Muon g-2 and New Physics

Radovan Dermisek

Indiana University, Bloomington

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Muon g-2

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

Muon g-2, Fermilab, arXiv:2104.03281 [hep-ex]

Muon g-2, BNL, arXiv:hep-ex/0602035

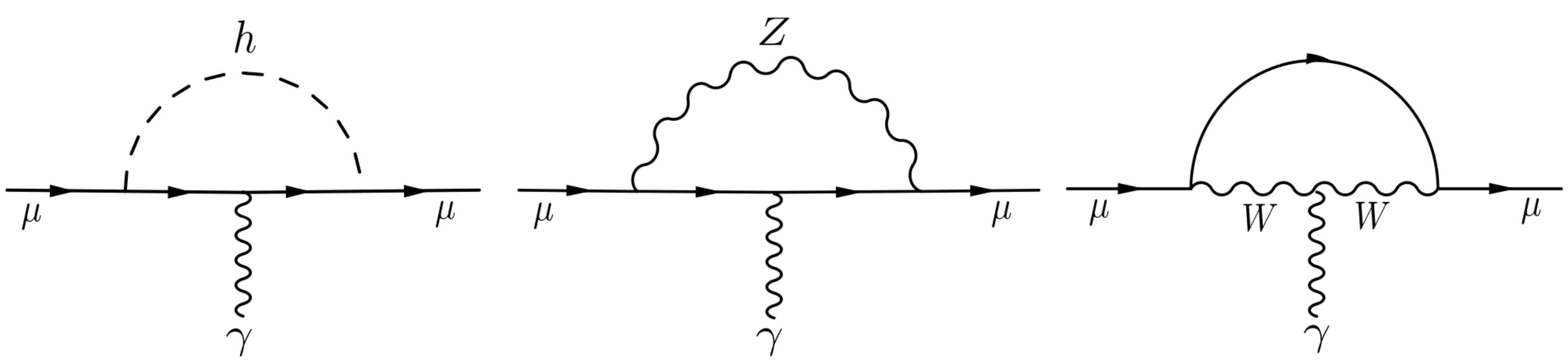
SM prediction, T. Aoyama, et al., Phys. Rept. 887, 1-166 (2020)

What is in the loop?

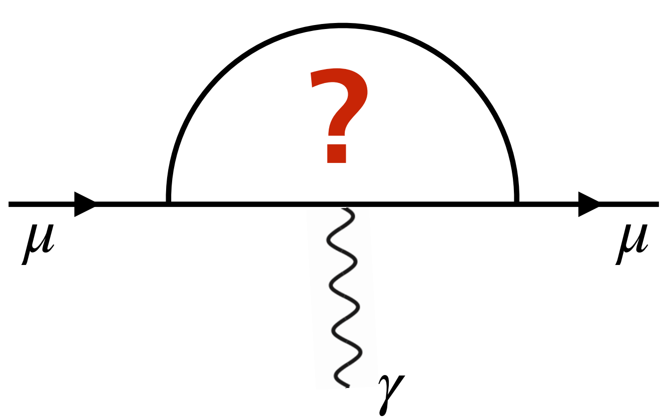
$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM} = (2.51 \pm 0.59) \times 10^{-9}$$

The size of the discrepancy is similar to the EW contribution

$$a_\mu^{EW} \simeq 2 \times 10^{-9}$$



Many possible explanations with new particles in the loop:



New physics contributions to muon g-2

Typical NP contribution

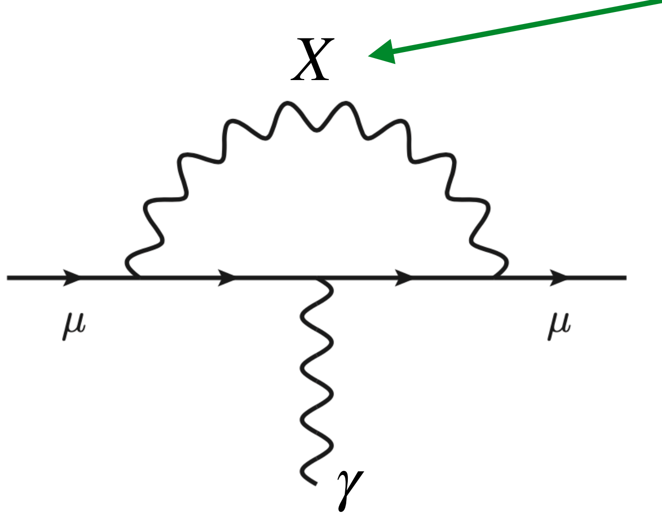
can be just one new scalar or vector particle

(new gauge bosons are highly constrained)

C.Y. Chen, M. Pospelov and Y.M. Zhong, arXiv:1701.07437 [hep-ph]

M. Bauer, P. Foldenauer and J. Jaeckel, arXiv:1803.05466 [hep-ph]

B. Batell, A. Freitas, A. Ismail and D. Mckeen, arXiv:1712.10022 [hep-ph]



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

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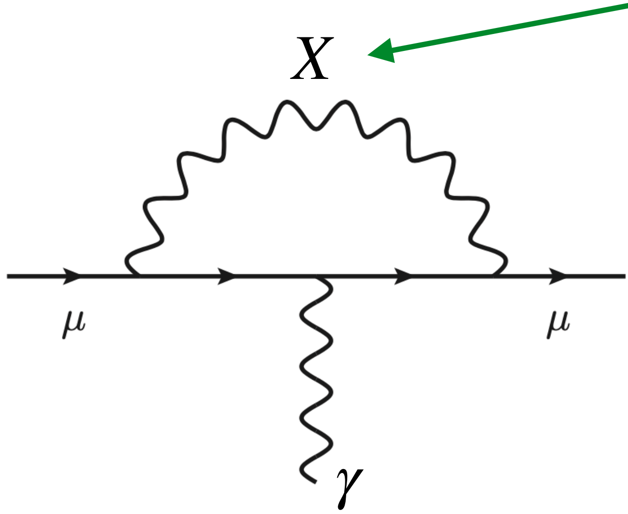

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SM singlet scalar coupling only to muon can explain Δa_μ with

$$1\ \mathrm{MeV} \lesssim m_X \lesssim 1\ \mathrm{TeV}$$

cosmological constraints

perturbativity

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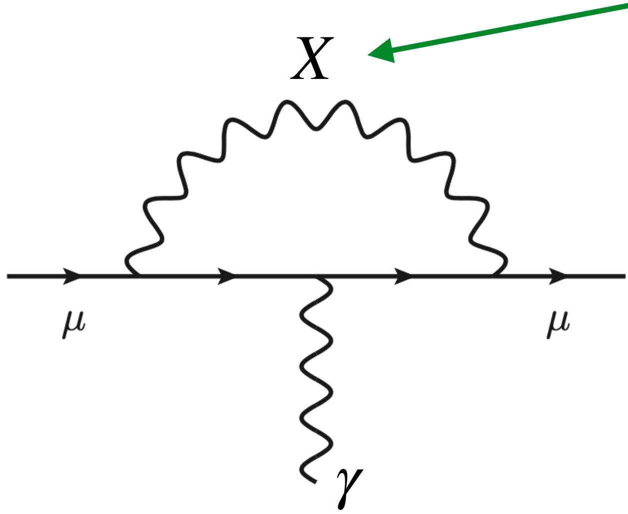

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$$1\ \mathrm{MeV} \lesssim m_X \lesssim 1\ \mathrm{TeV}$$

cosmological constraints perturbativity

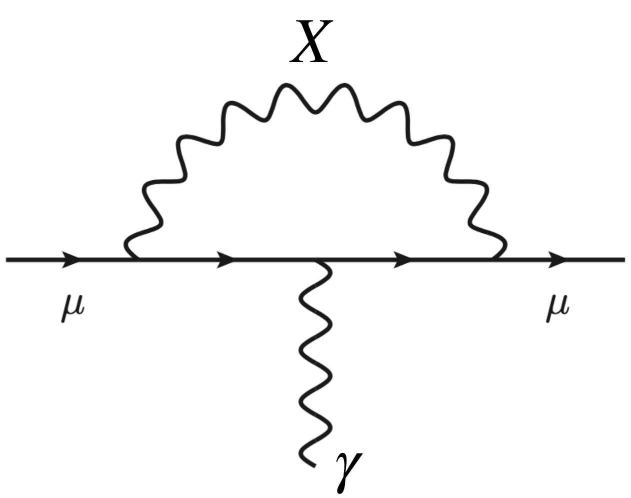
- up to ~1 GeV can be probed at muon-beam fixed-target experiments
- above ~1 GeV muon collider might be the only option

3 TeV muon collider is sufficient

R. Capdevilla, D. Curtin, Y. Kahn and G. Krnjaic, arXiv:2101.10334 [hep-ph]

New physics contributions to muon g-2

Typical NP contribution



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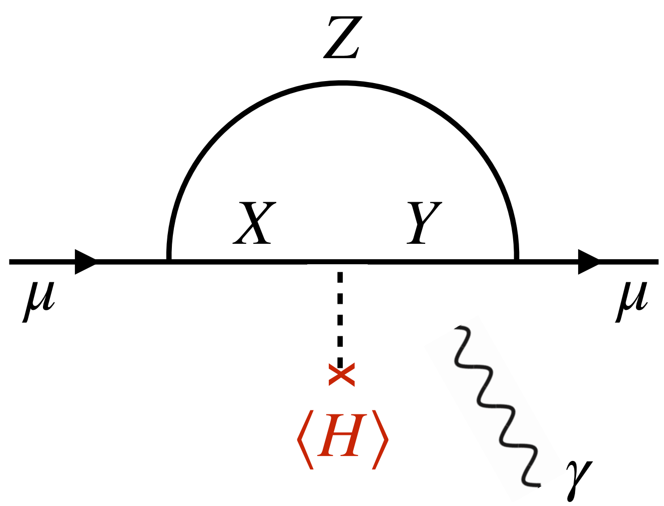
Mass enhanced NP contribution



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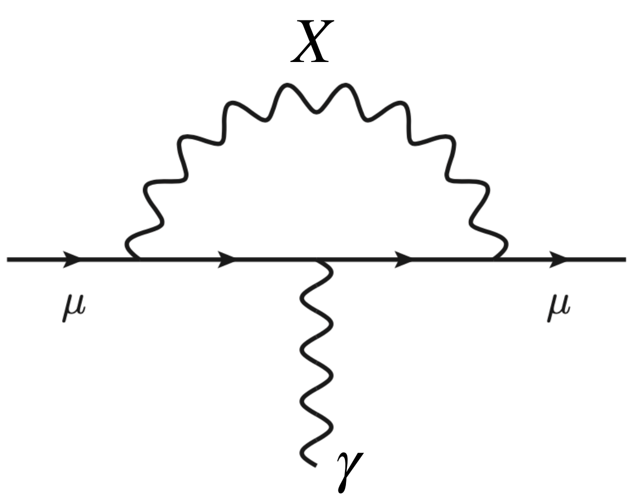

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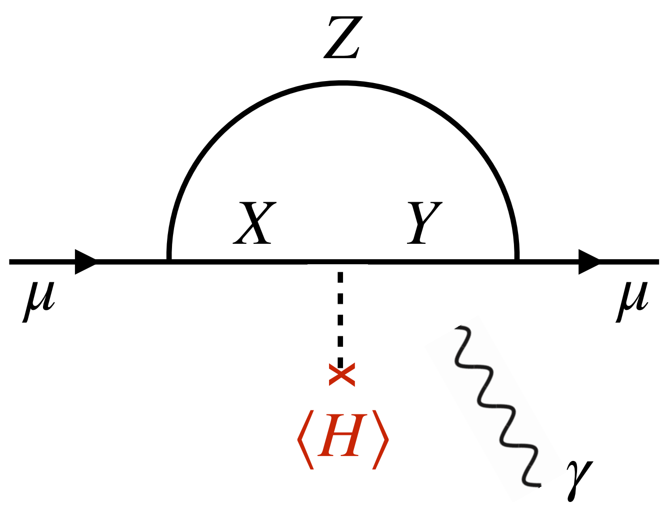
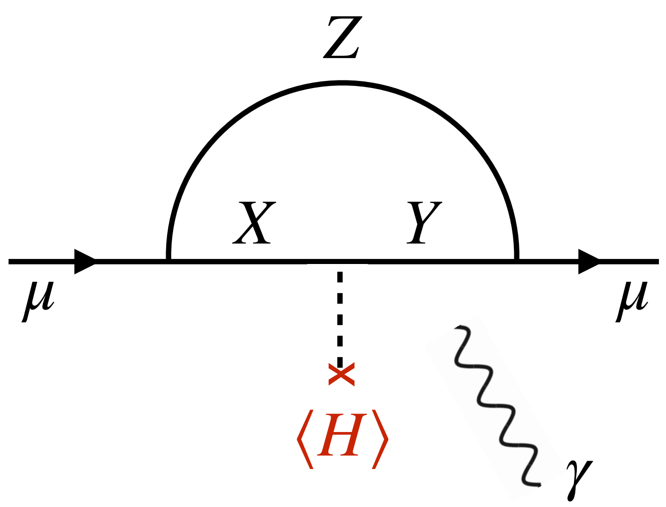


$$\Delta a_\mu \simeq \frac{\lambda_{NP}^3}{16\pi^2}\frac{m_\mu v}{m_{NP}^2}$$

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

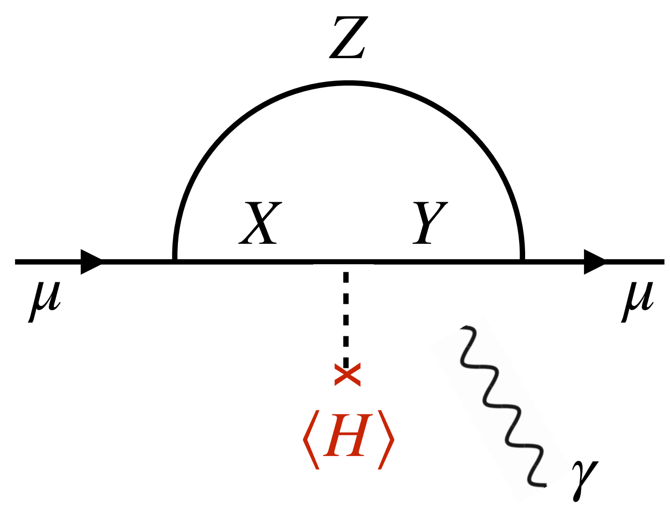
can explain Δa_μ with NP at $\lesssim 10$ TeV (50 TeV) **with $\lambda_{NP} \simeq 1$** ($\sqrt{4\pi}$)

Mass enhanced NP contributions to Δa_μ



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

Mass enhanced NP contributions to Δa_μ

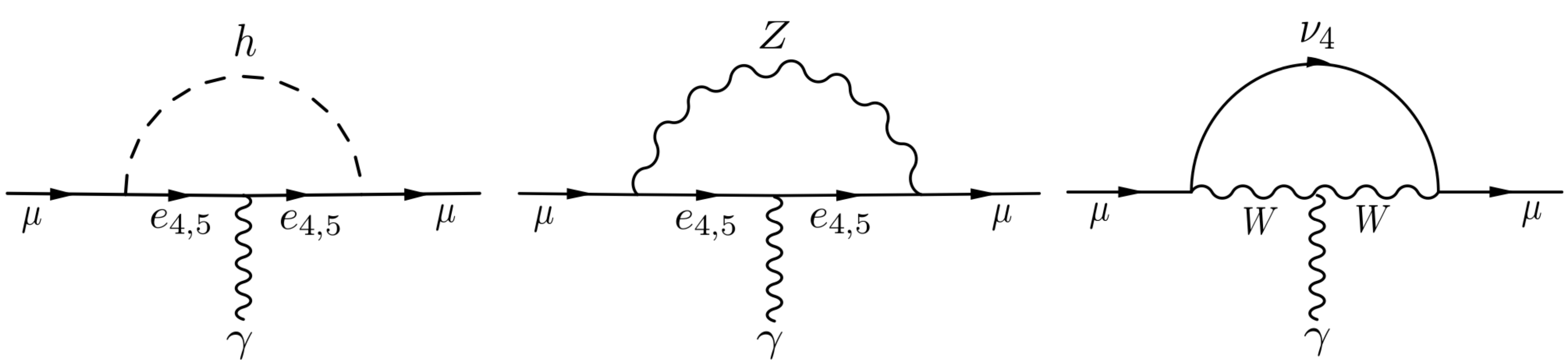


X, Y, Z can have any quantum numbers (allowing for the loop):

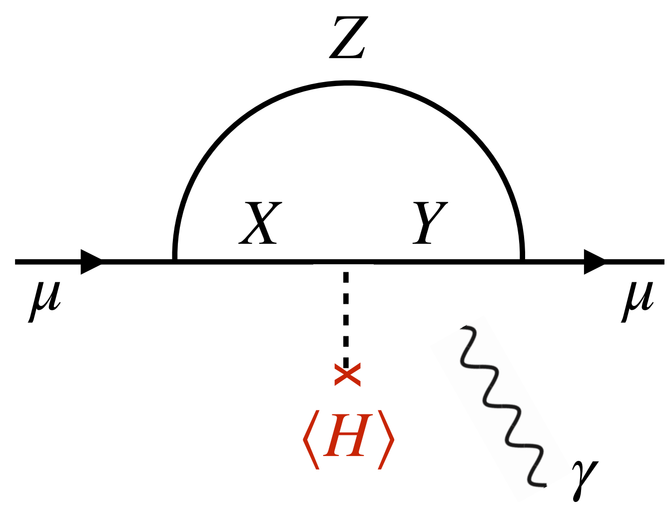
- $Z = h, Z, W$ **and** $X, Y =$ new (vectorlike) leptons

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]
A. Freitas, J. Lykken, S. Kell and S. Westhoff, arXiv:1402.7065 [hep-ph]



Mass enhanced NP contributions to Δa_μ



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

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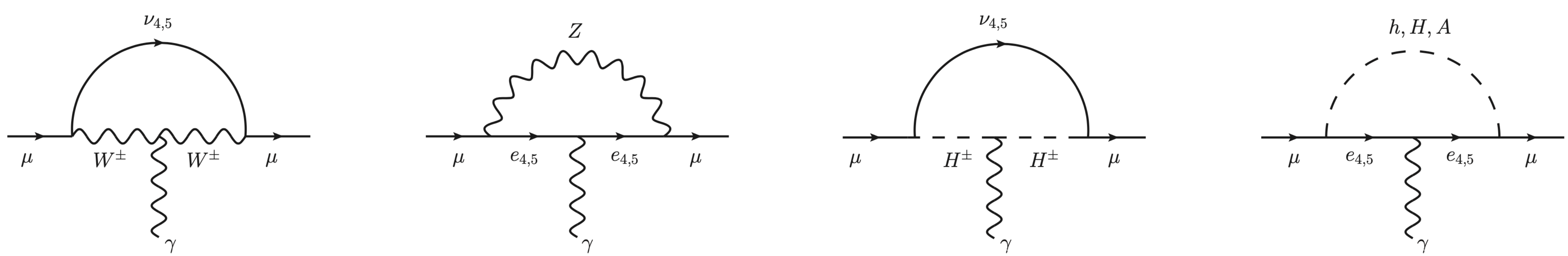
new scalars participating in EWSB

e.g. 2HDM with new leptons, dramatically changes the impact of constraints

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



see the talk of K. Hermanek

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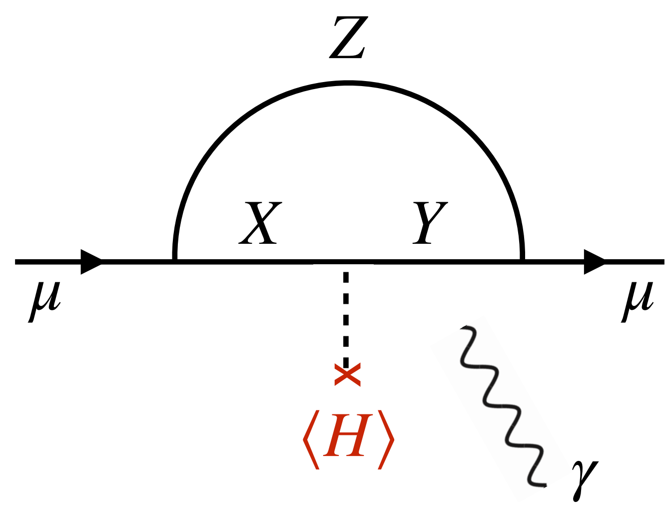


X, Y, Z can have any quantum numbers (allowing for the loop):

- $X, Y, Z =$ **2 fermions and 1 scalar or 2 scalars and 1 fermion**

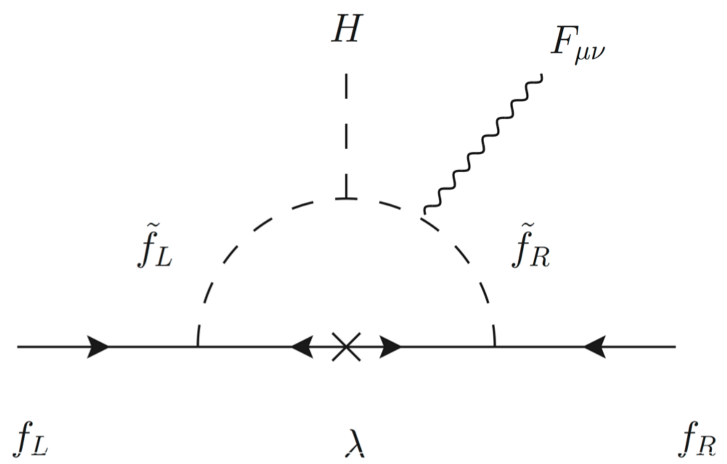
new scalars not participating in EWSB,
the most popular, many options, the least constrained

for summaries and systematic studies, see
R.L. Calibbi, R. Ziegler and J. Zupan, arXiv:1804.00009 [hep-ph]
A. Crivellin, M. Hoferichter and P. Schmidt-Wellenburg, arXiv:1807.11484 [hep-ph]
R. Capdevilla, D. Curtin, Y. Kahn and G. Krnjaic, arXiv:2101.10334 [hep-ph]
A. Crivellin, M. Hoferichter, arXiv:2104.03202 [hep-ph]

(similar options with new gauge fields, superpartners, or vectorlike quarks and scalar/vector leptoquarks)

Examples with familiar particles

- example of a fermion-scalar-scalar model



MSSM, $\tan\beta$ enhanced bino-smuon contribution

T. Moroi, hep-ph/9512396

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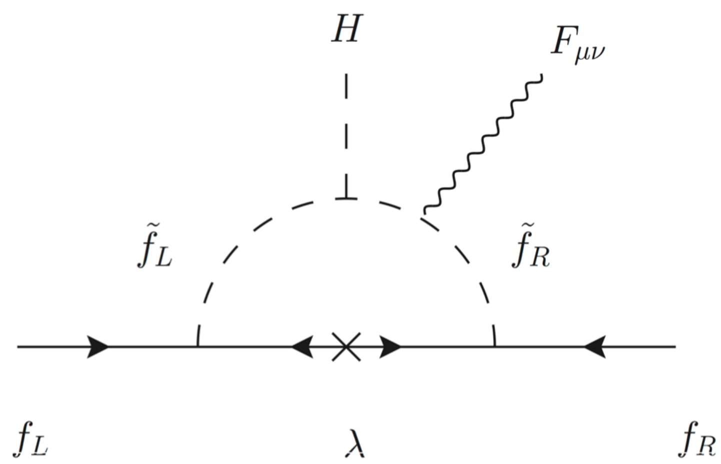
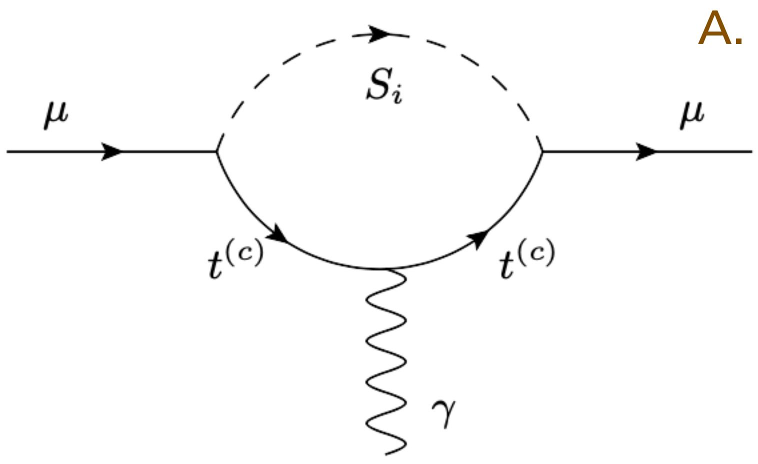


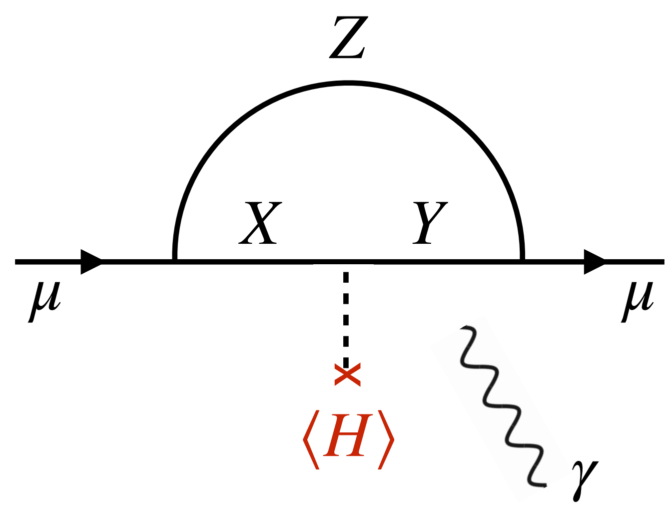
- example of a scalar-fermion-fermion model

top quark and scalar leptoquark

A. Crivellin, D. Mueller and F. Saturnino, arXiv:2008.02643 [hep-ph]



Mass enhanced NP contributions to Δa_μ



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  minimal, just SM with new leptons, constrained the most

- $Z = h, Z, W, H, A, H^{\pm}$ **and** $X, Y =$ vectorlike (or SM) leptons

  new scalars participating in EWSB

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

- $X, Y, Z =$ **2 fermions and 1 scalar or 2 scalars and 1 fermion**

  new scalars not participating in EWSB

  the most popular, many options, the least constrained

(similar options with new gauge fields, superpartners, or vectorlike quarks and scalar/vector leptoquarks)

Standard model with L + E

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

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

the same quantum numbers as SM leptons

Charged lepton mass matrix (after EWSB):

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

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

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At energies much below M_L, M_E:

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

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

$$m_\mu = y_\mu v + m_\mu^{LE}$$

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

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

and is directly linked to Δa_μ:

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

Δa_μ in SM with L + E and $h \to \mu^+\mu^-$

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

Δa_μ and muon mass (and thus $h \to \mu^+\mu^-$) highly correlated,
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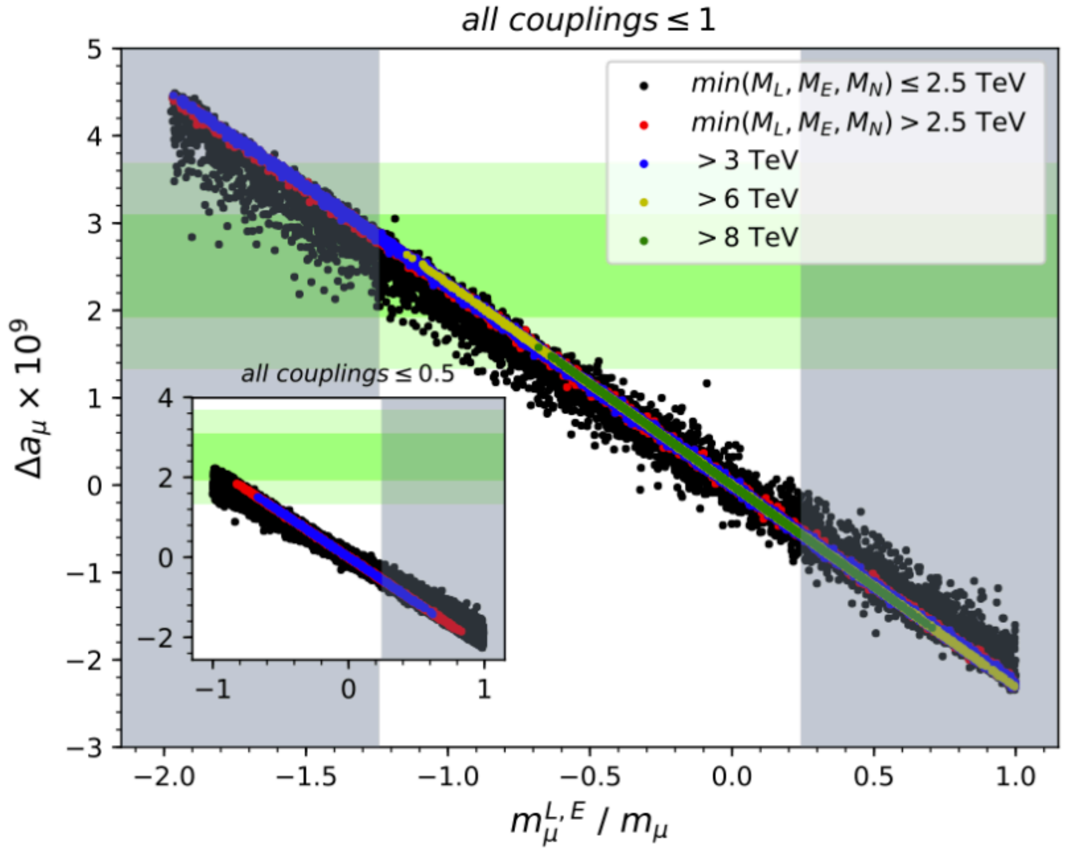

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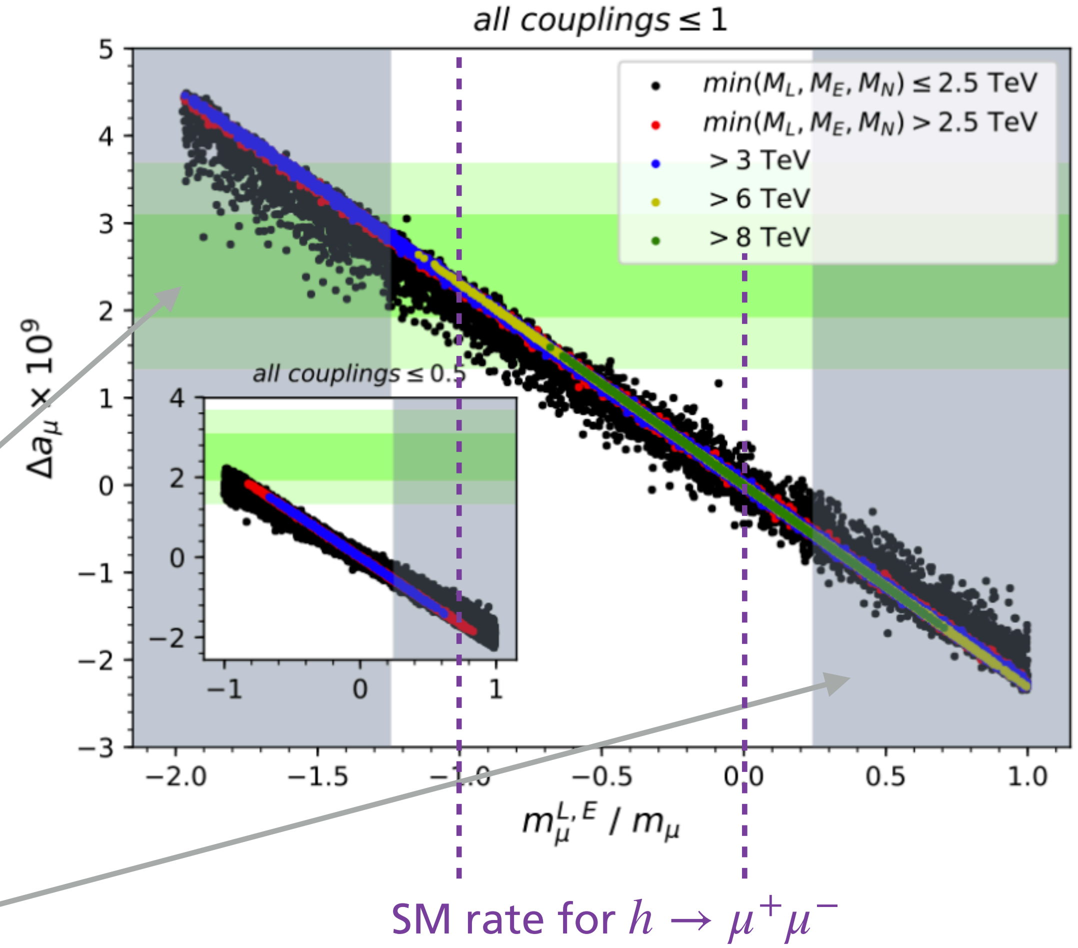


excluded by

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

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

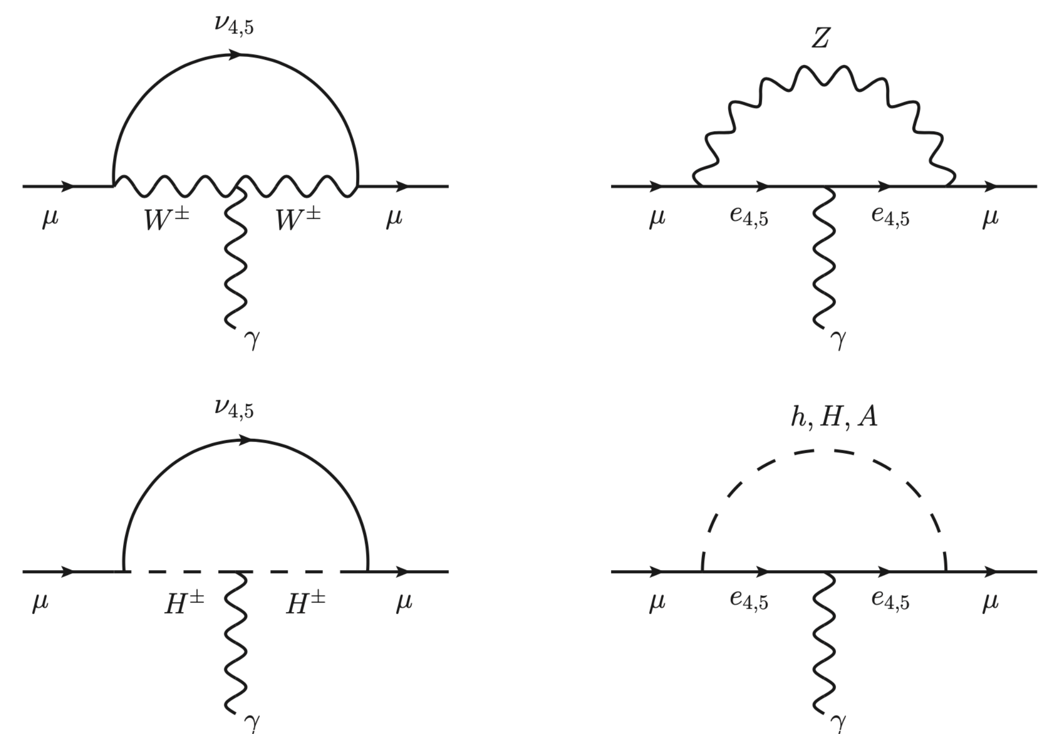
even if SM rate for $h \to \mu^+\mu^-$ is observed it cannot rule out this explanation of Δa_μ

Δa_μ in type-II 2HDM with L + E

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

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

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



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

sufficient to explain Δa_μ with couplings ~0.5

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

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

would be able to explain even 100 x Δa_μ

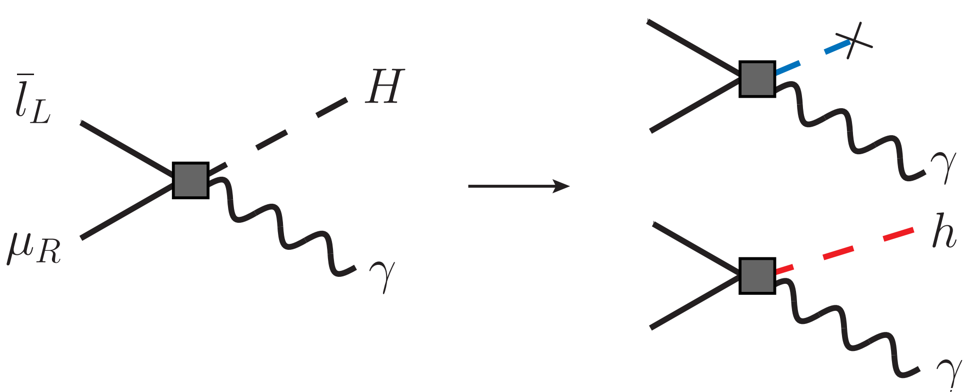
assuming $M_{L,E} \simeq m_{H,A,H^\pm}$

see the talk of K. Hermanek

Related observables

Signals from related operators (SM+L+E)

New leptons (~10(s) TeV) might be well beyond the reach of (foreseeable) future colliders, but there are related signals:



$\mu\mu \to h\gamma$

requires $\gtrsim 30$ TeV muon collider

D. Buttazzo and P. Paradisi, arXiv:2012.02769 [hep-ph]

W. Yin and M. Yamaguchi, arXiv:2012.03928 [hep-ph]

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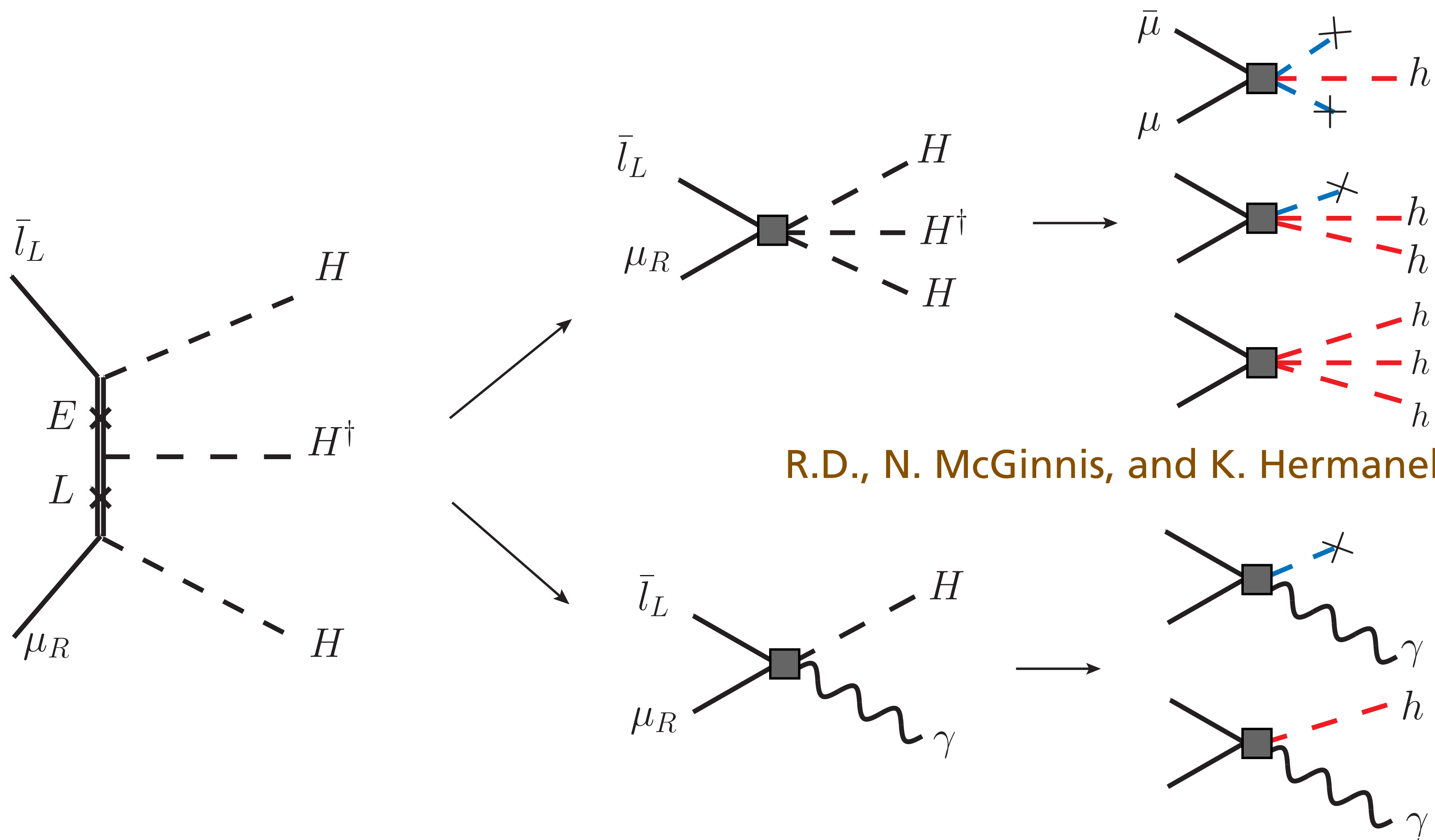

$h \to \mu\mu$

$\mu\mu \to hh$

$\mu\mu \to hhh$

R.D., N. McGinnis, and K. Hermanek, arXiv:2108.10950 [hep-ph]

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D. Buttazzo and P. Paradisi, arXiv:2012.02769 [hep-ph]

W. Yin and M. Yamaguchi, arXiv:2012.03928 [hep-ph]

Di-Higgs and tri-Higgs signals

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:

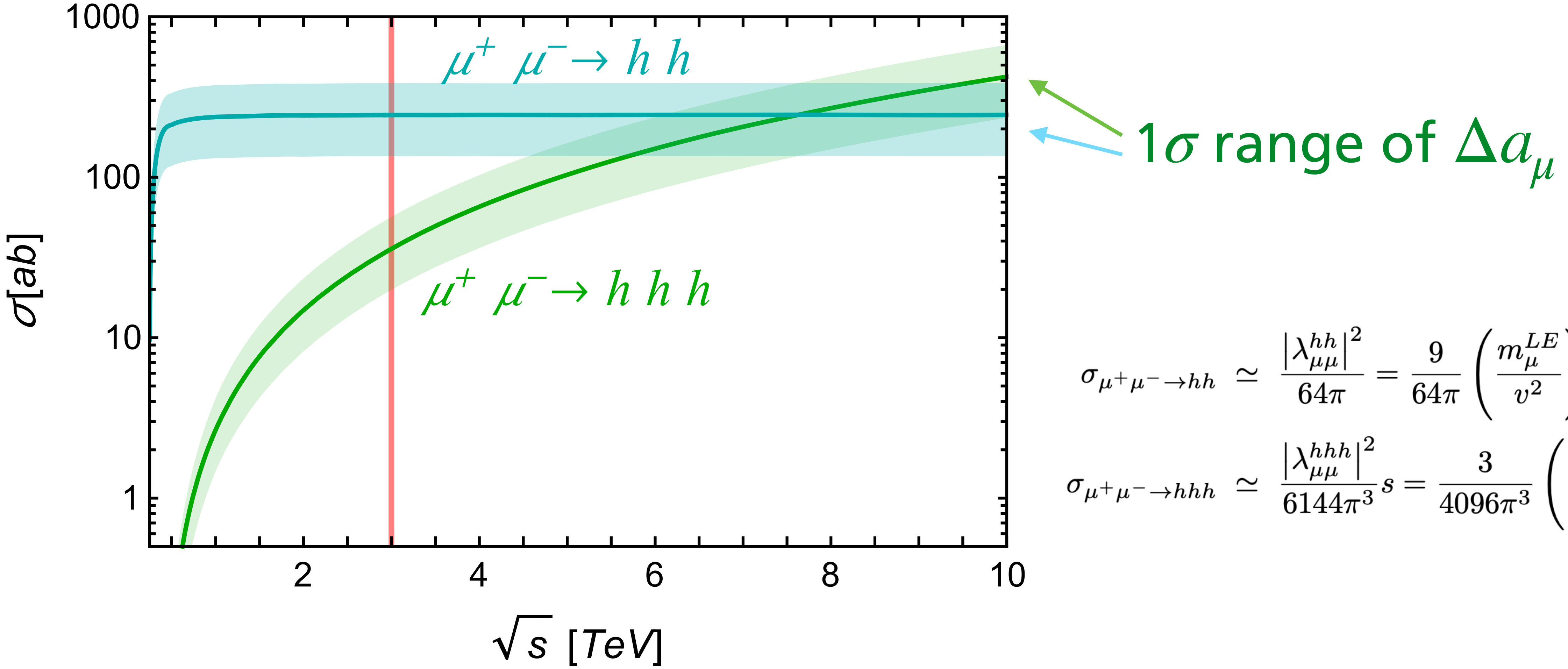
$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} \lambda_{\mu\mu}^h \bar{\mu}\mu h - \frac{1}{2} \lambda_{\mu\mu}^{hh} \bar{\mu}\mu h^2 - \frac{1}{3!} \lambda_{\mu\mu}^{hhh} \bar{\mu}\mu h^3$$

$$\lambda_{\mu\mu}^h = (m_\mu + 2m_\mu^{LE})/v \qquad \lambda_{\mu\mu}^{hh} = 3\, m_\mu^{LE}/v^2, \qquad \lambda_{\mu\mu}^{hhh} = \frac{3}{\sqrt{2}} m_\mu^{LE}/v^3,$$

are predicted without a free parameter!

Di-Higgs and tri-Higgs signals of Δa_μ

R.D., N. McGinnis, and K. Hermanek, arXiv:2108.10950 [hep-ph]



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

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

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

Connection with $\mu\mathrm{EDM}$

Dipole moments and the mass operator

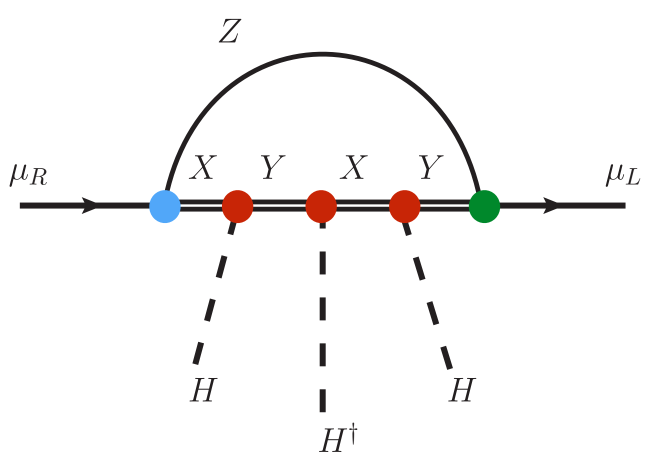
Couplings required for chiral enhancement in Δa_μ also generate dim. 6 mass operator:

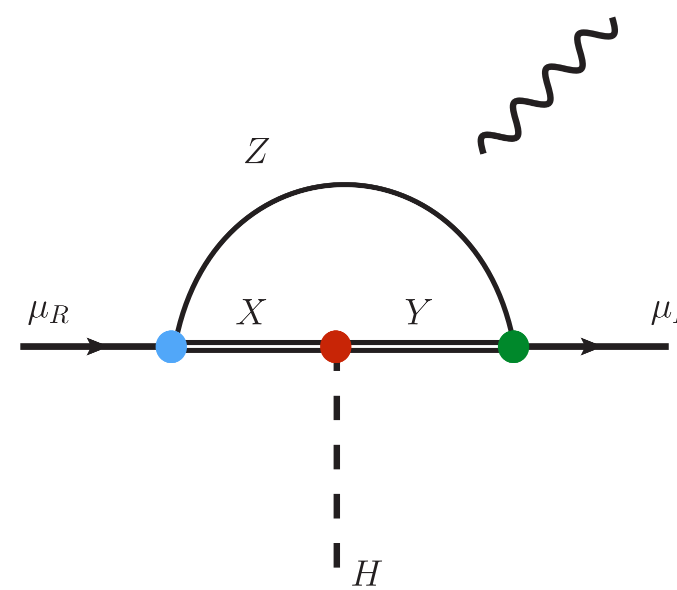
$$\mathcal{L} \supset -\; y_\mu \bar{l}_L \mu_R H \;-\; C_{\mu H} \bar{l}_L \mu_R H \left(H^\dagger H\right) \;-\; C_{\mu\gamma} \bar{l}_L \sigma^{\mu\nu} \mu_R H F_{\mu\nu} + h.c.$$

loop models:

A. Thalapillil and S. Thomas, arXiv:1411.7362 [hep-ph]

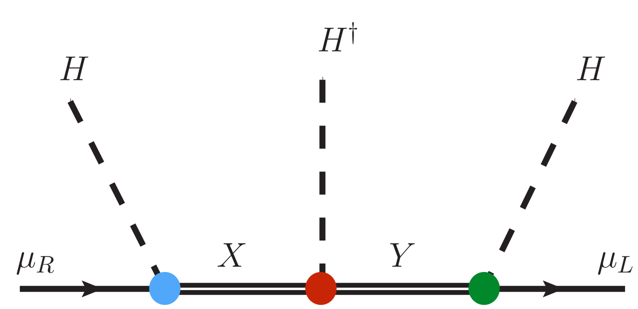
A.~Crivellin and M.~Hoferichter, arXiv:2104.03202 [hep-ph]





tree models:

SM or 2HDM with VLs



operators related by a real parameter: $C_{\mu H} = \frac{k}{e} C_{\mu\gamma}$

The muon ellipse

R. D., N. McGinnis, K. Hermanek, S. Yoon, to appear

After electroweak symmetry breaking:

$$\mathcal{L} \supset \; - \; m_\mu \bar{\mu}\mu - \frac{1}{\sqrt{2}}\left(\lambda^h_{\mu\mu}\bar{\mu}\mu h + h.c.\right) + \frac{\Delta a_\mu e Q_\mu}{4m_\mu}\bar{\mu}\sigma^{\mu\nu}\mu F_{\mu\nu} + \frac{i}{2}d_\mu \bar{\mu}\sigma^{\mu\nu}\gamma^5\mu F_{\mu\nu}$$

$$m_\mu = \left(y_\mu v + C_{\mu H}v^3\right)e^{-i\phi_{m_\mu}}$$

$$\lambda^h_{\mu\mu} = \left(y_\mu + 3C_{\mu H}v^2\right)e^{-i\phi_{m_\mu}}$$

$$\Delta a_\mu = -\frac{4m_\mu v}{e}\mathrm{Re}[C_{\mu\gamma}e^{-i\phi_{m_\mu}}]$$

$$d_\mu = -2v\mathrm{Im}[C_{\mu\gamma}e^{-i\phi_{m_\mu}}]$$

$$R_{h\to\mu\mu} \equiv \frac{BR(h\to\mu\mu)}{BR(h\to\mu\mu)_{SM}} = \left(\frac{v}{m_\mu}\right)^2 |\lambda^h_{\mu\mu}|^2$$

Because the operators are related, we have:

$$C_{\mu H} = \frac{k}{e}C_{\mu\gamma}$$

$$R_{h\to\mu\mu} = \left(\frac{\Delta a_\mu}{2\omega} - 1\right)^2 + \left(\frac{m_\mu d_\mu}{e\omega}\right)^2$$

$$\omega = m_\mu^2/\underline{k}v^2$$

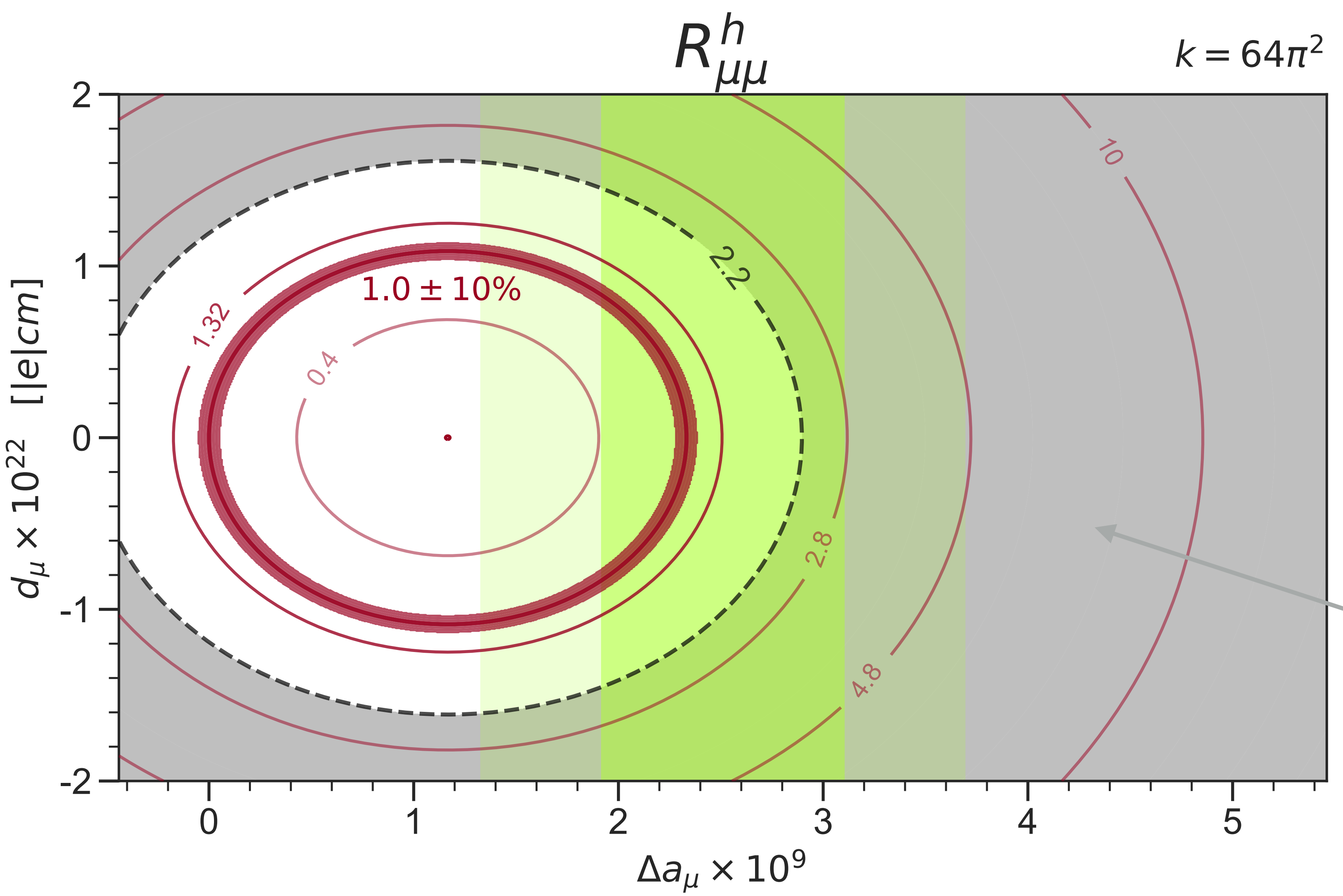
Δa_μ, d_μ and $h \to \mu\mu$ are highly correlated

Standard model with L + E

VLs with the same quantum numbers as SM leptons:

$SU(2) \times U(1)_Y$	c
$\mathbf{2}_{-1/2} \oplus \mathbf{1}_{-1}$	1

Relation completely fixed by quantum numbers

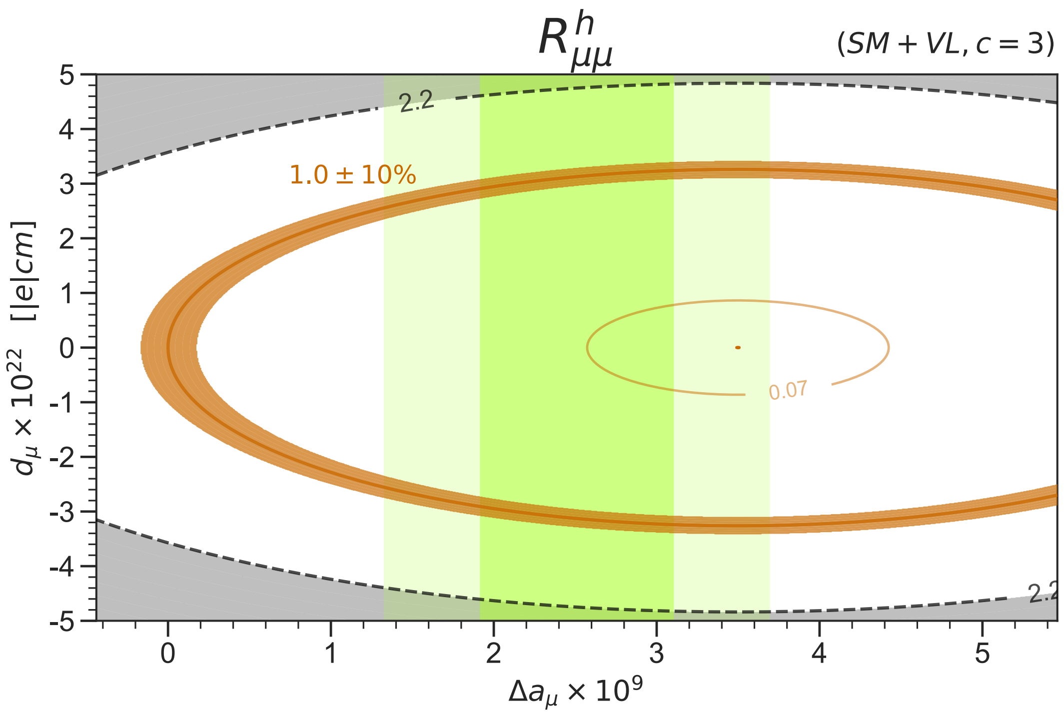


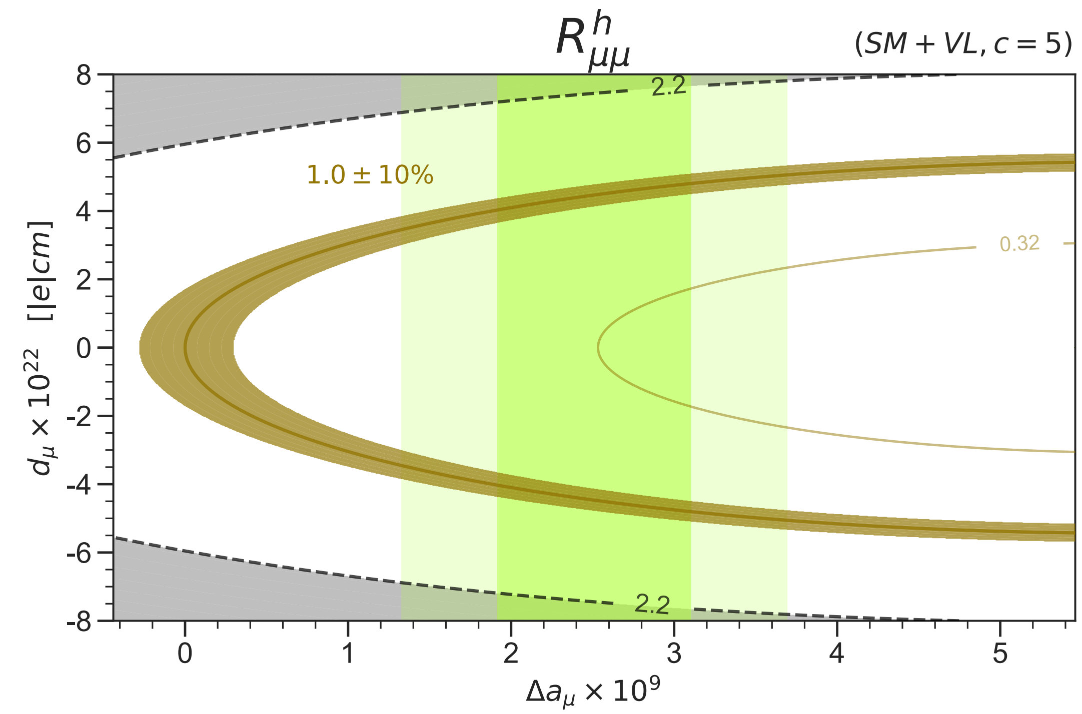
$$k = \frac{64\pi^2}{c}$$

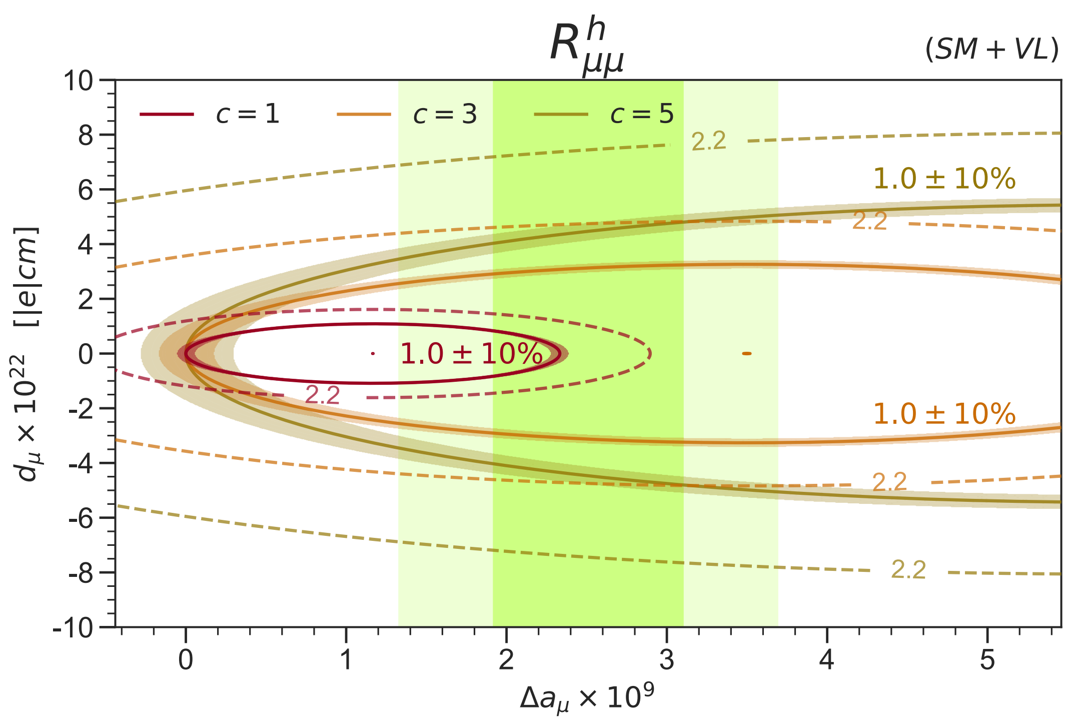
excluded by $h \to \mu\mu$

$d_\mu \lesssim 10^{-22}\,|e|\,cm$ **predicted**

Standard model + VLs







$$k = \frac{64\pi^2}{c}$$

$SU(2) \times U(1)_Y$	c
$\mathbf{2}_{-1/2} \oplus \mathbf{1}_{-1}$	1
$\mathbf{2}_{-1/2} \oplus \mathbf{3}_{-1}$	5
$\mathbf{2}_{-3/2} \oplus \mathbf{1}_{-1}$	3
$\mathbf{2}_{-3/2} \oplus \mathbf{3}_{-1}$	3
$\mathbf{2}_{-1/2} \oplus \mathbf{3}_{0}$	1

sharp predictions for d_μ once $h \to \mu\mu$ is precisely measured

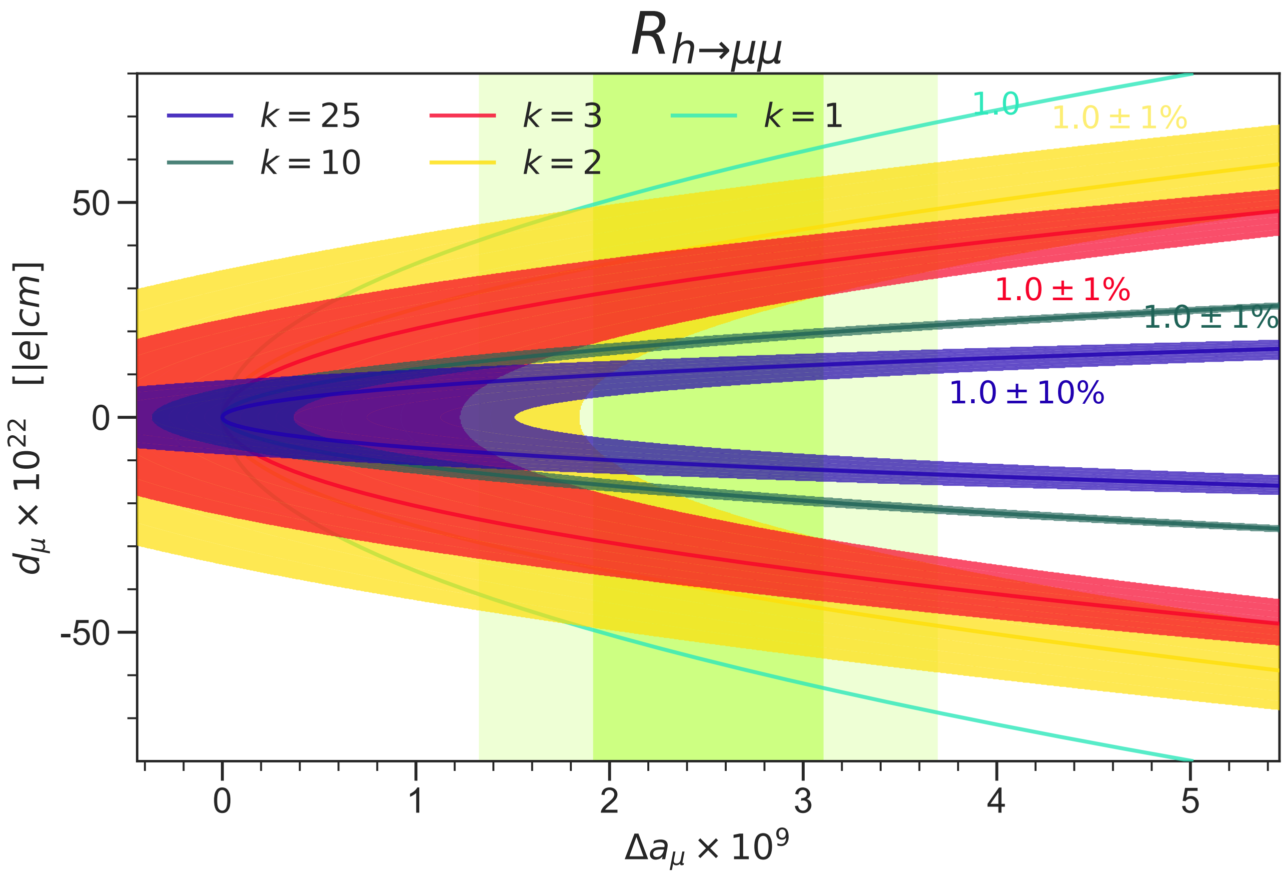
Other models

- Models with more scalars participating in EWSB

e.g. 2HDM, type-II:

see the talk of S. Yoon

$$k = \frac{64\pi^2}{c(1+\tan^2\beta)}$$



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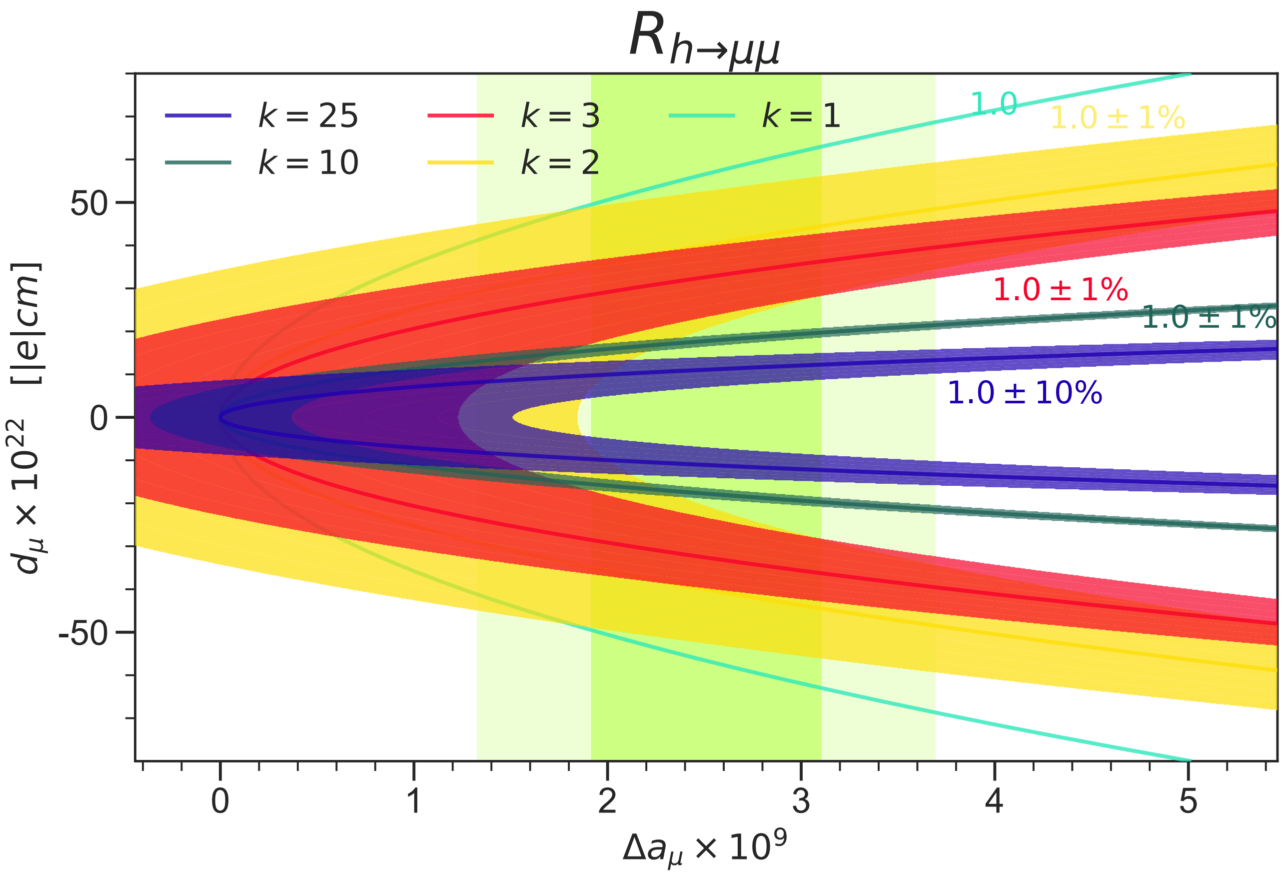


- Loop models:

$$k = \frac{4}{Q}|\lambda_{XY}|^2$$

group theoretical factor

e.g.

top quark+leptoquark: $k \simeq 3$

MSSM, bino+smuon (with large mixing): $-k \simeq 4 - 16$

In general, larger k means larger coupling and masses of new particles

Impact of future $h \to \mu\mu$ and μEDM

All models with chiral enhancement can be parameterized by k:

current limits:

$d_\mu \leq 1.8 \times 10^{-19}$ |e|cm

Muon g-2 (BNL)
arXiv:0811.1207 [hep-ex]

indirect limits:

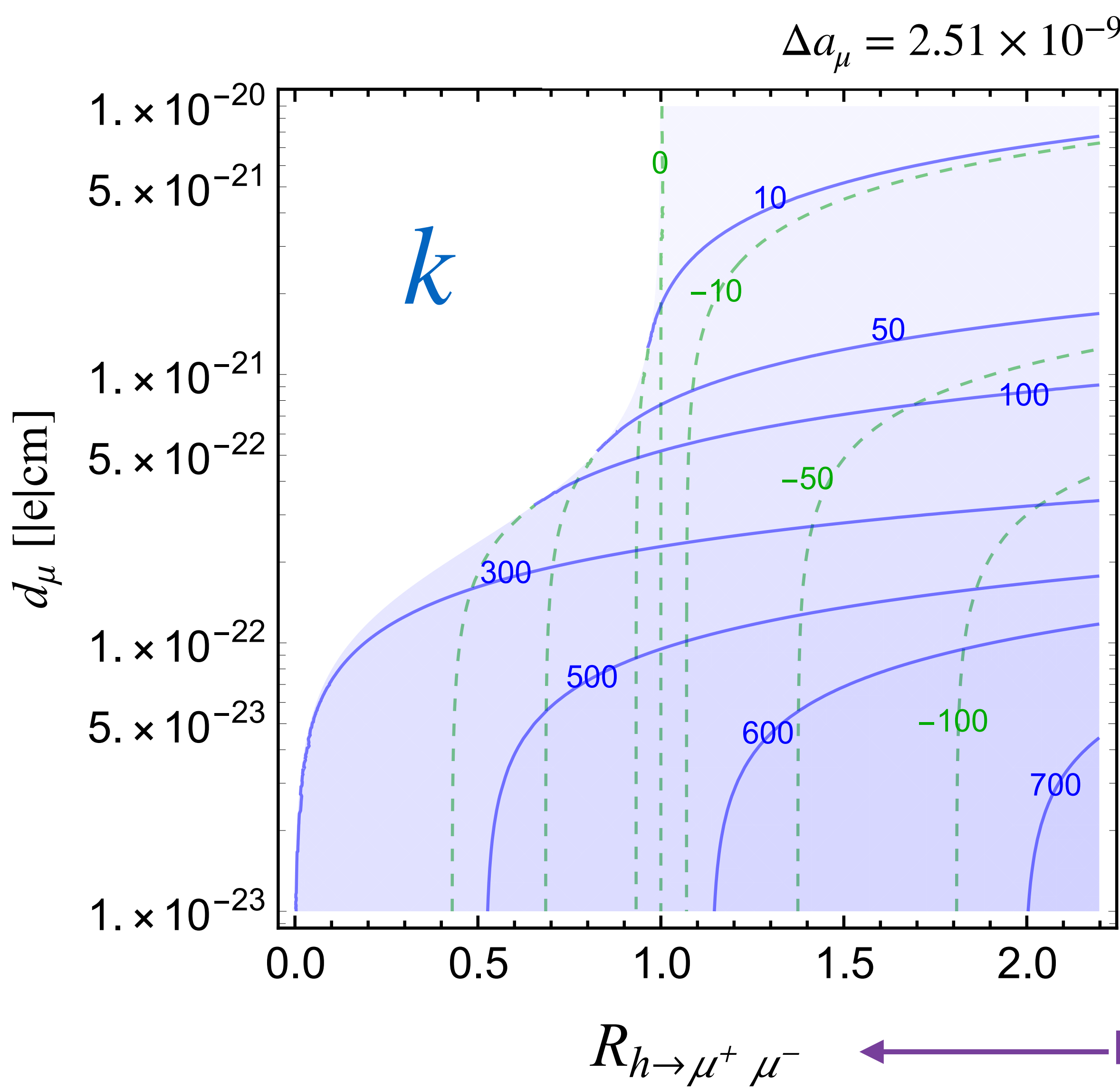
$d_\mu \leq 2 \times 10^{-20}$ |e|cm

Y. Ema, T. Gao and M. Pospelov, arXiv:2108.05398 [hep-ph]

future sensitivity:

$d_\mu \leq 6 \times 10^{-23}$ |e|cm

at Paul Scherrer Institute, arXiv:2102.08838 [hep-ex]



HL-LHC precision ~10%

many models (ranges of parameters) will be tested in near future

Summary

There are many possible explanations of Δa_μ.

Models with chiral enhancement are difficult to test directly since the anomaly can be explained with multi TeV (10s TeV) particles.

Indirect tests include measurements of:

- muon couplings to Z and W (not directly tight to Δa_μ)

  relevant especially for models with tree-level mixing, can be tested at Giga-Z or FCC-ee

- muon Yukawa coupling, $h \to \mu\mu$

  a deviation could be seen at the LHC, but SM-like observation would not rule out even tree models

- $\mu\mu \to h\gamma$

  model independent, but requires $\gtrsim 30$ TeV muon collider

- $\mu\mu \to hh$ and $\mu\mu \to hhh$

  fixed by Δa_μ in tree models, large rates even at low energy colliders

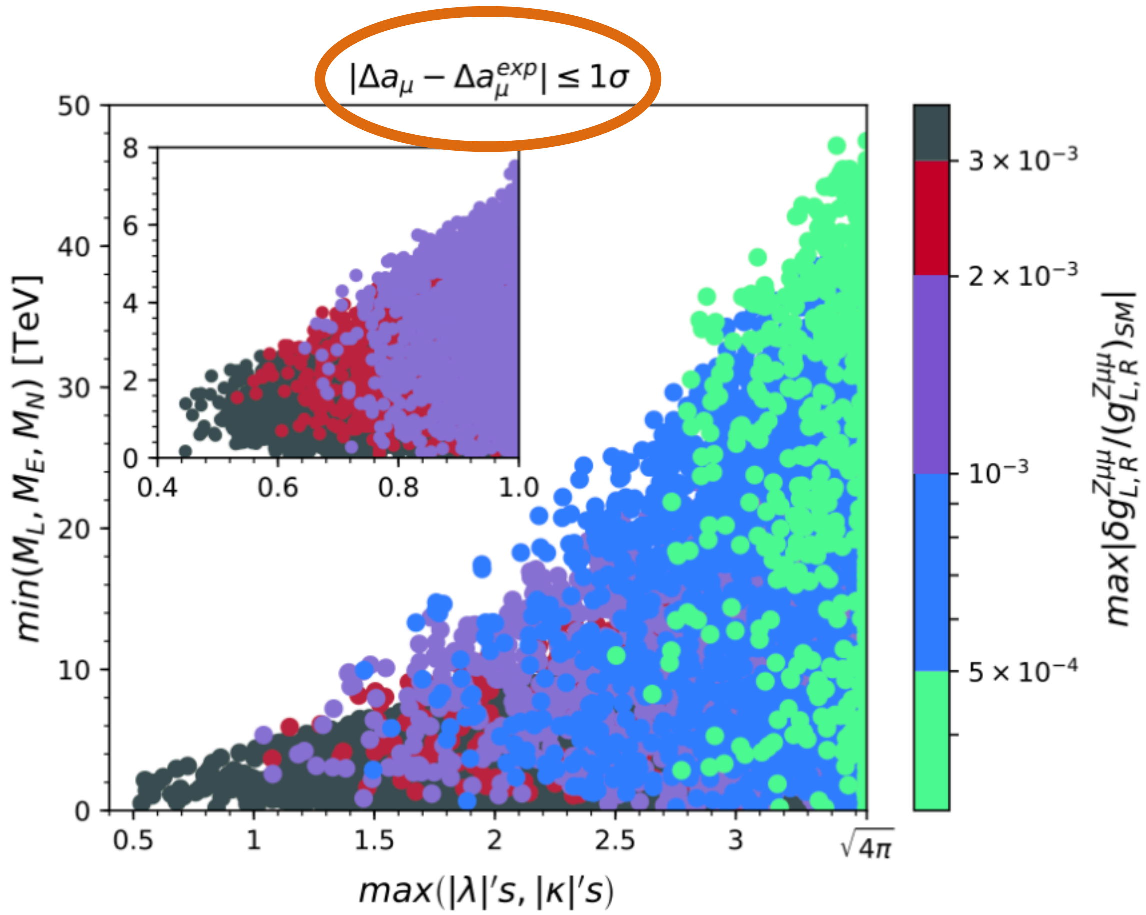
- μEDM and correlation of Δa_μ, d_μ and $h \to \mu\mu$

  many models (ranges of parameters) will be tested in near future

Supplemental material

Δa_μ in SM with L+E and muon Z couplings

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



all points satisfy constraints from direct searches and precision EW data

muon Z couplings modified at $> 3\times10^{-4}$ levels

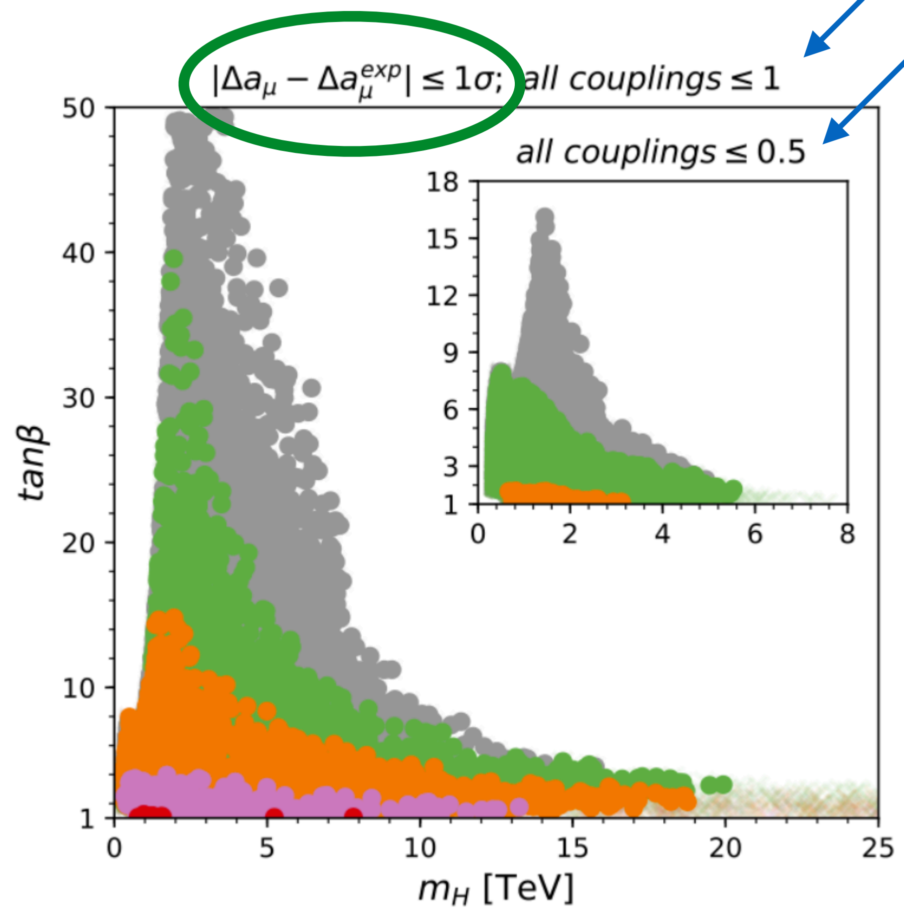
could be fully probed at Giga-Z, or FCC-ee

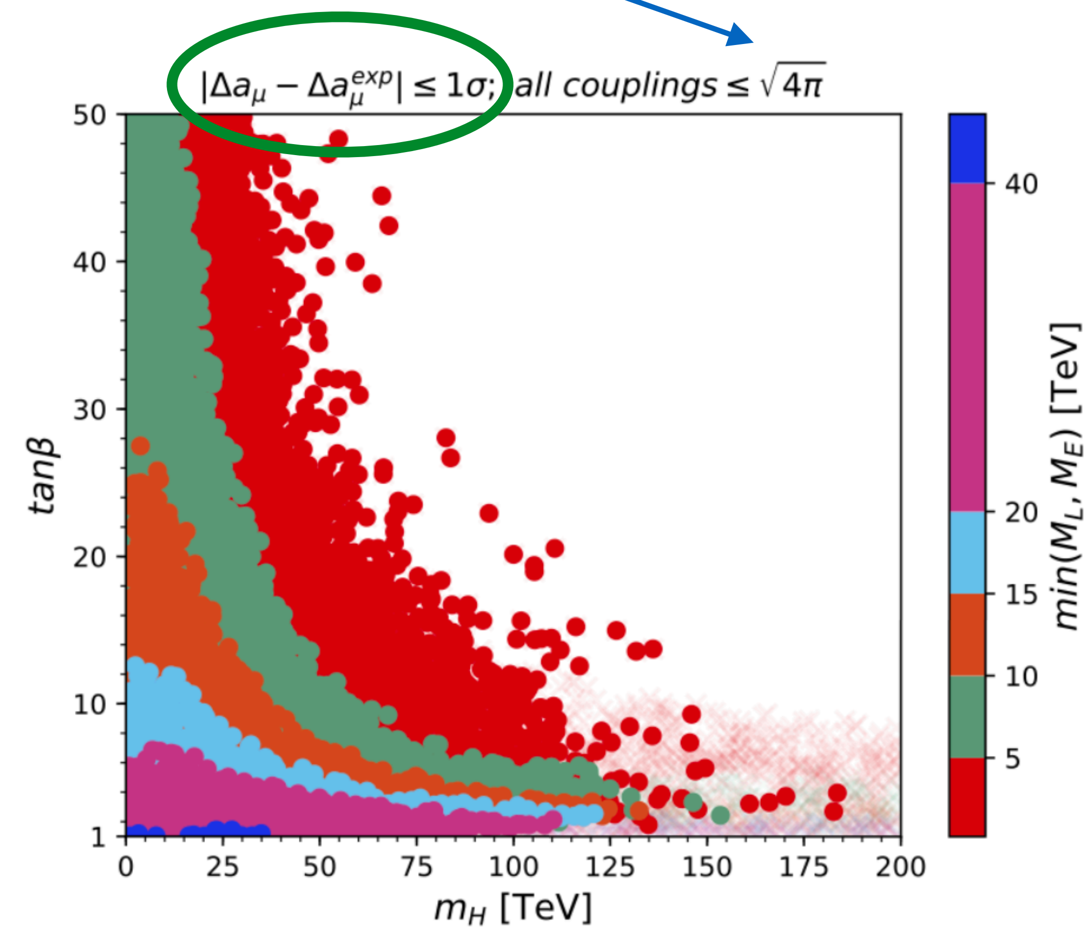
not directly tight to Δa_μ and the model could be extended to leave a smaller imprint in Z couplings

(2HDM can explain Δa_μ with modification of Z couplings below sensitivity of FCC-ee)

Δa_μ in type-II 2HDM with L + E

depending on the size of couplings



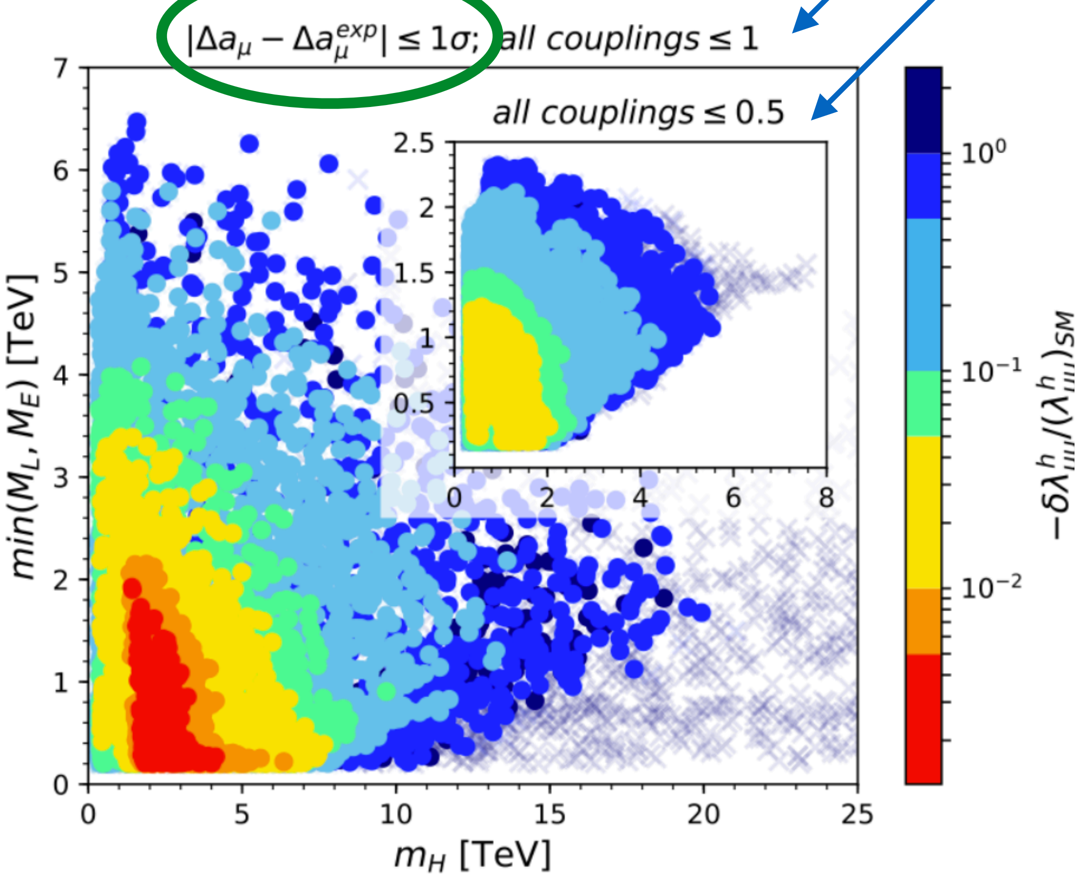


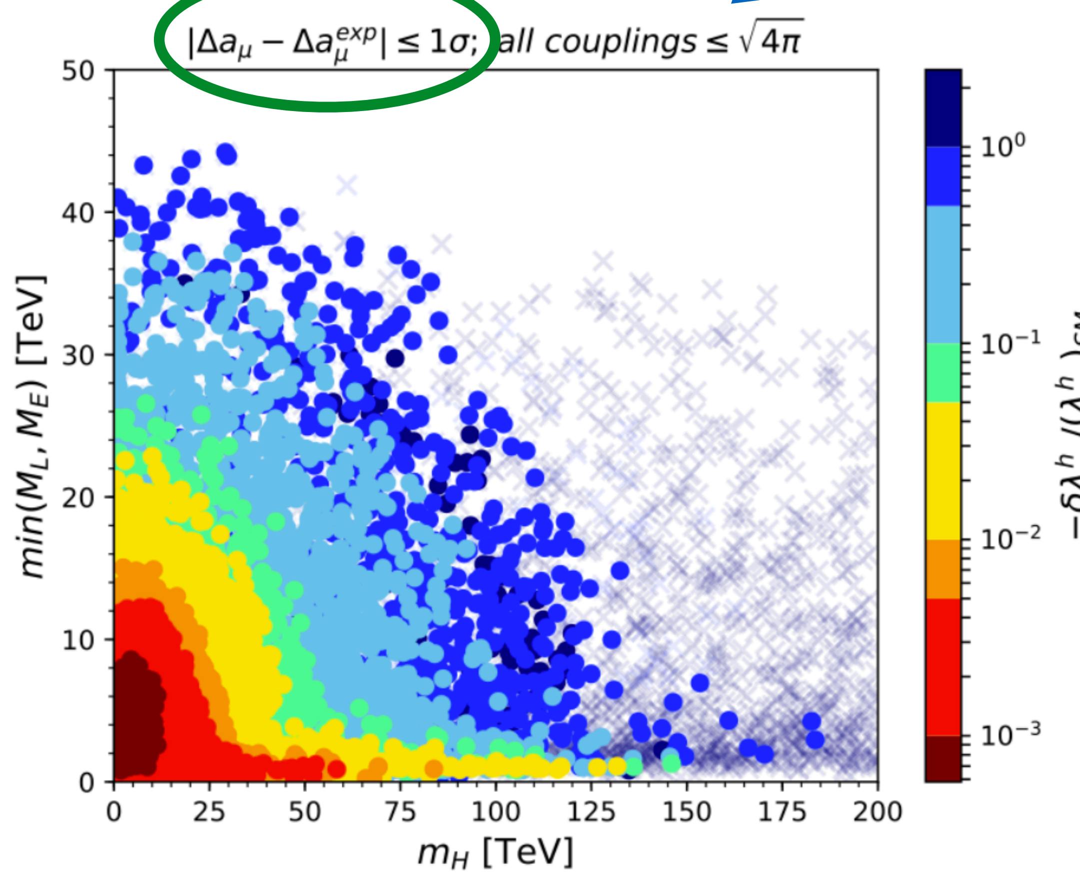
all experimental constraints from direct searches and precision EW data satisfied

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



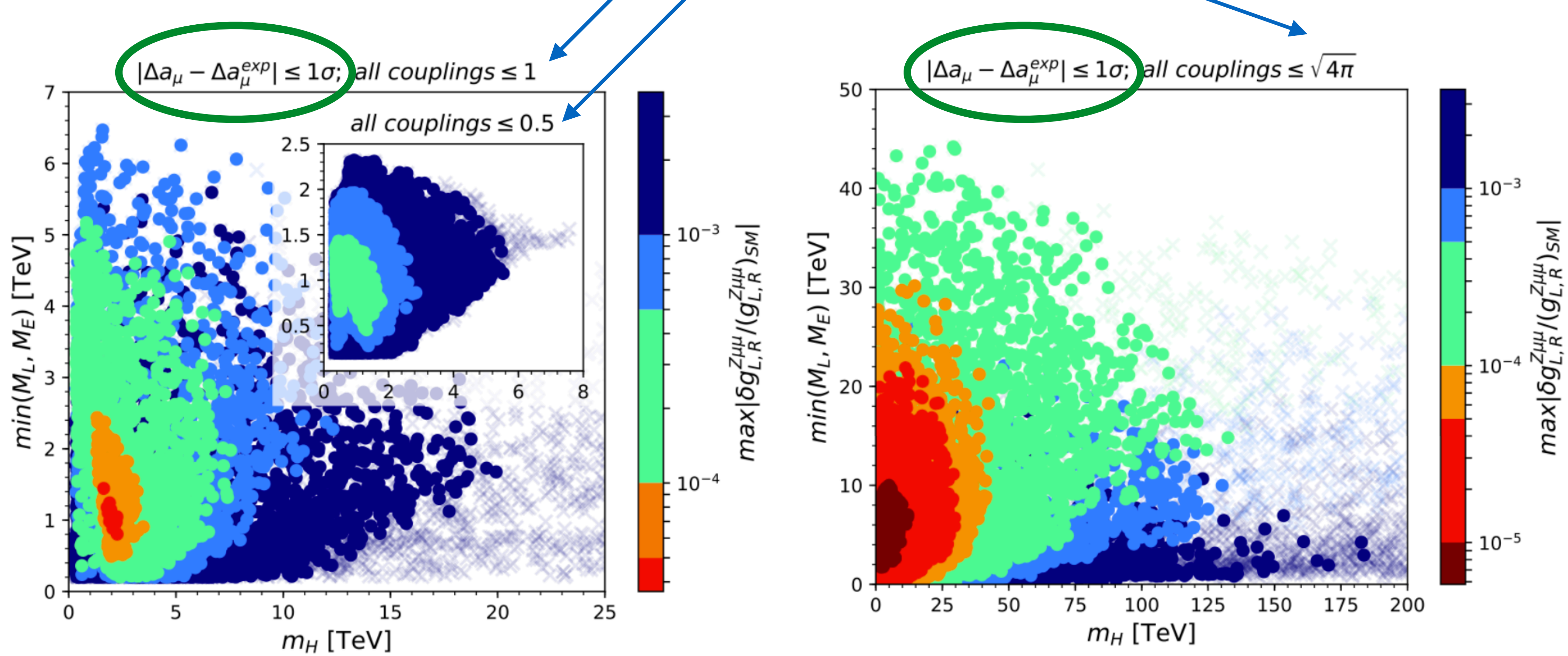


NOTE, both $-\delta\lambda^h_{\mu\mu}/(\lambda^h_{\mu\mu})_{SM} = 0$ and 2 correspond to SM expectation for $h \to \mu^+\mu^-$

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

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

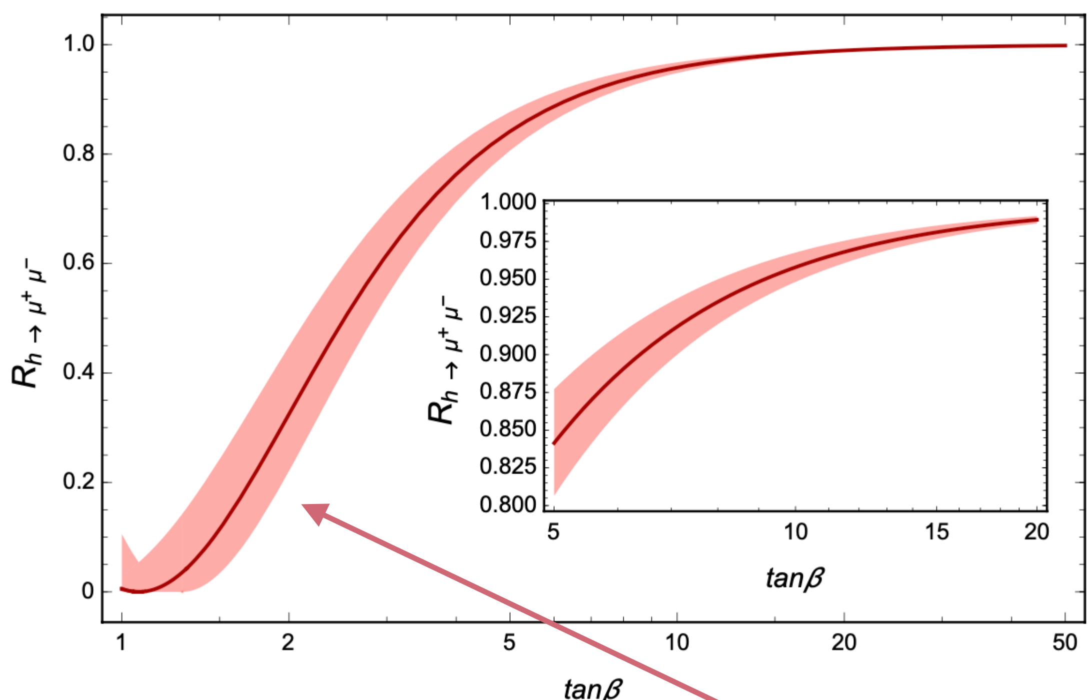
depending on the size of couplings

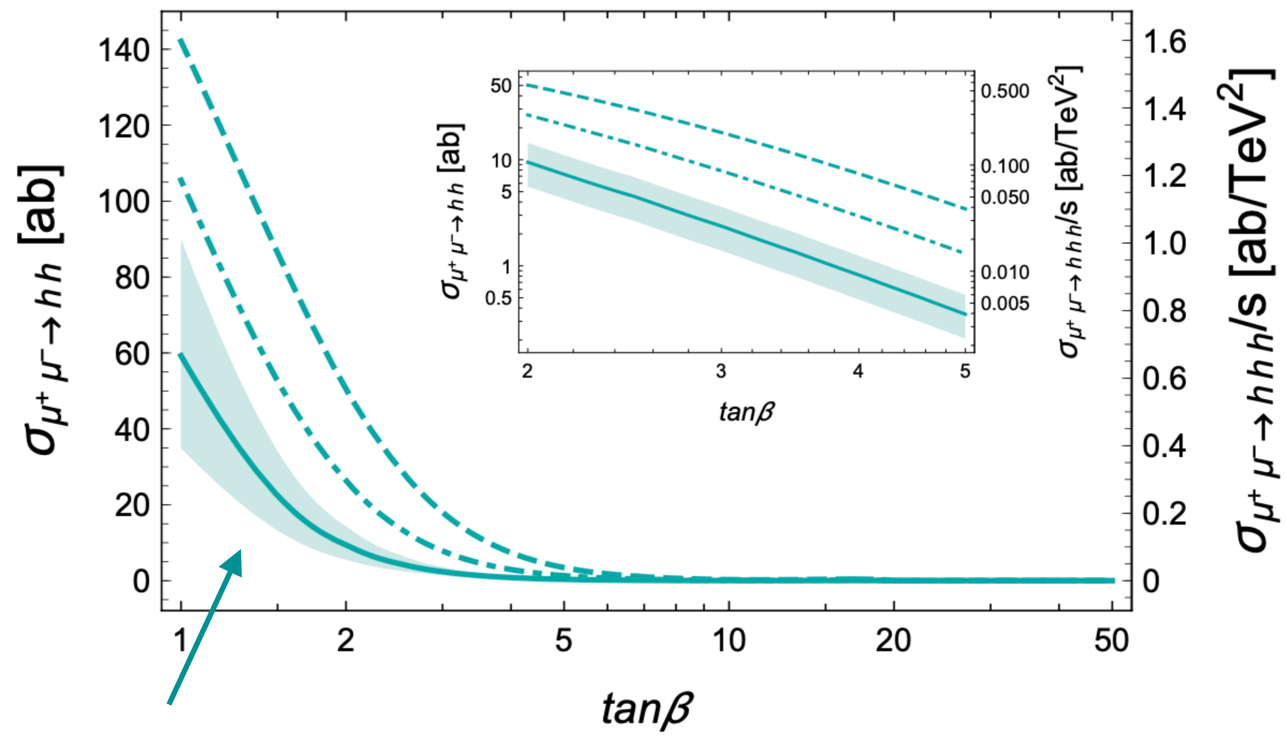


muon Z couplings modified at $> 3 \times 10^{-5}$ or 5×10^{-6} levels

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 $\sqrt{s}$