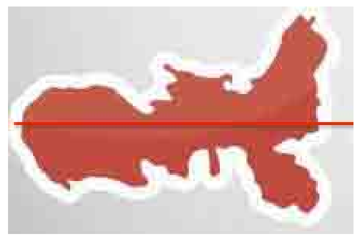
Beyond the Standard Model — theory

The problem of the flavour problem
Anomalies: R_K
Fundamental Composite Higgs



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Flavour and theory

Theorists do a great job in computing SM predictions, proposing what can be computed and measured. But the main job would be understanding flavour.

Flavour is the sector of fundamental physics with most measured digits

Constants	$g_{1,2,3}$	λ_H	y_ℓ	y_q	CKM	ν	cosmo	mass ratios	total
Digits	14	2.2	18	8	6.7	8	6	10	72

Weinberg tried in 1972: "the worst summer of my life". Same today, despite

- Higgs confirmed, m_b, m_τ are small Yukawas, not $\psi\psi HH^\dagger H/\Lambda^2$.
- Flavour and CP data agree with U(3)^5 structure of SM.

Coupling	U(3)$_L$	U(3)$_E$	U(3)$_Q$	U(3)$_U$	U(3)$_D$
y_ℓ	3	$\bar{3}$	1	1	1
$y_{\rm u}$	1	1	3	$\bar{3}$	1
$y_{\rm d}$	1	1	3	1	$\bar{3}$

- ν violate flavour with $\theta_\nu \sim 1$: $(LH)^2/(10^{12}\,\text{GeV})$.

Understanding flavour needs understanding: why 3 generations, what is H?

Field theory attempts

QFT does not predict field content nor parameters. Symmetries do. Masses and mixings shows some pattern, but no clear order. Break symmetries. Gain?

The $q+\ell$ Yukawa matrices contain $54+36$ parameters, but only $10+3$ are physical at SM energy, because interactions allow $\mathrm{U}(5)^3$ field redefinitions.

In models of flavour, extra parameters become physical.

- $\uparrow$ Kaluza Klein on e.g. $\mathrm{CP}^2 \otimes S^2 \otimes S^1$ gives $\mathrm{SU}(3)\otimes\mathrm{SU}(2)\otimes\mathrm{U}(1)$, but $N_{\rm gen}=0$.
- $\nearrow$ GUT-scale models: Planck suppressed non-renormalizable operators may affect smaller y: many more free parameters.
- $\rightarrow$ U(3), U(2) ... A_5, A_4, P: after breaking one remains with no predictions.
- $\searrow$ Froggatt-Nielsen: small Yukawas as powers of small vev$/M$. Observations resemble SU(5) with flavour symmetries acting on 10: $y_{\rm u} \sim y_{\rm d}^2 \sim y_\ell^2$, $\theta_\nu \sim 1$. Maybe right, but like Democritus: "bla bla atoms bla bla".
- $\downarrow$ Predictions after adding texture zeroes, numerology e.g. $\theta_{\rm Cabibbo} = \theta_{\rm golden}$.

The king theory of flavour

$$V_\nu = V_{\mathsf{CKM}} \cdot V_{\mathsf{bimax}} \qquad V_{\mathsf{bimax}} = R_{23}(\pi/4) R_{12}(\pi/4)$$

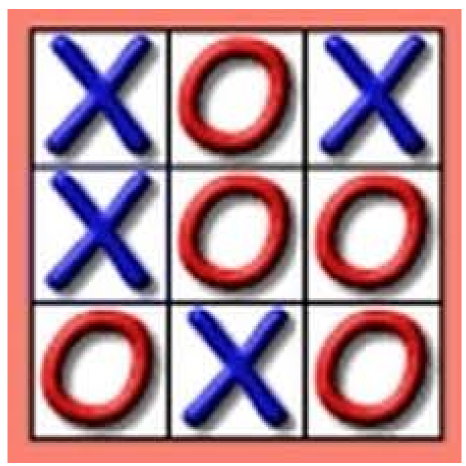
'predicts' correctly 3 angles

$$\theta_{23} = 44.2^\circ, \qquad \theta_{12} = 35.5^\circ, \qquad \theta_{13} = 9.3^\circ.$$

Was this already known? I found a Chinese group, who tried $V_\nu = V_{\mathsf{bimax}} V_{\mathsf{CKM}}$. Next another who tried $V_\nu = V_{\mathsf{CKM}} V_{\mathsf{bimax}} V_{\mathsf{CKM}}$. Finally another who did it.

Problem: whatever is measured one can find a 'theory' of type ↓.

Not many games can be played with 3×3 matrices. Field mostly abandoned.



String theory attempts

In some string models the number of generations depends on the number of handles of the compactification space, when compactifying from 10d to 4d

$$N_{\text{gen}} = |\chi|/2.$$

Unfortunately χ is a free parameter, and $10^{\sim 500}$ vacua seem possible.

So, possibly 10^{400} string models reproduce all ~ 100 known digits of the SM.

Minimal Flavour Violation

Most theorists believed: Higgs must come with new physics that keeps its mass naturally small. Then, the flavour structure of new physics had to be similar to the SM: Minimal Flavour Violation hypothesis i.e. $U(3)^5$ broken as in the SM.

Crazy? Realised in gauge mediated SUSY.

LHC: Higgs alone. 'Natural' theories unnatural.

Big theory guiding principle lost, and MFV no longer needed.
Furthermore: what is H? Just a scalar accidentally light?

$U(3)^5$ changes if gauge group changes: e.g. SU(5), $SU(3)^3$, FundamCompos$H$.

Maximal Flavour Violation

With theory in confusion, flavour become a hoped jolly:

sensitive to heavy new physics (100+ TeV) if its flavour differs from SM.

Anomalies in R_K and R_D — not in the most sensitive observables: ϵ_K, EDM...

R_D is tree-level SM, so challenging to explain with new physics, so most attention of theorists on R_D. I ignore R_D, waiting to see if it will go away.

R_K

As everybody knows

$$R_K = \frac{\text{BR}\left(B^+ \to K^+\mu^+\mu^-\right)}{\text{BR}\left(B^+ \to K^+e^+e^-\right)} \approx \begin{cases} 1 & \text{SM} \\ 0.745 \pm 0.09_{\text{stat}} \pm 0.036_{\text{syst}} & \text{exp} \end{cases}$$

can be fitted as new operators better written in the chiral basis

$$\mathscr{L}_{\text{eff}} = \sum_{\ell=\{e,\mu,\tau\}} \sum_{X,Y=\{L,R\}} c_{b_X \ell_Y} \mathcal{O}_{b_X \ell_Y} \qquad \mathcal{O}_{b_X \ell_Y} = (\bar{s}\gamma_\mu P_X b)(\bar{\ell}\gamma_\mu P_Y \ell)$$

with $C^{\text{SM}}_{b_L \ell_L} \approx 8.6$, $C^{\text{SM}}_{b_L \ell_R} = -0.18$ using the standard normalization

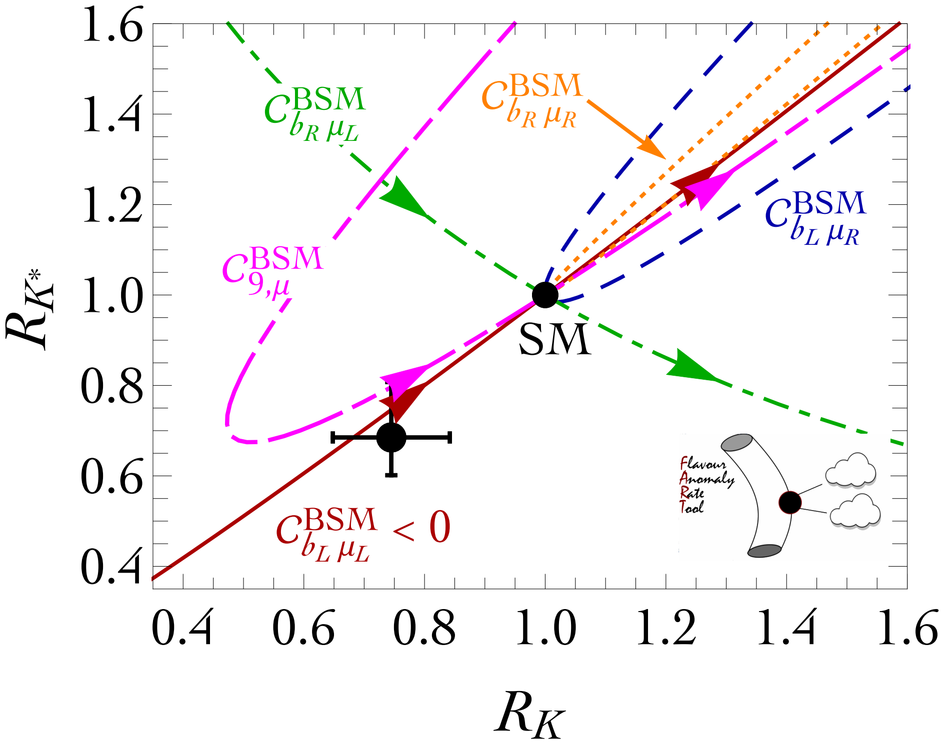
$$c_I = V_{tb} V^*_{ts} \frac{\alpha_{\text{em}}}{4\pi v^2} C_I = \frac{C_I}{(36\ \text{TeV})^2}$$

Then

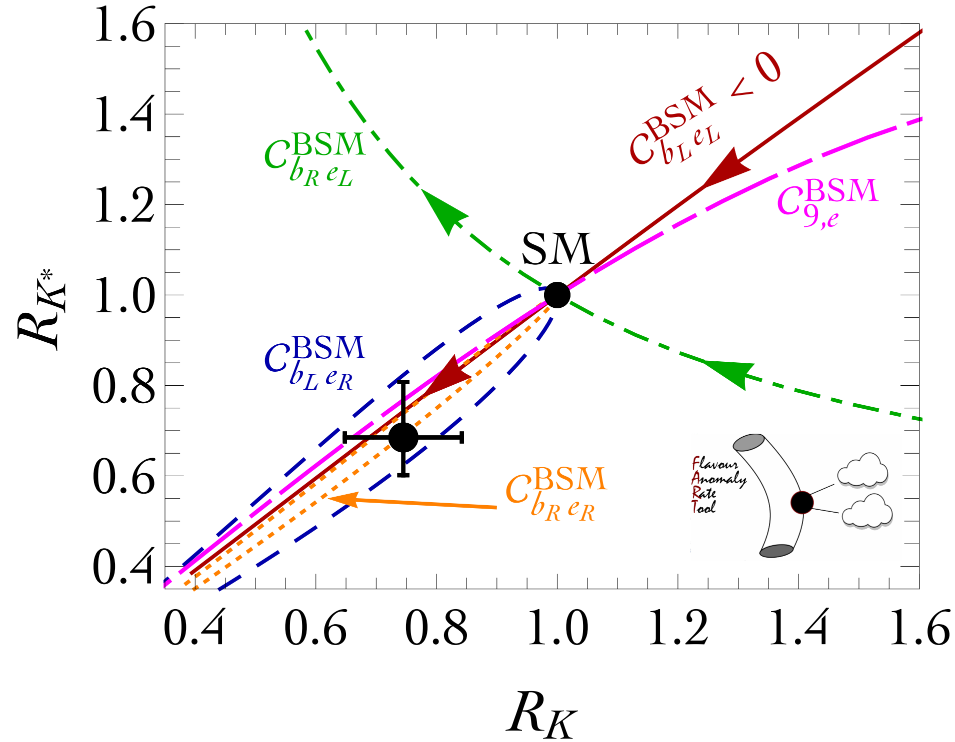
$$R_K \simeq 1 + 2\frac{\text{Re}\, C^{\text{BSM}}_{b_{L+R}(\mu-e)_L}}{C^{\text{SM}}_{b_L \mu_L}}, \qquad R_{K^*} \simeq R_K - 3.4\frac{\text{Re}\, C^{\text{BSM}}_{b_R(\mu-e)_L}}{C^{\text{SM}}_{b_L \mu_L}}$$

μ deficit or e enhancement?

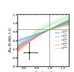
New physics in μ



New physics in e

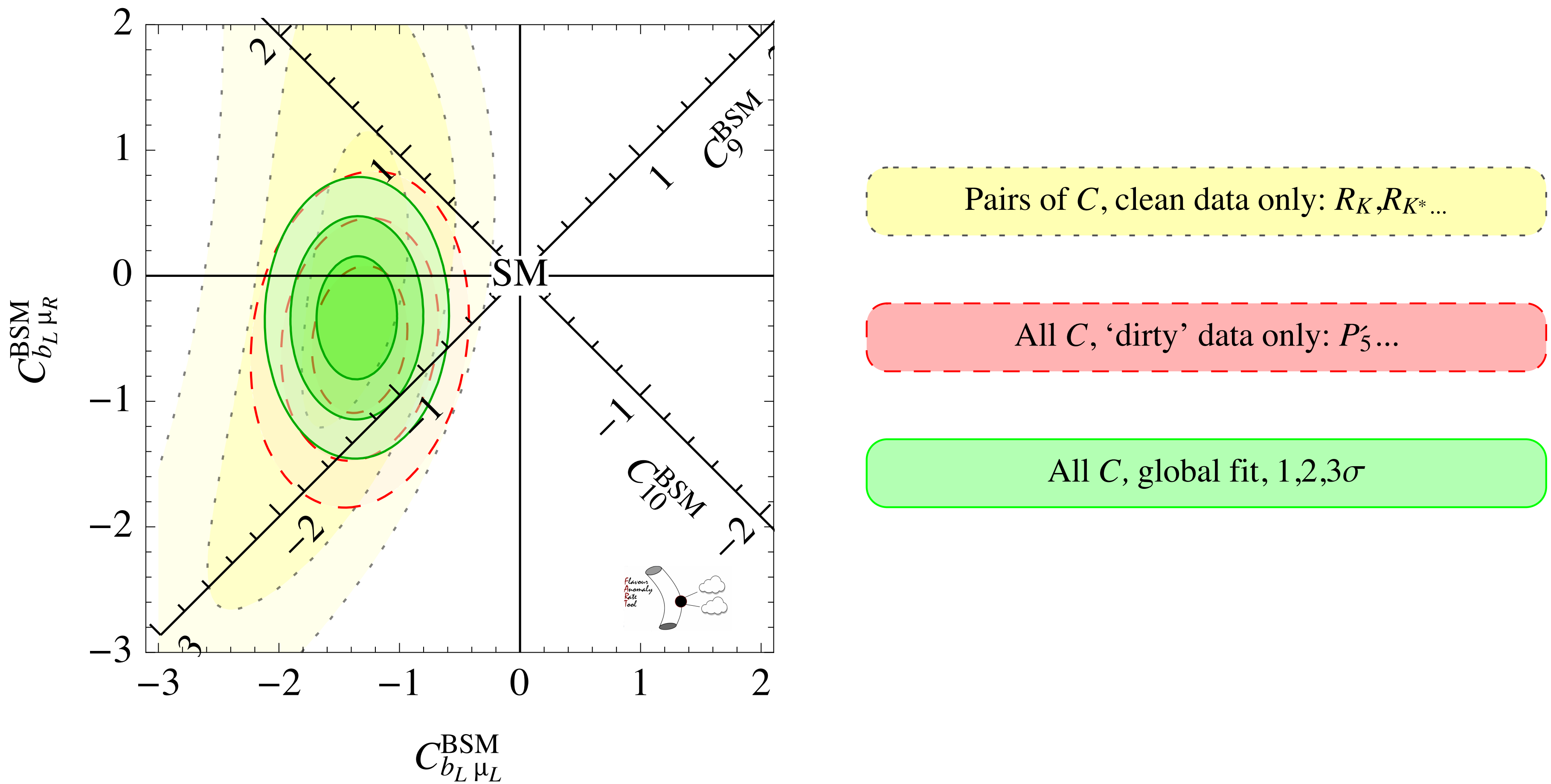


$R_K + R_{K^*}$ favour new physics in $C_{b_L\mu_L}$ . . . . or more variety if e involved

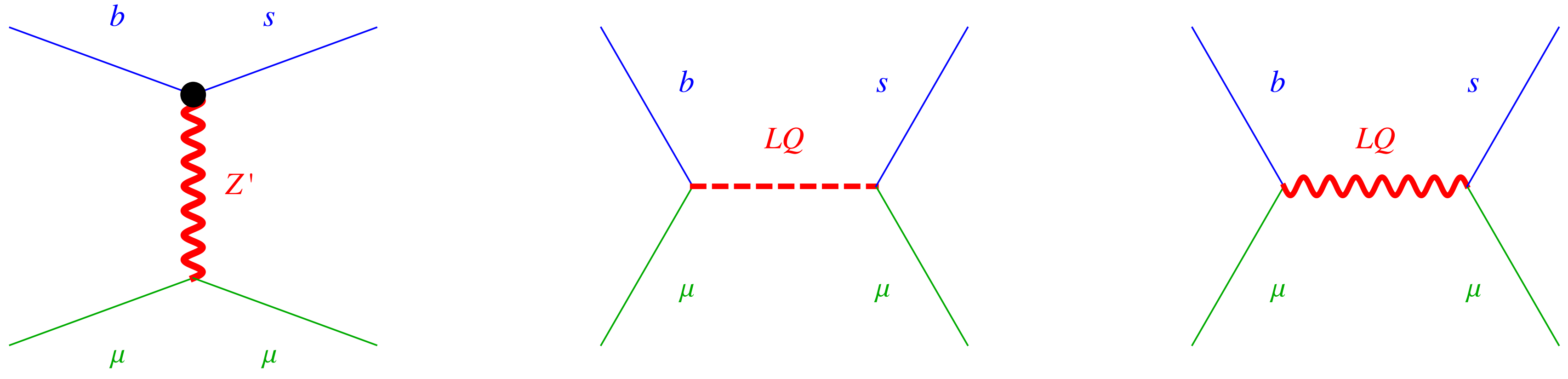
Low-energy bin of R_{K^*} not inconsistent, .

Consistent with $B \to K^* \mu^- \mu^+$ distributions

$C^{\mathsf{BSM}}_{b_L \mu_L} \approx -1.35 \pm 0.22$ if hadronic uncertainties correctly estimated (huge work).



Theories for R_K: tree level mediators

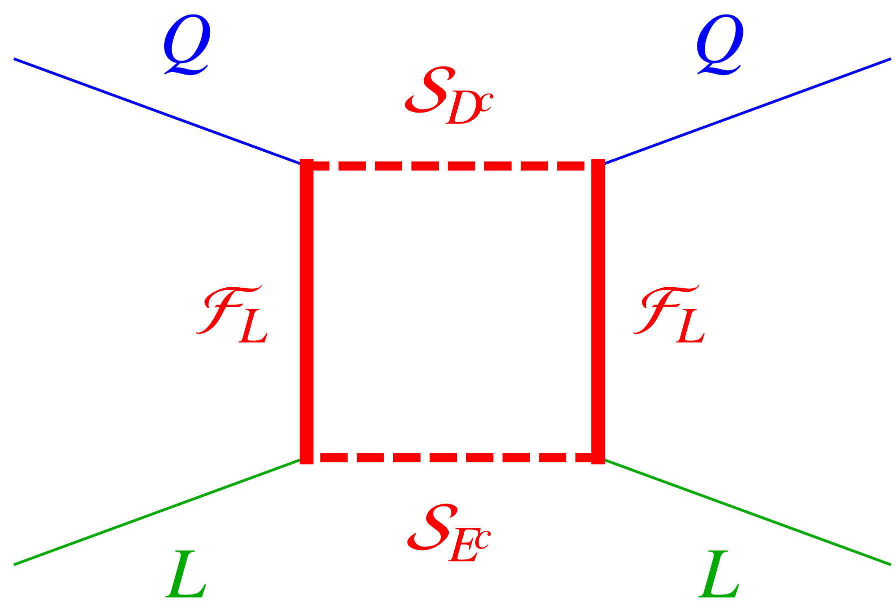


Z' or some LeptoQuark (no MSSM) with $g_{bs}g_{\mu\mu}/M_{Z'}^2 \approx 1/(30\,\text{TeV})^2 \approx y_{b\mu}y_{s\mu}/M_{\text{LQ}}^2$

LQ	Spin	Quantum Number	Clean observables new physics in e	Clean observables new physics in μ	All observables
S_3	0	$(\bar{3}, 3, 1/3)$	✓	✓	✓
R_2	0	$(3, 2, 7/6)$	✓		
$\tilde{R}_2$	0	$(3, 2, 1/6)$			
$\tilde{S}_1$	0	$(\bar{3}, 1, 4/3)$	✓		
U_3	1	$(3, 3, 2/3)$	✓	✓	✓
V_2	1	$(\bar{3}, 2, 5/6)$	✓		
U_1	1	$(\bar{3}, 1, 2/3)$	✓	✓	✓

Theories for R_K: loop level mediators

Extra scalars and fermions at the TeV scale can mediate



Fundamental Composite Higgs

Theorists avoid fundamental scalars. Then flavour becomes tasteless: composite Higgs studied in effective theories that don't tell what H is made of.

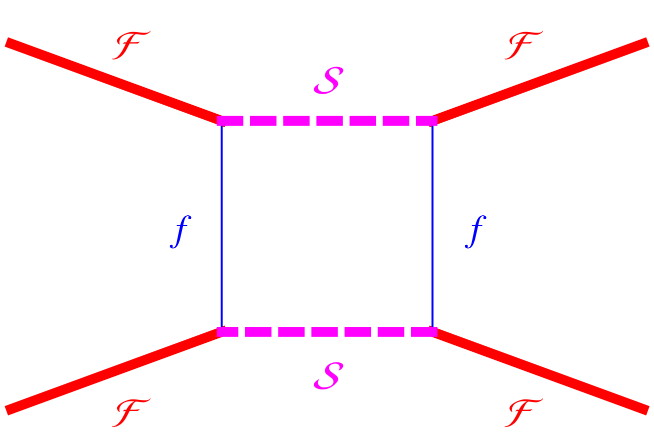
Here: fundamental theory written adding fundamental techni-scalars. Theory:

$$(\text{SM without } H) +$$

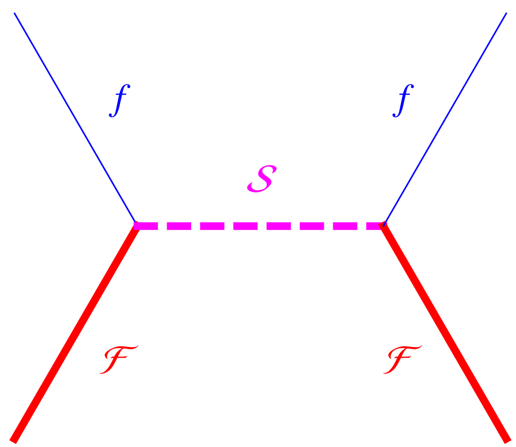
$$+ (\text{extra } G_{\rm TC} = \text{SU}(N) \text{ or SO}(N) \text{ or Sp}(N) \text{ strong at } \Lambda_{\rm TC}) +$$

+ (vector-like TCfermions $\mathcal{F}$) + (TCscalars $\mathcal{S}$) + Yukawa couplings such that

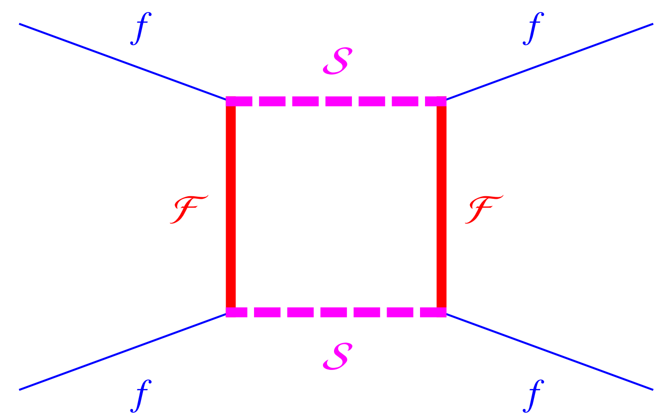
(each SM fermion $f = L, E, Q, U, D$)×(some TC scalar $\mathcal{S}$)×(some TC fermion $\mathcal{F}$).



Higgs potential
$\mathcal{F}^4 \sim H^2$



SM fermion masses
$ff\mathcal{F}\mathcal{F} \sim ffH$



Flavour violations
f^4

Global symmetries

Vector-like $\mathcal{F}$ with $\Delta m \ll \Lambda_{\rm TC}$ have accidental global symmetries. Condensates form if $\beta_{\rm TC} \lesssim \frac{1}{3}\beta_{\rm TC}|_{\rm gauge}$ and respect $G_{\rm TC}$ and minimally break $G_{\rm gl} \to H_{\rm gl}$. Despite the presence of TC-scalars, the mass of $H \sim \mathcal{F}\mathcal{F}$ remains calculable.

Gauge group	Fermion bilinear condensate	Intact scalar symmetries
$\mathrm{SU}(N)_{\rm TC}$	$\mathrm{SU}(N_F)_L \otimes \mathrm{SU}(N_F)_R \to \mathrm{SU}(N_F)$	$\mathrm{U}(N_S)$
$\mathrm{SO}(N)_{\rm TC}$	$\mathrm{SU}(N_F) \to \mathrm{SO}(N_F)$	$\mathrm{O}(N_S)$
$\mathrm{Sp}(N)_{\rm TC}$	$\mathrm{SU}(N_F) \to \mathrm{Sp}(N_F)$	$\mathrm{Sp}(2N_S)$

Quasi-degenerate TCscalars similarly have accidental global symmetries, but
- $\langle \mathcal{S} \rangle$ and $\langle \mathcal{S}\mathcal{S} \rangle$ not fixed by general arguments. Lattice?
- They can break $G_{\rm TC}$, giving H as elementary Goldstone boson.
- They can break $G_{\rm gl}$ giving more TCπ made of two TCscalars.

Custodial symmetries

Composite H has $|H^\dagger D_\mu H|^2$ giving $\hat{T} \sim v^2/f_{\rm TC}^2 \lesssim 2\times 10^{-3}$: unnatural $f_{\rm TC} \gtrsim 5$ TeV.

Suppressed if $G_{\rm gl} \to H_{\rm gl} \supset {\rm SU}(2)_L \otimes {\rm SU}(2)_R \to {\rm SU}(2)$. Minimal realizations:

$G_{\rm TC}$	${\rm SU}(N)_{\rm TC}$	${\rm SO}(N)_{\rm TC}$	${\rm Sp}(N)_{\rm TC}$
$\mathcal{F}$	$\mathcal{F}_L \oplus \mathcal{F}_{E^c} \oplus \mathcal{F}_N$	$\mathcal{F}_L \oplus \mathcal{F}_{L^c} \oplus \mathcal{F}_N$	$2_0 \oplus 1_{1/2} \oplus 1_{-1/2}$
$G_{\rm gl} \to H_{\rm gl}$	${\rm SU}(4)_L \otimes {\rm SU}(4)_R \to {\rm SU}(4)$	${\rm SU}(5) \to {\rm SO}(5)$	${\rm SU}(4) \to {\rm Sp}(4)$
TCπ	$2(2,2) \oplus 1 \oplus 3_L \oplus 3_R$	$(1,1) \oplus (2,2) \oplus (3,3)$	$(2,2) \oplus (1,1)$
$\mathcal{S}$	$\mathcal{S}_L \oplus \mathcal{S}_{E^c} \oplus \mathcal{S}_N$	$\mathcal{S}_L \oplus \mathcal{S}_N$	$\mathcal{S}_L \oplus \mathcal{S}_N$
$G_{\rm gl} \to H_{\rm gl}$	${\rm SU}(4) \to {\rm SU}(2)_L \otimes {\rm SU}(2)_R$	${\rm SO}(5) \to {\rm SO}(4)$	${\rm Sp}(6) \to {\rm Sp}(4) \otimes {\rm Sp}(2)$
if $\langle \mathcal{S}\mathcal{S} \rangle \propto$	${\rm diag}\,(0,0,1,1)$	${\rm diag}\,(0,0,0,0,1)$	$\varepsilon \otimes {\rm diag}\,(0,0,1)$
TCπ	$2 \times (2,2) \oplus (1,1)$	$(2,2)$	$2(2,2)$

$\mathcal{F}_L$ means TC-fermions with the same SM quantum numbers as SM L, etc.

One $(2,2)$ is ok. Two $(2,2)$ ok if vevs aligned.

Custodial for $Z \to b\bar{b}$ in ${\rm SO}(N)_{\rm TC}$ with $\mathcal{F}_L \oplus \mathcal{F}_{L^c} \oplus \mathcal{F}_N$ and $|m_L - m_{L^c}| \ll \Lambda_{\rm QCD}$.

Conditions for Fundamental Composite H

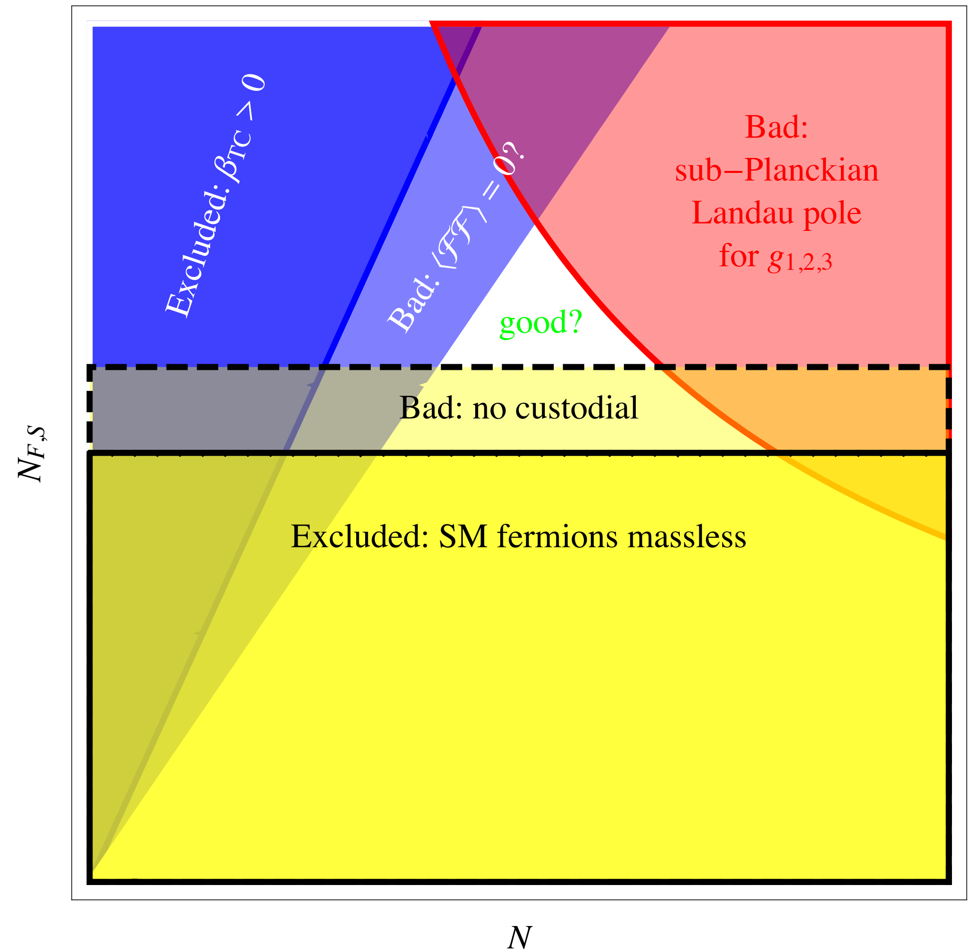
1) $G_{\rm TC}$ must be asymptotically free and form condensates:

$$N \gtrsim \begin{cases} \dfrac{3(4N_F+N_S)}{44} & {\rm SU}(N)_{\rm TC} \\ \dfrac{3(4N_F+N_S)}{44}+2 & {\rm SO}(N)_{\rm TC} \\ \dfrac{3(2N_F+N_S)}{22}-2 & {\rm Sp}(N)_{\rm TC} \end{cases}$$

2) No sub-Planckian Landau poles:

$$b_3 \lesssim 1.9\,, \qquad b_2 \lesssim 5.3\,, \qquad b_1 \lesssim 10$$

3) Each L, D, U, Q, E must get mass trough TC-Yukawas. And possibly custodial for T, maybe for $Zb\bar{b}$. Or for M_h.



These conditions might exclude all models

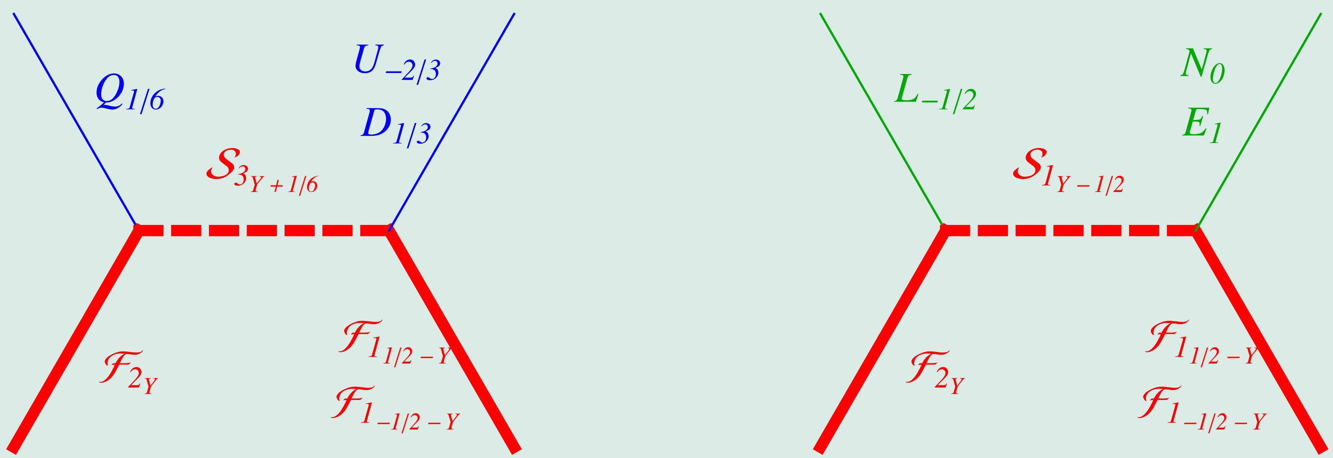
Do models exist?

Not adding a TCfermion for each SM fermion. More minimal $\sqrt{f}$ needed.

The good structure is SU(2)$_R$-like: same scalar coupled to U, D and to E, N

$$\mathscr{L}_Y \sim (Q\mathcal{F}\mathcal{S}_q^* + (\,U, D\,)\,\mathcal{F}^c\mathcal{S}_q) + (L\mathcal{F}\mathcal{S}_\ell^* + (\,E, N\,)\,\mathcal{F}^c\mathcal{S}_\ell)$$

SM-like miracle keeps fields minimal and implies custodial. For generic Y:



Some models found, one presented here

Fundamental Composite Higgs

Set $Y = -1/2$, the matter content is $\mathrm{SU}(5)_{\mathrm{GUT}}$ fragments

name	spin	generations	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	G_{TC}
$\mathcal{F}_N$	1/2	N_{g_F}	1	1	0	N
$\mathcal{F}_N^c$	1/2	N_{g_F}	1	1	0	$\bar{N}$
$\mathcal{F}_L$	1/2	N_{g_F}	1	2	$-1/2$	N
$\mathcal{F}_L^c$	1/2	N_{g_F}	1	2	$+1/2$	$\bar{N}$
$\mathcal{F}_{E^c}$	1/2	N_{g_F}	1	1	-1	N
$\mathcal{F}_{E^c}^c$	1/2	N_{g_F}	1	1	$+1$	$\bar{N}$
$\mathcal{S}_{E^c}$	0	N_{g_S}	1	1	-1	N
$\mathcal{S}_{D^c}$	0	N_{g_S}	3	1	$-1/3$	N

$$\mathscr{L}_Y = y_L\ L\mathcal{F}_L\mathcal{S}_{E^c}^* + y_E\ E\mathcal{F}_N^c\mathcal{S}_{E^c} + (y_D\ D\mathcal{F}_N^c + y_U\ U\mathcal{F}_{E^c}^c)\mathcal{S}_{D^c} + y_Q\ Q\mathcal{F}_L\mathcal{S}_{D^c}^* + \text{h.c.}$$

$$V = \lambda_E|S_{E^c}|^4 + \lambda_{ED}|S_{E^c}|^2\mathrm{Tr}\,(\mathcal{S}_{D^c}\mathcal{S}_{D^c}^\dagger) + \lambda_D\mathrm{Tr}\,(\mathcal{S}_{D^c}\mathcal{S}_{D^c}^\dagger)^2 + \lambda_D'\mathrm{Tr}\,(\mathcal{S}_{D^c}\mathcal{S}_{D^c}^\dagger\mathcal{S}_{D^c}\mathcal{S}_{D^c}^\dagger)$$

Fundamental Composite Higgs

β-functions ok for $\mathrm{SU}(2)_{\mathrm{TC}} = \mathrm{Sp}(2)_{\mathrm{TC}}$ and $\mathrm{SU}(3)_{\mathrm{TC}}$

For $N = 3$ no extra $\mathcal{F}\mathcal{F}\mathcal{S}, \mathcal{S}^3$ couplings are allowed

5 accidental global U(1):

- Baryon number, like in the SM.
- Lepton number. Get m_ν adding N with $N\mathcal{F}^c_{E^c}\mathcal{S}_{E^c} + y'_N N\,\mathcal{F}_{E^c}\mathcal{S}^*_{E^c}$.
- TC-baryon number. Lightest TCbaryon can be $\mathcal{F}^3_N$, DM candidate.
- 2 less relevant.

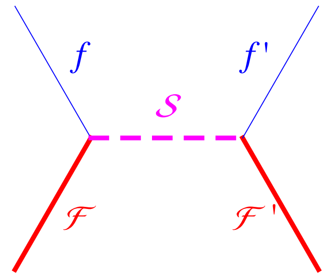
Light scalars: $\mathrm{TC}\pi = 2\times(1,1)_0 \oplus (1,3)_0 \oplus [(1,1)_1 \oplus 2\times(1,2)_{-1/2} + \text{h.c.}]$

T protected if $H \sim \mathcal{F}_L\bar{\mathcal{F}}_N$ has EW vev aligned with $H' \sim \mathcal{F}_L\bar{\mathcal{F}}_{E^c}$.

Limit $m_{\mathcal{S}} \gg \Lambda_{\mathrm{TC}}$: $\mathcal{F}\mathcal{F}$ Higgs coupled to SM fermions.
Limit $m_{\mathcal{F}} \gg \Lambda_{\mathrm{TC}}$: $\mathcal{S}\mathcal{S}$ lepto-quarks coupled to $\bar{Q}\gamma_\mu L$, $\bar{D}\gamma_\mu E$.

The top Yukawa coupling

SM Yukawas obtained as $y_{ff'} =$



$\approx \dfrac{y_f \cdot y_{f'}^T}{g_{\rm TC}}$. Minimal values: $y_f \sim y_{f'}$.

$y_t \sim y_Q y_U / g_{\rm TC}$ needs $y_Q \sim 1$, $y_U \sim g_{\rm TC}$: is this possible? Yes, the RGE are:

$$(4\pi^2)\frac{\partial g_{\rm TC}}{\partial \ln \mu} = b g_{\rm TC}^3, \qquad (4\pi^2)\frac{\partial y_f}{\partial \ln \mu} = f_f y_f^3 - f_g g_{\rm TC}^2 y_f,$$

where

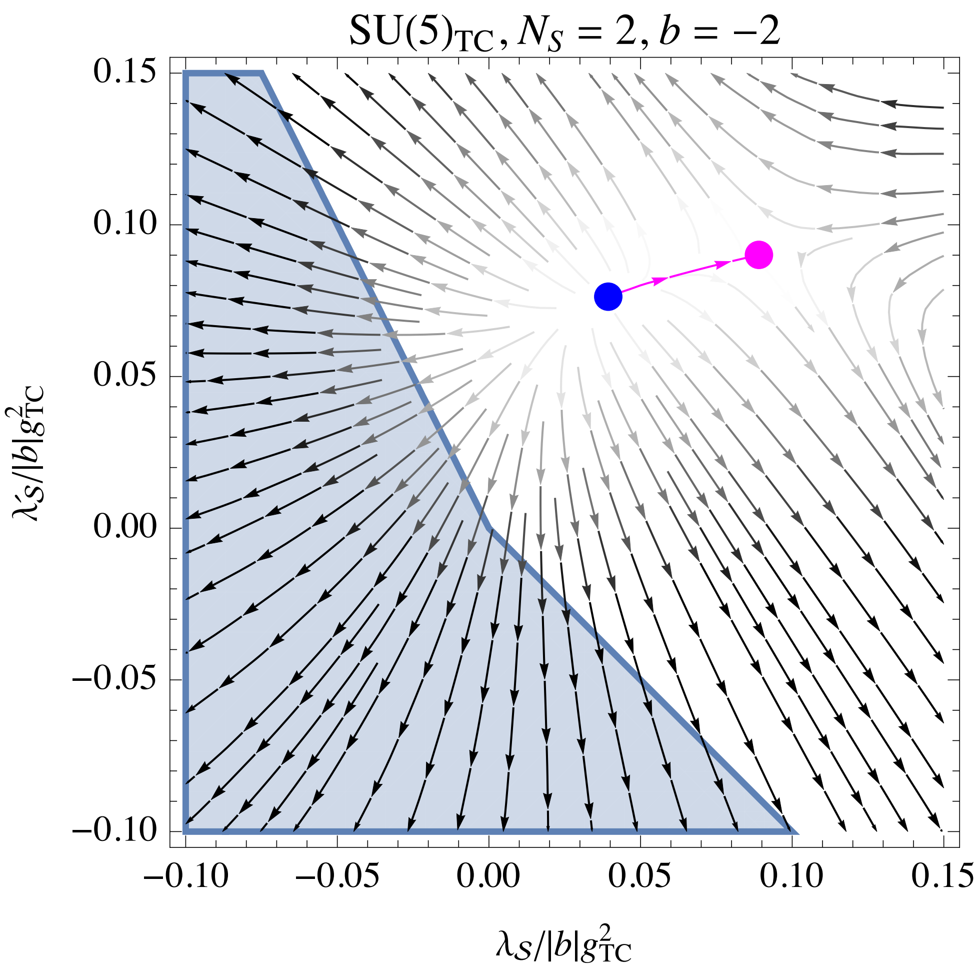
$$f_f = \frac{N + 2n_f + 1}{2}, \qquad f_g = 6C_N = 6\begin{cases} (N^2-1)/2N & \text{for } G_{\rm TC} = \mathrm{SU}(N) \\ (N-1)/2 & \text{for } G_{\rm TC} = \mathrm{SO}(N) \\ N(N+1)/4N & \text{for } G_{\rm TC} = \mathrm{Sp}(N) \end{cases}$$

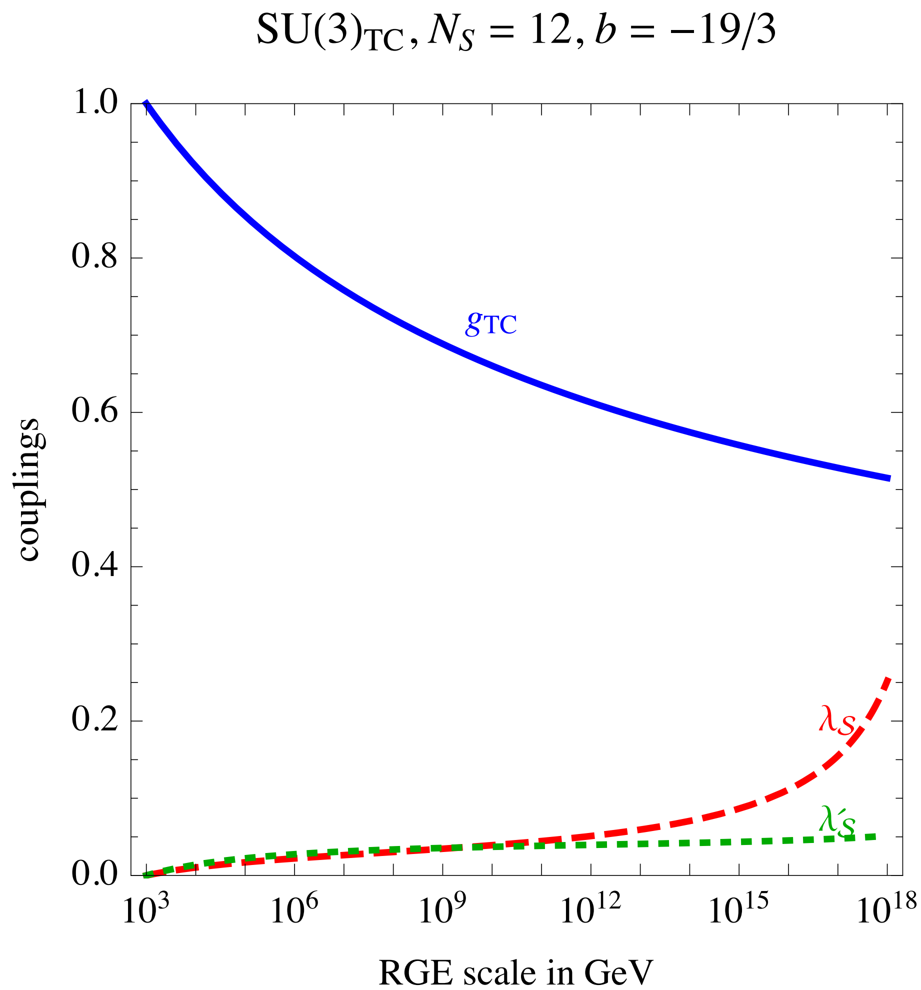
Quasi-fixed point: $y_f = g_{\rm TC}\sqrt{(f_g + b)/f_f} \sim g_{\rm TC}$.

Top partners not lighter than other states, $M \sim \Lambda_{\rm TC}$ up to Yukawa repulsion.

The TCscalar quartics

$(4\pi)^2\beta_\lambda \sim +\lambda^2 + g^4_{\rm TC} - \lambda g^2_{\rm TC}$ means that $\lambda \sim \pm g^2_{\rm TC}$ can run big and negative.
Explicit computation finds IR fixed points with $\lambda \sim +g^2_{\rm TC}$.
Away from them, numerical runnings show that λ can remain small.





Lattice needed to know what happens, works in progress

The Higgs potential

Computable using chiral Lagrangian techniques

$$\mathcal{F}\mathcal{F} = f_{\mathsf{TC}}^2 \Lambda_{\mathsf{TC}} \mathcal{U}, \qquad \mathcal{U} = \exp \frac{2i\Pi}{f_{\mathsf{TC}}} \qquad \Lambda_{\mathsf{TC}} \sim g_{\mathsf{TC}} f_{\mathsf{TC}} \sim 4\pi f_{\mathsf{TC}}$$

3 contributions:

1. From TC-fermion masses (neglected in effective theories);
2. From SM gauge interactions;
3. From Yukawa interactions (at order $y_Q^2 y_U^2$, no y_U^2).

Result: one can tune a small M_h:

$$-M_h^2 \sim c_m \left(\sum m_{\mathcal{F}_i}\right) \Lambda_{\mathsf{TC}} + \left(c_g \frac{3(3g_2^2 + g_Y^2)}{64\pi^2} - c_y \frac{3y_t^2}{16\pi^2}\right) \Lambda_{\mathsf{TC}}^2$$

$$\lambda_H \sim \frac{c_y y_Q^2 y_U^2}{4(4\pi)^2} - \frac{c_g g_{\mathsf{TC}}^2 (3g_2^2 + g_Y^2)}{16(4\pi)^2} \sim \frac{y_t^2}{N}$$

Flavour structure similar to SM

Fundamental Composite Higgs has a defined flavour structure similar to SM:

Coupling	Flavor symmetry of SM fermions					Flavor of TC-scalars	
	U(3)$_L$	U(3)$_E$	U(3)$_Q$	U(3)$_U$	U(3)$_D$	U(3)$_{\mathcal{S}_{E^c}}$	U(3)$_{\mathcal{S}_{D^c}}$
y_L	3	1	1	1	1	3	1
y_E	1	3	1	1	1	$\bar{3}$	1
y_Q	1	1	3	1	1	1	3
y_U	1	1	1	3	1	1	$\bar{3}$
y_D	1	1	1	1	3	1	$\bar{3}$
$m^2_{\mathcal{S}_E}$	1	1	1	1	1	$3 \otimes \bar{3}$	1
$m^2_{\mathcal{S}_D}$	1	1	1	1	1	1	$3 \otimes \bar{3}$
λ_E	1	1	1	1	1	$(3 \otimes \bar{3})^2$	1
$\lambda_{D,D'}$	1	1	1	1	1	1	$(3 \otimes \bar{3})^2$
λ_{ED}	1	1	1	1	1	$3 \otimes \bar{3}$	$3 \otimes \bar{3}$

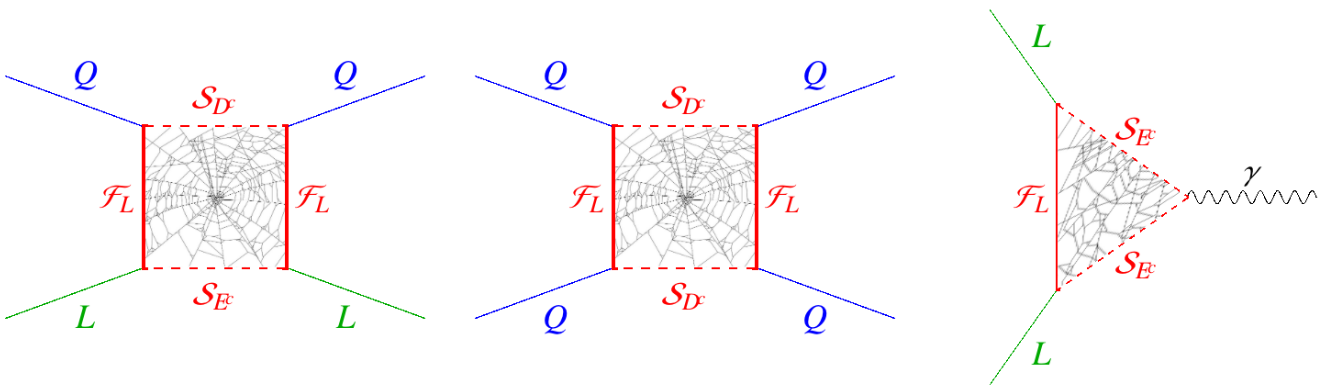
This means: (3 mixing matrices in y_f) + (2 in $m^2_{\mathcal{S}}$) + (more in quartics).

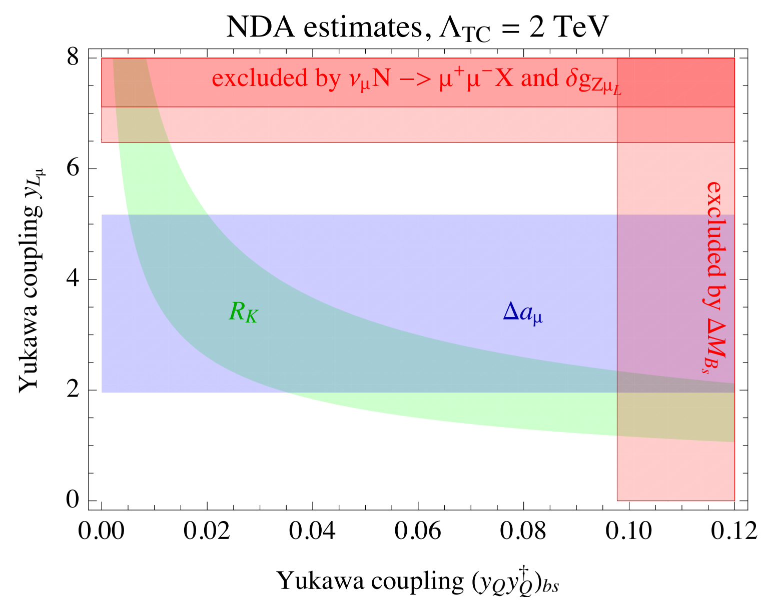
Flavour effects

Electric dipoles, $\mu \to e\gamma$ under bounds if: universal (or massless) TCscalars and minimal $y_f \sim y_{f'}$. 4-fermion operators and TCpenguins are ok, including ϵ_K

$$\mathcal{O}(1)\frac{(y_f^\dagger y_f)_{ij}(y_{f'}^\dagger y_{f'})_{i'j'}}{g_{\rm TC}^2\Lambda_{\rm TC}^2}(\bar f_i\gamma_\mu f'_{j'})(\bar f'_{i'}\gamma_\mu f_j) \qquad \text{for } f,f' = \{L,E,Q,U,D\}.$$

New physics in terms of few TC $\mathcal{O}(1)$ coefficients and of TC-Yukawas.





Can fit R_K assuming $y_{L_\mu} \approx 1$ above minimal. Associated effects: Δa_μ, $\delta g_{Z_{\mu_L}}$

Conclusions

We understand why we do not understand flavour.

LHC told us that the Higgs is not what most theorists expected.

Abandoning prejudices can lead to new ideas, e.g. fundamental composite H.
Maybe new ideas for flavour? Or new physics needed to make progress.

R_K? R_D? Data please.