} = \lambda^2 m_2^2 \quad \text{with} \quad V = m_1^2(\varphi)\,|\phi|^2$$

Gives $\langle\phi\rangle \sim \mu_0$ where $m_1^2(\mu_0) = 0$. In this case D.T. occurs by perturbative dynamics.

(need D.T. for supersym. breaking for origin of m^2!).

— Supersymmetric QCD with $N_f = N_c$

Coupling gets strong generating Λ

Mesons $M_{ij} = \bar{q}_i q_j$

Baryons $B = \epsilon_{ijk\ldots} q_i q_j q_k \ldots$

Constrained by: $\det M - \Lambda^{N-3}(\bar{B}B) = \Lambda^N$

$\boxed{\Rightarrow \text{There are a variety of ways in which dynamics generates a scale by D.T. \& vevs form at this scale.}}$

NEUTRINO MASSES:

1. With minimal matter content, 3-2-1 gauge interactions force ν masses to arise only at $d=5$

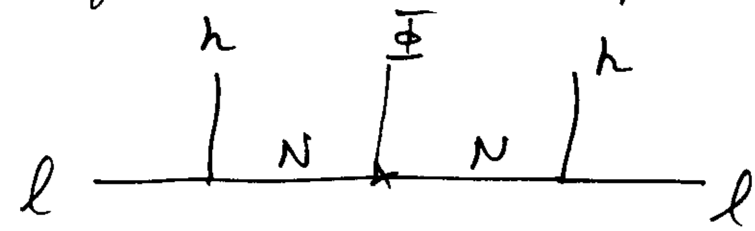
$$\mathcal{L}_{eff} = \mathcal{L}_R + \frac{g}{M}\, l l h h \quad (1) \qquad l = \begin{pmatrix} \nu \\ e \end{pmatrix} \quad h = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

For $M = M_P$, too small of interest.
Interesting to consider $M < M_P$, & invent physics ~~theory~~ which produces ~~these~~ such M.

2. Introduce RH. ν : N. They are singlet under 3-2-1 and acquire some large mass. This could occur by some field $\langle \Phi \rangle \approx M$ breaking lepton number via a D.T.

$$\mathcal{L} = \Phi N N + \lambda\, l h N$$

3. Integrate out N to obtain effective theory beneath M



This generates $\mathcal{L}_{eff}$ of (1), with $g = \lambda^2$.
Inserting $\langle h \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$ gives

$$\boxed{m_\nu = \frac{\lambda^2 v^2}{M}} \quad (55)$$

This is known as see-saw: as $M \uparrow$ so $m_\nu \downarrow$.

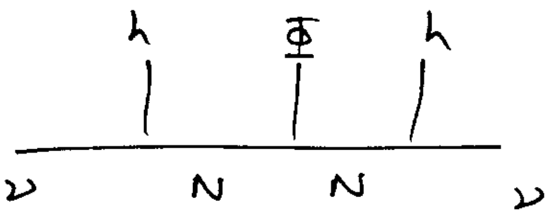
THE SEE-SAW AS HEAVY–LIGHT MIXING.

The result (55) is the approx. result of diagonalizing the mass matrix

$$\frac{1}{2}\,(\nu, N)\begin{pmatrix} 0 & \lambda v \\ \lambda v & M \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix}.$$

$$\begin{pmatrix} \nu' \\ N' \end{pmatrix} = \begin{pmatrix} c & -s \\ +s & c \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix} \quad \text{with} \quad \frac{s}{c} = \sqrt{\frac{m_{\nu'}}{M_{N'}}} \xrightarrow[\theta]{\text{small}} \frac{\lambda v}{M}$$

One may worry about whether



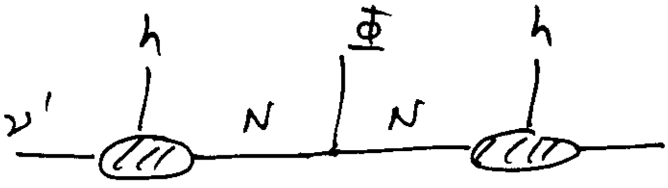
really gives the right answer, because we should integrate out N' not N. We can check by:

$$W = \frac{M}{2}(N\,N) + \lambda v(\nu\,N)$$

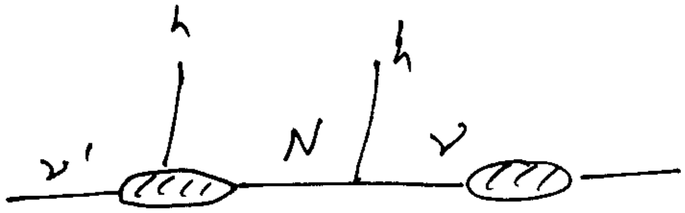
$$= \frac{M}{2}(N' - \theta\nu')^2 + \lambda v(\nu' + \theta N')(N' - \theta\nu')$$

$$\supset \Big(\underset{\text{(A)}}{\frac{M}{2}\theta^2} - \underset{\text{(B)}}{\lambda v\theta}\Big)\nu'^2 = -\frac{\lambda^2 v^2}{M}\,\frac{\nu'\nu'}{2}$$

Thus effective theory does reproduce correct result to leading order in $1/M$. We can understand (A) & (B) diagrammatically by writing down the initial mass terms and using mixing.

(A) 

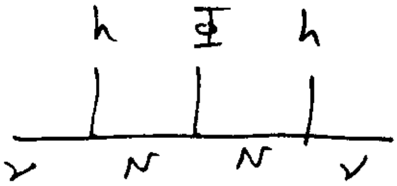
$+\left(\frac{M}{2}\right)(-\theta)^2$

(B) 

$+\lambda v\,(-\theta)(1)$

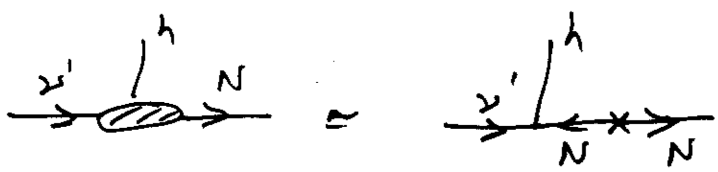
In these diagrams we are NOT integrating anything out — we are just doing the rotation of $N\Phi N$ and $Nh\nu$ couplings from (ν, N) to (ν', N') basis & looking at terms with external $\nu'\nu'$.

Thus to leading order in $1/M$, we get correct answer by either

i) 

pretending N heavy & ν light.

ii) Heavy – light mixing.



$\sim \frac{\lambda v}{M}$

SEE-SAW FOR CHARGED FERMIONS : "FROGGATT-NIELSEN MECHANISM"

Cannot be identical to ν : $m_\nu \propto \langle h \rangle^2$

want $m_e \propto \langle h \rangle$.

Ingredients: 0) G_f to explain absence of leh (for ν it was $SU(2)$)

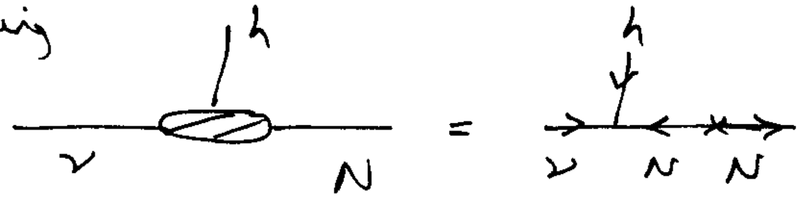
1) ~~Also~~ heavy charged particles with $SU(2) \times U(1)$ invariant mass

for leptons $W \supset \Phi L \bar{L} + \Phi E^c \bar{E^c}$

2) Heavy - light mixing

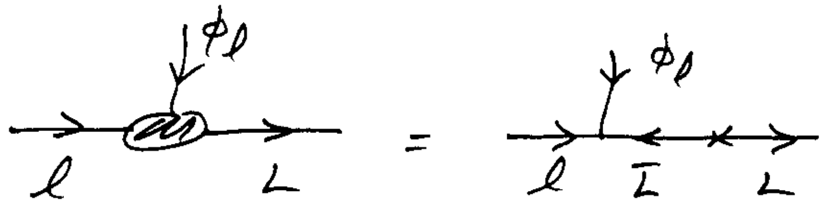
$$W \supset \bar{L} \phi_l l + \bar{E^c} \phi_e e^c$$

Thus ν are light because heavy - light mixing occurs via $SU(2)$ breaking



$= \lambda v / M$

Charged fermions are light because heavy - light mixing occurs via G_f breaking



$= \lambda \dfrac{\phi_l}{M}$

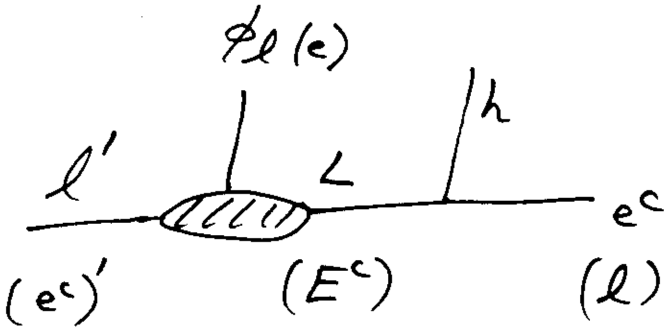
Clearly L and l transform differently under G_f.

3) <u>G_f invariant interactions of h</u> of form

$$L E^c h\ ,\quad l E^c h\ ,\quad L e^c h \qquad \text{(depending on model)}$$

while G_f forbids $l e^c h$.

Heavy-light mixing now produces small lepton masses:



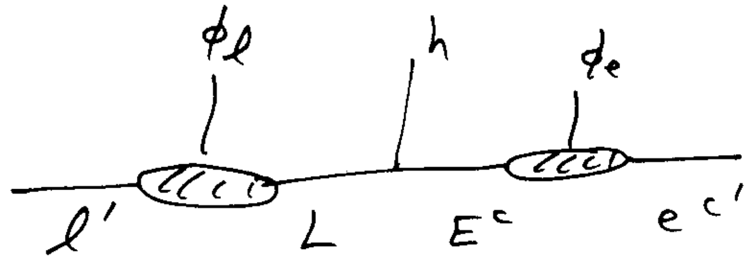
Type B

$$\boxed{\frac{m_e}{v} \approx \frac{\phi_{l,e}}{M}}$$

1st order FN

Compare:

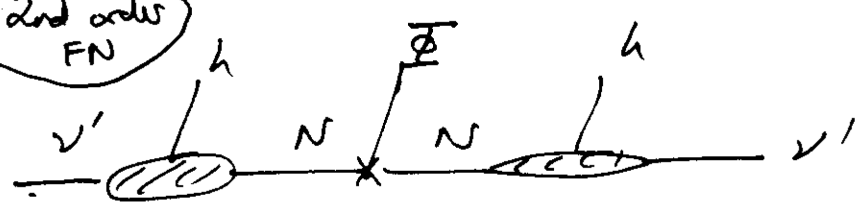
Type A



$$\boxed{\frac{m_e}{v} = \frac{\phi_l \phi_e}{M^2}}$$

2nd order FN

Compare



Notice inversion of roles of fields which violate flavor & those which violate SU(2)

FN for SCALARS. Dimopoulos, Pomarol 1995.

Write down the most general G_f invariant set of m^2 parameters:

$$V_{soft} \supset \left(l^* \; L^* \right) \begin{pmatrix} m_l^2 & 0 \\ 0 & m_L^2 \end{pmatrix} \begin{pmatrix} l \\ L \end{pmatrix}$$

0 by G_f.

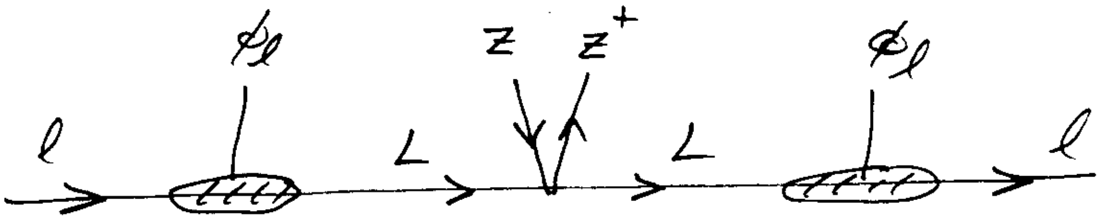
Do superfield rotation to diagonalize (heavy – light) & supersym mass terms:

$$\begin{pmatrix} l' \\ L' \end{pmatrix} = \begin{pmatrix} c & -s \\ s & c \end{pmatrix} \begin{pmatrix} l \\ L \end{pmatrix}$$

$$V_{soft} \longrightarrow \left(l'^* \; L'^* \right) \begin{pmatrix} c^2 m_l^2 + s^2 m_L^2 & \cdots \\ \cdots & \cdots \end{pmatrix} \begin{pmatrix} l' \\ L' \end{pmatrix}$$

This is just a quadratic FN :

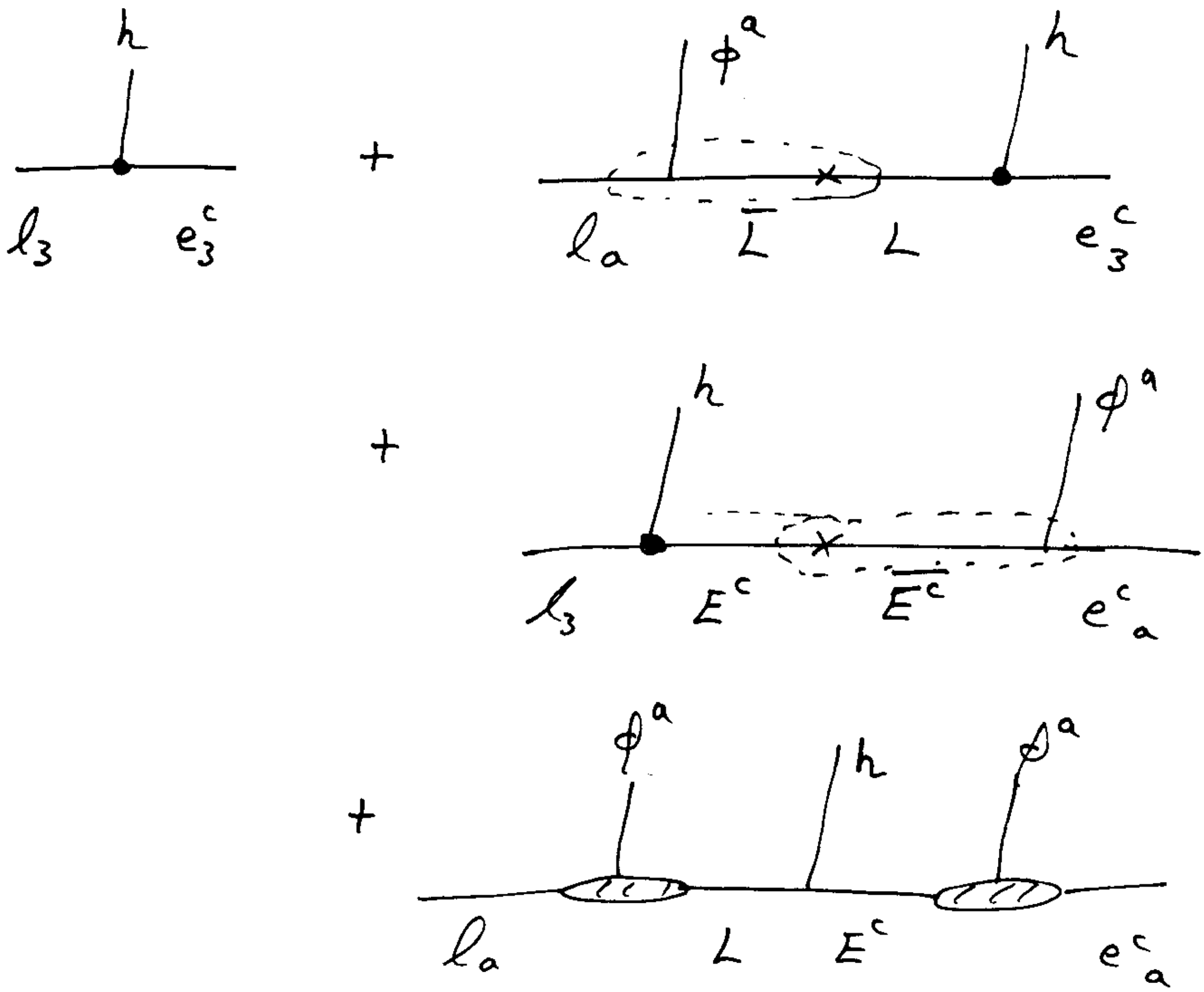
$$Z = m\theta^2$$



$$\Delta m_l^2 \sim \theta^2 m_L^2 \sim \left(\frac{\phi_l}{M} \right)^2 m_L^2$$

A $U(2)$ FN THEORY — FIRST ATTEMPT

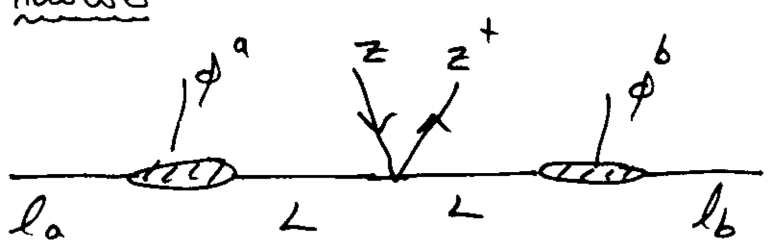
Choose heavy vector leptons as $U(2)$ singlets:



$$\boxed{\lambda_E \sim \begin{pmatrix} \epsilon^2 & \epsilon \\ \epsilon & 1 \end{pmatrix}} \qquad \epsilon = \phi/M$$

Interesting

However



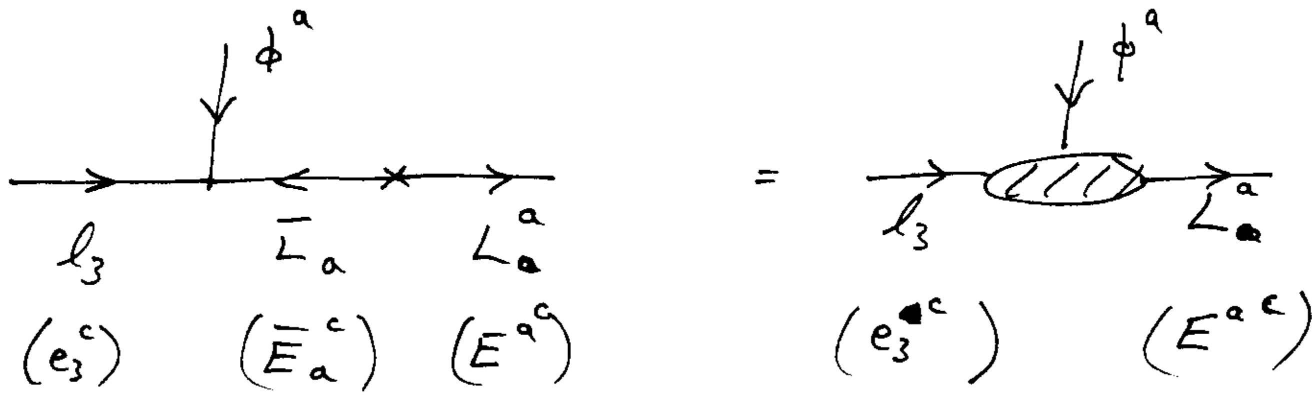
$$\Rightarrow \begin{pmatrix} m_1^2 & & \\ & m_1^2 + \epsilon^2 m_2^2 & \\ & & m_3^2 \end{pmatrix}$$

$\frac{m_\mu}{m_\tau} \sim \frac{1}{17}.$

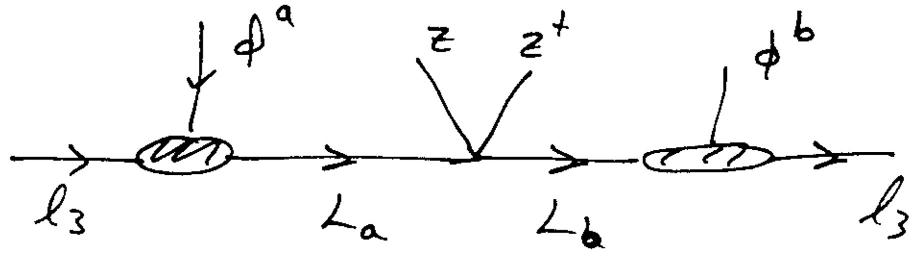
U(2) doublet heavy leptons: $M\left(L^a \bar{L}_a + E^{ca} \bar{E}^c_a\right)$

Note that l_a / L^a do transform differently.

The simplest heavy-light mixing is via ϕ^a:

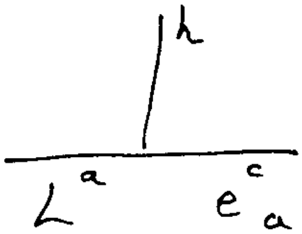


Thus the DP scalar effect shifts mass of $\tilde{l}_3$, $\tilde{e}_3^c$

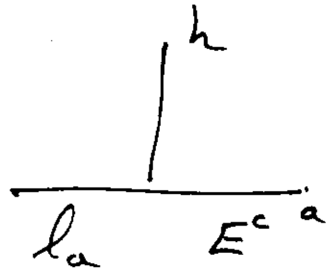


$$m^2 \longrightarrow \begin{pmatrix} m_1^2 & & \\ & m_1^2 & \\ & & m_3^2 + \epsilon^2 m_L^2 \end{pmatrix}$$ SAFE!

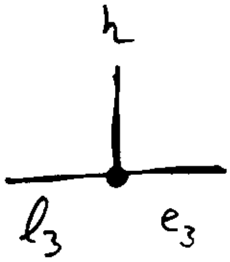
The h couplings are:

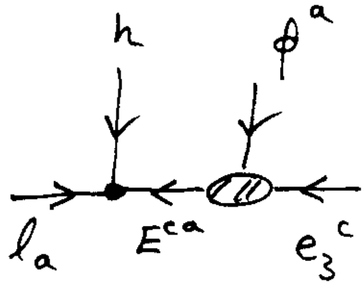


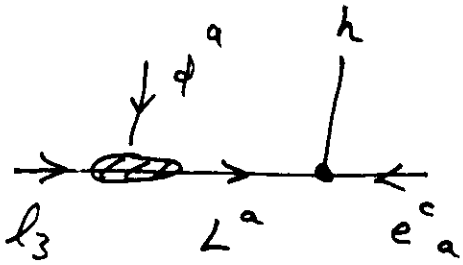
and



so the fermion diagrams are

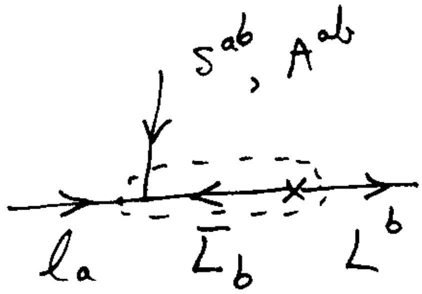




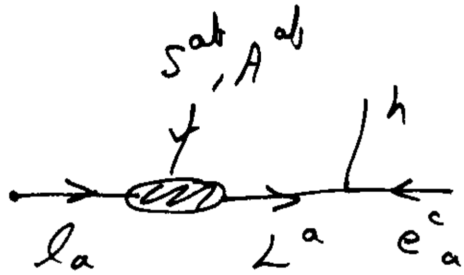


Generating $\lambda = \begin{pmatrix} & \epsilon \\ \epsilon & 1 \end{pmatrix}$.

Introduce S^{ab}, A^{ab} to get more heavy light mixings



giving



$\frac{\langle S^{ab} \rangle}{M} = \begin{pmatrix} 0 & 0 \\ 0 & \epsilon \end{pmatrix}$ $\quad \frac{\langle A^{ab} \rangle}{M} = \epsilon^{ab} \left(\frac{\epsilon'}{M} \right)$. gives

$$\boxed{\lambda = \begin{pmatrix} 0 & \epsilon' & 0 \\ -\epsilon' & \epsilon & \epsilon \\ 0 & \epsilon & 1 \end{pmatrix}}$$

D.P. effect now arises from S and gives $\Delta m_{12}^2 / m^2 = \epsilon^2 = (m_\mu / m_\tau$