Prospects of New Physics from a GUT-inspired 3HDM

J. P. Pino[1], António P. Morais[1,2], Roman Pasechnik[2], Werner Porod[3]

CFTC-UL, UA and LIP meeting – Experiment vs. Theory
(arXiv 2001.04804, arXiv 2001.06383)

[1]Departamento de Física, Universidade de Aveiro [2]Department of Astronomy and Theoretical Physics, Lund University
[3]Institut für Physik und Astrophysik, Uni Würzburg.

Presentation outline

1. Motivation and necessity

2. SHUT model from unifications principles

3. Implications in the quark sector

    - Quarks and VLQs
    - Numerical Analysis on the quark sector
    - Radiative effects for the quark sector

4. Conclusions and Future Work

The need for something more …

While the SM provides a remarkable framework for the description of subatomic phenomena, it still lacks in certain areas,

- Inability to explain the observed particle spectra (Number of generations, masses and couplings hierarchies, etc.),
- Matter/anti-matter asymmetry in the Universe,
- Neutrino mass.

In this work, we take a look at some of these fundamental questions, by tying everything together into a common framework in flavour and Grand Unification physics. We then explore some of the new physics at phenomenologically relevant energy scales.

The GUT theory

To arrive at the SM, one must find a single group (unifying force/symmetry) whose reduction steps leads to SM gauge group.

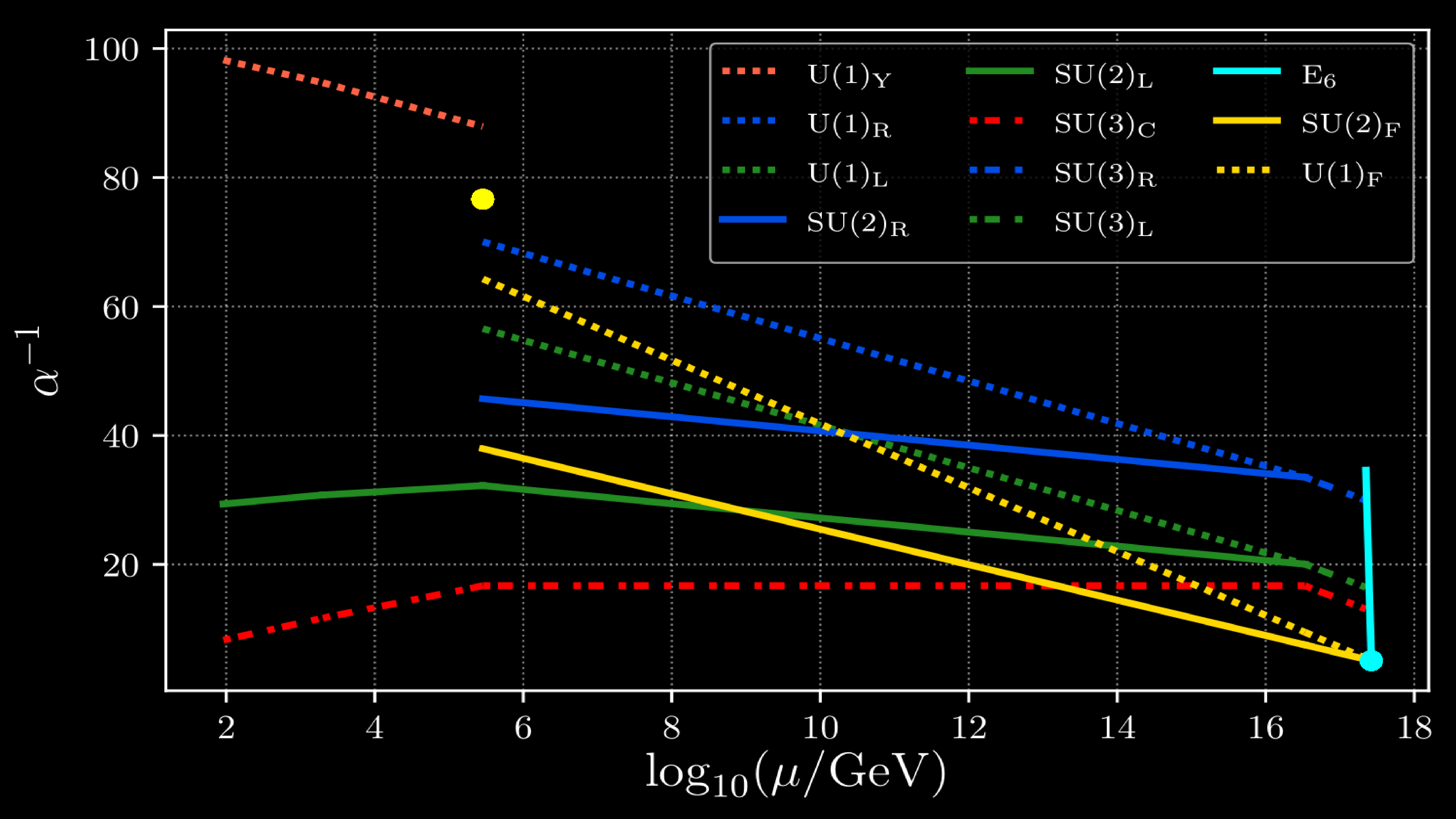
A promising candidate for this role is the E_8 symmetry,

$$E_8 \to E_6 \times SU(3)_F$$

arXiv 1806.03492
arXiv 1811.05199

In fact, via a series of symmetry breaking processes, (see: arXiv 2001.06383)

$$\begin{array}{c}
E_8 \\
\downarrow M_8 \\
E_6 \times SU(3)_F \\
\downarrow M_{3F} \\
E_6 \times SU(2)_F \times U(1)_F \\
\downarrow M_6 \\
[SU(3)]^3 \times SU(2)_F \times U(1)_F \\
\downarrow M_3 \\
SU(3)_C \times \prod_{A=L,R,F} SU(2)_A \times \prod_{A=L,R,F} U(1)_A \\
\downarrow p, f, \omega, s_i \\
SU(3)_C \times SU(2)_L \times U(1)_Y \\
\downarrow u_i, d_i \\
\boxed{SU(3)_C \times U(1)_{EM}}
\end{array}$$



U(1)$_\mathrm{Y}$
U(1)$_\mathrm{R}$
U(1)$_\mathrm{L}$
SU(2)$_\mathrm{R}$
SU(2)$_\mathrm{L}$
SU(3)$_\mathrm{C}$
SU(3)$_\mathrm{R}$
SU(3)$_\mathrm{L}$
E$_6$
SU(2)$_\mathrm{F}$
U(1)$_\mathrm{F}$
α^{-1}
100
80
60
40
20
2
4
6
8
10
12
14
16
18
$\log_{10}(\mu/\mathrm{GeV})$

Sparing everyone of the overly complicated mathematical details, I would like just to focus in a particular section of model at high energies.

At trinification symmetry level, we cast the superpotential as

$$W_3 = \varepsilon_{ij}\left(\mathcal{Y}_1 \boldsymbol{L}^i \boldsymbol{Q}_L^3 \boldsymbol{Q}_R^j - \mathcal{Y}_2 \boldsymbol{L}^i \boldsymbol{Q}_L^j \boldsymbol{Q}_R^3 + \mathcal{Y}_2 \boldsymbol{L}^3 \boldsymbol{Q}_L^i \boldsymbol{Q}_R^j\right)$$

$$\left(\boldsymbol{Q}_L^{i,3}\right)^x_l = \left(\boldsymbol{u}_L^x \;\; \boldsymbol{d}_L^x \;\; \boldsymbol{D}_L^x\right)^{i,3}$$

$$\left(\boldsymbol{Q}_R^{i,3}\right)^r_x = \left(\boldsymbol{u}_{Rx} \;\; \boldsymbol{d}_{Rx} \;\; \boldsymbol{D}_{Rx}\right)^{\mathrm{T}i,3}$$

$$\left\langle \tilde{L}^1 \right\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix} u_1 & 0 & 0 \\ 0 & d_1 & 0 \\ 0 & \omega & s_1 \end{bmatrix} \quad \left\langle \tilde{L}^2 \right\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix} u_2 & 0 & 0 \\ 0 & d_2 & 0 \\ 0 & s_2 & f \end{bmatrix}$$

$$\left\langle \tilde{L}^3 \right\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix} u_3 & 0 & 0 \\ 0 & d_3 & 0 \\ 0 & s_3 & p \end{bmatrix}$$

No lepton, and no first generation quark masses at tree level.

$$\Downarrow$$

All generated via loop corrections !

Post-EWSB and adopting a generic VEV setting, we can reproduce tree level masses for second and third generation quarks. **An explanation for quark mass hiearchies**

$$M_u = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & u_3\mathcal{Y}_2 & u_2\mathcal{Y}_2 \\ -u_3\mathcal{Y}_2 & 0 & -u_1\mathcal{Y}_2 \\ -u_2\mathcal{Y}_1 & u_1\mathcal{Y}_1 & 0 \end{bmatrix} \quad \Rightarrow \quad \begin{aligned} m_u^2 &= 0 \\ m_c^2 &= \frac{1}{2}\mathcal{Y}_2^2\left(u_1^2 + u_2^2 + u_3^2\right) \\ m_t^2 &= \frac{1}{2}[\mathcal{Y}_1^2\left(u_1^2 + u_2^2\right) + \mathcal{Y}_2^2 u_3^2] \end{aligned}$$

Standard model hiearchy is achieved for $\mathcal{Y}_1 \gg \mathcal{Y}_2$. The up quark remains massless at tree level, so its mass generated via radiative corrections.

For the down-quark sector, we have mixing between the would-be SM quarks, and the vector-like counterparts.

The generic mass matrix for the down quarks, post-EWSB,

$$M_d = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & d_3\mathcal{Y}_2 & d_2\mathcal{Y}_2 & 0 & 0 & 0 \\ -d_3\mathcal{Y}_2 & 0 & -d_1\mathcal{Y}_2 & 0 & 0 & 0 \\ -d_2\mathcal{Y}_1 & d_1\mathcal{Y}_2 & 0 & 0 & 0 & 0 \\ 0 & s_3\mathcal{Y}_2 & s_2\mathcal{Y}_2 & 0 & p\mathcal{Y}_2 & f\mathcal{Y}_2 \\ -s_3\mathcal{Y}_2 & 0 & -\omega\mathcal{Y}_2 & -p\mathcal{Y}_2 & 0 & -s_1\mathcal{Y}_2 \\ -s_2\mathcal{Y}_1 & \omega\mathcal{Y}_1 & 0 & -f\mathcal{Y}_1 & s_1\mathcal{Y}_1 & 0 \end{bmatrix}$$

VLQs adquire leading mass terms before EWSB (before VEV's s_i and d_i). So by setting them to zero we obtain the mass spectrum,

$$m_{S/D}^2 = \frac{1}{2}(f^2 + p^2)\mathcal{Y}_2^2$$

$$m_{S/D}^2 = \frac{\omega^2(f^2 + p^2 + \omega^2)}{2(f^2 + \omega^2)}\mathcal{Y}_2^2$$

$$m_B^2 = \frac{1}{2}(f^2 + \omega^2)\mathcal{Y}_1^2 + \frac{f^2 p^2}{2(f^2 + \omega^2)}\mathcal{Y}_2^2$$

f, p and ω are high scale VEV's, O(100 – 1000 TeV).

We define the D-quark as the lightest state, such as $m_S > m_D$.

For the SM down quarks, we obtain

$$m_d^2 = 0$$

$$m_s^2 = \frac{(d_3 f - d_2 p)^2}{2(f^2 + p^2 + \omega^2)} \mathcal{Y}_2^2$$

$$m_b^2 = \frac{1}{2}\left(d_2^2 \mathcal{Y}_1^2 + d_3^2 \mathcal{Y}_2^2\right)$$

Just like before, the lightest SM quark here is also massless at tree-level, so the origin of the mass is purely radiative.

Realistic VEV hierarchy requires

$$p, f, \omega \gg d_2, d_3$$

In fact, considering $\mathcal{Y}_1 \gg \mathcal{Y}_2$ and taking $u_3 = d_3 = 0$

$$\Downarrow$$

$$\frac{\mathcal{Y}_1}{\mathcal{Y}_2} = \frac{m_t}{m_c} \approx \frac{m_b}{m_s} \sim \mathcal{O}(100)$$

Their hiearchy is then controlled by two Yukawas from the initial SUSY framework.

Considering now the quark mixing. Neglecting at first the the effects of VLQs, the CKM matrix reads

$$V_{\text{CKM}} = \begin{bmatrix} \frac{d_2 u_2 \mathcal{Y}_1^2 + d_3 u_3 \mathcal{Y}_2^2}{\sqrt{\mathcal{A}\mathcal{B}}} & -\frac{u_1 \mathcal{Y}_1}{\sqrt{\mathcal{A}}} & \frac{(d_2 u_3 - d_3 u_2)\mathcal{Y}_1 \mathcal{Y}_2}{\sqrt{\mathcal{A}\mathcal{B}}} \\ -\frac{d_2 u_1 \mathcal{Y}_1}{\sqrt{\mathcal{B}\mathcal{C}}} & -\frac{u_2}{\sqrt{\mathcal{C}}} & \frac{d_3 u_1 \mathcal{Y}_2}{\sqrt{\mathcal{B}\mathcal{C}}} \\ \frac{(\mathcal{C} d_3 - d_2 u_2 u_3)\mathcal{Y}_1 \mathcal{Y}_2}{\sqrt{\mathcal{A}\mathcal{B}\mathcal{C}}} & \frac{u_1 u_3 \mathcal{Y}_2}{\sqrt{\mathcal{A}\mathcal{C}}} & \frac{\mathcal{C} d_2 \mathcal{Y}_1^2 + d_3 u_2 u_3 \mathcal{Y}_2^2}{\sqrt{\mathcal{A}\mathcal{B}\mathcal{C}}} \end{bmatrix}$$

Notice there is no dependence on f, p and ω VEV's, only the ones resulting from EWSB.

$$\mathcal{A} = \mathcal{C}\mathcal{Y}_1^2 + u_3^2 \mathcal{Y}_2^2$$

$$\mathcal{B} = d_2^2 \mathcal{Y}_1^2 + d_3^2 \mathcal{Y}_2^2$$

$$\mathcal{C} = u_1^2 + u_2^2$$

In the limit $\mathcal{Y}_1 \gg \mathcal{Y}_2$,

$$V_{tb} \approx 1 - \left(\frac{\mathcal{Y}_2}{\mathcal{Y}_1}\right)^2 \frac{d_3^2 \mathcal{C} + d_2 u_3 (d_2 u_3 - 2 d_3 u_2)}{2 d_2^2 \mathcal{C}}$$

The Yukawas ratio is also responsible for the supression of the V_{tb}, V_{ts}, V_{bu} and V_{bc} matrix elements.

In fact, taking the limit $u_3 \to 0$ and $d_3 \to 0$ the mixing matrix takes a simple Cabibbo form

$$V_{\mathrm{CKM}} = \begin{bmatrix} \cos\theta_C & \sin\theta_C & 0 \\ -\sin\theta_C & \cos\theta_C & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \theta_C = \arctan\left(\frac{u_1}{u_2}\right)$$

Thus, while the small ratio $\mathcal{Y}_2/\mathcal{Y}_1 \ll 1$ is responsible for the strong suppression on mixing between the third generation and the other two, one adquires additional suppression corresponding to a very small third generation Higgs VEV's.

Notice that one can not impose a limit vanishing $u_{1,2}$ and d_2 since that would ruin a realistic quark mixing.

Now we will be looking at some pratical numerical examples. For realistic parameter space points,

$$\mathcal{Y}_1 = 0.98, \quad \mathcal{Y}_2 = 0.0068, \quad u_1 = 59.65 \text{ GeV}, \quad u_2 = 238.6 \text{ GeV}, \quad d_2 = 6 \text{ GeV}.$$

With VEV's chosen such as $u_1^2 + u_2^2 + d_2^2 = (246 \text{ GeV})^2$.
This then yields,

$$m_t = 170.4 \text{ GeV}, \quad m_c = 1.18 \text{ GeV}, \quad m_b = 4.15 \text{ GeV}, \quad m_s = 0.017 \text{ GeV}$$

$$V_{\text{CKM}} = \begin{bmatrix} 0.97 & 0.24 & 0 \\ 0.24 & 0.97 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Scenarios	ω [TeV]	f [TeV]	p [TeV]	m_{D} [TeV]	m_{S} [TeV]	m_{B} [TeV]
$\omega \sim f \sim p$	100 - 1000	100 - 1000	100 - 1000	1 - 10	1 - 10	100 - 1000
$\omega \sim f \ll p$	10 - 100	10 - 100	100 - 1000	1 - 10	1 - 10	10 - 100
$\omega \ll f \sim p$	100	1000	1000	1	10	1000

More interesting scenarios involve the vector-like quarks $V_{\mathrm{CKM}} = \left[V_{\mathrm{CKM}}^{\mathrm{SM}} \mid V_{\mathrm{CKM}}^{\mathrm{VLQs}} \right]$

Scenario $\omega \sim f \sim p$:

$$m_s = 0.017 \text{ GeV}, \quad m_b = 4.15 \text{ GeV}, \quad m_D = 1.3 \text{ TeV}, \quad m_S = 1.5 \text{ TeV}, \quad m_B = 211.0 \text{ TeV}$$

$$V_{\mathrm{CKM}} = \left[\begin{array}{ccc|ccc} 0.97 & 0.24 & 2.31\times10^{-5} & 4.36\times10^{-6} & 7.29\times10^{-7} & \sim 0 \\ 0.24 & 0.97 & 9.23\times10^{-5} & 1.74\times10^{-5} & 2.92\times10^{-6} & \sim 0 \\ 0 & 9.51\times10^{-5} & 1 & 5.55\times10^{-5} & 1.15\times10^{-5} & 6.47\times10^{-7} \end{array}\right]$$

Scenario $\omega \sim f \ll p$:

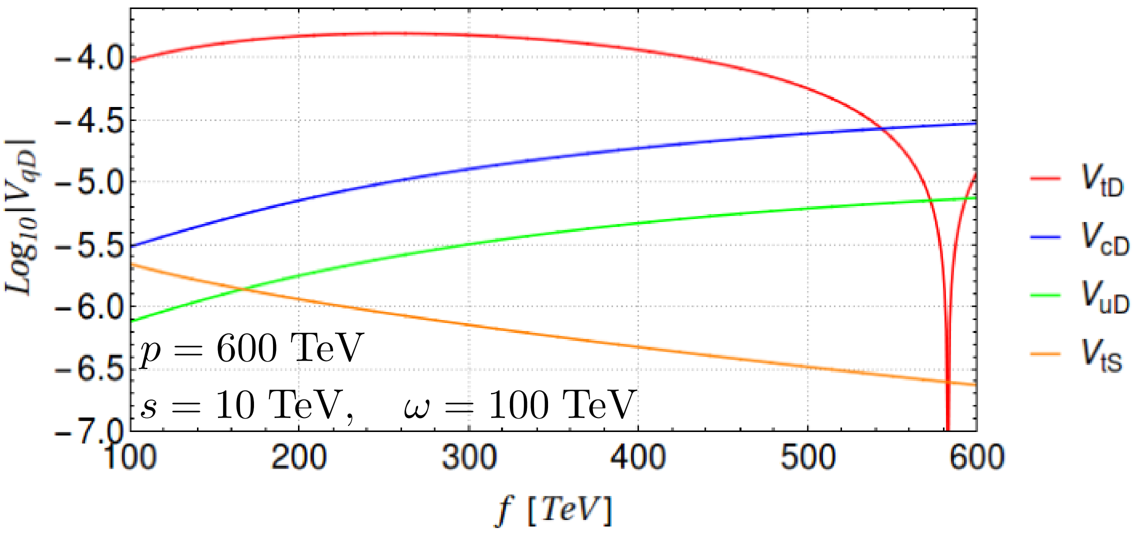
$$m_s = 0.028\ \text{GeV}, \quad m_b = 4.14\ \text{GeV}, \quad m_{\mathrm{D}} = 1.99\ \text{TeV}, \quad m_{\mathrm{S}} = 2.94\ \text{TeV}, \quad m_{\mathrm{B}} = 103.4\ \text{TeV}$$

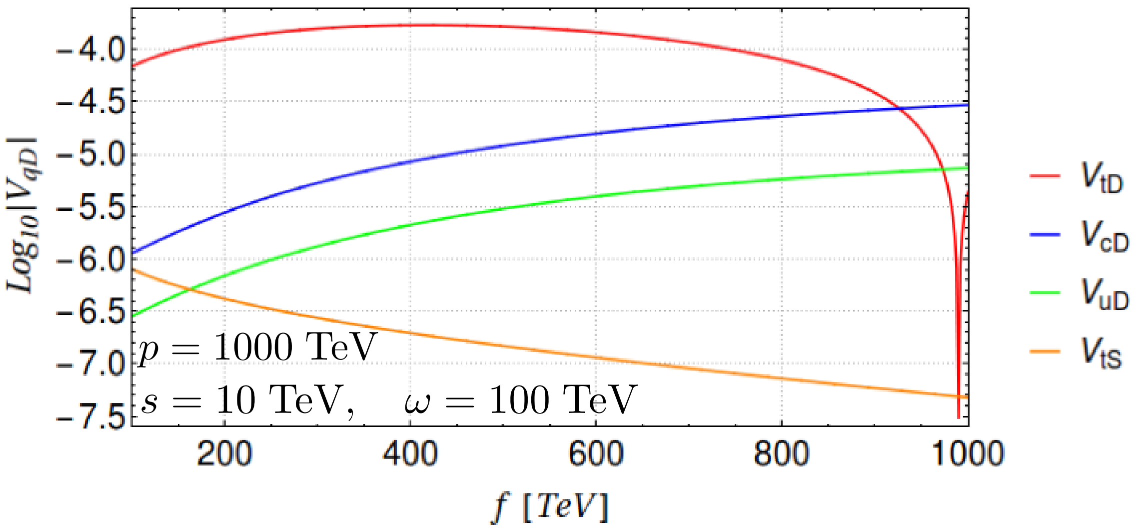
$$V_{\mathrm{CKM}} = \left[\begin{array}{ccc|ccc} 0.97 & 0.24 & 1.92 \times 10^{-5} & 8.33 \times 10^{-7} & 8.34 \times 10^{-8} & \sim 0 \\ 0.24 & 0.97 & 7.65 \times 10^{-5} & 3.33 \times 10^{-6} & 3.34 \times 10^{-7} & \sim 0 \\ 0 & 7.91 \times 10^{-5} & 1 & 1.0 \times 10^{-4} & 2.03 \times 10^{-6} & 2.69 \times 10^{-6} \end{array}\right]$$

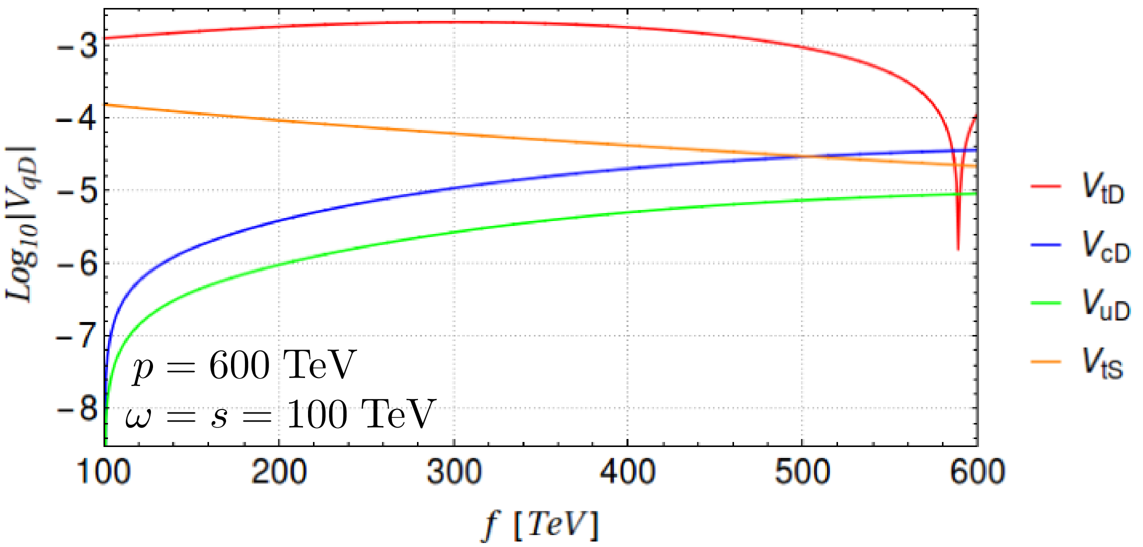
Scenario $\omega \ll f \sim p$:

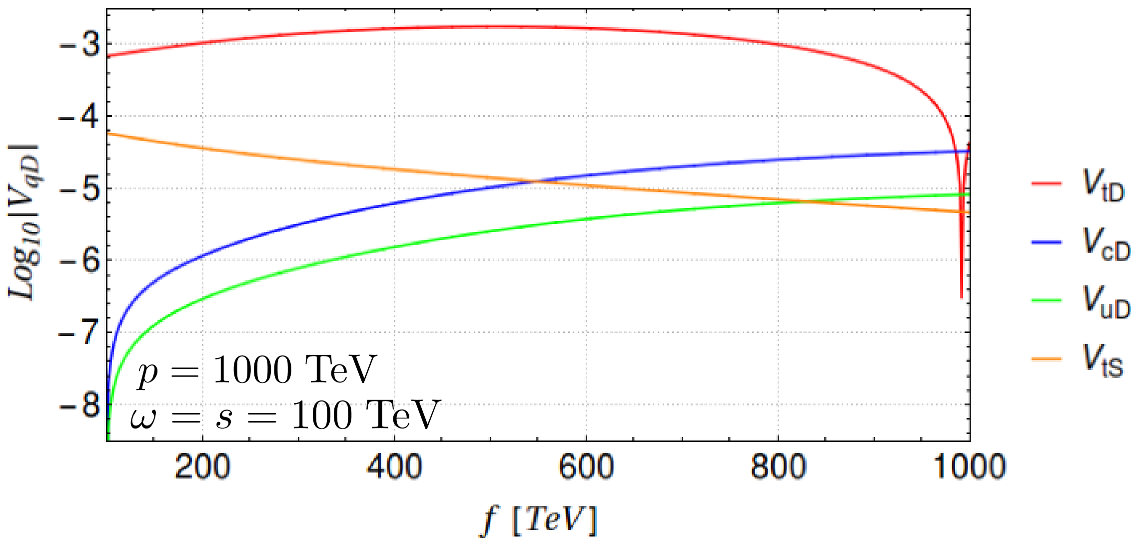
$$m_s = 0.020\ \text{GeV}, \quad m_b = 4.15\ \text{GeV}, \quad m_{\mathrm{D}} = 1.2\ \text{TeV}, \quad m_{\mathrm{S}} = 4.05\ \text{TeV}, \quad m_{\mathrm{B}} = 427.6\ \text{TeV}$$

$$V_{\mathrm{CKM}} = \left[\begin{array}{ccc|ccc} 0.97 & 0.24 & 3.34 \times 10^{-6} & 4.16 \times 10^{-6} & 2.91 \times 10^{-8} & \sim 0 \\ 0.24 & 0.97 & 1.34 \times 10^{-5} & 1.66 \times 10^{-5} & 1.16 \times 10^{-7} & \sim 0 \\ 0 & 1.38 \times 10^{-5} & 1 & 9.54 \times 10^{-6} & 2.70 \times 10^{-7} & 1.58 \times 10^{-7} \end{array}\right]$$

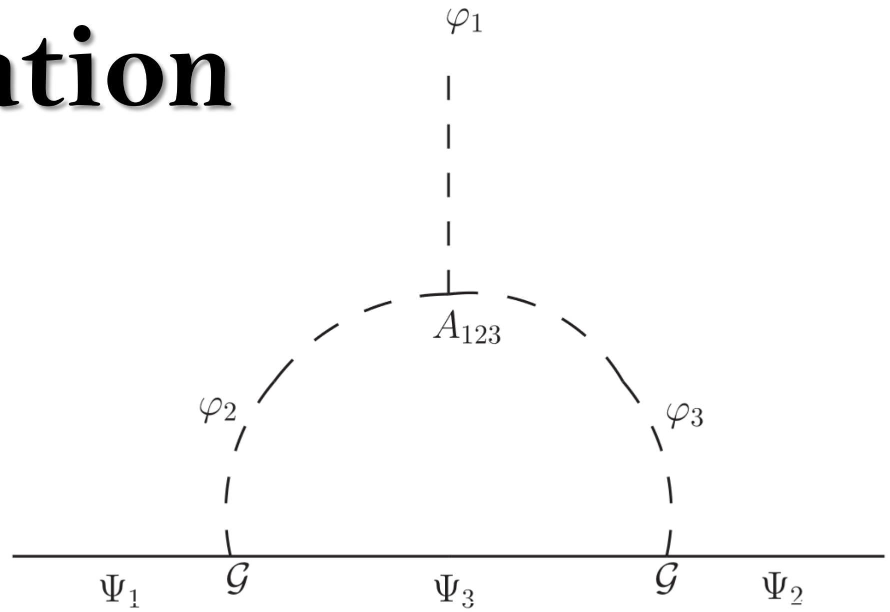

$Log_{10}|V_{qD}|$
f [TeV]
V_{tD}
V_{cD}
V_{uD}
V_{tS}
$p = 600$ TeV
$s = 10$ TeV, $\omega = 100$ TeV


$Log_{10}|V_{qD}|$
f [TeV]
V_{tD}
V_{cD}
V_{uD}
V_{tS}
$p = 1000$ TeV
$s = 10$ TeV, $\omega = 100$ TeV


$Log_{10}|V_{qD}|$
f [TeV]
V_{tD}
V_{cD}
V_{uD}
V_{tS}
$p = 600$ TeV
$\omega = s = 100$ TeV


$Log_{10}|V_{qD}|$
f [TeV]
V_{tD}
V_{cD}
V_{uD}
V_{tS}
$p = 1000$ TeV
$\omega = s = 100$ TeV

Fermion radiative mass generation



At zero momentum limit :

$$\kappa = 2i\mathcal{G}C_A A_{123} m_{\Psi_3} f(m^2_{\Psi_3}, m^2_{\varphi_2}, m^2_{\varphi_3})$$

Independent of hiearchy, the amplitude scales as $\kappa \sim \dfrac{A_{123} m_{\Psi_3}}{\max\left(m^2_{\Psi_3}, m^2_{\varphi_2}\right)}$

Scenarios where $m_{\varphi_2} > m_{\Psi_3}$ we can get and additional suppression of the corresponding Yukawa coupling, besides the loop suppression. Estimations leads $A_{123} \sim \mathcal{O}(0.01 - 100 \text{ TeV})$

$$\frac{m_{\Psi_3}}{m^2_{\varphi_2}} \sim \mathcal{O}\left(10^{-4} \text{ TeV}^{-1}\right) \Rightarrow \kappa \sim \mathcal{O}(10^{-8})$$

$$\frac{m_{\Psi_3}}{m^2_{\varphi_2}} \sim \mathcal{O}\left(\text{ TeV}^{-1}\right) \Rightarrow \kappa \sim \mathcal{O}(1)$$

This offers the possibility for large hiearchies in fermionic sector, without significant fine tuning.

Conclusions and what's left to do …

- A GUT model is presented from first principles. Provides a possible explanation to various arbitrary features in the SM, like the fermions mass spectra and mixings.
- Phenomenological studies of the VQLs (analysis of possible decay channels) through extensive use of software (e.g. MadGraph, SARAH, Pythia, etc) and possible application of deep learning.
- Same type of analysis for VLLs.
- Model contains a rich neutrino sector (15 neutrinos) and two new scalars at relevant energy scales.

Thank for your attention

J. P. Pino[1], António P. Morais[1,2], Roman Pasechnik[2], Werner Porod[3]

CFTC-UL, UA and LIP meeting – Experiment vs. Theory
(arXiv 2001.04804, arXiv 2001.06383)

[1]Departamento de Física, Universidade de Aveiro [2]Department of Astronomy and Theoretical Physics, Lund University
[3]Institut für Physik und Astrophysik, Uni Würzburg.