Muon g-2 and other observables in models with extended Higgs and matter sectors

with N. McGinnis and K. Hermanek

arXiv:2011.11812 [hep-ph]

arXiv:2103.05645 [hep-ph]

to appear

Radovan Dermisek

Indiana University, Bloomington

20th Lomonosov Conference, Moscow, Russia, August 21, 2021

Simple Extensions of the Standard Model

Standard Model

$$3 \times \{q, \bar{u}, \bar{d}, l, \bar{e}\}, g, \gamma, Z, W^{\pm}, h$$

more Higgses? 2HDM?

$$H, A, H^{\pm}$$

more matter?

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

Appear in many models: SUSY, composite Higgs, phenomenologically motivated extensions…

My personal motivation: exactly this particle content + SUSY provide an understanding of the values of all large couplings in the SM from the IR fixed point behavior from random large boundary conditions

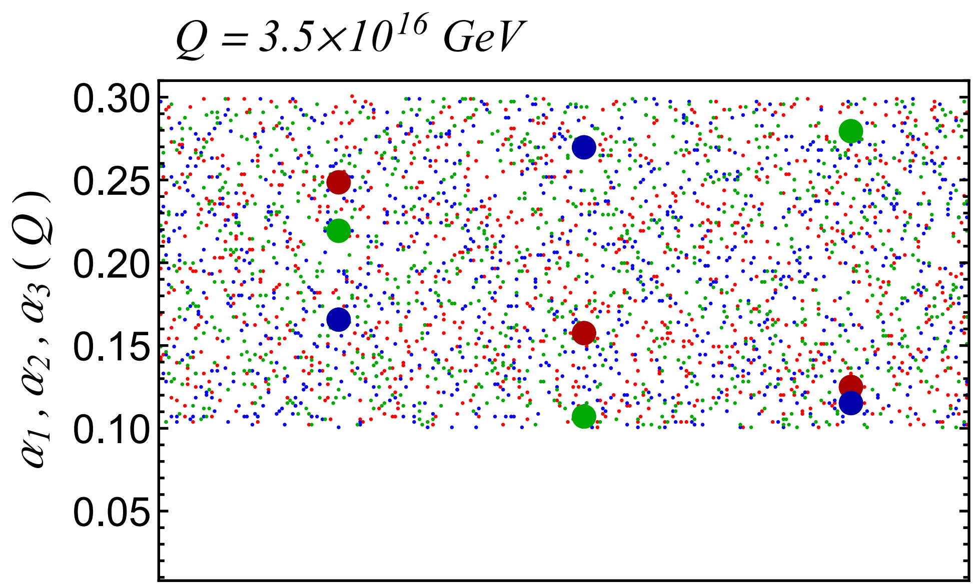
R.D. and N. McGinnis, arXiv:1812.05240 [hep-ph]

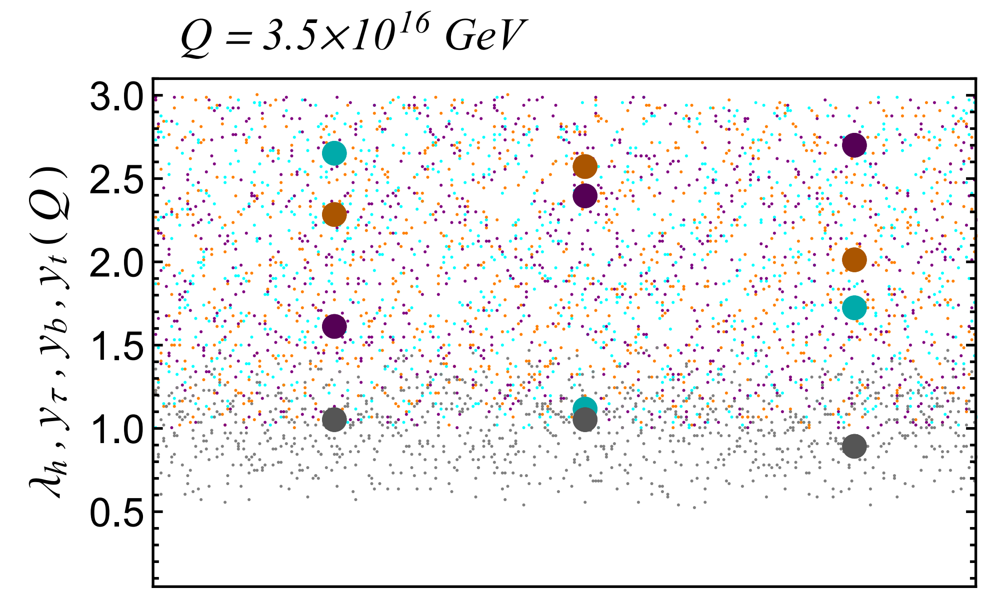
7 largest SM couplings from random b.c.

GUT scale

$\sim 3 \times 10^{16}$ GeV

MSSM+1VF





Random unrelated boundary conditions:

$\alpha_1(M_G), \alpha_2(M_G), \alpha_3(M_G) \in [0.1, 0.3]$ $\quad$ $y_t(M_G), y_b(M_G), y_\tau(M_G), Y_V(M_G) \in [1, 3]$

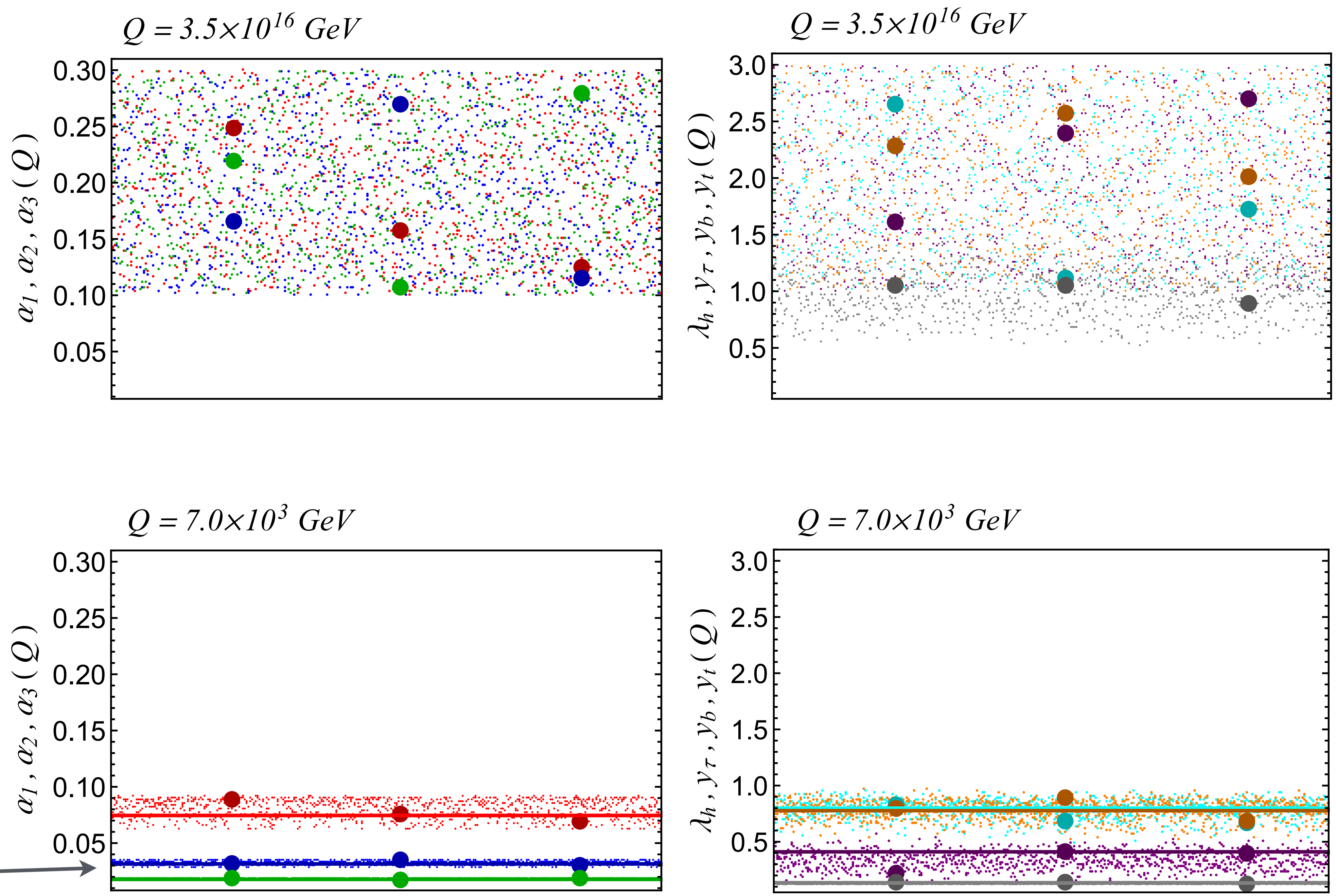
(larger values of couplings do not affect results significantly)

Higgs quartic given by gauge couplings at any scale:

$$\lambda_h(Q) \equiv \frac{g_2^2(Q) + (3/5)g_1^2(Q)}{4} \cos^2 2\beta$$

the plots assume: $\tan\beta = 40$

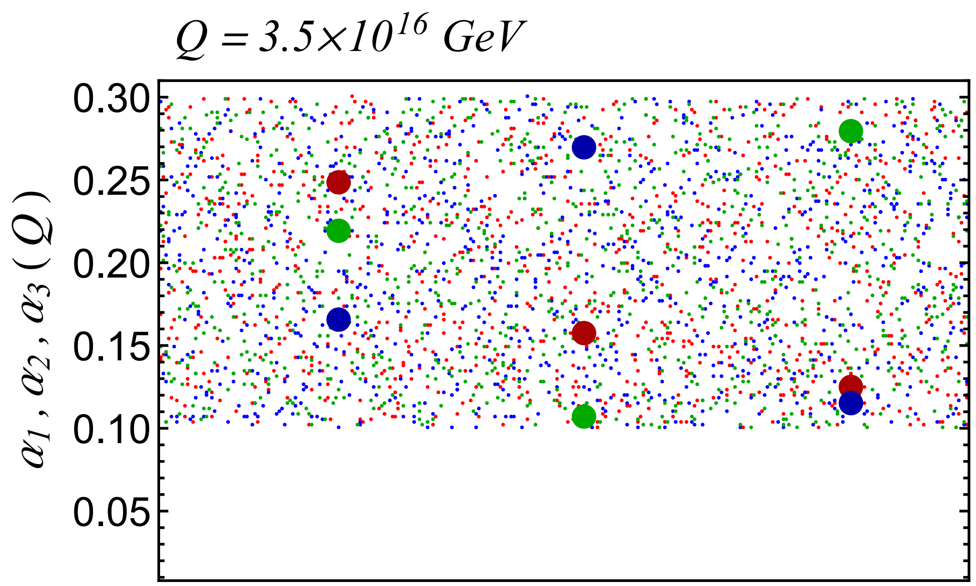
7 largest SM couplings from random b.c.

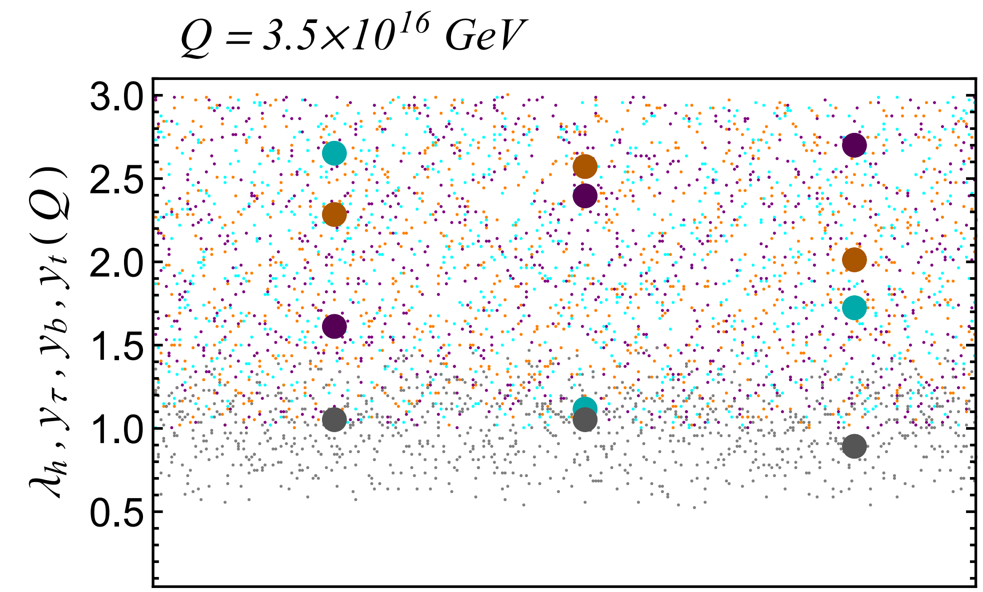


solid line are SM measured values evolved to a given scale, they include SUSY threshold corrections assuming $\tan\beta = 40$

Distinctive pattern of couplings emerges

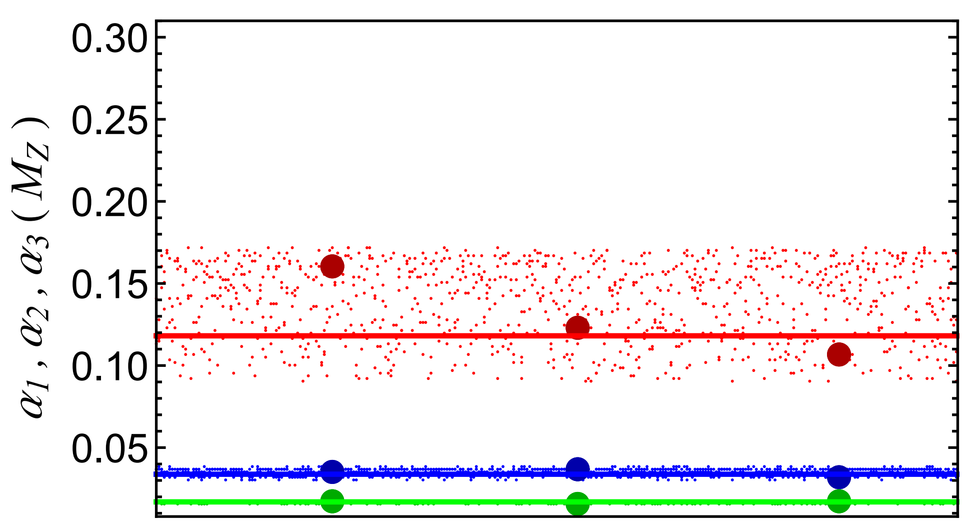
7 largest SM couplings from random b.c.

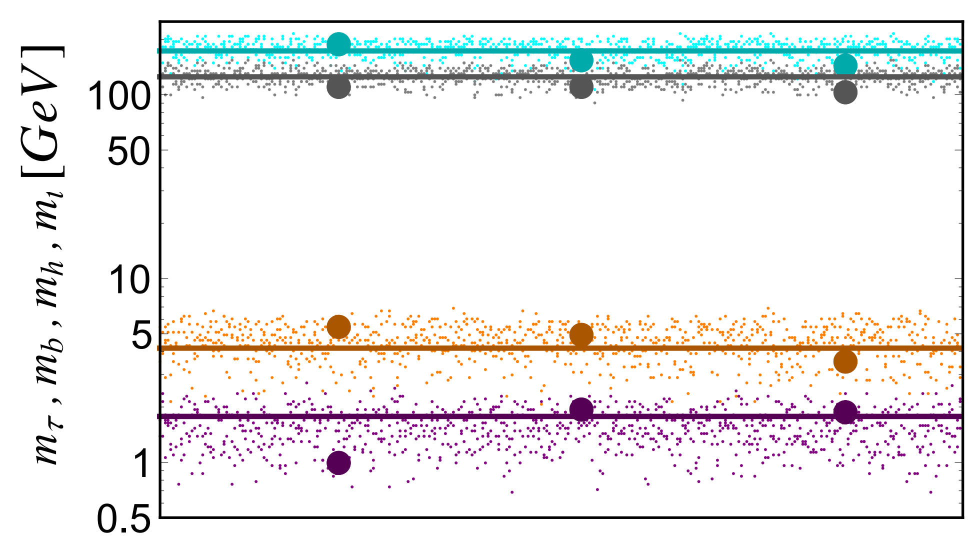




GUT: Random boundary conditions

EW: familiar pattern of couplings and masses





Optimizing parameters related to scales

R.D. and N. McGinnis, arXiv:1812.05240 [hep-ph]

For random unrelated (or unified) parameters:

$$\alpha_1(M_G), \alpha_2(M_G), \alpha_3(M_G) \in [0.1, 0.3]$$

$$y_t(M_G), y_b(M_G), y_\tau(M_G), Y_V(M_G) \in [1, 3]$$

three parameters,

$$M_G,\ M,\ \tan\beta,$$

can be optimized so that none of the seven observables is more than 25% (or 15%) from the measured values.

Further optimizing Y_V to obtain the required overall scale of Yukawa couplings, all 7 observables are within 11% (or 7.5%) from their measured values.

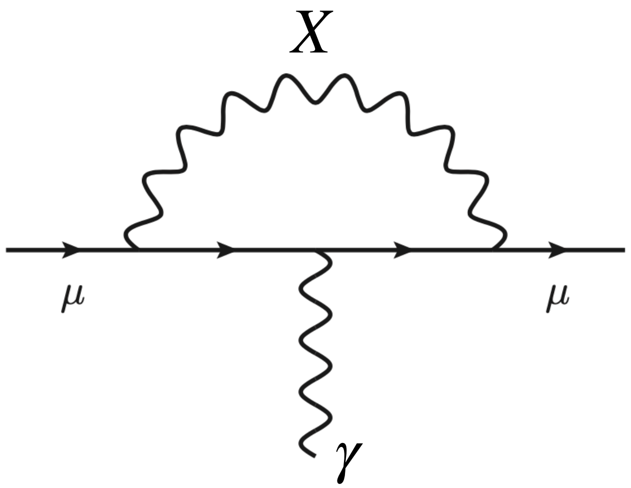
Muon g-2

$$\Delta a_\mu^{exp} \equiv a_\mu^{exp} - a_\mu^{SM} = (2.51 \pm 0.59) \times 10^{-9}$$

Muon g-2, arXiv:2104.03281 [hep-ex]
T. Aoyama, et al., Phys. Rept. 887, 1-166 (2020)

New physics contributions to muon g-2

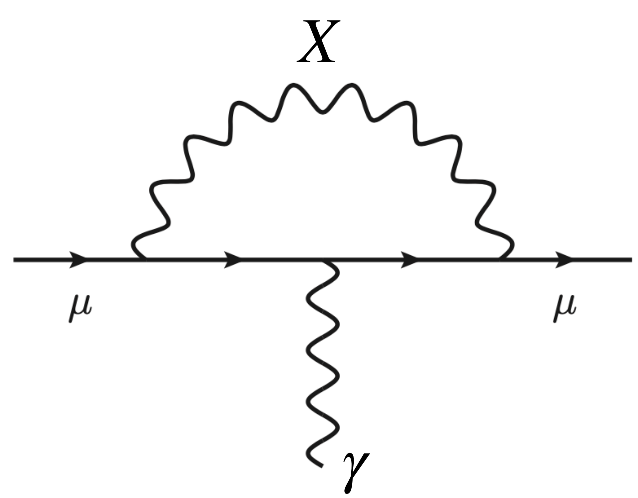
Typical NP contribution



$$\Delta a_\mu \simeq \frac{g_{NP}^2}{16\pi^2}\frac{m_\mu^2}{m_{NP}^2}$$

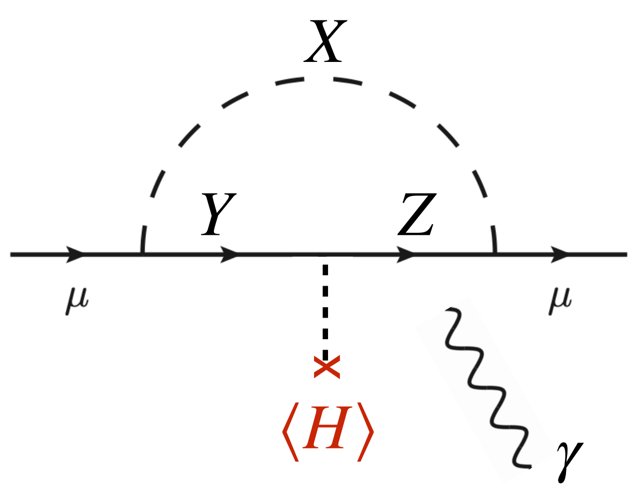
New physics contributions to muon g-2

Typical NP contribution



$$\Delta a_\mu \simeq \frac{g_{NP}^2}{16\pi^2}\frac{m_\mu^2}{m_{NP}^2}$$

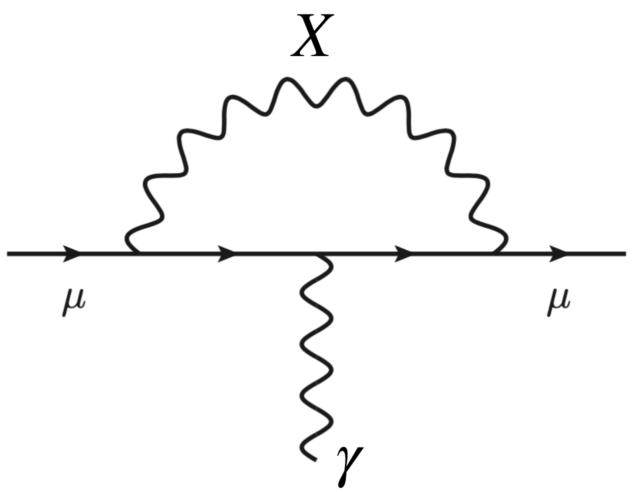
Mass enhanced NP contribution



$$\Delta a_\mu \simeq \frac{\lambda_{NP}^3}{16\pi^2}\frac{m_\mu v}{m_{NP}^2}$$

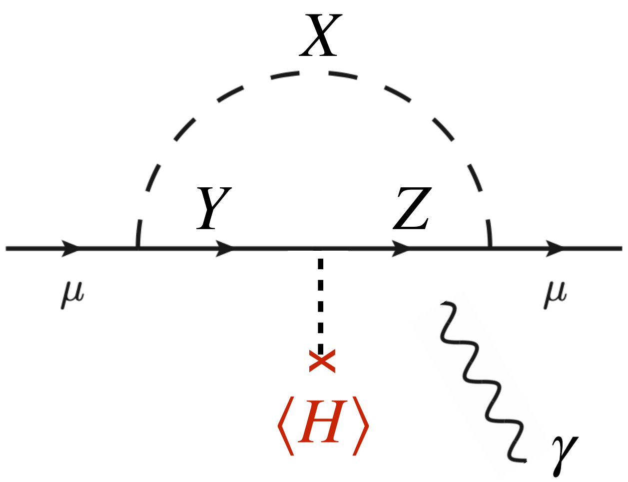
New physics contributions to muon g-2

Typical NP contribution



$$\Delta a_\mu \simeq \frac{g_{NP}^2}{16\pi^2}\frac{m_\mu^2}{m_{NP}^2}$$

Mass enhanced NP contribution



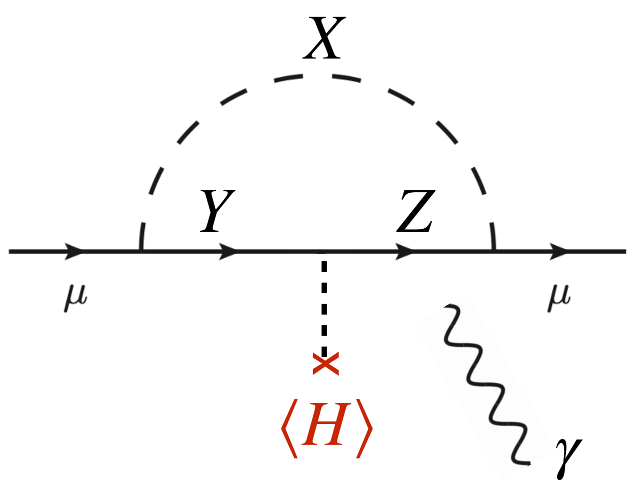
$$\Delta a_\mu \simeq \frac{\lambda_{NP}^3}{16\pi^2}\frac{m_\mu v}{m_{NP}^2}$$

Enhancement:

$$\frac{\lambda_{NP} v}{m_\mu}$$

possible to explain Δa_μ with NP at 10s TeV

Mass enhanced NP contributions to Δa_μ



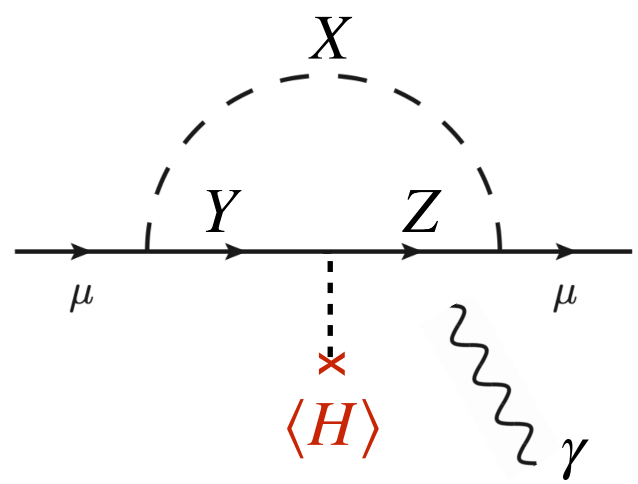
X, Y, Z can have any quantum numbers (allowing for the loop):

- $X = h, Z, W$ **and** $Y, Z =$ vectorlike leptons

minimal, just SM with new leptons, constrained the most

K. Kannike, M. Raidal, D. M. Straub and A. Strumia, arXiv:1111.2551 [hep-ph]
R. D. and A. Raval, arXiv:1305.3522 [hep-ph]

Mass enhanced NP contributions to Δa_μ



X, Y, Z can have any quantum numbers (allowing for the loop):

- $X = h, Z, W$ **and** $Y, Z =$ vectorlike leptons

minimal, just SM with new leptons, constrained the most

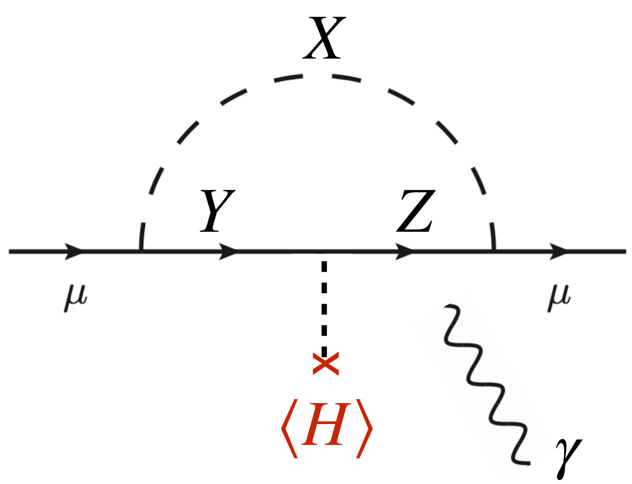
K. Kannike, M. Raidal, D. M. Straub and A. Strumia, arXiv:1111.2551 [hep-ph]
R. D. and A. Raval, arXiv:1305.3522 [hep-ph]

- $X = S$ (not participating in EWSB)

the most popular, many options, the least constrained

(similar options with new gauge fields, $X = V$, or superpartners)

Mass enhanced NP contributions to Δa_μ



X, Y, Z can have any quantum numbers (allowing for the loop):

- $X = h, Z, W$ **and** $Y, Z =$ vectorlike leptons

  minimal, just SM with new leptons, constrained the most

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

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

- $X = H, A, H^{\pm}$ **and** $Y, Z =$ vectorlike leptons

  e.g. 2HDM with new leptons, interpolates between the the other two options

- $X = S$ (not participating in EWSB)

  the most popular, many options, the least constrained

(similar options with new gauge fields, $X = V$, or superpartners)

Type-II 2HDM with L + E (+ N)

General lagrangian describing mixing of the 2nd generation with new leptons:

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

	l_L	e_R	H_u	H_d	$L_{L,R}$	$N_{L,R}$	$E_{L,R}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	0	-1
Z_2	$+$	$-$	$+$	$-$	$+$	$+$	$-$

Charged lepton mass matrix (after EWSB):

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

diagonalizing this matrix leads to:
two new mass eigenstates, e_4, e_5,
modification of muon couplings,
and couplings between the muon and e_4, e_5

Type-II 2HDM with L + E (+ N)

General lagrangian describing mixing of the 2nd generation with new leptons:

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

At energies much below M_L, M_E:

$$\mathcal{L} \supset -y_\mu \bar{l}_L \mu_R H_d - \frac{\lambda_L \bar{\lambda} \lambda_E}{M_L M_E} \bar{l}_L \mu_R H_d H_d^\dagger H_d + h.c.,$$

dim. 6 operator is a new source of muon mass:

$$m_\mu = y_\mu v_d + m_\mu^{LE} \qquad m_\mu^{LE} \equiv \frac{\lambda_L \bar{\lambda} \lambda_E}{M_L M_E} v_d^3$$

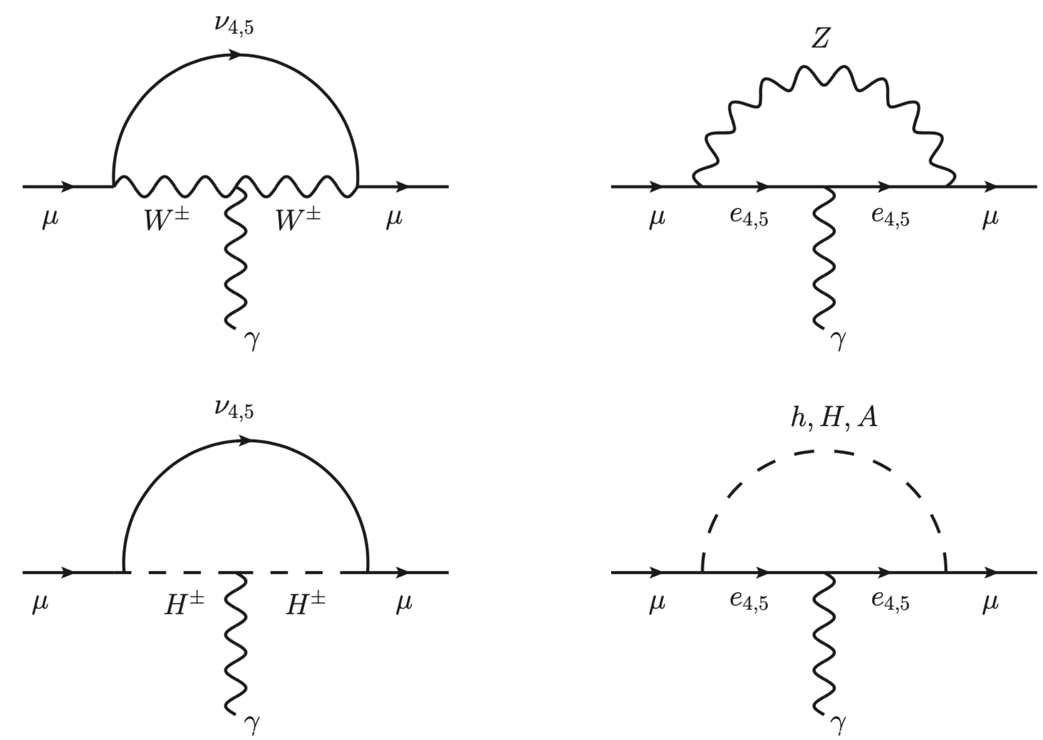
and is directly linked to contributions to Δa_μ

Δa_μ in type-II 2HDM with L + E (+ N)

R.D., N. McGinnis, and K. Hermanek, arXiv:2011.11812 [hep-ph]
arXiv:2103.05645 [hep-ph]

$$m_\mu^{LE} \equiv \frac{\lambda_L \bar{\lambda} \lambda_E}{M_L M_E} v_d^3$$

$$\Delta a_\mu^i \simeq \frac{k^i}{16\pi^2} \frac{m_\mu m_\mu^{LE}}{v^2}$$



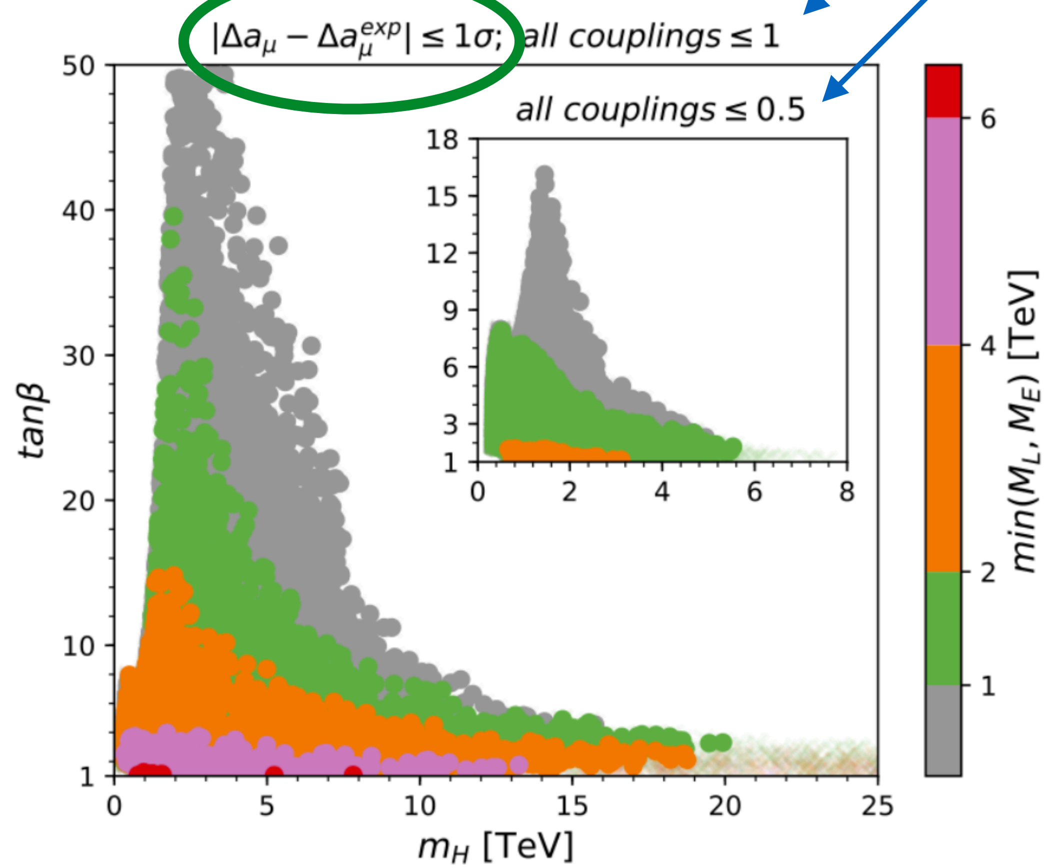
$$\left.\begin{aligned} k^W &= 1 \\ k^Z &= -1/2 \\ k^h &= -3/2 \end{aligned}\right\} \quad k^W + k^Z + k^h = -1$$

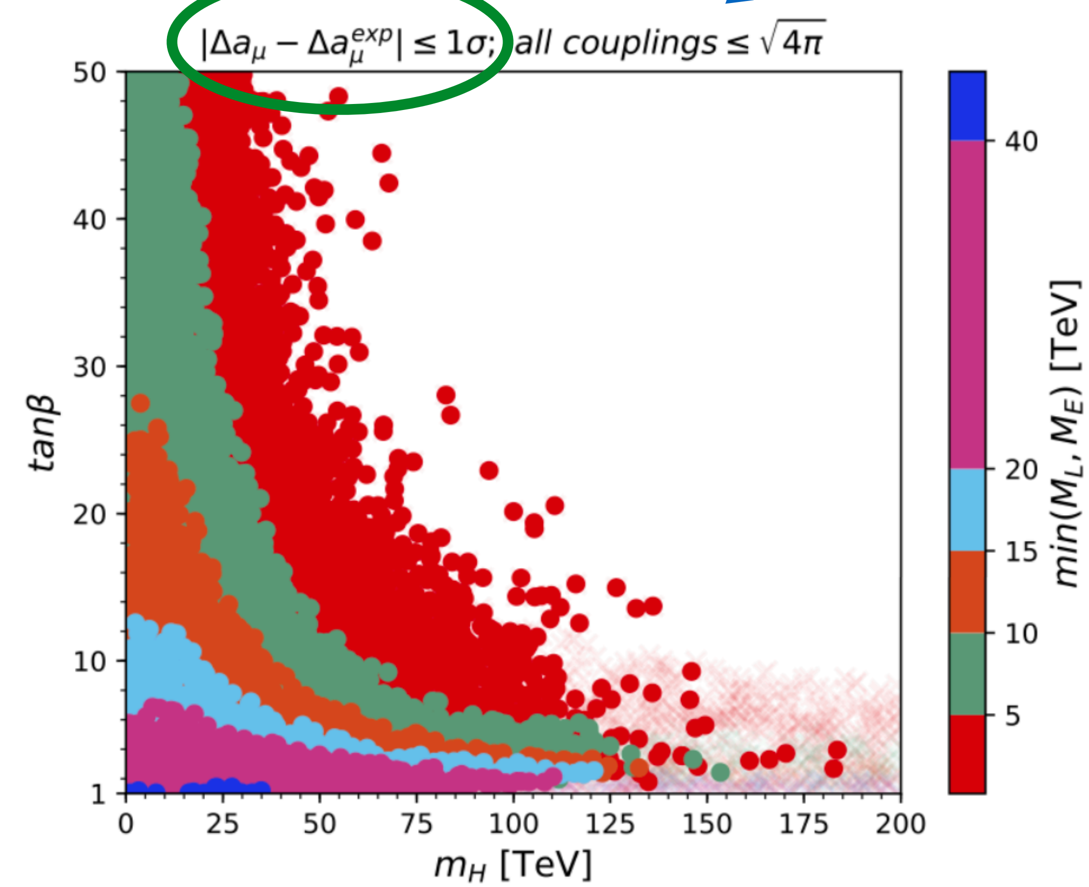
$$\left.\begin{aligned} k^H &= -(11/12)\tan^2\beta \\ k^A &= -(5/12)\tan^2\beta \\ k^{H^\pm} &= (1/3)\tan^2\beta \end{aligned}\right\} \quad k^H + k^A + k^{H^\pm} = -\tan^2\beta$$

contributions of $H, A, H^\pm$ to Δa_μ enhanced by $\tan^2\beta$

Δa_μ in type-II 2HDM with L + E

depending on the size of couplings



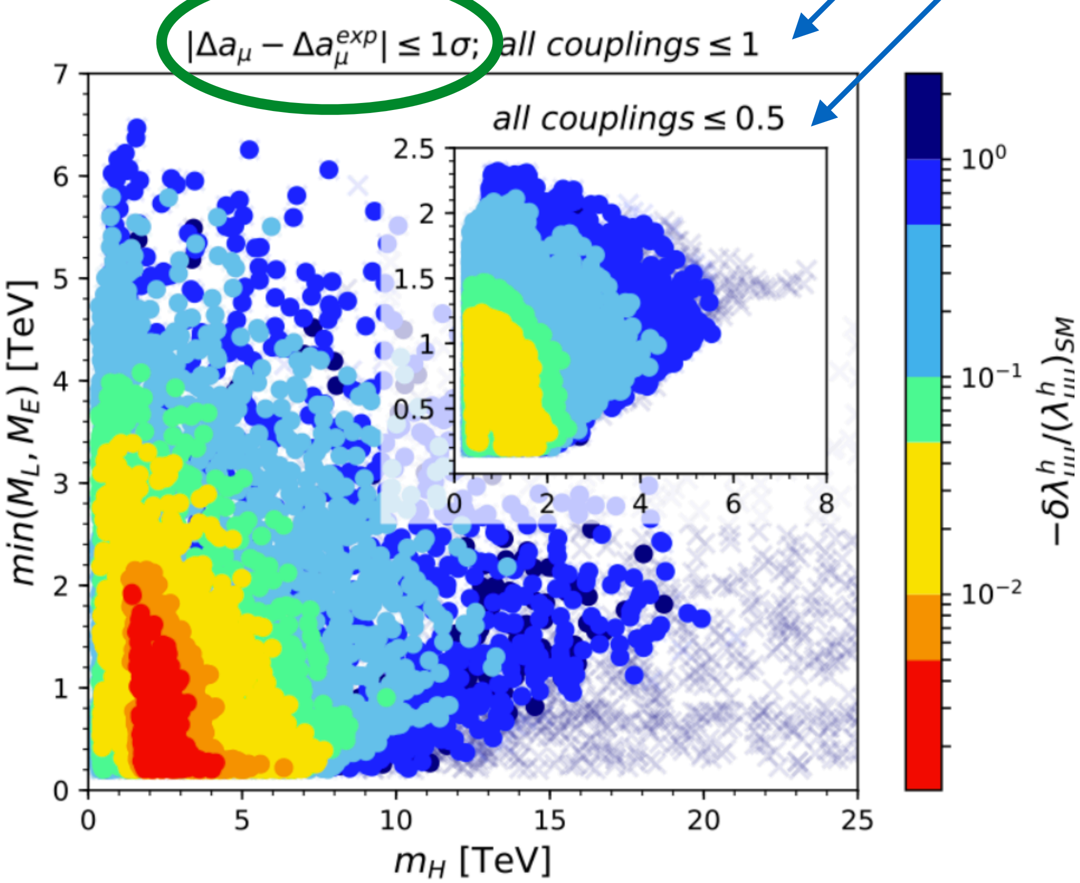


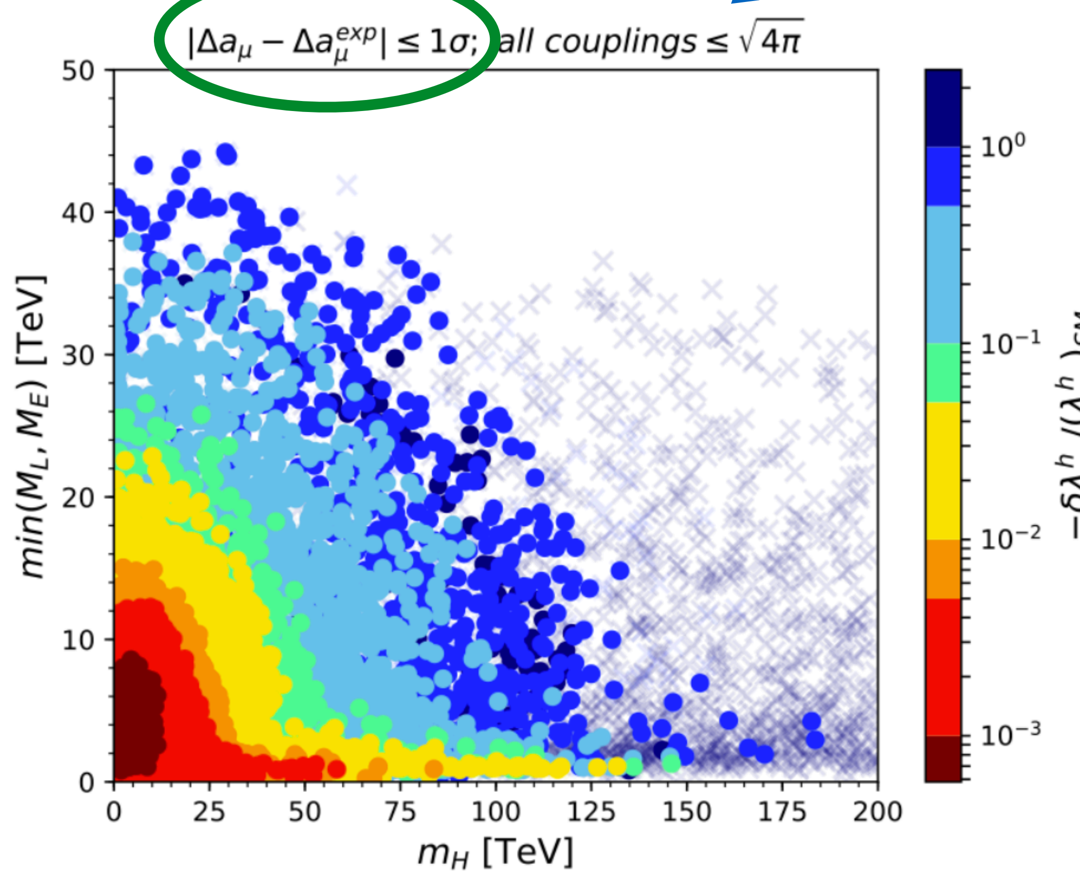
all experimental constraints from direct searches and precision EW data satisfied

multi TeV (10s TeV) new leptons and Higgses can explain Δa_μ

Δa_μ in type-II 2HDM and muon Yukawa c.

depending on the size of couplings



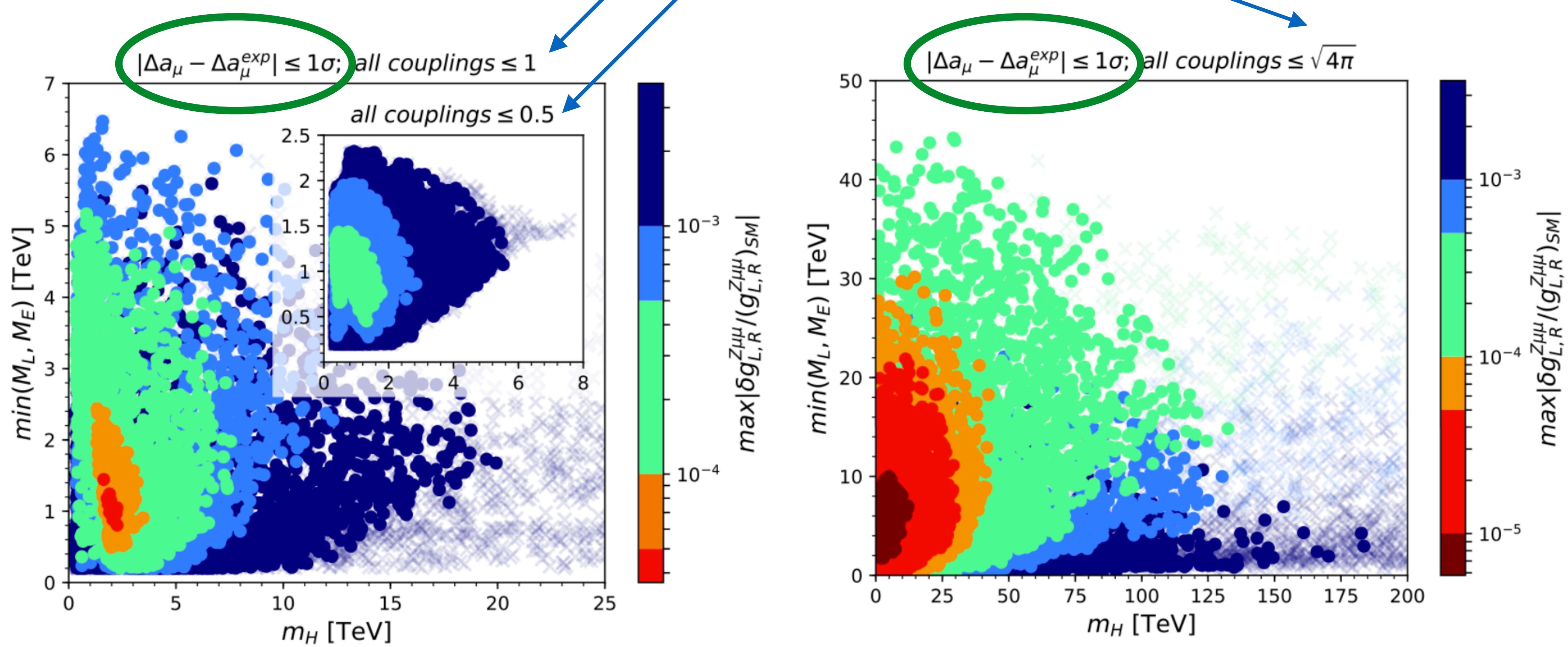


NOTE, both $-\delta\lambda^h_{\mu\mu}/(\lambda^h_{\mu\mu})_{SM} = 0$ and 2 correspond to SM expectation for $h \to \mu^+\mu^-$

muon Yukawa coupling modified at $\gtrsim 10^{-3}$ or 5×10^{-4} levels

Δa_μ in type-II 2HDM and muon gauge c.

depending on the size of couplings



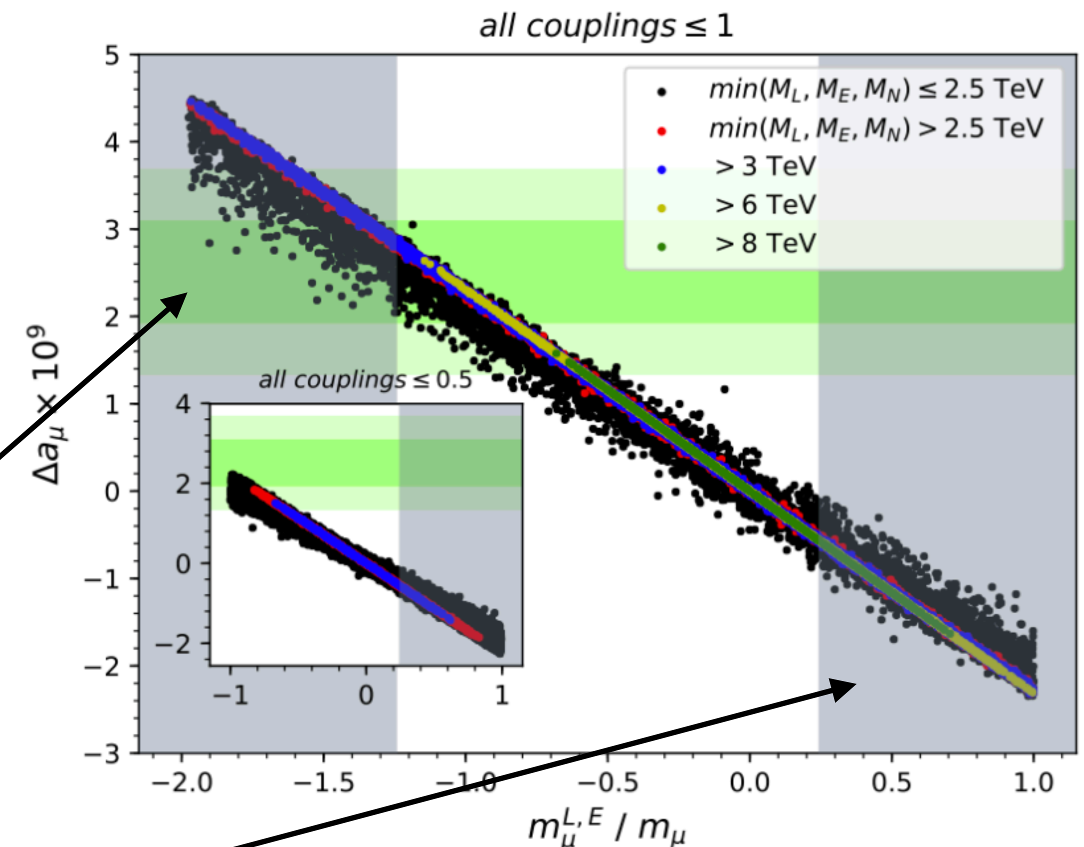
muon Z couplings modified at $> 3 \times 10^{-5}$ or 5×10^{-6} levels

Standard Model with L + E

R.D., N. McGinnis, and K. Hermanek, arXiv:2103.05645 [hep-ph]

Δa_μ and $h \to \mu^+\mu^-$ highly correlated,

no free parameter for $M_{L,E} \gg M_{EW}$

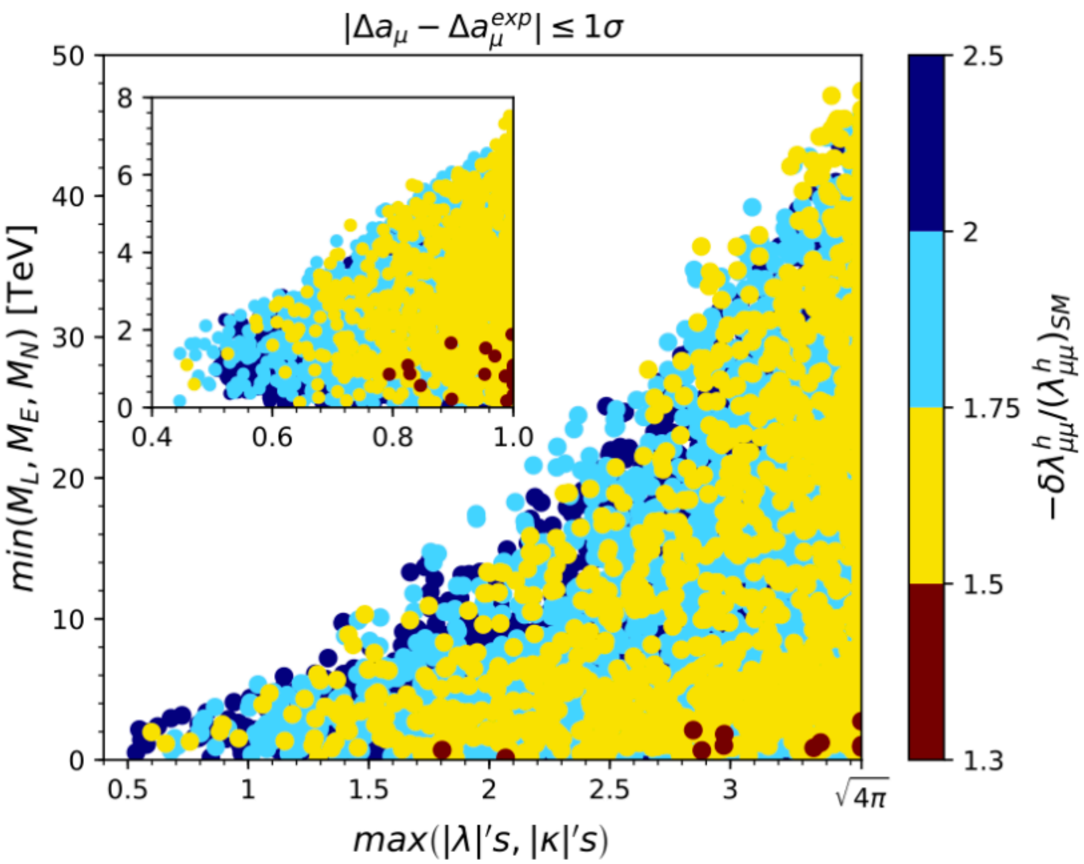


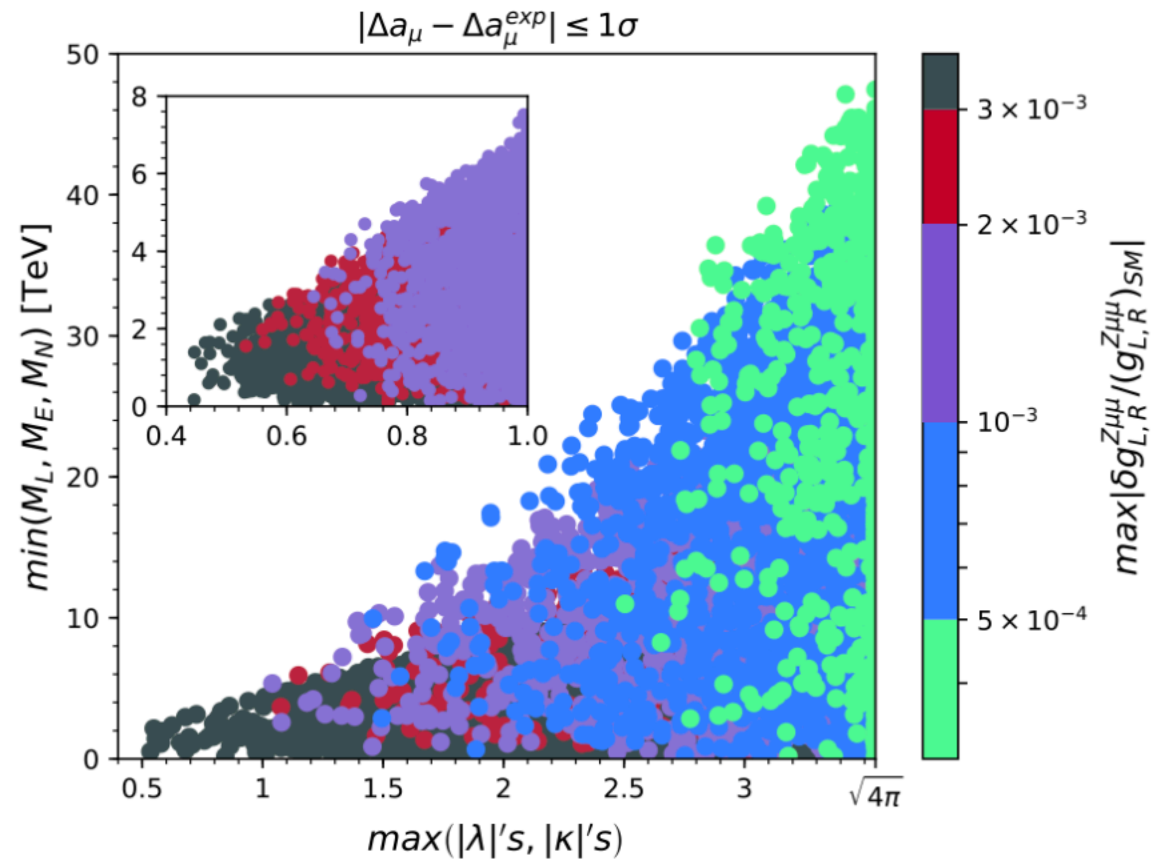
excluded by

$$R_{h\to\mu^+\mu^-} \equiv \frac{BR(h \to \mu^+\mu^-)}{BR(h \to \mu^+\mu^-)_{SM}} = \left(1 + 2\frac{m_\mu^{LE}}{m_\mu}\right)^2$$

1σ range of Δa_μ predicts $R_{h\to\mu^+\mu^-} = 1.32^{+1.40}_{-0.90}$

Δa_μ in SM with L+E and muon couplings





muon Z couplings modified at $> 3 \times 10^{-4}$ levels

Related observables in SM with L + E

Effective lagrangian:

$$H = \begin{pmatrix} 0 \\ v + \frac{1}{\sqrt{2}}h \end{pmatrix}$$

$$\mathcal{L} \supset -y_\mu \bar{l}_L \mu_R H - \frac{\lambda_L \bar{\lambda} \lambda_E}{M_L M_E} \bar{l}_L \mu_R H H^\dagger H + h.c.,$$

is completely fixed by muon mass and g-2:

$$m_\mu^{LE} \equiv \frac{\lambda_L \bar{\lambda} \lambda_E}{M_L M_E} v^3$$

$$m_\mu = y_\mu v + m_\mu^{LE} \qquad \Delta a_\mu = -\frac{1}{16\pi^2} \frac{m_\mu m_\mu^{LE}}{v^2}.$$

Interactions of the muon with SM Higgs boson:

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} \lambda^h_{\mu\mu}\, \bar{\mu}\mu h - \frac{1}{2} \lambda^{hh}_{\mu\mu}\, \bar{\mu}\mu h^2 - \frac{1}{3!} \lambda^{hhh}_{\mu\mu}\, \bar{\mu}\mu h^3$$

are predicted without a free parameter!

Di-Higgs and tri-Higgs signals of Δa_μ

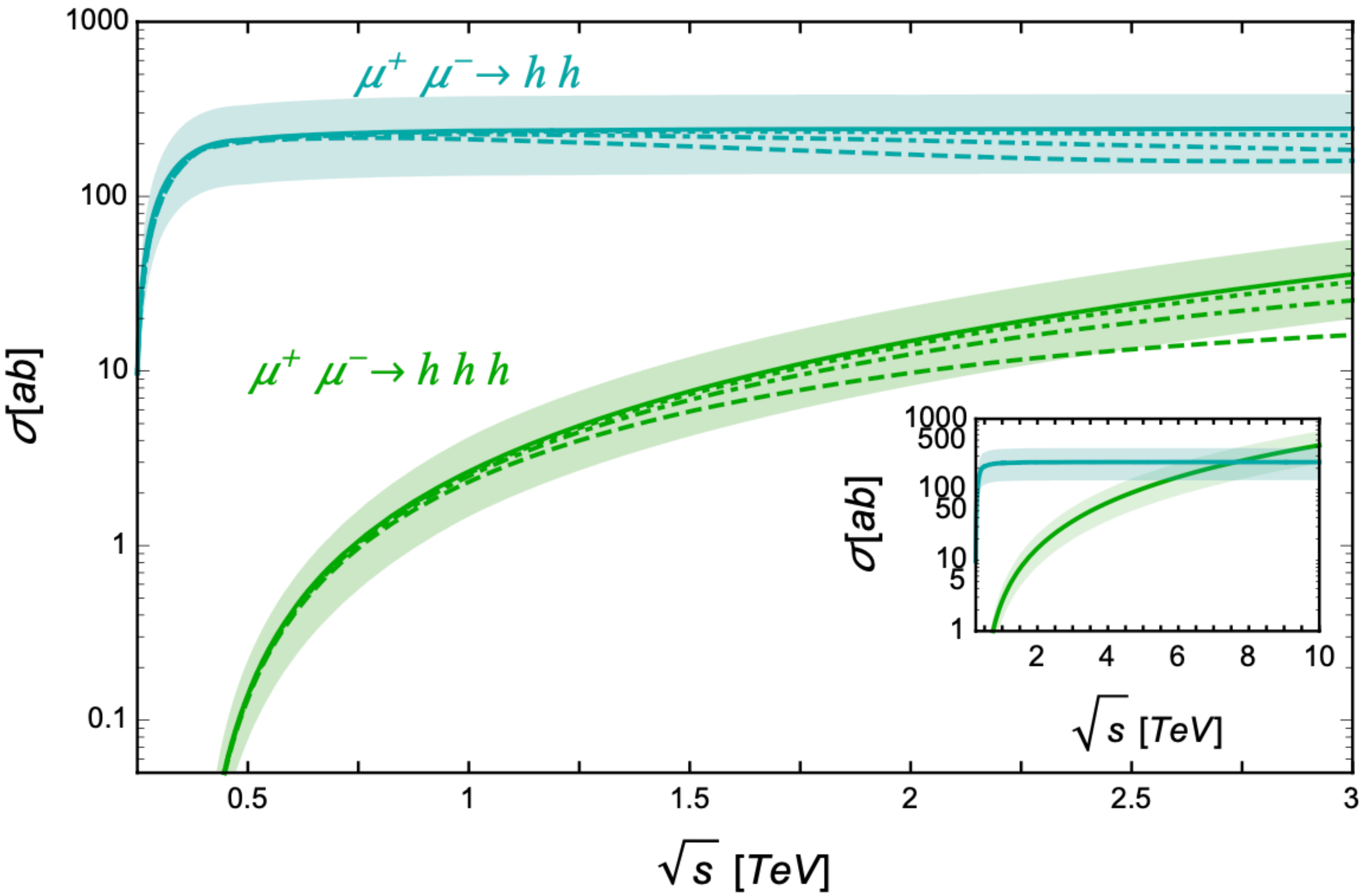
R.D., N. McGinnis, and K. Hermanek, to appear

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}}\lambda^h_{\mu\mu}\,\bar{\mu}\mu h - \frac{1}{2}\lambda^{hh}_{\mu\mu}\,\bar{\mu}\mu h^2 - \frac{1}{3!}\lambda^{hhh}_{\mu\mu}\,\bar{\mu}\mu h^3$$

$$\lambda^h_{\mu\mu} = (m_\mu + 2m_\mu^{LE})/v$$

$$\lambda^{hh}_{\mu\mu} = 3\,m_\mu^{LE}/v^2,$$

$$\lambda^{hhh}_{\mu\mu} = \frac{3}{\sqrt{2}}\,m_\mu^{LE}/v^3,$$



1σ range of Δa_μ

$$\sigma_{\mu^+\mu^-\to hh} \simeq \frac{|\lambda^{hh}_{\mu\mu}|^2}{64\pi} = \frac{9}{64\pi}\left(\frac{m_\mu^{LE}}{v^2}\right)^2,$$

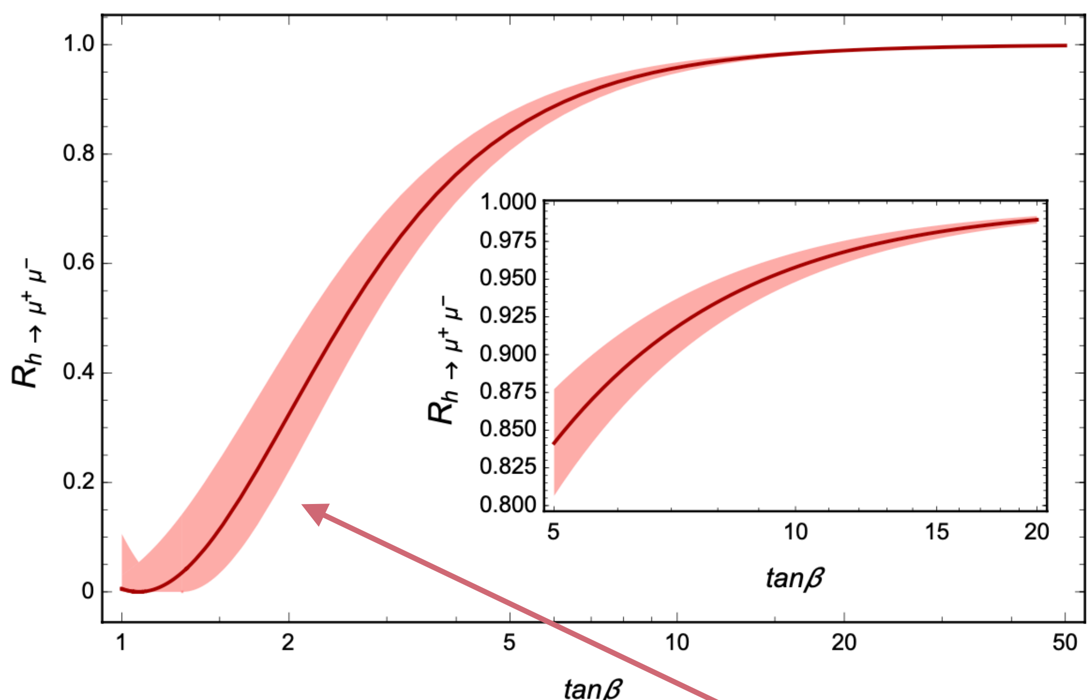
$$\sigma_{\mu^+\mu^-\to hhh} \simeq \frac{|\lambda^{hhh}_{\mu\mu}|^2}{6144\pi^3}s = \frac{3}{4096\pi^3}\left(\frac{m_\mu^{LE}}{v^3}\right)^2 s$$

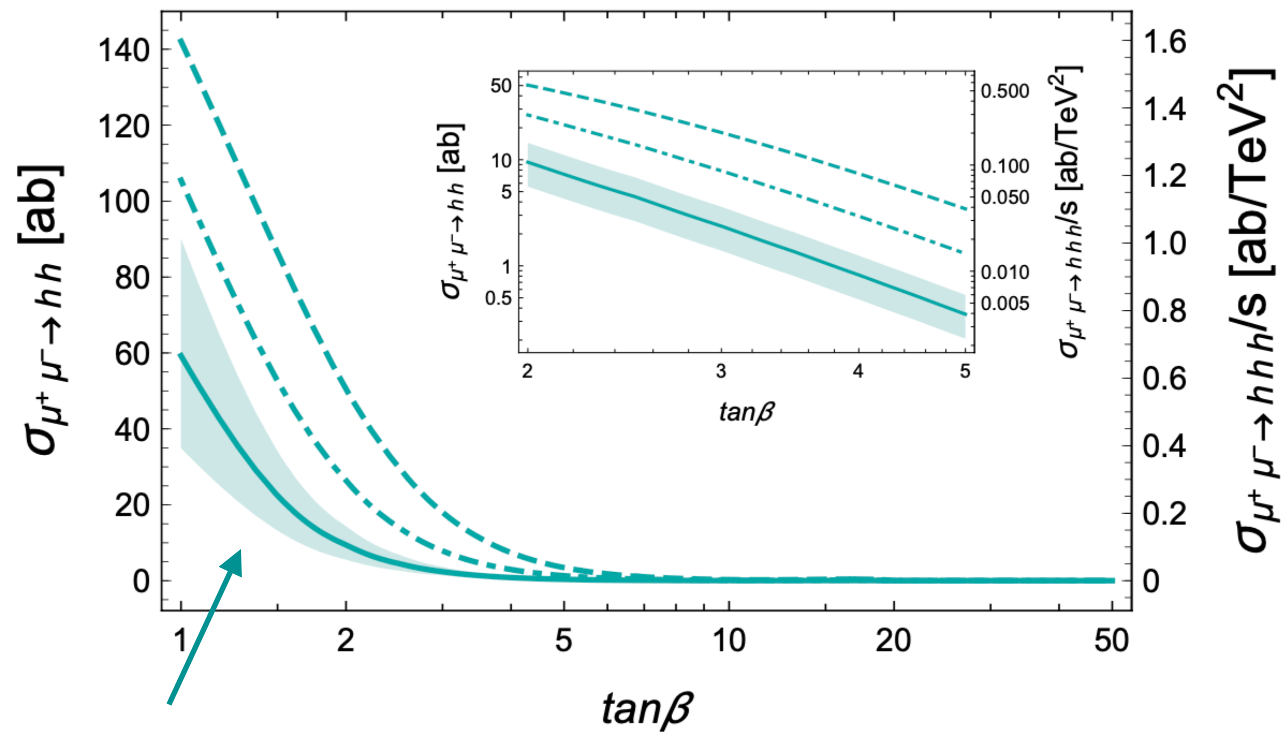
1 TeV muon collider with 0.2 ab^{-1} could see ~50 di-Higgs events

3 TeV muon collider with 1 ab^{-1} could see ~30 tri-Higgs events

Di-Higgs and tri-Higgs in 2HDM with L+E

In 2HDM one free parameter, $\tan\beta$, remains:





1σ range of Δa_μ

di-Higgs and tri-Higgs cross sections large at small $\tan\beta$

at large $\tan\beta$: $HH,\ hHH,\ hH^+H^-, \ldots$ expected for sufficient $\sqrt{s}$

Conclusions

Models with more Higgses and vectorlike matter are among the simplest extensions of the standard model,

and can provide understanding of values of 7 largest couplings in the SM.

Muon g-2 can be explained with multi TeV (10s TeV) leptons:

- **SM with L + E (+ N):**
  - **the most economical**
  - **the most constrained by precision EW data**
  - **the most unique predictions**

possible effects at the LHC, can be tested at Giga-Z or 1 TeV muon collider

di-Higgs and tri-Higgs signals especially striking

- **2HDM with L + E (+ N)**
  - $\tan^2\beta$ **enhanced contributions of heavy Higgses**
  - **would require FCC-ee (precision) and FCC-hh (energy) to be tested**
  - **interpolates between the SM and models with scalars not participating in EWSB**