Unification and light vectorlike fermions

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Outline

Insensitive unification of gauge couplings:

- understanding values of gauge couplings from particle content
- extensions of the SM or MSSM by complete vector-like families

Possible phenomenological consequences:

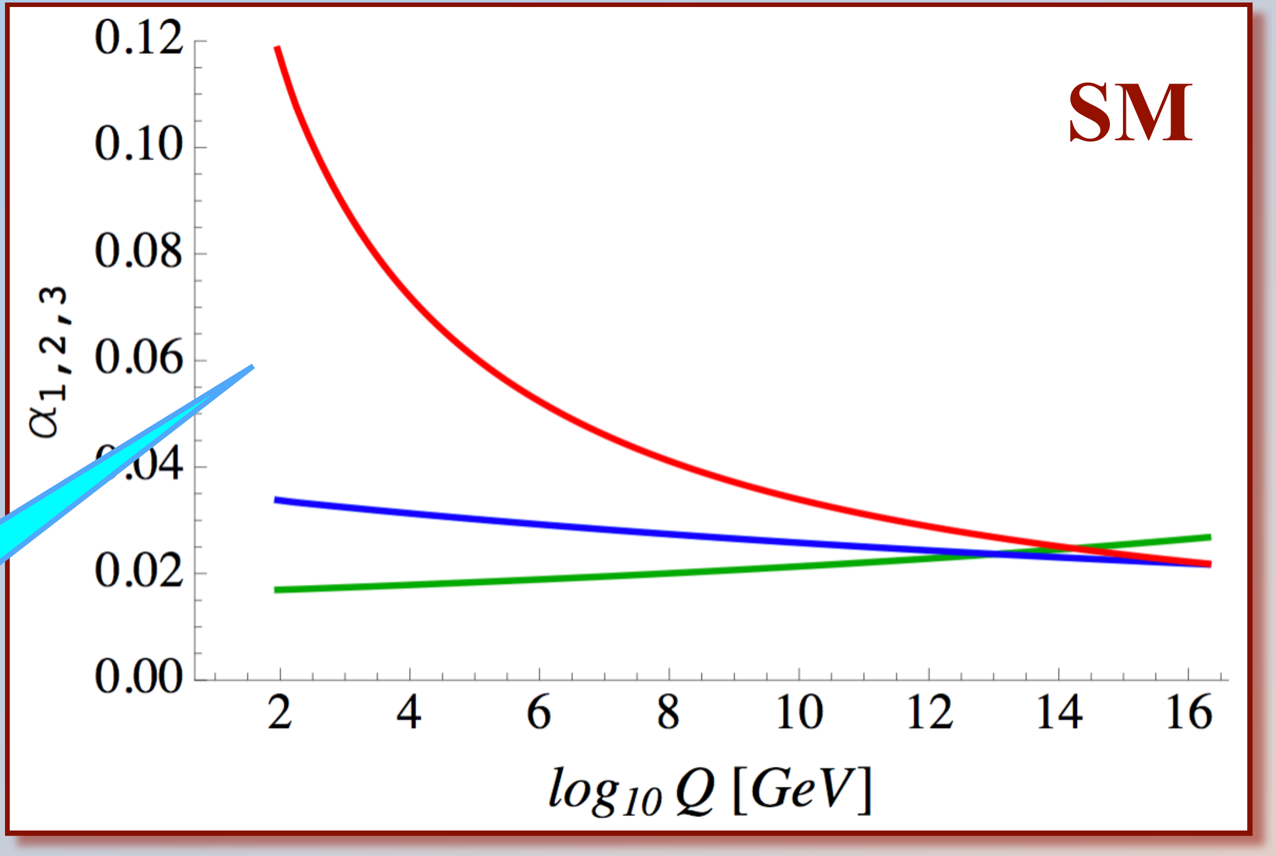
- muon g-2, $h \to \mu\mu$, $h \to \gamma\gamma$, $h \to ZZ^*$, $h \to WW^*$, …
- new (possibly discovery) decay modes for heavy Higgs bosons

Proton decay

Gauge couplings in the standard model

$\alpha_3(M_Z)_{exp} = 0.1184$
$\alpha_2(M_Z)_{exp} = 0.03380$
$\alpha_1(M_Z)_{exp} = 0.01695$

$\alpha_{EM}(M_Z) = 1/127.916$
$\sin^2\theta_W = 0.2313$



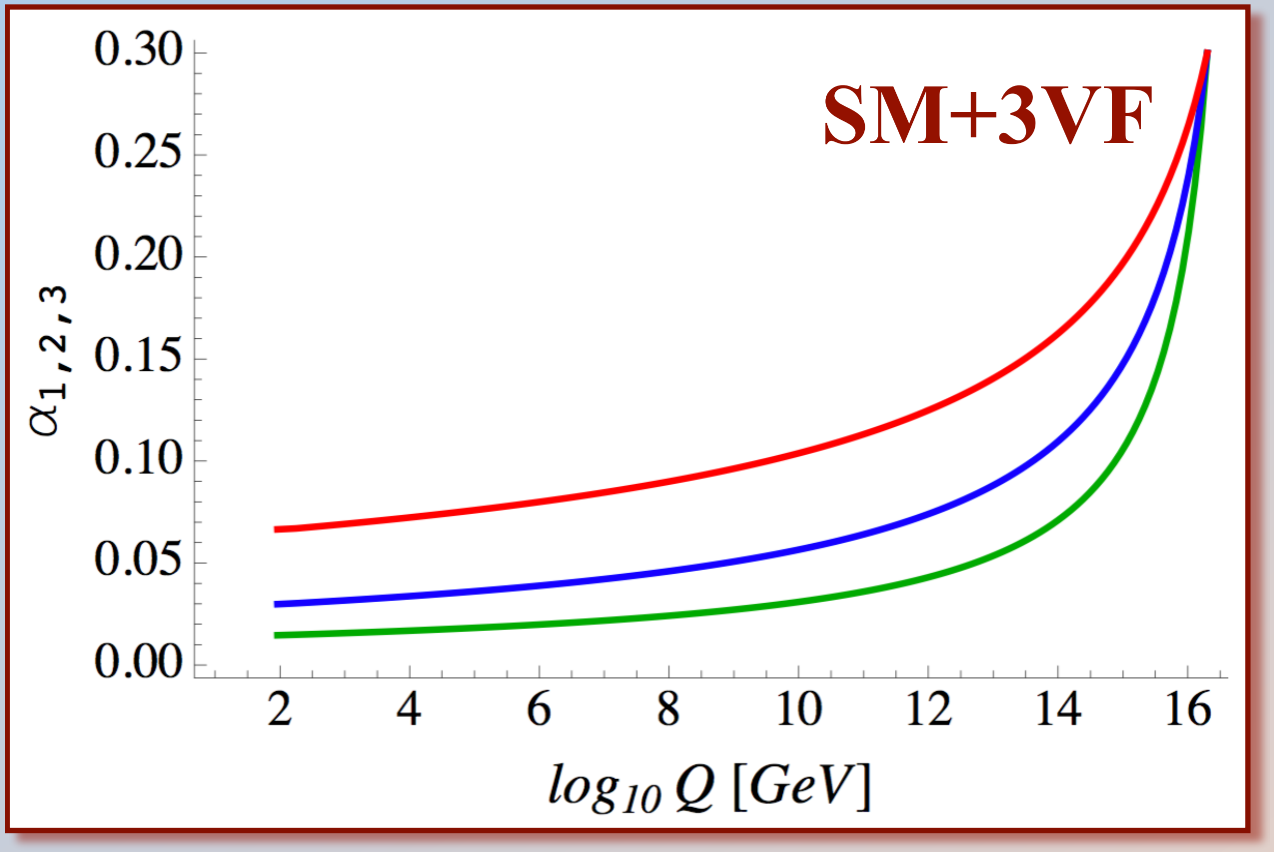
couplings run away from each other, ratios sensitive to boundary conditions

solution to RGEs:

$$\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi}\ln\frac{M_G}{M_Z} + \alpha_i^{-1}(M_G)$$

$b_i = (41/10,\ -19/6,\ -7)$

Gauge couplings in the SM + 3VFs



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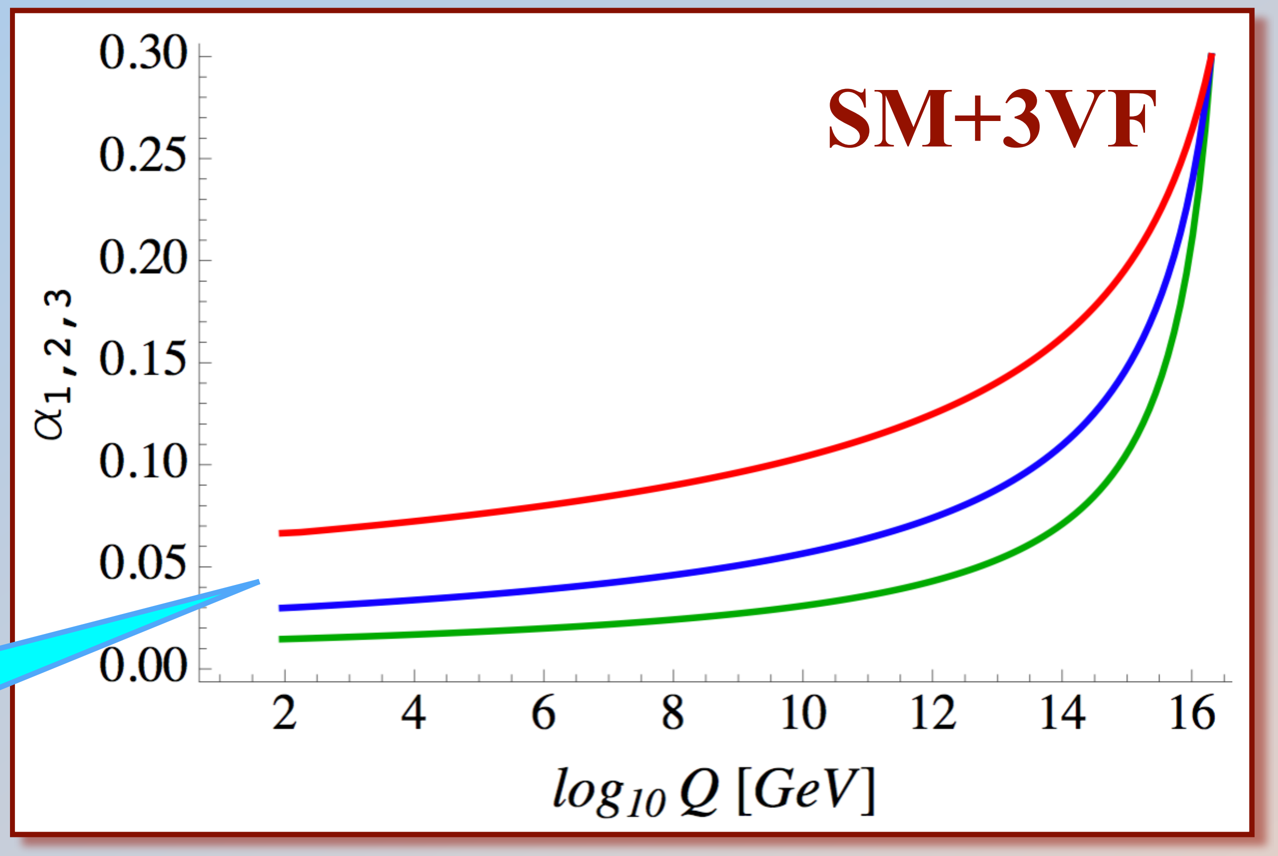
$$b_i \;=\; (121/10,\;\; 29/6,\;\; +1)$$

Gauge couplings in the SM + 3VFs



couplings run to fixed ratios, insensitive to boundary conditions

solution to RGEs:

$$\boxed{\alpha_i^{-1}(M_Z) \;=\; \frac{b_i}{2\pi}\ln\frac{M_G}{M_Z} + \alpha_i^{-1}(M_G)}$$

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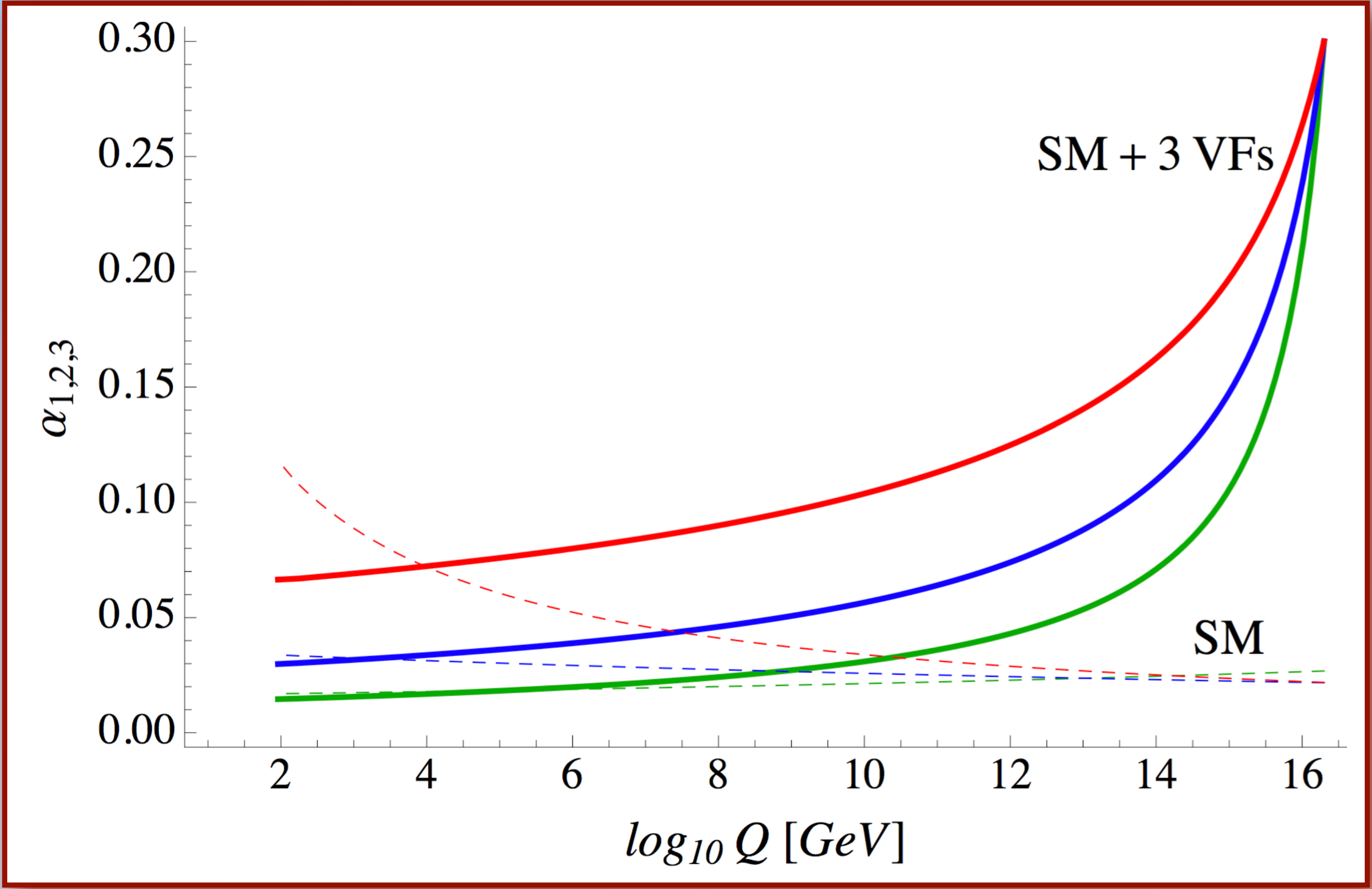
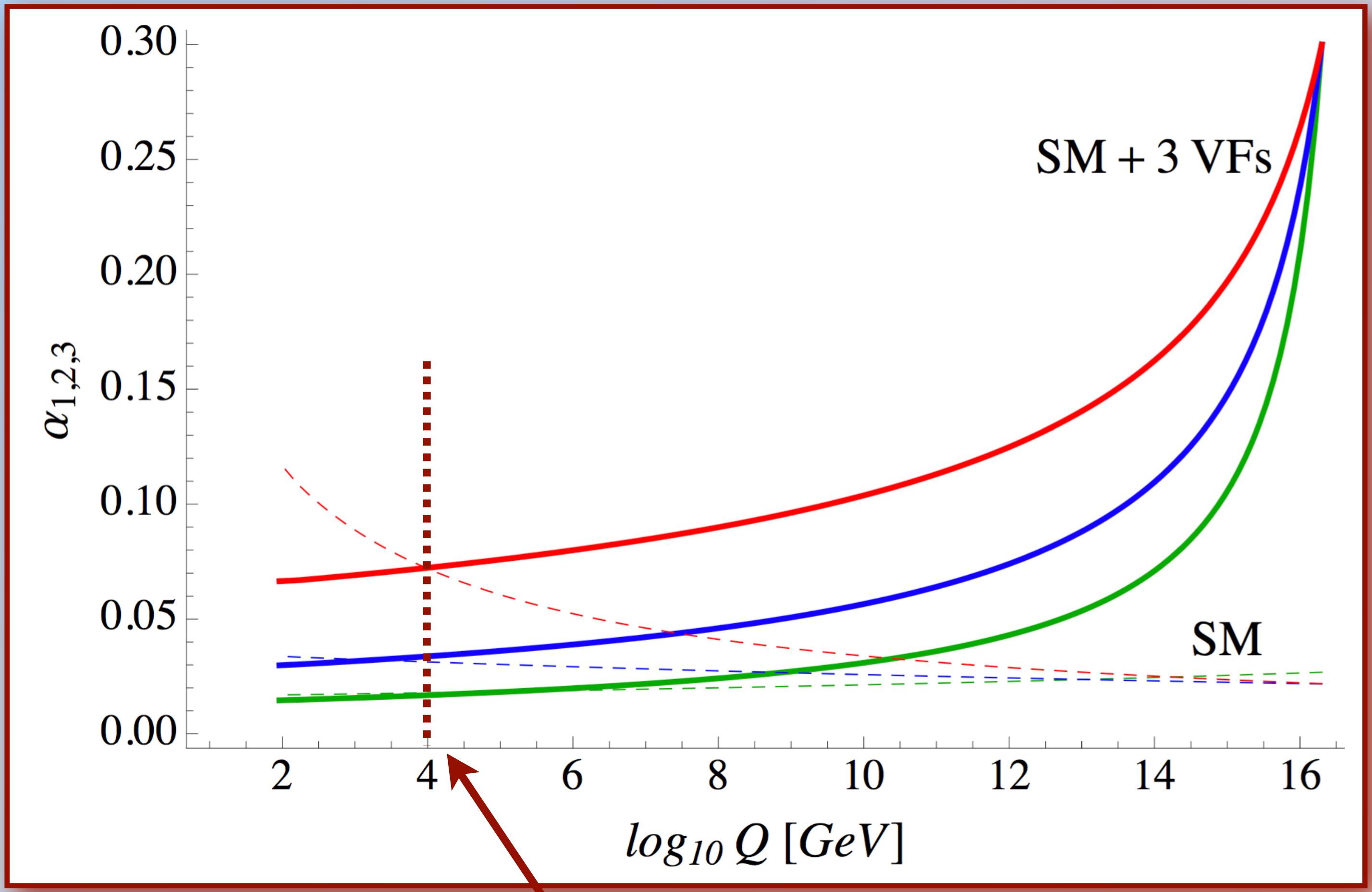
Gauge couplings in the SM + 3VFs

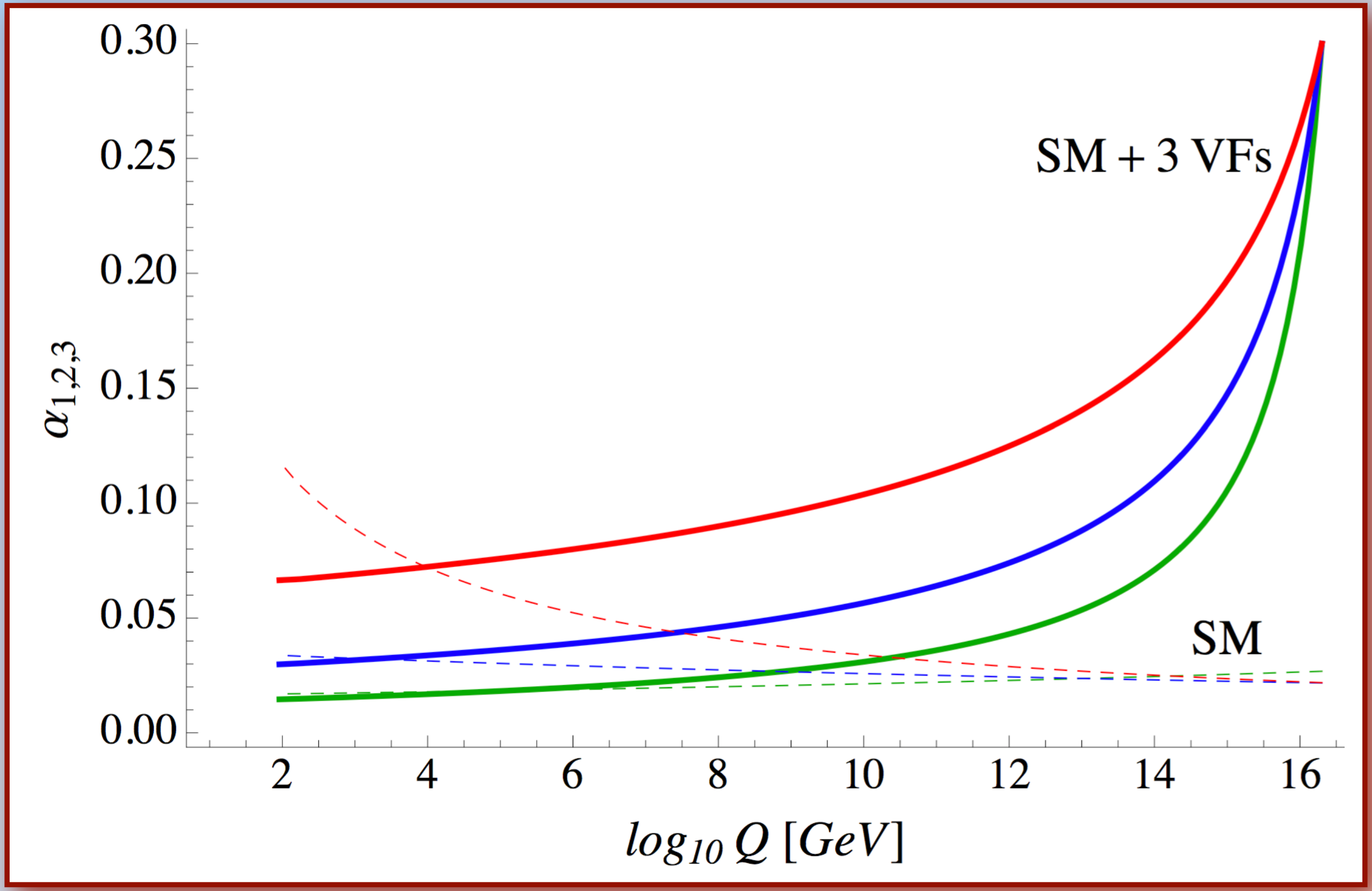


Gauge couplings in the SM + 3VFs



Is this a threshold effect?

Gauge couplings in the SM + 3VFs



$$\frac{\alpha_i(M_Z)}{\alpha_j(M_Z)} \simeq \frac{b_j}{b_i}$$

$$\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi}\ln\frac{M_G}{M_Z} + \alpha_i^{-1}(M_G)$$

gauge couplings understood from:

- **IR fixed point predictions (two parameter free predictions)**

$$\sin^2\theta_W \equiv \frac{\alpha'}{\alpha_2+\alpha'} = \frac{b_2}{b_2+b'} = 0.193$$

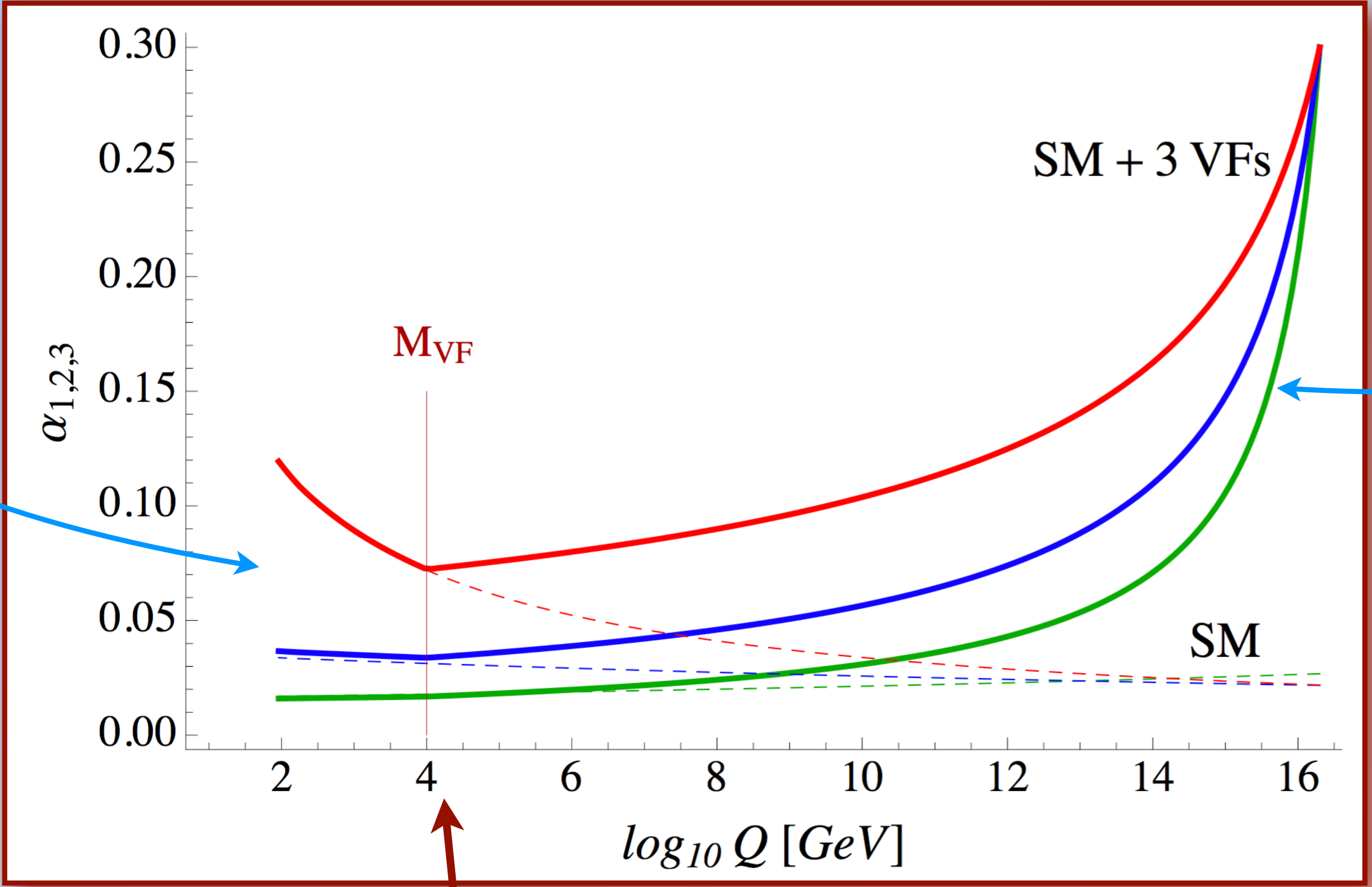
Maiani, Parisi, and Petronzio (1978)

$$\alpha_3\big|_{\alpha_{EM}^{exp}} \simeq 0.072$$

(includes 2-loop)

Gauge couplings in the SM + 3VFs

$b_i = (41/10,\ -19/6,\ -7)$



$b_i = (121/10,\ 29/6,\ +1)$

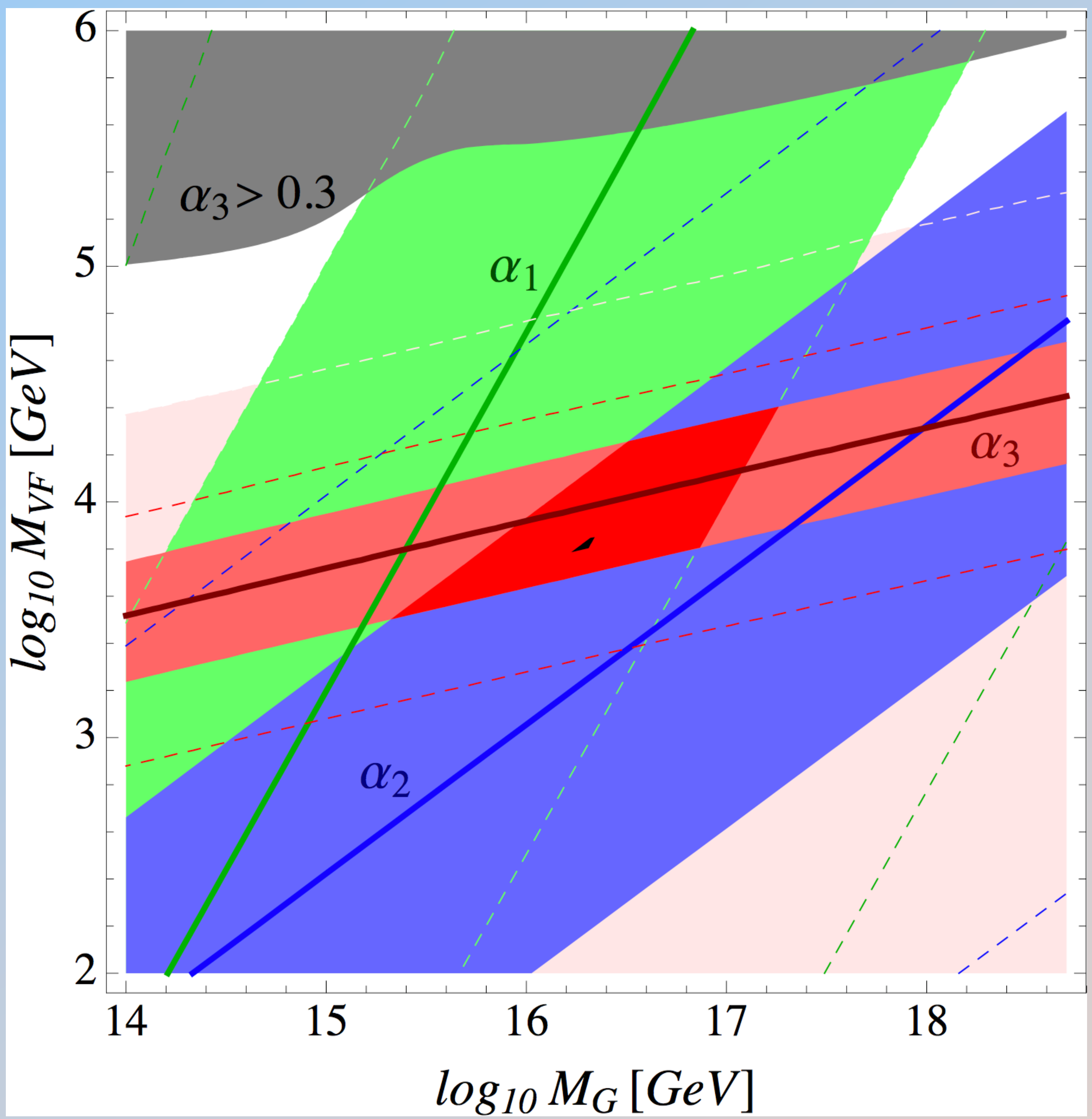
$$\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi} \ln \frac{M_G}{M_Z} + \alpha_i^{-1}(M_G)$$

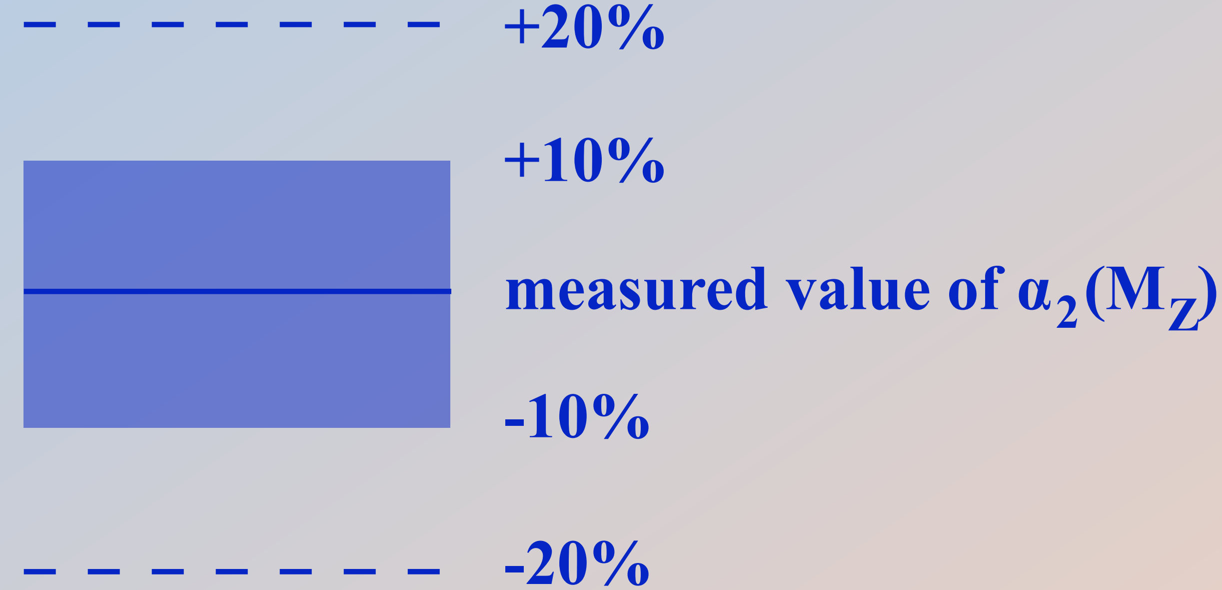
gauge couplings understood from:

- **IR fixed point predictions** **(two parameter free predictions)**
- **threshold effects from masses of VFs**

Ranges of M_G and M_{VF}

$\alpha_G = 0.3$ (for larger values results almost identical)





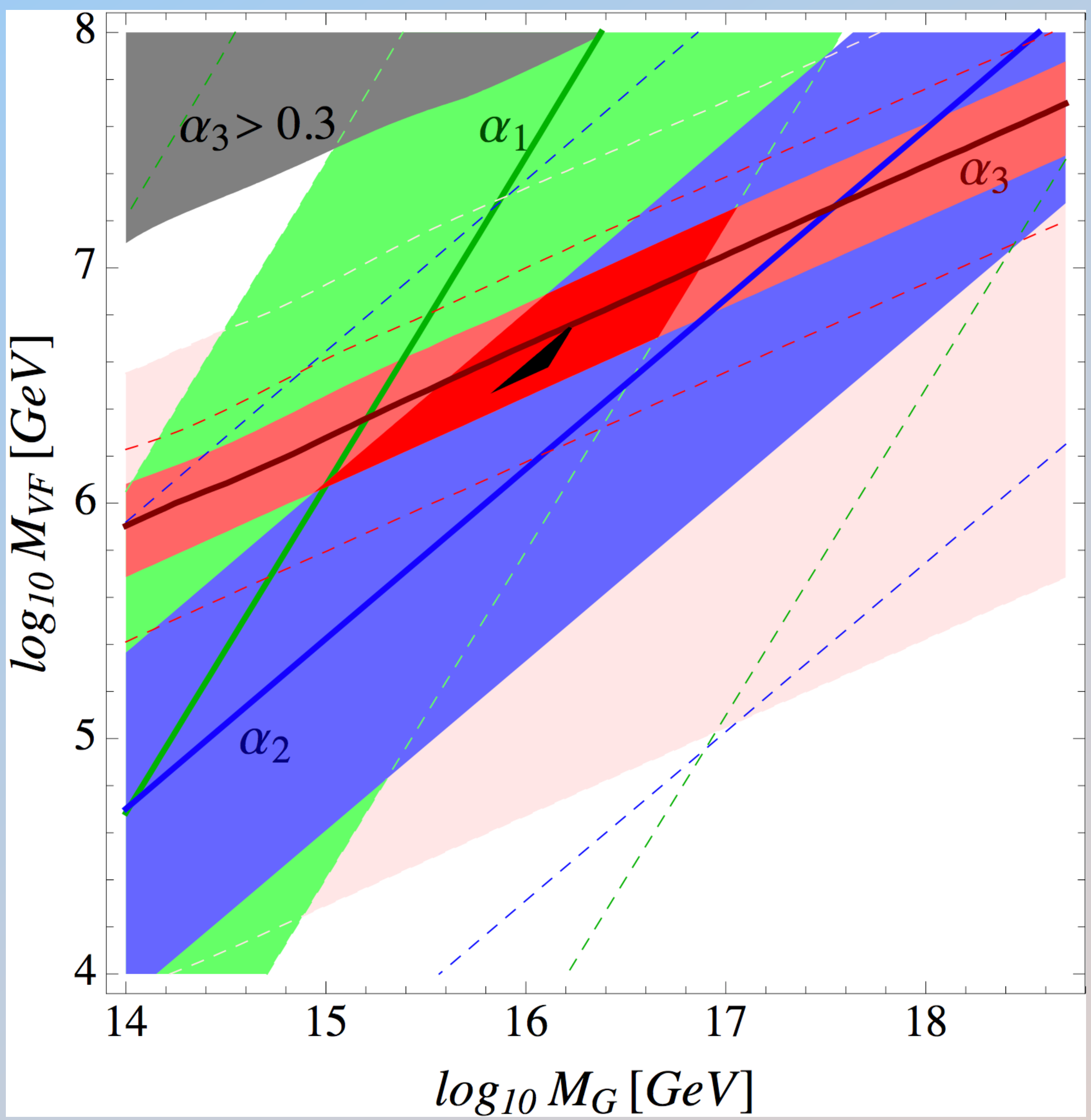
● **the best fit (all three couplings within 6%)**

Gauge couplings at M_Z within 10% in a large range of parameters!

And within 50% in basically the whole range!

Ranges of M_G and M_{VF} for SM+4VFs

$\alpha_G = 0.3$ (for larger values results almost identical)



+20%

+10%

measured value of $\alpha_2(M_Z)$

-10%

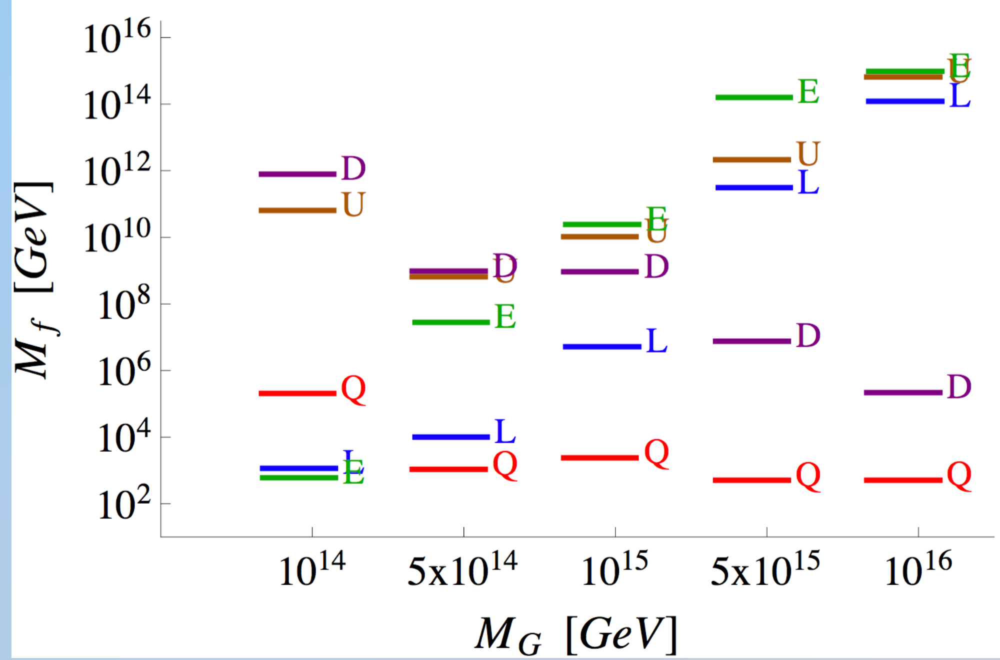
-20%

● the best fit
(all three couplings within 6%)

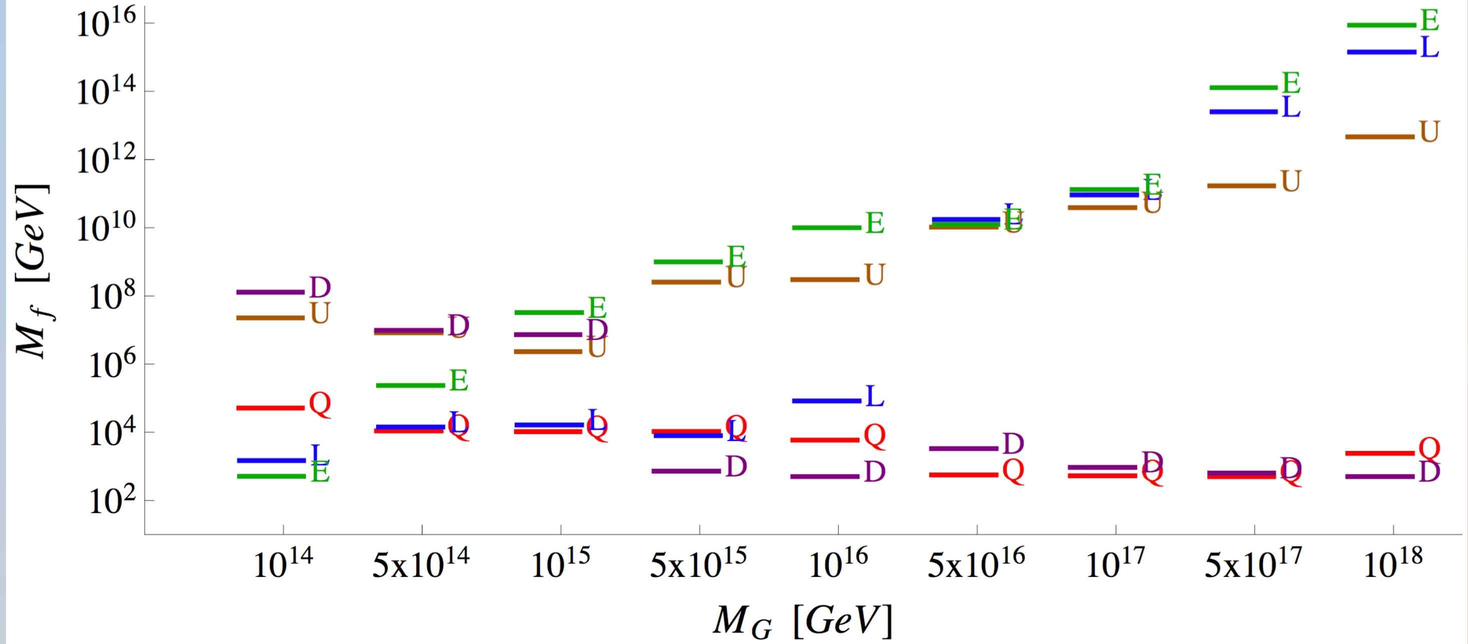
Gauge couplings at M_Z within 10% in a large range of parameters!

Spectrum consistent with g.c.u.

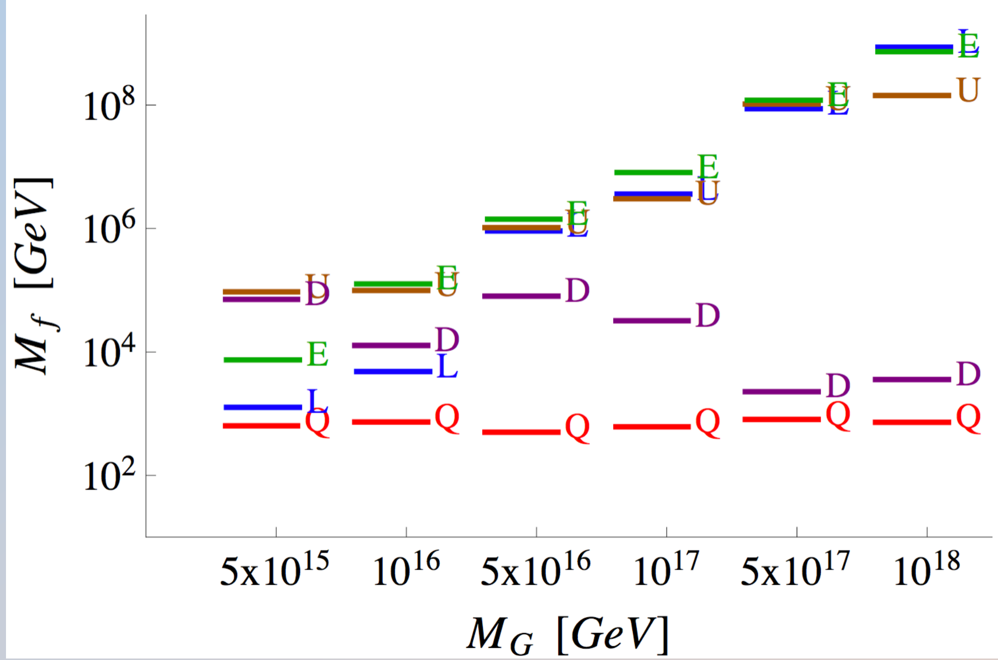
SM + 1VF



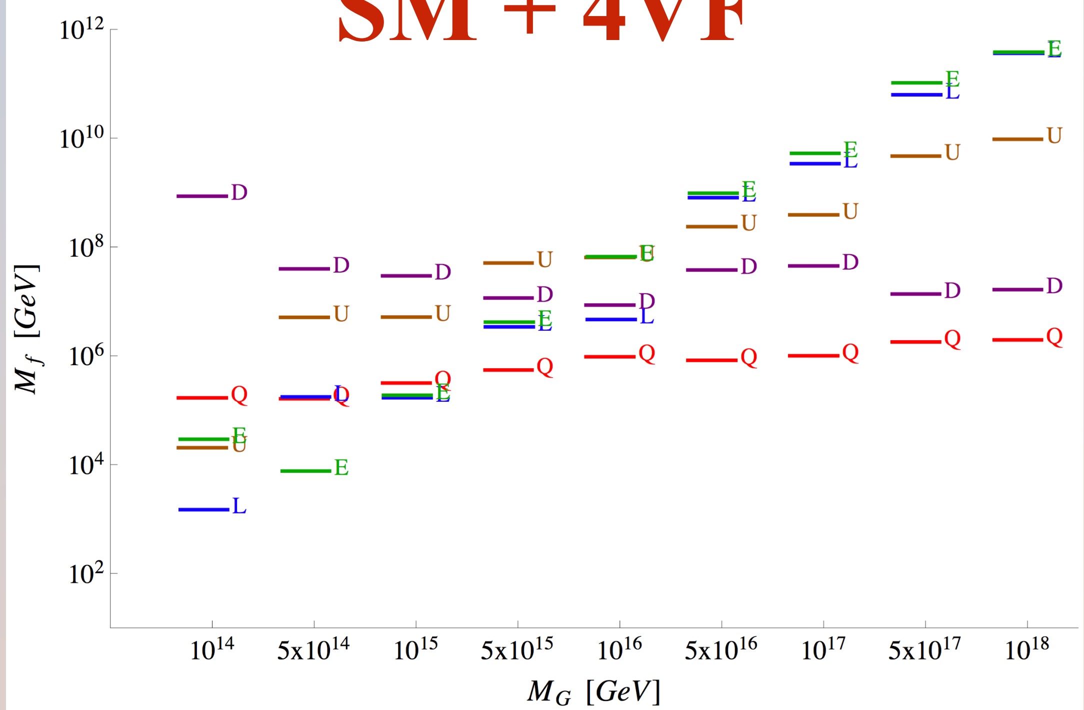
SM + 2VF



SM + 3VF



SM + 4VF



Realistic example

$\alpha_3(M_Z)_{exp} = 0.1184$
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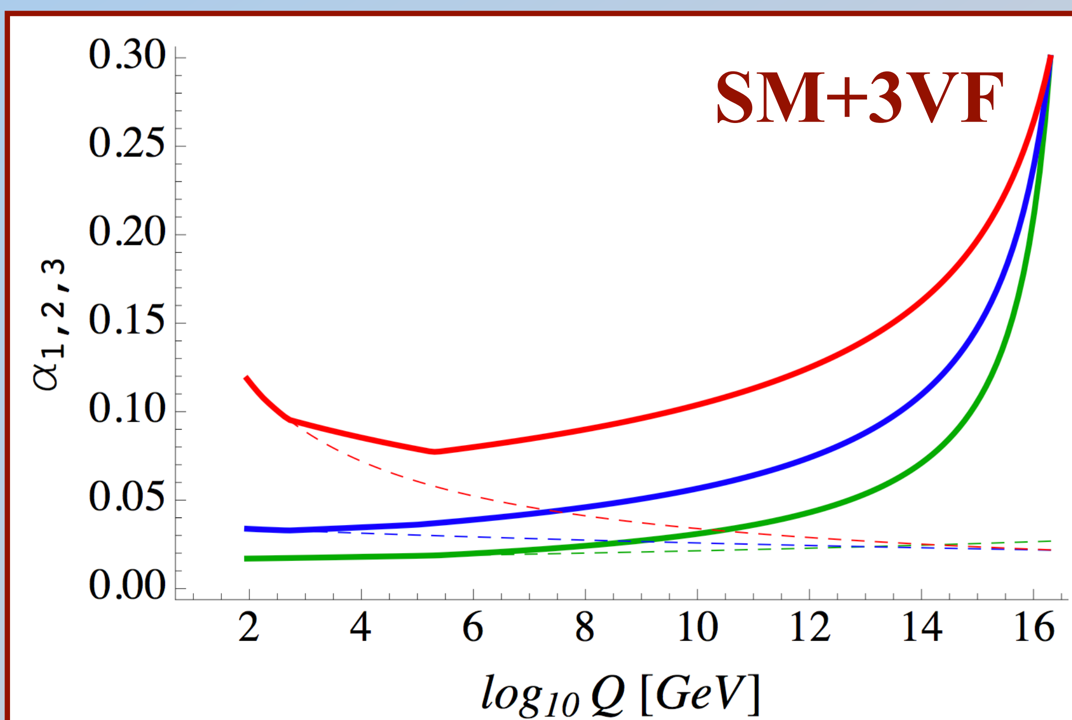
$\alpha_{EM}(M_Z) = 1/127.916$
$\sin^2\theta_W = 0.2313$

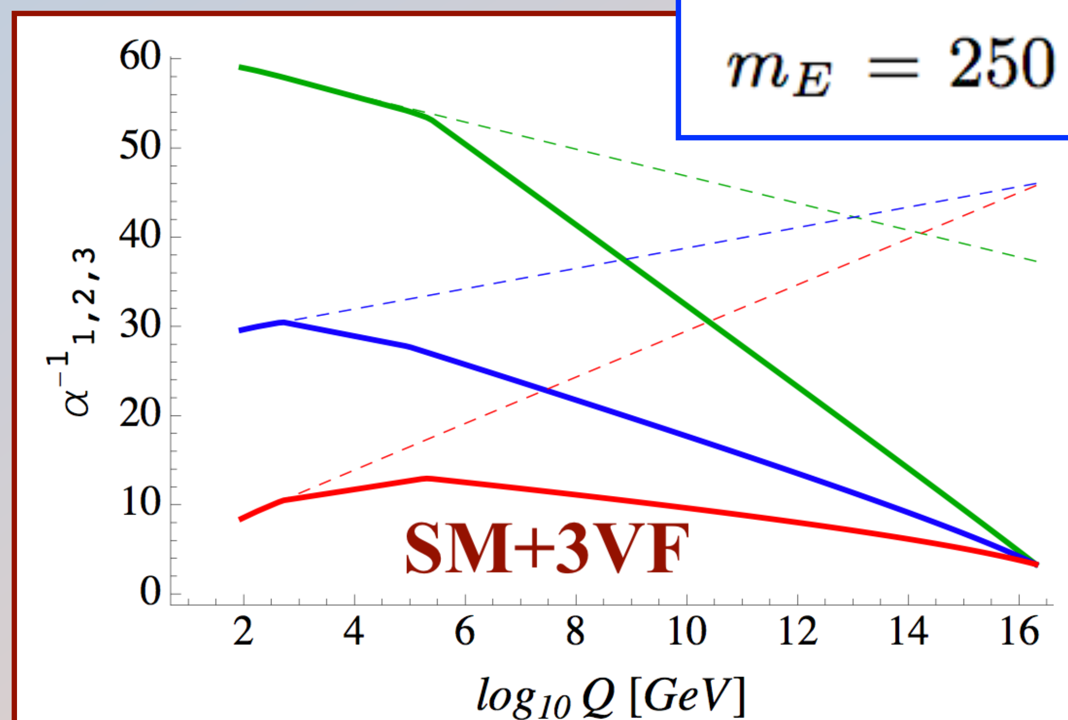
Gauge couplings reproduced (within fractions of exp. uncertainties) for :

4 sig. figures

2 sig. figures

$$
\begin{aligned}
m_Q &= 500 \text{ GeV} \\
m_L &= 95 \text{ TeV} \\
m_U &= 220 \text{ TeV} \\
m_D &= 180 \text{ TeV} \\
m_E &= 250 \text{ TeV}
\end{aligned}
$$

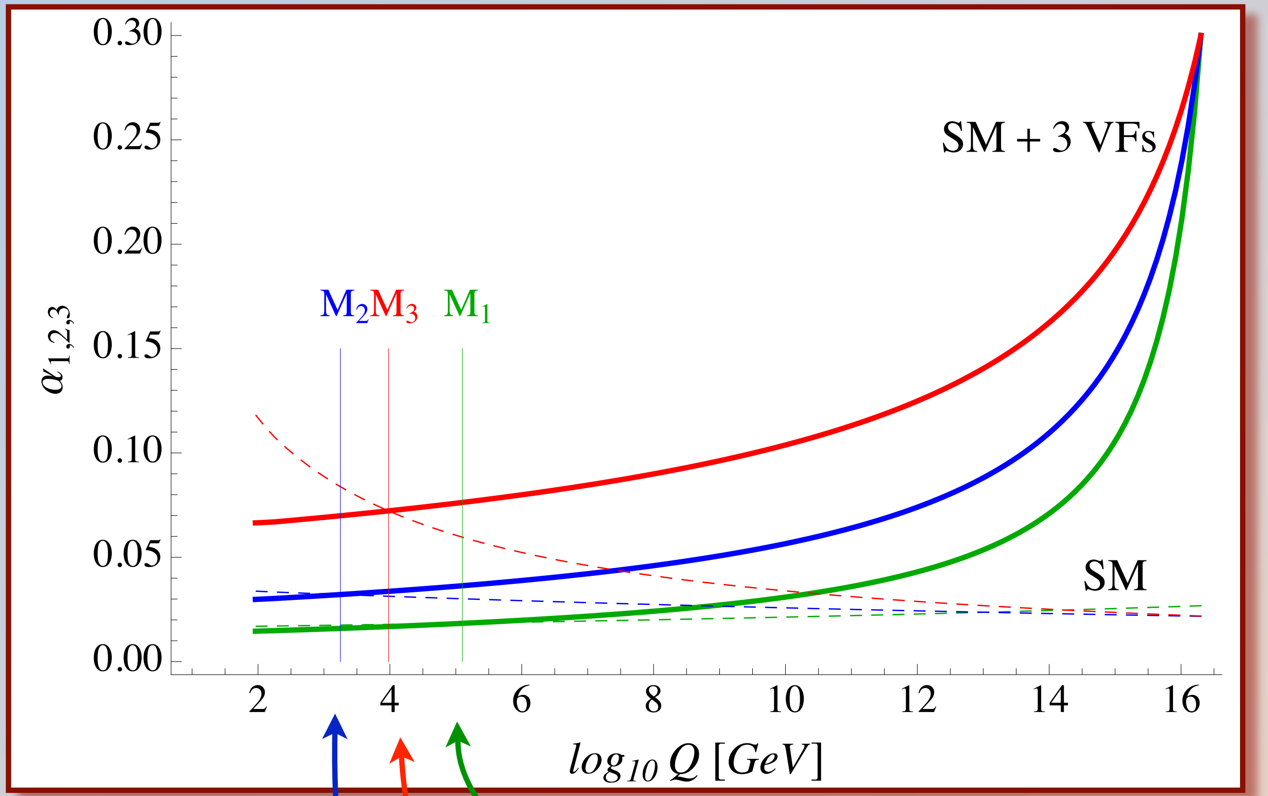




Many possible solutions!

Classifying solutions - mass rules

To get gauge coupling unification, weighted sum of logs of masses of particles charged under given symmetry must be as if all particles had the mass equal to the crossing scale of RG evolutions of the gauge coupling in the SM and SM+3VFs:



$$\frac{1}{2\pi}\sum_{i=1}^{3}\left(b_3^Q \ln\frac{M_{Qi}}{M_Z} + b_3^U \ln\frac{M_{Ui}}{M_Z} + b_3^D \ln\frac{M_{Di}}{M_Z}\right) = \frac{4}{\pi}\ln\frac{M_3}{M_Z}$$

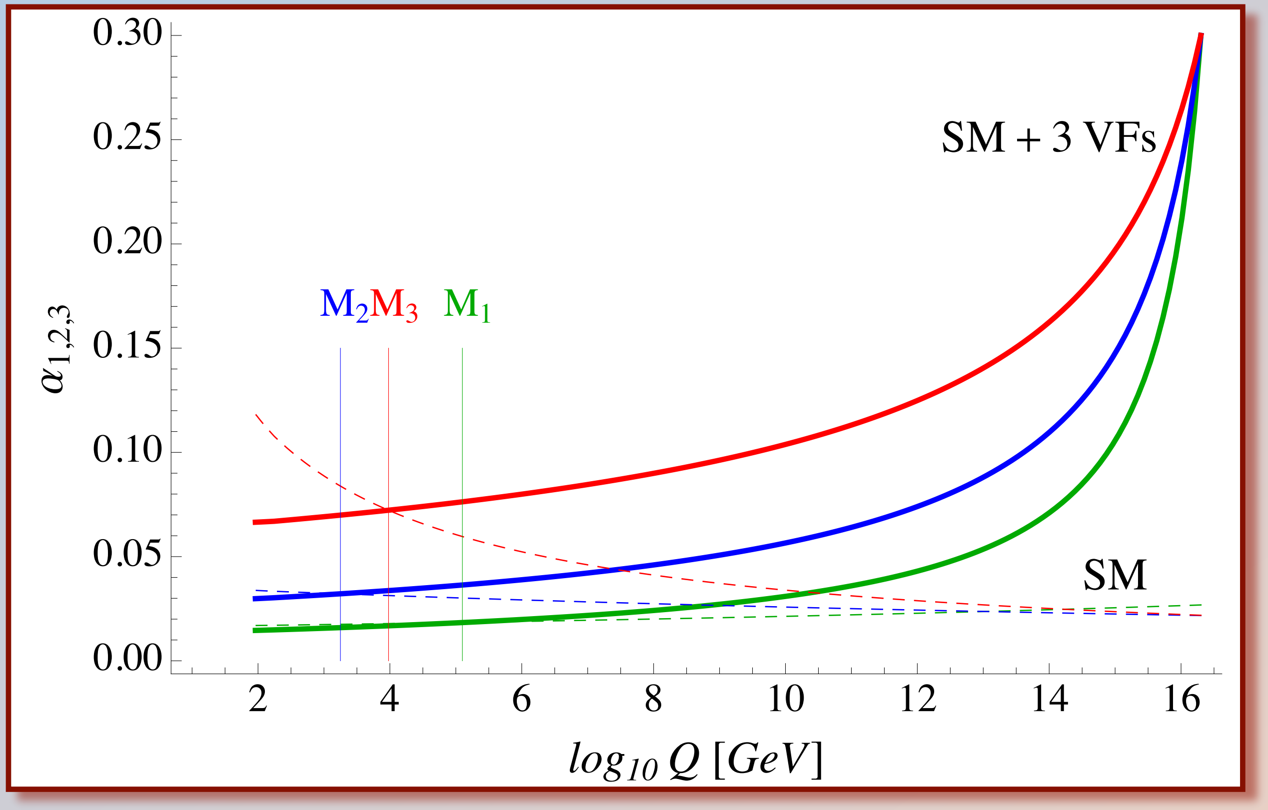
$$\frac{1}{2\pi}\sum_{i=1}^{3}\left(b_2^Q \ln\frac{M_{Qi}}{M_Z} + b_2^L \ln\frac{M_{Li}}{M_Z}\right) = \frac{4}{\pi}\ln\frac{M_2}{M_Z}$$

$$\frac{1}{2\pi}\sum_{i=1}^{3}\left(b_1^Q \ln\frac{M_{Qi}}{M_Z} + b_1^U \ln\frac{M_{Ui}}{M_Z} + b_1^D \ln\frac{M_{Di}}{M_Z} + b_1^L \ln\frac{M_{Li}}{M_Z} + b_1^E \ln\frac{M_{Ei}}{M_Z}\right) = \frac{4}{\pi}\ln\frac{M_1}{M_Z}$$

$$T_i = \frac{1}{2\pi}\sum_f b_i^f \ln\frac{M_f}{M_Z}$$

Classifying solutions - mass rules

To get gauge coupling unification, weighted sum of logs of masses of particles charged under given symmetry must be as if all particles had the mass equal to the crossing scale of RG evolutions of the gauge coupling in the SM and SM+3VFs:



$$M_3^4 = M_Q^2 M_U M_D,$$

$$M_2^4 = M_Q^3 M_L,$$

$$M_1^{20} = M_Q M_U^8 M_D^2 M_L^3 M_E^6.$$

$$M_F \equiv (M_{F_1} M_{F_2} \ldots M_{F_N})^{1/N}$$

What else are extra VFs good for?

- **muon g-2**

  K. Kannike, M. Raidal, D.M. Straub and A. Strumia, 1111.2551 [hep-ph]

  R.D. and A. Raval, 1305.3522 [hep-ph]

  $$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 2.7 \pm 0.80 \times 10^{-9}$$

- **anomalies in Z-pole observables $\mathbf{A_{FB}^b}$ and $\mathbf{A_e}$**

  D. Choudhury, T.M.P. Tait and C.E.M. Wagner, hep-ph/0109097

  R.D., S.G. Kim and A. Raval, 1105.0773 [hep-ph], 1201.0315 [hep-ph]

  B. Batell, S. Gori and L.T. Wang 1209.6382 [hep-ph]

- **Higgs boson mass and EWSB**

  K.S. Babu, I. Gogoladze, M.U. Rehman, Q. Shafi, 0807.3055 [hep-ph]

  S.P. Martin, 0910.2732 [hep-ph]

- **h → γγ, ZZ*, WW*, …**

  really many papers

- **…**

Two Higgs doublet model - type II

VL mixing only with 2nd generation of leptons:

R.D., E. Lunghi and S. Shin, 1509.04292

$$\mathcal{L} \supset -y_\mu \bar{\mu}_L \mu_R H_d - \lambda_E \bar{\mu}_L E_R H_d - \lambda_L \bar{L}_L \mu_R H_d - \lambda \bar{L}_L E_R H_d - \bar{\lambda} H_d^\dagger \bar{E}_L L_R$$
$$- \kappa_N \bar{\mu}_L N_R H_u - \kappa \bar{L}_L N_R H_u - \bar{\kappa} H_u^\dagger \bar{N}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R - M_N \bar{N}_L N_R + \text{h.c.} \;,$$

$$\mu_L = \begin{pmatrix} \nu_\mu \\ \mu_L^- \end{pmatrix}, \; L_{L,R} = \begin{pmatrix} L_{L,R}^0 \\ L_{L,R}^- \end{pmatrix}, \; H_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}, \; H_u = \begin{pmatrix} H_u^0 \\ H_u^- \end{pmatrix}$$

couplings to gauge bosons are modified because SU(2) doublets mix with SU(2) singlets and couplings to Higgs are modified because of explicit vectorlike mass terms:

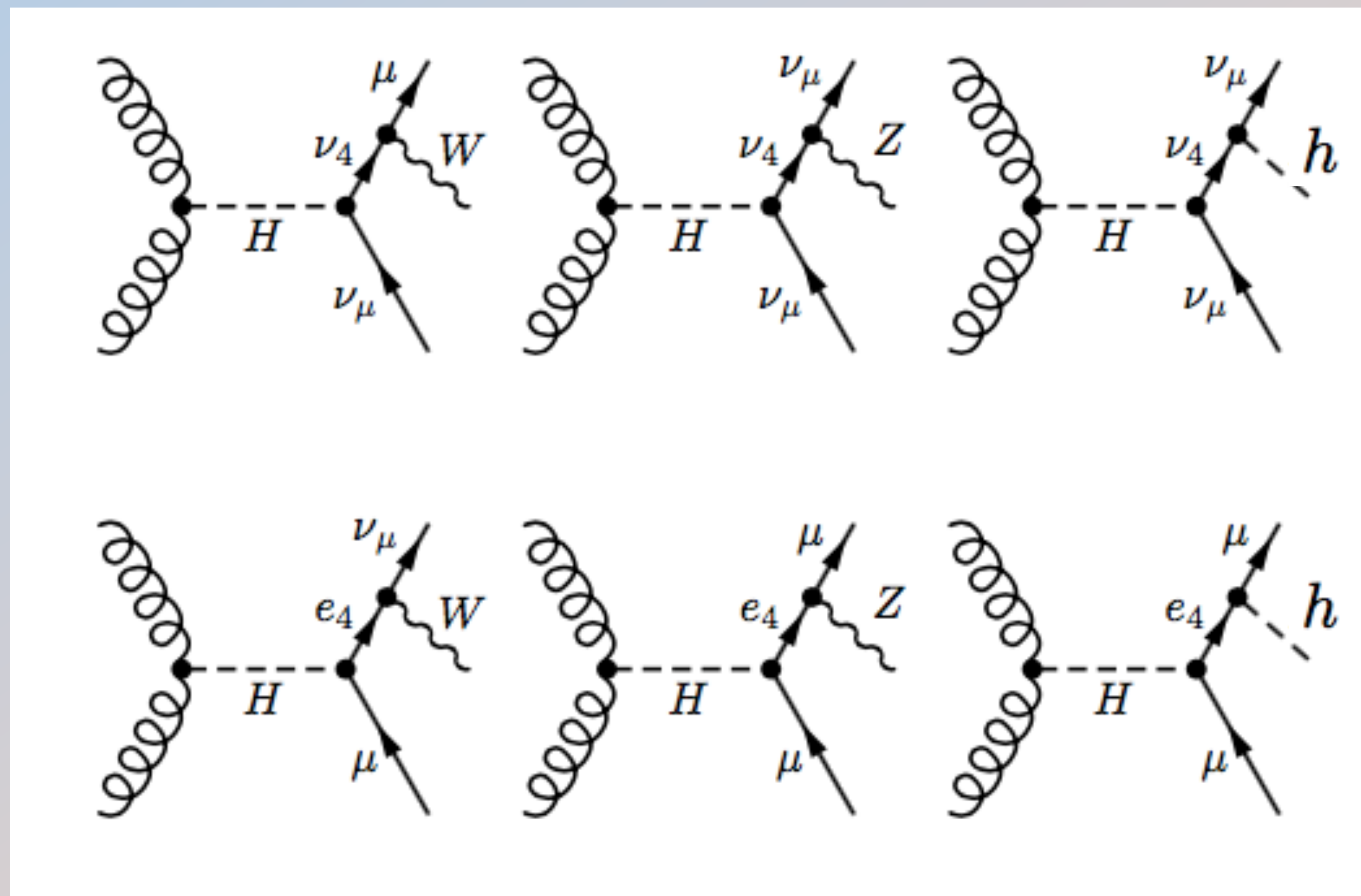
$$(\bar{\mu}_L, \bar{L}_L^-, \bar{E}_L) \begin{pmatrix} y_\mu v_d & 0 & \lambda^E v_d \\ \lambda^L v_d & M_L & \lambda v_d \\ 0 & \bar{\lambda} v_d & M_E \end{pmatrix} \begin{pmatrix} \mu_R \\ L_R^- \\ E_R \end{pmatrix}$$

$$\begin{pmatrix} \bar{\nu}_\mu & \bar{L}_L^0 & \bar{N}_L \end{pmatrix} \begin{pmatrix} 0 & 0 & \kappa_N v_u \\ 0 & M_L & \kappa v_u \\ 0 & \bar{\kappa} v_u & M_N \end{pmatrix} \begin{pmatrix} \nu_R = 0 \\ L_R^0 \\ N_R \end{pmatrix}$$

New (possibly discovery) decay modes

$$H \to \cancel{WW},\ \cancel{ZZ},\ \gamma\gamma,\ \cancel{t\bar{t}},\ b\bar{b},\ \tau\bar{\tau},\ \ldots$$

if h is SM-like and H (or A) is below ~350 GeV flavor violating decays can be dominant:



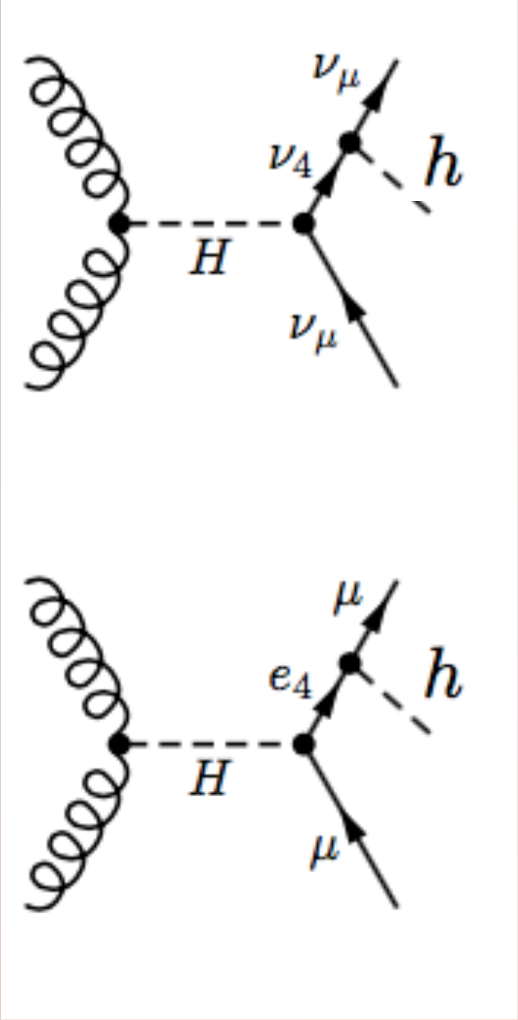
decays to pairs of heavy leptons also possible but limited to smaller mass ranges (constraints from pair-production can be applied)

they all look similar to WW, ZZ, hZ decay modes of H or ZZ, WW, Zh production!

H -> h ν ν and H -> h μ μ

look like Zh production, with potentially much larger cross section, (no Z, but no penalty for 2 leptons)

R.D., E. Lunghi and S. Shin, in progress



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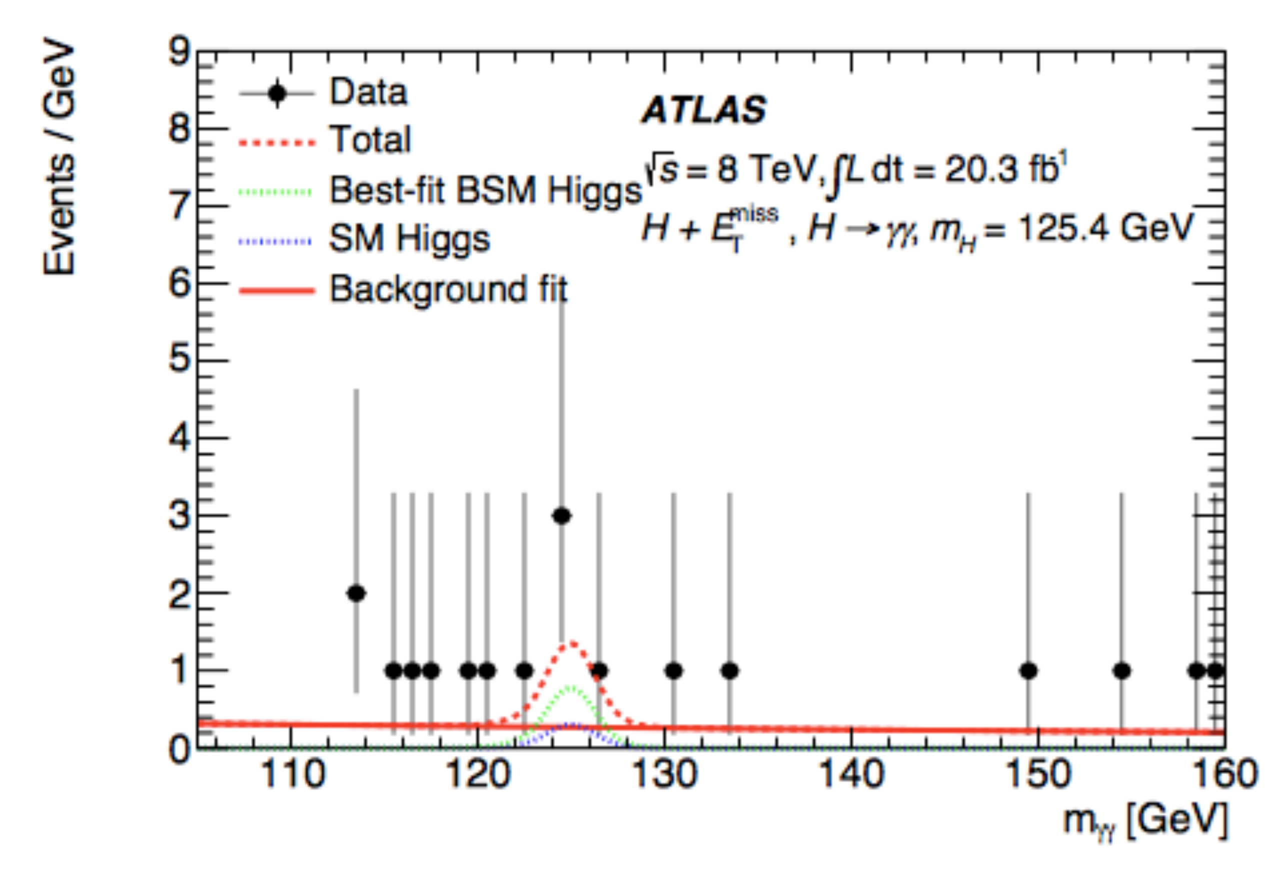
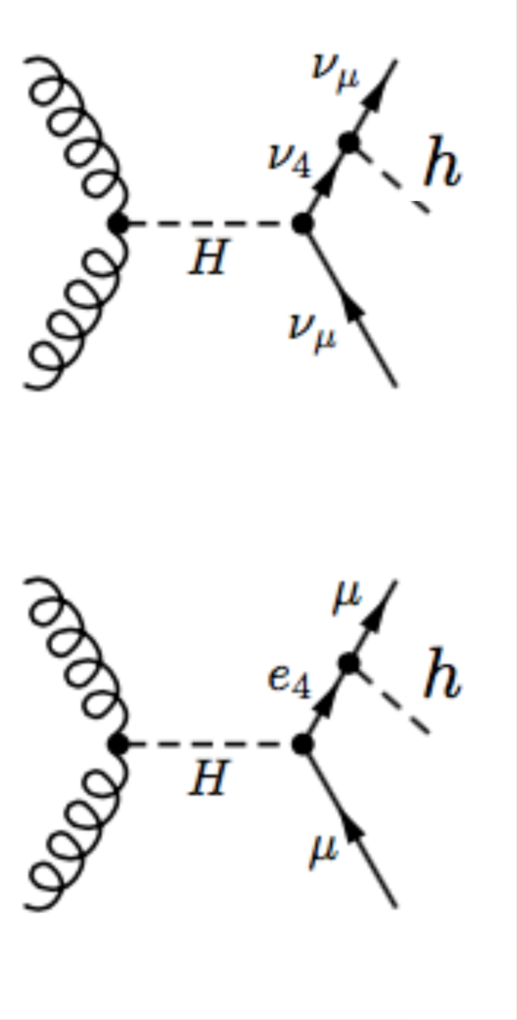
some decay modes almost background free, e.g. h $\longrightarrow$ $\gamma\gamma$:

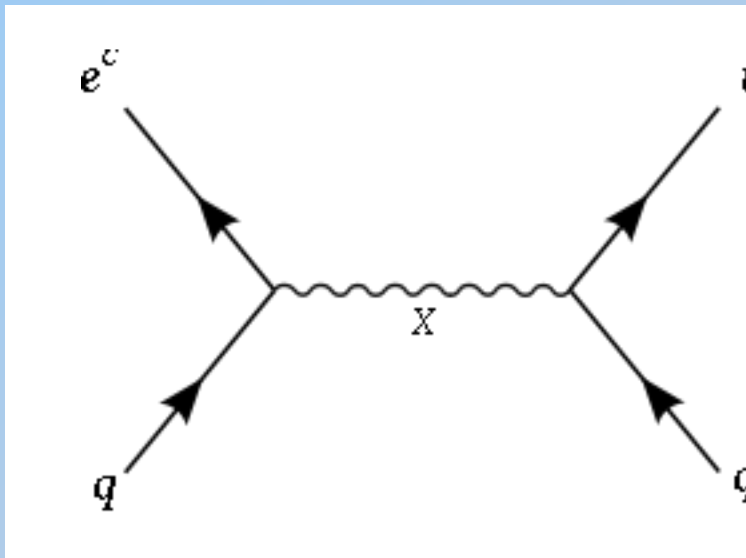


ATLAS, 1506.01081



Effects of VFs on proton lifetime

dimension 6 operators:



$$\propto \frac{\alpha_G}{M_G^2}$$

dominant decay mode:

$$p \longrightarrow \pi^0 e^+$$

experimental limit:

$$\boxed{\tau(p \to \pi^0 e^+) \gtrsim 10^{34}\ \mathrm{yrs}}$$

typical prediction of SUSY GUTs: $\sim 10^{36}\mathrm{yrs}$

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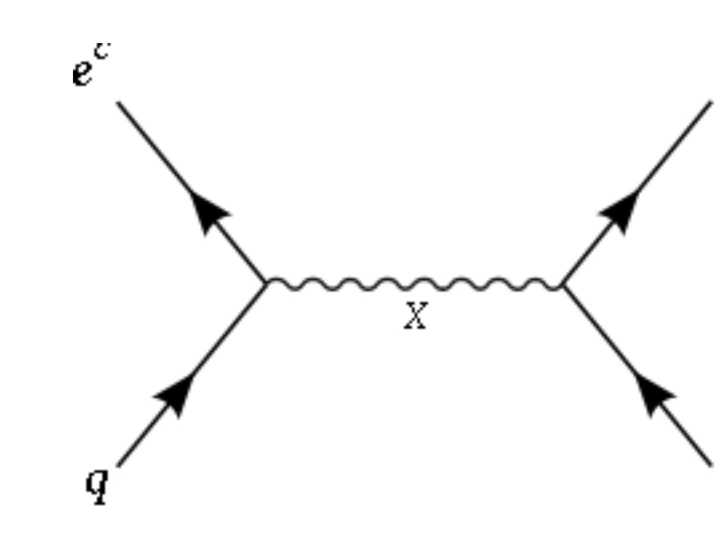

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typical prediction of SUSY GUTs: $\sim 10^{36}$yrs

With complete vectorlike families: the value of unified gauge coupling is significantly larger (and adjustable)

with or without SUSY the optimal GUT scale is similar

Dim. 6 operators can be close to experimental limits!

Conclusions

- SM+3VFs, MSSM+1VF (or more) allow for insensitive unification of gauge couplings

  predictive (in a different way)

- even without supersymmetry the optimal GUT scale is high enough to survive limits on proton lifetime

- the value of unified gauge coupling is larger (and adjustable)

  dim. 6 proton decay operators can be close to current limits

- minimal scenarios predict VFs near the EW scale

  and can lead to very interesting and rich phenomenology