# Chirally-Enhanced Muon $g-2$ and Its Implications to Higgs-Related Observables

Keith Hermanek
Indiana University

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Based on
Phys. Rev. Lett. 26, 191801 (2021), Phys. Rev. D 104, 055033 (2021), Phys. Rev. D 104, L091301 (2021)
w/ Radovan Dermisek and Navin McGinnis

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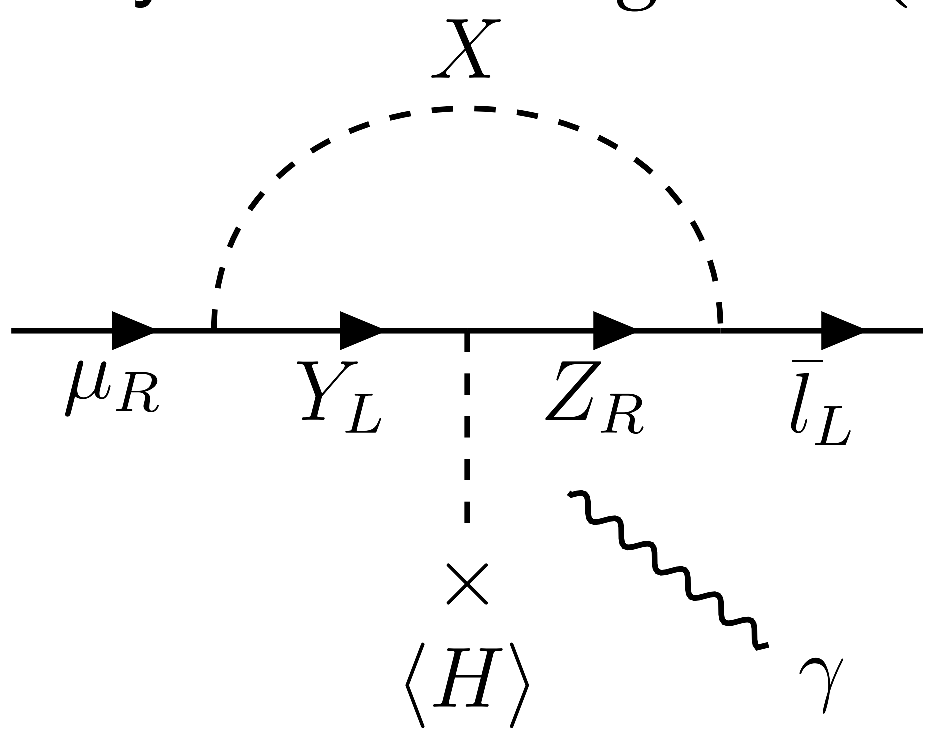
# Chiral Enhancement in $g-2$

- Chirally-enhanced $g-2$ $(\Delta a_\mu)$ can be generated by new particles coupling to the muon and Higgs inside the loop:




$$\Delta a_\mu \simeq \frac{1}{16\pi^2}\left(\frac{m_\mu v \lambda_{NP}^3}{m_{NP}^2}\right)$$

Muon g-2 Collab., Phys. Rev. Lett. 126, 141801 (2021)

$\Delta a_\mu^{exp} = (2.51 \pm 0.59) \times 10^{-9}$ **requires** $\sim 10\ (50)$ **TeV scale for couplings** $1\ (\sqrt{4\pi})$

- We can do this by working in a type-II two-Higgs-Doublet Model ($H_u$ and $H_d$ couple exclusively to the up- and down-type sectors (2HDM-II) ) extended with *vectorlike leptons (VLs)*

- $X$ can be SM bosons or new Higgses and $Y, Z$ are the new VLs

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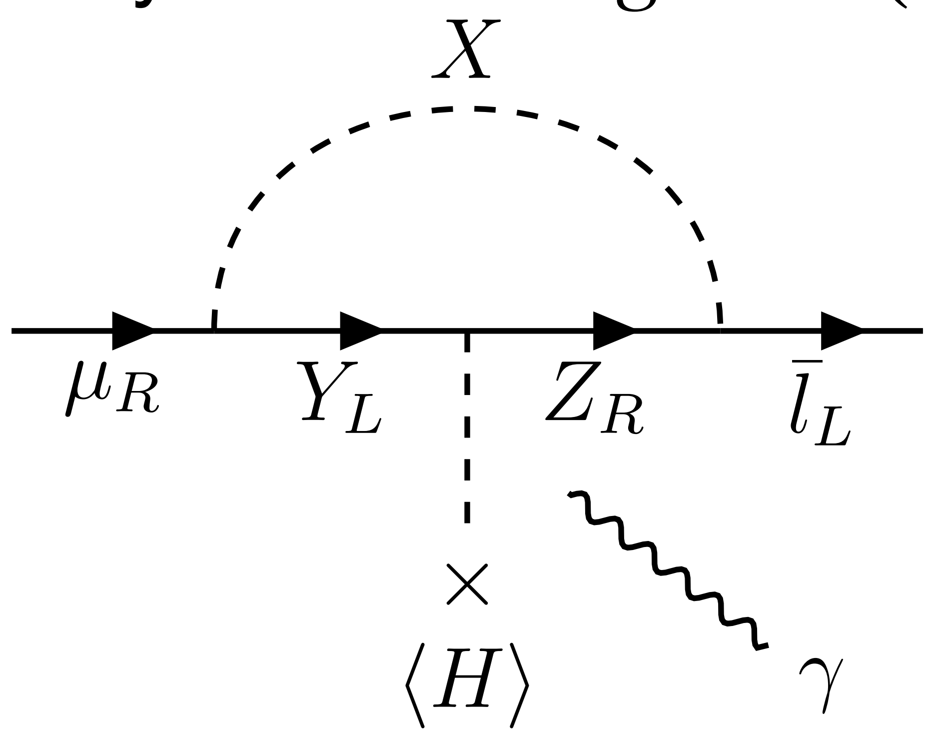


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| | $l_L$ | $\mu_R$ | $H_u$ | $H_d$ | $L_{L,R}$ | $E_{L,R}$ |
|---|---|---|---|---|---|---|
| $SU(2)_L$ | **2** | **1** | **2** | **2** | **2** | **1** |
| $U(1)_Y$ | $-\frac{1}{2}$ | $-1$ | $-\frac{1}{2}$ | $\frac{1}{2}$ | $-\frac{1}{2}$ | $-1$ |
| $Z_2$ | $+$ | $-$ | $+$ | $-$ | $+$ | $-$ |

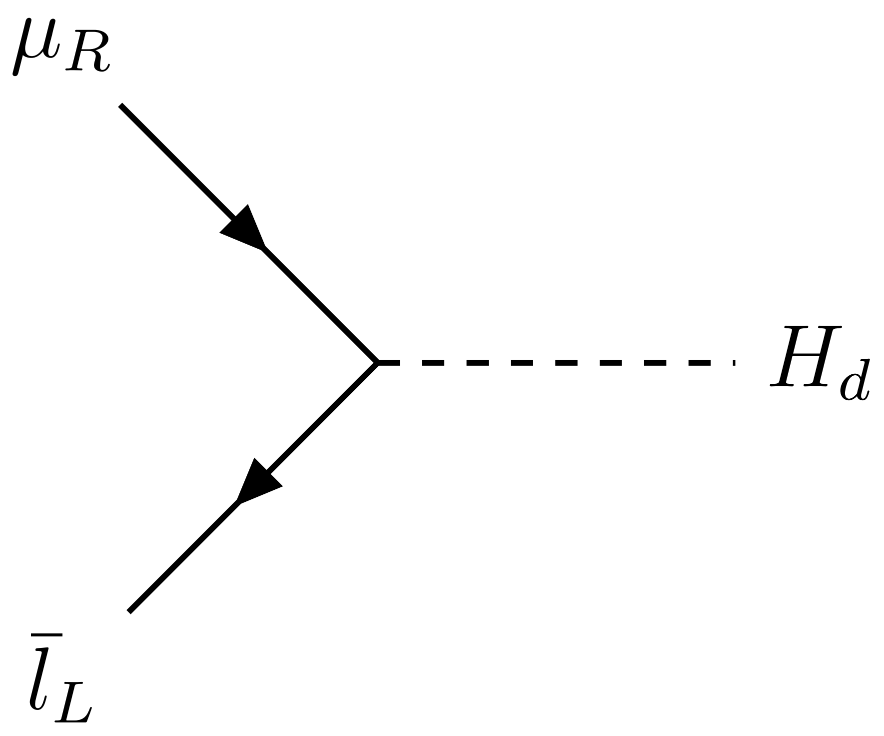
$$\mathscr{L} = -y_\mu \bar{l}_L \mu_R H_d - \lambda_E \bar{l}_L E_R H_d - \lambda_L \bar{L}_L \mu_R H_d$$
$$-\lambda \bar{L}_L E_R H_d - \bar{\lambda} H_d^\dagger \bar{E}_L L_R - M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + h.c.$$

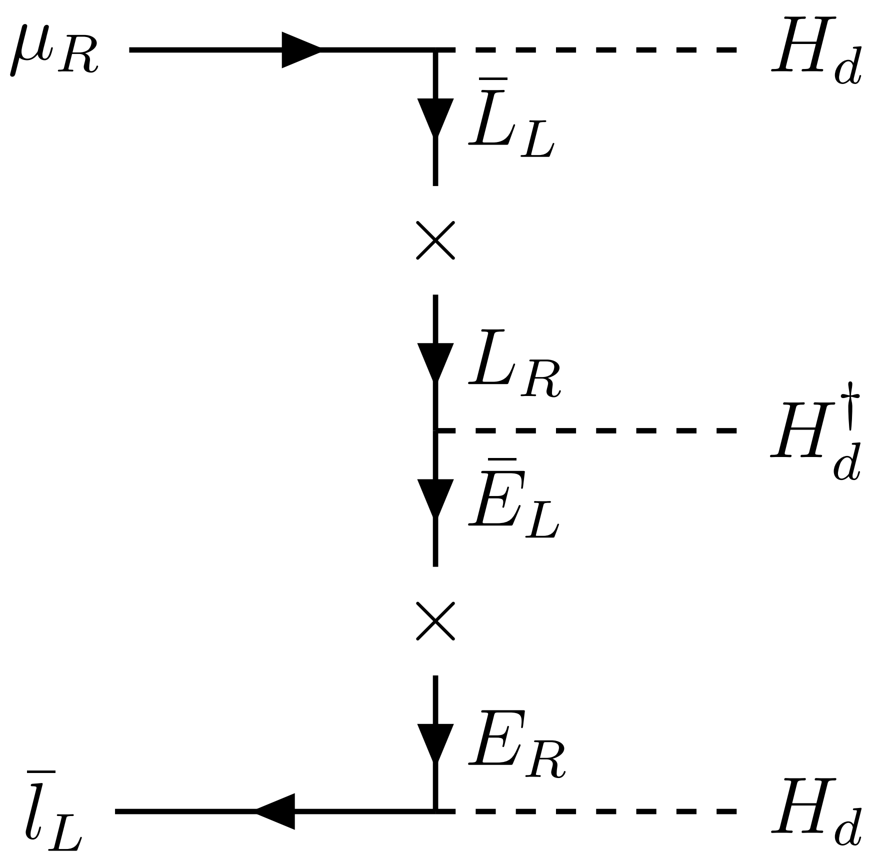
$\langle H_d^0 \rangle = v_d = v\cos\beta \qquad \langle H_u^0 \rangle = v_u = v\sin\beta$

$v = 174\ GeV \qquad v_u/v_d = \tan\beta$

# Tree-level Mixing

- For $M_{L,E} \gg v$, the heavy VLs *modify* $m_\mu$ and $y_\mu$ since the full Lagrangian reduces to




**Necessarily modifies**
$h \to \mu^+\mu^-$

$$\mathscr{L} = -y_\mu \bar{l}_L \mu_R H_d - \underbrace{\left(\frac{\lambda_L \lambda_E \bar{\lambda}}{M_L M_E}\right)}_{m_\mu^{LE}/v_d^3} \bar{l}_L \mu_R H_d \left(H_d^\dagger H_d\right) + h.c.$$

$$m_\mu \simeq y_\mu v_d + m_\mu^{LE} \longrightarrow \lambda^h_{\mu\mu} \simeq (m_\mu + 2m_\mu^{LE})/v \longrightarrow R_\mu \equiv \frac{BR\left(h \to \mu^+\mu^-\right)}{BR\left(h \to \mu^+\mu^-\right)_{SM}} = \left(1 + 2\frac{m_\mu^{LE}}{m_\mu}\right)^2$$

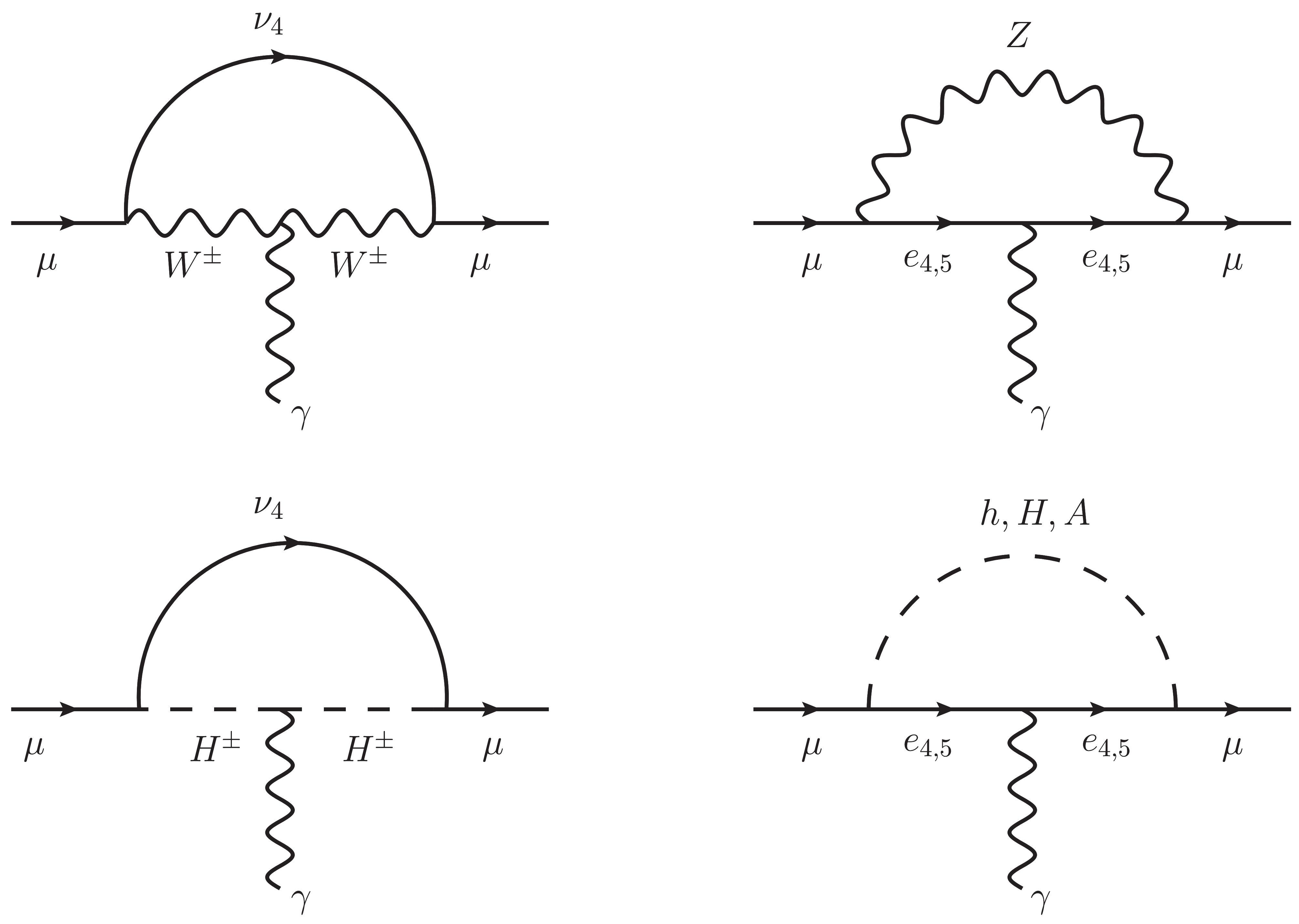
$m_\mu^{LE}$ **is interpreted to be the muon's mass *if*** $y_\mu = 0$

# The Anomalous Magnetic Moment

- Rotating the Lagrangian to the physical basis via bi-unitary transformations

$$(\bar{\mu}_L, \bar{L}_L^-, \bar{E}_L)\begin{pmatrix} y_\mu v_d & 0 & \lambda_E v_d \\ \lambda_L v_d & M_L & \lambda v_d \\ 0 & \bar{\lambda} v_d & M_E \end{pmatrix}\begin{pmatrix} \mu_R \\ L_R^- \\ E_R \end{pmatrix} \Rightarrow U_L^{e\dagger} M_e U_R^e = diag\left(m_{e_2}, m_{e_4}, m_{e_5}\right)$$

- We can calculate $\Delta a_\mu$ in the mass eigenstate basis and take the heavy mass limit $M_{L,E} \sim m_{H,A,H^\pm} \gg m_Z$




$$\Delta a_\mu = -\frac{1}{16\pi^2}\left(\frac{m_\mu m_\mu^{LE}}{v^2}\right)\left(1 + \tan^2\beta\right)$$

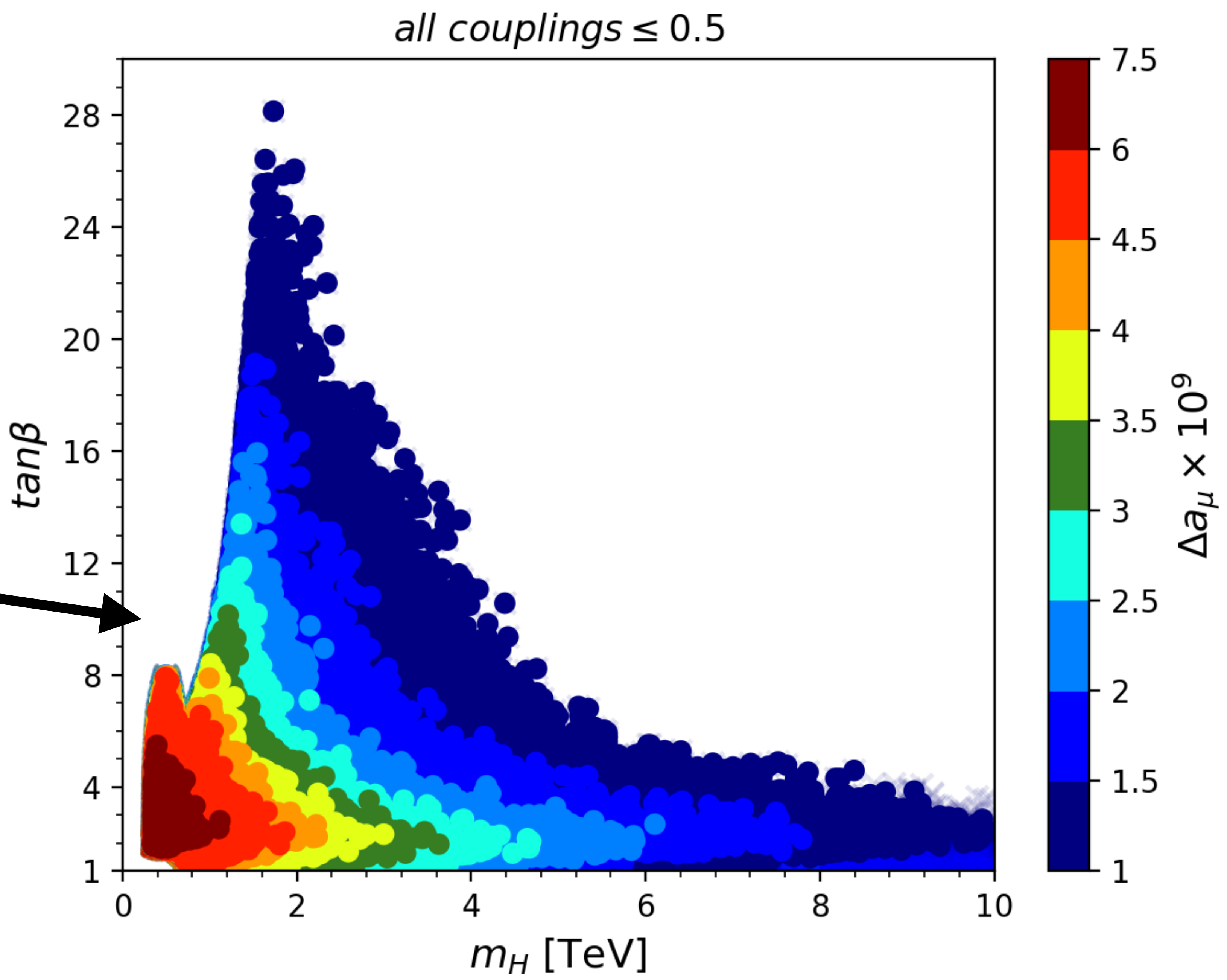
- Heavy Higgses $(H, A, H^\pm)$ give additional $\tan^2\beta$ enhancement compared to the $(Z, W, h)$ mediators

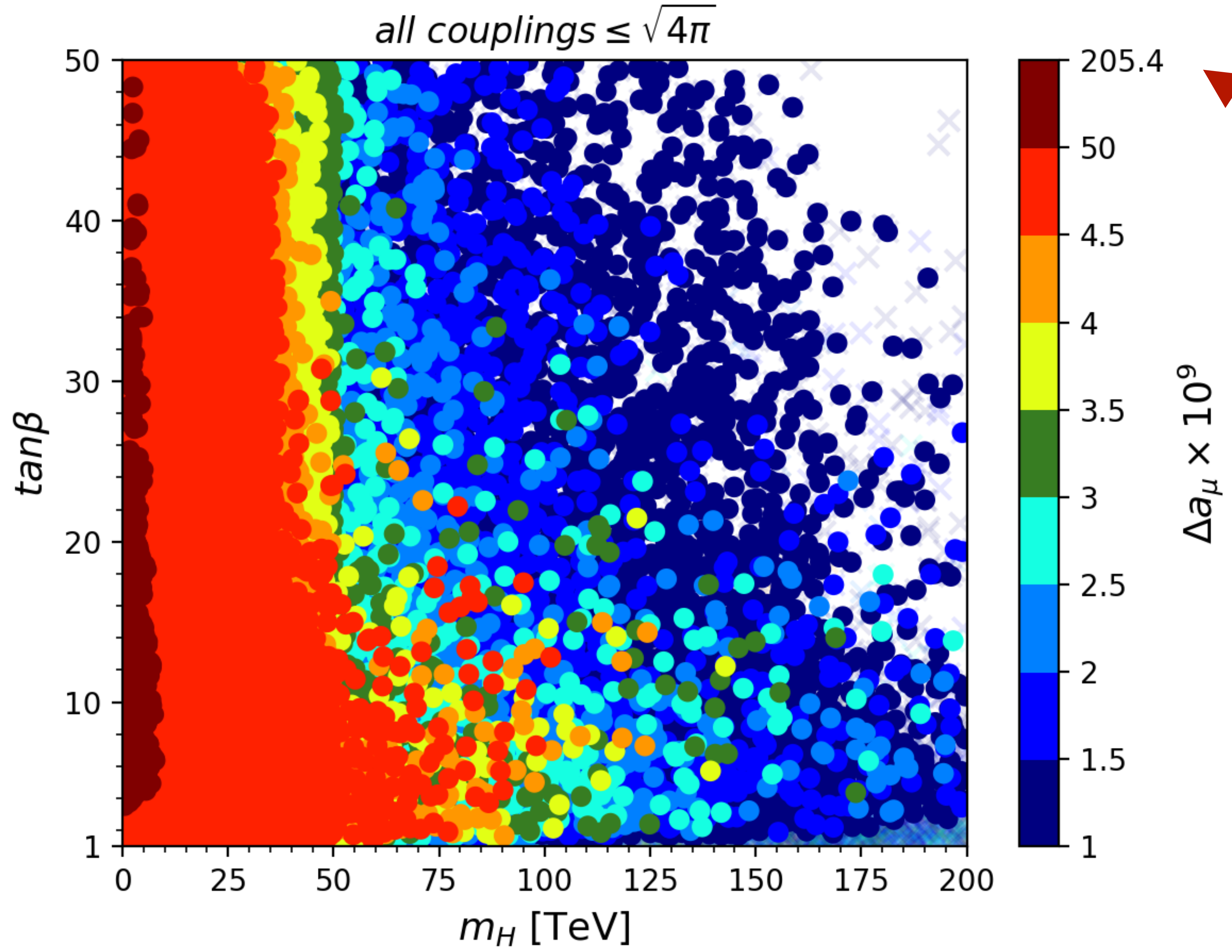
- Notice that $m_\mu^{LE}$ is present. We'll see why later!

# $\Delta a_\mu$ in 2HDM-II + VLs

**Region ruled out by**
$H(A) \to \tau^+\tau^-$

ATLAS Collab., Phys. Rev. Lett. 125, 051801 (2020)




**Couplings up to $\sqrt{4\pi}$ give almost 100 times $\Delta a_\mu^{exp}$ !**

$$\Delta a_\mu = -\left(\frac{1}{16\pi^2}\right)\left(\frac{m_\mu m_\mu^{LE}}{v^2}\right)\left(1+\tan^2\beta\right) \qquad m_\mu^{LE} = v_d^3\left(\frac{\lambda_L\lambda_E\bar{\lambda}}{M_L M_E}\right)$$

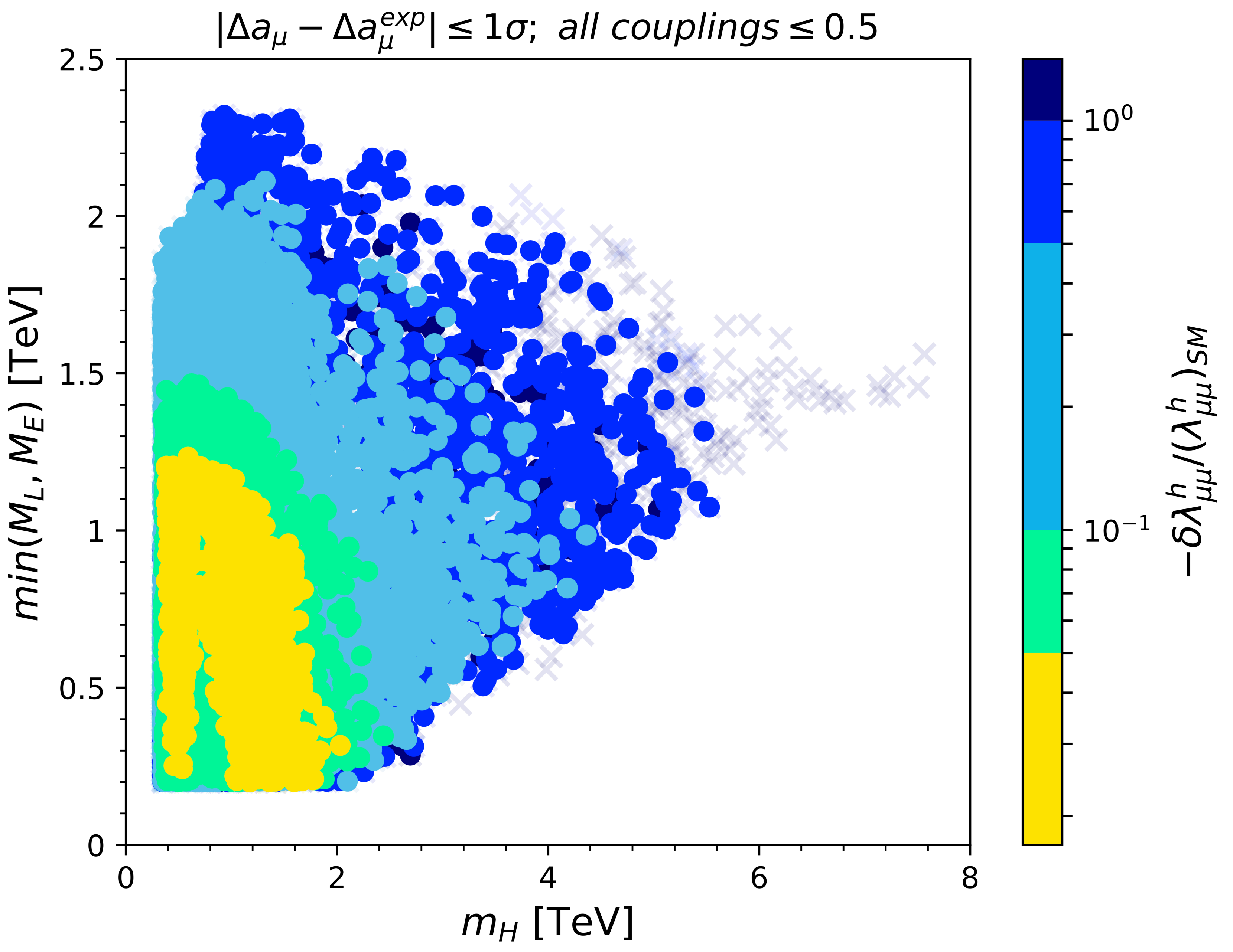
- Largest contributions occur for intermediate $\tan\beta$ values and light Higgs masses ($\tan^2\beta$ enhancement from heavy Higgs loops)

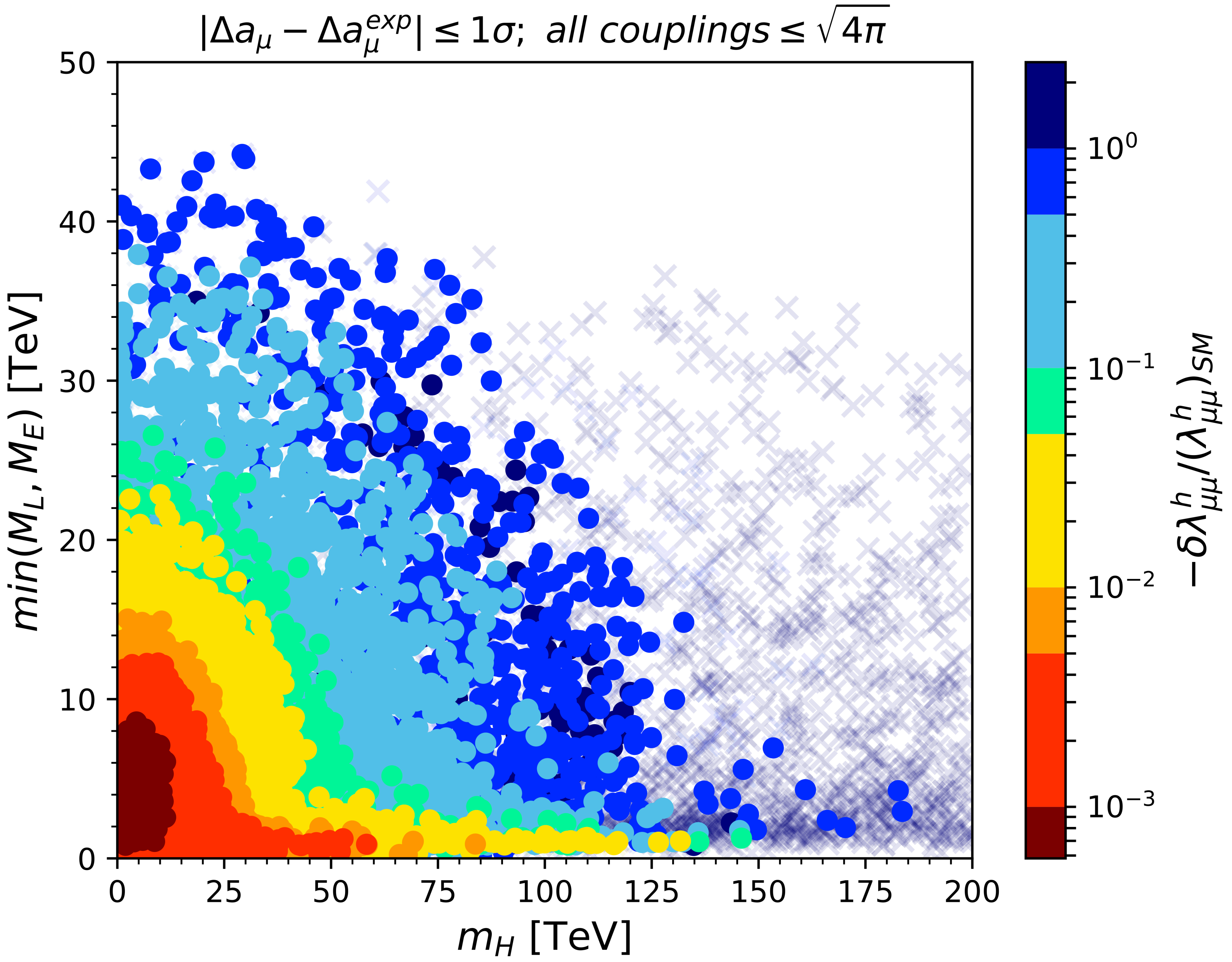
- All relevant constraints like EW precision constraints $|\lambda_L| \lesssim 0.04 \times M_L/v_d$ and $|\lambda_E| \lesssim 0.03 \times M_E/v_d$ are satisfied in these scenarios

R. Dermisek *et al.* J. High Energy Phys. 02 (2016) 119

# Modifying Yukawa Couplings in 2HDM-II + VLs

**Bright points w/ X correspond to** $\Delta a_\mu^{H,A,H^\pm}/\Delta a_\mu > 50\,\%$



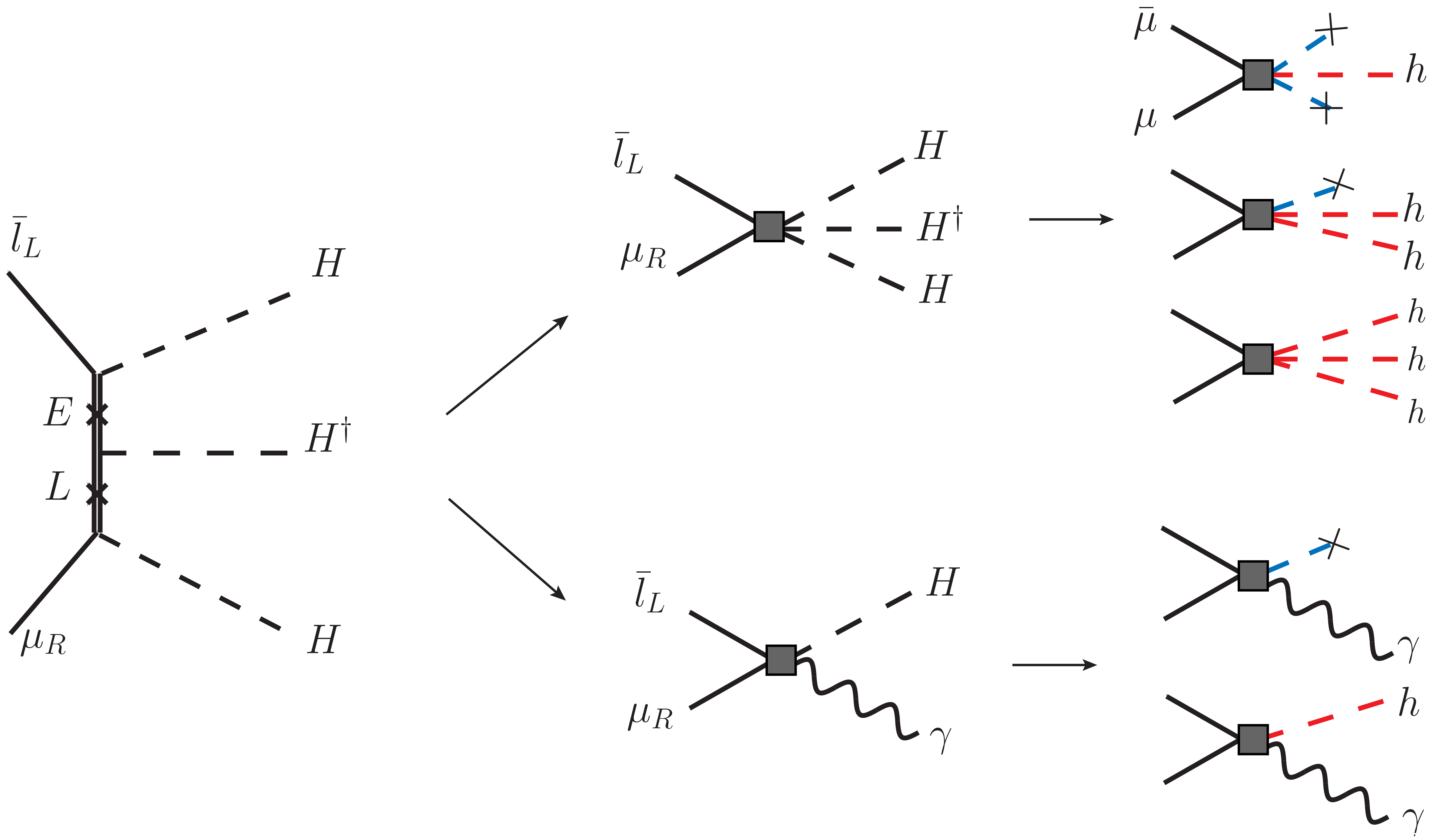

$$R_{h\to\mu^+\mu^-} = \frac{|\lambda^h_{\mu\mu}|^2}{|(\lambda^h_{\mu\mu})_{SM}|^2} = \left(1 + 2\frac{m_\mu^{LE}}{m_\mu}\right)^2$$

- The mass spectrum of leptons goes from $M_{L,E} > 2.5\ (45)$ TeV for $0.5\ (\sqrt{4\pi})$ and couplings
- $-\delta\lambda^h_{\mu\mu}/(\lambda^h_{\mu\mu})_{SM} = 2$ corresponds to $m_\mu^{LE} = -m_\mu$ and predicts the same $h \to \mu^+\mu^-$ decay rate as the SM
- At LHC (FCC-hh), $\lambda^h_{\mu\mu}$ is expected to be measured at $5\times10^{-2}\ (5\times10^{-3})$ precision

FCC Collab., Eur. Phys. J. C 79, 474 (2019)

# SM Effective Field Theory

- Let's look at the dimension-6 operator $\bar{l}_L H \mu_R (H^\dagger H)$




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

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

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

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

**In the 2HDM-II, this $\Delta a_\mu$ is multiplied by $1 + \tan^2\beta$; Same result as earlier!**

- Because of this connection, the experimental value $\Delta a_\mu^{exp} = (2.51 \pm 0.59) \times 10^{-9}$ fixes

$$\frac{m_\mu^{LE}}{m_\mu} = -1.07 \pm 0.25$$

$$R_{h\to\mu^+\mu^-} \equiv \frac{BR\left(h \to \mu^+\mu^-\right)}{BR\left(h \to \mu^+\mu^-\right)_{SM}} = \left(1 + 2\frac{m_\mu^{LE}}{m_\mu}\right)^2 = 1.32^{+1.40}_{-0.90}$$

**We can make a prediction for di- and ti-Higgs signals!**
**How can we test this model?**

**Current limit is 2.2**

ATLAS Collab., Phys. Lett. B 812, 135980 (2021)

# Testing at a Muon Collider

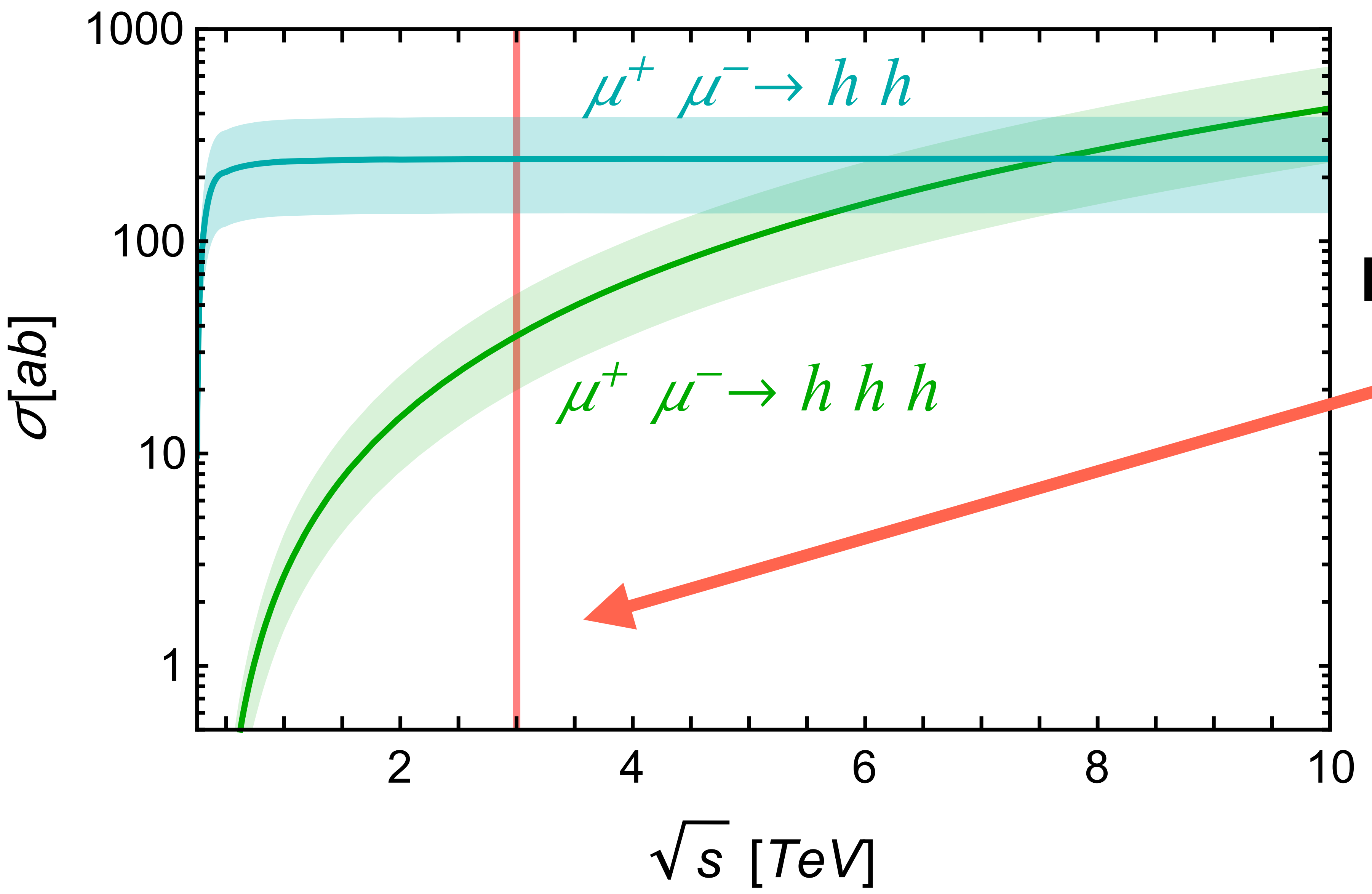
- The effective cross-sections for $\mu^+\mu^- \to hh$ and $\mu^+\mu^- \to hhh$ can be written within $\Delta a_\mu^{exp} \pm 1\sigma$

$$\sigma_{\mu^+\mu^-\to hh} = \frac{|\lambda_{\mu\mu}^{hh}|^2}{64\pi} = \frac{9}{64\pi}\left(\frac{m_\mu^{LE}}{v^2}\right)^2 \qquad \sigma_{\mu^+\mu^-\to hhh} = \frac{|\lambda_{\mu\mu}^{hhh}|^2}{6144\pi^3}s = \frac{3}{4096\pi^3}\left(\frac{m_\mu^{LE}}{v^3}\right)^2 s$$

- A $\sqrt{s} = 3$ TeV MuC with $1\ ab^{-1}$ luminosity predicts 244 and 36 events for di- and ti-Higgs processes at the central value of $\Delta a_\mu^{exp}$

- At $\sqrt{s} > 1$ TeV, SM predictions for di- and tri-Higgs signals are small by *at least* 3-4 orders

T. Han *et al.* JHEP12(2021)162




**Possible future MuC COM energy:**
$\sqrt{s} = 3\ TeV$

**Different representations of VLs coupling to the muon can decrease $\mu^+\mu^- \to hh$, $\mu^+\mu^- \to hhh$ dramatically; sharp distinction between models!**

# Takeaways

- 2HDM-II + VLs generates chiral and $\tan^2\beta$ enhancements that can generate even up to two orders larger contributions to $\Delta a_\mu$ while satisfying constraints

- Precision measurements of $\lambda^h_{\mu\mu}$ can indirectly probe the parameter space of heavy VL masses and Higgses

- In the SM with VLs, the dimension-6 operator $\bar{l}_L H \mu_R (H^\dagger H)$ connects $\Delta a_\mu$ with $h \to \mu^+\mu^-$, $\mu^+\mu^- \to hh$, $\mu^+\mu^- \to hhh$

- $1\ ab^{-1}$ luminosity at $\sqrt{s} = 3\ TeV$ predicts 244 events for $\mu^+\mu^- \to hh$ and 36 events for $\mu^+\mu^- \to hhh$ at the central value of $\Delta a_\mu^{exp}$. Other representations may lower the rate up to a factor of 25

**Thank you for listening!**

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