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

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* Pattern of $U(3)^5$ breaking from Yukawa sector (most SM pars)

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

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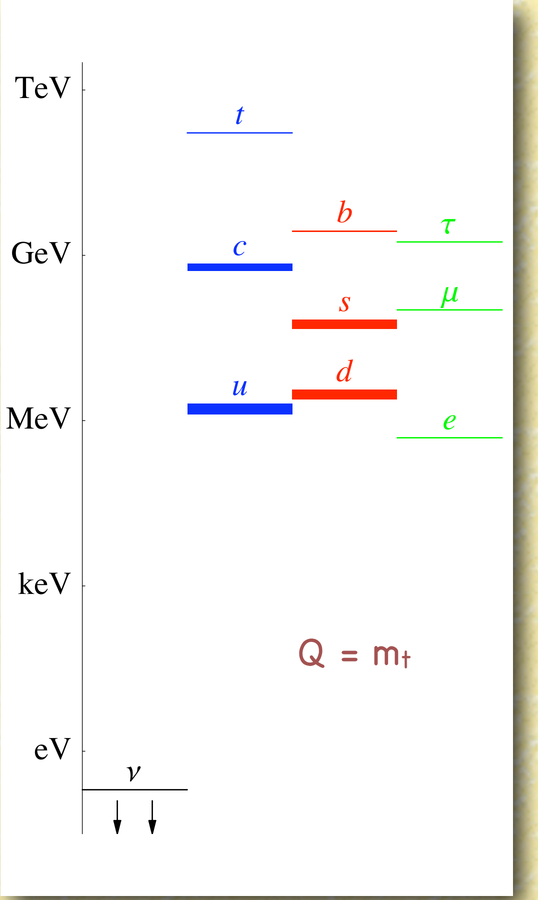
  - CKM mixing angles « 1



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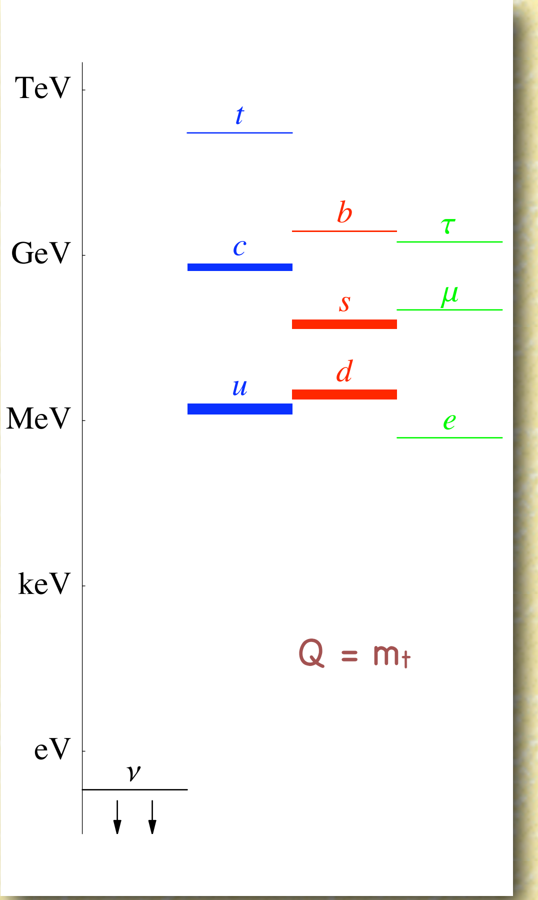

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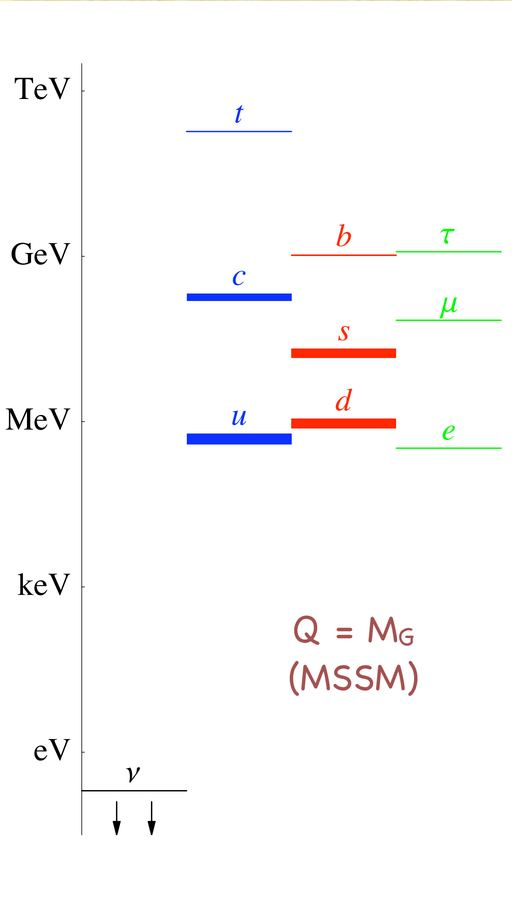

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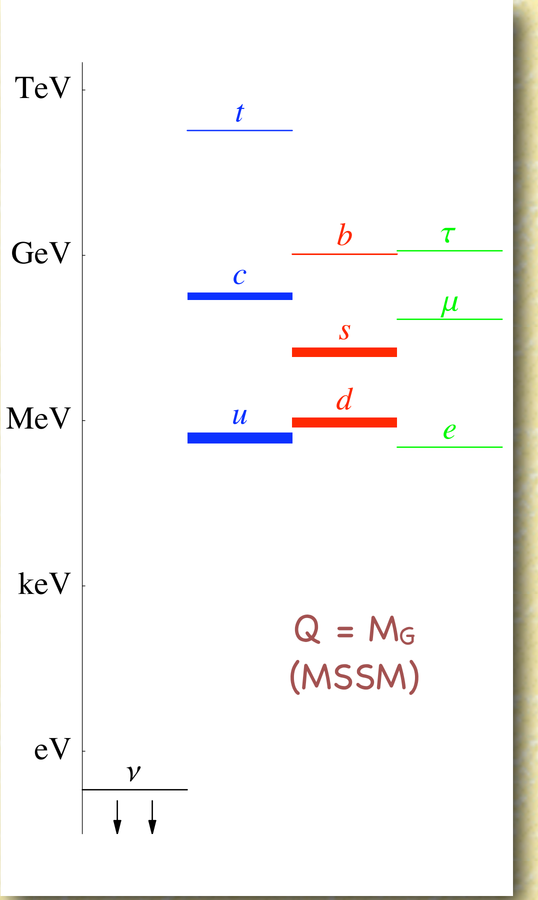

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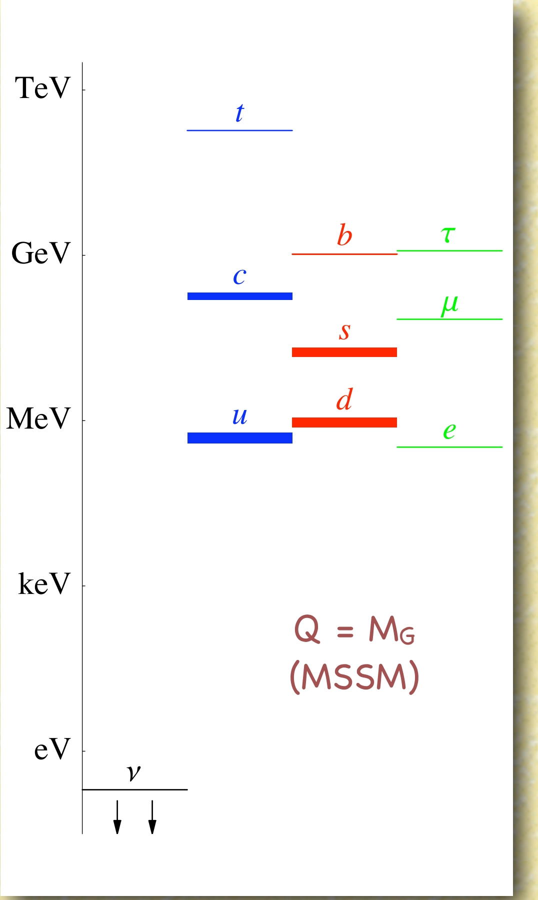
    - 2 PMNS mixing angles $O(\pi/4)$, 1 small
    - $\theta_{23} = O(\pi/4)$ & $|\Delta m^2|_{12} \ll |\Delta m^2|_{23}$, $\theta_{12} \neq \pi/4$



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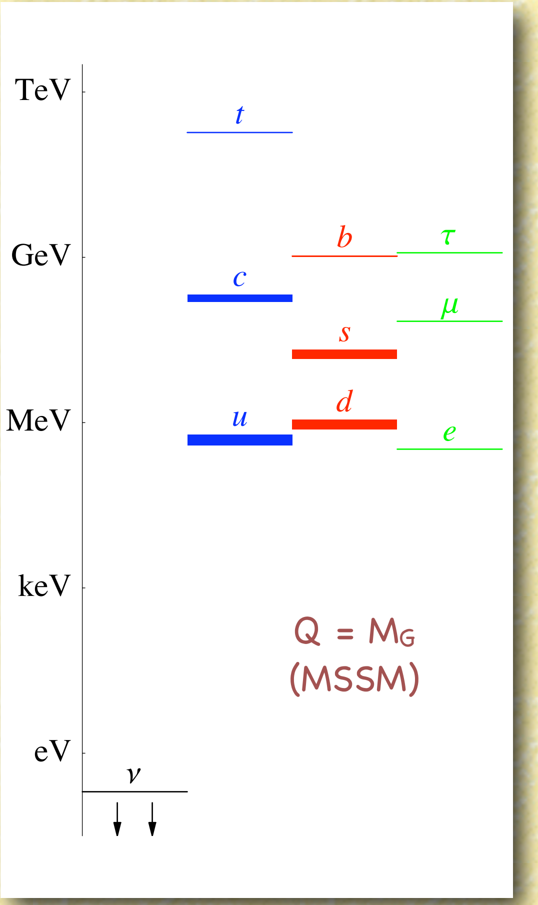

The flavour puzzle in SM extensions

* 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)
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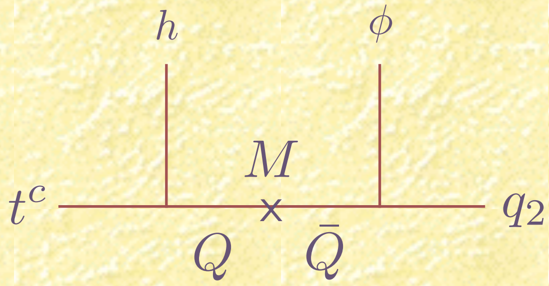

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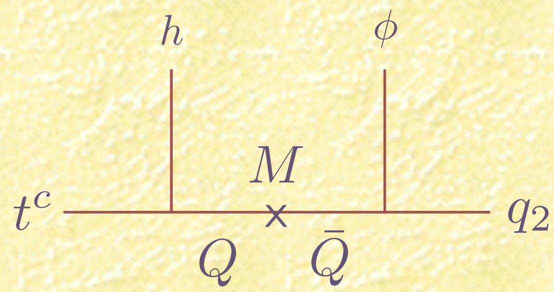

$\rightarrow \quad \frac{\phi}{M} t^c q_2\, h$

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

* Extra-dimension mechanisms
  - flavour symmetry breaking with boundary conditions
  - localized fermions

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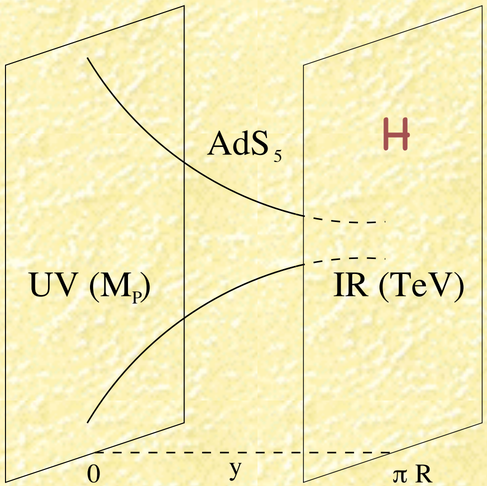
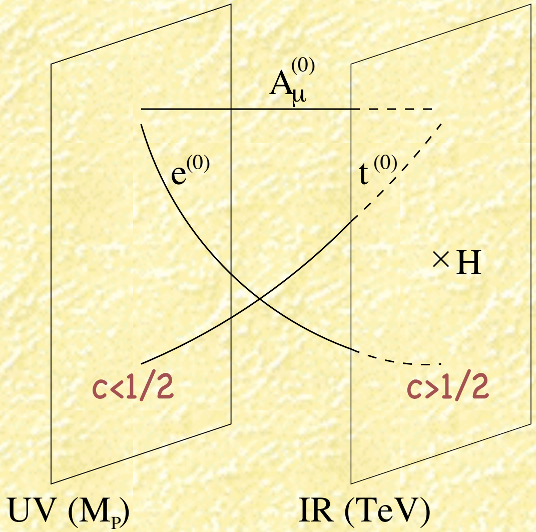
  - localized fermions
    - e.g. in RS-type models:



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

$k =$ curvature



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

$c =$ bulk mass in k 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

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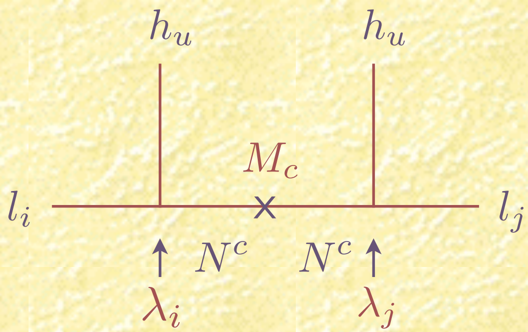
Large ϑ_{23} (from m_ν) and normal hierarchy



Exchange of a single N^c

↓

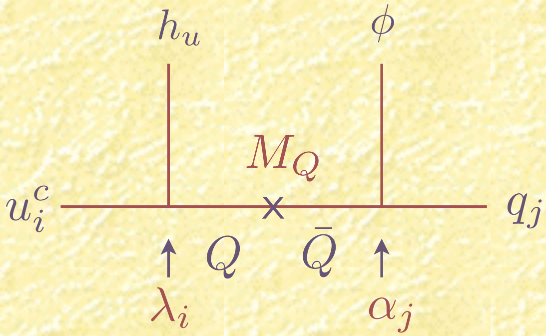
$$m^\nu_{ij} = -\lambda_i \lambda_j \frac{\langle h_u \rangle^2}{M_c}$$

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)

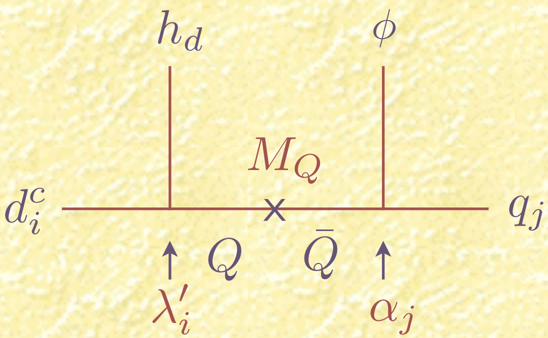
Charged fermions



Exchange of a single family of messengers
(no Yukawas at ren. level)

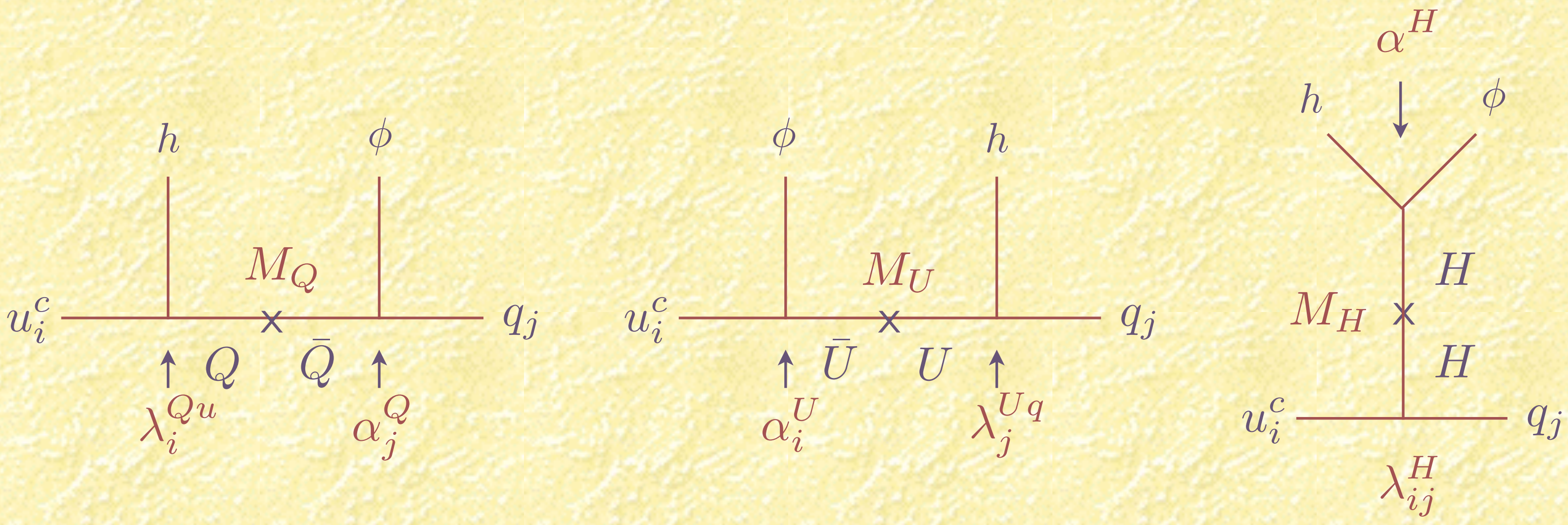
$$\lambda_{ij}^U = -\lambda_i \alpha_j \frac{\langle \phi \rangle}{M_Q}$$

- **Single messenger:** $m_t \gg m_c = 0 \to$ **hierarchy** (whatever λ_i & α_j!); $m_2 \neq 0$ from subdominant contributions
- **λ_i & α_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]

$m_2 \neq 0$


h
ϕ
M_Q
u_i^c
q_j
Q
$\bar{Q}$
λ_i^{Qu}
α_j^Q
ϕ
h
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q_j
$\bar{U}$
U
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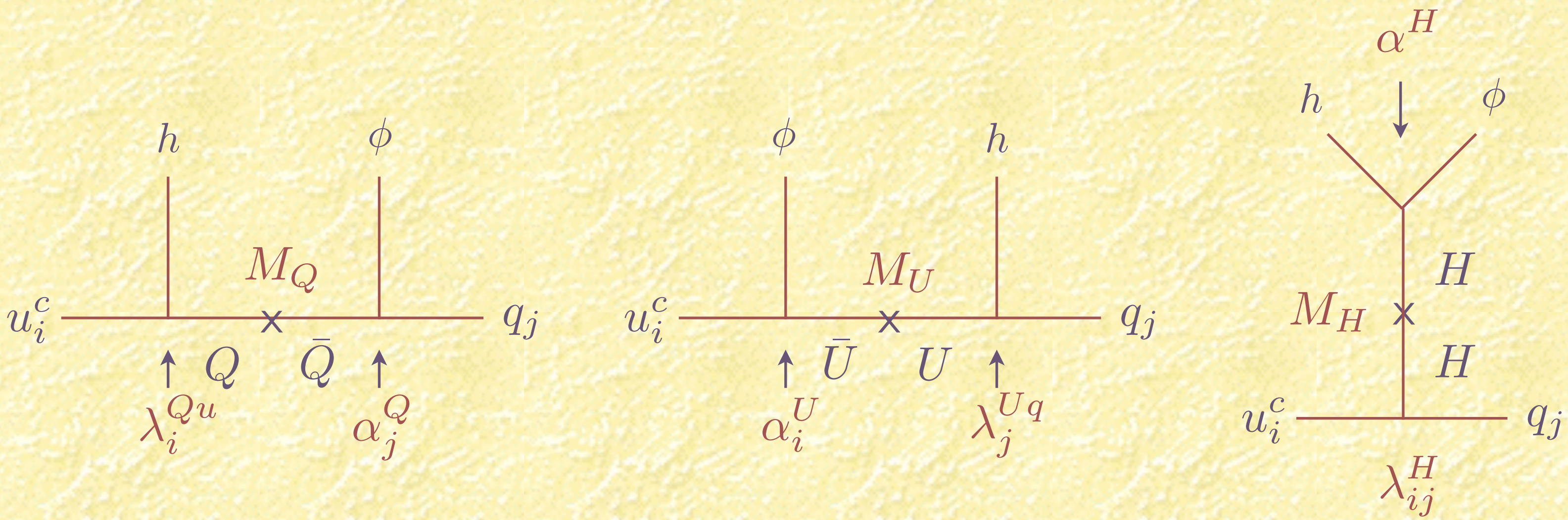

* Neglect H and 1st family for now (will turn out not to contribute)

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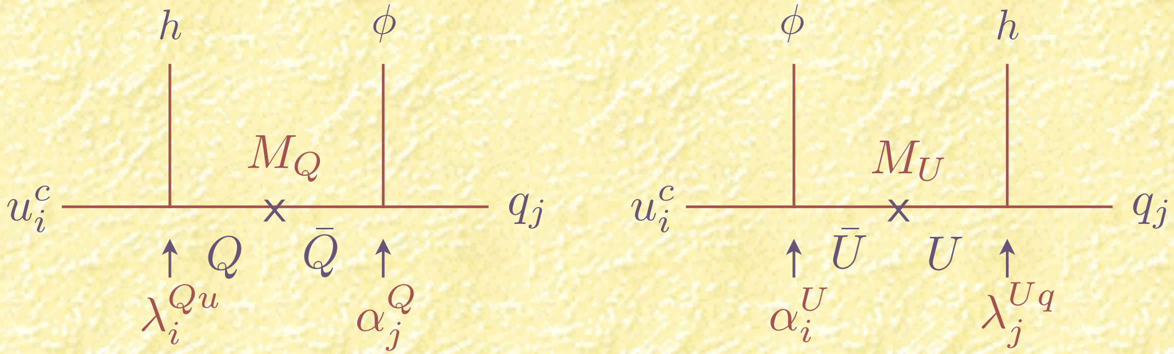

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$$Y^U_{ij} = \lambda_i^{Qu}\alpha_j^Q \frac{\langle\phi\rangle}{M_Q} + \alpha_i^U \lambda_j^{Uq}\frac{\langle\phi\rangle}{M_U}$$

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

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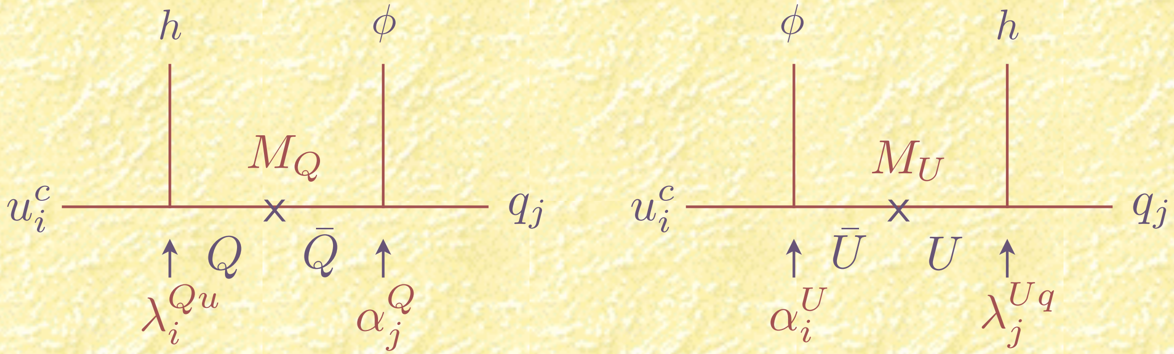

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$$Y^D_{ij} = \lambda^{Qd}_i \alpha^Q_j \frac{\langle\phi\rangle}{M_Q} + \alpha^D_i \lambda^{Dq}_j \frac{\langle\phi\rangle}{M_D}.$$

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

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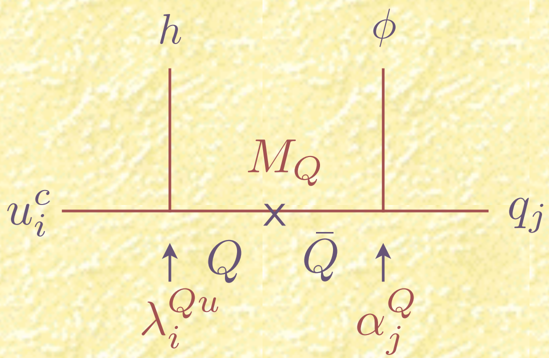
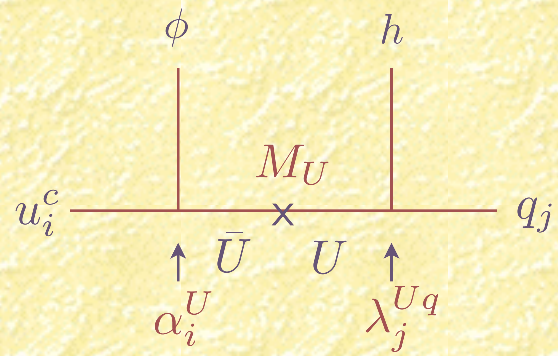




- Neglect H and 1[st] family for now (will turn out not to contribute)

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

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

- $m_2 \ll m_3$: one term must dominate
- $|V_{cb}| \ll 1$: $M_Q \ll M_U, M_D$ (left-handed dominance)

Early comments

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

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 $U(1)_1$

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

  - in the effective theory below $M_{U,D}$, the second family mass is protected by an accidental symmetry $U(1)_2$

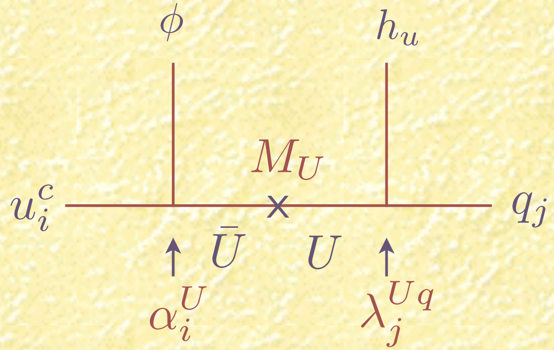
* $m_s/m_b \sim |V_{cb}|$ ✔

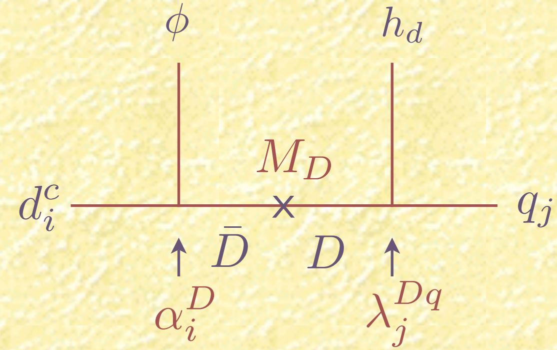
  U(1)'s and RS-type: $Y \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon_1\epsilon_2 & \epsilon_2 \\ 0 & \epsilon_1 & 1 \end{pmatrix}$ up to O(1) coefficients

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

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 $(\lambda^{Uq})_i \approx (\lambda^{Dq})_i$ → $SU(2)_R$ (or mild fine-tuning)

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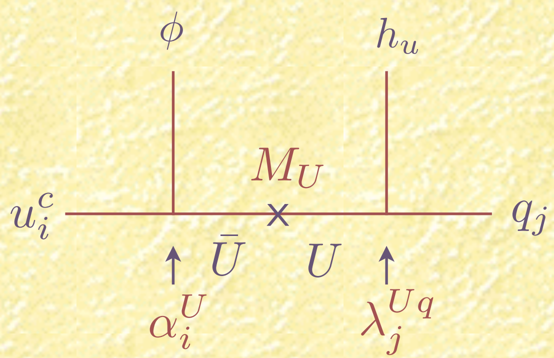
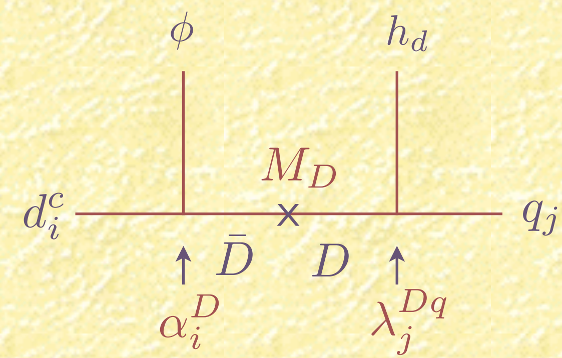




$|V_{us}| \sim 1$ unless $(\lambda^{Uq})_i \approx (\lambda^{Dq})_i \rightarrow SU(2)_R$ (or mild fine-tuning)

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

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

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

* $m_c/m_t \sim m_s/m_b$ unless $M_U \gg M_D$
* Unbroken $SU(2)_R$: $M_c\, \bar{Q}^c Q^c \Rightarrow M_U = M_D = M_c \Rightarrow m_c/m_t = m_s/m_b$
* $SU(3)_c \to SU(4)_c$: $SU(4)_c$ 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: $N^c(\lambda_3^c l_3 + \lambda_2^c l_2)h_u$ (with charged leptons (almost) diagonal)
* Takes care of ϑ_{23} + normal hierarchy if N^c dominates the seesaw:

$$\tan\theta_{23} \sim \frac{\lambda_2^c}{\lambda_3^c} \qquad |\Delta m_{12}^2| \ll |\Delta m_{23}^2|$$

* n^c_i also contribute to the seesaw: $\lambda_3 n_3^c L h_u$
* Must give mass to 2 massless linear combinations: $\eta_{ki} s_k f_i^c \bar{F}'_c$, s_k = (111++)
* Note: no new mass scale (n^c_i and N^c at the same scale, but N^c dominates)

* $m_3 = \rho_\nu \dfrac{v_{\rm EW}^2}{2 s_{23}^2 M_c}, \qquad m_{1,2} \approx 0$

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

The model

Below the cutoff Λ (will turn out to be > $10^{16\text{-}17}$ 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)
  - $\mathbf{Z}_2$ breaking (along B−L) at $v \ll M_c$ (T_{3R}, N'_c)

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

$v \equiv \langle \phi \rangle$

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

* The most general ren. superpotential

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

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

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

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

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

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

$s = \sin\theta$

* 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

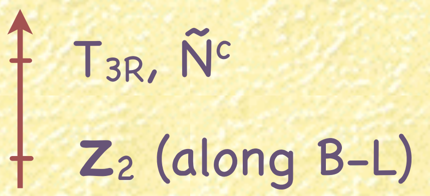
- $v/M_c = \epsilon$
- $M/V_c \sim \epsilon$

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

* 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



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

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

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

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))

Supersymmetry breaking

* The sfermion mass spectrum depends on whether $E < M_c$ or $E > M_c$
* In the absence of flavour symmetries, a GMSB-like mechanism is the natural option
* If $E \geq M_c$: large RGE-induced FCNCs in the "23" sector of right-handed fermions

* Flavour messengers = SUSY-breaking messengers?
* Z_2-breaking = SUSY-breaking (through G_{PS} adjoint or fundamental)?
* Peculiar sfermion spectrum?

Summary

* Neutrinos might suggest that the peculiar hierarchical pattern of charged fermion masses and mixings (up to O(1) factors) does not require special horizontal structure
* 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 content of the effective theory below a cutoff
  - 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?