The flavour puzzle and accidental symmetries

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based on: Ferretti, King, R hep-ph/0609047

Outline

* The flavour puzzle in the SM
* Approaches to the flavour puzzle
* A new approach
  - Basic idea
  - Vus and LR symmetry
  - s/b vs c/t and Pati-Salam
  - Neutrinos
  - A model

The flavour puzzle in the SM

* 3 families, or $U(3)^5$ symmetry of the fermion gauge lagrangian

	1	2	3
l	l_1	l_2	l_3
e^c	$(e^c)_1$	$(e^c)_2$	$(e^c)_3$
q	q_1	q_2	q_3
u^c	$(u^c)_1$	$(u^c)_2$	$(u^c)_3$
d^c	$(d^c)_1$	$(d^c)_2$	$(d^c)_3$

family number (horizontal) not understood

gauge irreps (vertical) well understood

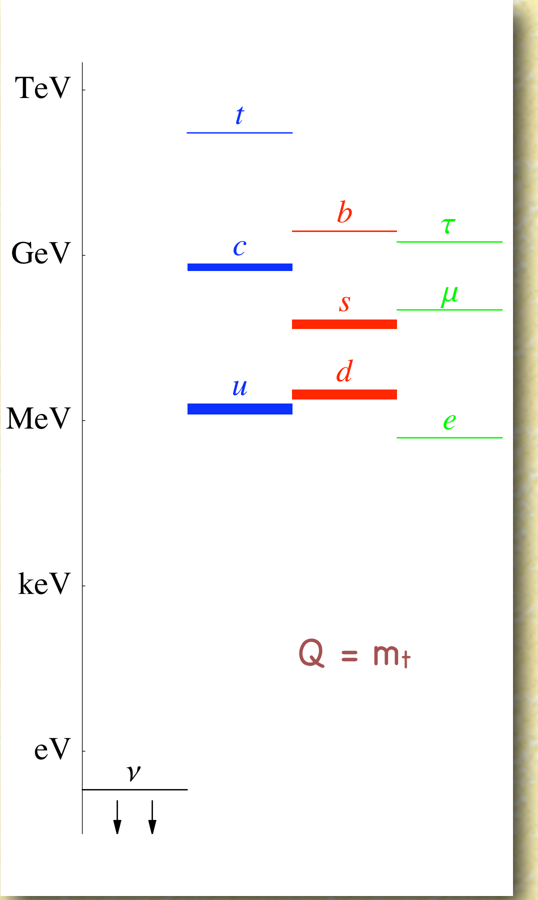
The flavour puzzle in the SM

* 3 families, or $U(3)^5$ symmetry of the fermion gauge lagrangian
* Pattern of $U(3)^5$ breaking from Yukawa sector (most SM pars)

$$\mathcal{L}_{\rm SM}^{\rm flavor} = \lambda_{ij}^E e_i^c L_j H^\dagger + \lambda_{ij}^D d_i^c Q_j H^\dagger + \lambda_{ij}^U u_i^c Q_j H + \text{h.c.}$$

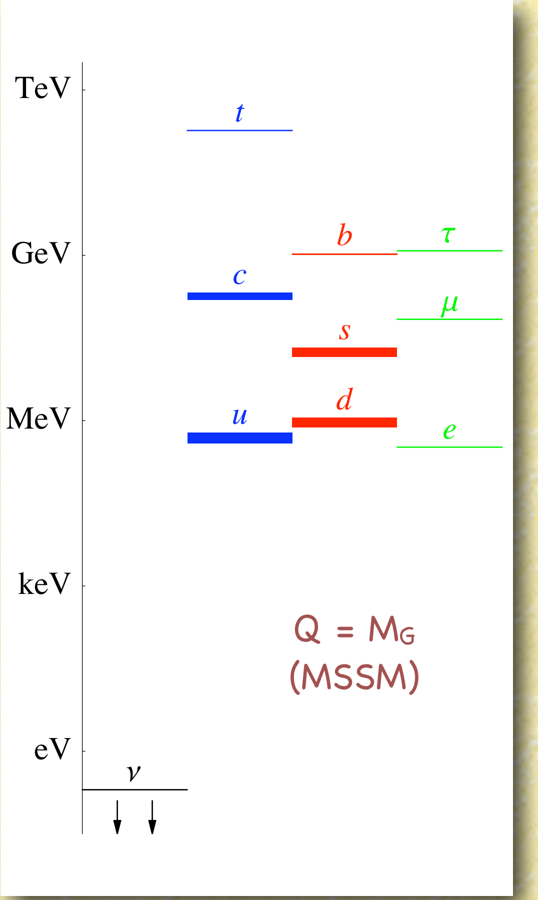
The flavour puzzle in the SM

- 3 families, or $U(3)^5$ symmetry of the fermion gauge lagrangian
- Pattern of $U(3)^5$ breaking from Yukawa sector (most SM pars)
  - (horizontal) hierarchy of fermion$^{\pm}$ masses: 1 « 2 « 3
  - CKM mixing angles « 1



The flavour puzzle in the SM

* 3 families, or $U(3)^5$ symmetry of the fermion gauge lagrangian
* Pattern of $U(3)^5$ breaking from Yukawa sector (most SM pars)
  - (horizontal) hierarchy of fermion$^\pm$ masses: $1 \ll 2 \ll 3$
  - CKM mixing angles $\ll 1$
  - U vs D vs E
    - different hierarchies: U $\gg$ D, E
    - $m_b \approx m_\tau$, $3m_s \approx m_\mu$, $m_d \approx 3m_e$ @ M_G
  - mass hierarchy vs mixing hierarchy
    - $|V_{cb}| \sim m_s/m_b$, $|V_{us}| \approx (m_d/m_s)^{1/2}$
  - neutrino sector
    - 2 PMNS mixing angles $O(\pi/4)$, 1 small
    - $\theta_{23} = O(\pi/4)$ & $|\Delta m^2|_{12} \ll |\Delta m^2|_{23}$, $\theta_{12} \neq \pi/4$



The flavour puzzle in SM extensions

* The peculiar SM flavour structure (m_1, $m_2 \ll \langle H \rangle$, $|V_{td}|$,$|V_{ts}| \ll 1$) allows the SM to pass the FCNC test

$$\mathcal{L}(Q \ll \langle H \rangle) \supset \frac{\bar{s}d\bar{s}d}{\Lambda_f^2}, \quad \frac{1}{\Lambda_f^2} \sim \frac{1}{(10^3\,\mathrm{TeV})^2}$$

$$\left(\frac{1}{\Lambda_f^2}\right)_{\mathrm{SM}} \sim \frac{g^4}{(4\pi)^2} \times (V^\dagger_{su_i} V_{u_i d})(V^\dagger_{su_j} V_{u_j d}) f\left(\frac{m^2_{u_i}}{M_W^2}, \frac{m^2_{u_j}}{M_W^2}\right) \times \frac{1}{M_W^2}$$

* The unknown physics at the SM cutoff should not provide new generic flavour structure

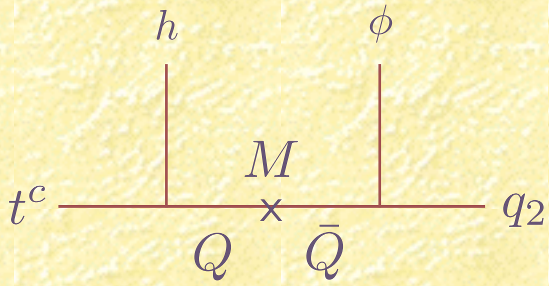
$$\left(\frac{1}{\Lambda_f^2}\right)_{\mathrm{NP}} \sim ? \times \frac{1}{\Lambda^2_{\mathrm{NP}}}$$

  - e.g. in the MSSM $\delta_{12} \ll 1$, or $(\tilde{m}^2_d - \tilde{m}^2_s)/\tilde{m}^2$ and $|W_{31}|$,$|W_{32}| \ll 1$

* Is the origin of the peculiar structure in SM and the MSSM/NP the same?

(Some) approaches to the flavour puzzle

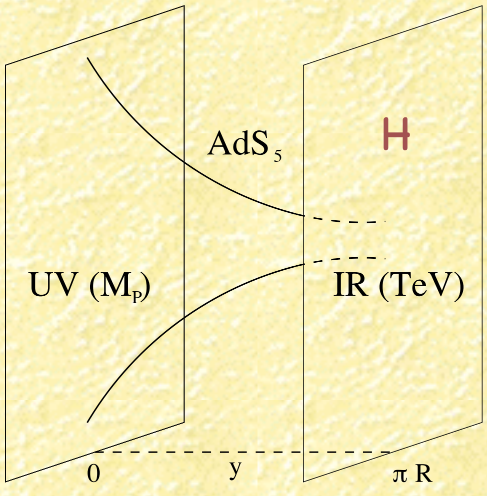
* "Flavour symmetries" acting on family indexes (subgroup of $U(3)^5$)
  - symmetric limit: only O(1) Yukawas possibly allowed: λ_t (λ_b λ_τ)
    - e.g. t^c, q_3, h neutral under a U(1): $Y_{33}\, t^c q_3 h$ is allowed
  - spontaneous breaking of U(1) by SM singlets ϕ at high scale
    - e.g. $Q(q_2) = 1$, $Q(\phi) = -1$: $\frac{\phi}{M} t^c q_2\, h$ is allowed $\Rightarrow$ $Y_{32} = \frac{\langle\phi\rangle}{M}$
  - breaking communicated to SM fermions by heavy messengers (M = mass)
    - at E « M



$\rightarrow \quad \frac{\phi}{M} t^c q_2\, h$

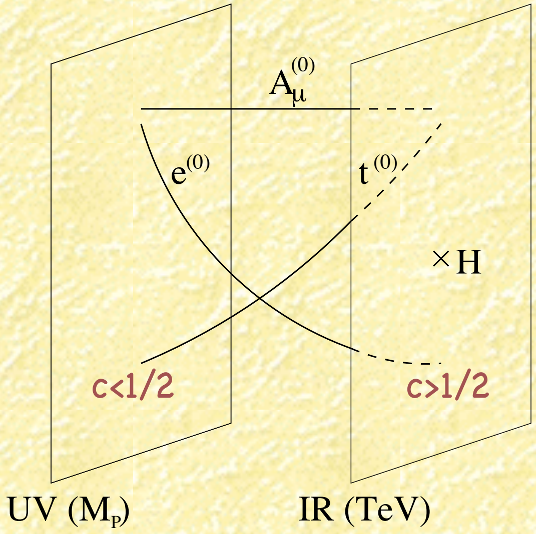
  - gauge/global, continuous/discrete, abelian/non-abelian

* Extra-dimension mechanisms
    - flavour symmetry breaking with boundary conditions
    - localized fermions
        - e.g. in RS-type models:



$$m_H \sim M_5 e^{-\pi k R}$$

$$k = \text{curvature}$$



$$\psi_i(y) \propto e^{(1/2-c_i)ky}$$

$$c = \text{bulk mass in } k \text{ units}$$

$$\lambda_{ij} \propto e^{(1-c_i-c_j)\pi k R}$$

A new (economical) approach

* The knowledge (or existence) of special horizontal dynamics is not required to explain the fermion hierarchical pattern

* The pattern follows from the relative lightness of one set of heavy fields and is associated to the breaking of the gauge group (Pati-Salam)

* Chiral symmetries acting on family indexes "protecting" the mass of the lighter families emerge in this context as accidental symmetries

	1	2	3
l	l_1	l_2	l_3
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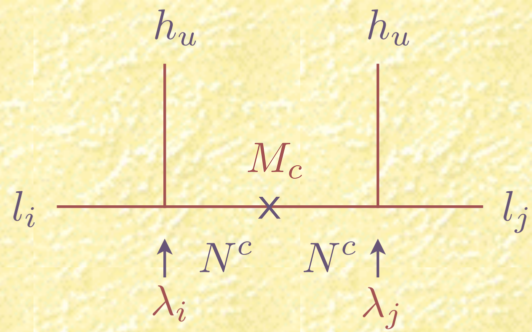
Large ϑ_{23} (from m_ν) and normal hierarchy



Exchange of a single N^c

↓

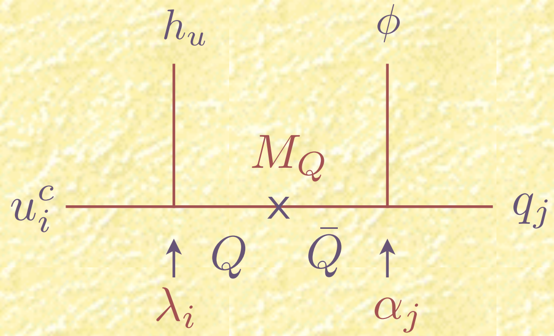
$$m^\nu_{ij} = -\lambda_i \lambda_j \frac{\langle h_u \rangle^2}{M_c}$$

Focus on "23" block:

- Single N^c: $m_3 \gg m_2 = 0$ hierarchy ($m_2 \neq 0$ from subdominant contributions)
- $\lambda_2 \approx \lambda_3$: $\tan \vartheta_{23} \approx 1$ large ϑ_{23} (barring charged lepton rotation)

(for generic λ_i's)

Charged fermions

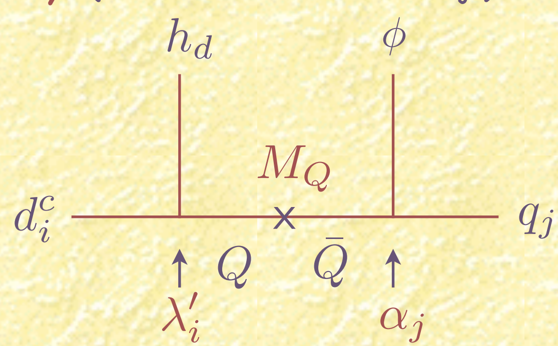


$$\lambda_{ij}^U = -\lambda_i \alpha_j \frac{\langle \phi \rangle}{M_Q}$$

No Yukawas at ren. level

Exchange of a single family of messengers

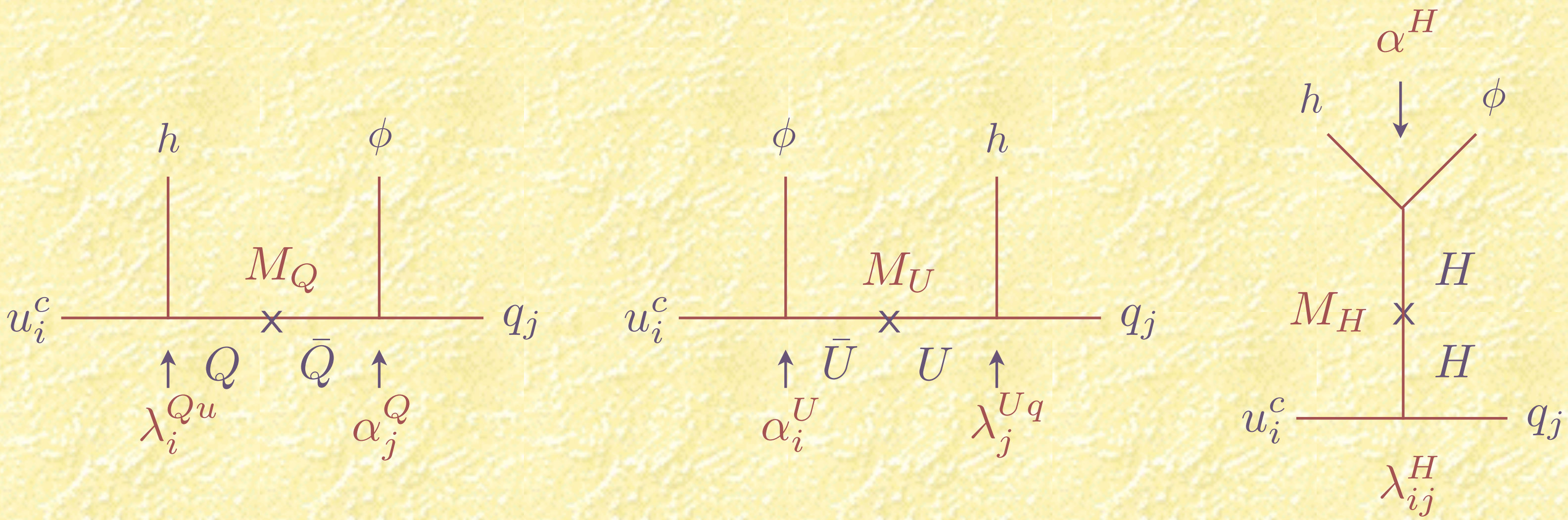
* Single messenger: $m_t \gg m_c = 0 \rightarrow$ hierarchy (whatever λ_i & α_j!); $m_2 \neq 0$ from subdominant contributions
* λ_i & $\alpha_j = O(1)$: large angles in CKM? No:



same rotation of L-handed fields

* No need of constraints on couplings, family symmetry [see also: Barr hep-ph/0106241]

$m_2 \neq 0$



* Neglect H and 1st family for now (will turn out not to contribute)

$$Y_{ij}^U = \lambda_i^{Qu}\alpha_j^Q\frac{\langle\phi\rangle}{M_Q} + \alpha_i^U\lambda_j^{Uq}\frac{\langle\phi\rangle}{M_U}$$

$$Y_{ij}^D = \lambda_i^{Qd}\alpha_j^Q\frac{\langle\phi\rangle}{M_Q} + \alpha_i^D\lambda_j^{Dq}\frac{\langle\phi\rangle}{M_D}$$

* $m_2 \ll m_3$: one term must dominate

* $|V_{cb}| \ll 1$: $M_Q \ll M_U, M_D$ (left-handed dominance)

Early comments

* $m_2 \ll m_3$ in terms of $M_Q \ll M_{U,D}$ (horizontal from vertical)

* $$Y^U \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon_U & \epsilon_U \\ 0 & \epsilon_U & 1 \end{pmatrix}, \quad Y^D \propto \begin{pmatrix} 0 & 0 & 0 \\ \epsilon_D & \epsilon_D & \epsilon_D \\ \epsilon_D & \epsilon_D & 1 \end{pmatrix}$$

  with a proper basis choice
  up to O(1) coefficients
  $\epsilon_U = M_Q/M_U$
  $\epsilon_D = M_Q/M_D$

* $m_1 = 0$: first family "protected" by accidental flavour symmetry $U(1)_1$
  - in the effective theory below $M_{U,D}$, the second family mass is protected by an accidental symmetry $U(1)_2$

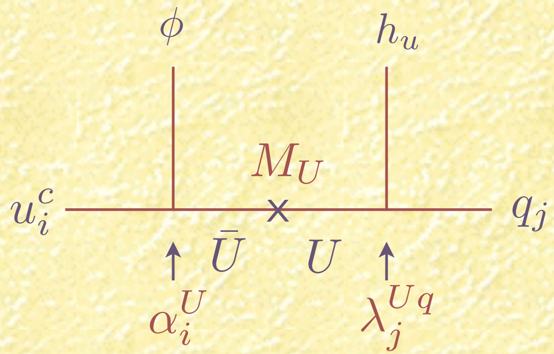
* $m_s/m_b \sim |V_{cb}|$ ✔

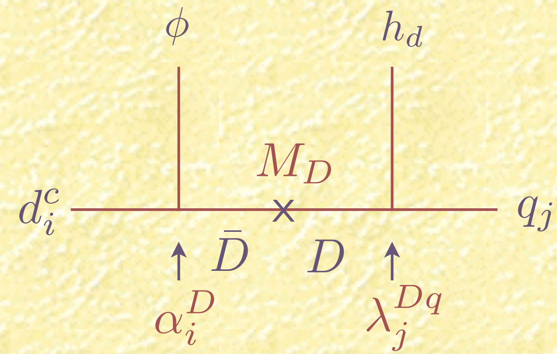
  U(1)'s and RS-type: $$Y \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon_1\epsilon_2 & \epsilon_2 \\ 0 & \epsilon_1 & 1 \end{pmatrix}$$ up to O(1) coefficients

  $\Rightarrow m_s/m_b \sim \epsilon_2 \, |V_{cb}|$

V_{us} and $SU(2)_R$

$$Y^U \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon_U & \epsilon_U \\ 0 & \epsilon_U & 1 \end{pmatrix} \qquad Y^D \propto \begin{pmatrix} 0 & 0 & 0 \\ \epsilon_D & \epsilon_D & \epsilon_D \\ \epsilon_D & \epsilon_D & 1 \end{pmatrix}$$





$|V_{us}| \sim 1$ unless $(\lambda^{Uq})_i \approx (\lambda^{Dq})_i \to SU(2)_R$ (or mild fine-tuning)

- $G_{LR} = SU(2)_L \times SU(2)_R \times SU(3)_c \times U(1)_{B-L}$
- $q_i^c = \begin{pmatrix} u_i^c \\ d_i^c \end{pmatrix} \quad Q^c = \begin{pmatrix} U^c \\ D^c \end{pmatrix} \quad l_i^c = \begin{pmatrix} n_i^c \\ e_i^c \end{pmatrix} \quad L^c = \begin{pmatrix} N^c \\ E^c \end{pmatrix} \quad h = \begin{pmatrix} h_u \\ h_d \end{pmatrix}$
- $\lambda^c_i \, q_i \, Q^c \, h \Rightarrow (\lambda^{Uq})_i = (\lambda^{Dq})_i = \lambda^c_i$

m_c/m_t vs m_s/m_b and $SU(4)_c$

$$Y^U \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon_U & \epsilon_U \\ 0 & \epsilon_U & 1 \end{pmatrix} \qquad\qquad Y^D \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon_D & \epsilon_D \\ 0 & \epsilon_D & 1 \end{pmatrix}$$

* $m_c/m_t \sim m_s/m_b$ unless $M_U \gg M_D$
* Unbroken $SU(2)_R$: $M_c\, \bar{Q}^c Q^c \Rightarrow M_U = M_D = M_c \Rightarrow m_c/m_t = m_s/m_b$
* $SU(3)_c \rightarrow SU(4)_c$: $SU(4)_c$ adjoint couples $SU(2)_R$ breaking to Q^c ($SU(2)_R$ breaking by $\tilde{L}^c$, $\tilde{\bar{L}}^c$ scalars with vevs along $\tilde{N}^c$, $\tilde{\bar{N}}^c$ (standard))
* Then $m_c/m_t \ll m_s/m_b$ does not require a new ad hoc scale

Neutrinos

- Prediction: $N^c(\lambda^c_3 l_3 + \lambda^c_2 l_2)h_u$ (with charged leptons (almost) diagonal)
- Takes care of ϑ_{23} + normal hierarchy if N^c dominates the seesaw:

  $$\tan\theta_{23} \sim \frac{\lambda^c_2}{\lambda^c_3} \qquad |\Delta m^2_{12}| \ll |\Delta m^2_{23}|$$

- n^c_i also contribute to the seesaw: $\lambda_3 n^c_3 L h_u$
- Must give mass to 2 massless linear combinations: $\eta_{ki} s_k f^c_i \bar{F}'_c$, s_k = (111++)
- Note: no new mass scale (n^c_i and N^c at the same scale, but N^c dominates)

- $$m_3 = \rho_\nu \frac{v^2_{\rm EW}}{2 s^2_{23} M_c}, \qquad m_{1,2} \approx 0$$

  $$M_c \approx 0.6 \cdot 10^{15}\,\text{GeV}\rho_\nu, \quad \rho_\nu = \mathcal{O}(1)$$

The model

Below the cutoff Λ (will turn out to be > 10^{16-17} GeV):

* $G = G_{PS} = SU(2)_L \times SU(2)_R \times SU(4)_c + Z_2$ and SUSY (with R_P)
* Field content:

	f_i	f_i^c	h	ϕ	F	$\bar{F}$	F^c	$\bar{F}^c$	H	F'	$\bar{F}'$	F'_c	$\bar{F}'_c$	Σ	X_c
$SU(2)_L$	2	1	2	1	2	2	1	1	2	2	2	1	1	1	1
$SU(2)_R$	1	2	2	1	1	1	2	2	2	1	1	2	2	1	3
$SU(4)_c$	4	$\bar{4}$	1	15	4	$\bar{4}$	$\bar{4}$	4	1	4	$\bar{4}$	$\bar{4}$	4	15	1
$\mathbf{Z}_2$	−	−	−	−	+	+	+	+	+	+	+	+	+	+	+
R_P	−	−	+	+	−	−	−	−	+	+	+	+	+	−	+

$F = (L\ Q_1\ Q_2\ Q_3)$, $F^c = (L^c\ Q^c{}_1\ Q^c{}_2\ Q^c{}_3)$, $\Sigma = (A\ T\ \bar{T}\ G)$

* Assumptions:
  - Heavy masses through $\langle X_c \rangle$, $\langle F'_c \rangle$ (PS breaking)
  - Z_2 breaking (along B−L) at $v \ll M_c$ (T_{3R}, N'_c)

$M_R \sim V_c \equiv \langle \tilde{N}'_c \rangle$

$M_L \equiv v = \langle \phi \rangle$

$\epsilon \equiv v/M_c \ll 1$

* The most general ren. superpotential

$$W_{\rm ren} = \lambda_i f_i^c F h + \lambda_i^c f_i F^c h + \lambda_{ij}^H f_i^c f_j H + \alpha_i \phi f_i \bar{F} + \alpha_i^c \phi f_i^c \bar{F}^c$$
$$+ M \bar{F} F + M_c \bar{F}^c F^c + \gamma M \Sigma^2 + \bar{\sigma}_c \bar{F}_c' \Sigma F^c + \sigma_c \bar{F}^c \Sigma F_c' + \eta' F_c' F' H + \bar{\eta}' \bar{F}_c' \bar{F}' H + \ldots$$

gives rise to the full pattern of II and III family charged fermion masses and mixing

* D, E sector: $Y^D = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \alpha_2^c \lambda_2^c \epsilon/3 & \alpha_2^c \lambda_3^c c\, \epsilon/3 \\ 0 & \alpha_3^c \lambda_2^c \epsilon/3 & -s\lambda_3 \end{pmatrix}$ $\quad Y^E = -\begin{pmatrix} 0 & 0 & 0 \\ 0 & \alpha_2^c \lambda_2^c \epsilon & \alpha_2^c \lambda_3^c c\, \epsilon \\ 0 & \alpha_3^c \lambda_2^c \epsilon & s\lambda_3 \end{pmatrix}$

- $m_b = m_{tau}$
- $3m_s = m_{mu}$
- $|V_{cb}| \sim m_s/m_b$
- $\epsilon = 0.06 \times O(1)$

$\epsilon \equiv v/M_c \ll 1$

$\tan\theta \equiv \alpha_3 v/M = O(1)$

$s = \sin\theta$

* U sector: $Y^U = -\begin{pmatrix} 0 & 0 & 0 \\ 0 & (4/9)\alpha_2^c\lambda_2^c\rho_u\epsilon^2 & (4/9)\alpha_2^c\lambda_3^c c\rho_u\epsilon^2 \\ 0 & (4/9)\alpha_3^c\lambda_2^c\rho_u\epsilon^2 & s\lambda_3 \end{pmatrix}$

Notation: ρ denotes a combination of O(1) parameters

ϵ^2: Y_c from $\lambda^c{}_i U^c q_i h_u$ with $U^c \to (U^c)_{light}$

where the $(U^c)_{light}$ component of U^c is suppressed by

- $v/M_c = \epsilon$
- $M/V_c \sim \epsilon$

$$\bar{U}^c\left[M_c U^c + \frac{\sigma_c}{\sqrt{2}} V_c \bar{T}_\Sigma + \frac{v}{3}(\alpha_3^c u_3^c + \alpha_2^c u_2^c)\right] + T_\Sigma\left[M_\Sigma \bar{T}_\Sigma + \frac{\bar{\sigma}_c}{\sqrt{2}} V_c U^c\right]$$

* 2 hierarchies in terms of 1

To summarize (charged fermions)

* Assumptions:
  - Field content below Λ
  - Messenger masses along T_{3R}, $\tilde{N}^c$
  - $\mathbf{Z}_2$ breaking at lower scale (ϕ) along B-L

M_R: T_{3R}, $\tilde{N}^c$

M_L: $\mathbf{Z}_2$ (along B-L)

* Results:
  - $m_s \ll m_b$, $m_{mu} \ll m_{tau}$
  - $|V_{cb}| \sim m_s/m_b$
  - $(m_{tau}/m_b)_M \approx 1$, $(m_{mu}/m_s)_M \approx 3$
  - $m_c/m_t \ll m_s/m_b$
  - $m_{u,d,e}$ further suppressed (no $Hh\phi$)
  - ϑ_{23} + normal hierarchy in neutrino sector: easy
  - $M_c \approx 0.6 \cdot 10^{15}\,\mathrm{GeV}\rho_\nu, \quad \rho_\nu = \mathcal{O}(1)$ (N^c = FN)

The first family

* Masses and mixings of the first family originate above the cutoff Λ (not specified) and can be parameterized by NR operators
* There exists a choice of NR operators accounting for 1st family masses and mixings (some should be forbidden, e.g. $f^c_i f_j \Phi h$, $F'_c F' \Phi h \to m_u$ too large)):
  - $\bar{F}'_c \bar{F}' \Phi h$ induces h-H mixing in the down (but not up) sector, thus communicating the $U(1)_1$ breaking from $f^c_i f_j H$ to the light D, E sectors (but not to the U sector)
  - The up quark mass is consistent with an effect from M_{Pl}
  - $M_c/\Lambda \sim m_2/m_3$ (determines Λ up to O(1))

    $$\theta_{13} = \frac{m_2}{m_3} \frac{\tan\theta_{12}}{1+\tan^2\theta_{12}} \frac{a+b}{a-b} + \dots$$

    $|V_{us}| \sim M_c/\Lambda \sim m_2/m_3$

A problem

* $Y^D = \begin{pmatrix} \rho_h \lambda^H_{11}\epsilon' & \rho_h \lambda^H_{12}\epsilon' & \rho_h \lambda^H_{13} c\,\epsilon' \\ \rho_h \lambda^H_{21}\epsilon' & \alpha^c_2 \lambda^c_2 \epsilon/3 & \alpha^c_2 \lambda^c_3 c\,\epsilon/3 \\ \rho_h \lambda^H_{31}\epsilon' & \alpha^c_3 \lambda^c_2 \epsilon/3 & -s\lambda_3 \end{pmatrix}$ $\quad Y^E = \begin{pmatrix} \rho_h \lambda^H_{11}\epsilon' & \rho_h \lambda^H_{12}\epsilon' & \rho_h \lambda^H_{13} c\,\epsilon' \\ \rho_h \lambda^H_{21}\epsilon' & -\alpha^c_2 \lambda^c_2 \epsilon & -\alpha^c_2 \lambda^c_3 c\,\epsilon \\ \rho_h \lambda^H_{31}\epsilon' & -\alpha^c_3 \lambda^c_2 \epsilon & -s\lambda_3 \end{pmatrix}$

  gives $m_e \approx m_d$, $|V_{us}| \approx m_d/m_s$ unless

  $\lambda^H_{11}/\lambda^H_{12,21} < \sqrt{m_d/m_s}/3 \sim 0.08$

* Then: $3m_e \approx m_d$, $|V_{us}| \approx (m_d/m_s)^{1/2}$ (at the price of a fine-tuning > O(10))

Grand Unification

* The Pati-Salam gauge group does not provide grand-unification:
  $G_{PS} = SU(2)_L \times SU(2)_R \times SU(4)_c$

* The fields at the Z_2 breaking scale do not form full SU(5) multiplets: MSSM-like gauge coupling unification is expected to be spoiled

  - One-loop prediction for α_3: $\frac{1}{\alpha_3} = \frac{1}{\alpha_2} + \frac{b_3 - b_2}{b_1 - b_2}\left(\frac{1}{\alpha_1} - \frac{1}{\alpha_2}\right)$

  - MSSM: $(b_3,b_2,b_1) = (-3,1,33/5)$
    $b_3-b_2 = -4$, $b_1-b_2 = 28/5$, $(b_3-b_2)/(b_1-b_2) = -7/5$

  - MSSM + SU(5) multiplets: $(b_3,b_2,b_1) = (-3,1,33/5) + (n,n,n)$
    $b_3-b_2 = -4$, $b_1-b_2 = 28/5$, $(b_3-b_2)/(b_1-b_2) = -7/5$

  - MSSM + Q+Q + L+L + Σ_8 + H_3: $(b_3,b_2,b_1) = (-3,1,33/5) + (6,4,6/5)$
    $b_3-b_2 = -2$, $b_1-b_2 = 14/5$, $(b_3-b_2)/(b_1-b_2) = -7/5$

"Magic field sets"

n	field content	b_1^{new}	b_2^{new}	b_3^{new}	$-(b_1^{\text{new}} - b_2^{\text{new}})/(b_1 - b_2)$	SU(5)
2	$(D^c + \bar{D}^c) + (L + \bar{L})$	1	1	1	0	yes
2	$G + (Q + \bar{Q})$	1/5	3	5	1	no
3	$(Q + \bar{Q}) + (U^c + \bar{U}^c) + (E^c + \bar{E}^c)$	3	3	3	0	yes
3	$W + G + (V + \bar{V})$	5	5	5	0	yes
3	$W + (U^c + \bar{U}^c) + (D^c + \bar{D}^c)$	2	2	2	0	no
3	$(L + \bar{L}) + (E^c + \bar{E}^c) + (V + \bar{V})$	34/5	4	2	$-1/3$	no
4	$W + 2(D^c + \bar{D}^c) + (E^c + \bar{E}^c)$	2	2	2	0	no
4	$(Q + \bar{Q}) + (D^c + \bar{D}^c) + 2(E^c + \bar{E}^c)$	3	3	3	0	no
4	$(Q + \bar{Q}) + 2(U^c + \bar{U}^c) + (L + \bar{L})$	4	4	4	0	no
4	$W + (U^c + \bar{U}^c) + (E^c + \bar{E}^c) + (V + \bar{V})$	39/5	5	3	$-1/3$	no
4	$(U^c + \bar{U}^c) + 2(L + \bar{L}) + (V + \bar{V})$	39/5	5	3	$-1/3$	no
4	$(Q + \bar{Q}) + 2(D^c + \bar{D}^c) + (V + \bar{V})$	6	6	6	0	no
4	$(Q + \bar{Q}) + (U^c + \bar{U}^c) + 2(V + \bar{V})$	59/5	9	7	$-1/3$	no
4	$(L + \bar{L}) + 3(V + \bar{V})$	78/5	10	6	$-1/2$	no

Pati-Salam → SO(10)

* L and R messengers unified
* 4D Model:
  - SO(10) breaking along T_{3R} at M_R
  - There is no real intermediate PS
  - Cumbersome but possible
* 5D model:
  - SO(10) breaking to PS through boundary conditions
  - $M_R = 1/R$, messengers in the bulk, ϕ on SO(10) brane, h on PS brane
  - Either R-messengers or L-messengers have no zero mode (bonus)

Supersymmetry

RGE effect associated to R-messengers give large off-diagonal entries in the R-handed squark and slepton 23 sector (but not in the L-handed)

- $\tau \to \mu\gamma$
- $\Delta S=1$ B-decays
- LHC

Summary

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  - the full pattern of I family masses and mixings in terms of a selection of NR operators + FT > O(10)
* Other features:
  - extended see-saw with dominance from extra singlet neutrinos
  - see-saw fields = FN fields
  - new supersymmetry breaking options?

To do list

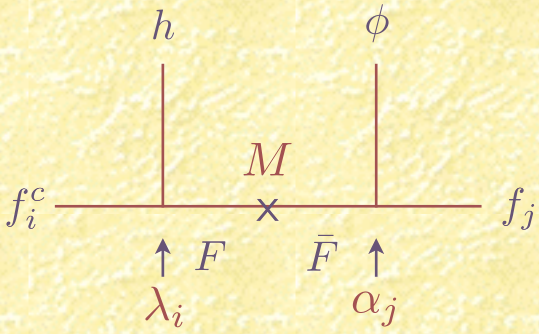
* FCNC: contribution of lighter states
* PS → SO(10) and unification
* Right-handed dominance
* R_P and a mimimal model
* The origin of the scales in the model

The basic idea

* Fermions — Scalars — $\mathbf{Z}_2$

Fermions	Scalars	$\mathbf{Z}_2$	
$\psi_i = q_i, u^c_i, d^c_i, l_i, n^c_i, e^c_i, \quad i = 1,2,3$	$h = h_u, h_d \quad \phi$	-	• + SUSY (with R_P)
$\Psi + \overline{\Psi}, \quad \Psi = Q, U^c, D^c, L, N^c, E^c$	$H = H_u, H_d$	+	• below Λ

* Unbroken $\mathbf{Z}_2$: chiral odd fields light, no Yukawas; even fields at $O(M_G)$
* $\mathbf{Z}_2$ breaking: by ϕ = heavy SM singlet (family blind)
  - Yukawas generated by "messenger" exchange



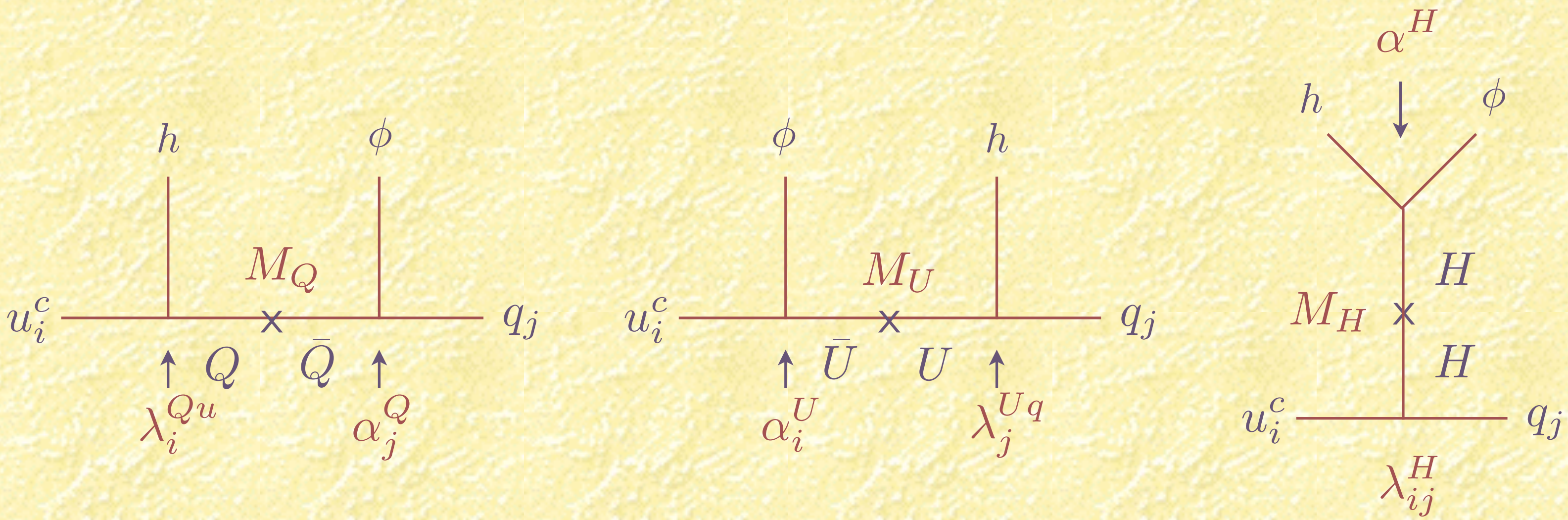
$$W = M\bar{\Psi}\Psi + \alpha_i \bar{\Psi}\psi_i\phi + \lambda_i \Psi\psi_i h$$

with α_i, $\lambda_i = \mathcal{O}(1)$ **and uncorrelated**

$$Y_{ij} \sim \lambda_i \, \alpha_j \frac{\langle\phi\rangle}{M}$$

* Hierarchy: 1 messenger ↔ Yukawa for 1 family ≡ 3[rd]
  (choose a basis in which $\alpha_{1,2}$ and $\lambda_{1,2} = 0$)
* Mixings? Lighter families?

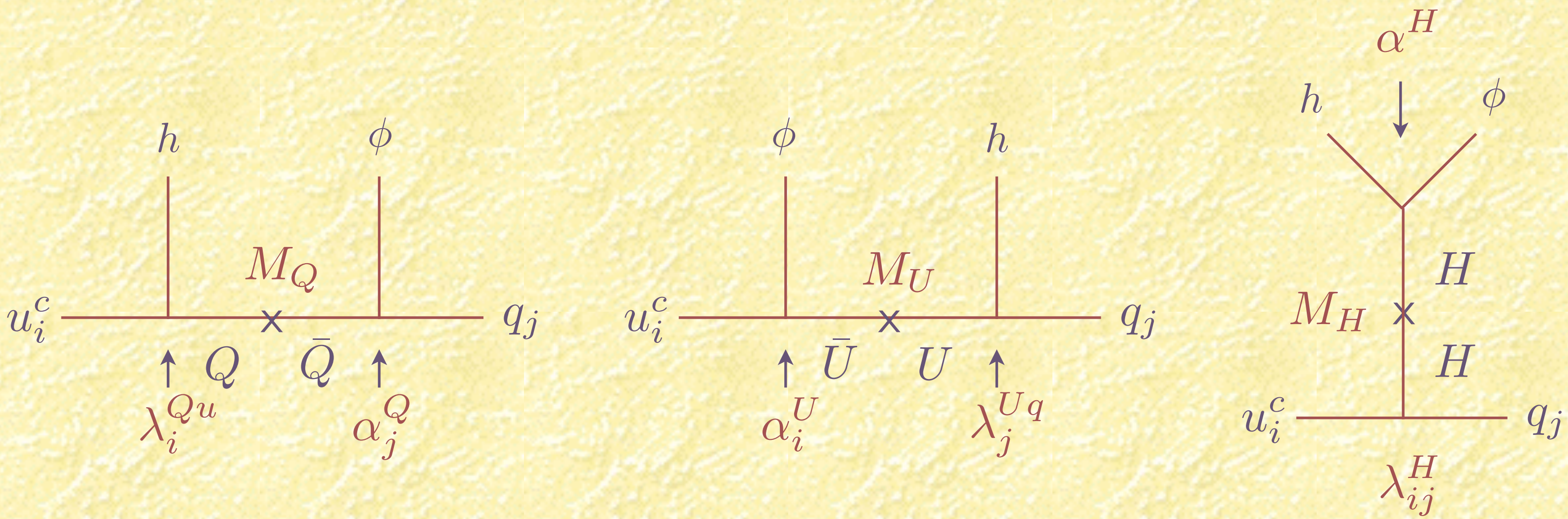
Left-handed dominance



$$W = M\bar{\Psi}\Psi + \alpha_i \bar{\Psi}\psi_i\phi + \lambda_i \Psi\psi_i h$$

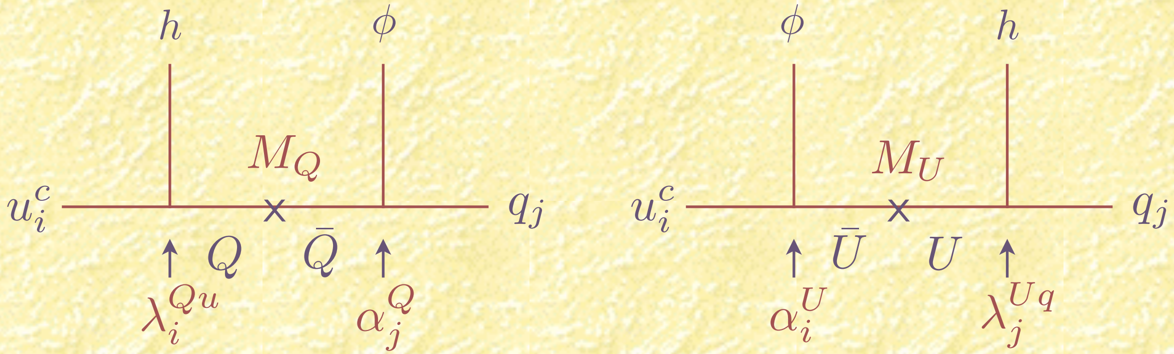
$$\begin{pmatrix} M\bar{\Psi}\Psi \equiv M_Q\bar{Q}Q + M_U\bar{U}^c U^c + M_D\bar{D}^c D^c + \dots \\ \alpha_i\bar{\Psi}\psi_i\phi \equiv \alpha_i^Q\bar{Q}q_i\phi + \alpha_i^U\bar{U}^c u_i^c\phi + \alpha_i^D\bar{D}^c d_i^c\phi + \dots \\ \lambda_i\Psi\psi_i h \equiv \lambda_i^u Q u_i^c h_u + \lambda_i^U U^c q_i h_u + \lambda_i^d Q d_i^c h_d + \lambda_i^D D^c q_i h_d + \dots \end{pmatrix}$$

Left-handed dominance



* Neglect H and 1^{st} family for now (will turn out not to contribute)

Left-handed dominance



* Neglect H and 1st family for now (will turn out not to contribute)

$$Y^U_{ij} = \lambda_i^{Qu}\alpha_j^Q \frac{\langle\phi\rangle}{M_Q} + \alpha_i^U \lambda_j^{Uq}\frac{\langle\phi\rangle}{M_U}$$

$$Y^D_{ij} = \lambda_i^{Qd}\alpha_j^Q \frac{\langle\phi\rangle}{M_Q} + \alpha_i^D \lambda_j^{Dq}\frac{\langle\phi\rangle}{M_D}.$$

$$Y^U \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon_U & \epsilon_U \\ 0 & \epsilon_U & 1 \end{pmatrix}, \quad Y^D \propto \begin{pmatrix} 0 & 0 & 0 \\ \epsilon_D & \epsilon_D & \epsilon_D \\ \epsilon_D & \epsilon_D & 1 \end{pmatrix}$$

up to O(1) coefficients

$\epsilon_U = M_Q/M_U$

$\epsilon_D = M_Q/M_D$

* $m_2 \ll m_3$: $M_Q \ll M_U$ or $M_Q \gg M_U$ and $M_Q \ll M_D$ or $M_Q \gg M_D$
* $|V_{cb}| \ll 1$: $M_Q \ll M_U, M_D$ (left-handed dominance)
* Basis choice: $\alpha^Q_{1,2} = 0$, $\lambda^{Qu}_{1,2} = 0$, $\lambda^{Qd}_{1,2} = 0$; $\alpha^U_1 = 0$, $\alpha^D_1 = 0$, $\lambda^{Uq}_1 = 0$, $(\lambda^{Dq}_1 = O(1))$

(   )

Neutrino masses « charged fermion masses: well understood in terms of the breaking of lepton number = accidental symmetry of the SM

- Lepton number (violently) broken at high scale M » <H>
- After integration of heavy dof the lagrangian is (accidentally) symmetric under lepton number at the renormalizable level
- At E « M lepton number violation only reappears at the NR level, thus suppressed by E/M

( )

* Is the origin of the flavour structure in the SM and the MSSM the same?
  - in the SM: $\lambda_1, \lambda_2 \ll 1, \lambda_3 = O(1) \rightarrow$ approximate U(2) symmetry
  - in the MSSM: approximate U(2) symmetry $\rightarrow (m^2_1 - m^2_2)/m^2 \ll 1$

[Barbieri Dvali Hall hep-ph/9512388]

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  - see-saw fields = FN fields
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Summary

* Dominance of a set of messengers ↔ lightness of first family (accidental $U(1)_1$ chiral symmetry below Λ)
* Left-handed dominance ↔ lightness of second family (accidental $U(1)_2$ chiral symmetry below M_c)
  - bonus: $|V_{cb}| \sim m_s/m_b$
* In the context of an economical PS model we obtained
  - the full pattern of II and III family masses and mixings with mild assumptions on the breaking pattern of PS
  - the full pattern of I family masses and mixings in terms of a selection of NR operators + FT > O(10)
  - an example of extended see-saw with dominance from extra singlet neutrinos
  - the determination of the scales of the model in terms of neutrino masses

with no need of horizontal dynamics