Theoretical constraints on models with vector-like fermions

Michał Ryczkowski

In collaboration with:
A. Adhikary, M. Olechowski, J. Rosiek

based on Phys.Rev.D 110 (2024) 7, 075029, [2406.16050]

Particle Physics and Cosmology Seminar
Warsaw 07.11.2024

Università degli Studi di Padova

Faculty of Physics
University of Warsaw

Outline

Part I - Introduction

Standard Model fermions vs vector-like fermions

Standard Model fermions (SMF)

- Ψ_L^{SM} and Ψ_R^{SM}
  Different transformation properties under the SM gauge group
- Gauge invariant mass term:

$$\mathcal{L} \supset y\, \bar{\Psi}_L^{SM}\, \Phi\, \Psi_R^{SM}$$

- **Dependence** on the electroweak symmetry breaking mechanism

Vector-like fermions (VLF)

- Ψ_L^{VLF} and Ψ_R^{VLF}
  Same transformation properties under the SM gauge group
- Gauge invariant mass term:

$$\mathcal{L} \supset M\, \bar{\Psi}_L^{VLF}\, \Psi_R^{VLF}$$

- **No connection** to the electroweak symmetry breaking mechanism

Vector-like fermions in the literature

Vector-like quarks (VLQ) and leptons (VLL) have been studied in various contexts, including:

- Stability of the electroweak vacuum, S.Gopalakrishna, A. Velusamy, 1812.11303
- Double Higgs boson production, K. Cheung et al., 2003.11043
- Electroweak phase transition and baryogenesis, D. Egana-Ugrinovic, 1707.02306
- Gauge coupling unification, R. Dermisek, 1212.3035
- Electroweak precision observables, J. Kearney et al., 1207.7062
- Dark matter, J. Fan et al., 1507.06993

Vector-like fermions in this study - multiplets

ψ	$SU(3)_c$	$SU(2)_L$	Y_W	T_3	Q_{EM}
$Q^d_{L,R} = \begin{pmatrix} U^d_{L,R} \\ D^d_{L,R} \end{pmatrix}$	3	2	$+1/6$	$+1/2$ $-1/2$	$+2/3$ $-1/3$
$U^s_{L,R}$	3	1	$+2/3$	0	$+2/3$
$D^s_{L,R}$	3	1	$-1/3$	0	$-1/3$
$L^d_{L,R} = \begin{pmatrix} N^d_{L,R} \\ E^d_{L,R} \end{pmatrix}$	1	2	$-1/2$	$+1/2$ $-1/2$	0 -1
$N^s_{L,R}$	1	1	0	0	0
$E^s_{L,R}$	1	1	-1	0	-1

Table: VLF multiplets extending the SM field content.

Vector-like fermions in this study - Lagrangian

ψ	$SU(3)_c$	$SU(2)_L$	Y_W	T_3	Q_{EM}
$Q^d_{L,R} = \begin{pmatrix} U^d_{L,R} \\ D^d_{L,R} \end{pmatrix}$	3	2	$+1/6$	$+1/2$ $-1/2$	$+2/3$ $-1/3$
$U^s_{L,R}$	3	1	$+2/3$	0	$+2/3$
$D^s_{L,R}$	3	1	$-1/3$	0	$-1/3$
$L^d_{L,R} = \begin{pmatrix} N^d_{L,R} \\ E^d_{L,R} \end{pmatrix}$	1	2	$-1/2$	$+1/2$ $-1/2$	0 -1
$N^s_{L,R}$	1	1	0	0	0
$E^s_{L,R}$	1	1	-1	0	-1

$$
\begin{aligned}
\mathcal{L} \supset & -\sum_{i,j=1}^{n_Q} M^{ij}_{Q^d} \bar{Q}^d_i Q^d_j - \sum_{i,j=1}^{n_U} \left(M^{ij}_{U^s} \bar{U}^s_i U^s_j + (y^{ij}_U \bar{Q}^d_i \tilde{\Phi} U^s_j + \text{h.c.}) \right) - \sum_{i,j=1}^{n_D} \left(M^{ij}_{D^s} \bar{D}^s_i D^s_j + (y^{ij}_D \bar{Q}^d_i \Phi D^s_j + \text{h.c.}) \right) \\
& -\sum_{i,j=1}^{n_L} M^{ij}_{L^d} \bar{L}^d_i L^d_j - \sum_{i,j=1}^{n_N} \left(M^{ij}_{N^s} \bar{N}^s_i N^s_j + (y^{ij}_N \bar{L}^d_i \tilde{\Phi} N^s_j + \text{h.c.}) \right) - \sum_{i,j=1}^{n_E} \left(M^{ij}_{E^s} \bar{E}^s_i E^s_j + (y^{ij}_E \bar{L}^d_i \Phi E^s_j + \text{h.c.}) \right)
\end{aligned}
$$

Vector-like fermions in this study - assumptions

Simplifying assumptions:

- VLQ **or** VLL included
- Number of multiplets $n \leq 1$: $M_F^{ij} \equiv M_F$, $y_F^{ij} \equiv y_F$
- Uniform values of VLF doublet and singlet masses: $M_{F^d} = M_{F^s} \equiv M_F$
- Single universal value of VLF Yukawas y_F
- No SMF-VLF and VLF-S mixing

$$\mathcal{L} \supset -n_Q M_Q \bar{Q}^d Q^d - n_U \Big(M_Q \bar{U}^s U^s + (y_Q \bar{Q}^d \tilde{\Phi} U^s + \text{h.c.}) \Big) - n_D \Big(M_Q \bar{D}^s D^s + (y_Q \bar{Q}^d \Phi D^s + \text{h.c.}) \Big)$$
$$- n_L M_L \bar{L}^d L^d - n_N \Big(M_L \bar{N}^s N^s + (y_L \bar{L}^d \tilde{\Phi} N^s + \text{h.c.}) \Big) - n_E \Big(M_L \bar{E}^s E^s + (y_L \bar{L}^d \Phi E^s + \text{h.c.}) \Big)$$

Vector-like fermions in this study - masses

- VLF physical masses after SSB and mass matrix diagonalization:

$$M_{F_{1/2}} = M_F \pm \frac{\sqrt{2}}{2} v\, y_F$$

- Experimental constraints from direct searches:
  ATLAS, 2201.07045
  CMS, 2201.02227

$$M_{VLF} \gtrsim 1 \text{ TeV}$$

Real scalar singlet (with $\mathbb{Z}_2$ symmetry)

SM extension studied in various contexts, such as:

- Electroweak phase transition and collider phenomenology, D. Curtin et al., 1409.0005
- Electroweak phase transition and gravitational waves, J. Ellis et al., 2210.16305
- Dark matter, M. Gonderinger et al., 0910.3167

$$V(\Phi, S) = V_{SM}(\Phi) + \frac{1}{2}\mu_S^2\, S^2 + \frac{1}{2}\lambda_{HS}\, \Phi^\dagger\Phi\, S^2 + \frac{1}{4}\lambda_S\, S^4$$

$$V_{SM}(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2\,, \quad \Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + H + iG^0\right) \end{pmatrix}$$

Scalar masses after SSB (assuming $\langle S \rangle = 0$):

$$M_H^2 = 2\lambda v^2 = 2\mu^2, \quad M_S^2 = \mu_S^2 + \frac{1}{2}\lambda_{HS} v^2$$

Our goal in this work

Study the impact of theoretical constraints on three classes of models

- Class A - models with SM extended by vector-like fermions only
- Class B - models with SM extended by real scalar only
- Class C - models extended by both, vector-like fermions and real scalar

Three conditions - source of theoretical constraints

1. **Stability of the electroweak vacuum up to the cut-off scale Λ**

$$\lambda(\mu) > 0 \quad \text{for} \quad \mu \leq \Lambda$$

2. **Perturbativity of the model couplings up to the cut-off scale Λ**

$$\kappa_i(\mu) \leq 4\pi \quad \text{for} \quad \mu \leq \Lambda$$

3. **Stability of the perturbative expansion up to the cut-off scale Λ**

$$\min_{[\mu,\mu\times 10^{\delta}]} \left| \frac{\beta_{\kappa_i}^{(2-\text{loop})}(\mu)}{\beta_{\kappa_i}^{(1-\text{loop})}(\mu)} \right| \leq \Delta \quad \text{for} \quad \mu \leq \Lambda$$

where $\kappa_i = (\lambda, y_t^2, g_1^2, g_2^2, g_3^2, y_F^2, \lambda_{HS}, \lambda_S)$ and for most of the analysis $\Delta = 0.4$

Additional remarks #1

- Our conditions (and resulting constraints) are based on 2-loop renormalization group equations (RGEs) obtained and cross checked using `SARAH`, `RGBeta`
- For any given $\kappa_i = (\lambda, y_t^2, g_1^2, g_2^2, g_3^2, y_F^2, \lambda_{HS}, \lambda_S)$ we have:

$$\beta_{\kappa_i} = \beta_{\kappa_i}^{SM} + \beta_{\kappa_i}^{VLF} + \beta_{\kappa_i}^{S} + \beta_{\kappa_i}^{VLF\times S}$$

and:

$$\frac{d\kappa_i(\mu)}{d\ln\mu} = \beta_{\kappa_i}\left(\kappa_j(\mu)\right) \equiv \beta_{\kappa_i}$$

- For example at 1-loop:

$$\beta_\lambda^{SM(1)} = \frac{1}{16\pi^2}\left[\frac{9}{8}\left(\frac{3}{25}g_1^4 + g_2^4 + \frac{2}{5}g_1^2 g_2^2\right) - 6y_t^4 + 24\lambda^2 + 12y_t^2\lambda - \frac{9}{5}g_1^2\lambda - 9g_2^2\lambda\right]$$

$$\beta_\lambda^{VLF(1)} = \frac{1}{16\pi^2}\left[2n_{F_1}N_c'\left(4y_{F_1}^2\lambda - 2y_{F_1}^4\right) + 2n_{F_2}N_c'\left(4y_{F_2}^2\lambda - 2y_{F_2}^4\right)\right], \quad \beta_\lambda^{S(1)} = \frac{1}{16\pi^2}\left[\frac{1}{2}\lambda_{HS}^2\right]$$

Additional remarks #2

- We treat considered models as effective valid up to a given cut-off energy scale Λ
- We include contributions from new particles to the RGE β-functions only for $\mu \geq M_F$ and $\mu \geq M_S$
- Input parameters used in this analysis are set following D. Butazzo et al., 1307.3536, with updated experimental input parameters taken as central values from R. L. Workman et al., PDG 2022:

$$M_t = 172.83\ \text{GeV}, \quad g_1\left(M_{\text{t}}\right) = \sqrt{5/3} \times g' = \sqrt{5/3} \times 0.358144$$
$$g_2\left(M_{\text{t}}\right) = 0.64772, \quad g_3\left(M_{\text{t}}\right) = 1.1646, \quad y_{\text{t}}\left(M_{\text{t}}\right) = 0.93436, \quad \lambda\left(M_{\text{t}}\right) = 0.12637$$

Part II - Parameter space

Class A - models with SM extended by vector-like fermions

Vector-like fermions and running of λ

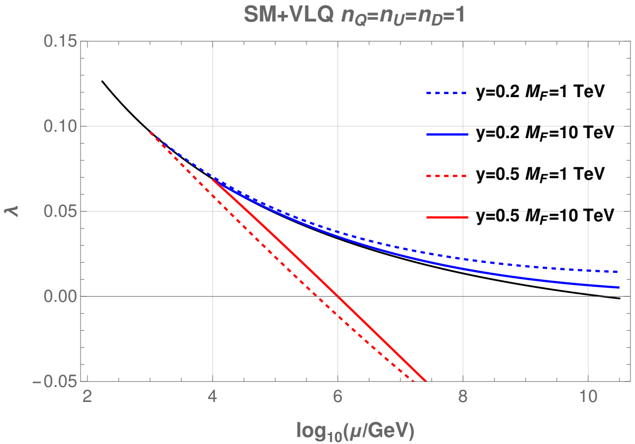
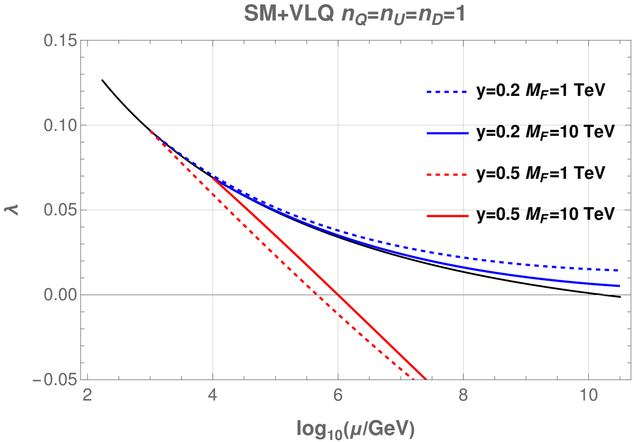


Figure: Running of λ coupling for chosen values of M_F and y. Black line indicates λ in the SM.

Vector-like fermions and running of λ



- VLF affect stability of the electroweak vacuum - condition #1
- No problems with perturbativity - conditions #2 and #3

Parameter space of VLF scenarios #1

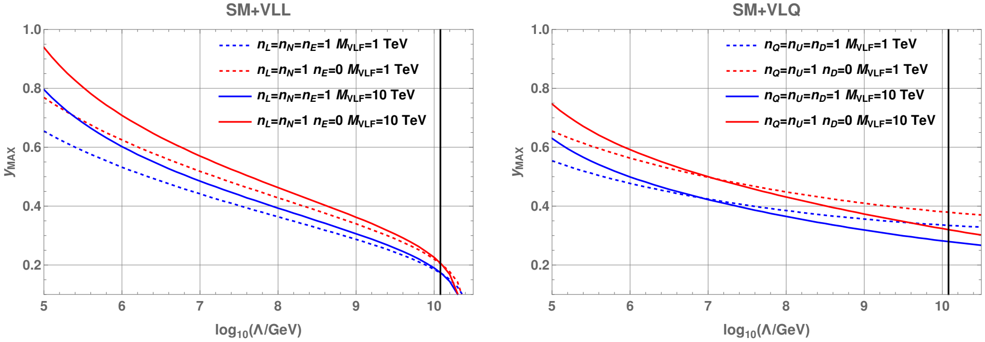
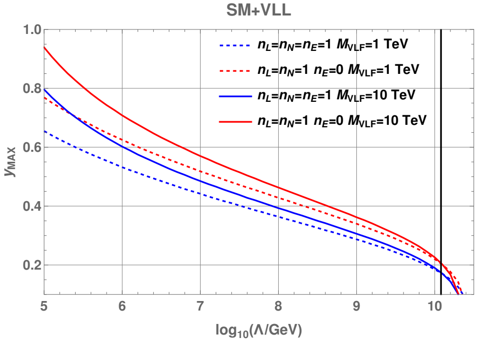
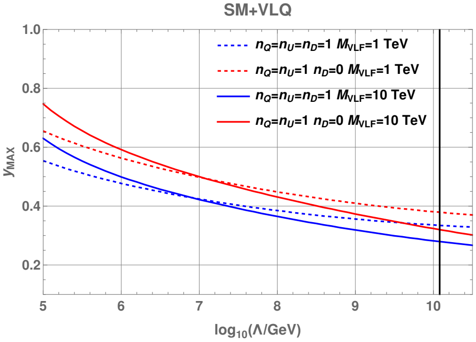


Figure: Maximal values of VLF Yukawa coupling for which stability condition is satisfied up to the given scale μ. The vertical lines indicate the scale of the SM stability breakdown.

Parameter space of VLF scenarios #1





- Maximal value of VLF Yukawa $y < 1$ due to the vacuum stability - condition #1

Parameter space of VLF scenarios #2

	Scenario	y_{MAX}	
		$M_F = 1$ TeV	$M_F = 10$ TeV
VLQ	$n_Q = n_U = n_D = 1$	0.55	0.63
	$n_Q = n_U = 1 \; n_D = 0$	0.66	0.75
VLL	$n_L = n_E = n_N = 1$	0.66	0.80
	$n_L = n_N = 1 \; n_E = 0$	0.77	0.94

Table: Maximal values of VLF Yukawa couplings allowed by the vacuum stability condition up to the scale $\Lambda = 100$ TeV for two values of M_F.

- Magnitude of VLF Yukawa y dictates the impact on phenomenology
- $y < 1$ too low to be significant!

Class B - models with SM extended by real scalar only

Real scalar singlet S and running of λ

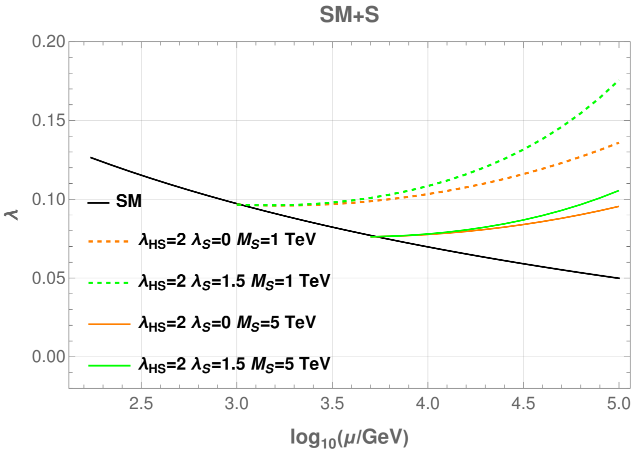
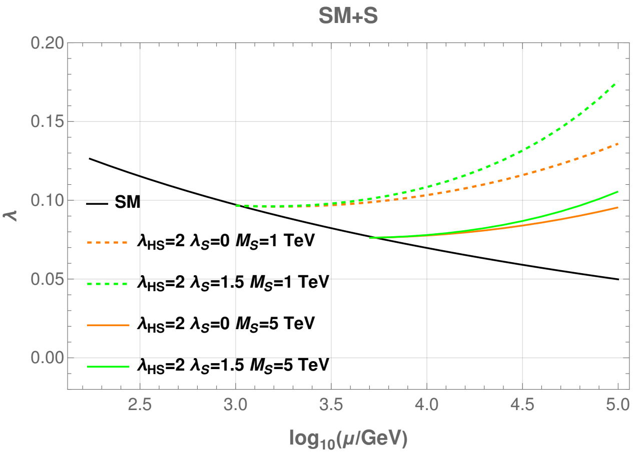


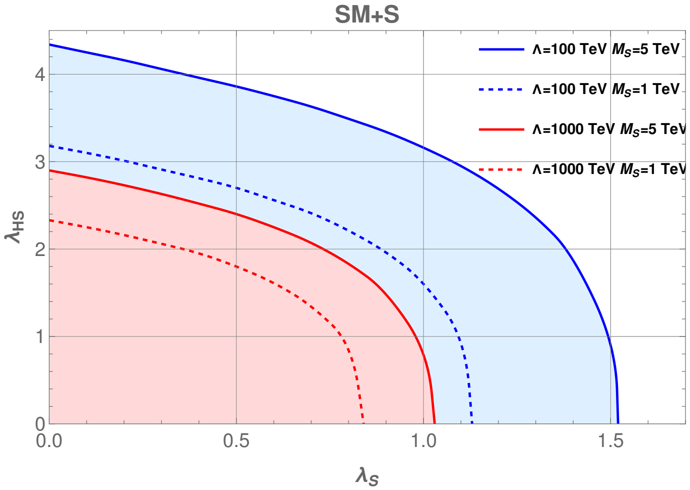
Figure: Impact of scalar couplings λ_{HS}, λ_S and mass M_S on running of λ.

Real scalar singlet S and running of λ



- Non-zero scalar couplings λ_{HS} and λ_S improve stability - condition $\#1$
- But may lead to problems perturbativity - conditions $\#2$ and $\#3$

Real scalar singlet S parameter space #1



- Perturbativity conditions #2 and #3 constrain S parameter space

Real scalar singlet S parameter space #2

λ_{HS}^{max}				
λ_S	$M_S = 1$ TeV	$M_S = 5$ TeV	$M_S = 1$ TeV	$M_S = 5$ TeV
	$\Lambda = 100$ TeV		$\Lambda = 1000$ TeV	
0	3.18	4.34	2.33	2.90
1	1.60	3.16	-	1.03

Table: Maximal allowed values of λ_{HS} in the SM extended by real singlet satisfying perturbativity conditions for selected values of λ_S, Λ and M_S.

- Perturbativity conditions #2 and #3 constrain S parameter space
- Magnitude of λ_{HS} (and to some extent λ_S) dictates the impact on phenomenology
- Obtained values are lower than in the literature (see e.g. 1409.0005)

Class C - models with SM extended by VLF and real scalar

Can S lead to larger values of VLF Yukawas?

Combined impact of VLF and S on running of λ

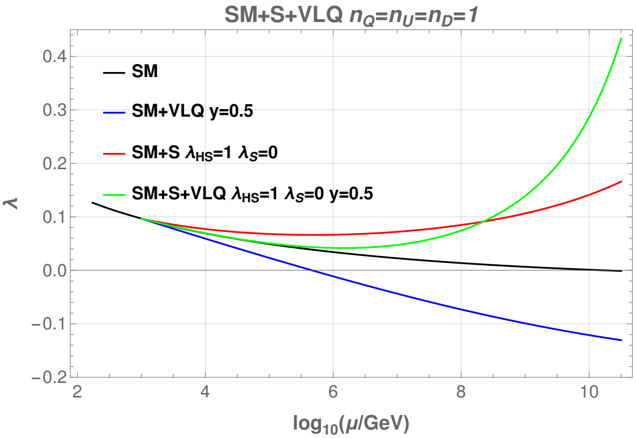
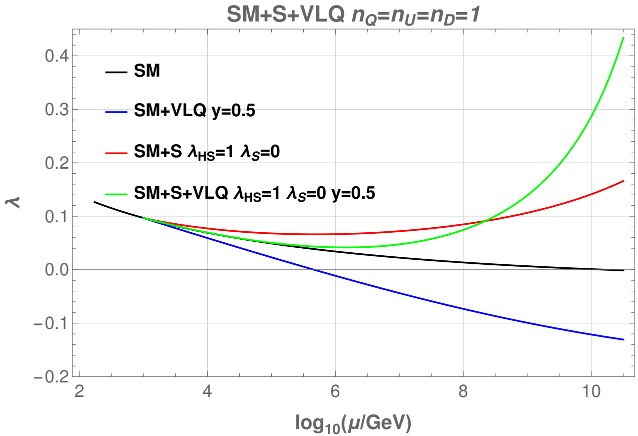


Figure: Running of λ in a combined SM+S+VLF model for $M_S = 1$ TeV and $M_F = 1$ TeV.

Combined impact of VLF and S on running of λ



- VLF lead to problems with vacuum stability - condition #1
- S leads to problems with perturbativity - conditions #2 and #3
- Combining VLF and S - conditions #1, #2 and #3

Parameter space of SM+S+VLF model #1

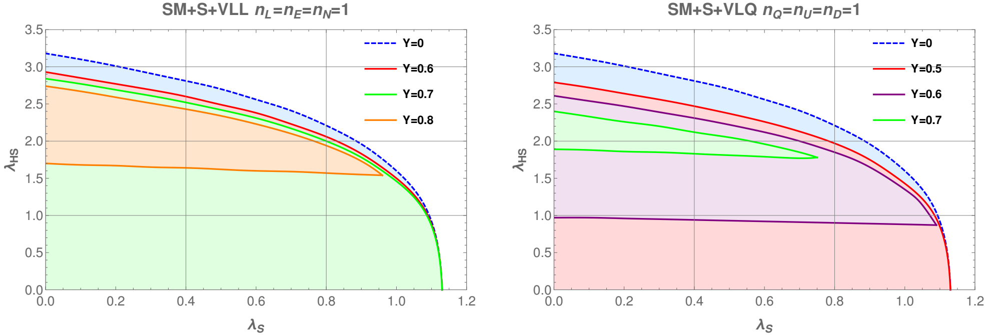


Figure: Allowed regions of the singlet scalar couplings in the SM extended by real singlet and VLF for the cut-off scale $\Lambda = 100$ TeV with $M_F = M_S = 1$ TeV and for different values of y.

- Lower bounds - stability condition #1
- Upper bounds - perturbativity conditions #2 and #3

Parameter space of SM+S+VLF model #2

Scenario	SM+VLF y_{MAX} $M_F = 1$ TeV	SM+VLF y_{MAX} $M_F = 10$ TeV	SM+S+VLF $\lambda_{HS}^{y_{MAX}}$ $M_F = 1$ TeV	SM+S+VLF y_{MAX} $M_F = 1$ TeV	SM+S+VLF $\lambda_{HS}^{y_{MAX}}$ $M_F = 10$ TeV	SM+S+VLF y_{MAX} $M_F = 10$ TeV
$n_Q = n_U = n_D = 1$	0.55	0.63	2.30	0.74	2.46	0.87
$n_Q = n_U = 1$ $n_D = 0$	0.65	0.74	2.55	0.91	2.66	1.07
$n_L = n_E = n_N = 1$	0.65	0.79	2.59	0.93	2.71	1.16
$n_L = n_N = 1$ $n_N = 0$	0.76	0.92	2.77	1.11	2.85	1.40

Table: Maximal values of VLF Yukawa couplings y_{MAX} and the corresponding values of $\lambda_{HS}^{y_{MAX}}$ for which they can be achieved in the combined VLF + S model for $M_S = 1$ TeV, $\lambda_S = 0$ and two values of M_F.

Addition of S leads to $\approx 50\%$ increase in y_{MAX}!

Gauge coupling unification in the presence of VLF #1

- Unification of pairs of gauge couplings at some energy scale μ_{ij}:

$$\Delta g_{ij} \equiv g_i(\mu_{ij}) - g_j(\mu_{ij}) = 0, \quad i = \{1, 2, 3\}$$

- "Grand" unification when:

$$\mu_{12} = \mu_{13} = \mu_{23}$$

- Grand unification in some of the BSM scenarios (GUT, SUSY, ...)
- Unification scale impacts proton stability
- While not a strict requirement, unification offers interesting insights into BSM physics

What is the impact of VLF multiplets (no impact of S) on the gauge coupling unification?

gauge coupling unification in the presence of VLF #2

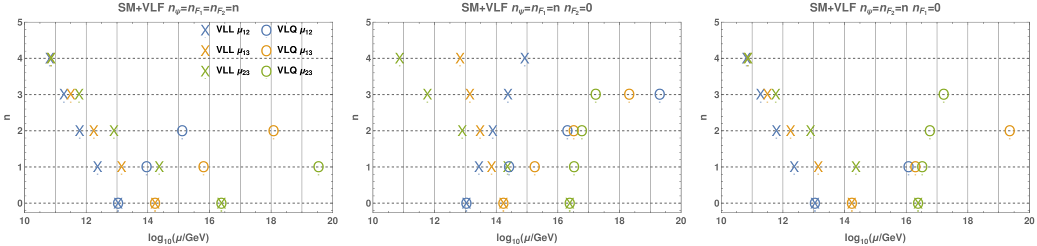


Figure: Energy scales μ_{ij} at which pairs of running gauge couplings have equal values $\Delta g_{ij} = 0$ in models with n families of VLL (crosses) of VLQ (circles) with $y_F = 0$ and $M_F = 3$ TeV.

VLQs with $n_Q = n_U = 2\, n_D = 0$ and $n_Q = n_D = 1\, n_U = 0$ the most advantageous!

Wrapping up parts I and II

1. Class A: purely VLF scenarios are constrained by vacuum stability condition $\#1$ resulting in small allowed values of VLF Yukawa couplings $y < 1$
2. Class B: real scalar S is constrained by perturbativity conditions $\#2$ and $\#3$ resulting in limited $\lambda_{HS} - \lambda_S$ parameter space
3. Class C: joint extension of VLF and S results in moderate (up to $\approx 50\%$) increase in allowed values of VLF Yukawa couplings
4. Some of the studied VLF model scenarios may be advantageous from the point of view of gauge coupling unification

Additional remarks

- Inclusion of additional couplings between SMF-VLF and VLF-S further shrinks allowed parameter space
- Increasing the number of multiplets doesn't drastically change the picture and the impact on phenomenology
- VLF scenarios with $n_{Q/L} = n_{U/N} = 1$, $n_{D/E} = 0$ and $n_{Q/L} = n_{D/E} = 1$, $n_{U/N} = 0$ are very similar (unless stated otherwise, e.g. unification)
- These results do not automatically extend to all possible VLF models, our conditions should be applied in case-by-case basis

Part III - Phenomenology

Double Higgs boson production

Double Higgs boson production and its importance

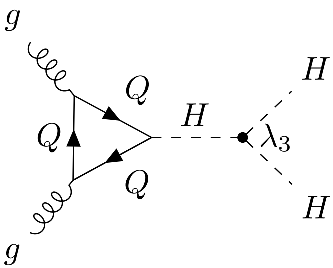
- Understanding Higgs sector and mechanism of EWSB
- Probing Higgs self-coupling λ

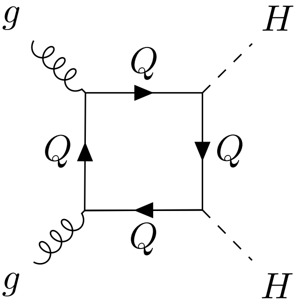
$$V_{SM}(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

- Potential sensitivity to BSM physics,
  with current constraints (LHC $\sqrt{s} = 13$ TeV):

$$\sigma(pp \to hh) \quad < \quad 2.4 \times \sigma^{SM}(pp \to hh) \quad \text{ATLAS, 2211.01216}$$
$$\sigma(pp \to hh) \quad < \quad 3.4 \times \sigma^{SM}(pp \to hh) \quad \text{CMS, 2207.00043}$$

Double Higgs boson production via gluon fusion #1

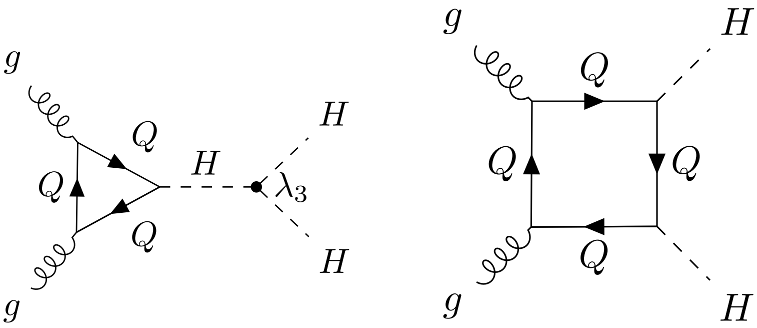




Main production channel, SM & LHC prediction with $\sqrt{s} = 14$ TeV at NNLO
J. Baglio et al., 2008.11626:

$$\sigma_{SM}^{ggF}(pp \to hh) = 36.69^{+6\%}_{-23\%}\ \text{fb}$$

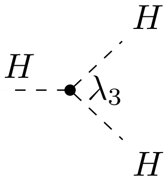
Double Higgs boson production via gluon fusion #2



Two types of BSM contributions:

1. Triple Higgs coupling λ_3 - VLF and S
2. Loop contributions - VLQ

Triple Higgs coupling λ_3



$$\lambda_3 \equiv \lambda_3^{SM} + \Delta\lambda_3^{BSM}$$

Current constraints on $\kappa_{\lambda_3} = \lambda_3/\lambda_3^{SM}$:

$\kappa_{\lambda_3} \in [-0.4, 6.3]$, ATLAS, 2211.01216

$\kappa_{\lambda_3} \in [-1.24, 6.49]$, CMS, 2207.00043

Triple Higgs coupling λ_3 with VLF and S

$$\lambda_3 \equiv \lambda_3^{SM} + \Delta\lambda_3^{BSM} = \lambda_3^{SM} + \Delta\lambda_3^{S} + \Delta\lambda_3^{VLF}$$

$$\Delta\lambda_3^{S} \approx \frac{\lambda_{HS}^3 v^3}{32\pi^2 M_S^2}, \quad \Delta\lambda_3^{VLF} \approx n_{F_1}\frac{N_c' v^3 y_{F_1}^6}{8\pi^2 M_{F_1}^2} + n_{F_2}\frac{N_c' v^3 y_{F_2}^6}{8\pi^2 M_{F_2}^2}$$

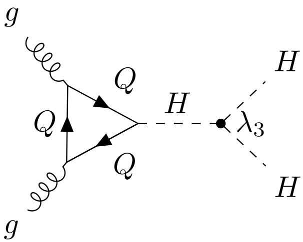
- At most 10% enhancement from S:

$$\frac{\Delta\lambda_3^{S}}{\lambda_3^{SM}} \leq 10\%$$

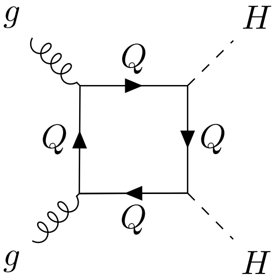
- Negligible contribution from VLF:

$$\frac{\Delta\lambda_3^{VLF}}{\lambda_3^{SM}} \leq 1\%$$

Double Higgs loop contributions with VLQ

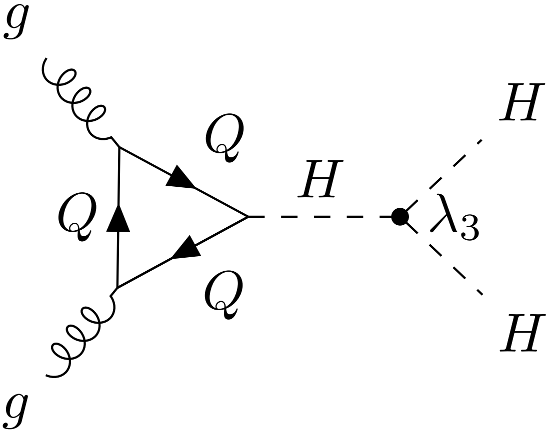


$$\mathcal{M}_{gghh}^{VLQ\triangle} \propto n_U \frac{y_U^2}{M_U^2} + n_D \frac{y_D^2}{M_D^2}$$

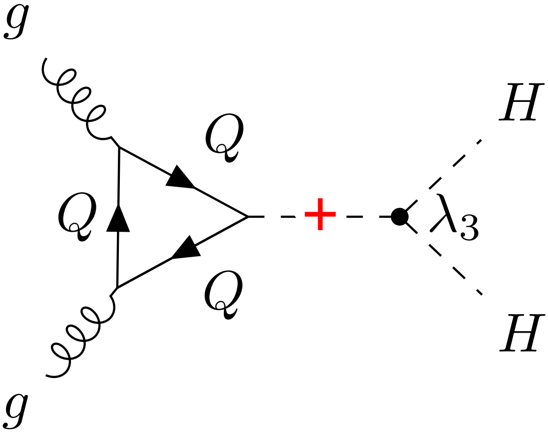


$$\mathcal{M}_{gghh}^{VLQ\square} \propto n_U \frac{y_U^2}{M_U^2} + n_D \frac{y_D^2}{M_D^2}$$

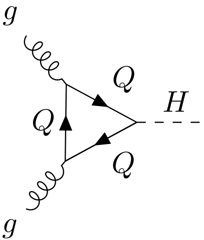
Double and single Higgs production with VLQ



Double and single Higgs production with VLQ



Single Higgs production with VLQ



$$\mathcal{M}_{gghh}^{VLQ\triangle} \propto \mathcal{M}_{gghh}^{VLQ\Box} \propto \mathcal{M}_{ggh}^{VLQ} \propto n_U \frac{y_U^2}{M_U^2} + n_D \frac{y_D^2}{M_D^2}$$

Single Higgs production with VLQ - additional constraints

$$\mathcal{M}_{gghh}^{VLQ\triangle} \propto \mathcal{M}_{gghh}^{VLQ\square} \propto \mathcal{M}_{ggh}^{VLQ} \propto n_U \frac{y_U^2}{M_U^2} + n_D \frac{y_D^2}{M_D^2}$$

$K_H^{VLQ} \leq 10\%(18\%)$ at $68\%(95\%)$ CL, CMS, 2207.00043

$$K_{\text{final}}^{X} = \frac{\sigma_{\text{ggF}}^{SM+X}(pp \to \text{final}) - \sigma_{\text{ggF}}^{SM}(pp \to \text{final})}{\sigma_{\text{ggF}}^{SM}(pp \to \text{final})}$$

Another potential source of constraints on VLQ!

Double Higgs production in the presence of VLF and S

SM+VLQ	y_{MAX}^{RGE}	y_{MAX}^{H}	K_{HH}^{VLQ}	y_{MAX}^{RGE}	y_{MAX}^{H}	K_{HH}^{VLQ}
	68% CL			95% CL		
$n_Q = n_U = n_D = 1$	0.74	**0.65**	+8.4%	**0.74**	0.89	+11.3%
$n_Q = n_U = n_D = 2$	0.60	**0.46**	+8.2%	**0.60**	0.63	+15.0%
$n_Q = n_U = n_D = 3$	0.50	**0.37**	+8.3%	**0.50**	0.51	+15.5%
$n_Q = n_U = 1\ n_D = 0$	**0.91**	0.92	+8.2%	**0.91**	1.26	+8.2%
$n_Q = n_U = 2\ n_D = 0$	0.74	**0.65**	+8.4%	**0.74**	0.89	+11.3%
$n_Q = n_U = 3\ n_D = 0$	0.65	**0.53**	+8.2%	**0.66**	0.73	+13.5%

Table: Maximal enhancement of the double Higgs production cross section from VLQ loop gluon fusion diagrams for $M_F = 1$ TeV.

At most 15% enhancement of double Higgs production!

Electroweak precision observables

Electroweak precision observables (EWPO) - STU parameters

- $\mathbb{S}$, $\mathbb{T}$ and $\mathbb{U}$ oblique parameters parametrize radiative corrections to the self-energies of electroweak gauge bosons
- In the SM: $\mathbb{S} = \mathbb{T} = \mathbb{U} = 0$
- So in the presence of VLF (S doesn't contribute):

$$\mathbb{T} \equiv \mathbb{T}_{VLF}, \quad \mathbb{S} \equiv \mathbb{S}_{VLF}, \quad \mathbb{U} \equiv \mathbb{U}_{VLF}$$

- Current experimental constraints R. L. Workman et al., PDG 2022 (assuming $\mathbb{U} = 0$ due to its suppression):

$$\mathbb{T} = 0.04 \pm 0.6,$$
$$\mathbb{S} = -0.01 \pm 0.07.$$

Can VLF impact significantly these parameters?

Electroweak precision observables - VLF and T parameter

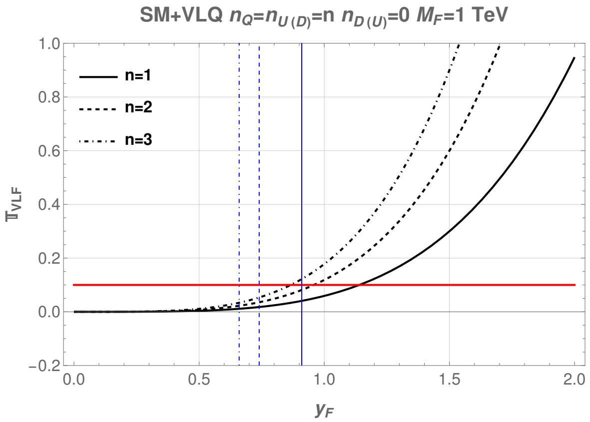
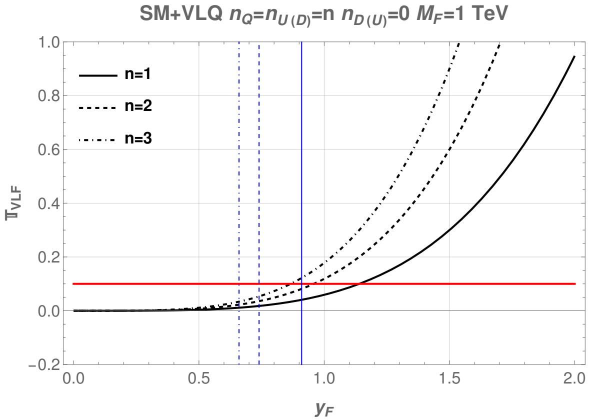


Figure: Value of $\mathbb{T}$ parameter as function of VLF Yukawa coupling y_F (black lines) for different number of VLF families. Also shown: theoretical upper bounds on y_F (blue lines) and experimental upper bound on $\mathbb{T}$ (red line)

Electroweak precision observables - VLF and T parameter



- Theoretical constraints - blue lines - more stringent than experimental - red line

Electroweak precision observables - maximal VLF contributions

SM+VLQ	y_{MAX}^{RGE}	$\mathbb{T}_{VLF}$	$\mathbb{S}_{VLF}$
$n_Q = n_U = n_D = 1$	0.74	0	0.006
$n_Q = n_U = n_D = 2$	0.60	0	0.007
$n_Q = n_U = n_D = 3$	0.50	0	0.008
$n_Q = n_U = 1\ n_D = 0$	0.91	0.041	0.012
$n_Q = n_U = 2\ n_D = 0$	0.74	0.035	0.015
$n_Q = n_U = 3\ n_D = 0$	0.65	0.031	0.018

Table: Maximal contributions to $\mathbb{T}$ and $\mathbb{S}$ oblique parameters for the maximal allowed values of VLQ Yukawa couplings for $M_{VLF} = 1$ TeVs.

Not even close to $\mathbb{T} = 0.04 \pm 0.6$ **and** $\mathbb{S} = -0.01 \pm 0.07$**!**

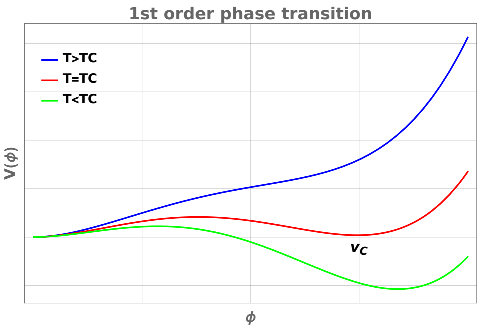
Electroweak phase transition

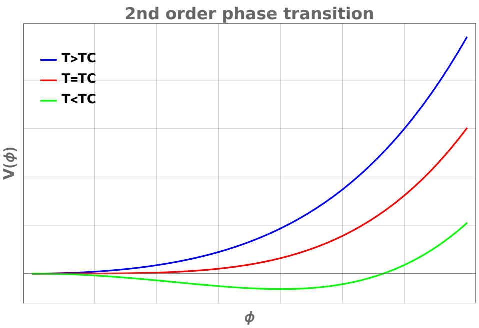
Electroweak phase transition

- Hypothetical process in the early universe
- May play a role in baryogenesis and explanation of matter-antimatter asymmetry
- Leaves detectable traces in gravitational wave signals
- Described through temperature-dependent effective potential of form:

$$V_{\mathrm{eff}}(H, S, T) = V_0(H, S) + V_{CW}(H, S) + V_T(H, S, T)$$

Electroweak phase transition - 1st vs 2nd order





Our interest - strong first order electroweak phase transition!

$$\xi = \frac{v_C(T_C)}{T_C} \gtrsim (0.6 \div 1.0)$$

Electroweak phase transition with real scalar S

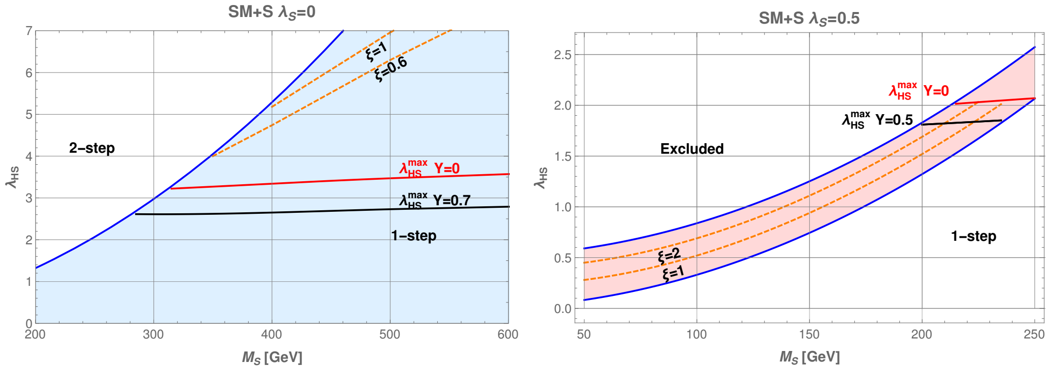
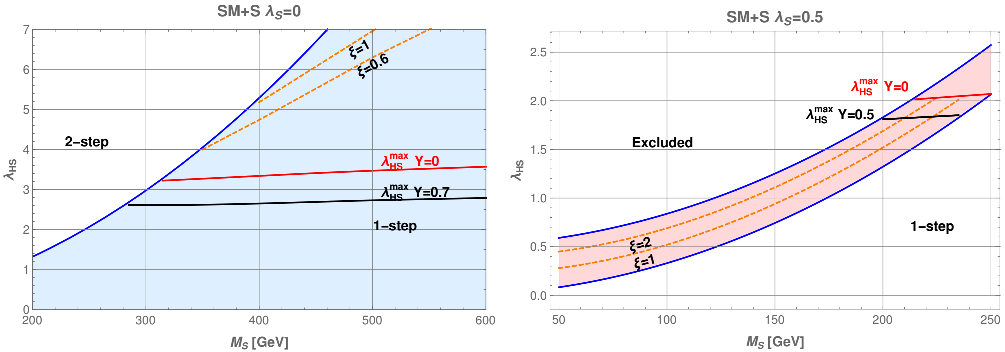


Figure: Parameter space allowing for the 1-step (left panel) and 2-step (right panel) EWPT in the SM extended by S. The orange dashed lines indicate ξ. The red and black lines indicate maximal λ_{HS} allowed by the perturbativity constraints for two values of the VLF Yukawas.

Electroweak phase transition with real scalar S



- **Limited** impact on the strength of EWPT of S within the allowed parameter space in the 1-step region - left panel
- **Detectable** impact on the strength of EWPT of S within the allowed parameter space in the 2-step region - right panel
- **Negligible** impact of VLF on the EWPT within the allowed parameter space

Summary and conclusions

1. Electroweak vacuum stability and perturbativity conditions strongly constrain the allowed parameter space of considered classes of models:
    - Class A - models with SM extended by vector-like fermions only
    - Class B - models with SM extended by real scalar only
    - Class C - models extended by both, vector-like fermions and real scalar
2. This results in a limited or negligible impact on phenomenology:
    - Double Higgs boson production via gluon fusion
    - Electroweak precision observables
    - Electroweak phase transition
3. Our analysis provides independent set of constraints on studied classes of models
4. And suggests the necessity of careful treatment of vacuum stability and perturbativity conditions in future analyses

Thank you!

Additional slides

Additional couplings #1

- SMF-VLF couplings:

$$\mathcal{L} \supset -y_{Qt}\left(\bar{Q}_L^d \tilde{\Phi} t_R + \text{h.c.}\right)$$

- VLF-S couplings:

$$\mathcal{L} \supset -y_{QS}\, S\, \bar{Q}_i^d Q_i^d - y_{US}\, S\, \bar{U}_j^s U_j^s - y_{DS}\, S\, \bar{D}_k^s D_k^s$$

Additional couplings #2

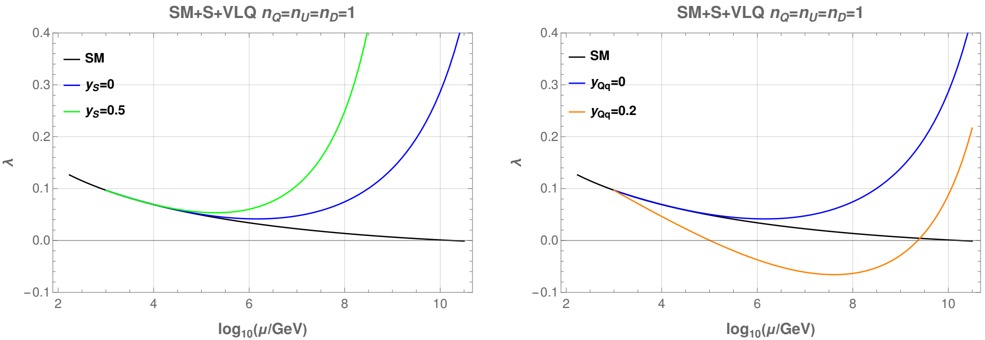
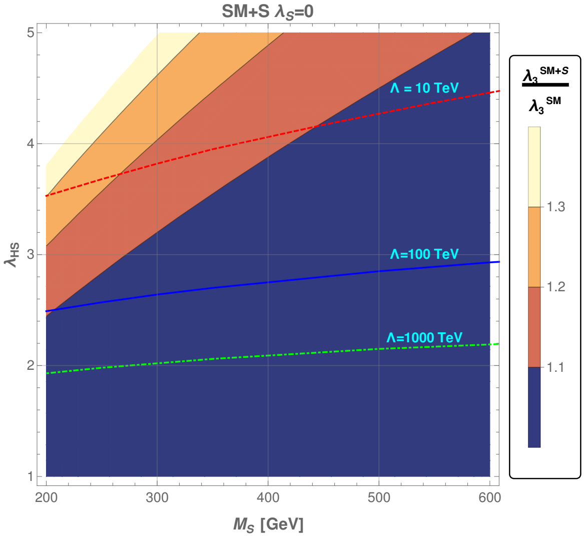


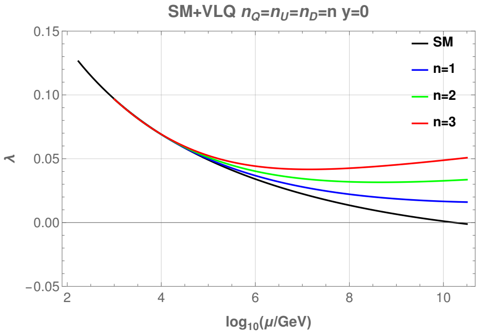
Figure: Running of λ in a combined SM+S+VLF model for $M_S = 1$ TeV and $M_F = 1$ TeV with $y_F = 0.5$, $\lambda_{HS} = 1$ and $\lambda_S = 0$, including VLF-S Yukawa (left) and VLF-SMF (right) coupling.

No "improvement" in parameter space!

Triple Higgs coupling with S



More multiplets #1



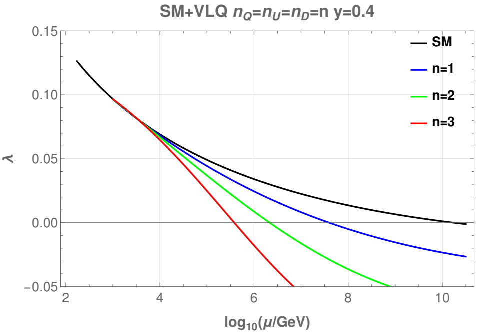


Figure: Impact of varying number of VLQ multiplets on the running of λ for small (vanishing) Yukawa coupling - left panel, and larger Yukawa coupling - rigth panel.

More multiplets #2

	SM+VLL	SM+VLQ
Scenario I	$n_L^{max} = 4$	$n_Q^{max} = 2$
Scenario II	$n_L^{max} = 12$	$n_Q^{max} = 3$
Scenario III	$n_L^{max} = 4$	$n_Q^{max} = 3$

Table: Maximal number of allowed VLF multiplet families based on the perturbativity conditions.

SM 1-loop RGEs

$$\beta_\lambda^{SM(1)} = \frac{1}{16\pi^2}\left[\frac{9}{8}\left(\frac{3}{25}g_1^4 + g_2^4 + \frac{2}{5}g_1^2 g_2^2\right) - 6y_t^4 + 24\lambda^2 + 12y_t^2\lambda - \frac{9}{5}g_1^2\lambda - 9g_2^2\lambda\right]$$

$$\beta_{y_t^2}^{SM(1)} = \frac{y_t^2}{16\pi^2}\left[9y_t^2 - \frac{17}{10}g_1^2 - \frac{9}{2}g_2^2 - 16g_3^2\right]$$

$$\beta_{g_1^2}^{SM(1)} = \frac{1}{16\pi^2}\left[\frac{41}{5}g_1^4\right],$$

$$\beta_{g_2^2}^{SM(1)} = \frac{1}{16\pi^2}\left[-\frac{19}{3}g_2^4\right],$$

$$\beta_{g_3^2}^{SM(1)} = \frac{1}{16\pi^2}\left[-14g_3^4\right].$$

VLF 1-loop RGEs

$$\beta_{\lambda}^{VLF(1)} = \frac{1}{16\pi^2}\left[2n_{F_1}N_c'\left(4y_{F_1}^2\lambda - 2y_{F_1}^4\right) + 2n_{F_2}N_c'\left(4y_{F_2}^2\lambda - 2y_{F_2}^4\right)\right],$$

$$\beta_{y_t^2}^{VLF(1)} = \frac{y_t^2}{16\pi^2}\left[4N_c'\left(n_{F_1}y_{F_1}^2 + n_{F_2}y_{F_2}^2\right)\right],$$

$$\beta_{g_1^2}^{VLF(1)} = \frac{g_1^4}{16\pi^2}\left[\frac{8}{5}N_c'\left(2n_\psi Y_{W_\psi}^2 + n_{F_1}Y_{W_{F1}}^2 + n_{F_2}Y_{W_{F2}}^2\right)\right],$$

$$\beta_{g_2^2}^{VLF(1)} = \frac{1}{16\pi^2}\left[\frac{4}{3}N_c' n_\psi g_2^4\right],$$

$$\beta_{g_3^2}^{VLF(1)} = \frac{1}{16\pi^2}\left[\frac{4}{3}n_3 g_3^4\right],$$

S 1-loop RGEs

$$
\begin{aligned}
\beta_{\lambda}^{S(1)} &= \frac{1}{16\pi^2}\left[\frac{1}{2}\lambda_{HS}^2\right], \\
\beta_{\lambda_{HS}}^{S(1)} &= \frac{\lambda_{HS}}{16\pi^2}\left[12\lambda + 6\lambda_S + 4\lambda_{HS} + 6y_t^2 - \frac{3}{2}g_1^2 - \frac{9}{2}g_2^2\right], \\
\beta_{\lambda_S}^{S(1)} &= \frac{1}{16\pi^2}\left[2\lambda_{HS}^2 + 18\lambda_S^2\right], \\
\beta_{\lambda_{HS}}^{VLF(1)\times S(1)} &= \frac{\lambda_{HS}}{16\pi^2}\left[4N_c'(n_{F_1}y_{F_1}^2 + n_{F_2}y_{F_2}^2)\right].
\end{aligned}
$$

Oblique parameters L. Lavoura, J. P. Silva, 1992

$$\mathbb{T}_{VLF} = \frac{N_c}{8\pi \sin^2\theta_W \cos^2\theta_W} \times \left[\sum_{\alpha,i} \left[|\mathcal{V}_{\alpha i}|^2 \left(\theta_+\left(x_\alpha, x_i\right) + \theta_-\left(x_\alpha, x_i\right)\right)\right] \right.$$

$$\left. - \sum_{\beta<\alpha} \left[|\mathcal{U}_{\alpha\beta}|^2 \left(\theta_+\left(x_\alpha, x_\beta\right) + \theta_-\left(x_\alpha, x_\beta\right)\right)\right] - \sum_{j<i} \left[|\mathcal{D}_{ij}|^2 \left(\theta_+\left(x_i, x_j\right) + \theta_-\left(x_i, x_j\right)\right)\right] \right],$$

$$\mathbb{S}_{VLF} = \frac{N_c}{\pi} \times \left[\sum_{\alpha,i} \left[|\mathcal{V}_{\alpha i}|^2 \left(\psi_+\left(x_\alpha, x_i\right) + \psi_-\left(x_\alpha, x_i\right)\right)\right] \right.$$

$$\left. - \sum_{\beta<\alpha} \left[|\mathcal{U}_{\alpha\beta}|^2 \left(\chi_+\left(x_\alpha, x_\beta\right) + \chi_-\left(x_\alpha, x_\beta\right)\right)\right] - \sum_{j<i} \left[|\mathcal{D}_{ij}|^2 \left(\chi_+\left(x_i, x_j\right) + \chi_-\left(x_i, x_j\right)\right)\right] \right],$$

$$x_{i(\alpha)} \equiv M^2_{i(\alpha)}/M_Z^2,$$

$$\theta_+\left(x_1, x_2\right) \equiv x_1 + x_2 - \frac{2x_1x_2}{x_1 - x_2} \ln\frac{x_1}{x_2}, \quad \theta_-\left(x_1, x_2\right) \equiv 2\sqrt{x_1x_2}\left(\frac{x_1 + x_2}{x_1 - x_2}\ln\frac{x_1}{x_2} - 2\right)$$

Effective potential #1

Coleman-Weinberg part of the potential in on-shell renormalization scheme with cutoff regularisation reads:

$$
\begin{aligned}
V_{CW}(H) = \sum_k \frac{r_k N_k}{64\pi^2}\left(2M_k^2(H)M_k^2(v) + M_k^4(H)\left(\log\frac{M_k^2(H)}{M_k^2(v)} - \frac{3}{2}\right)\right) \\
-\frac{N_F}{64\pi^2}\sum_{i=1,2} n_{F_i}\left(M_{F_i}(H)^4\left(\log\frac{M_{F_i}(H)^2}{\mu_R^2} - \frac{3}{2}\right) + C_1\phi^2 + C_2\phi^4\right),
\end{aligned}
$$

$r_k = +(-)$ for bosons (fermions), we use the following notation:

$$
\begin{aligned}
k &= (t, W, Z, h, S), \quad N_k = (12, 6, 3, 1, 1), \\
M_k(H)^2 &= M_{0,k}^2 + a_k h^2, \quad M_{0,k}^2 = \left(0, 0, 0, -\mu^2,\ \mu_S^2\right), \\
a_k &= \left(\frac{\lambda_t^2}{2}, \frac{g^2}{4}, \frac{g^2 + g'^2}{4}, 3\lambda, \frac{1}{2}\lambda_{HS}\right).
\end{aligned}
$$

$$
\begin{aligned}
F &= (VLQ, VLL), \quad N_F = (12, 4) \\
n_{F_1} &\in \{n_U, n_N\}, \quad n_{F_2} \in \{n_D, n_E\}, \\
M_{F_{1(2)}} &= M_F \pm \frac{\sqrt{2}}{2} y_F v,
\end{aligned}
$$

Effective potential #2

Renormalization conditions:

$$\frac{\partial}{\partial\phi} V_{CW}\bigg|_{\phi=v} = 0 \qquad \frac{\partial^2}{\partial\phi^2} V_{CW}\bigg|_{\phi=v} = 0.$$

Effective potential #3

$$V_T(H,S,T) = \sum_k \frac{N_k T^4}{2\pi^2} J_{r_k}\left(M_k(H,S)/T\right) + N_F \sum_{i=1,2} \frac{n_{F_i} T^4}{2\pi^2} J_-\left(M_{F_i}(H,S)/T\right),$$

$$J_\pm(y) = \pm \int_0^\infty \mathrm{d}x x^2 \log\left[1 \mp e^{-\sqrt{x^2+y^2}}\right].$$

Thermal contributions to masses:

$$\begin{aligned}
\Pi_H(0) &= \left(\frac{3g^2}{16} + \frac{g'^2}{16} + \frac{\lambda}{2} + \frac{y_t^2}{4} + \frac{1}{2}\sum_F y_F^2 + \frac{\lambda_{HS}}{24}\right) T^2, \\
\Pi_s(0) &= \left(\frac{1}{6}\lambda_{HS} + \frac{1}{4}\lambda_S\right) T^2, \\
\Pi_{GB}^L(0) &= \frac{11}{6} T^2 \,\mathrm{diag}\left(g^2, g^2, g^2, g'^2\right).
\end{aligned}$$