Insensitive Unification of Gauge Couplings, Muon g-2 and Higgs decays

Radovan Dermisek
Indiana University, Bloomington

R.D., arXiv:1204.6533 [hep-ph], arXiv:1212.3035 [hep-ph]
R.D. and A. Raval, arXiv:1305.3522 [hep-ph], to appear

Gunion Fest, UC Davis, March 28, 2014

Escaping the large fine tuning and little hierarchy problems in the next to minimal supersymmetric model and h ---> aa decays
Radovan Dermisek, John F. Gunion (UC, Davis). Feb 2005. 4 pp.
Published in **Phys.Rev.Lett. 95 (2005) 041801**
DOI: 10.1103/PhysRevLett.95.041801
e-Print: **hep-ph/0502105** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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Consistency of LEP event excesses with an h ---> aa decay scenario and low-fine-tuning NMSSM models
Radovan Dermisek (Princeton, Inst. Advanced Study), John F. Gunion (UC, Davis). Oct 2005. 5 pp.
Published in **Phys.Rev. D73 (2006) 111701**
DOI: 10.1103/PhysRevD.73.111701
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ADS Abstract Service; Phys. Rev. D Serve
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Nonstandard Higgs Boson Decays
Spencer Chang (New York U., CCPP), Radova
Published in **Ann.Rev.Nucl.Part.Sci. 58 (2008**
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Probing NMSSM Scenarios with Mi
Radovan Dermisek (Princeton, Inst. Advanced
Published in **Phys.Rev. D76 (2007) 051105**
UCD-2006-17
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Radovan Dermisek (Princeton, Inst. Advanced
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The NMSSM Solution to the Fine-Tu
Radovan Dermisek (Princeton, Inst. Advanced
Published in **Phys.Rev. D76 (2007) 095006**
DOI: 10.1103/PhysRevD.76.095006
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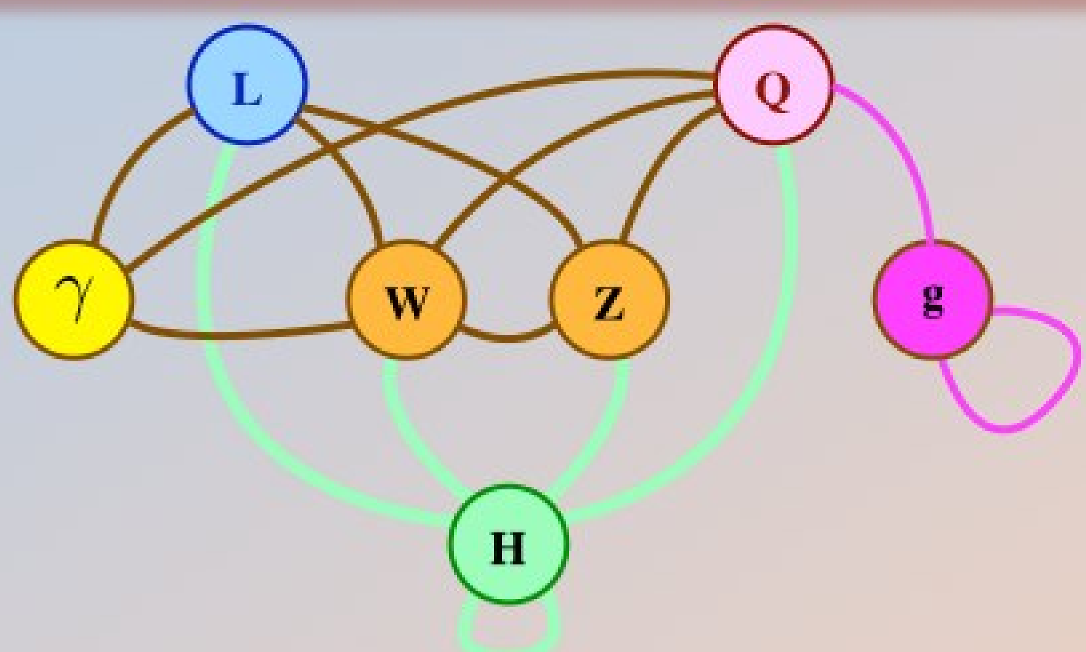
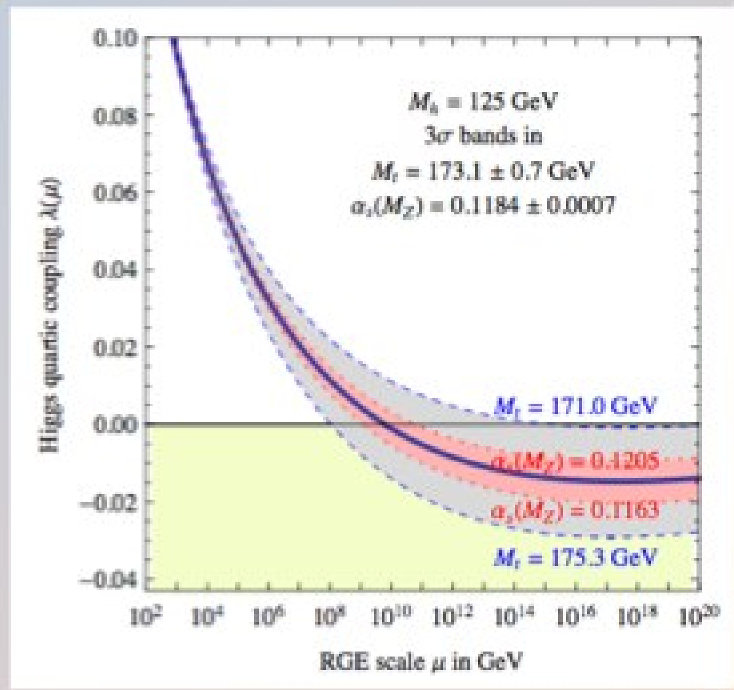
Motivation - Just the Standard Model?

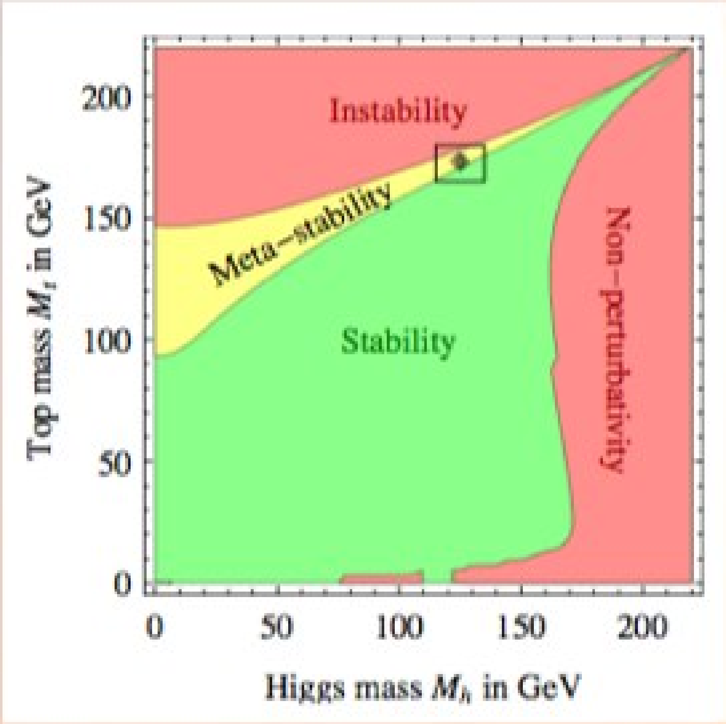
$$SM \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$$

Names	Content $i=1$	2	3	SM
Quarks and Leptons				
Q_i	$\begin{pmatrix} u \\ d \end{pmatrix}_\alpha$	$\begin{pmatrix} c \\ s \end{pmatrix}_\alpha$	$\begin{pmatrix} t \\ b \end{pmatrix}_\alpha$	$(\mathbf{3}, \mathbf{2}, 1/3)$
$\bar{u}_i$	$\bar{u}_\alpha$	$\bar{c}_\alpha$	$\bar{t}_\alpha$	$(\bar{\mathbf{3}}, \mathbf{1}, -4/3)$
$\bar{d}_i$	$\bar{d}_\alpha$	$\bar{s}_\alpha$	$\bar{b}_\alpha$	$(\bar{\mathbf{3}}, \mathbf{1}, 2/3)$
L_i	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, -1)$
$\bar{e}_i$	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$	$(\mathbf{1}, \mathbf{1}, 2)$
Higgs H		$\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$		$(\mathbf{1}, \mathbf{2}, 1)$
Gauge bosons				
gluon		g_α		$(\mathbf{8}, \mathbf{1}, 0)$
W bosons		$W^\pm$, W^0		$(\mathbf{1}, \mathbf{3}, 0)$
B boson		B^0		$(\mathbf{1}, \mathbf{1}, 0)$



Degrassi et al, arXiv:1205.6497





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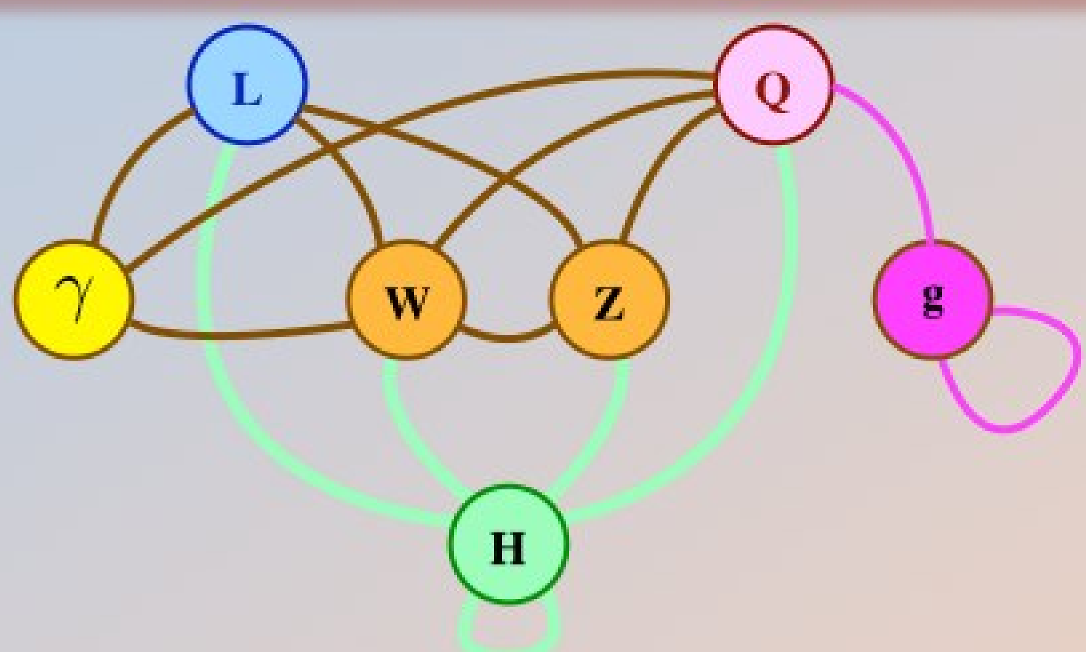
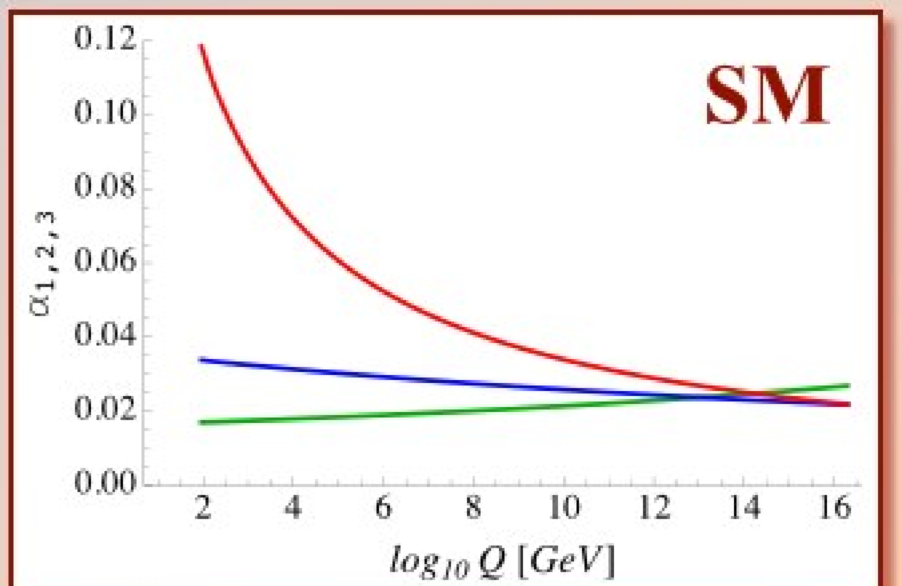
16 of SO(10)

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

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





Outline

Extensions of the SM by complete vector-like families:

- **gauge coupling unification**

  couplings at the EW scale are highly insensitive to fundamental parameters,
  their ratios are understood from the particle content,
  GUT scale can be identified with string/Planck scale

- **top Yukawa can be understood from closeness to the IR f.p.**

- **the electroweak minimum is stable**

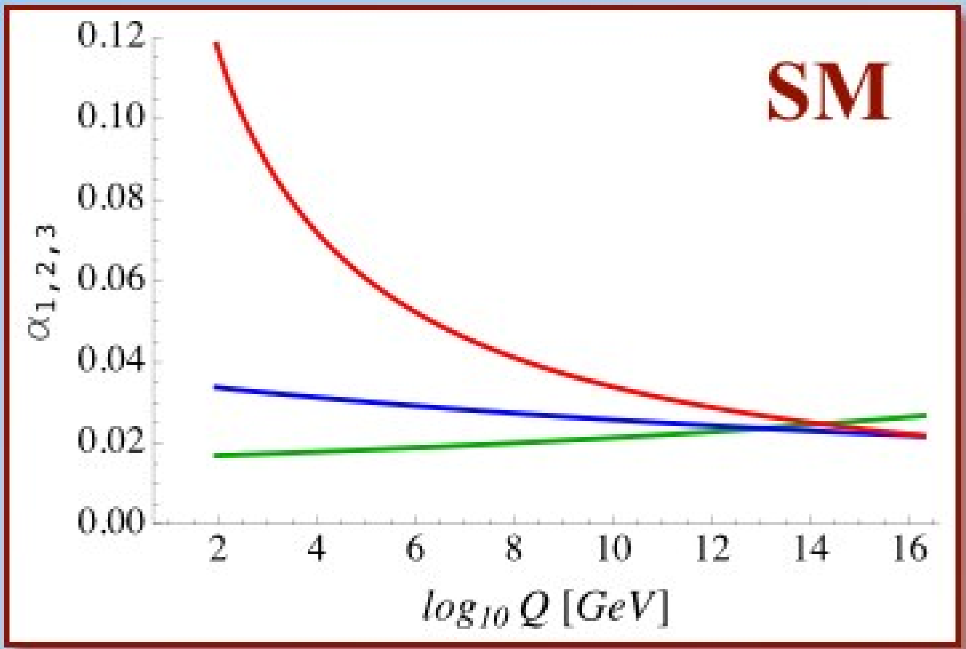
  Higgs quartic coupling remains positive all the way to GUT scale,
  the EW scale value less sensitive to boundary conditions

Possible phenomenological consequences:

- **muon g-2**
- **$h \to \mu\mu$**
- **$h \to \gamma\gamma$**
- **$h \to ZZ^*$**

Insensitive Unification of Gauge Couplings

Gauge couplings in the standard model



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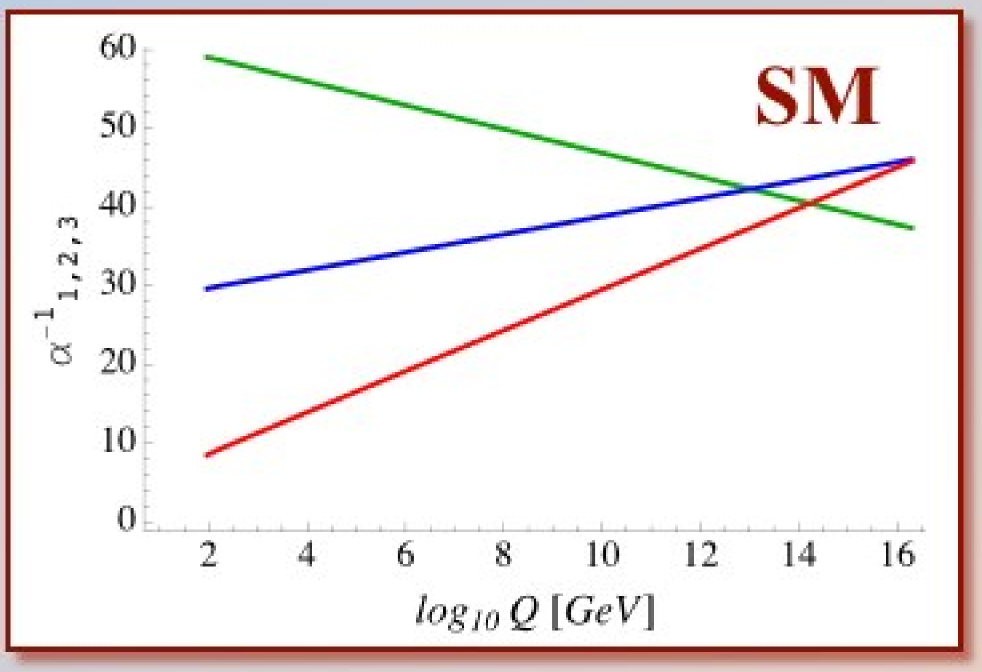


RGEs:

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

$$t = \ln Q/Q_0$$

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

$$b_i = \left(\frac{1}{10} + \frac{4}{3}n_g,\ -\frac{43}{6} + \frac{4}{3}n_g,\ -11 + \frac{4}{3}n_g\right)$$

sensitivity

$$\frac{\delta\alpha_3(M_Z)}{\alpha_3(M_Z)} = \frac{\alpha_3(M_Z)}{\alpha_G}\frac{\delta\alpha_G}{\alpha_G}$$

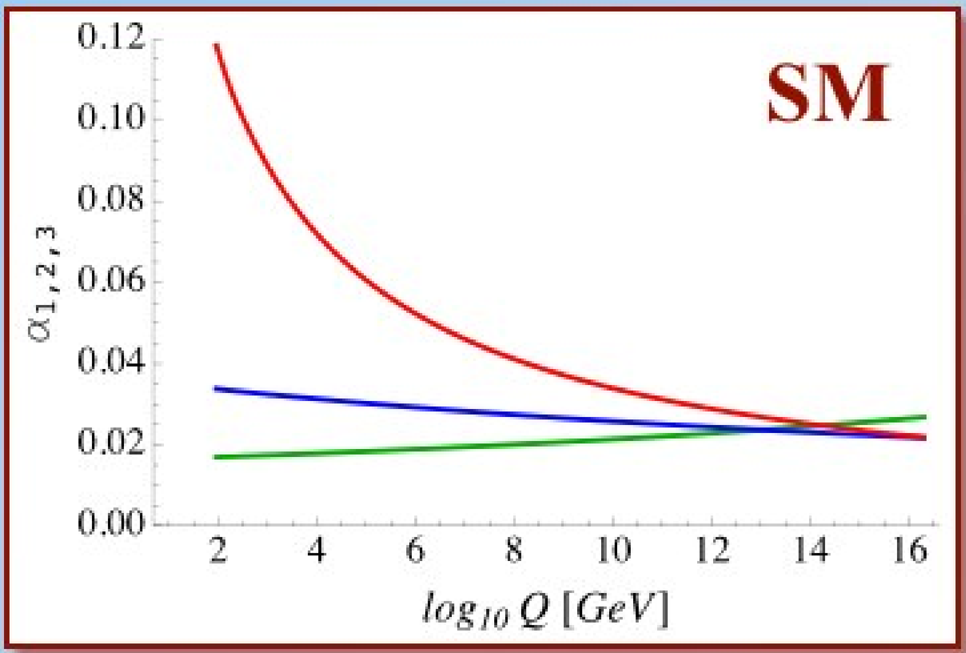
~4

solution:

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

SM

SM+3VF



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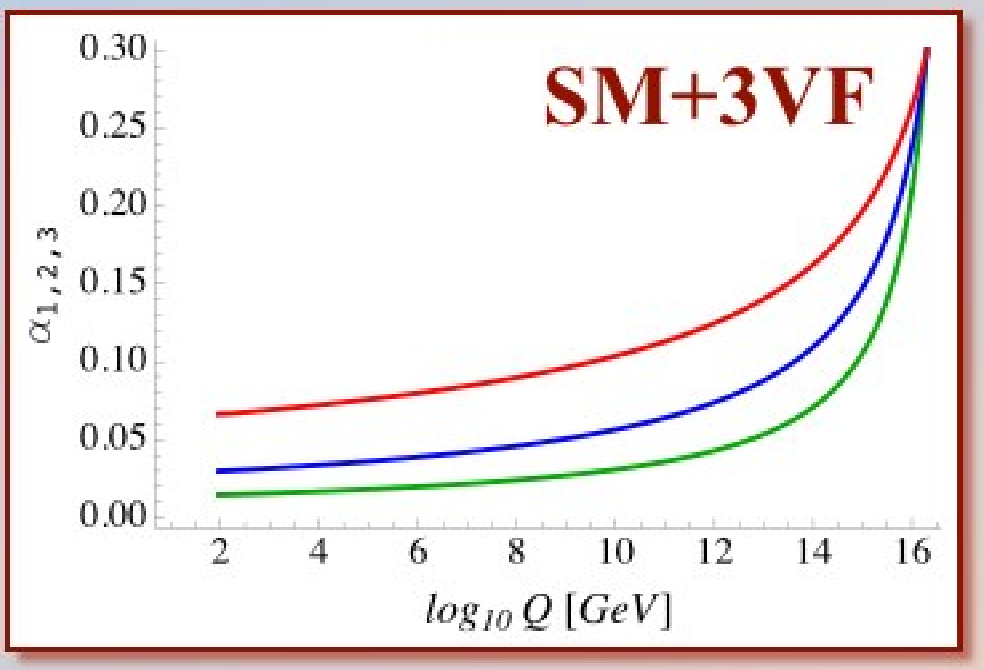

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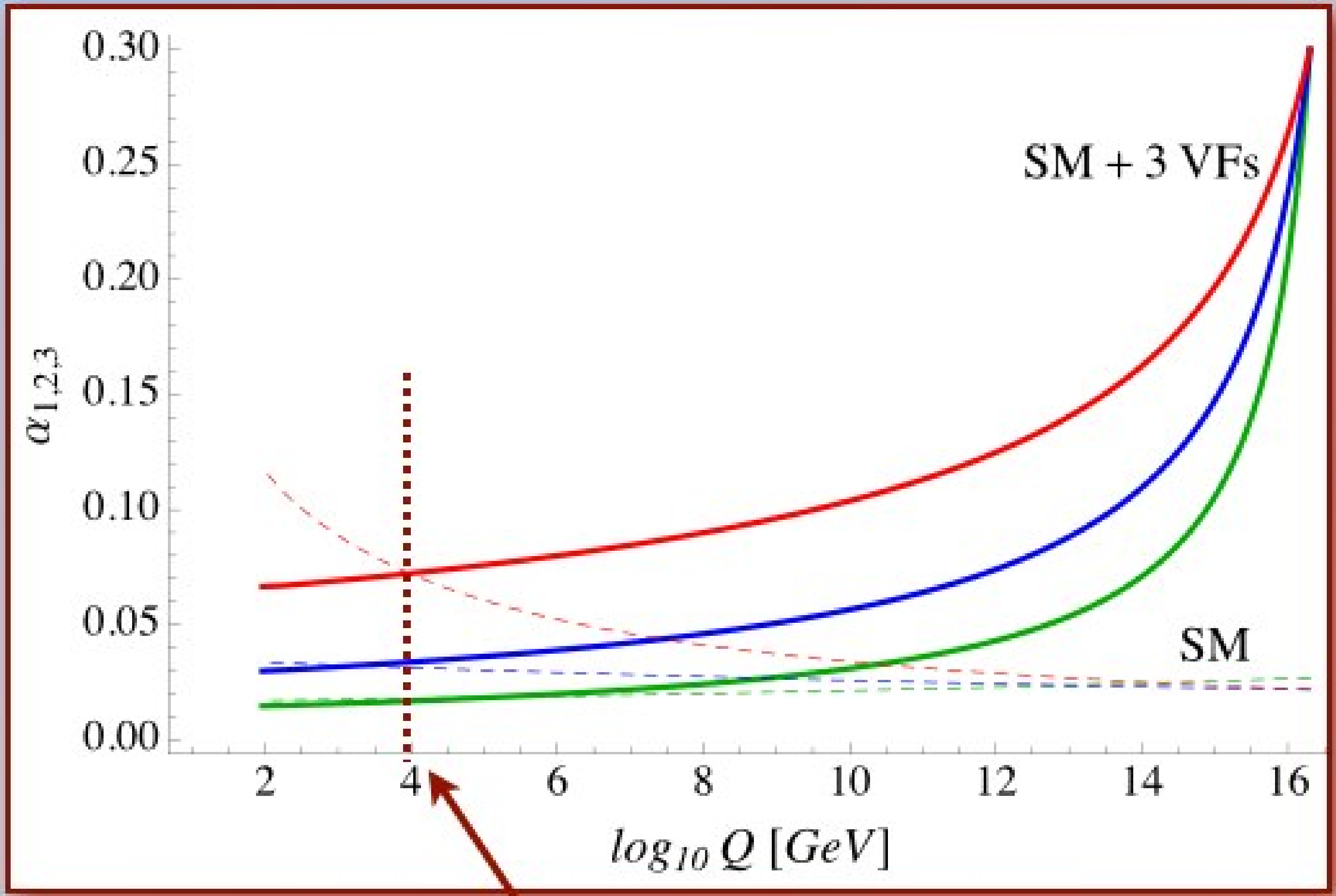
$$b_i = (121/10,\ 29/6,\ +1)$$

solution:

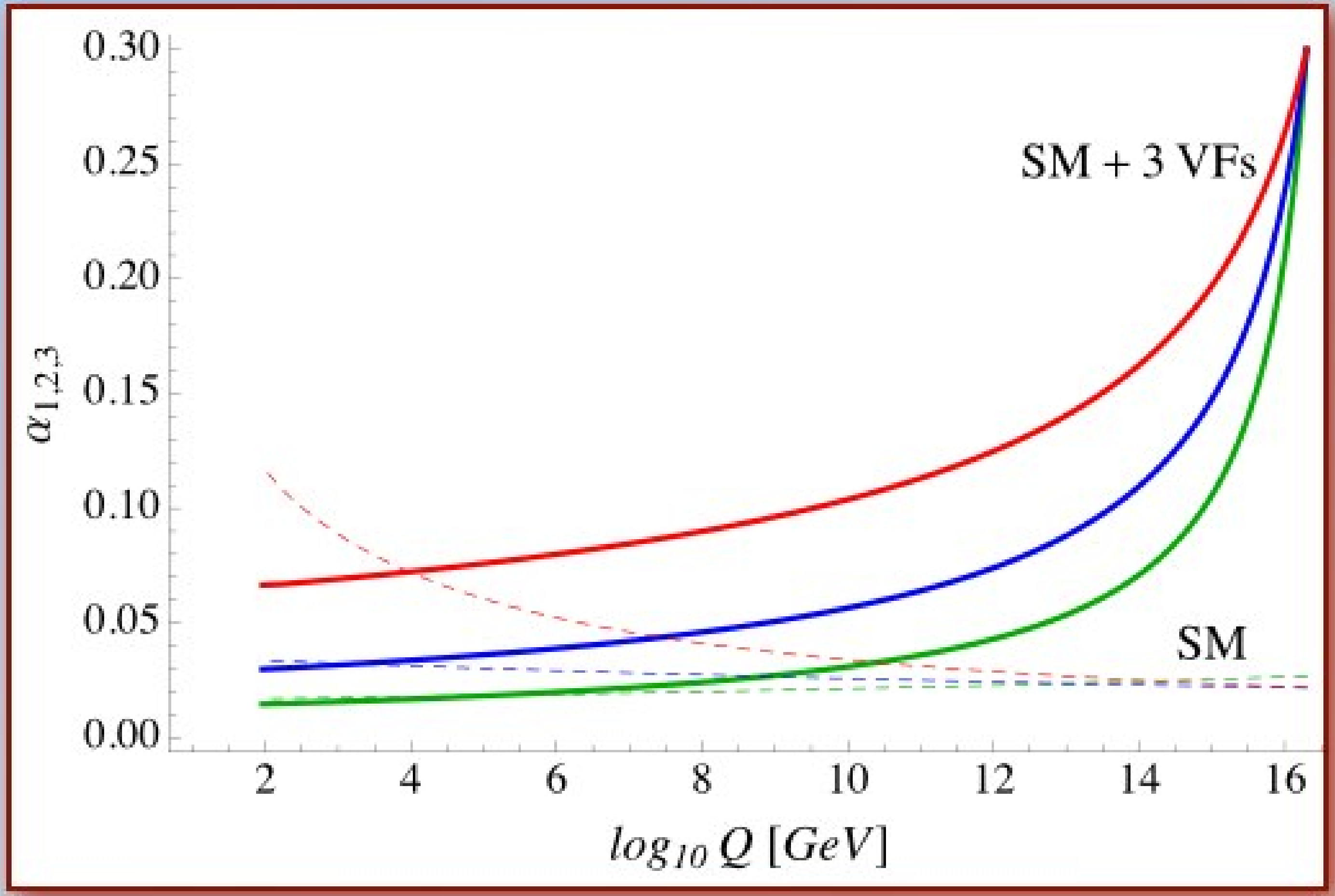
$$\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi}\ln\frac{M_G}{M_Z} + \alpha_i^{-1}(M_G)$$

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)**

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

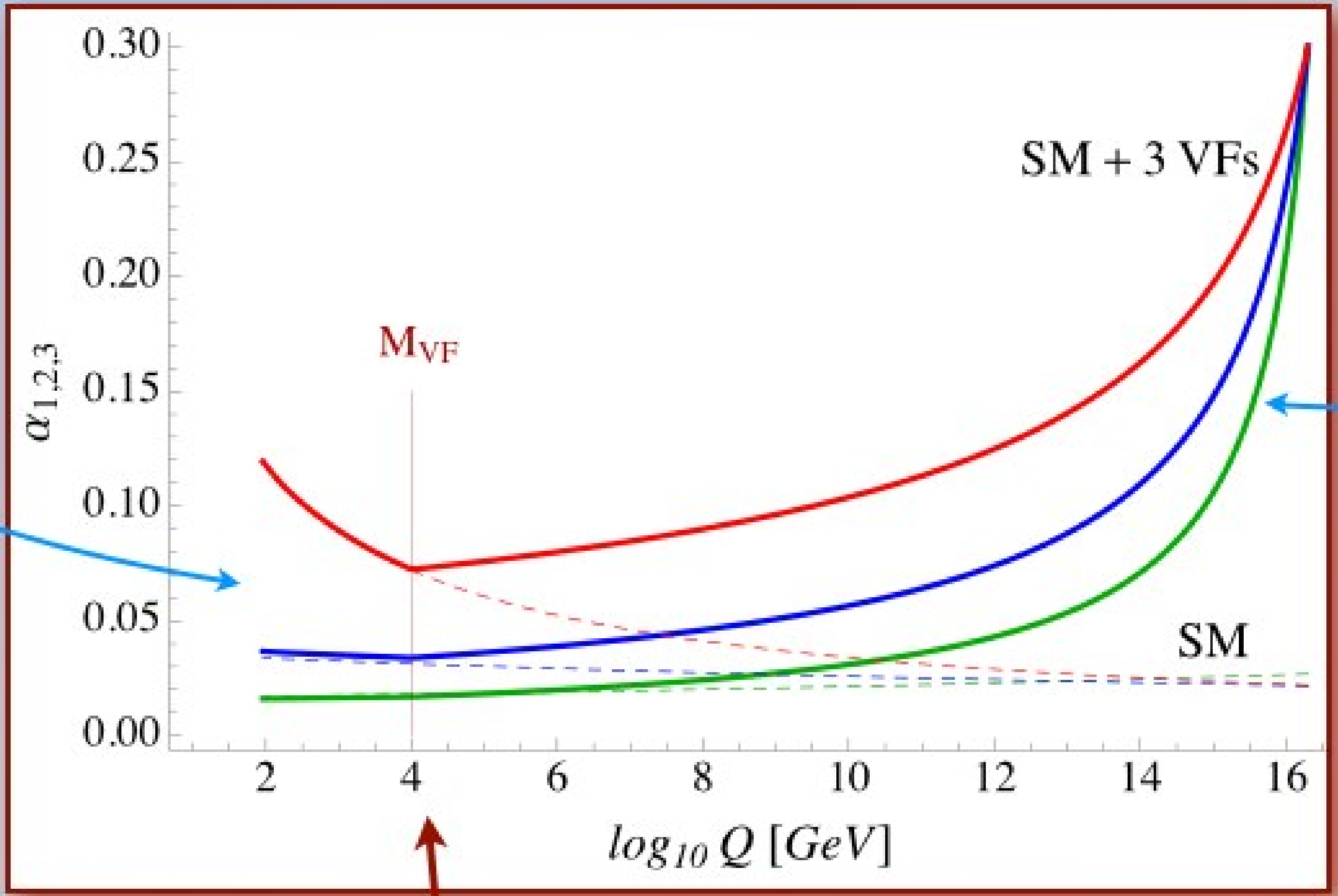
Maiani, Parisi, and Petronzio (1978)

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

(includes 2-loop)

Gauge couplings in the SM + 3VFs

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



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

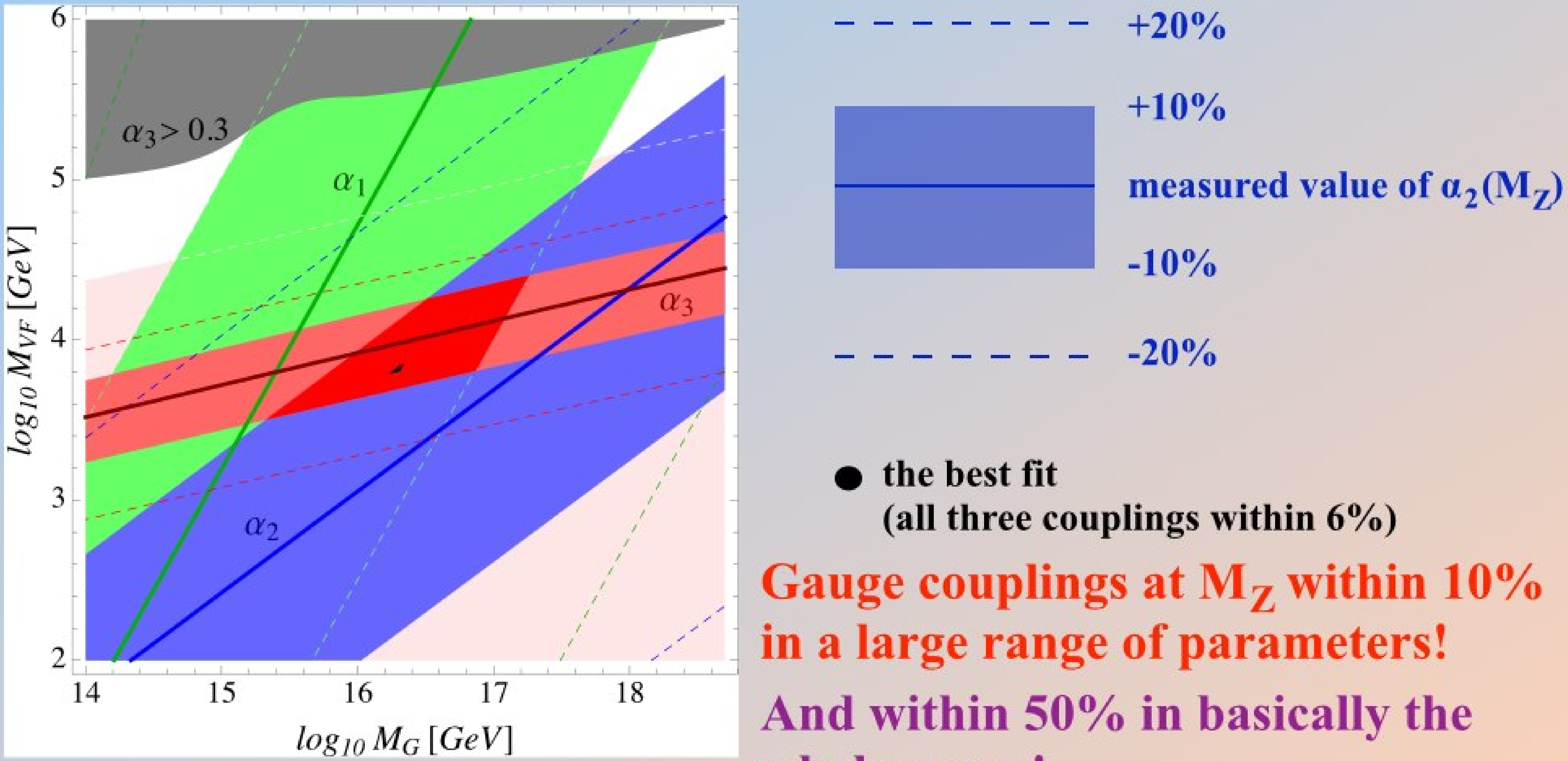
$$\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi} \ln \frac{M_G}{M_Z} + \alpha_i^{-1}(M_G)$$

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}

α_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!

Realistic example

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

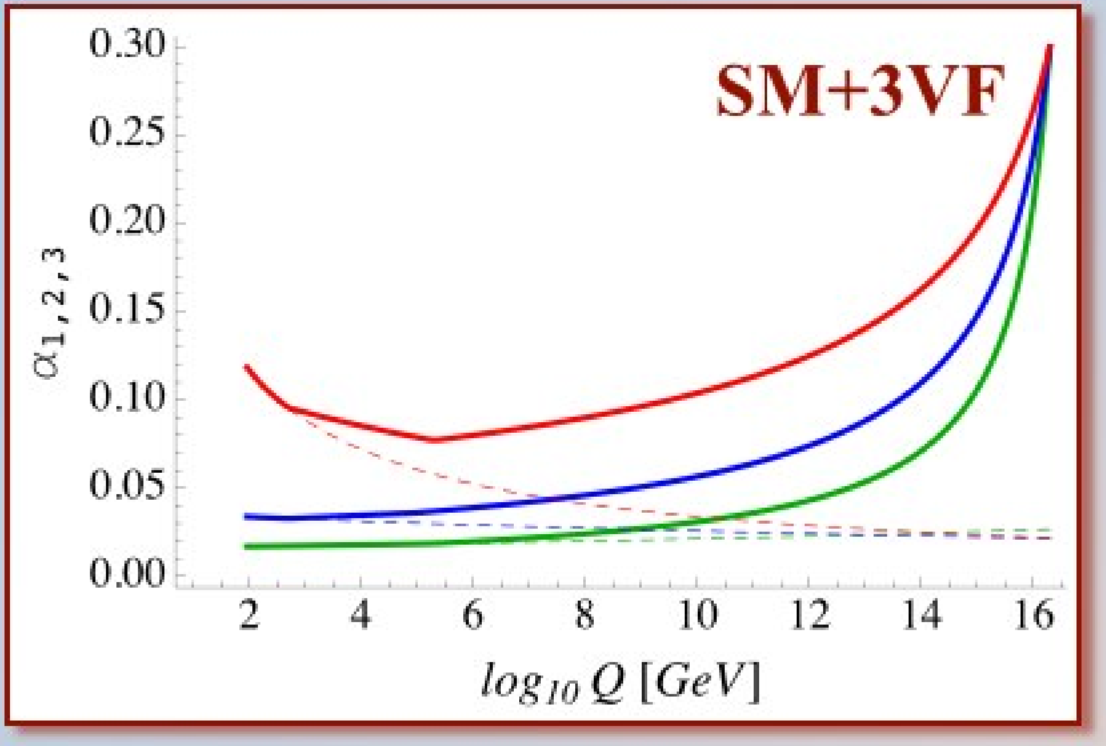
$\alpha_{EM}(M_Z) = 1/127.916$
$\sin^2\theta_W = 0.2313$

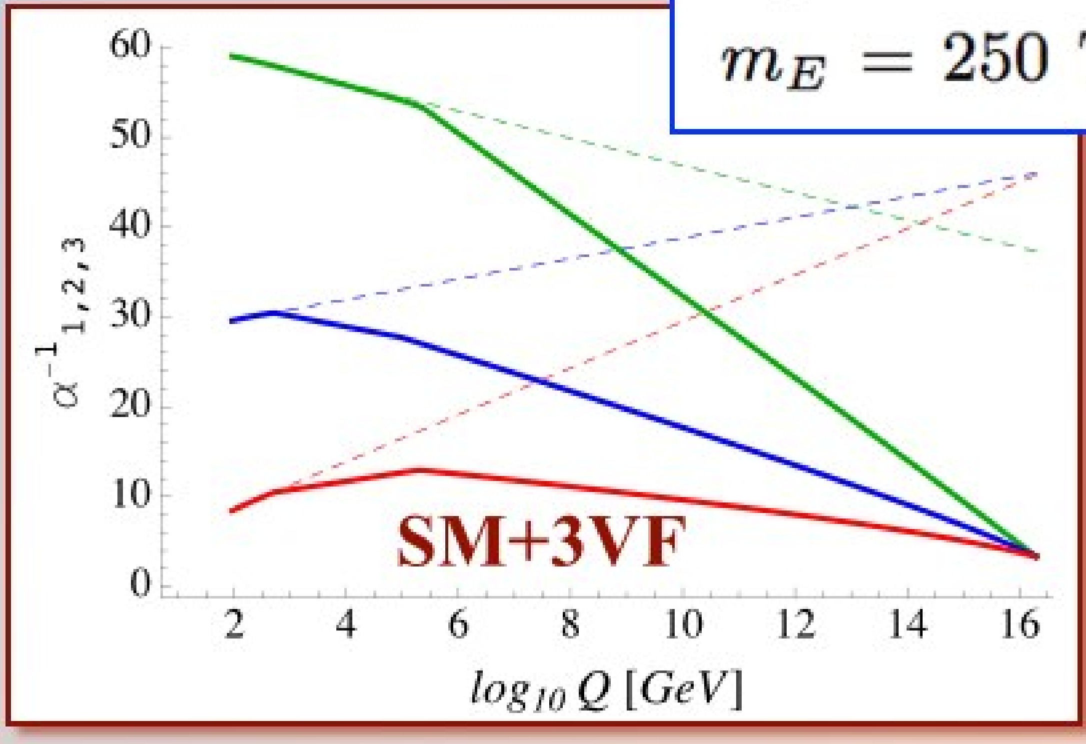
Gauge couplings reproduced (within fractions of exp. uncertainties) for :

4 sig. figures

2 sig. figures

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

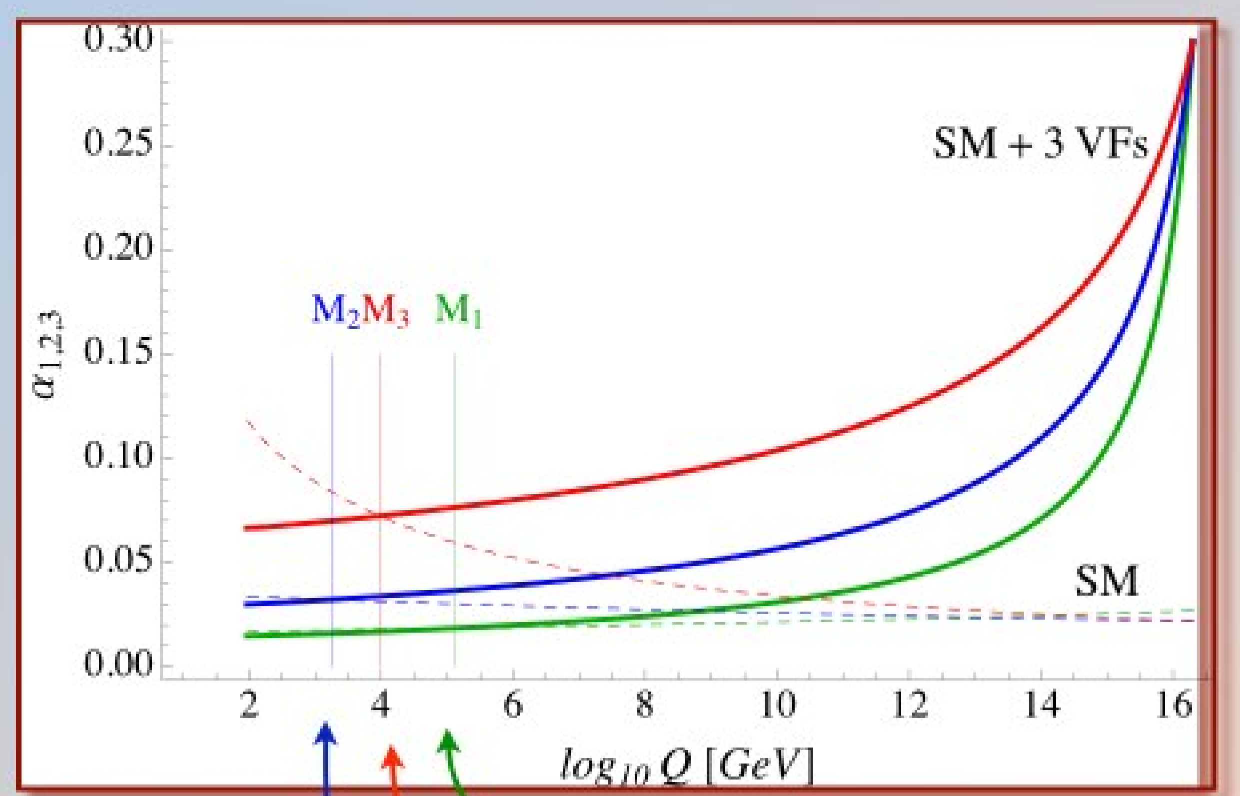




Many possible solutions!

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:



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

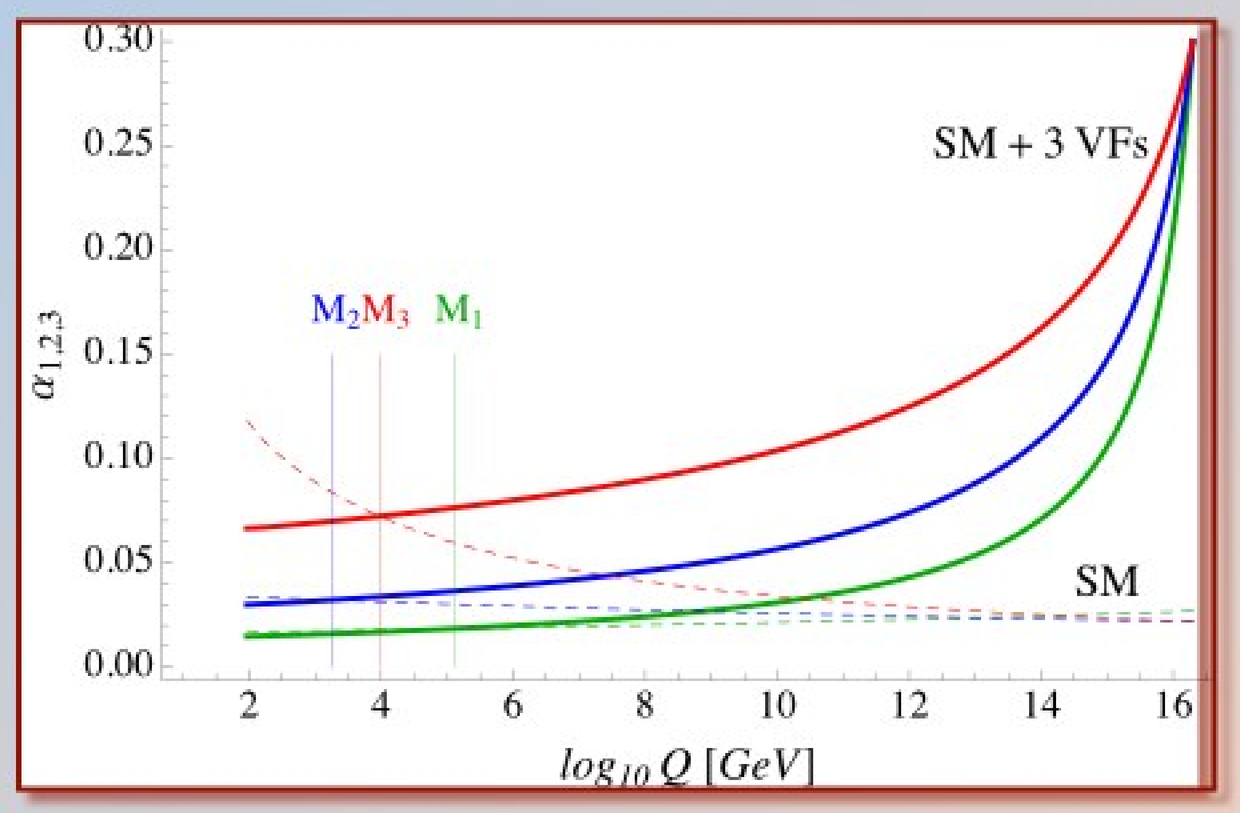
$$\frac{1}{2\pi}\sum_{i=1}^{3}\left(b_2^Q \ln\frac{M_{Qi}}{M_Z} + b_2^L \ln\frac{M_{Li}}{M_Z}\right) = \frac{4}{\pi}\ln\frac{M_2}{M_Z}$$

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

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

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:



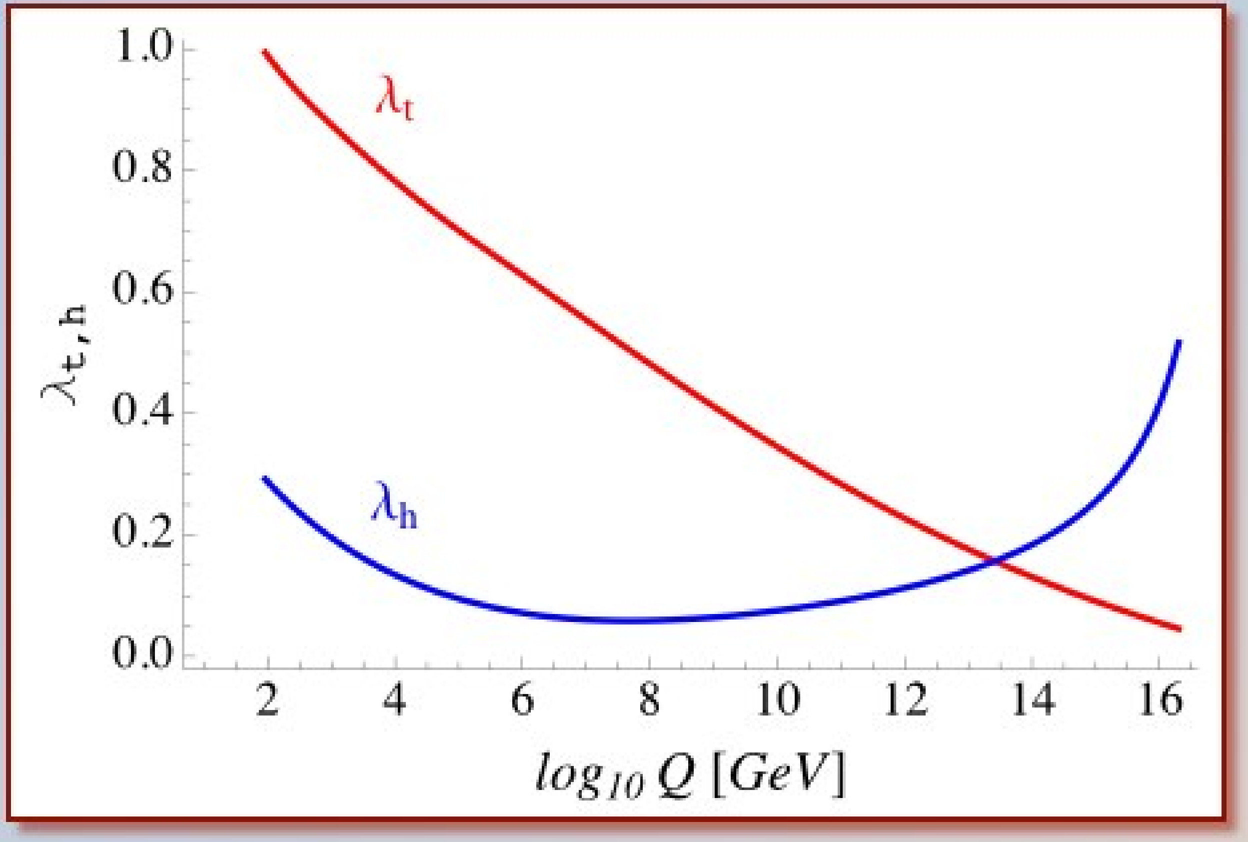
$$M_3^4 = M_Q^2 M_U M_D,$$

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

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

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

Top Yukawa and Higgs quartic couplings



$m_H = 125$ GeV

- **top Yukawa can be understood from closeness to the IR f.p.**

  (different textures for fermion masses compared to usual GUTs)

- **the electroweak minimum is stable**

  Higgs quartic coupling remains positive all the way to GUT scale,
  the EW scale value less sensitive to boundary conditions

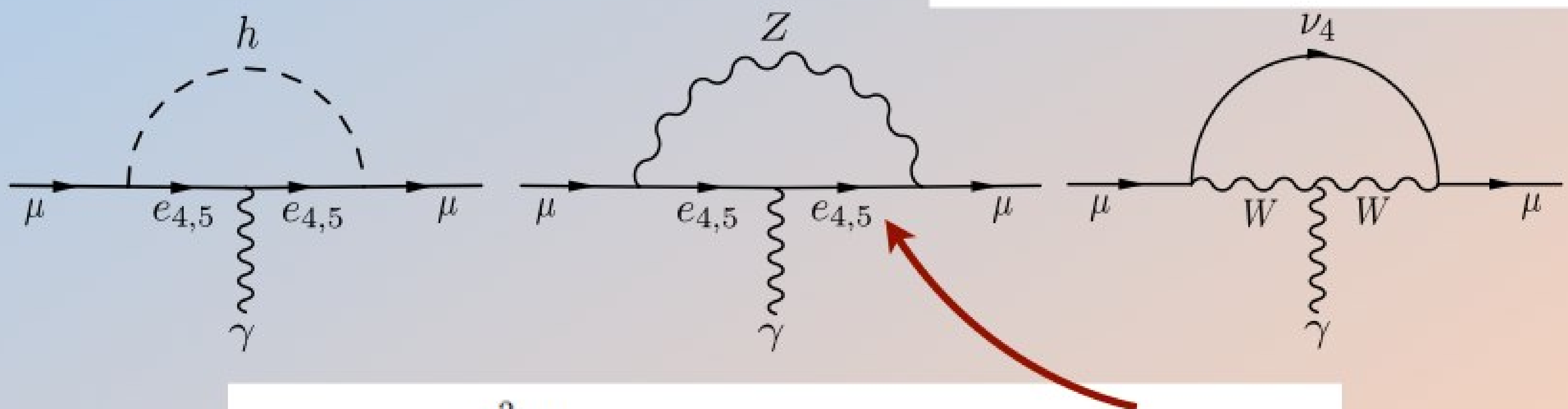
Muon g-2 and Higgs decays

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]

$$\mathcal{L} \supset -\bar{l}_{Li} y_{ij} e_{Rj} H - \bar{l}_{Li} \lambda_i^E E_R H - \bar{L}_L \lambda_j^L e_{Rj} H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + h.c.,$$

$$(\bar{e}_{Li}, \bar{L}_L^-, \bar{E}_L) \begin{pmatrix} y_{ij} v & 0 & \lambda_i^E v \\ \lambda_j^L v & M_L & \lambda v \\ 0 & \bar{\lambda} v & M_E \end{pmatrix} \begin{pmatrix} e_{Rj} \\ L_R^- \\ E_R \end{pmatrix}$$



$$\delta a_\mu^Z = -\frac{g^2 m_\mu}{8\pi^2 M_W^2} \left\{ (g_L^2 + g_R^2) m_\mu F_Z(x) + g_L g_R m_f G_Z(x) \right\}$$

$$x = (m_f / M_Z)^2$$

Interesting insight can be obtained by integrating out vectorlike leptons:

$$\mathcal{L} \supset -\bar{l}_{Li} y_{ij} e_{Rj} H - \bar{l}_{Li} \lambda_i^E E_R H - \bar{L}_L \lambda_j^L e_{Rj} H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + h.c.,$$

$$\lambda_E v, \lambda_L v, \bar{\lambda} v, \lambda v \ll M_E, M_L$$

Effective lagrangian is given by:

$$\mathcal{L}_{eff} \supset -\bar{\mu}_L \left(y_\mu + \frac{\lambda^L \bar{\lambda} \lambda^E}{M_L M_E} H H^\dagger \right) \mu_R H + h.c. \longrightarrow -\left(m_\mu^H + m_\mu^{LE} \right) \bar{\mu}_L \mu_R + h.c.$$

Contribution to the muon g-2 can be written as:

$$\Delta a_\mu \simeq c \frac{m_\mu m_\mu^{LE}}{(4\pi v)^2} \simeq 0.85\, c \frac{m_\mu^{LE}}{m_\mu} \Delta a_\mu^{exp}$$

contribution to the muon mass and muon g-2 is correlated!

$c = -1$

$M_E \simeq M_L \gg M_Z$

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

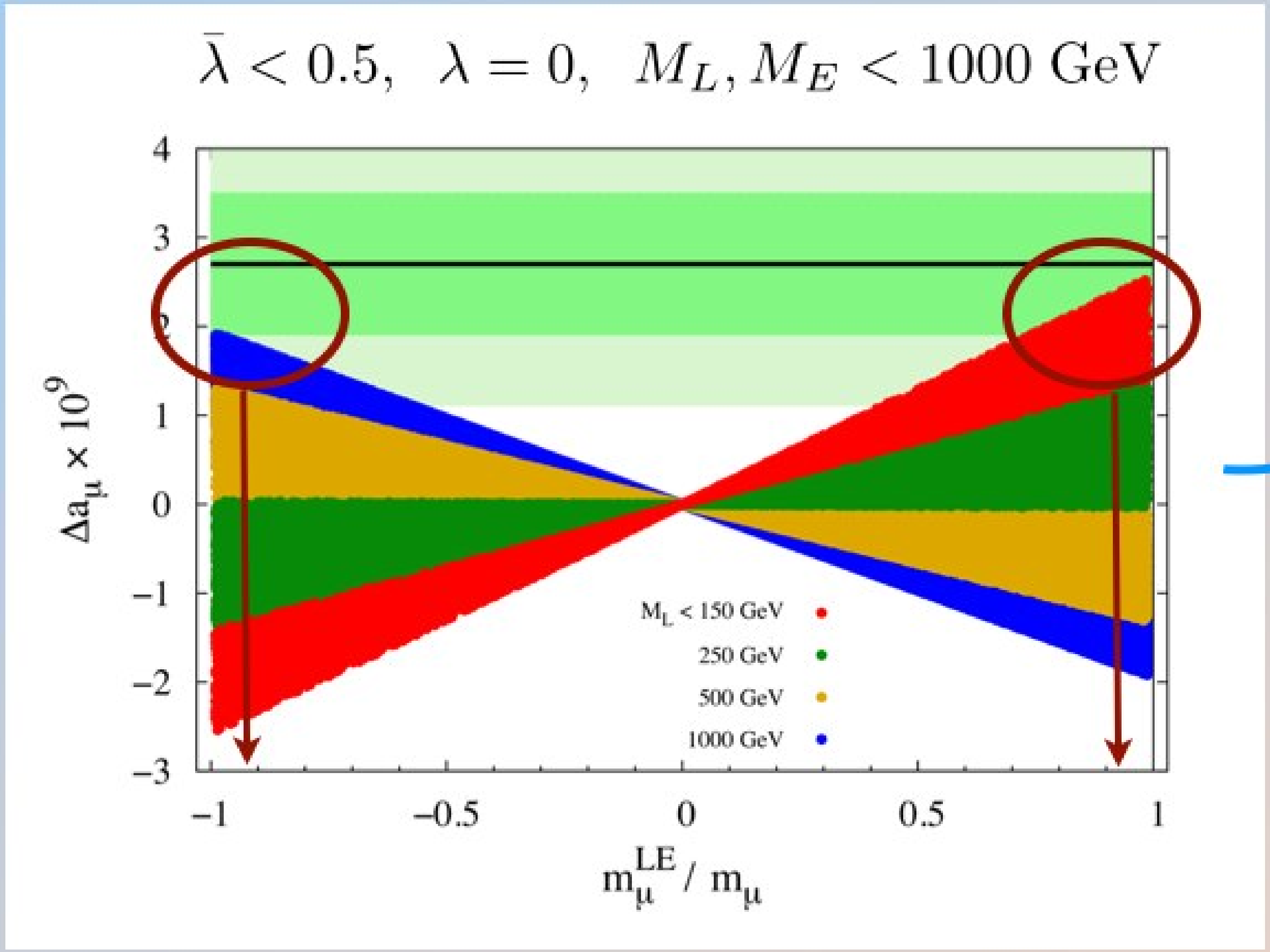
integrating out vectorlike leptons:

$$\mathcal{L}_{eff} \supset -\bar{\mu}_L \left(y_\mu + \frac{\lambda^L \bar{\lambda} \lambda^E}{M_L M_E} H H^\dagger \right) \mu_R H + h.c. \longrightarrow -\left(m_\mu^H + m_\mu^{LE}\right) \bar{\mu}_L \mu_R + h.c.$$

$$\Delta a_\mu \simeq c \frac{m_\mu m_\mu^{LE}}{(4\pi v)^2} \simeq 0.85\, c \frac{m_\mu^{LE}}{m_\mu} \Delta a_\mu^{exp}$$

Random scan:

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



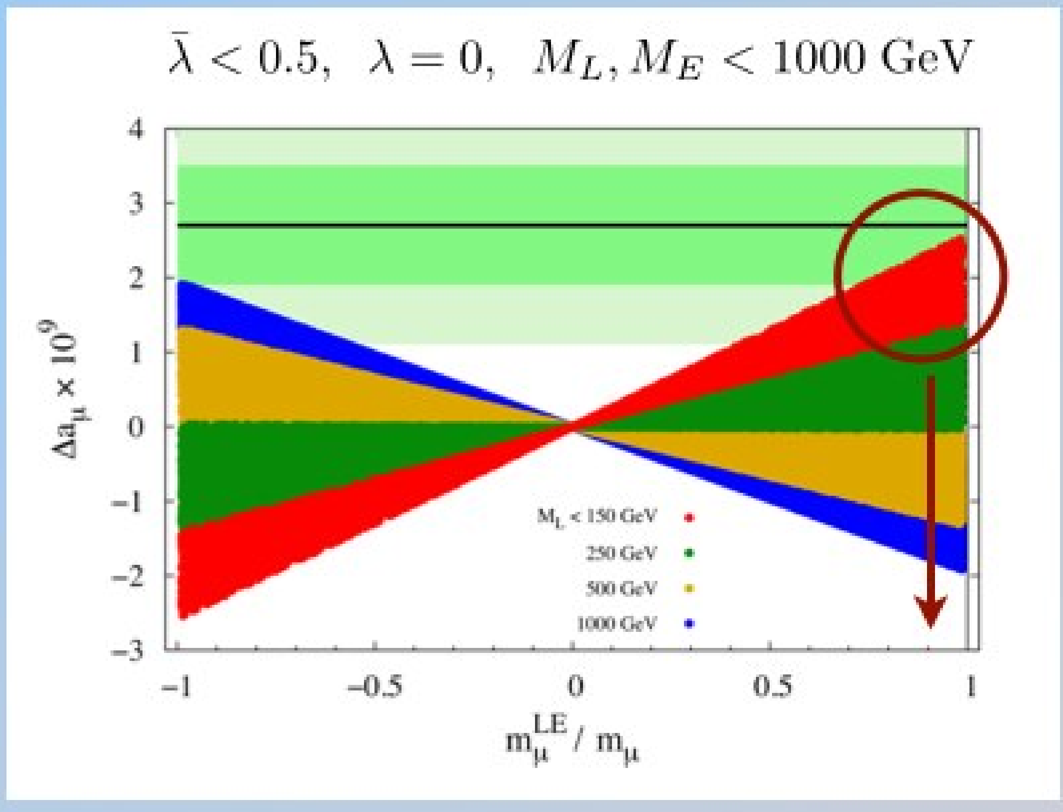
$$c = f(M_L)$$

Constraints from precision EW data:

$$\frac{\lambda_E v}{M_E} < 0.03, \qquad \frac{\lambda_L v}{M_L} < 0.04$$

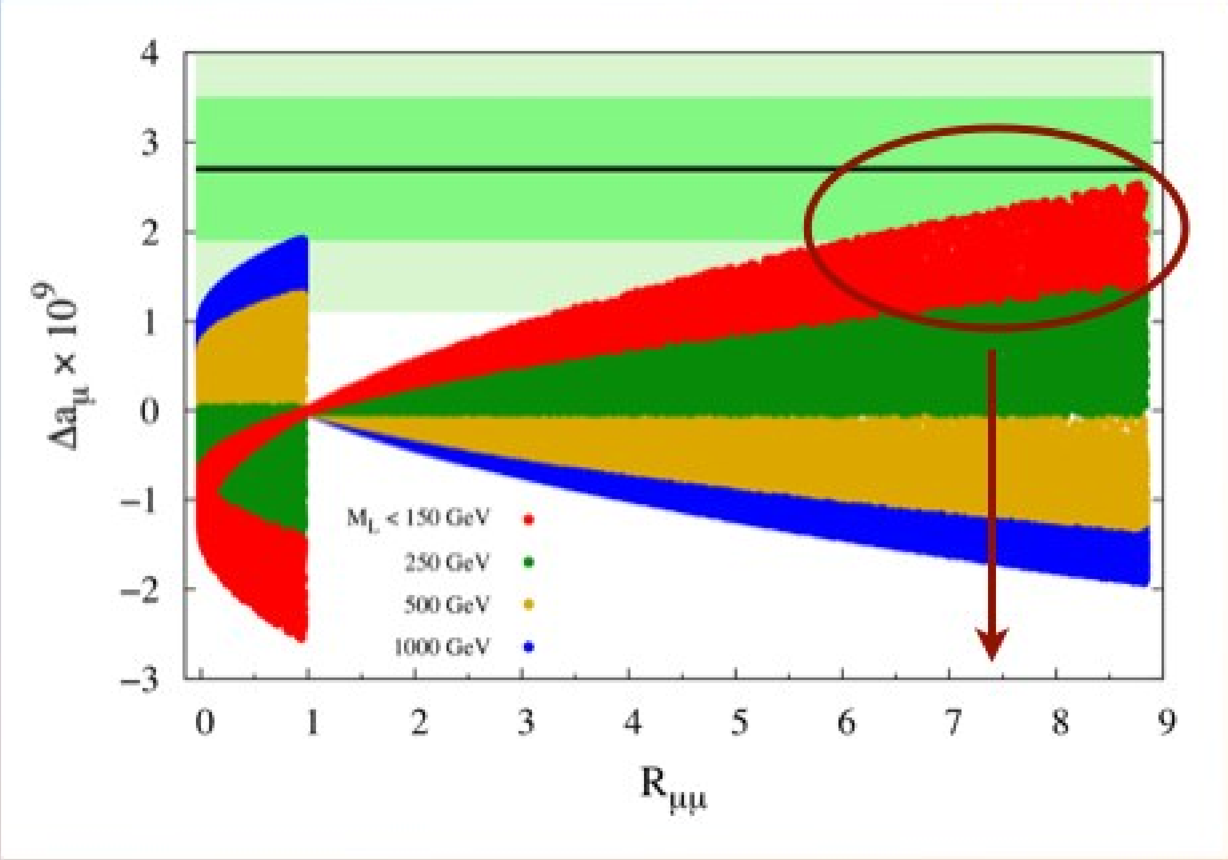
$$(\bar{e}_{Li}, \bar{L}_L^-, \bar{E}_L) \begin{pmatrix} y_{ij} v & 0 & \lambda_i^E v \\ \lambda_j^L v & M_L & \lambda v \\ 0 & \bar{\lambda} v & M_E \end{pmatrix} \begin{pmatrix} e_{Rj} \\ L_R^- \\ E_R \end{pmatrix}$$

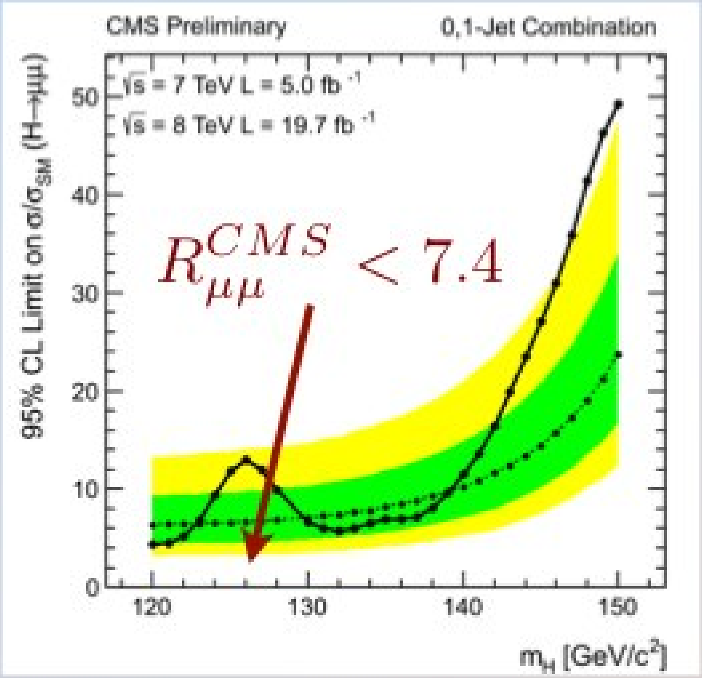
h → μμ



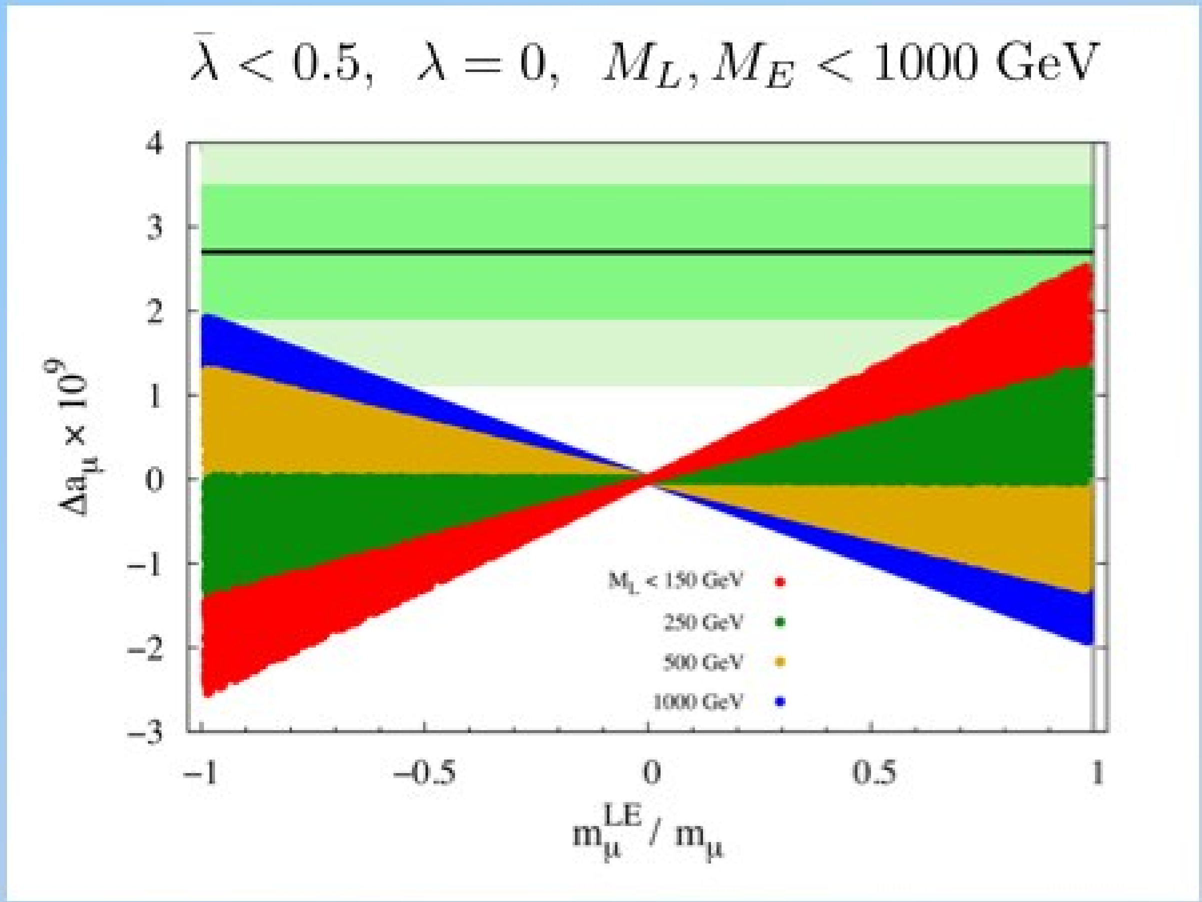
$$\mathcal{L}_{eff} \supset -\bar{\mu}_L \left(y_\mu + \frac{\lambda^L \bar{\lambda} \lambda^E}{M_L M_E} H H^\dagger \right) \mu_R H + h.c. \longrightarrow -\left(m_\mu^H + m_\mu^{LE} \right) \bar{\mu}_L \mu_R + h.c.$$

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



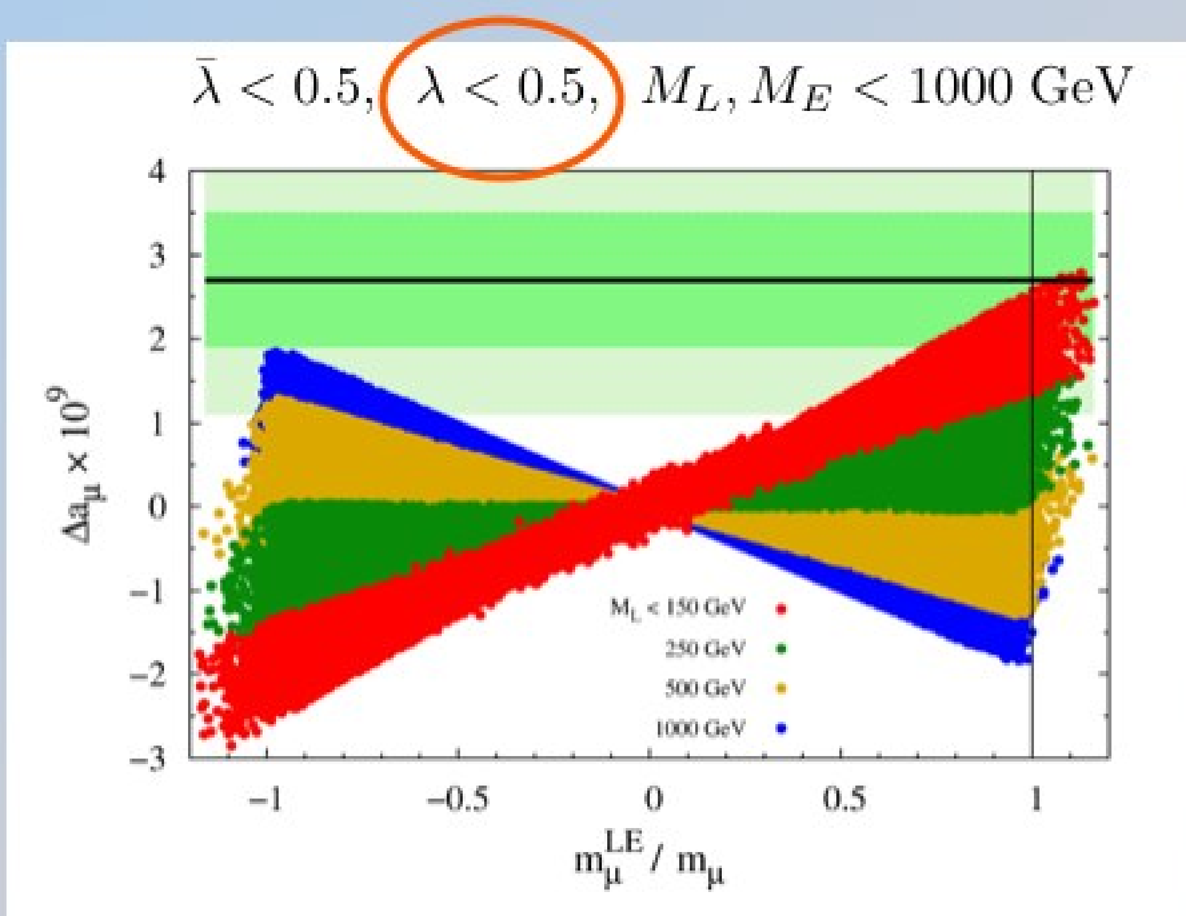


$$R_{\mu\mu} = \frac{\Gamma(h \to \mu^+ \mu^-)}{\Gamma(h \to \mu^+ \mu^-)_{SM}}$$



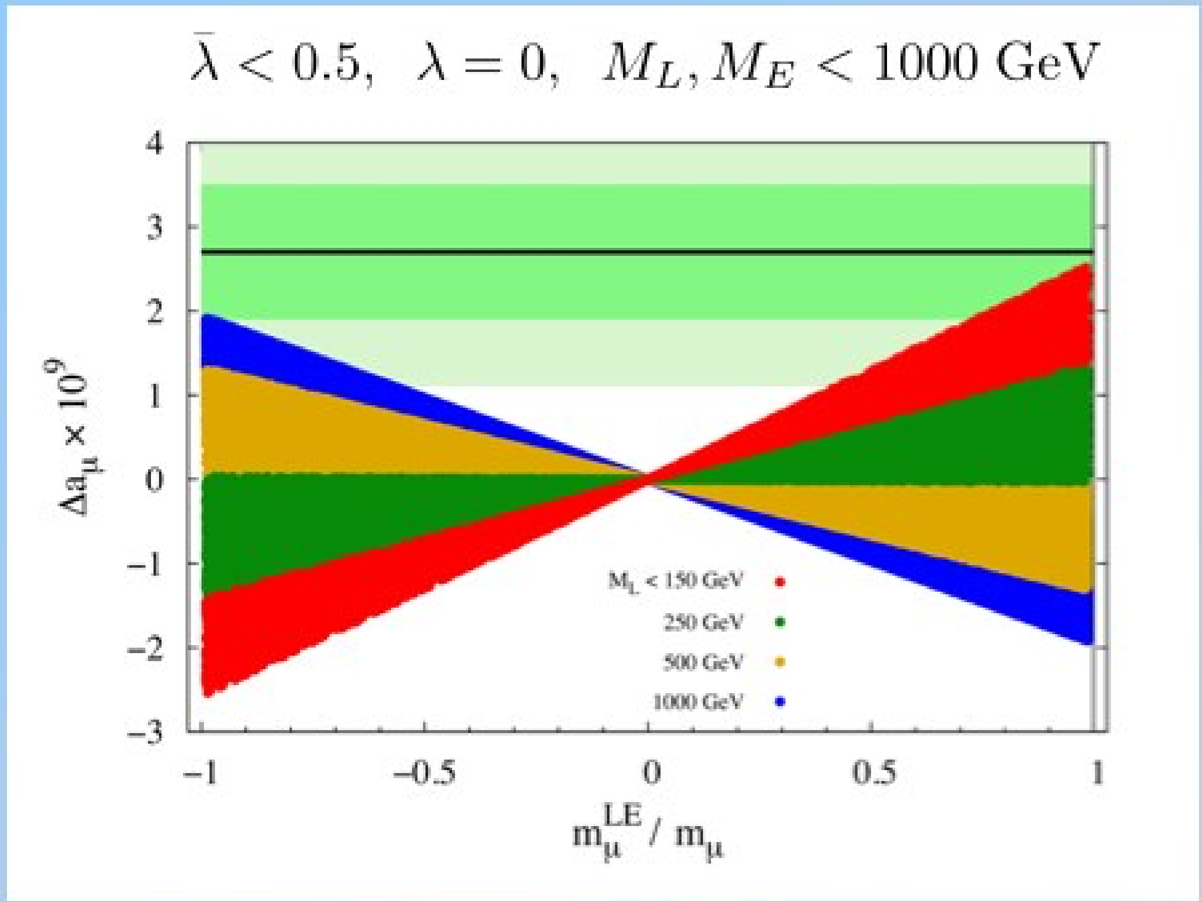
$$\mathcal{L} \supset -\bar{l}_{Li} y_{ij} e_{Rj} H - \bar{l}_{Li} \lambda_i^E E_R H - \bar{L}_L \lambda_j^L e_{Rj} H - \lambda \bar{L}_L E_R H - \bar{\lambda} H^\dagger \bar{E}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + h.c.,$$

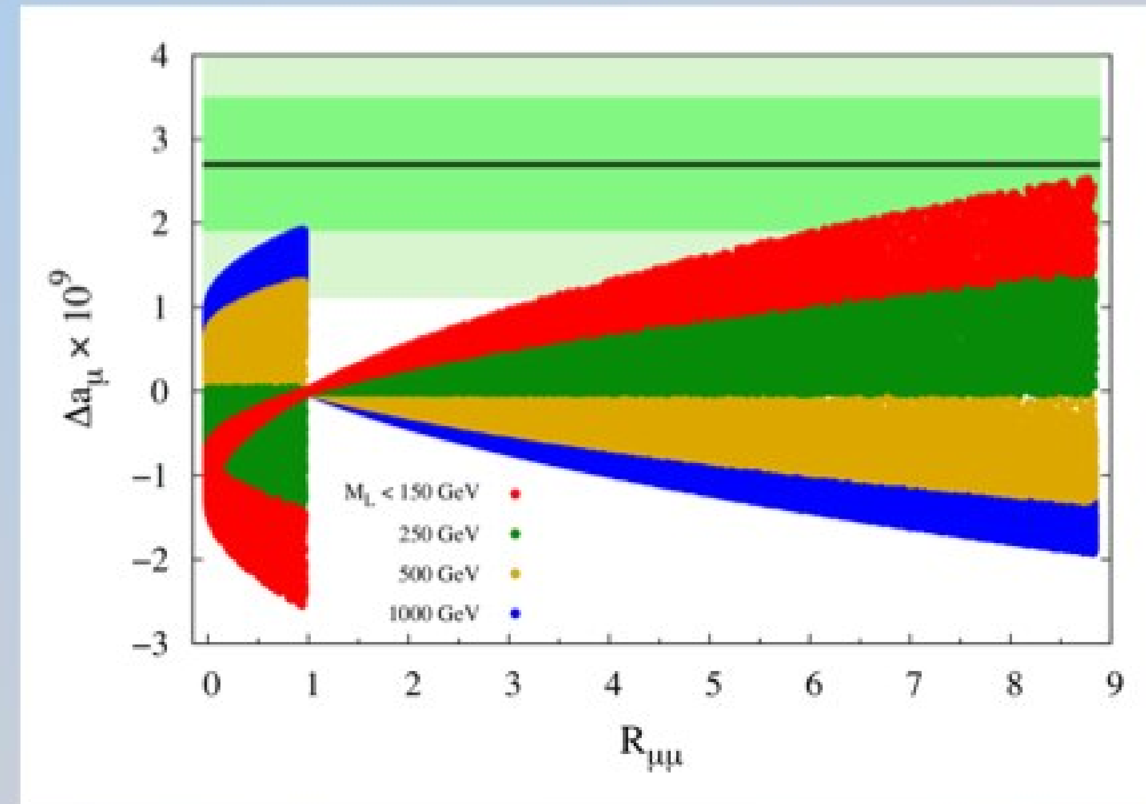
$$(\bar{e}_{Li}, \bar{L}_L^-, \bar{E}_L) \begin{pmatrix} y_{ij} v & 0 & \lambda_i^E v \\ \lambda_j^L v & M_L & \lambda v \\ 0 & \bar{\lambda} v & M_E \end{pmatrix} \begin{pmatrix} e_{Rj} \\ L_R^- \\ E_R \end{pmatrix}$$

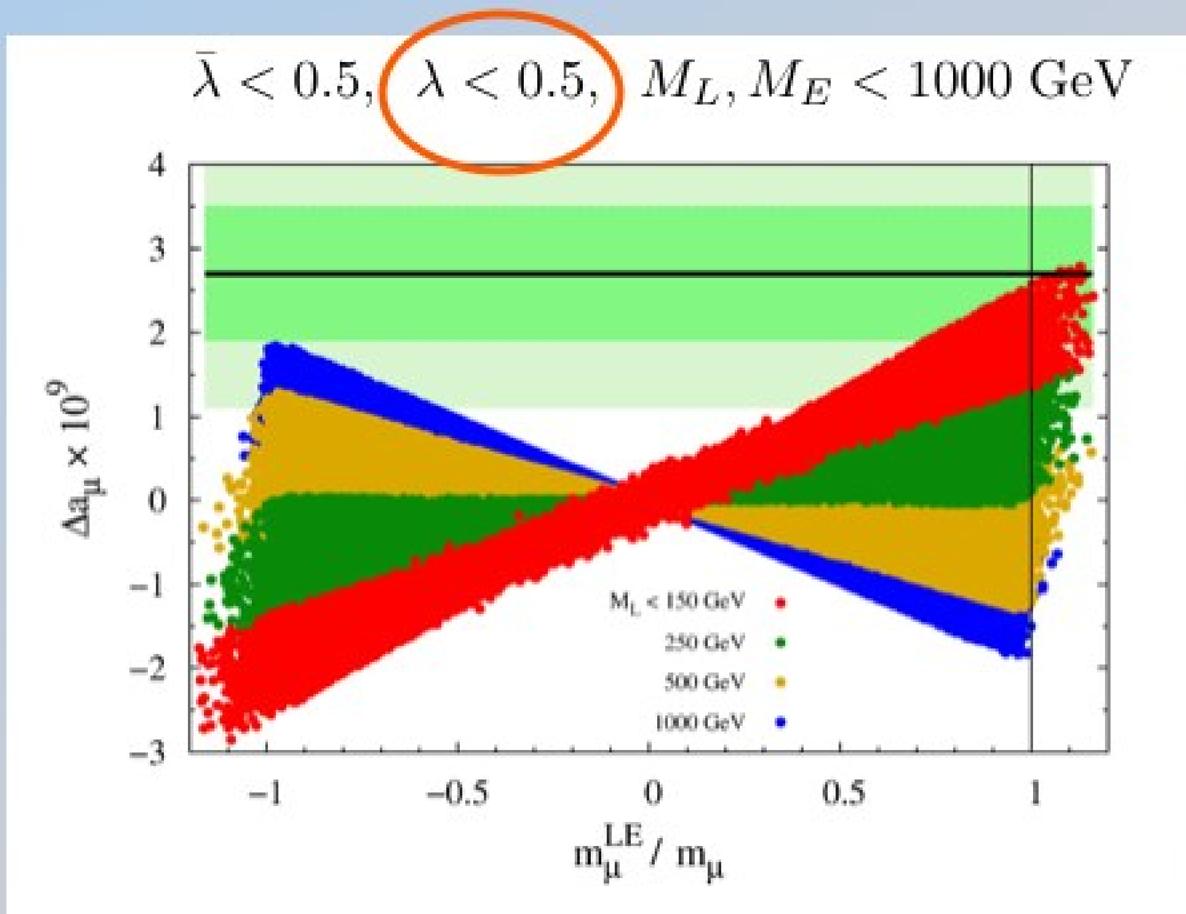


$$\mathcal{L}_{eff} \supset -\bar{\mu}_L \left(y_\mu + \frac{\lambda^L \bar{\lambda} \lambda^E}{M_L M_E} H H^\dagger \right) \mu_R H + h.c. \longrightarrow -\left(m_\mu^H + m_\mu^{LE}\right) \bar{\mu}_L \mu_R + h.c.$$

$$\Delta a_\mu \simeq c \frac{m_\mu m_\mu^{LE}}{(4\pi v)^2} \simeq 0.85\, c \frac{m_\mu^{LE}}{m_\mu} \Delta a_\mu^{exp}$$


$\bar{\lambda} < 0.5, \quad \lambda = 0, \quad M_L, M_E < 1000$ GeV
$\Delta a_\mu \times 10^9$
m_μ^{LE} / m_μ
M_L < 150 GeV
250 GeV
500 GeV
1000 GeV


$\Delta a_\mu \times 10^9$
$R_{\mu\mu}$
M_L < 150 GeV
250 GeV
500 GeV
1000 GeV


$\bar{\lambda} < 0.5, \quad \lambda < 0.5, \quad M_L, M_E < 1000$ GeV
$\Delta a_\mu \times 10^9$
m_μ^{LE} / m_μ
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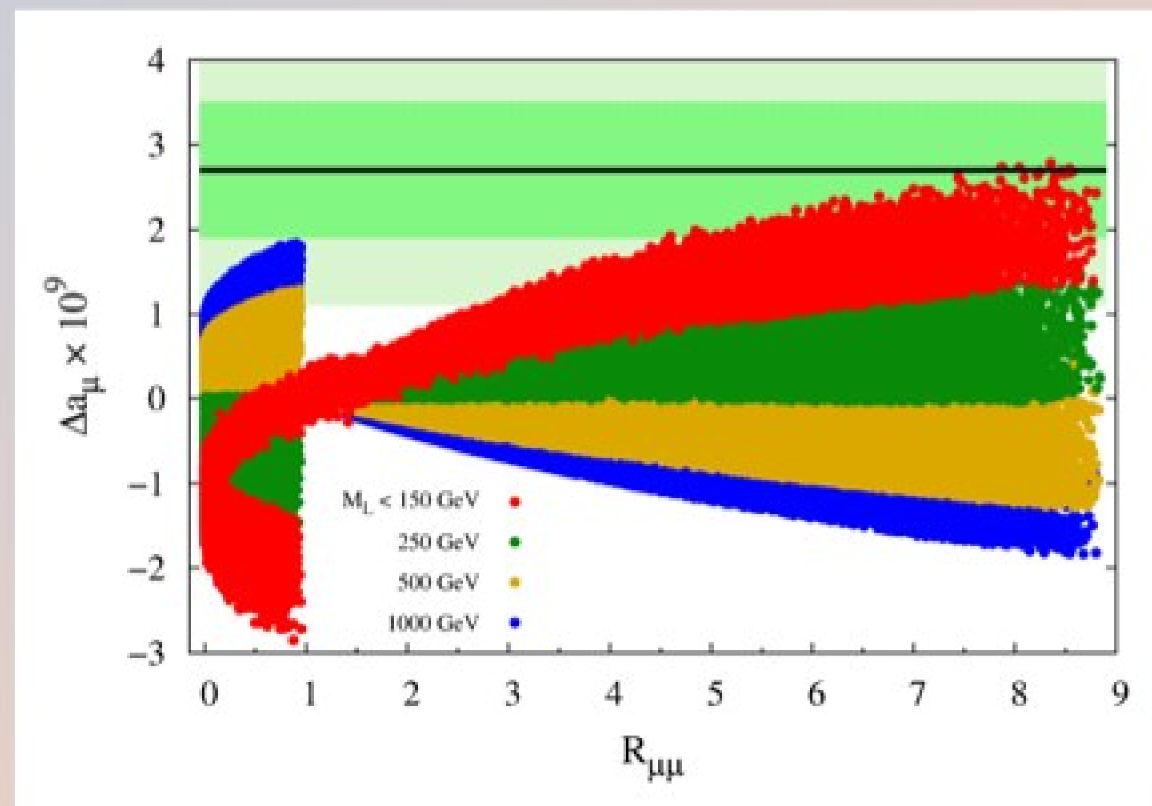
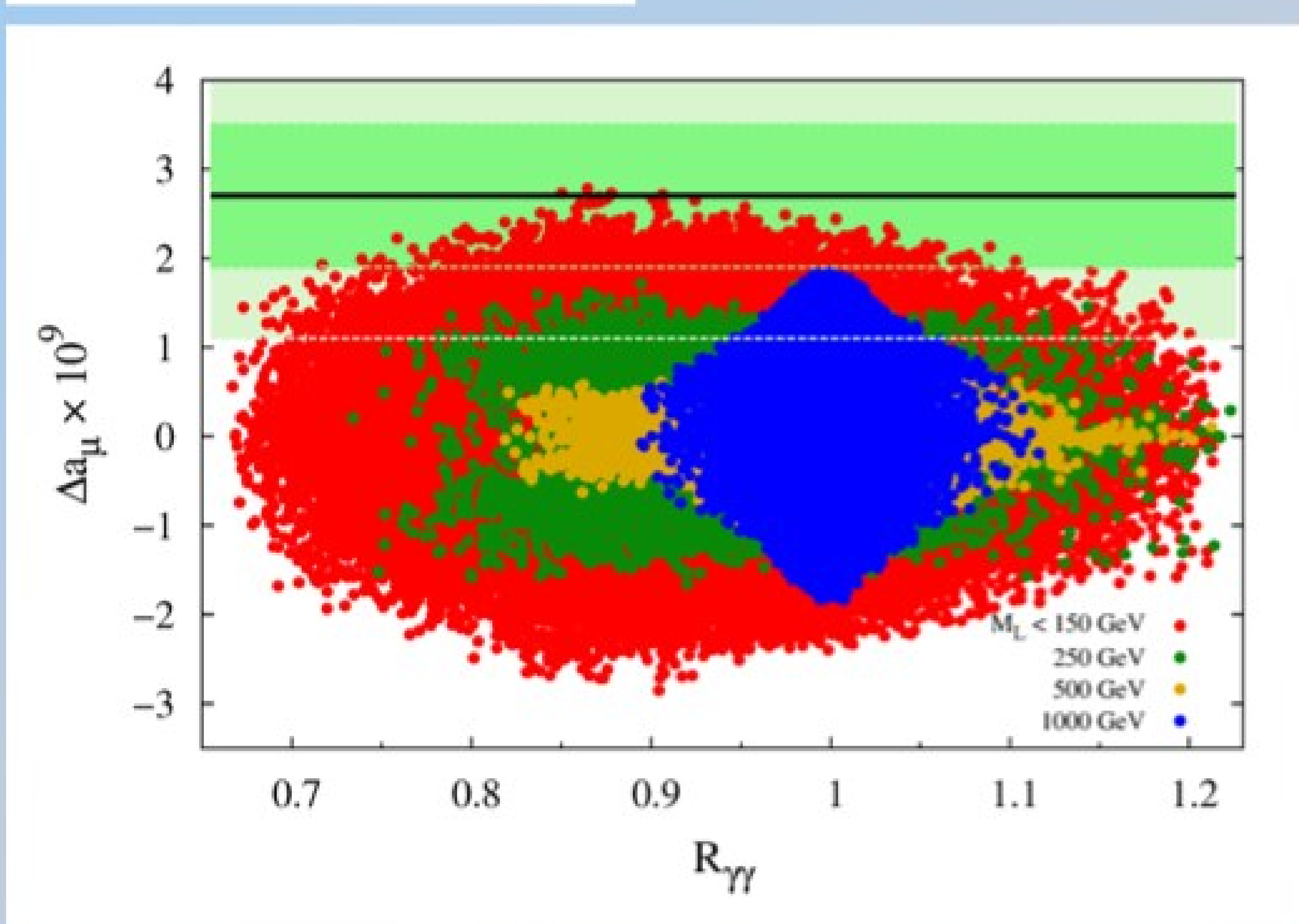
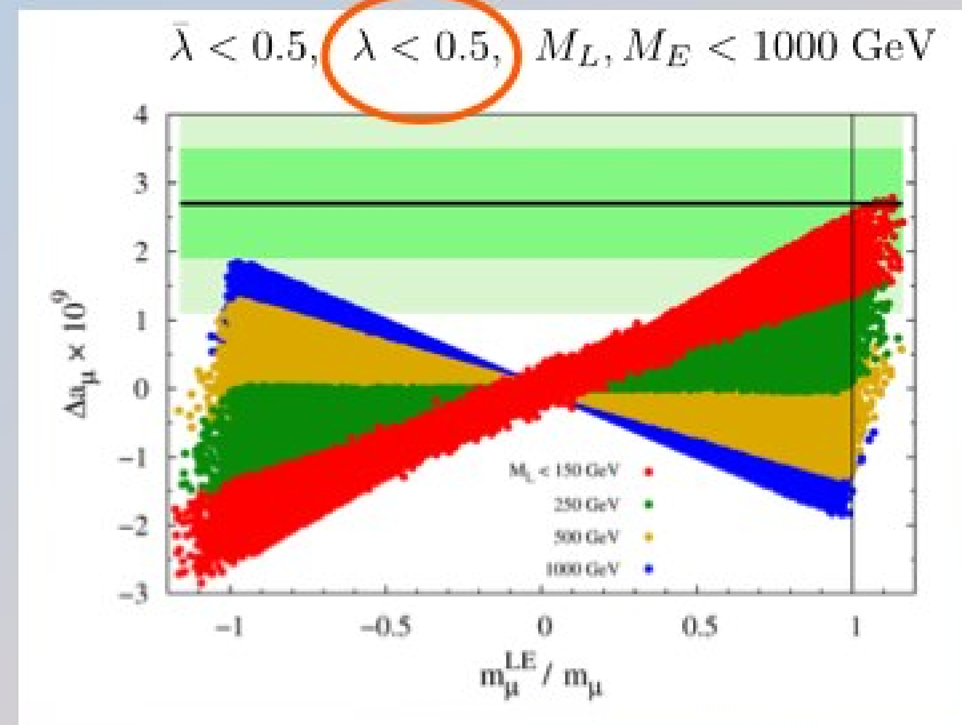

$\Delta a_\mu \times 10^9$
$R_{\mu\mu}$
M_L < 150 GeV
250 GeV
500 GeV
1000 GeV

h → γ γ

$$R_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}}$$

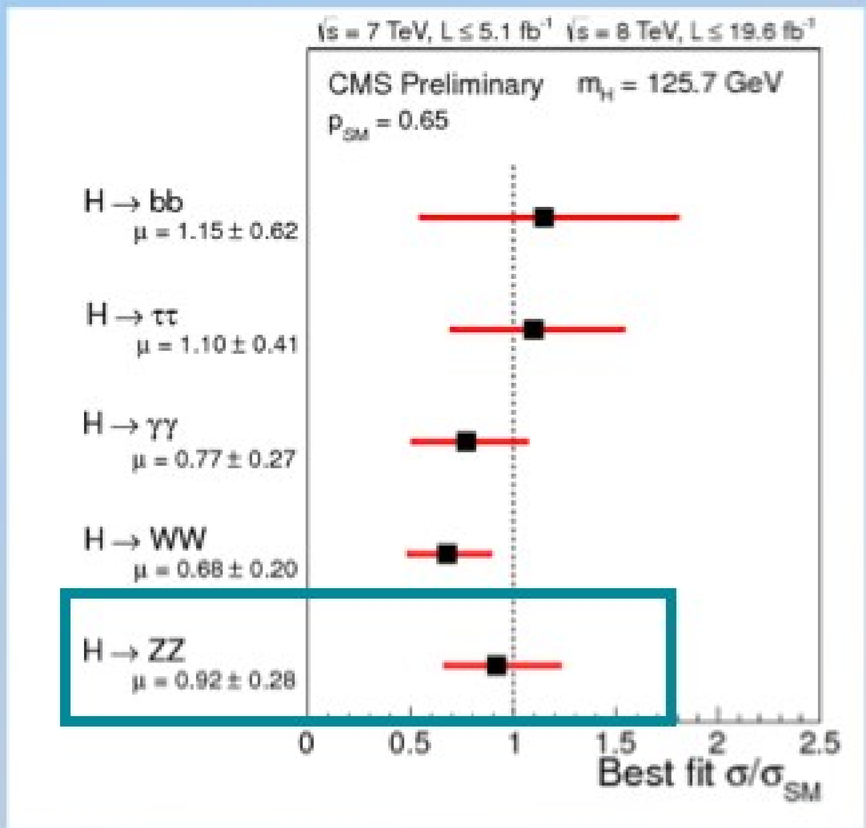


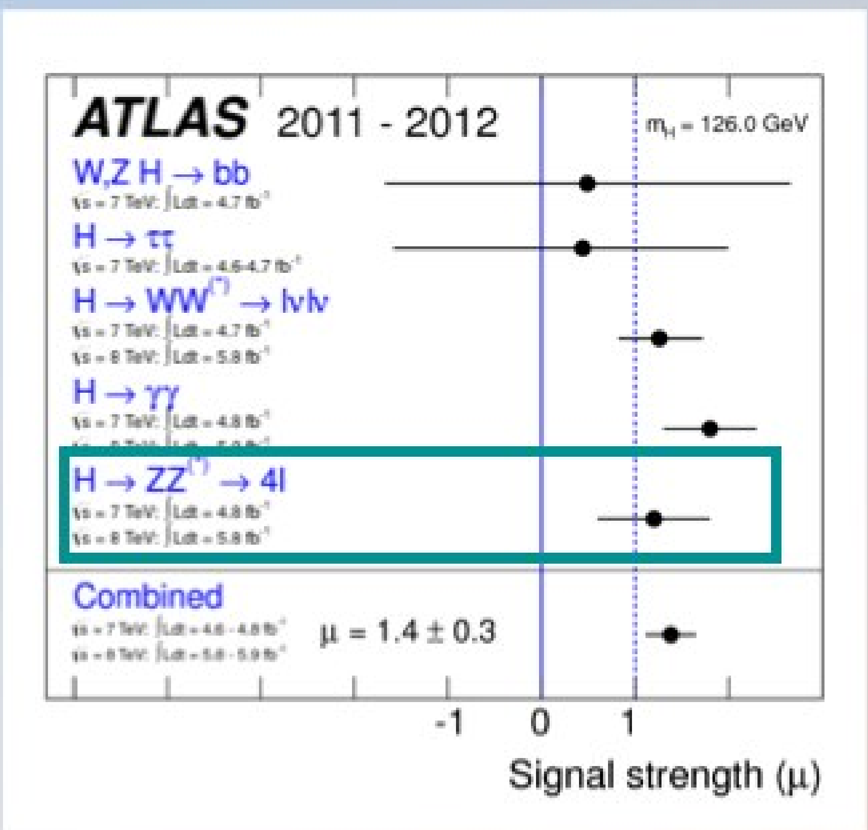
$$\text{amplitude} \propto -\frac{\bar{\lambda}\lambda v^2}{M_L M_E - \bar{\lambda}\lambda v^2}$$



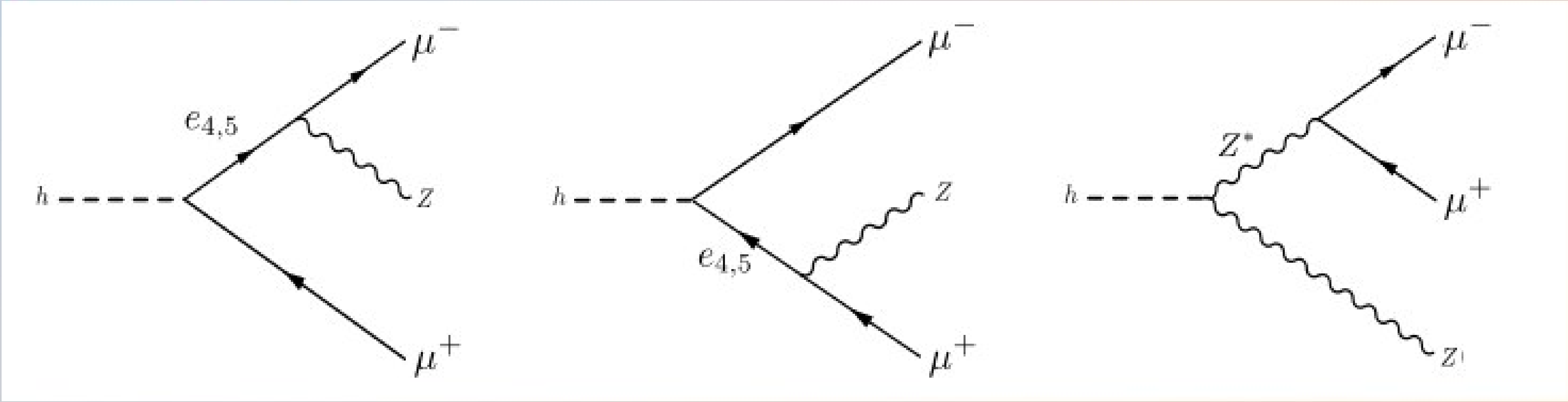
$$(\bar{e}_{Li}, \bar{L}_L^-, \bar{E}_L) \begin{pmatrix} y_{ij} v & 0 & \lambda_i^E v \\ \lambda_j^L v & M_L & \lambda v \\ 0 & \bar{\lambda} v & M_E \end{pmatrix} \begin{pmatrix} e_{Rj} \\ L_R^- \\ E_R \end{pmatrix}$$

h → ZZ*





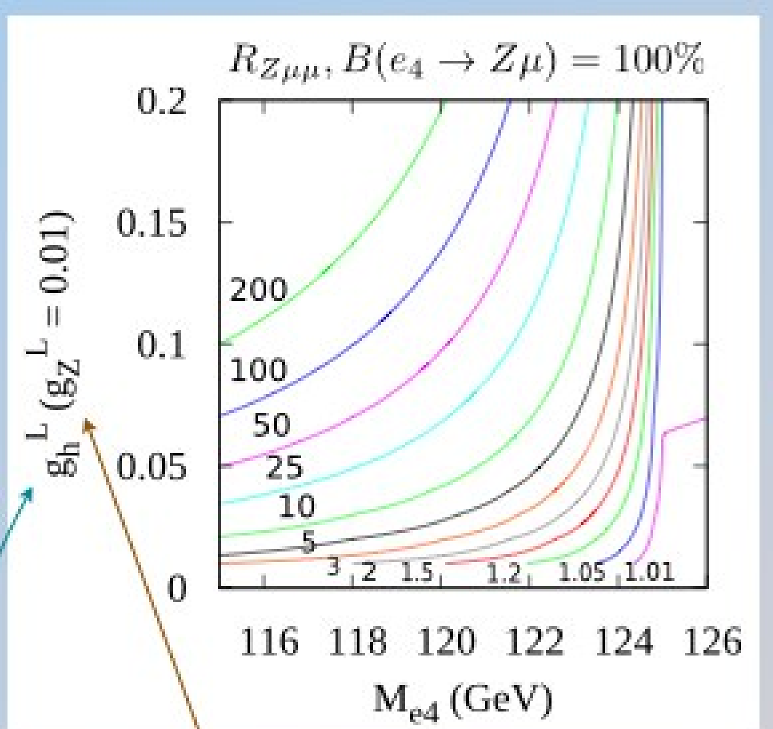
h → Eμ → Zμμ produces the same final state as h → ZZ* → Zμμ:

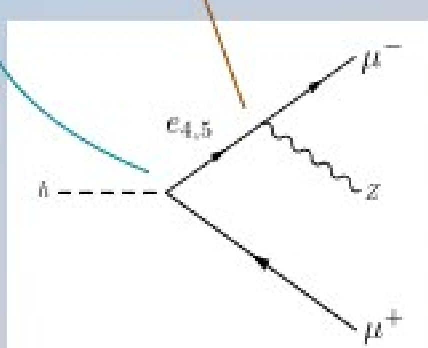


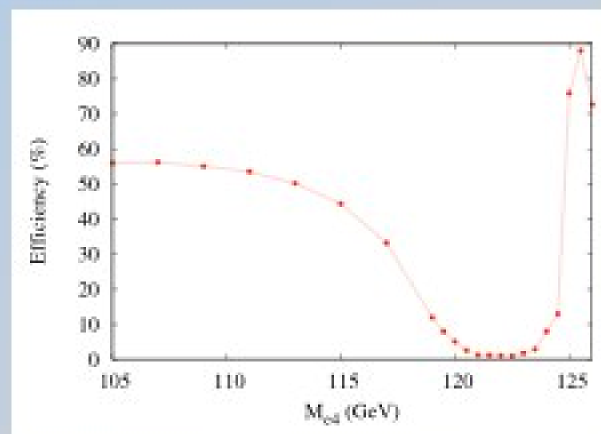
h → ZZ*

contribution from heavy leptons:

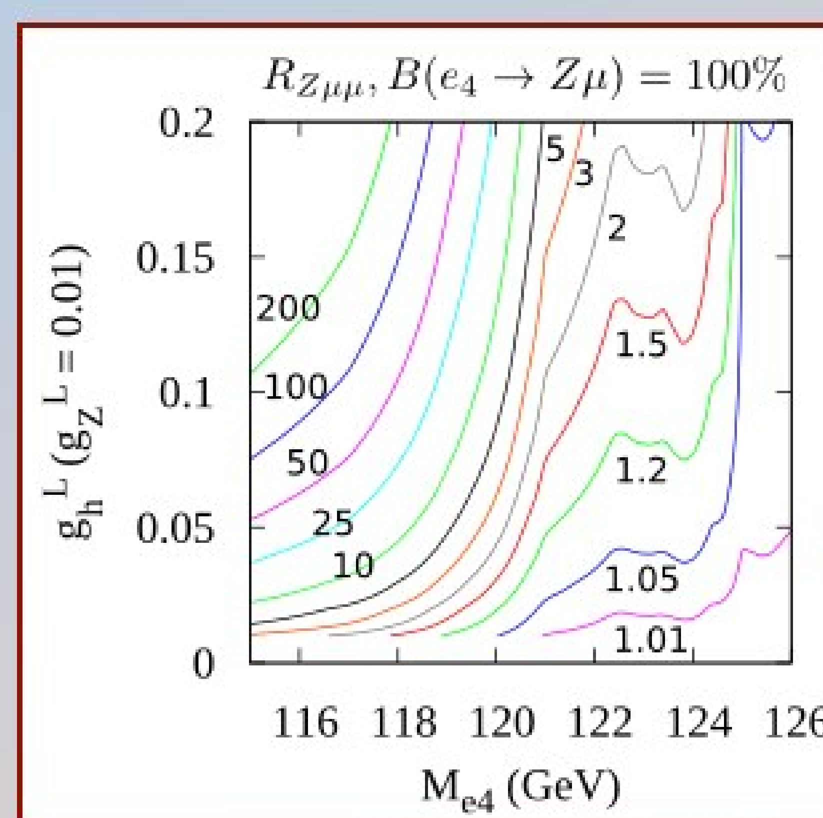
$$R_{Z\mu\mu} = \frac{\Gamma(h \to Z\mu\mu)}{\Gamma(h \to Z\mu\mu)_{SM}}$$

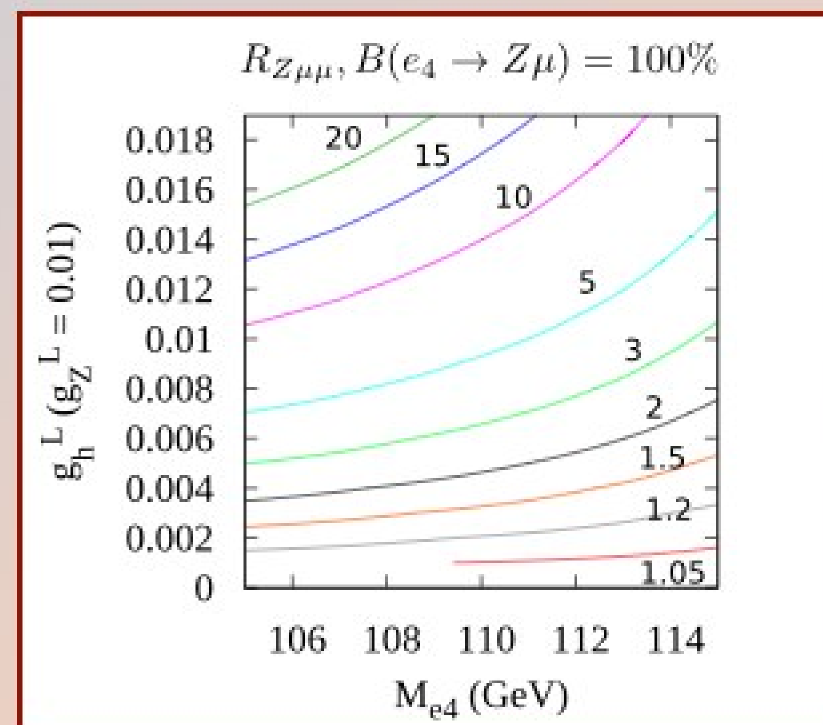






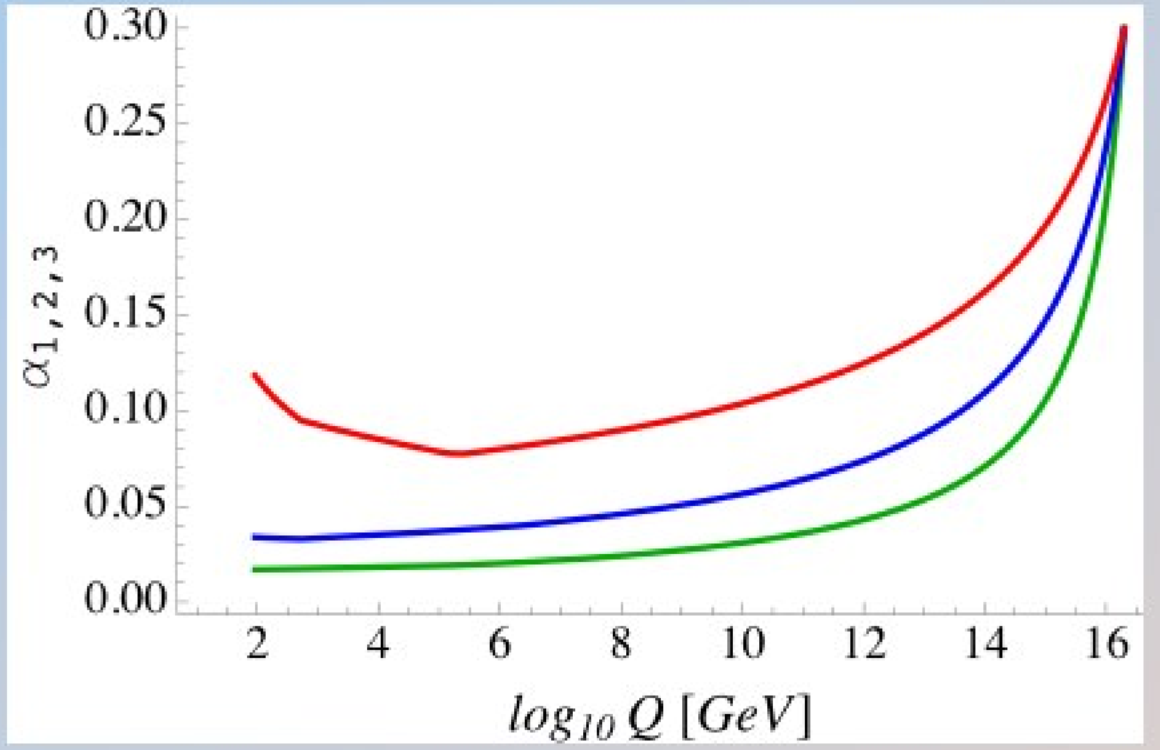
efficiency to pass ZZ* cuts

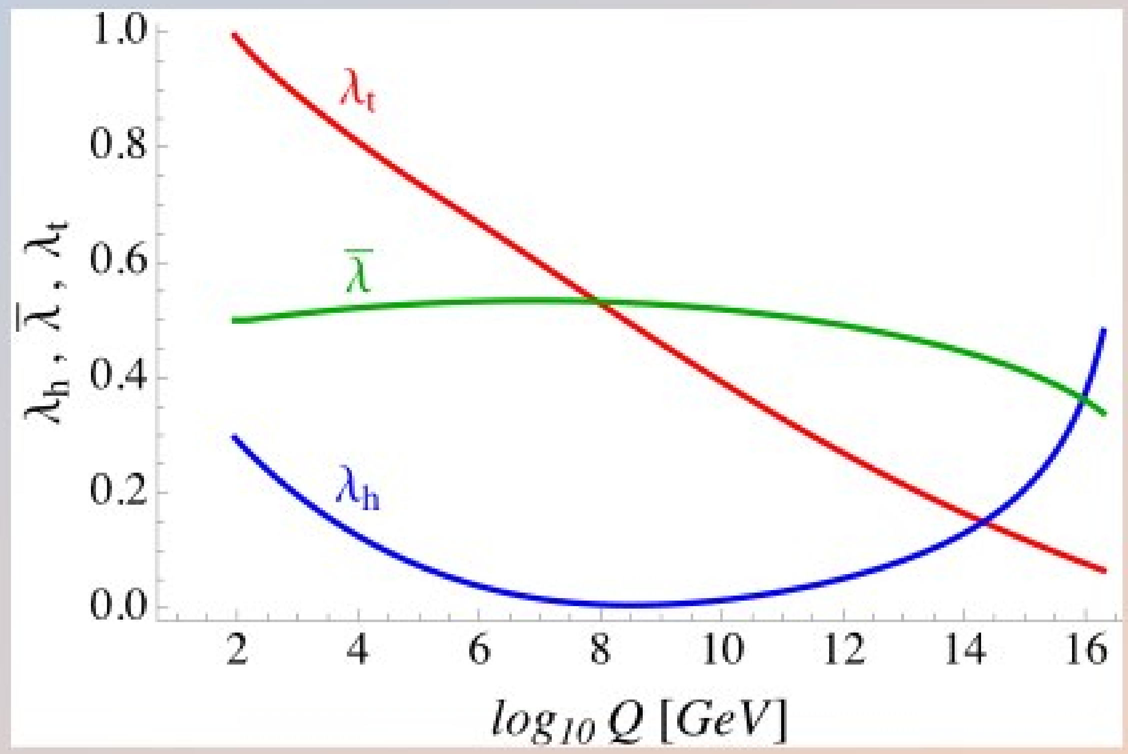




UV completion with 3VFs

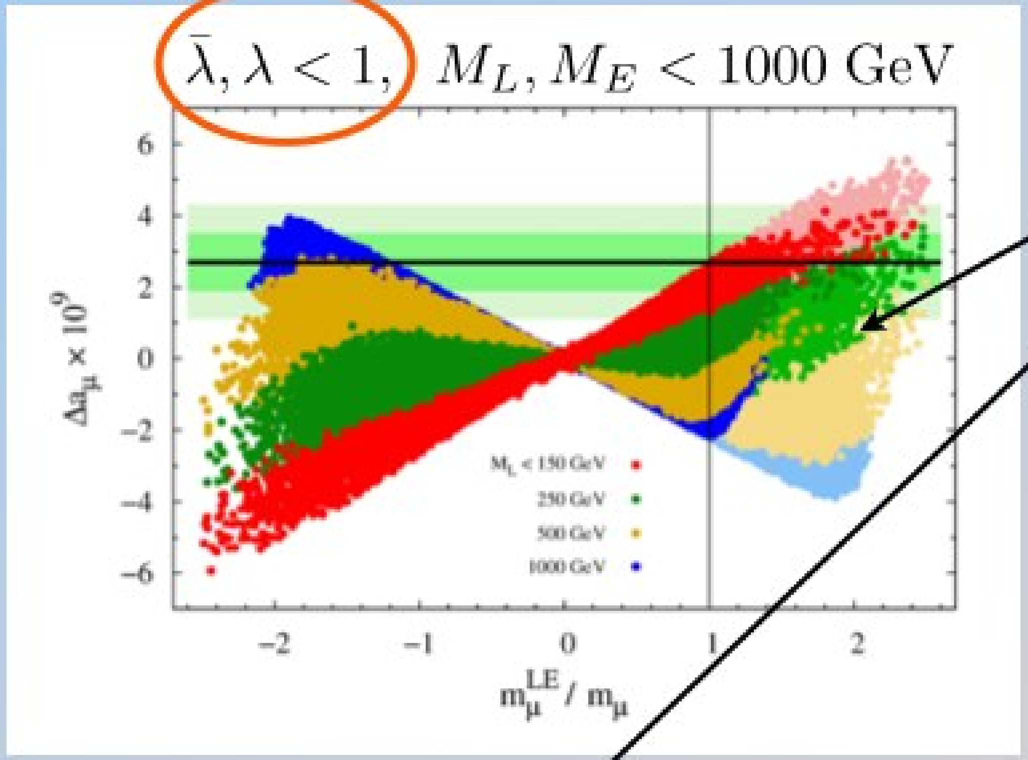
All the features of insensitive unification, including the stability of the EW minimum of the Higgs potential are preserved even with extra Yukawa couplings needed for the explanation of the muon g-2 anomaly:



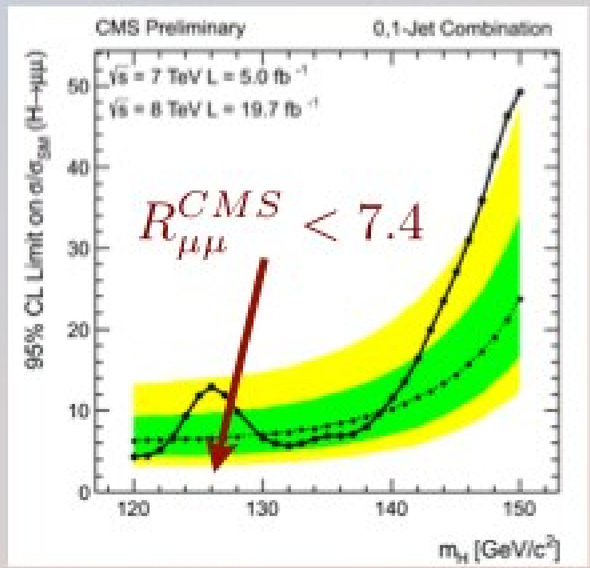


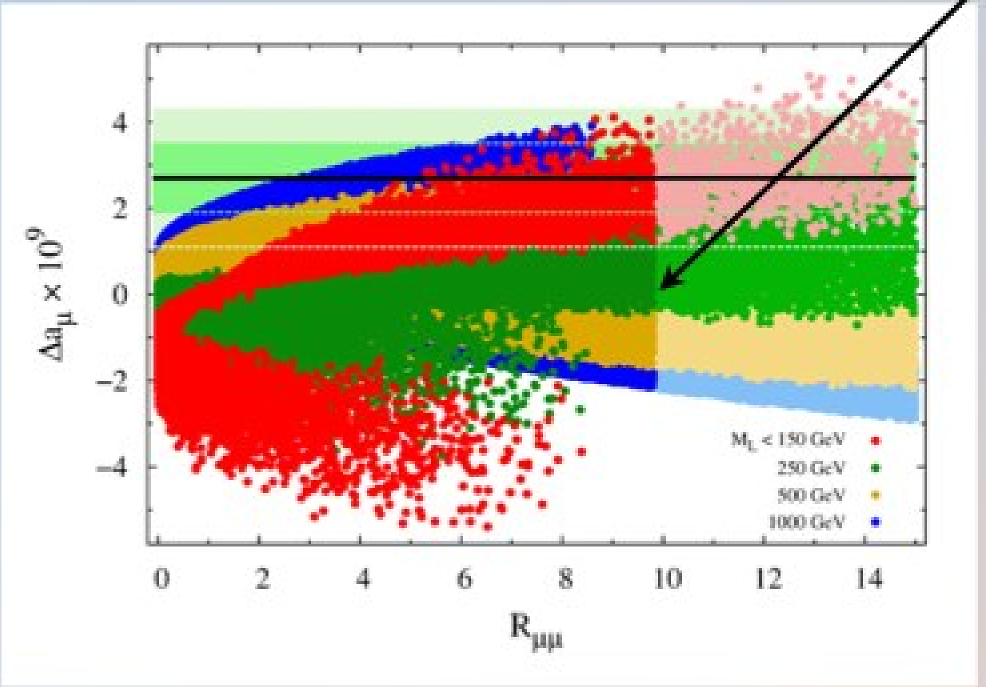
$M_{L_1} = M_{E_1} = 150$ GeV

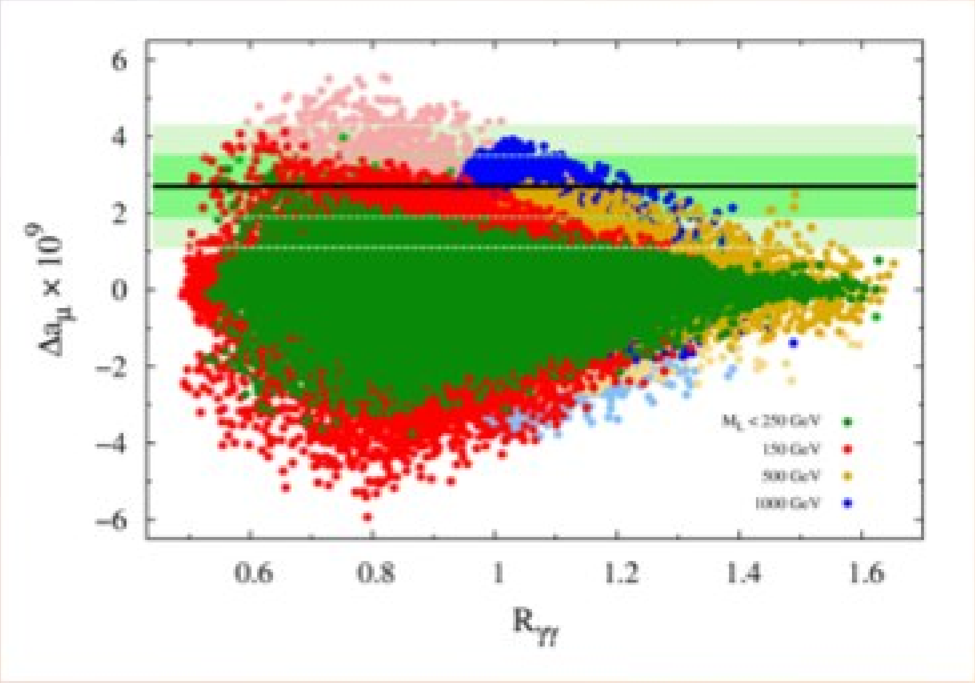
Allowing larger Yukawa couplings



lightly shaded points ruled out by Atlas search for h → μμ







Conclusions

- 3 (or more) pairs of vectorlike families allow for **insensitive unification of gauge couplings**

  predictive

- resurrects simple non-supersymmetric GUTs (proton decay)

  the GUT scale is adjustable and could be identified with the string or Planck scale

- the electroweak minimum is stable all the way to the GUT scale

- some of the extra fermions might be within the reach of the LHC

  and modify phenomenology of the SM: small flavor violation from mixing through Yukawa couplings, contributions in loops, ...