Understanding gauge and top-bottom-tau Yukawa couplings

as IR fixed points in the MSSM with vectorlike family

with N. McGinnis, arXiv:1712.03527
with N. McGinnis, to appear

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Standard model

Out of 17 dimensionless parameters:

$$\alpha_1,\ \alpha_2,\ \alpha_3,\ y_t,\ y_b,\ y_\tau,\ \lambda_h$$

all others = 0 (in the first approximation)

only 7 couplings are sizable

Are their values random or predictable?

In the MSSM+1VF

$$\alpha_1,\ \alpha_2,\ \alpha_3,\ y_t,\ y_b,\ y_\tau,\ \lambda_h$$

their values can be understood as IR fixed points

MSSM with a complete vectorlike family

We add to the MSSM:

$$Q,\ \bar{U},\ \bar{D},\ L,\ \bar{E} \quad + \quad \bar{Q},\ U,\ D,\ \bar{L},\ E$$

or $16 + \overline{16}$ **in SO(10) language**

We consider:

- universal Yukawa coupling at the GUT scale:

$$y_t = y_b = y_\tau \equiv Y_0$$

motivated by SO(10)

- universal Yukawa c. of vectorlike fields at the GUT scale: Y_V
- common scale for superpartners: M_{SUSY}
- common scale for vectorlike matter: M_V

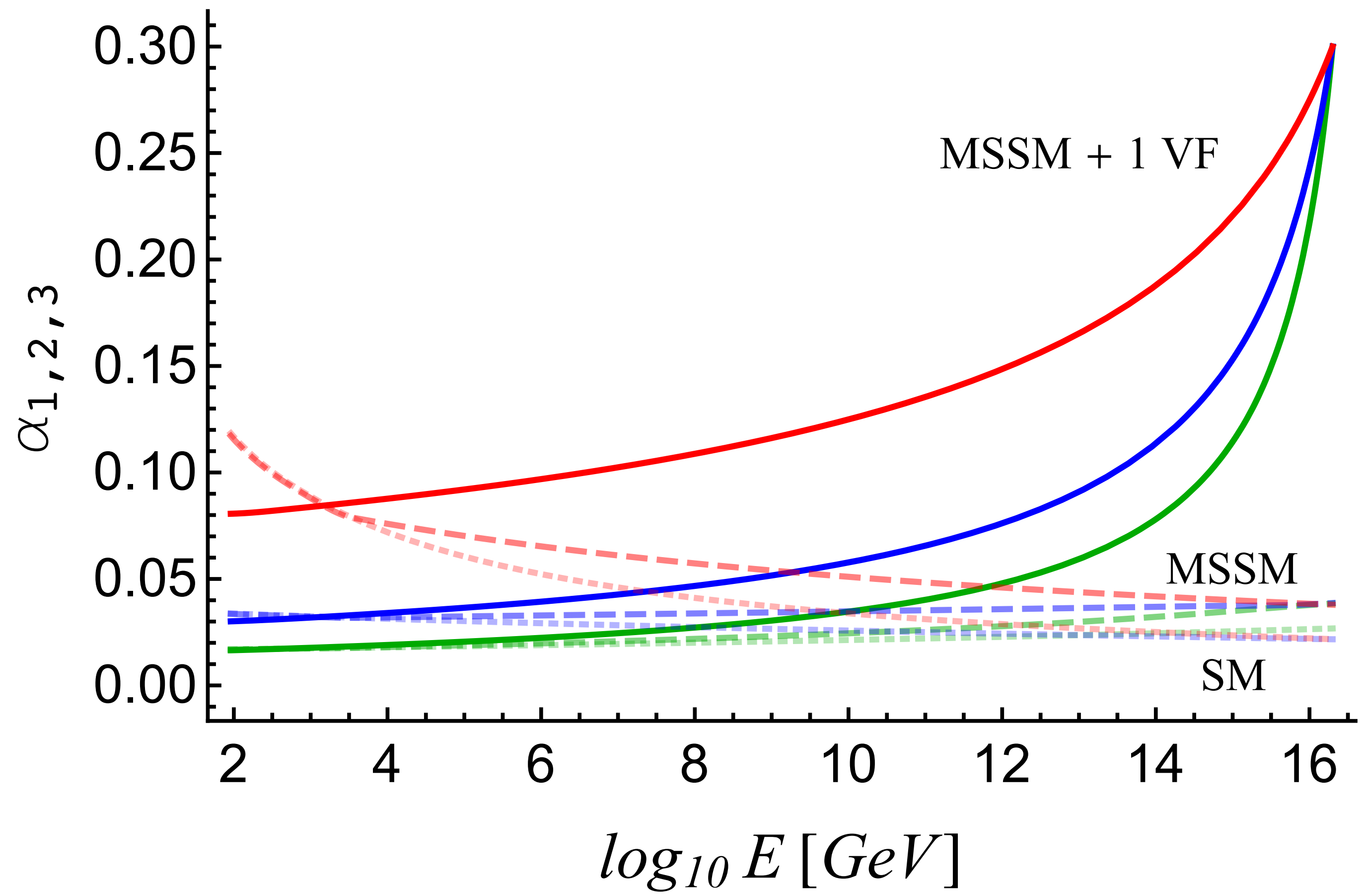
often we identify the two scales: $M_{SUSY} = M_V \equiv M$

Gauge couplings in MSSM+1VF

1 loop RG equations:

$$\frac{d\alpha_i}{dt} = \beta(\alpha_i) = \frac{\alpha_i^2}{2\pi} b_i$$

$$b_i = (33/5, 1, -3) + n_5(1,1,1) + 3n_{10}(1,1,1)$$



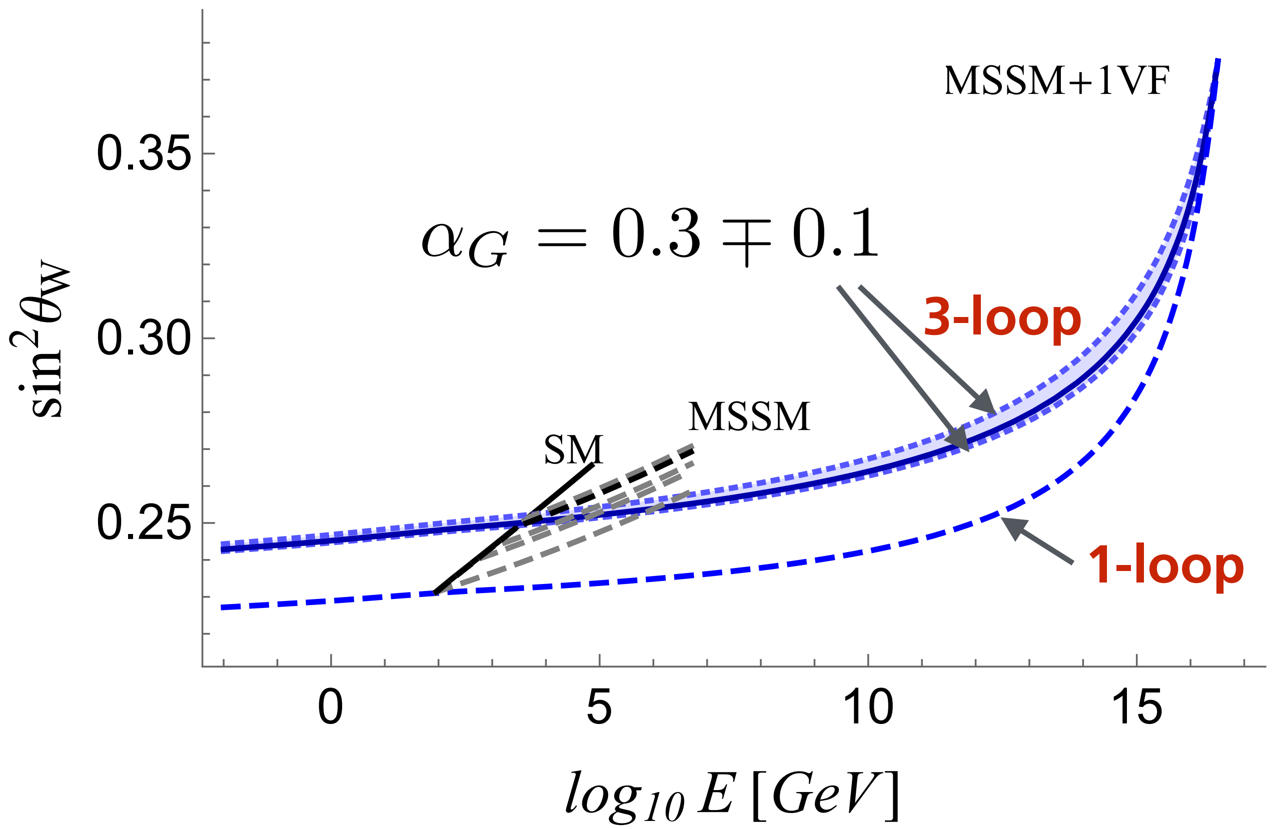
Solution:

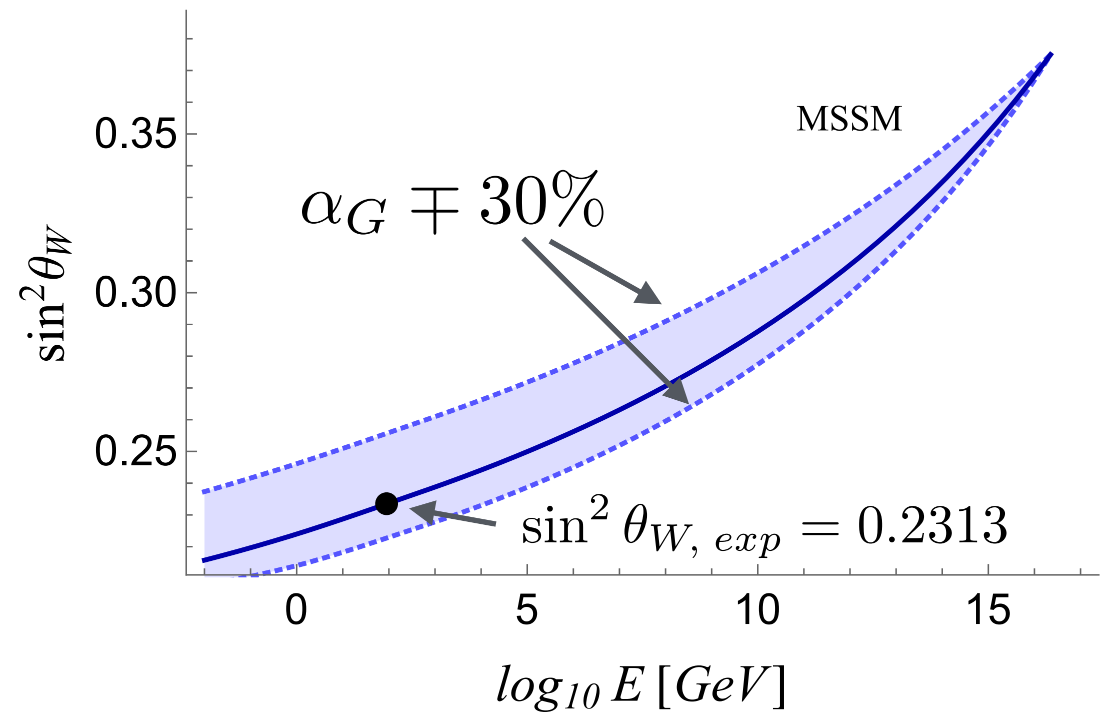
$$\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi} \ln \frac{M_G}{M_Z} + \alpha^{-1}(M_G)$$

Two parameter free predictions:

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

Weak mixing angle



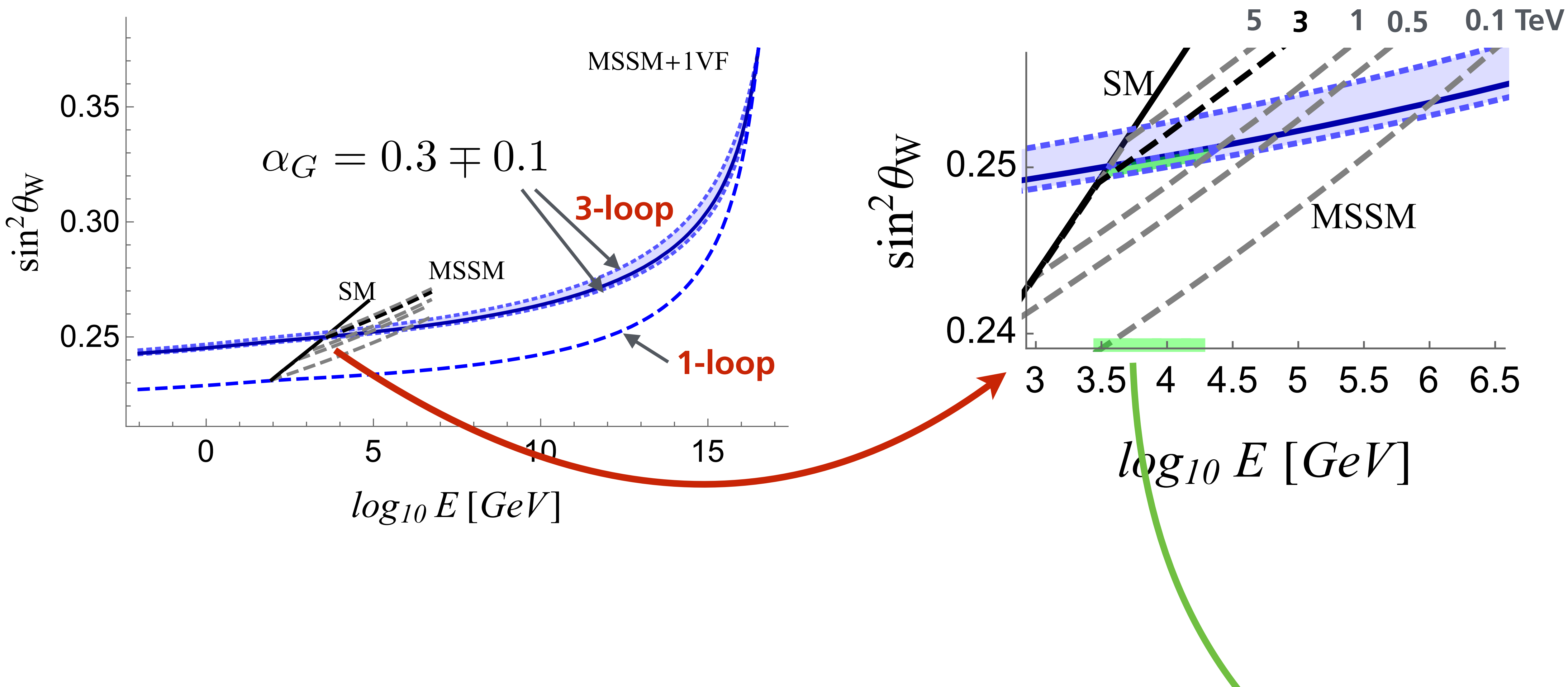


$$\sin^2\theta_W = \frac{\alpha'}{\alpha_2 + \alpha'} \simeq \frac{b_2}{b' + b_2} = \underline{0.2205} \qquad \text{(1-loop)}$$

$b' = (5/3)b_1$

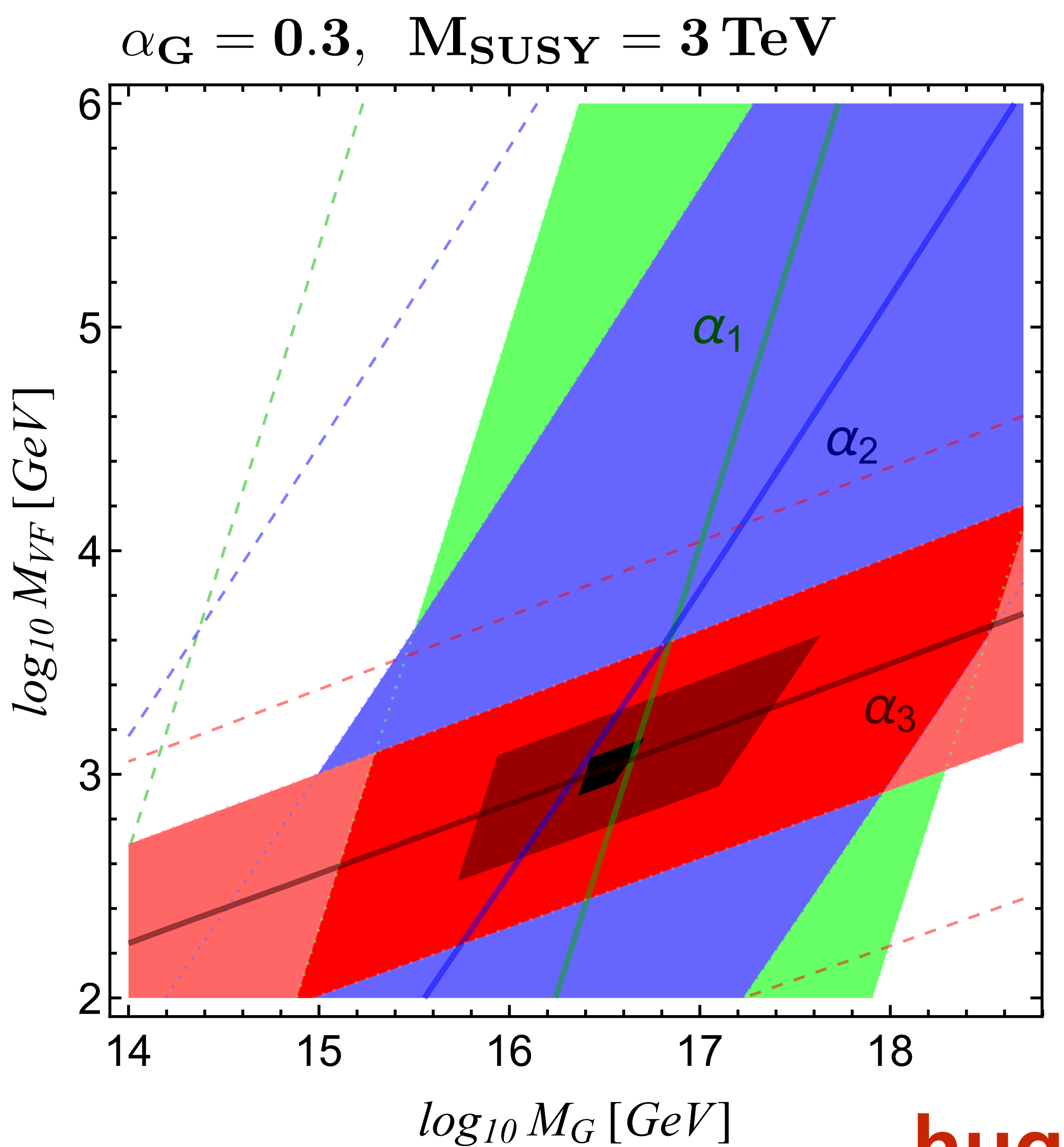
robust prediction away from the GUT scale

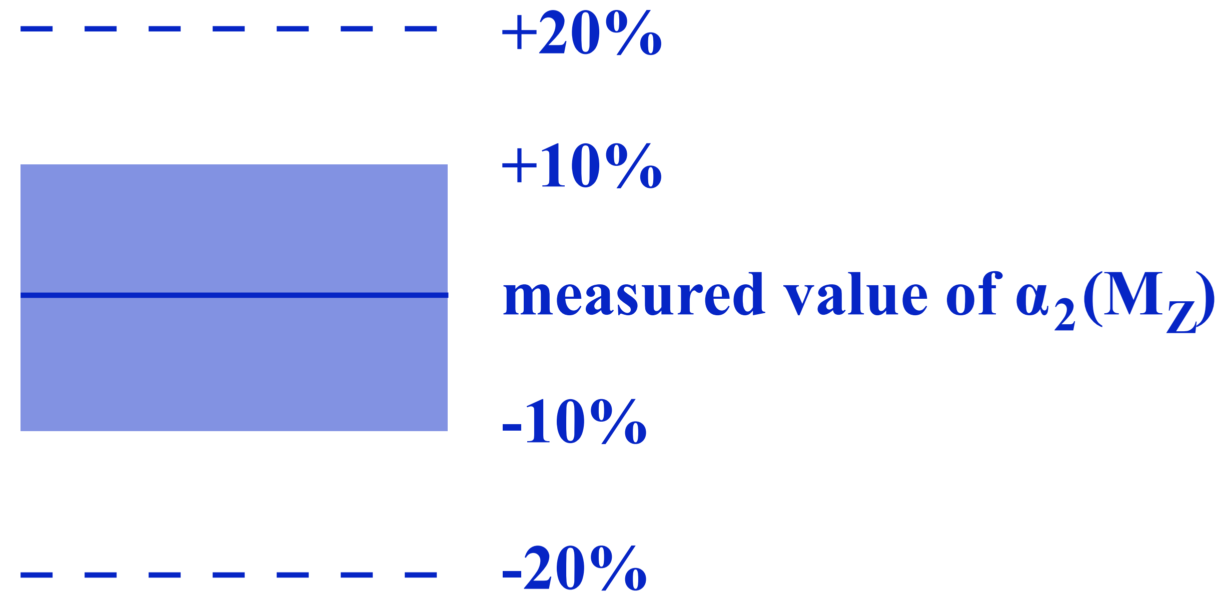
Weak mixing angle



for any $\alpha_G > 0.3$ and superpartners above 1 TeV vectorlike matter is expected below 20 TeV

Optimal VF and GUT scales in MSSM+1VF





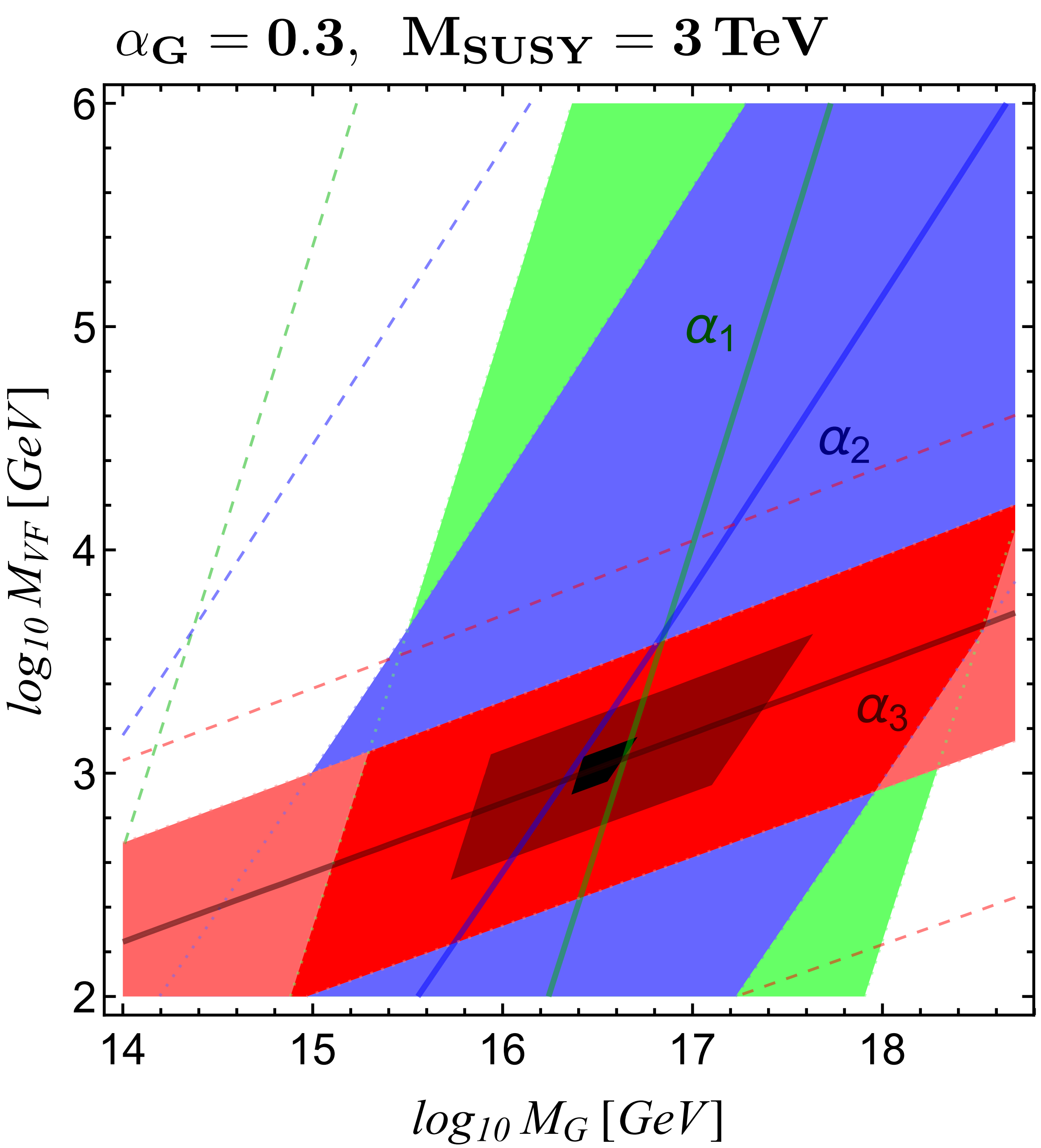
All three gauge couplings within:

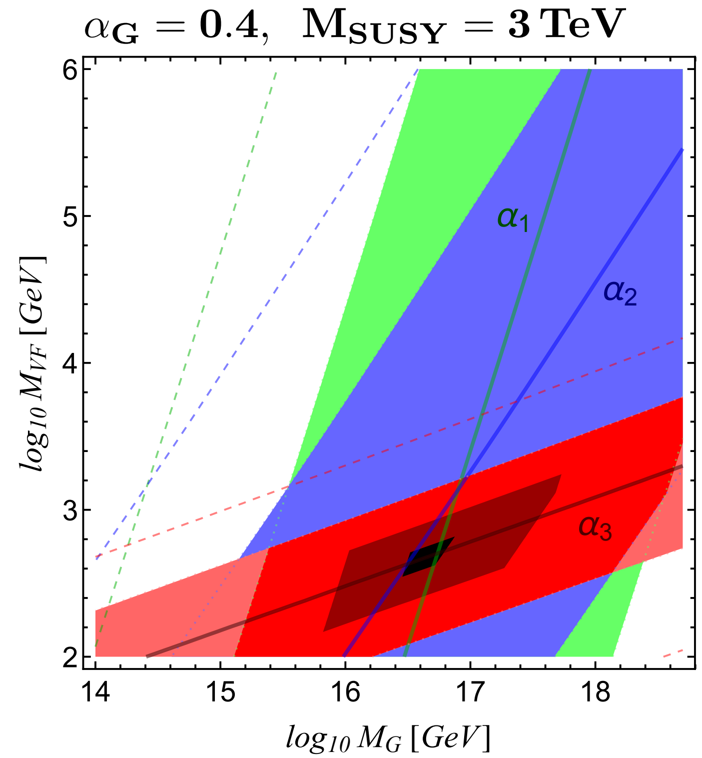
- 1.5%
- 5%
- 10%

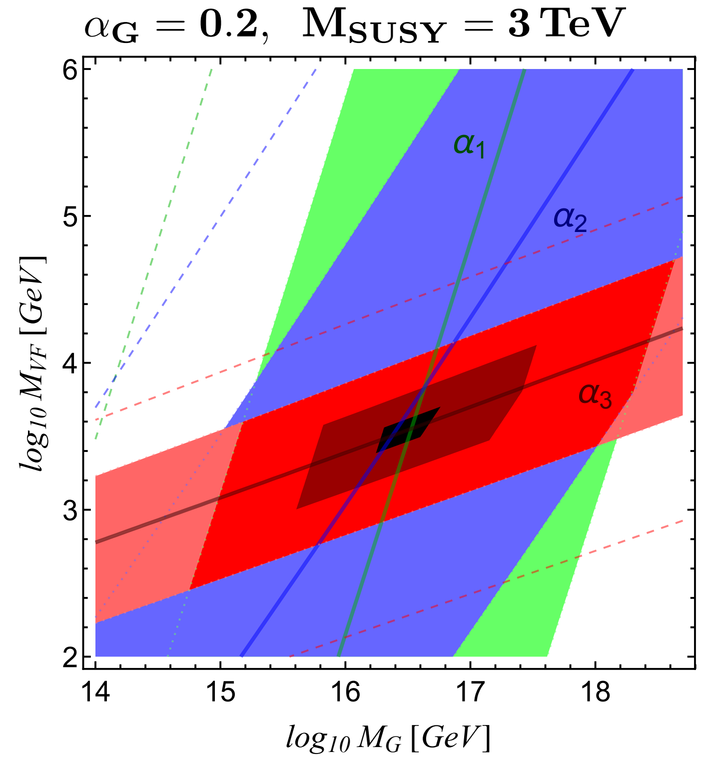
from the measured values.

huge range of parameters results in observed pattern of gauge couplings

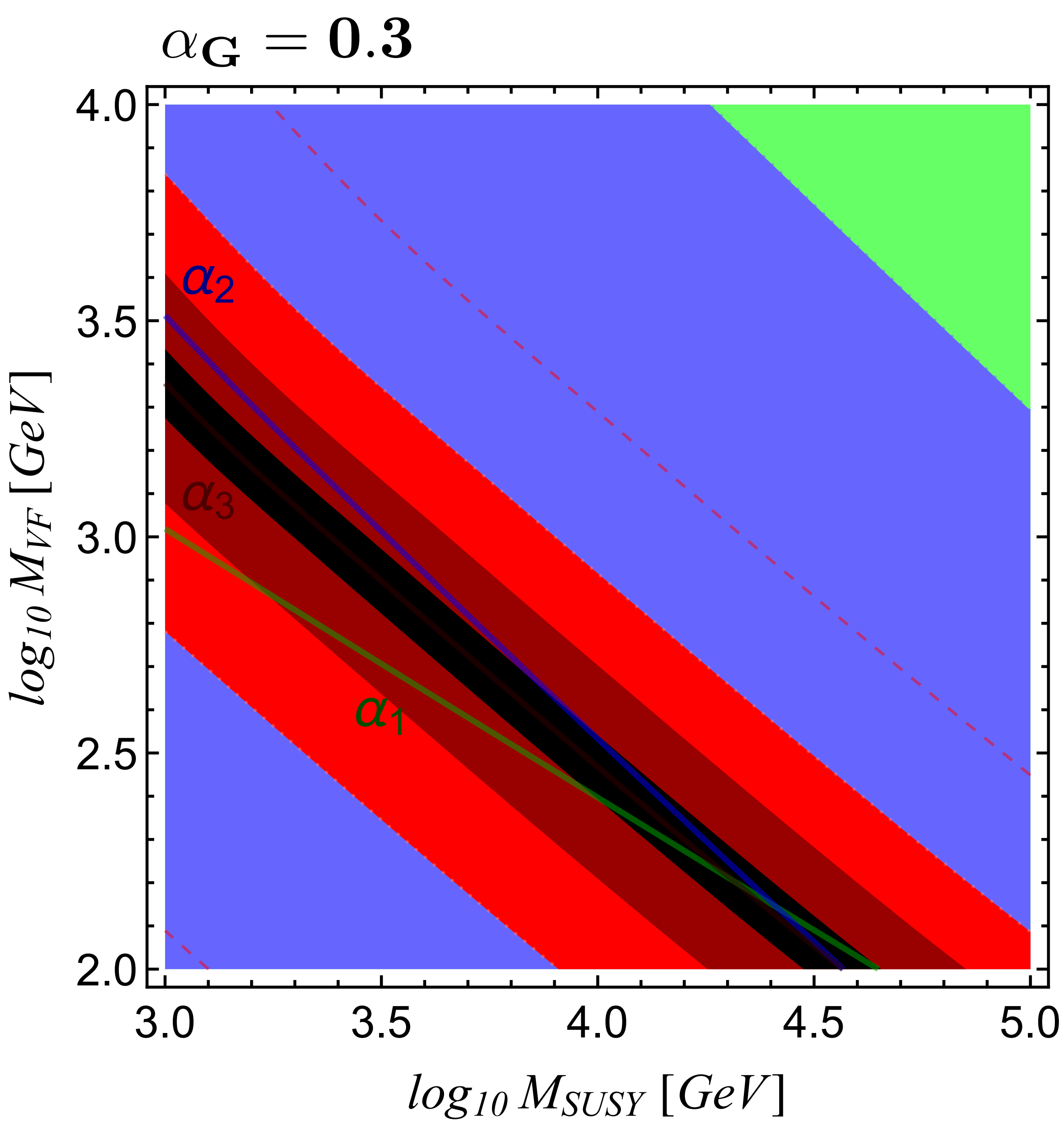
Varying unified gauge coupling







Optimal VF and SUSY scale in MSSM+1VF

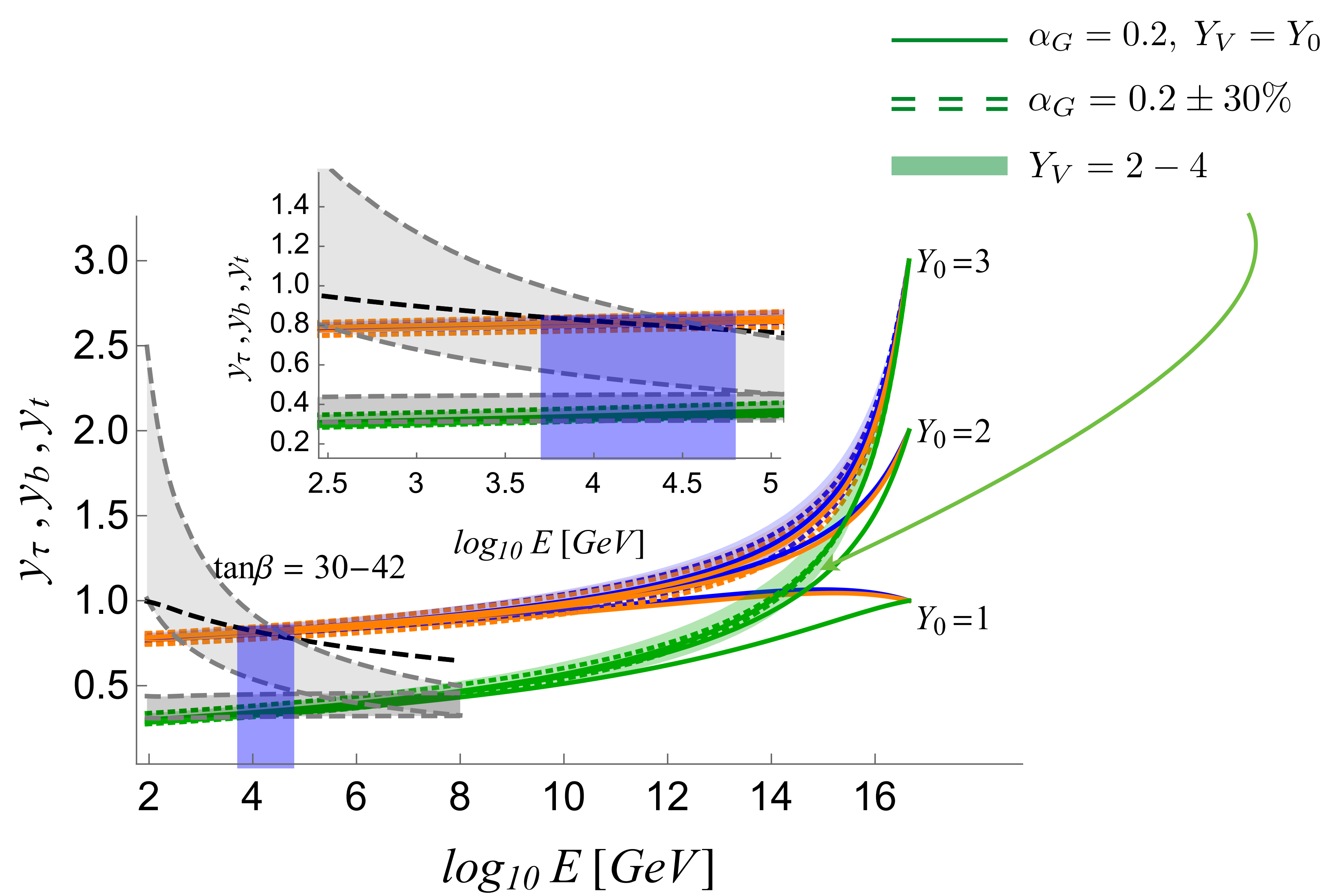


For any $\alpha_{\mathbf{G}} > \mathbf{0.3}$ VF or SUSY expected within 1.7 TeV (2.5 TeV) based on all three gauge couplings being simultaneously within 1.5% (5%) from observed values.

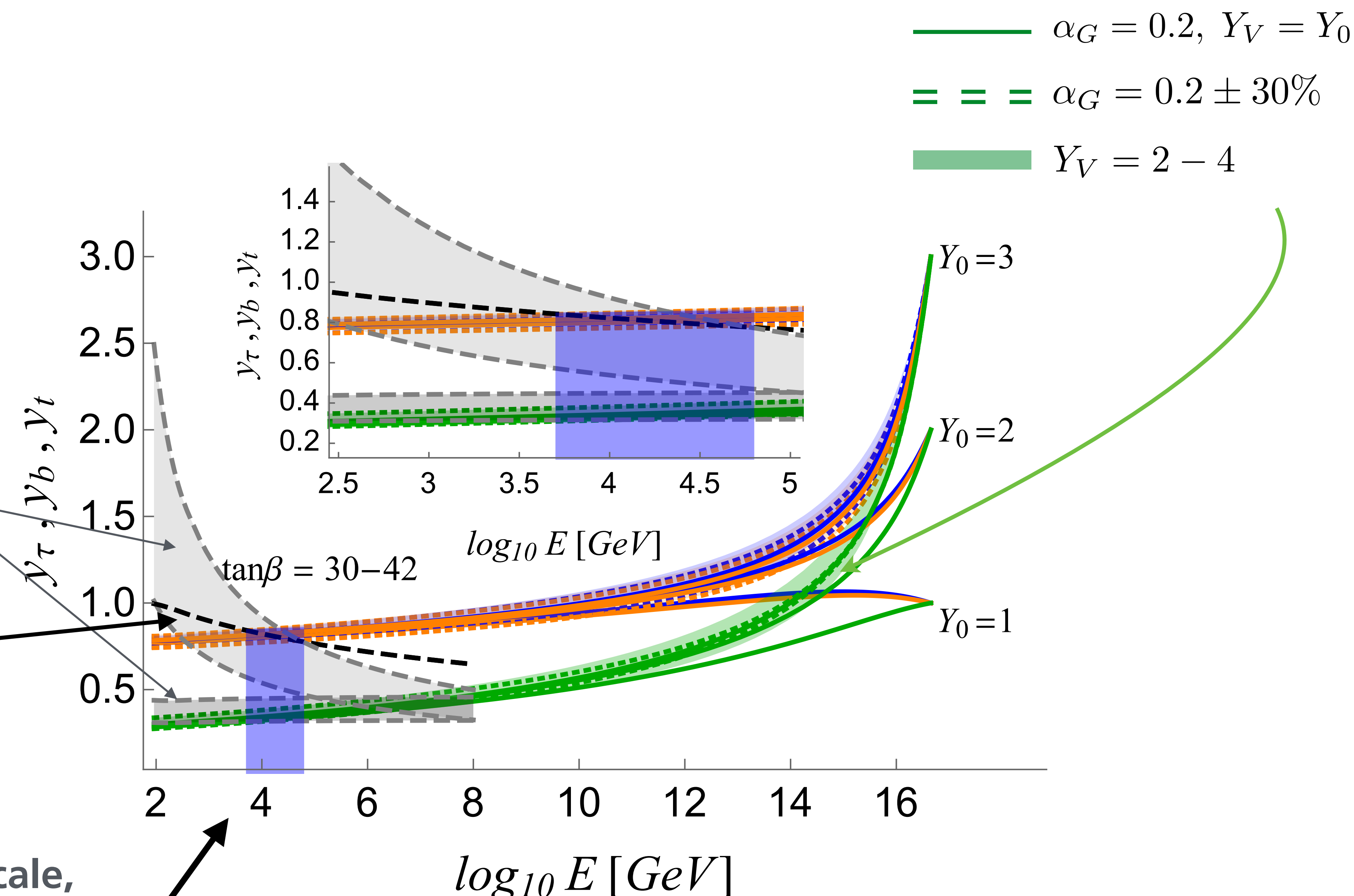
(extends to ~4 TeV for $\alpha_{\mathbf{G}} > \mathbf{0.2}$)

gauge couplings point (independently of the Higgs mass) to a multi-TeV scale for VF and SUSY

Top-bottom-tau IR fixed points



Top-bottom-tau IR fixed points



bottom, tau Y.c.:
$m_{b,\tau} = y_{b,\tau} v \cos\beta (1 + \epsilon_{b,\tau})$

top Y.c.:
$m_t = y_t v \sin\beta (1 + \epsilon_t)$

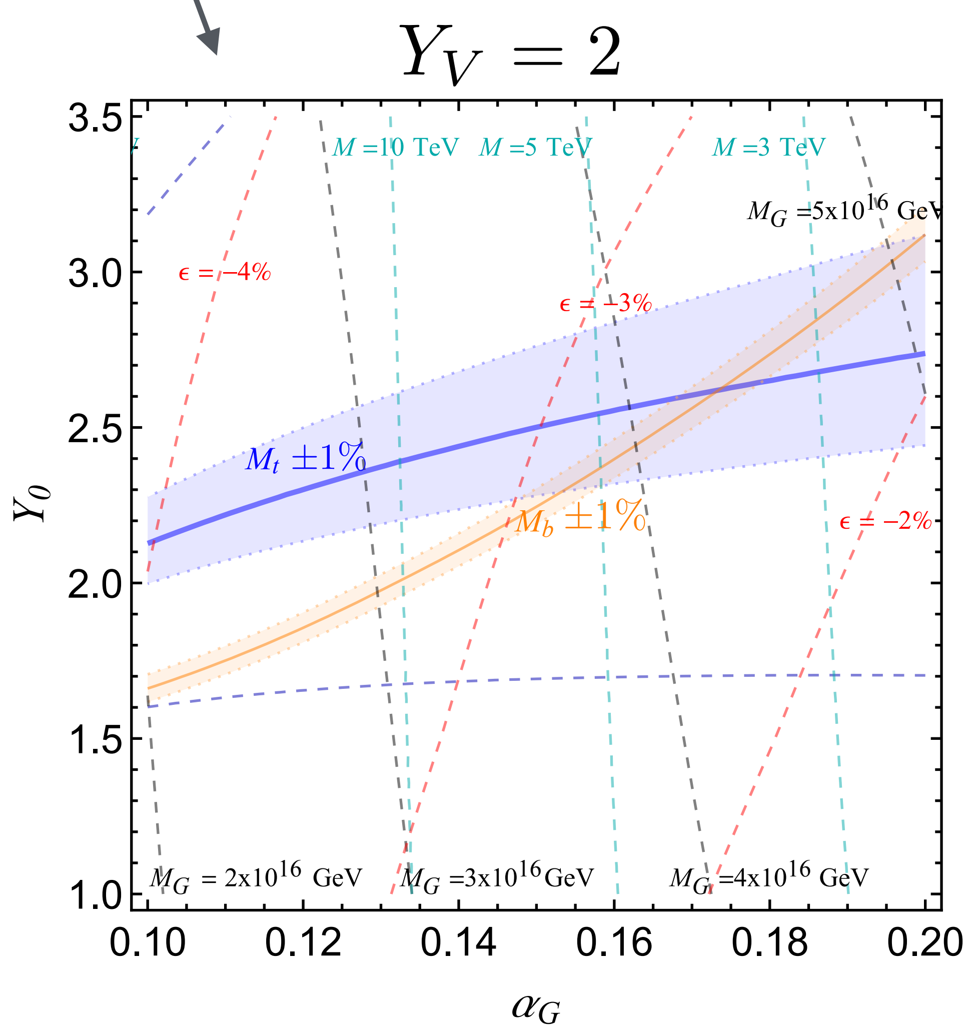
SUSY corrections assume all superpartners at the same scale, zero A-terms and $\mu = -\sqrt{2} M_{SUSY}$

very sharp IR fixed point predictions again point to a multi-TeV scale for VF and SUSY

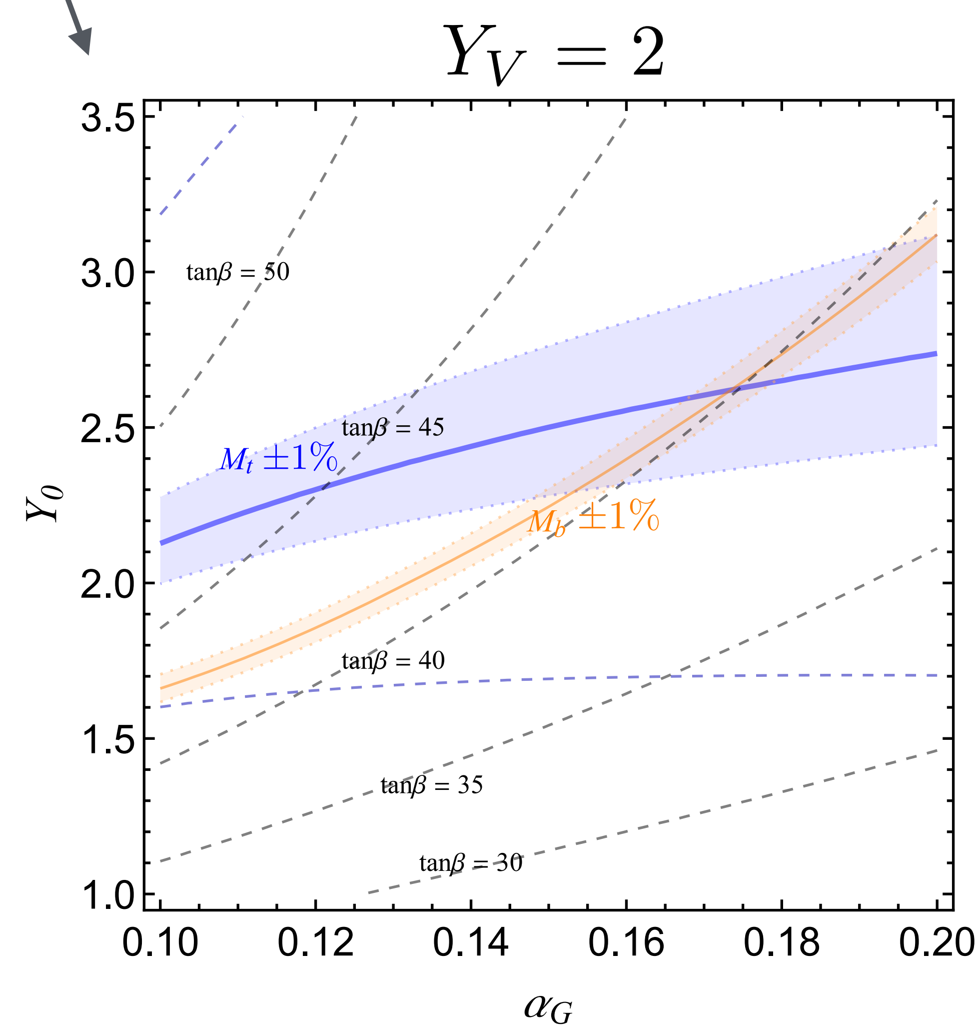
Exploring the parameter space

Gauge couplings and tau mass are fit to central values:

$M_G,\ \epsilon,\ M$



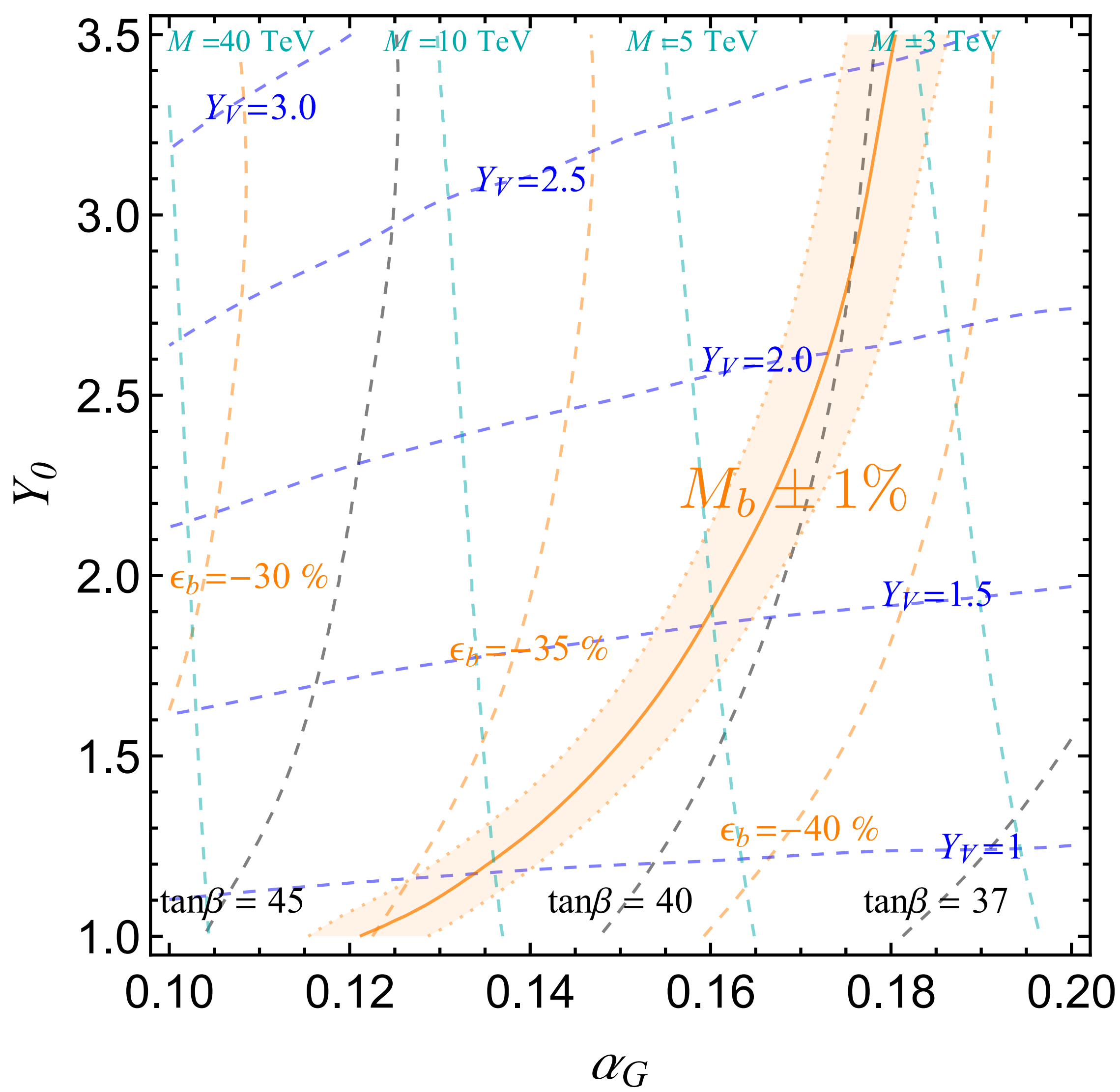
$\tan\beta$



exact Yukawa coupling unification possible

Exploring the parameter space

Everything fit to central values except for bottom mass:



fitting bottom mass in the whole plane requires SUSY corrections of a typical size

fitting everything suggests M = 3 - 10 TeV!

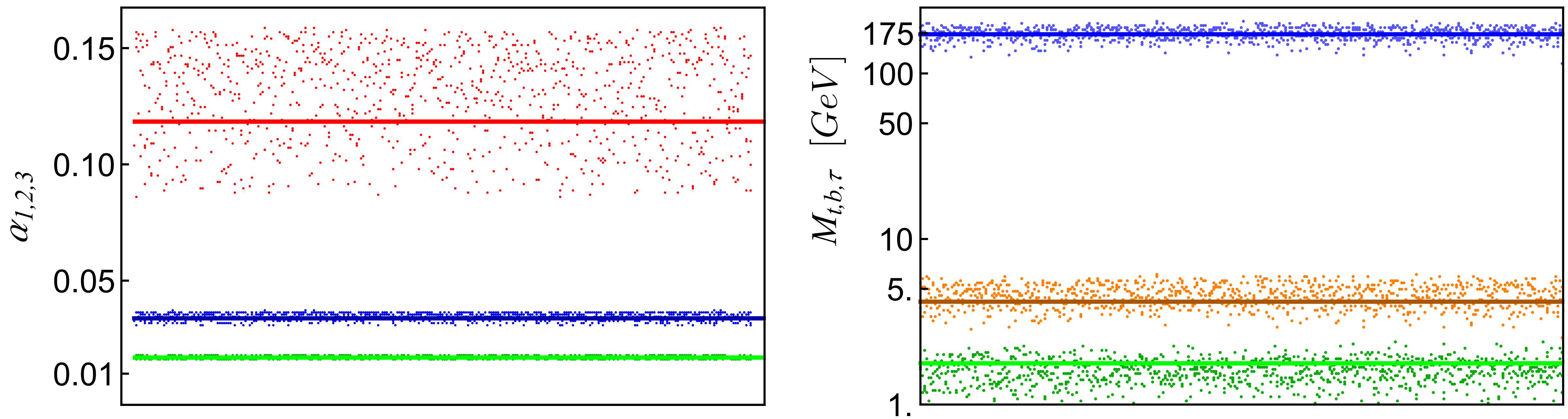
MSSM with a complete vectorlike family

with vectorlike masses and superpartners at multi-TeV

for randomly generated: $\alpha_G \in [0.1, 0.3],\ Y_0 \in [1,3],\ Y_V \in [1,3]$

$M_G = 3 \times 10^{16}\ \mathrm{GeV},\ M_{SUSY} = M_{VF} = 5\ \mathrm{TeV},\ \tan\beta = 40$

(larger values of couplings do not affect results significantly)



provides an understanding of all large couplings in the SM as IR fixed points

Comment on Naturalness

EWSB with multi-TeV SUSY is viewed as very fine-tuned

based on intuition that contributions of two parameters precisely cancel only if parameters are carefully chosen/tuned

usually demonstrated by small probability in scans, sensitivity measures…

However, SUSY models typically have a handful of parameters that significantly contribute to the determination of the EW scale.

What is a tuned outcome in a model with 2 parameters may be a completely ordinary outcome in a more complex model, e.g.:
10 random choices of handful of SUSY parameters will produce an outcome with the EW scale ~2 orders of magnitude smaller (no parameter has to be chosen carefully). **With increasing the complexity, more "special/extreme/unexpected" outcomes become ordinary.**

for more discussion, see:

RD, arXiv:1611.03188 ; RD and N. McGinnis, arXiv:1705.01910

Conclusions

In the **MSSM+1VF** with vectorlike matter and superpartners at a multi-TeV scale:

$$\alpha_1, \ \alpha_2, \ \alpha_3, \ y_t, \ y_b, \ y_\tau, \ \lambda_h$$

can be understood as a consequence of the particle content of the model!