Quark masses and mixings in a minimally parameterised ultraviolet completion of the Standard Model

Quark masses and CKM determined by RG FPs?

Reinhard Alkofer

Institute of Physics, University Graz

Gießen, January 22, 2020

RA, Astrid Eichhorn, Aaron Held, Carlos M. Nieto,
Roberto Percacci, Markus Schröfl,

Quark masses and mixings in a minimal, parameterized ultraviolet completion of the Standard Models,

arXiv:20nn.nnnnn, to be submitted to Annals of Physics

Outline

A few facts about the Standard Model

The Standard Model of particle physics (SM) comprises:

- **22.5** [24] Dirac **fermions**, **4 scalars**, **12** gauge bosons = **vectors**
  SM dominated by fermions: no SUSY, Pauli sum rules violated, etc.
- U(1), SU(2) & SU(3) gauge, Higgs &Yukawa **interactions**
  SU(2) and SU(3) gauge interactions asymptotically free
- . . . many (>20) parameters . . .
  Determined to a high precision by many experiments!
  Only an “aesthetic” problem?
- Huge differences between masses & complicated mixing patterns!
  Flavour puzzle!!!
- Triviality problem (Landau’s zero charge), resp., Landau poles
  SM is an Effective Field Theory!!!

A modern perception of QFTs: The EFT paradigm?

At each energy scale:

- Model (i.e., a QFT) for observed d.o.f. & symmetries;
- in principle infinitely many parameters
  but only “a few” relevant for observables.
- Threshold at some higher mass scale:
  update the model!
- No need for a well-defined UV limit!
- Conversely: Fundamental theory is “shielded” from observation.

Introduction: Standard Model is incomplete

A paradigm change? Or,

why is the Higgs m_H=125 GeV so special?

If it were

- larger ⇒ low-scale Landau pole!
- smaller ⇒ vacuum instability![1]

m_H=125 GeV: SM is theoretically viable at much higher scales.

Nevertheless: Transplanckian Landau poles,
new physics at high scales has to exist.

[1] *cf.*, Higgs mass prediction of Shaposnikov & Wetterich.

UV completion

For the presented investigation we assume:

A modification of the β-function of the Abelian gauge coupling

$$\beta_Y = \beta_Y^{SM} - f_g g_Y, \quad f_g = \begin{cases} 0, & k < M_{\mathrm{NP}} \\ \mathrm{const}, & k \geq M_{\mathrm{NP}}, \end{cases}$$

and analogously for all Yukawa couplings,

$$\beta_{y_i} = \beta_{y_i}^{SM} - f_y y_i, \quad i \in \{d, u, s, c, b, t\}, \quad f_y = \begin{cases} 0, & k < M_{\mathrm{NP}} \\ \mathrm{const}, & k \geq M_{\mathrm{NP}}, \end{cases}$$

with M_{NP} at or close to the Planck scale $\propto 1/\sqrt{8\pi G_N}$.

NB: 1. M_{NP} can thus be also a GUT scale.
2. Includes assuming no (or only little) new physics up to M_{NP}.

UV completion from Asymptotically Safe Gravity

Evidence for an interacting UV fixed point in gravity:

- Viable theory of quantum gravity (Asymptotically Safe Quantum Gravity)
- Verified for Einstein-Hilbert, f(R), . . . gravity
- Coupling of SM matter: Quantitative but no qualitative changes

Impact of quantum-gravity fluctuations on SM matter:

QUANTUM-GRAVITY INDUCED UV COMPLETION!

such that leading-order terms are parameterized by form above.

1.) $f_g > 0$ (i.e., anti-screening) from positive G_N.
2.) One universal ("flavour-blind") f_y, sign undetermined.

UV completion

Note that this is only an example!

Minimal parameterization of BSM physics:

Within this approach one can stay completely agnostic but novel fields and/or additional symmetries of the new physics!

In this talk: Neglect leptons.

Fixed Points and Permutation Symmetry

Use one-loop (two-loop) expressions for SM β-functions + postulated linear terms:

- Zeros of the β-functions: Fixed Points
- Gaußian and interacting FPs possible
- UV and IR FPs
- Permutation Symmetry S_3 of up-type and down-type quarks
  - S_3 symmetric FP:
    Different values of the Yukawa couplings due to RG flow.
  - Multiplet of FPs:
    Additional symmetry breaking by choice of FP.

CKM unitarity & RG flow

- *New-physics contribution drops out of the running of CKM.* The corresponding SM IR attractive fixed point persists. This fixed point dominates the IR physics of the CKM matrix.
- Unitarity of the CKM matrix: non-polynomial β-functions for the mixing angles.
- Singular for identical Yukawa couplings! (see below)
- No FPs with finite / non-vanishing equal up-type (down-type) Yukawa couplings.
- Starting from a FP which is member of a multiplet: **Neither the three up- nor the three down-type quarks can have equal masses.**
- Poles in β-functions limits the values of the masses in the flow and thus in the IR.

FPs & RG flow for one generation

Non-Abelian gauge couplings asymptotically free: $g_{2\,*} = 0 = g_{3\,*}$.

Eight FPs:
Four with asymp. free Abelian gauge coupling,
four interacting ones s.t. $g_{Y\,*} = 4\pi\sqrt{6\,f_g/41}$.

All FPs fulfill:

$$y_{t\,*}^2 - y_{b\,*}^2 = \frac{1}{3} g_{Y\,*}^2 \,.$$

Finite FP value for Abelian charge:
- different top and bottom masses!
- larger top mass due larger hypercharge!

Phenomenological values for top and bottom mass in IR ($k = 173\text{GeV}$).

FPs & RG flow for two generations

Best parameterization for mixing = Cabbibo matrix squared:

$$\left[\{|V_{ij}|^2\}\right] = \begin{bmatrix} W & 1-W \\ 1-W & W \end{bmatrix}$$

Corresponding β-function:

$$\beta_W = \frac{3}{16\pi^2} W\,(W-1)\left[(y_t^2+y_c^2)\frac{y_b^2-y_s^2}{y_t^2-y_c^2} + (y_b^2+y_s^2)\frac{y_t^2-y_c^2}{y_b^2-y_s^2}\right]$$

System of β-functions:
20 FPs and two lines of FPs in one-loop truncation[2],
24 FPs in two-loop truncation,
grouped in six quartets.

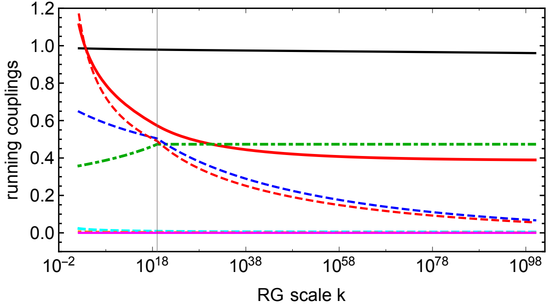
[2] RG invariant combinations of couplings at one-loop level

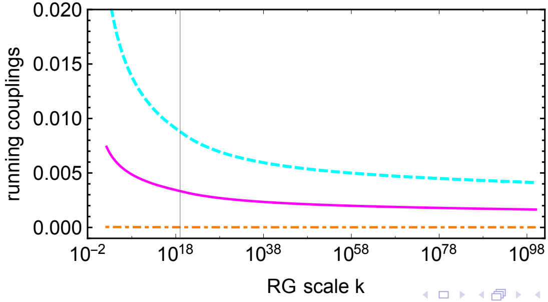
FPs & RG flow for two generations

Structure of one quartet of FPs:

#	$y_{t*}^2 / \left(\frac{15}{615}\pi^2\right)$	$y_{c*}^2 / \left(\frac{15}{615}\pi^2\right)$	$y_{b*}^2 / \left(\frac{15}{615}\pi^2\right)$	$y_{s*}^2 / \left(\frac{15}{615}\pi^2\right)$	W_*
1a	$41\left(f_g + 2f_y\right)$	0	$-19f_g + 82f_y$	0	0
1b	$41\left(f_g + 2f_y\right)$	0	0	$-19f_g + 82f_y$	1
1c	0	$41\left(f_g + 2f_y\right)$	0	$-19f_g + 82f_y$	0
1d	0	$41\left(f_g + 2f_y\right)$	$-19f_g + 82f_y$	0	1

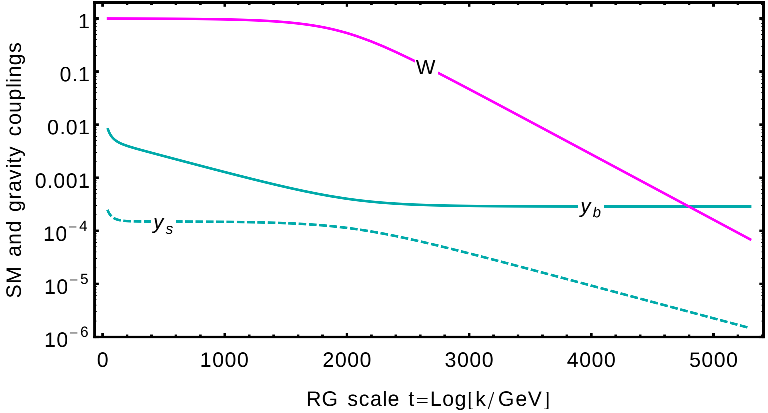
FPs & RG flow for two generations





FPs & RG flow for two generations

Limit on strange mass due to singularity:



FPs & RG flow for two generations

For FP 1a and $f_g = 9.7 \cdot 10^{-3}$, $f_y = 2.248 \cdot 10^{-3}$,

at k = 173 GeV:

- All three gauge couplings correct.
- $W \approx 0.999$.
- $M_t \approx 193\,\mathrm{GeV}$, $M_b \approx 4.2\,\mathrm{GeV}$, $M_c \approx 1.3\,\mathrm{GeV}$ and $M_s \approx 97\,\mathrm{MeV}$.

I.e., besides an overestimated top mass astonishingly well reproduced SM parameters.

FPs & RG flow for three generations

System has more then 1000 FPs!

Use the heavy-top limit to screen for phenomenologically viable FPs and solve then the flow for the full system.

Parameterization of mixing:

$$\left[\{|V_{ij}|^2\}\right] = \begin{bmatrix} X & Y & 1-X-Y \\ Z & W & 1-Z-W \\ 1-X-Z & 1-Y-W & X+Y+Z+W-1 \end{bmatrix}$$

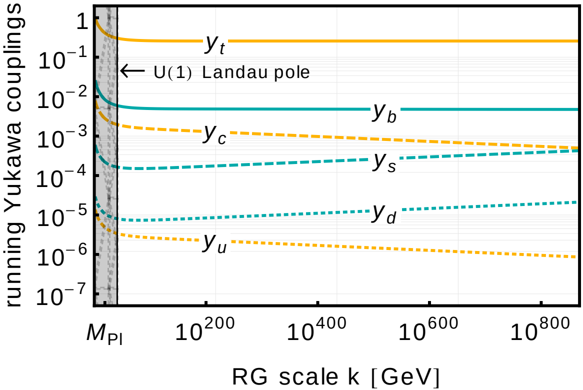
FP structure of mixing:

$$M_{123} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad M_{132} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \quad M_{321} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix},$$

$$M_{213} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad M_{312} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \quad M_{231} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

FPs & RG flow for three generations

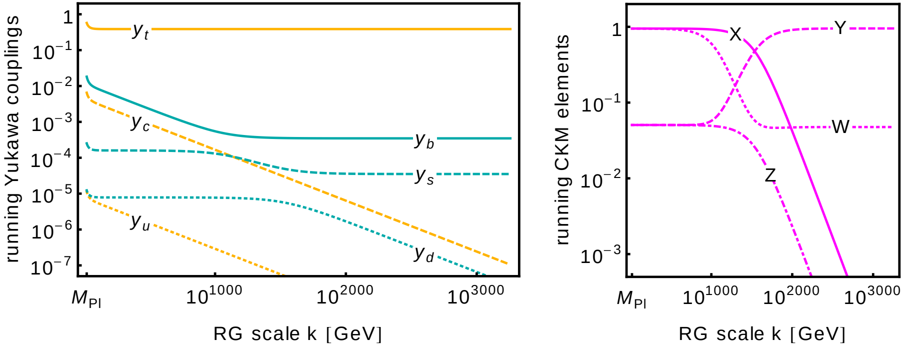
A strictly viable, predictive, but not fully fundamental UV completion:



All gauge couplings, quark masses and mixings reproduced with $m_{NP} = 10^{15}$GeV, $f_g = 8.4 \times 10^{-3}$ and $f_y = 1.4303 \times 10^{-4}$.
SM Landau pole at 10^{41} GeV shifted to 10^{1000} Gev.

FPs & RG flow for three generations

A strictly fundamental but only approximately viable UV completion:

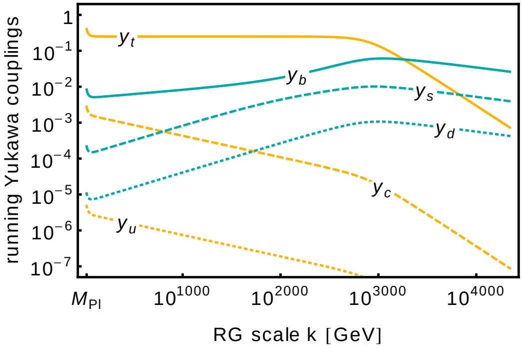


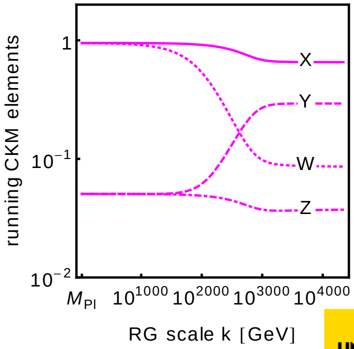
Top mass overestimated by 10%!

FPs & RG flow for three generations

A less-predictive but strictly viable and fundamental UV completion:

Use negative f_y,
choose FP such that all Yukawa couplings are asymptotically free,
then quark masses are not predicted (IR values used as input).





Conclusions and outlook

Three main conclusions:

- New-physics contribution drops out of the running of the CKM. The corresponding **SM IR attractive fixed point** persists. This fixed point **dominates the IR physics of the CKM matrix.**
- Top and bottom masses: Predictions in qualitative agreement with phenomenology. Measured IR values of all other quarks can be accommodated (free parameters at the UV fixed point of the system).
- Interplay of CKM matrix elements and Yukawa couplings leads to **upper bounds on the free-parameter Yukawa couplings.**

Outlook:

- Include leptons.
- Θ term.
- Higher-dimensional operators.
- Explore BSM candidates.