Higgs boson signals of muon g-2 at the LHC and future colliders

with N. McGinnis and K. Hermanek

arXiv:2011.11812 [hep-ph]

arXiv:2103.05645 [hep-ph]

arXiv:2108.10950 [hep-ph]

Radovan Dermisek

Indiana University, Bloomington

Higgs 2021 Conference, SBU & BNL, NY, October 19, 2021

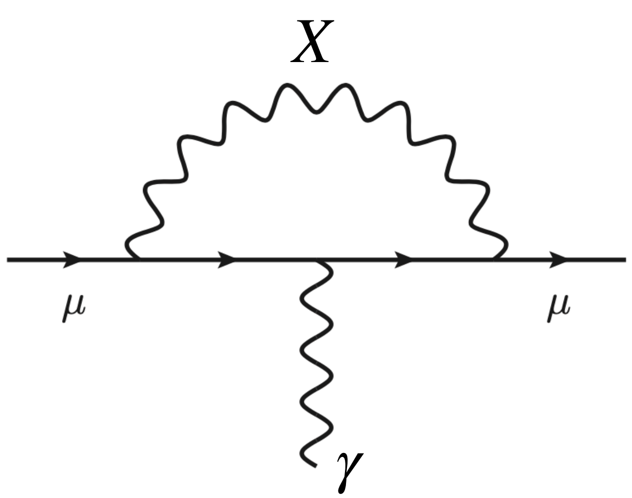
Muon g-2

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

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

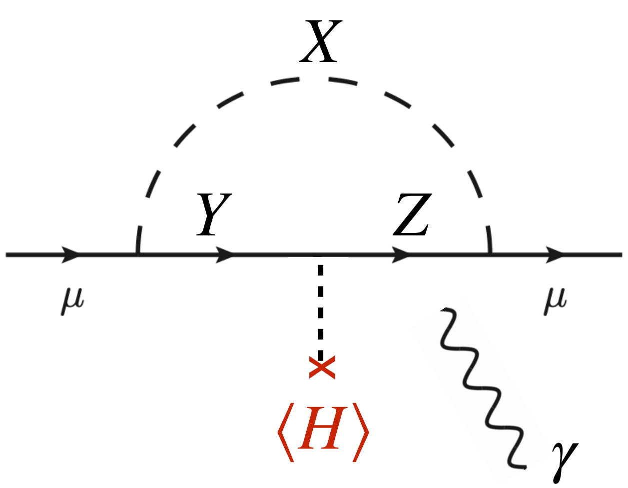
New physics contributions to muon g-2

Typical NP contribution



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

Mass enhanced NP contribution

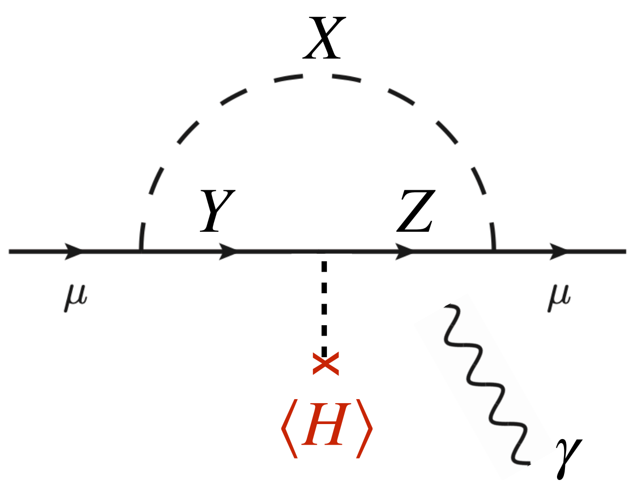


$$\Delta a_\mu \simeq \frac{\lambda_{NP}^3}{16\pi^2}\frac{m_\mu v}{m_{NP}^2}$$

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

possible to explain Δa_μ with NP at 10s TeV

Mass enhanced NP contributions to Δa_μ



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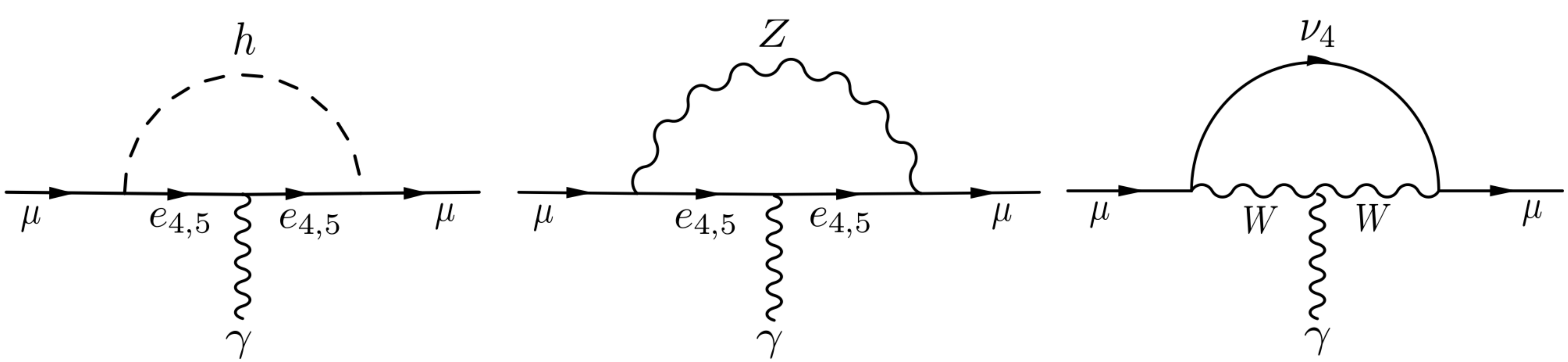
- $X = h, Z, W$ **and** $Y, Z =$ vectorlike leptons

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]



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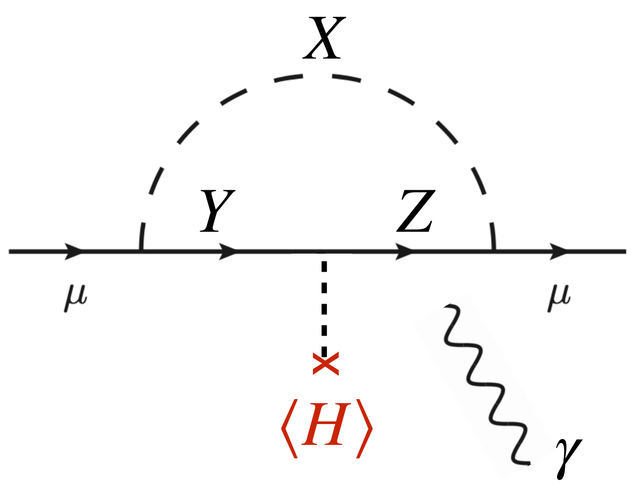

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  the most popular, many options, the least constrained

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

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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$$- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R - M_N \bar{N}_L N_R + h.c.,$$

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:

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

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

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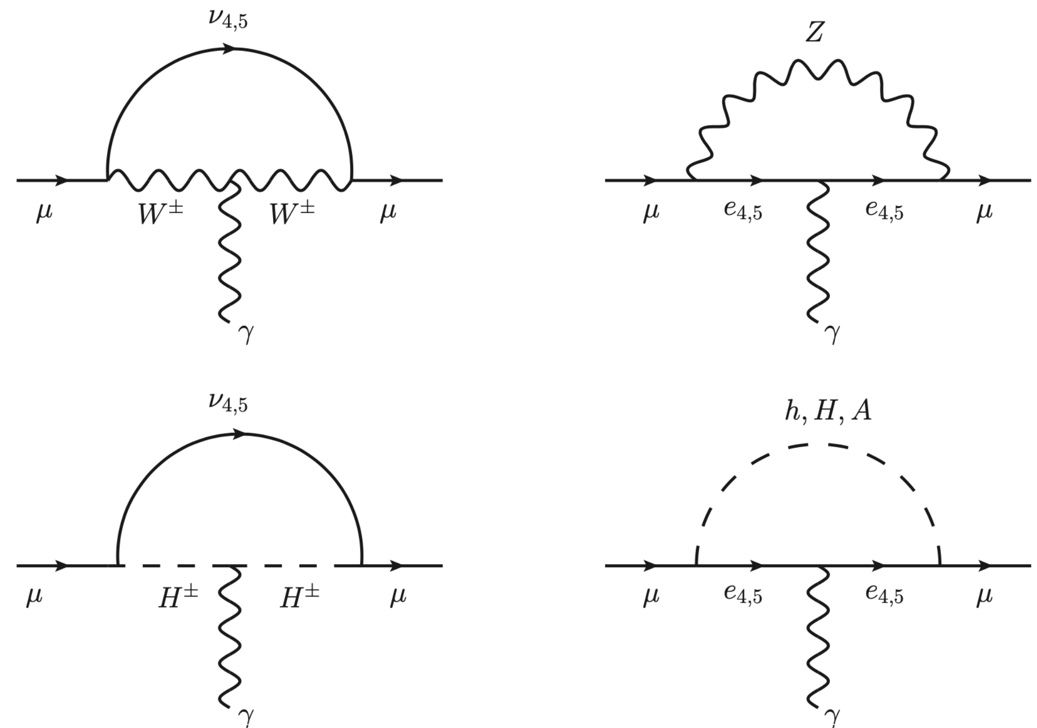
$$m_\mu^{LE} \equiv \frac{\lambda_L \bar{\lambda} \lambda_E}{M_L M_E} v_d^3$$

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



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

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

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 $\tan^2\beta$

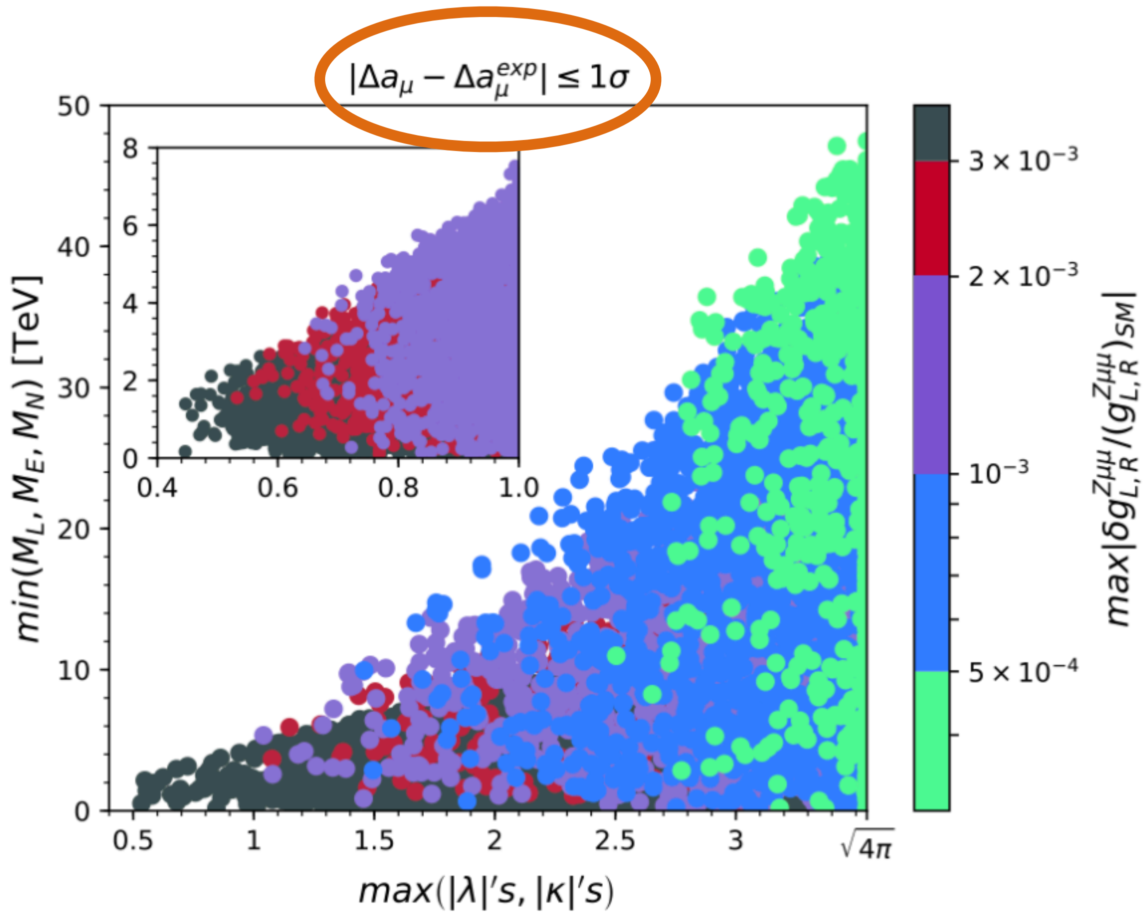
would be able to explain even 100 x Δa_μ

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

in the rest of the talk I will focus on the SM

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 $> 3 \times 10^{-4}$ 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

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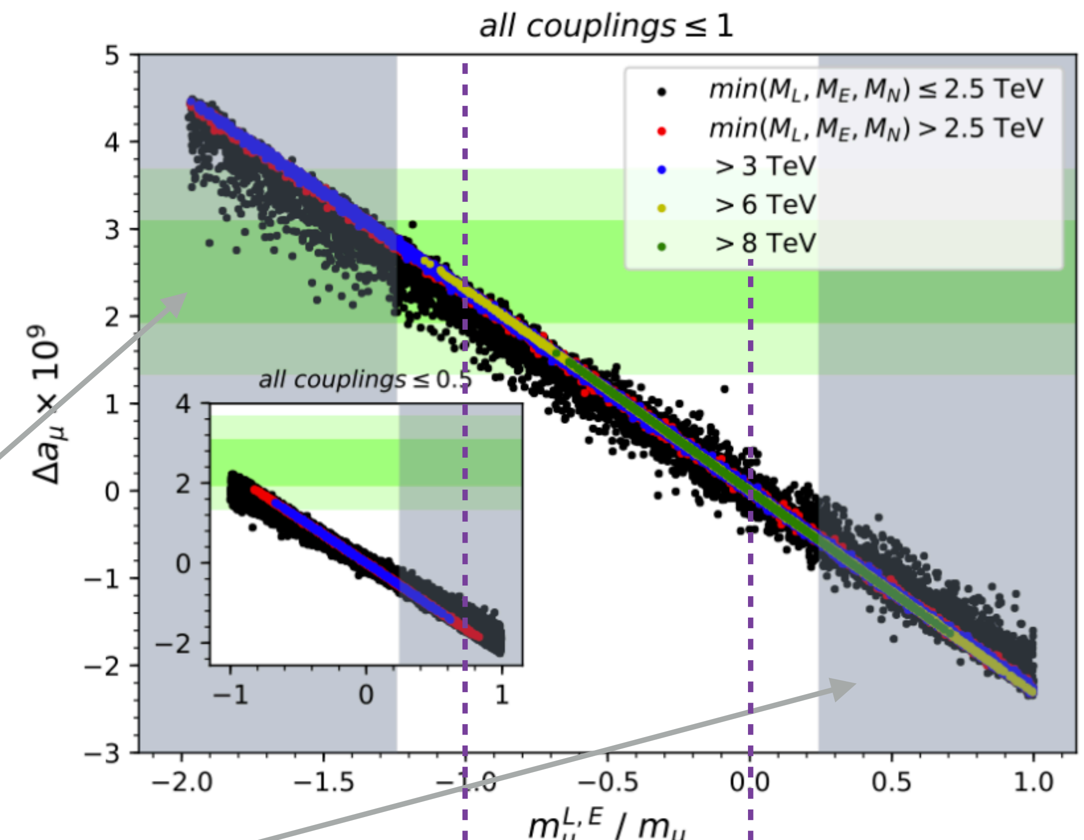
Δa_μ and muon mass (and thus $h \to \mu^+\mu^-$)
highly correlated,
no free parameter for $M_{L,E} \gg M_{EW}$



SM rate for $h \to \mu^+\mu^-$

excluded by

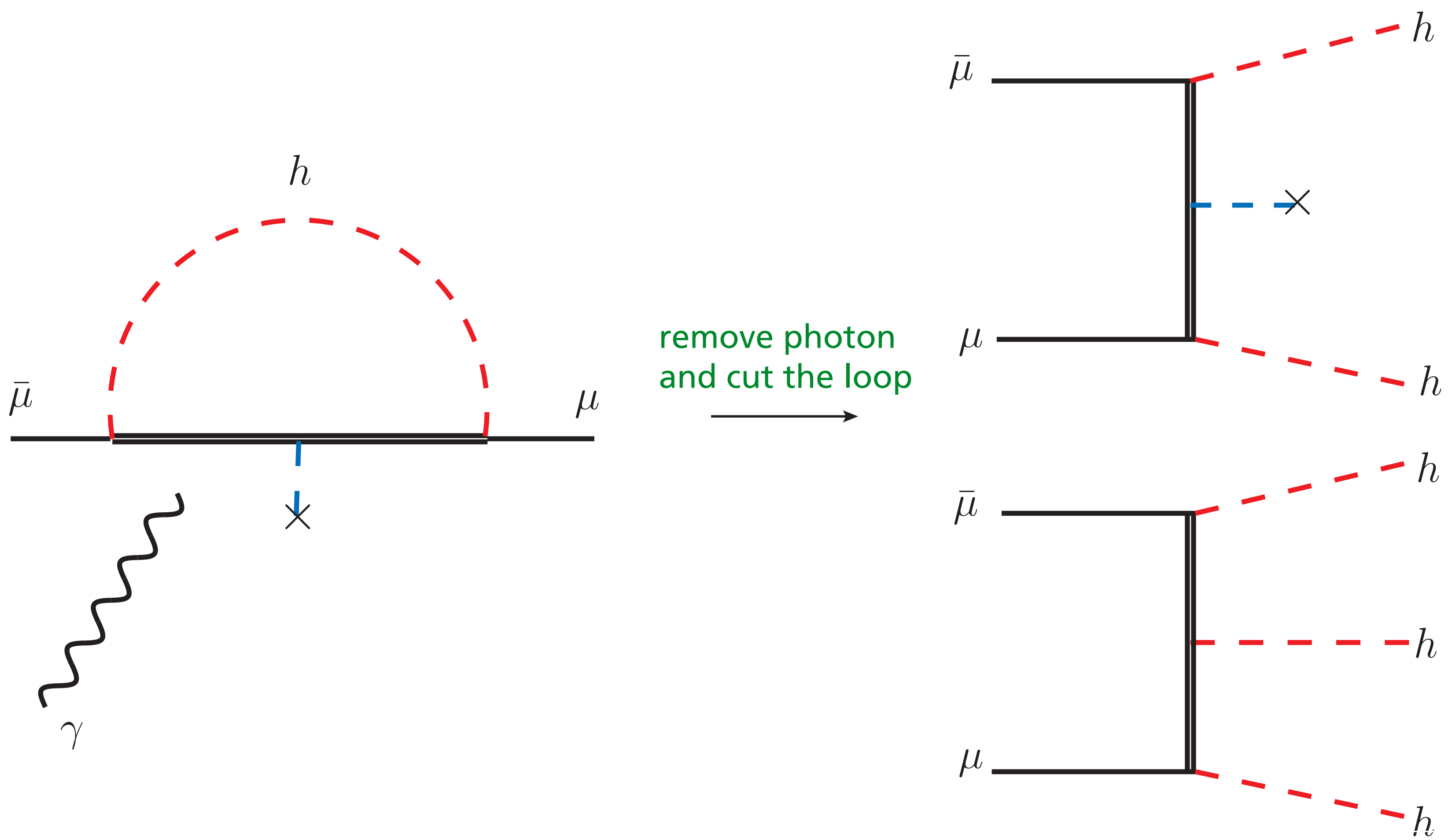
$$R_{h\to\mu^+\mu^-} \equiv \frac{BR(h\to\mu^+\mu^-)}{BR(h\to\mu^+\mu^-)_{SM}} = \left(1 + 2\frac{m_\mu^{LE}}{m_\mu}\right)^2$$

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

Di-Higgs and tri-Higgs signals



are tightly related to muon g-2

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:

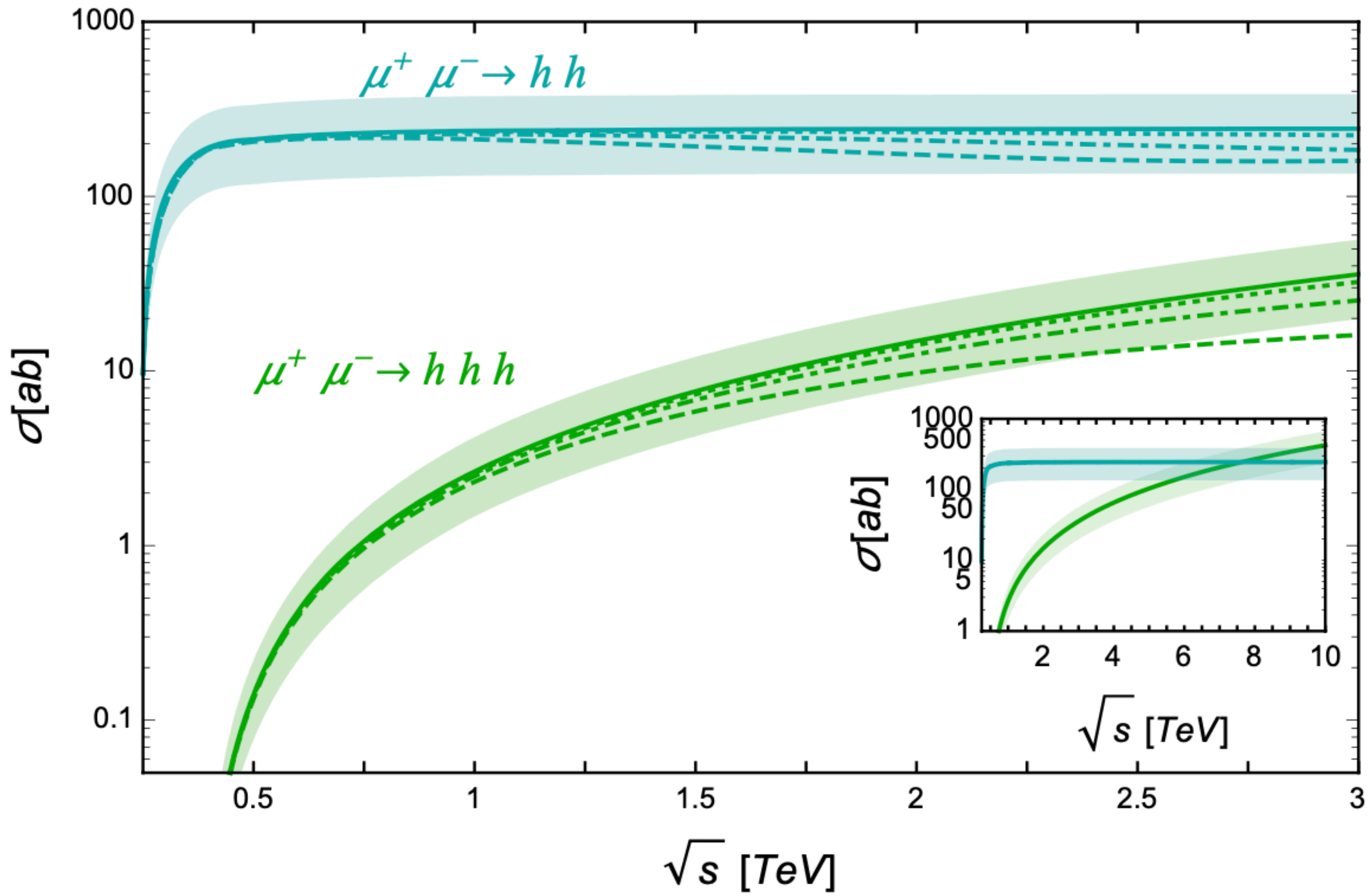
$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} \lambda_{\mu\mu}^{h} \bar{\mu}\mu h - \frac{1}{2} \lambda_{\mu\mu}^{hh} \bar{\mu}\mu h^2 - \frac{1}{3!} \lambda_{\mu\mu}^{hhh} \bar{\mu}\mu h^3$$

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

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]



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

Conclusions

Loops of SM gauge/Higgs bosons and new leptons are among the simplest new physics explanations of Δa_μ

- Δa_μ **can be explained with multi TeV (10s TeV) leptons**

  leptons might be beyond the reach of future colliders

- **modifications of muon Z couplings (not directly tight to Δa_μ)**

  can be tested at Giga-Z or FCC-ee

- **modifications of muon Yukawa coupling**

  could be seen at the LHC

  but exactly SM rate for $h \to \mu^+\mu^-$ well within 1σ of Δa_μ

- **di-Higgs and tri-Higgs signals at a muon collider fixed by Δa_μ**

  large rates even at low energy colliders

  depend only on quantum numbers of new leptons

  (we can learn quantum numbers of new leptons without observing them directly)

2HDM less constrained, a viable explanation till FCC-ee & -hh

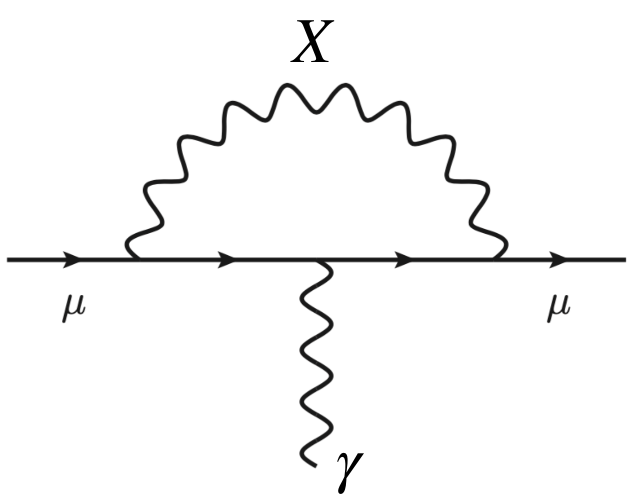
or a 100 TeV muon collider

many interesting possible signals at muon colliders

Brief summary

New physics contributions to muon g-2

Typical NP contribution



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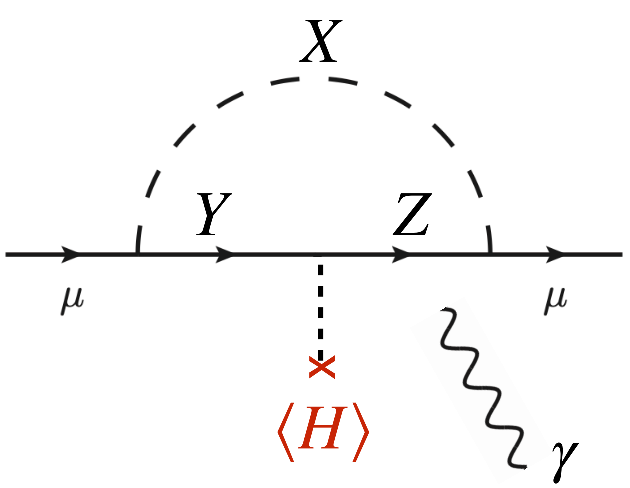

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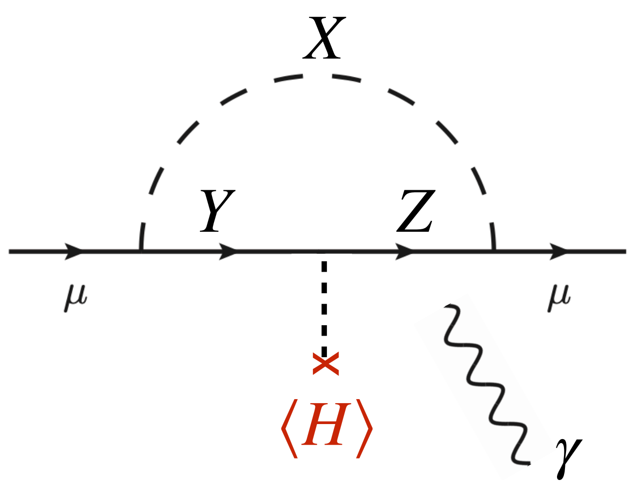

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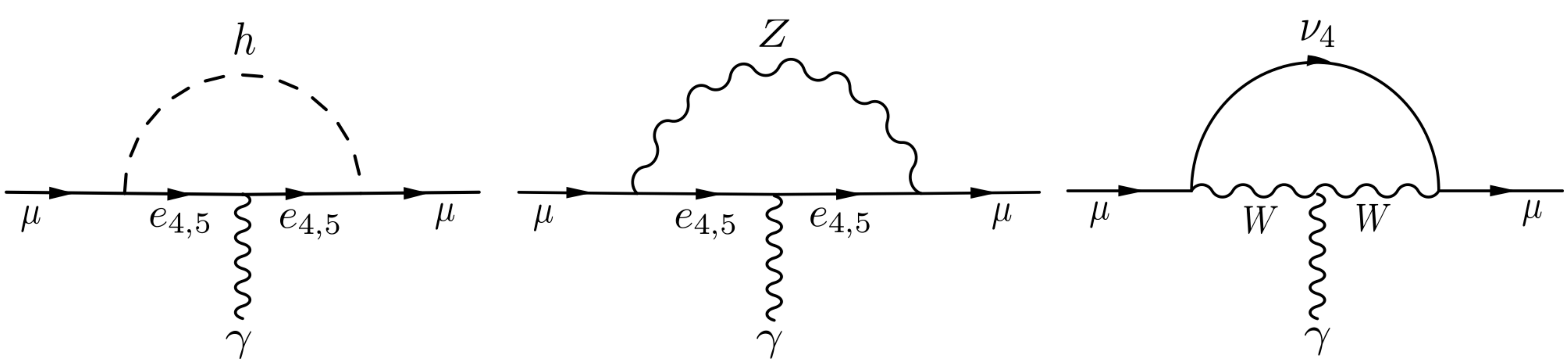

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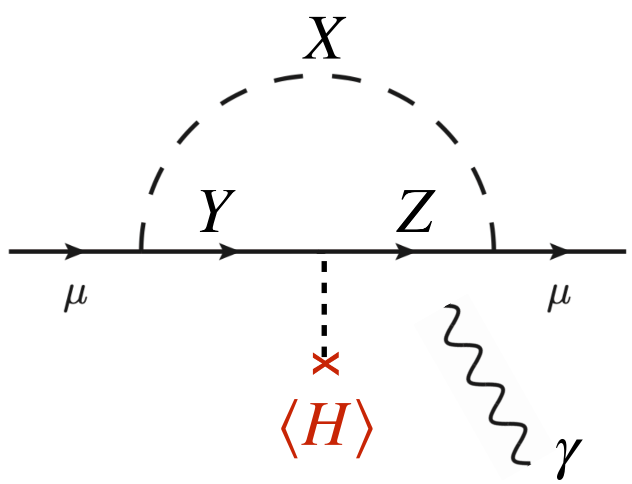

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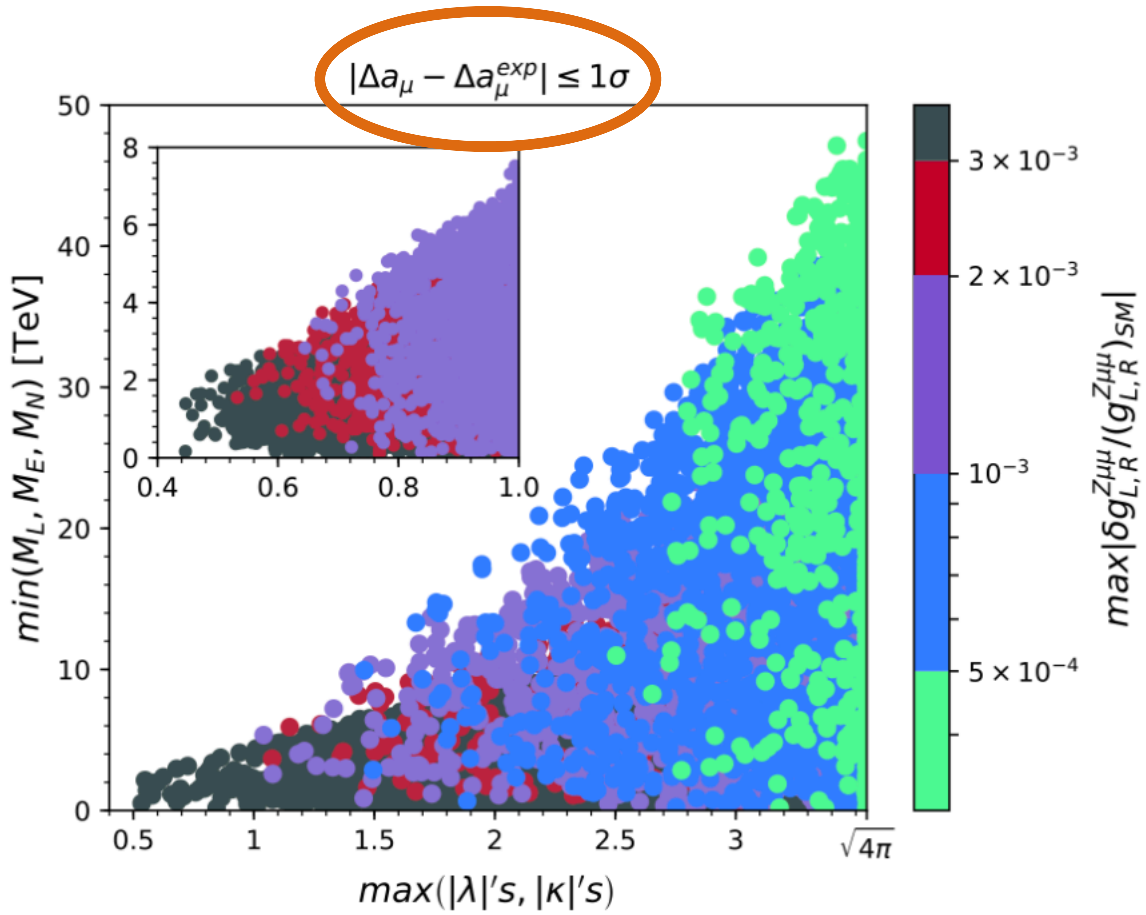

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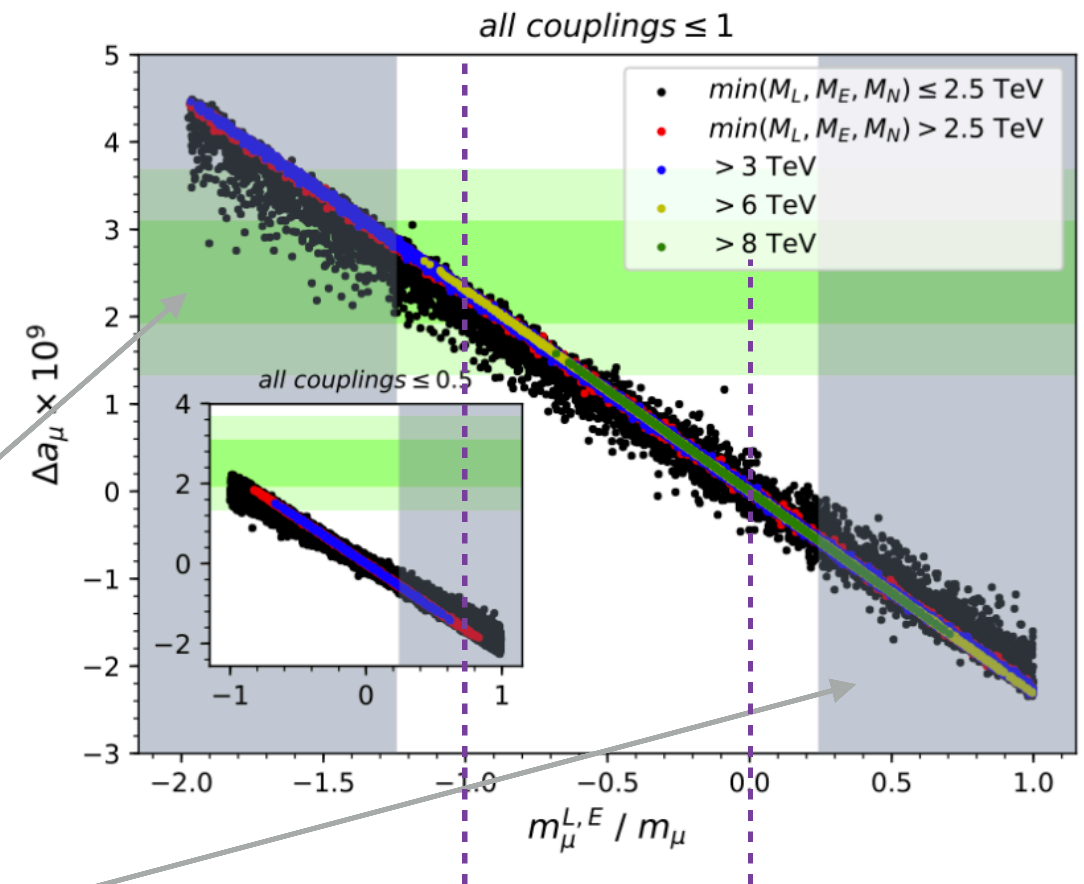

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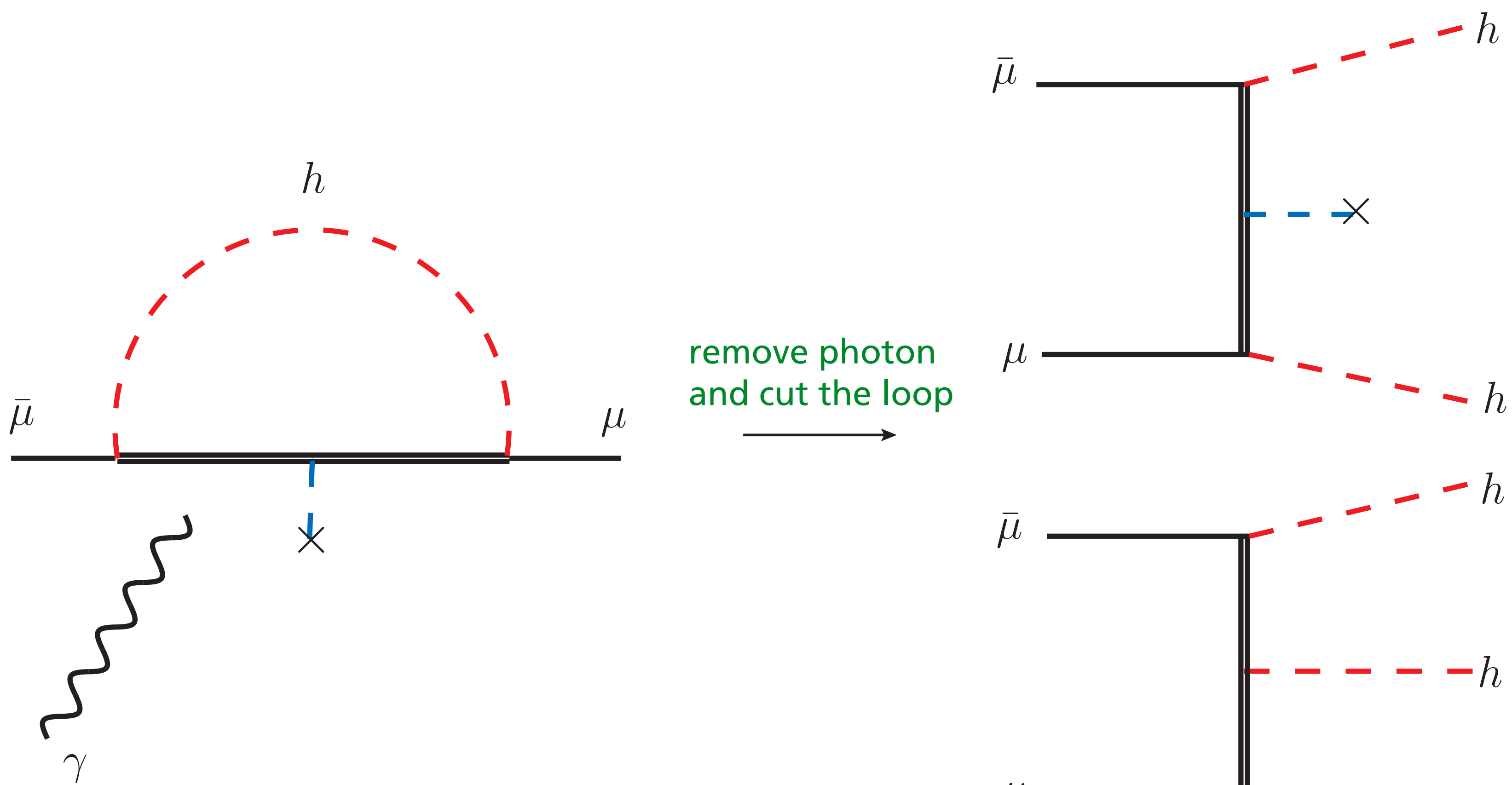

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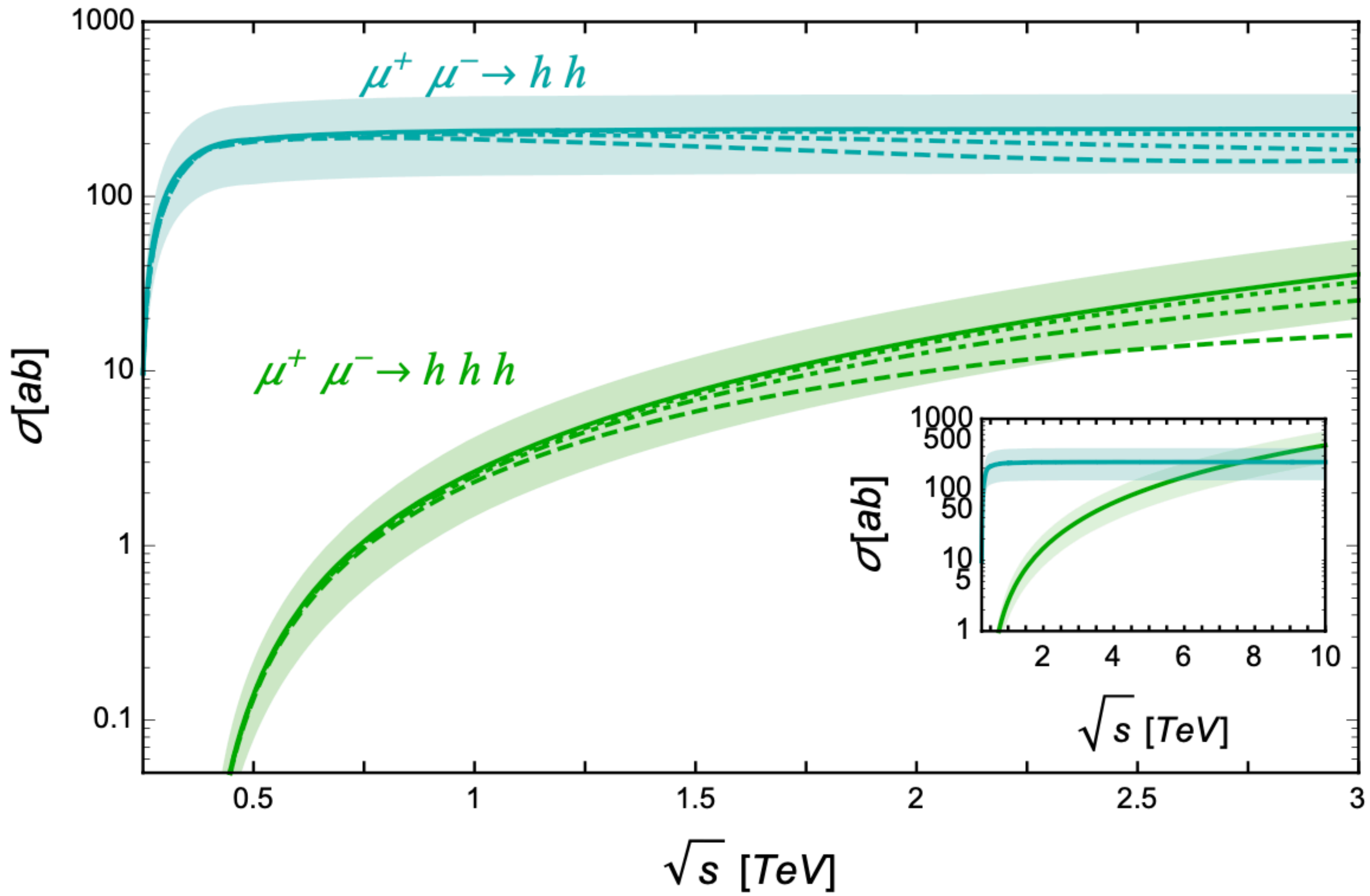

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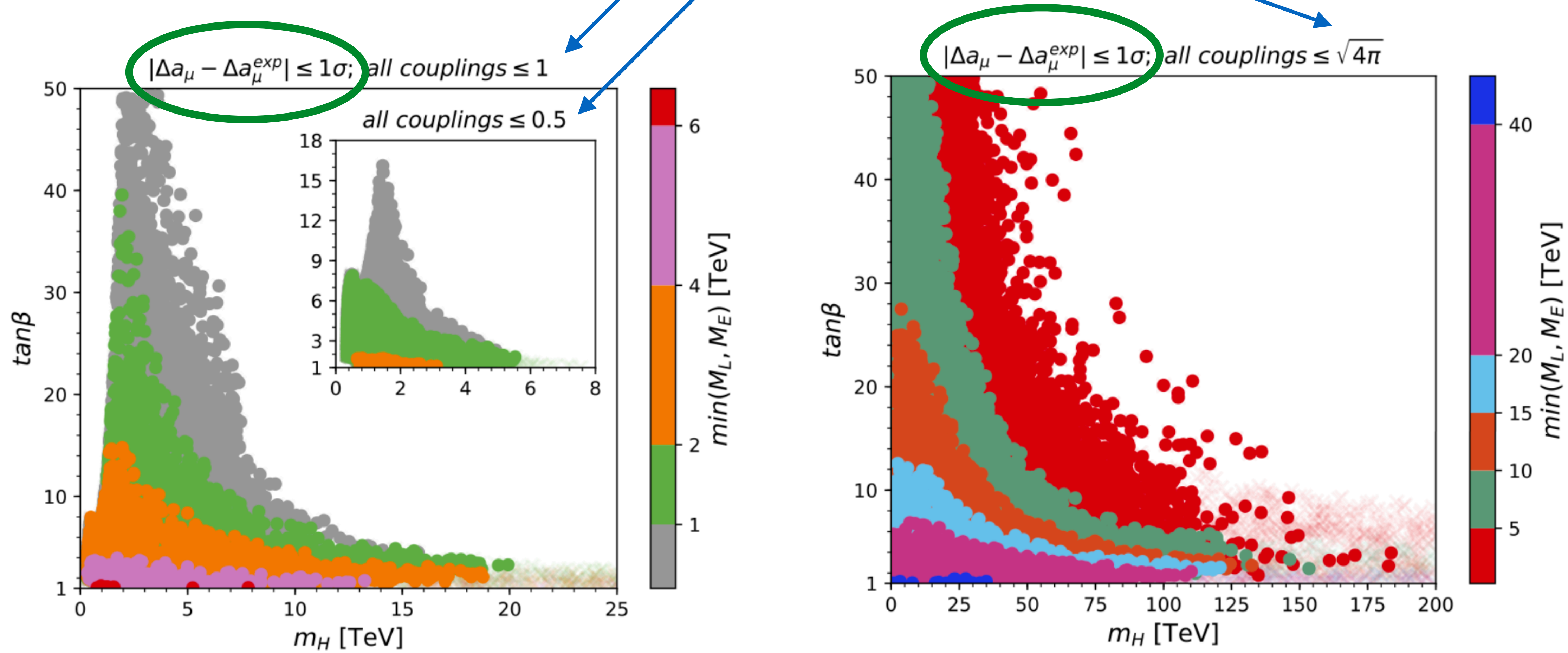
Supplemental material

Δa_μ in type-II 2HDM with L + E

depending on the size of couplings

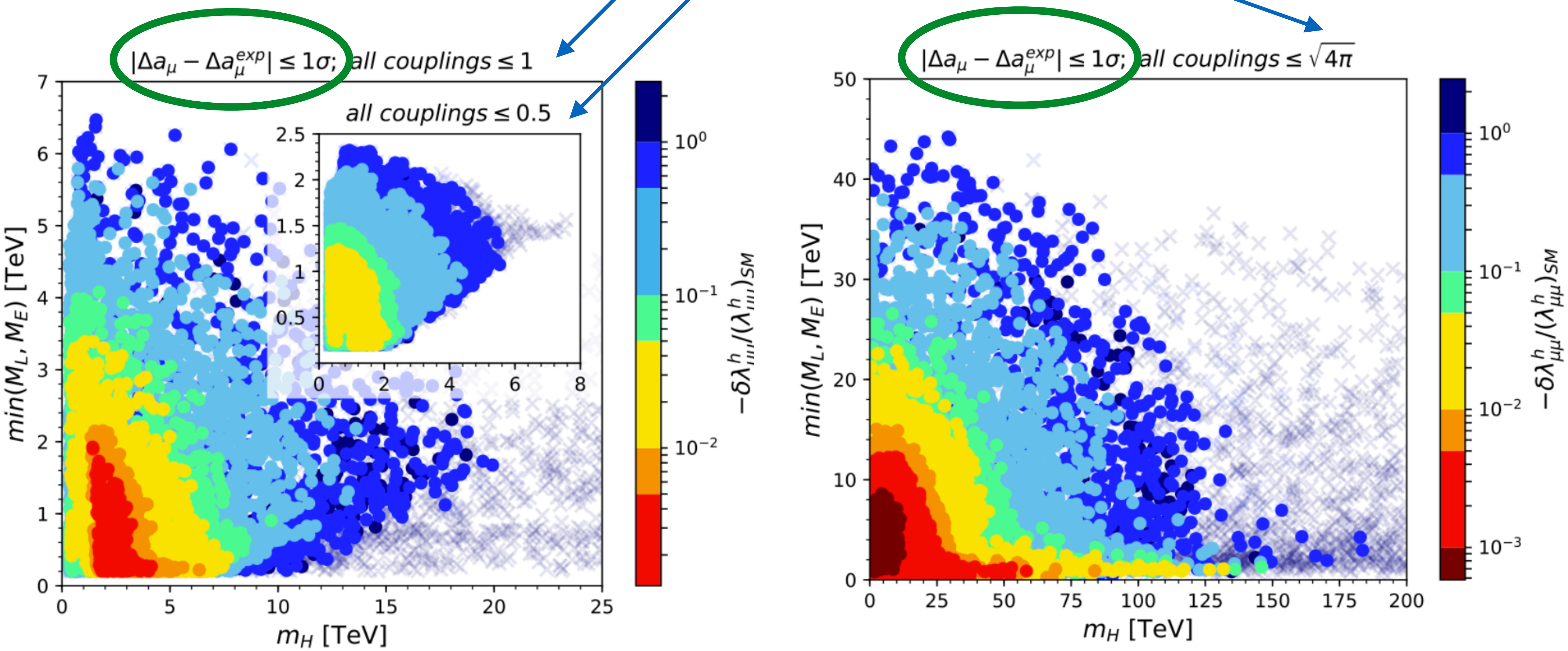


all experimental constraints from direct searches and precision EW data satisfied

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

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

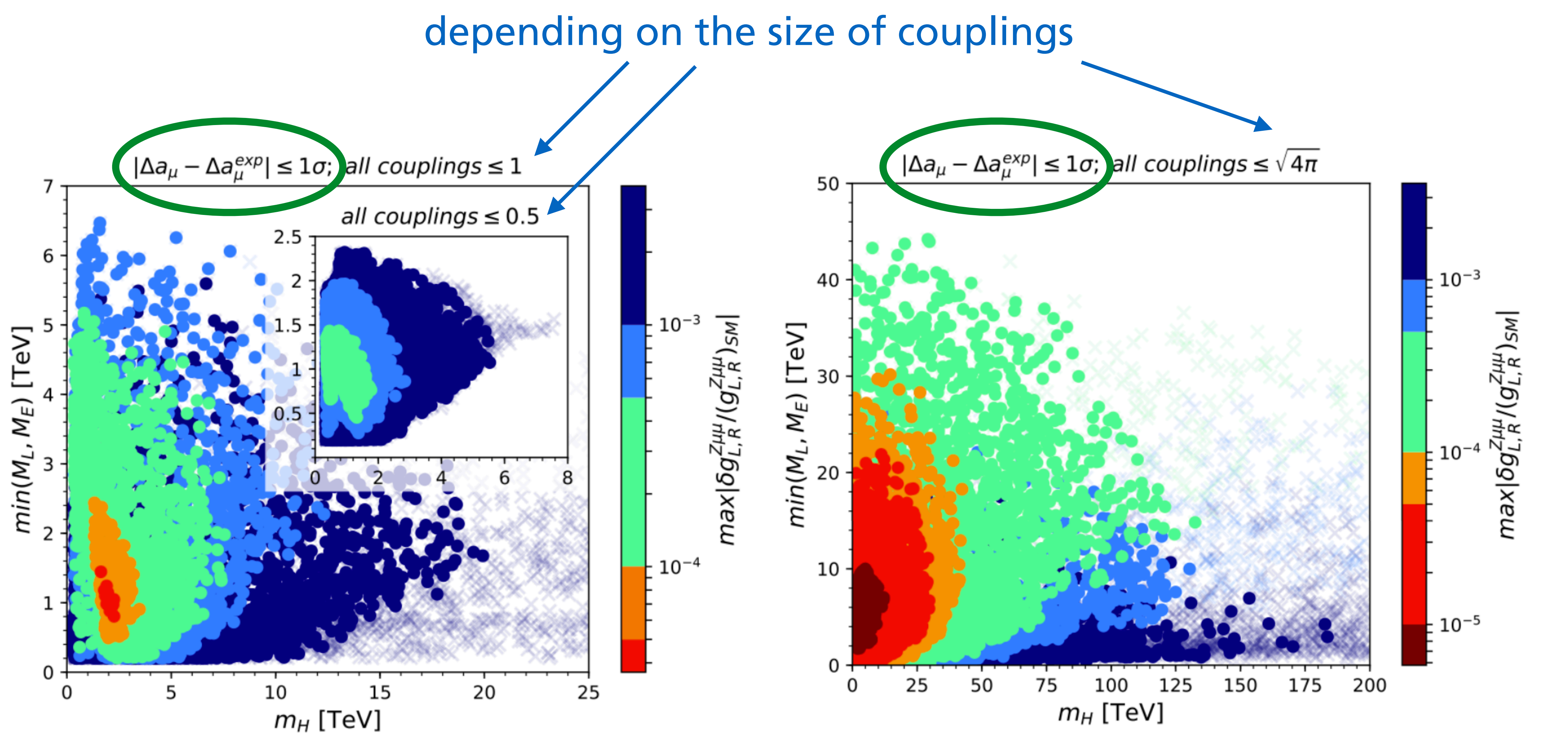
depending on the size of couplings



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

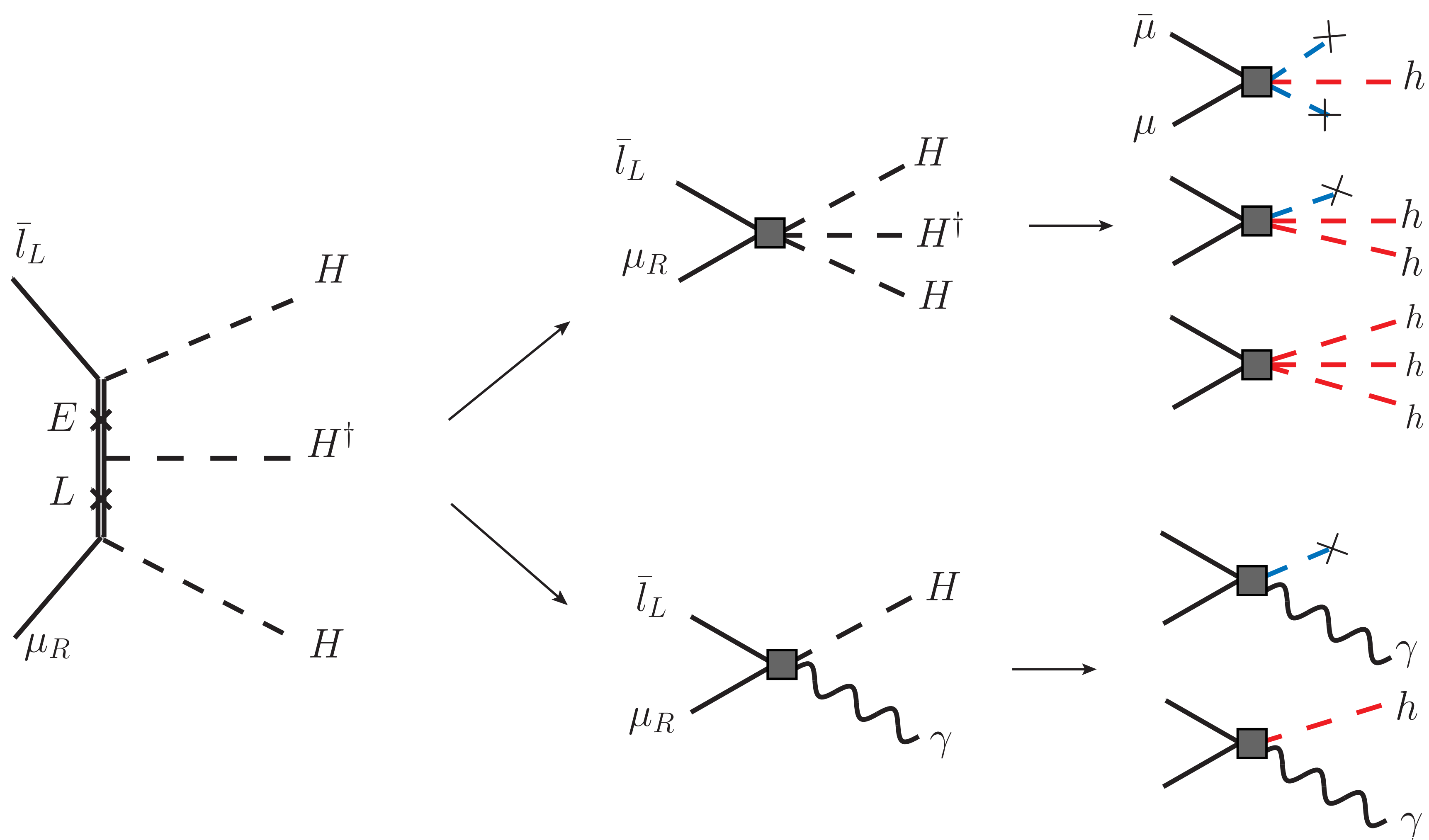
muon Yukawa coupling modified at $\gtrsim 10^{-3}$ or 5×10^{-4} levels

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



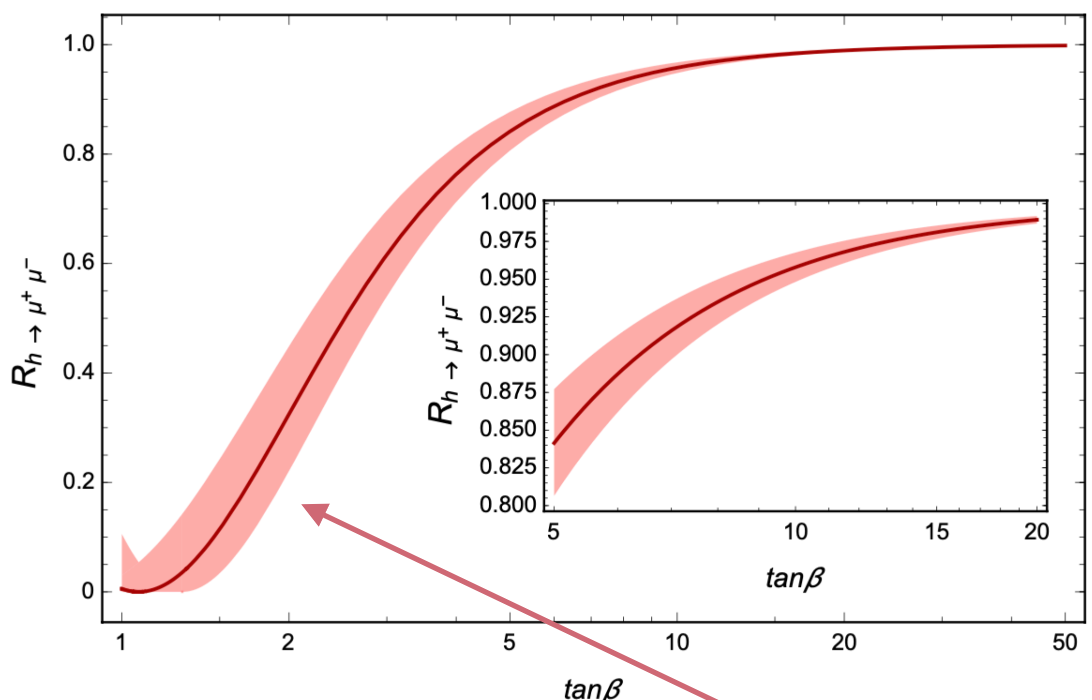
muon Z couplings modified at $> 3 \times 10^{-5}$ or 5×10^{-6} levels

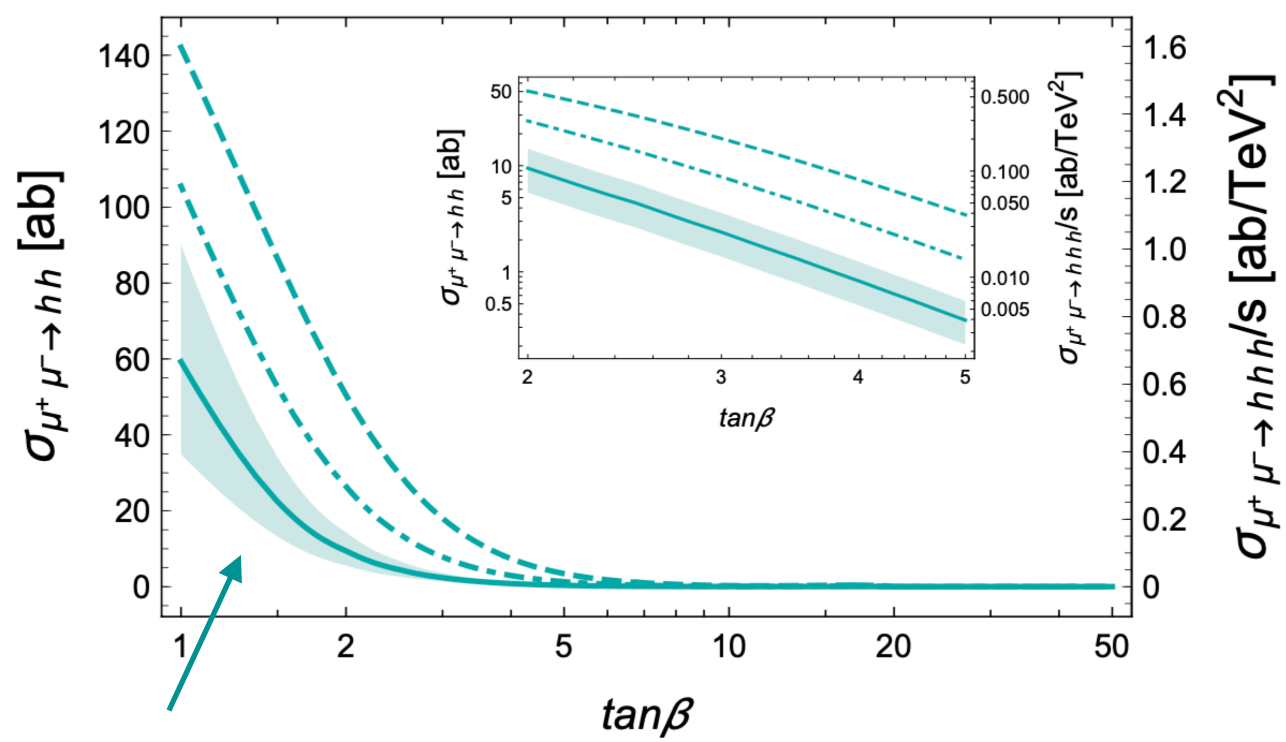
Effective operators in SM with L + E



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 $\sqrt{s}$