Chirally enhanced muon g-2 and related observables

with N. McGinnis, K. Hermanek and S. Yoon

arXiv:2011.11812 [hep-ph]

arXiv:2103.05645 [hep-ph]

arXiv:2108.10950 [hep-ph]

arXiv:2205.14243 [hep-ph]

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Planck 2022, Paris, June 1, 2022

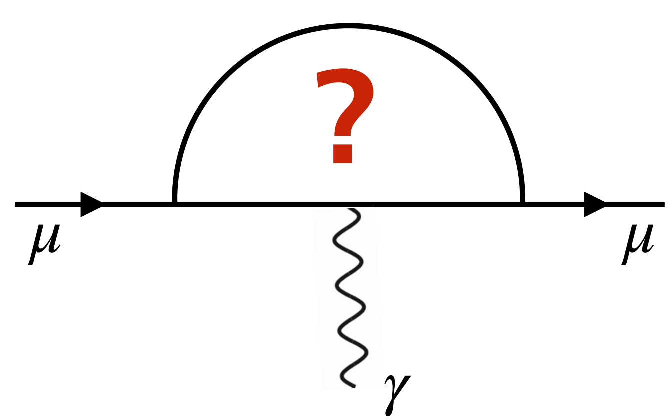
Muon g-2

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

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

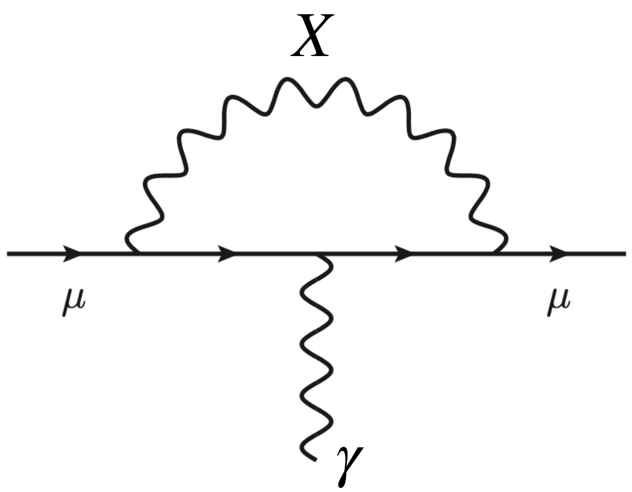
Muon g-2, BNL, arXiv:hep-ex/0602035

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



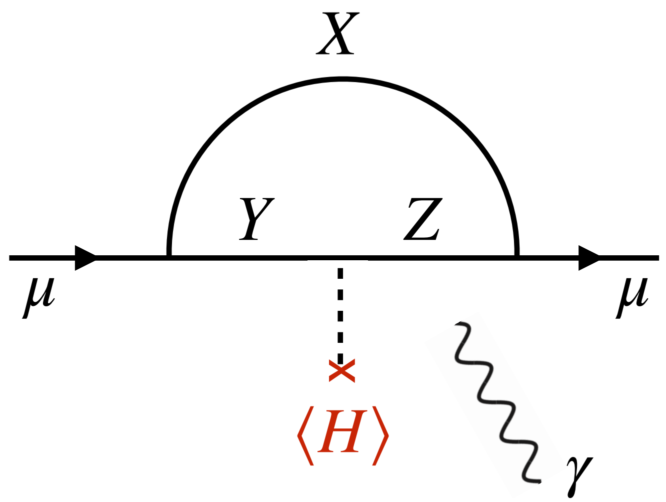
New physics contributions to muon g-2

Typical NP contribution



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

Mass enhanced NP contribution



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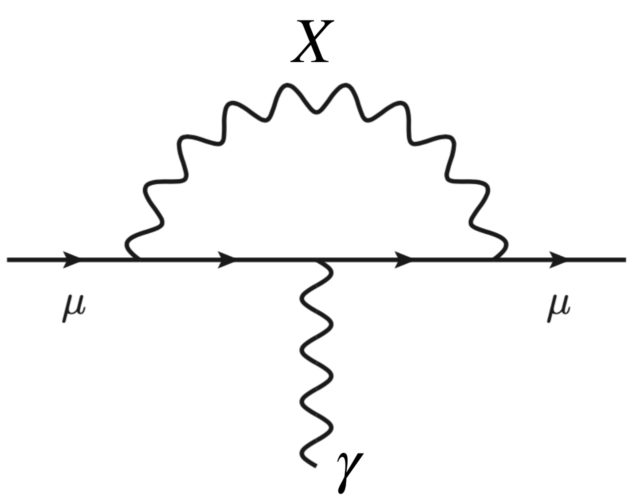

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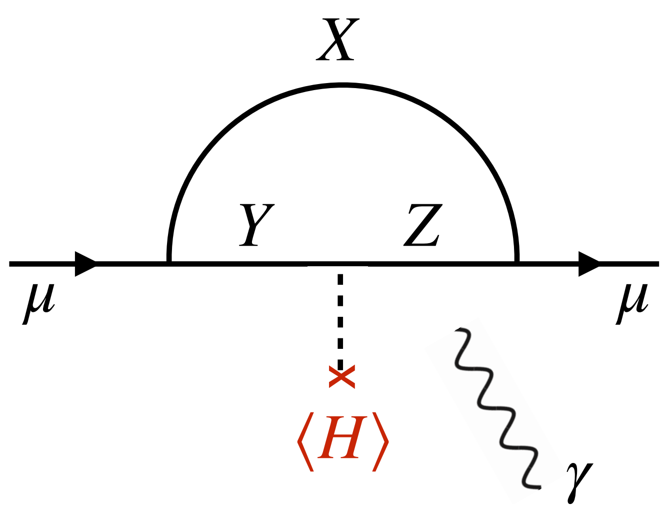
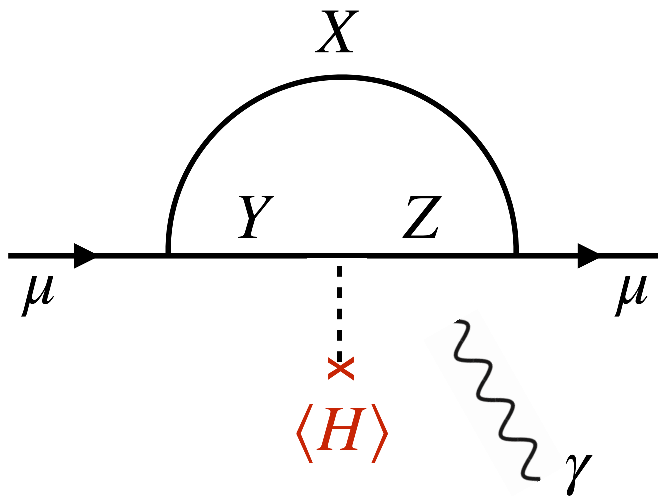


$$\Delta a_\mu \simeq \frac{\lambda_{NP}^3}{16\pi^2}\frac{m_\mu v}{m_{NP}^2}$$

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

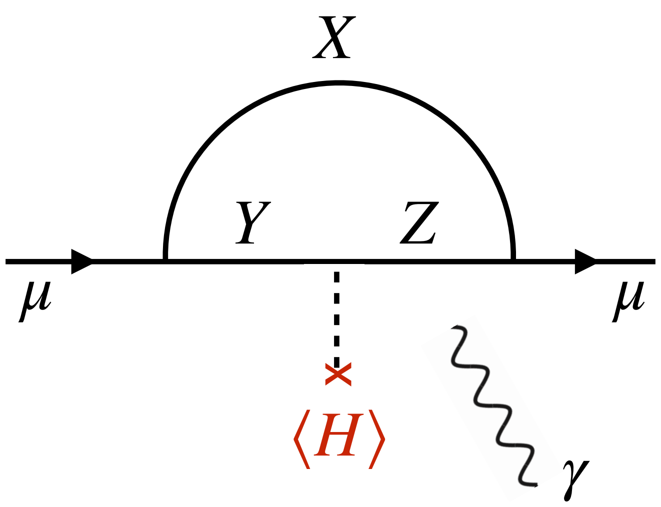
can explain Δa_μ with NP at $\lesssim 10$ TeV (50 TeV) **with** $\lambda_{NP} \simeq 1$ ($\sqrt{4\pi}$)

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



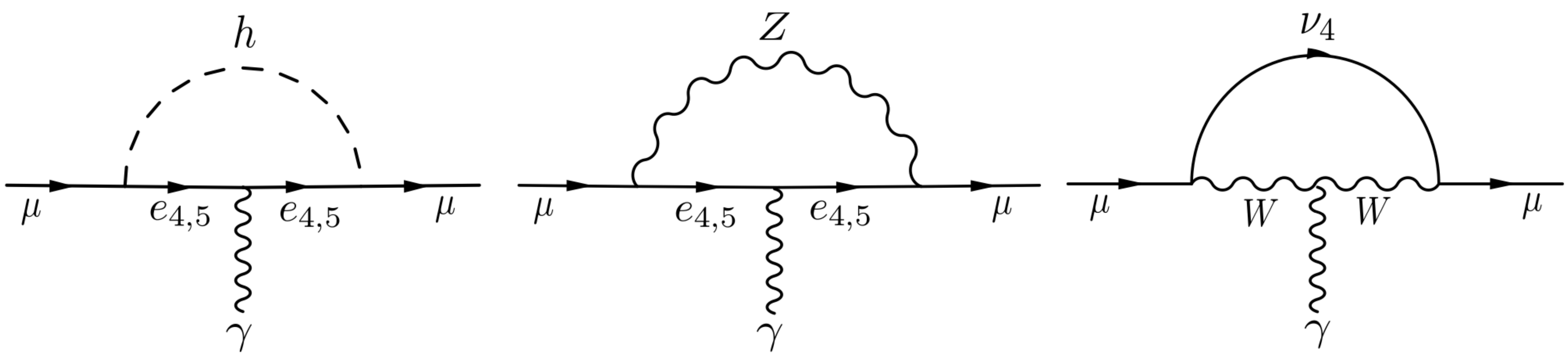
X, Y, Z can have any quantum numbers (allowing for the loop):

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

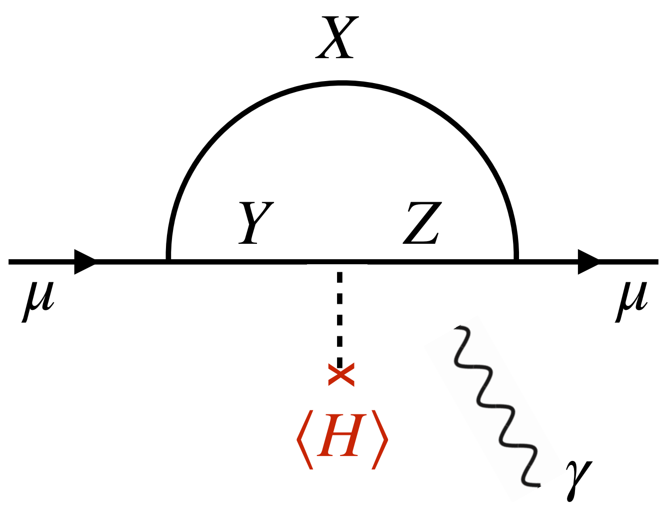
minimal, just SM with new leptons, constrained the most

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



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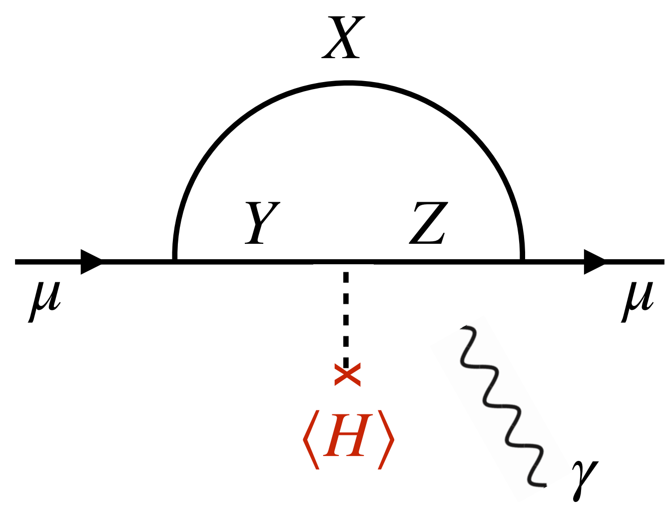
- $X, Y, Z =$ 2 fermions and 1 scalar or 2 scalars and 1 fermion

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

(include models with superpartners)

Mass enhanced NP contributions to Δa_μ



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  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]

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

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

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

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

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

  (include models with 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	$L_{L,R}$	$N_{L,R}$	$E_{L,R}$
$SU(2)_L$	**2**	**1**	**2**	**2**	**2**	**1**	**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

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$$- \kappa_N \bar{l}_L N_R H_u - \kappa \bar{L}_L N_R H_u - \bar{\kappa} H_u^\dagger \bar{N}_L L_R$$
$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R - M_N \bar{N}_L N_R + h.c.,$$

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 and Yukawa coupling:

$$m_\mu = y_\mu v_d + m_\mu^{LE}$$
$$\lambda_{\mu\mu}^h = (m_\mu + 2 m_\mu^{LE})/v$$

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

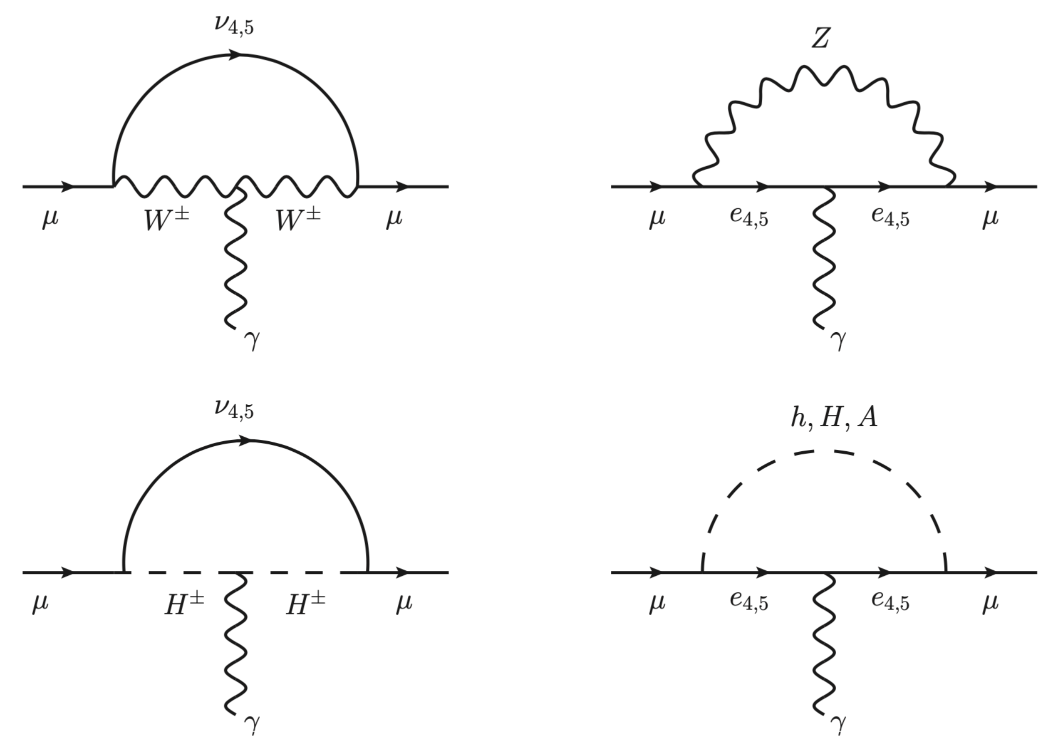
and is directly linked to contributions to Δa_μ

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]

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

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



$$k^W = 1$$
$$k^Z = -1/2$$
$$k^h = -3/2$$

$$k^W + k^Z + k^h = -1$$

$$k^H = -(11/12)\tan^2\beta$$
$$k^A = -(5/12)\tan^2\beta$$
$$k^{H^\pm} = (1/3)\tan^2\beta$$

$$k^H + k^A + k^{H^\pm} = -\tan^2\beta$$

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

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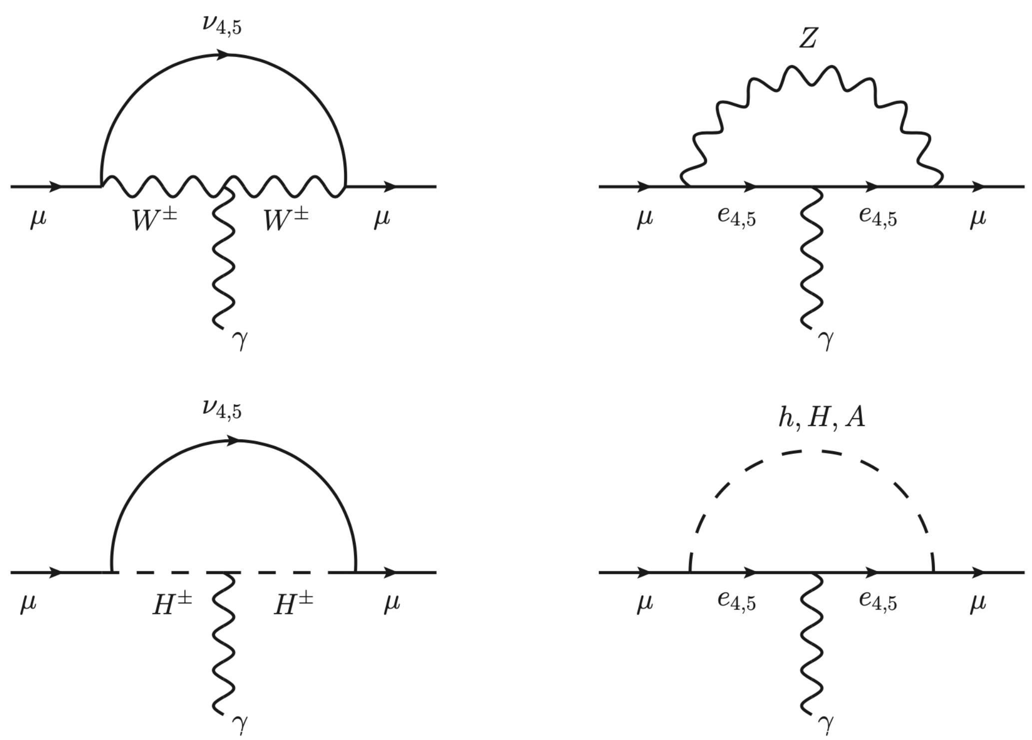

$k^W = 1$
$k^Z = -1/2$
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$$k^W + k^Z + k^h = -1$$

sufficient to explain Δa_μ with couplings ~0.5

$k^H = -(11/12)\tan^2\beta$
$k^A = -(5/12)\tan^2\beta$
$k^{H^\pm} = (1/3)\tan^2\beta$

$$k^H + k^A + k^{H^\pm} = -\tan^2\beta$$

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

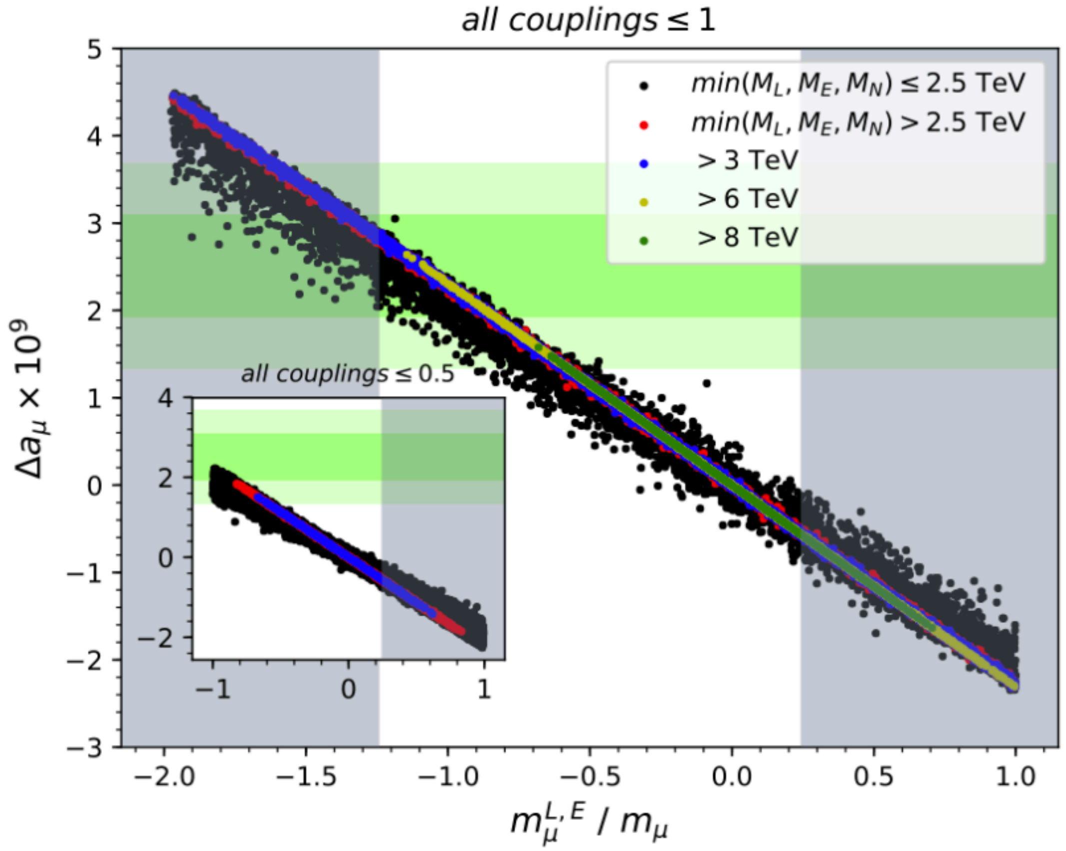
in the next few slides, I will focus on the SM+L+E

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

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



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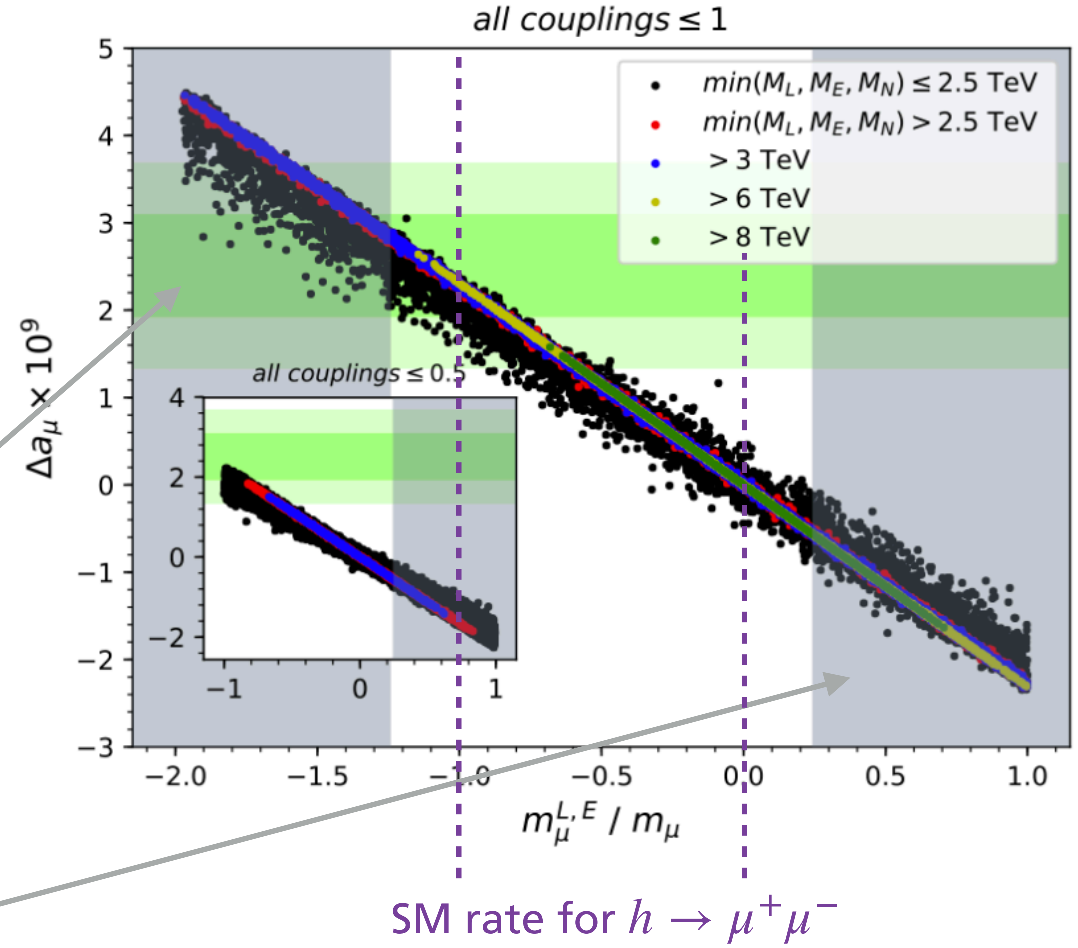


excluded by

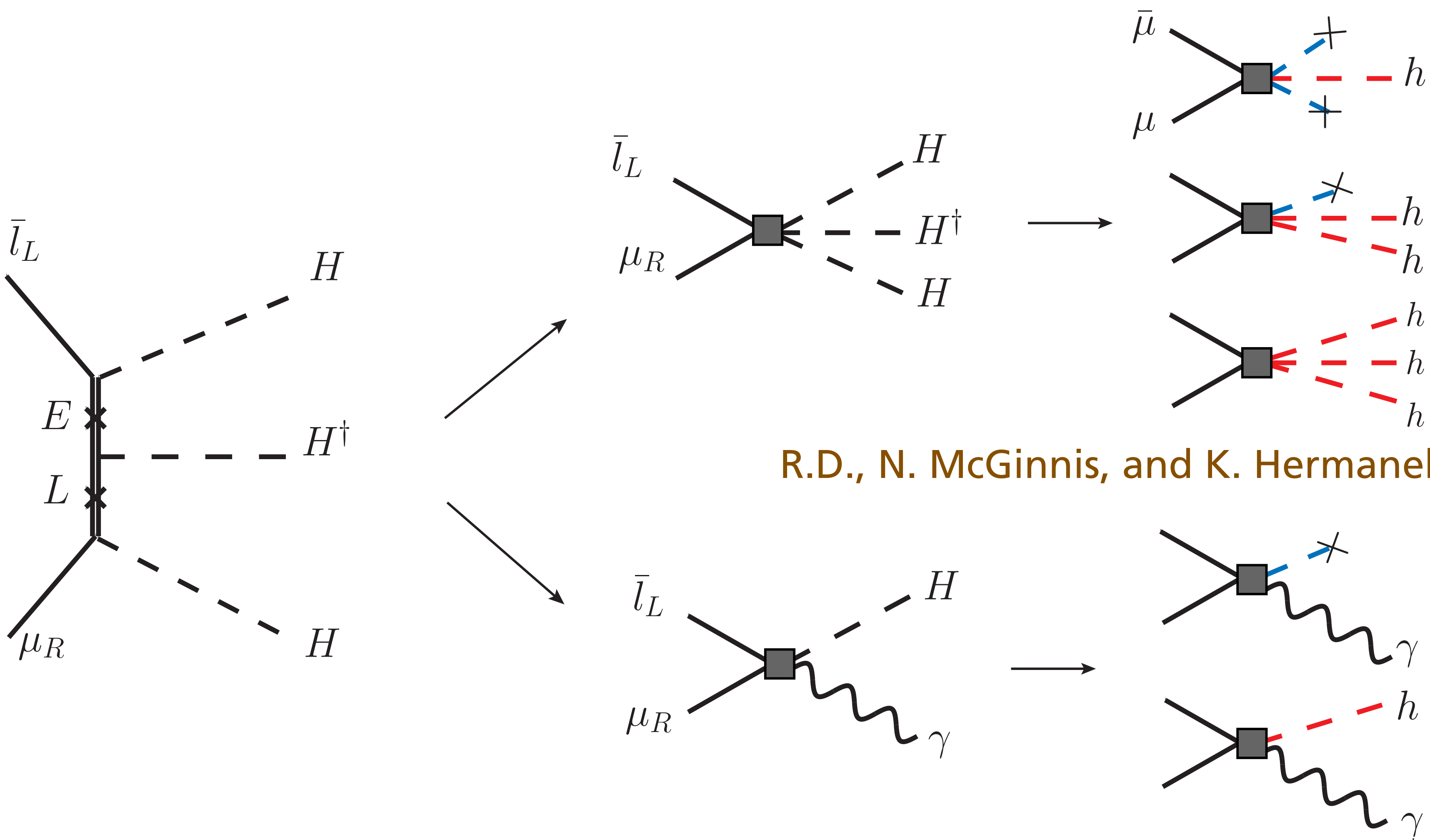
$$R_{h\to\mu^+\mu^-} \equiv \frac{BR(h \to \mu^+\mu^-)}{BR(h \to \mu^+\mu^-)_{SM}} = \left(1 + 2\frac{m_\mu^{LE}}{m_\mu}\right)^2$$

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

Related observables

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



$h \to \mu\mu$

$\mu\mu \to hh$

$\mu\mu \to hhh$

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

$\mu\mu \to h\gamma$

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]

Di-Higgs and tri-Higgs signals in SM+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:

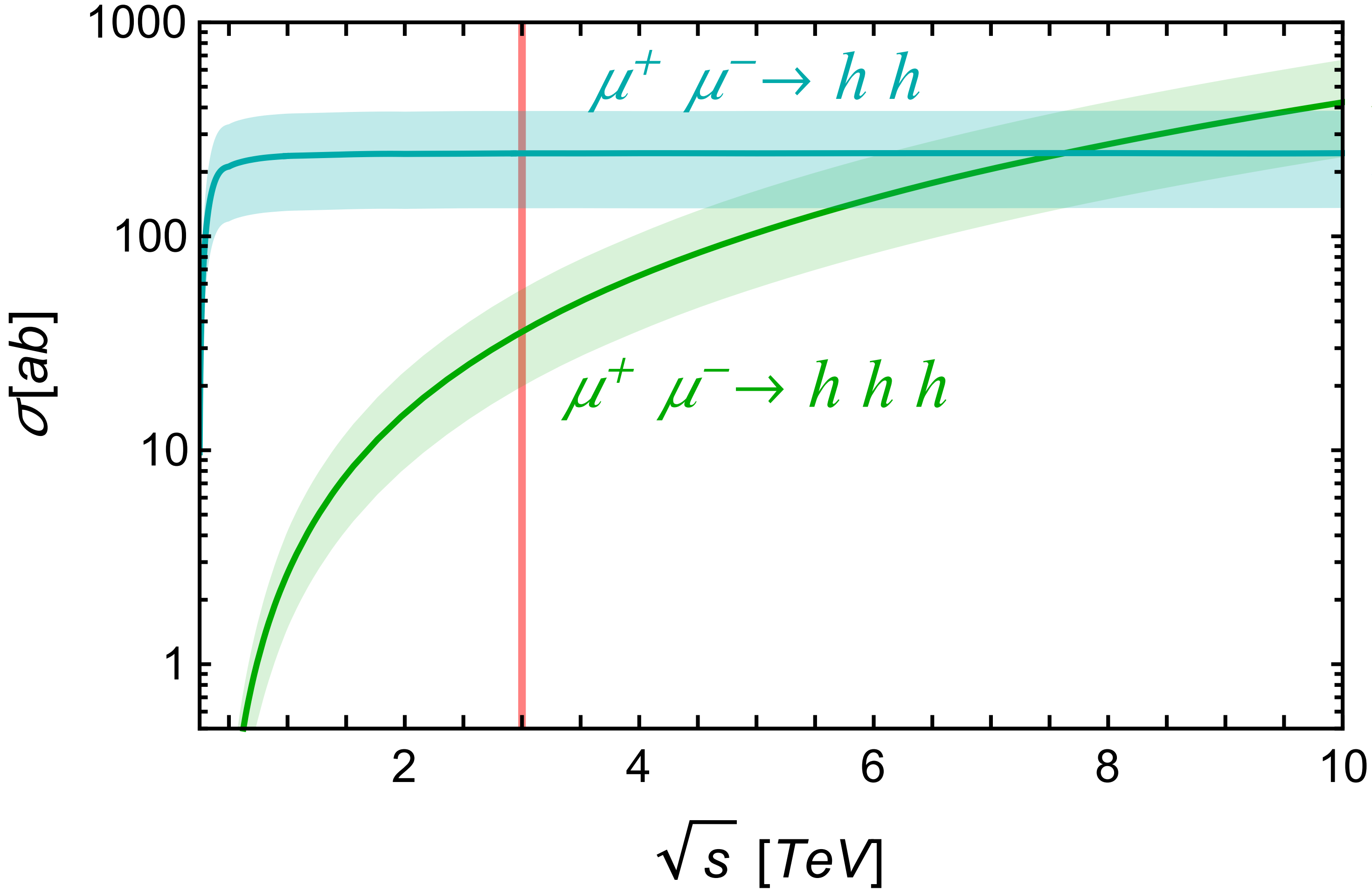
$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} \lambda^h_{\mu\mu} \bar{\mu}\mu h - \frac{1}{2} \lambda^{hh}_{\mu\mu} \bar{\mu}\mu h^2 - \frac{1}{3!} \lambda^{hhh}_{\mu\mu} \bar{\mu}\mu h^3$$

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

are predicted without a free parameter!

Di-Higgs and tri-Higgs signals in SM+L+E

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



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

Connection with μEDM

Dipole moments and the mass operator

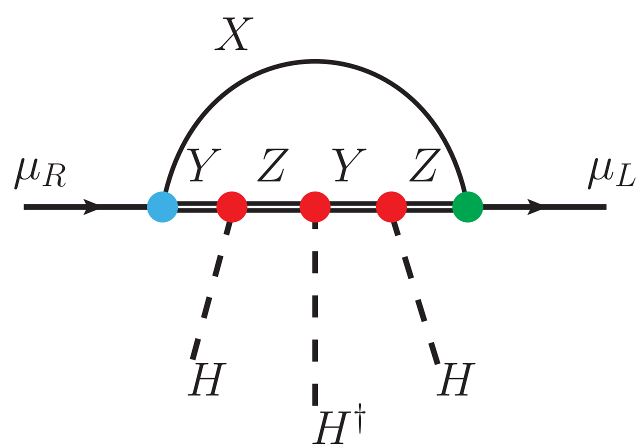
Couplings required for chiral enhancement in Δa_μ also generate dim. 6 mass operator:

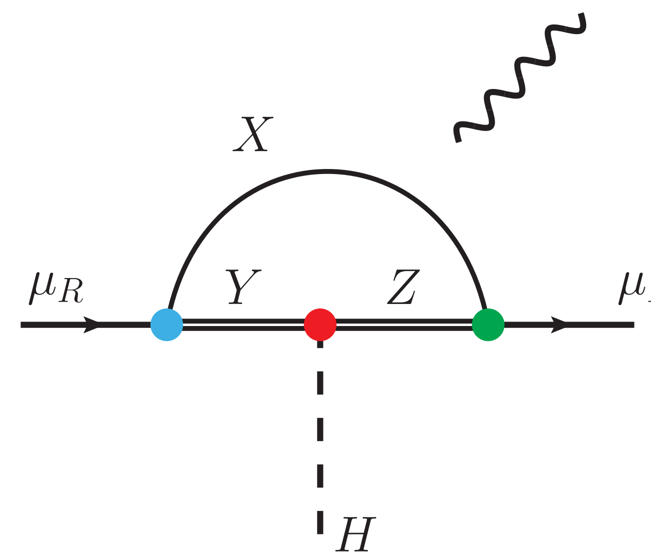
$$\mathcal{L} \supset \; - \; y_\mu \bar{l}_L \mu_R H \; - \; C_{\mu H} \bar{l}_L \mu_R H \left(H^\dagger H \right) \; - \; C_{\mu\gamma} \bar{l}_L \sigma^{\mu\nu} \mu_R H F_{\mu\nu} + h.c.$$

loop models:

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

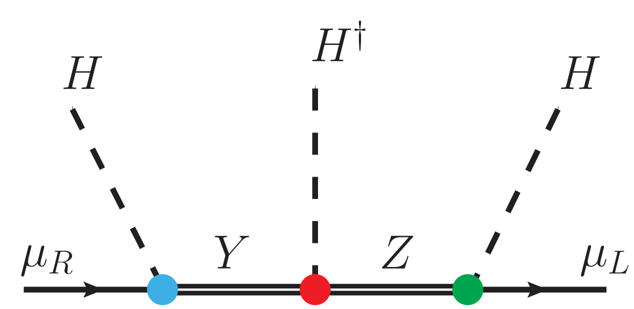
A.~Crivellin and M.~Hoferichter, arXiv:2104.03202 [hep-ph]





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 and S. Yoon, arXiv:2205.14243 [hep-ph]

After electroweak symmetry breaking:

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

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

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

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

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

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

Because the operators are related, we have:

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

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

$$\omega = m_\mu^2/kv^2$$

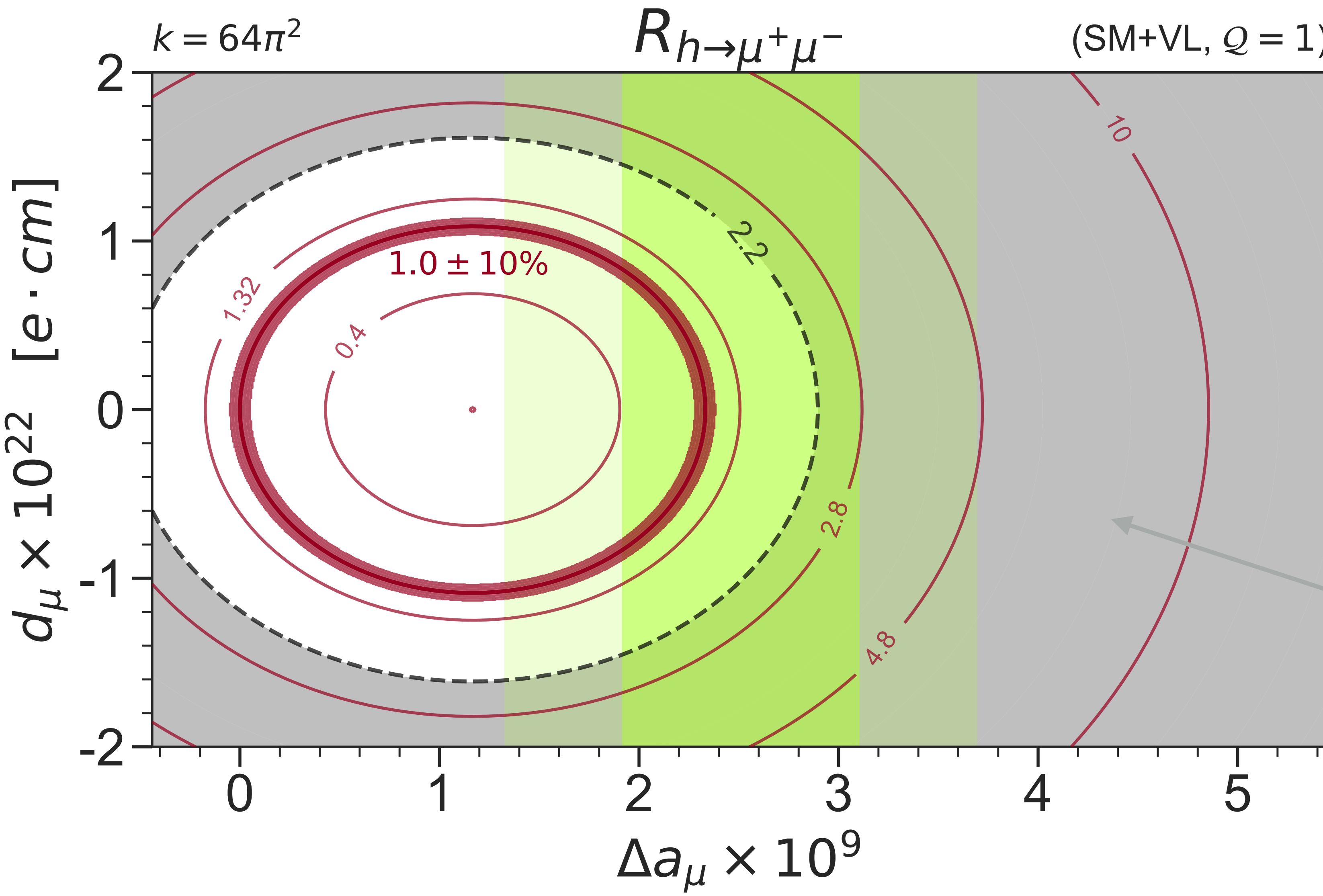
Δa_μ, d_μ and $h \to \mu\mu$ are highly correlated

Standard model with L + E

VLs with the same quantum numbers as SM leptons:

Relation completely fixed by quantum numbers

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



$$k = \frac{64\pi^2}{\mathcal{Q}}$$

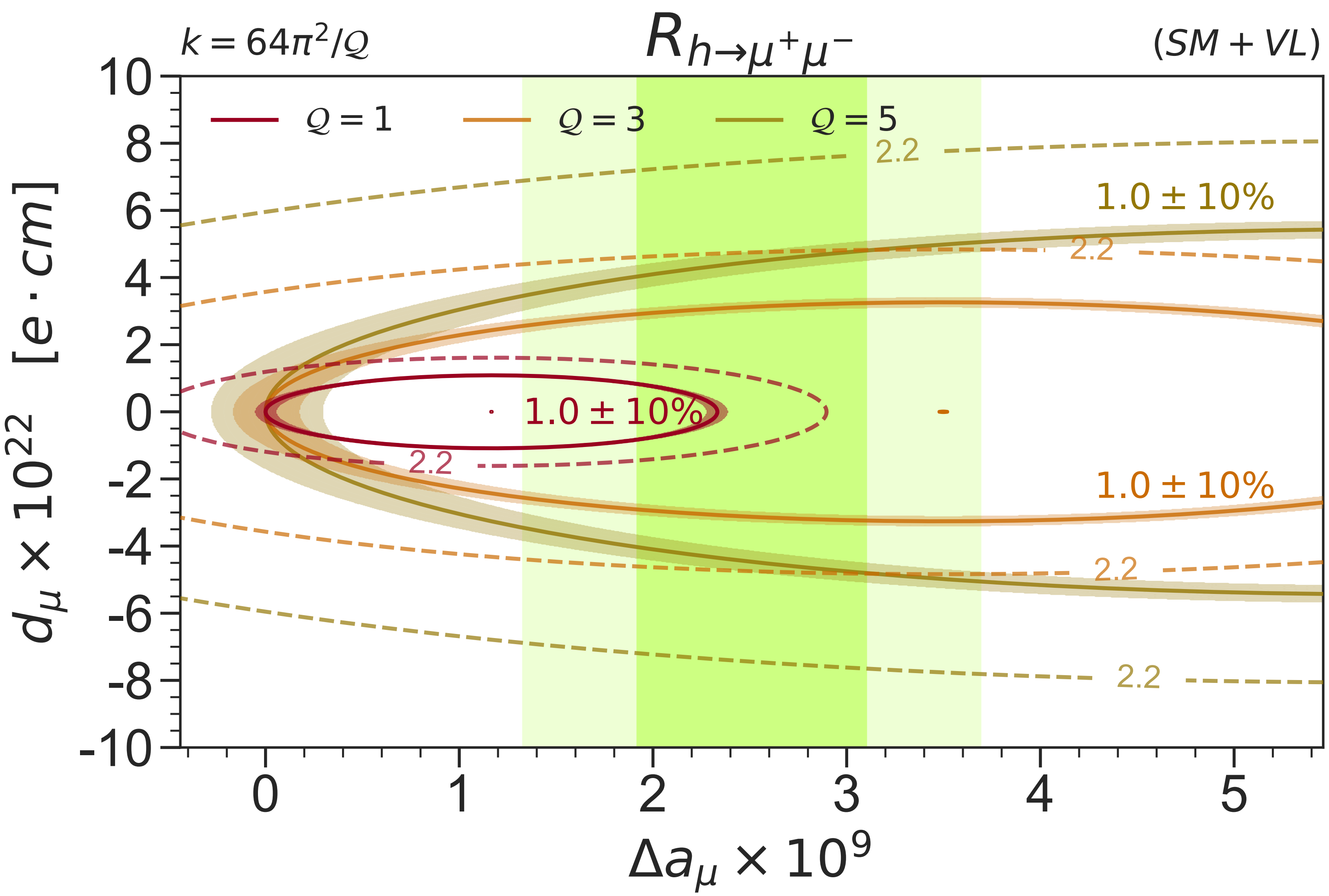
excluded by $h \to \mu\mu$

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

Standard model + VLs

Five possible quantum number assignments for VLs:

(with mass enhanced contributions)



$$k = \frac{64\pi^2}{\mathcal{Q}}$$

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

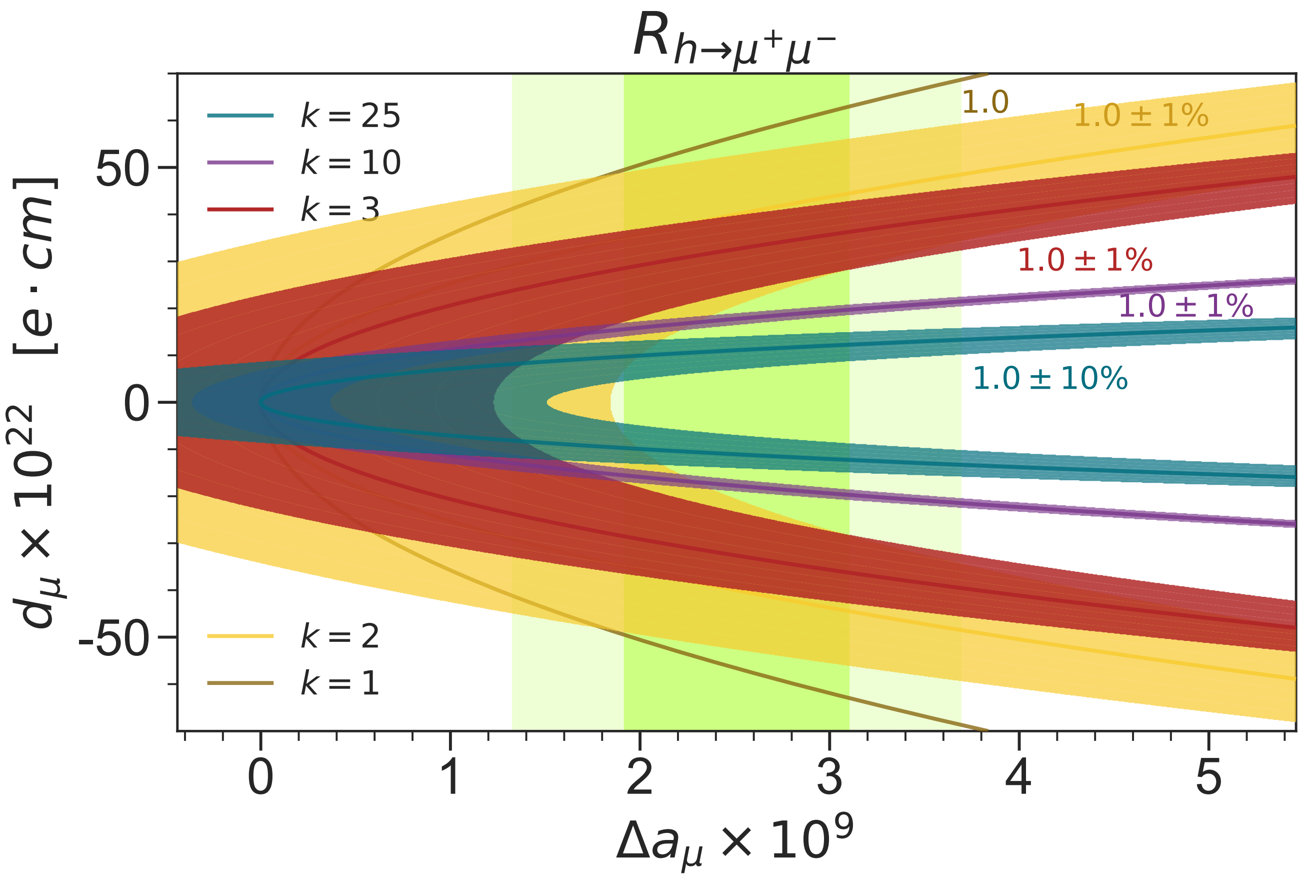
sharp predictions for d_μ once $h \to \mu\mu$ is precisely measured

Other models

- Models with more scalars participating in EWSB

e.g. 2HDM, type-II:

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



Other models

- Models with more scalars participating in EWSB

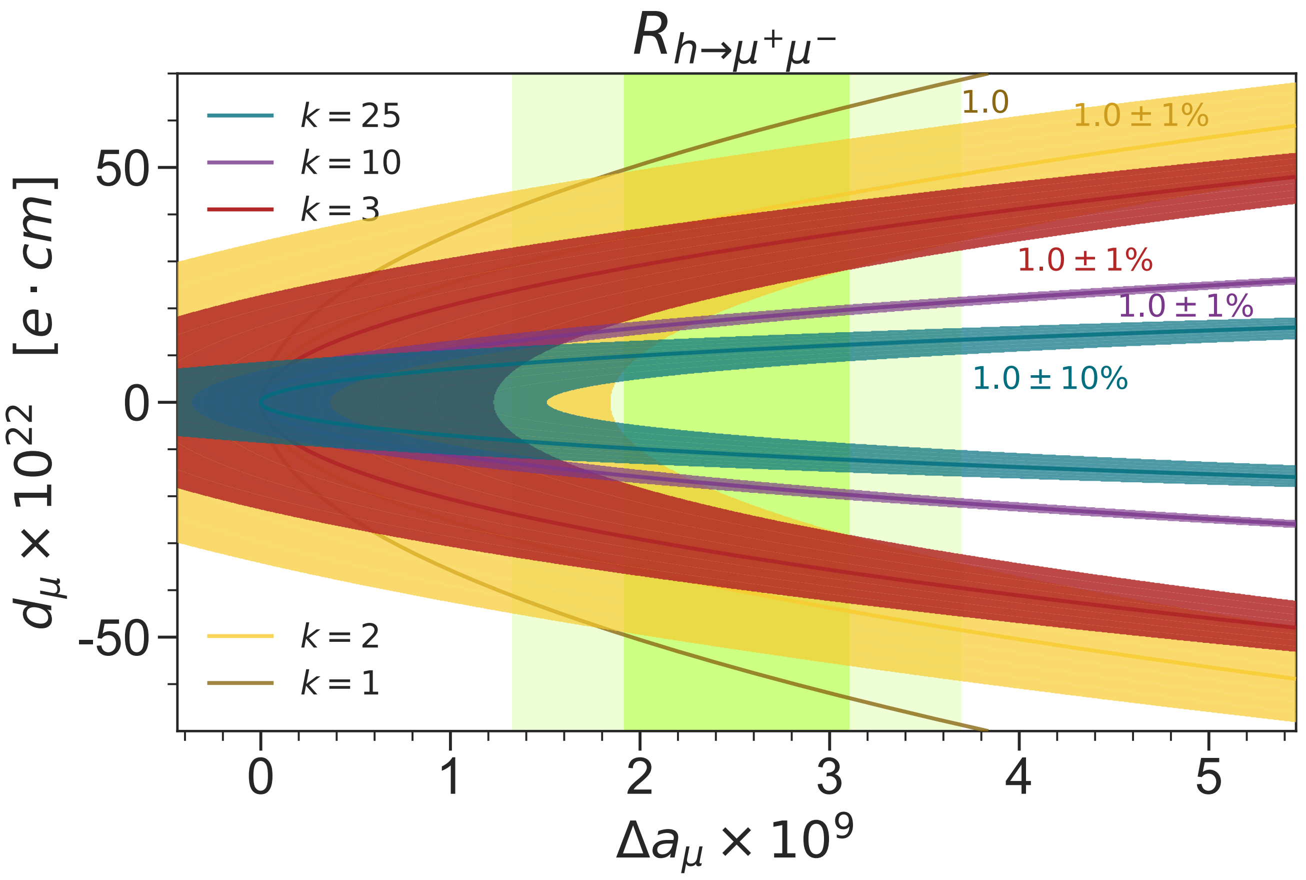
  e.g. 2HDM, type-II:

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

- Loop models:

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

group theoretical factor



e.g.

top quark+leptoquark: $k \simeq 3$

MSSM, bino+smuon (with large mixing): $k \simeq 10 - 50$

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:

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

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

indirect limits:

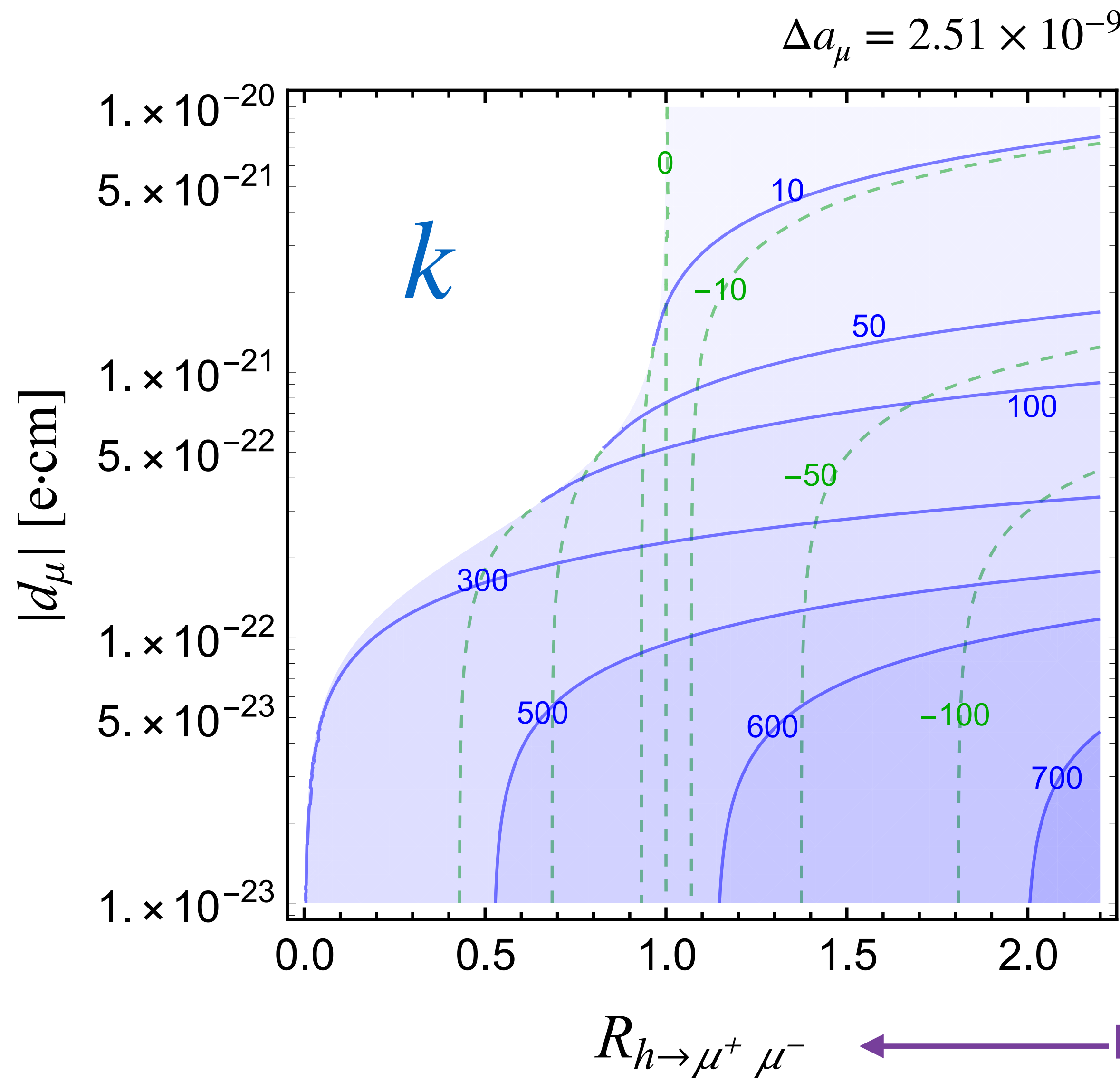
$|d_\mu| \leq 2 \times 10^{-20}\,\mathrm{e \cdot cm}$

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

future sensitivity:

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

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

- $\mu\mu \to hh$ 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