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Multi Higgs boson signals of a modified muon Yukawa coupling

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arXiv:2311.05078

Collaboration with R. Dermisek, K. Hermanek, N. McGinnis, and S. Yoon

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Deviation in muon Yukawa coupling

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$$\mathscr{L} \supset -y_\mu \bar{l}_L \mu_R H + \text{h.c.}$$

$$l_L = (\nu_\mu, \mu_L)^T \qquad H = (G^+, v + (h + iG^0)/\sqrt{2})^T$$

$$\supset -m_\mu \bar{\mu}_L \mu_R - \frac{1}{\sqrt{2}} \lambda_{\mu\mu}^{h,\,\text{SM}} \bar{\mu}_L \mu_R h + \text{h.c.}$$

$$m_\mu = y_\mu v \qquad \lambda_{\mu\mu}^{h,\,\text{SM}} = \frac{m_\mu}{v}$$

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$$m_\mu = y_\mu v \qquad \lambda^{h,\mathrm{SM}}_{\mu\mu} = \frac{m_\mu}{v}$$

Using the general Kappa Framework, we can express deviation in Yukawa coupling

Kappa framework arXiv:1209.0040. arXiv:1307.1347.

$$\lambda^{h}_{\mu\mu} = \frac{m_\mu}{v} \kappa_\mu$$

For SM, $\kappa_\mu = 1.$

$$\Delta\kappa_\mu = \kappa_\mu - 1$$

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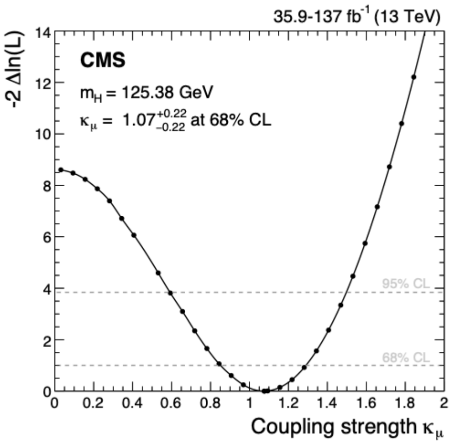

CMS : arXiv:2009.04363

Currently, $0.59 < \kappa_\mu < 1.50$ at 95 % confidence level

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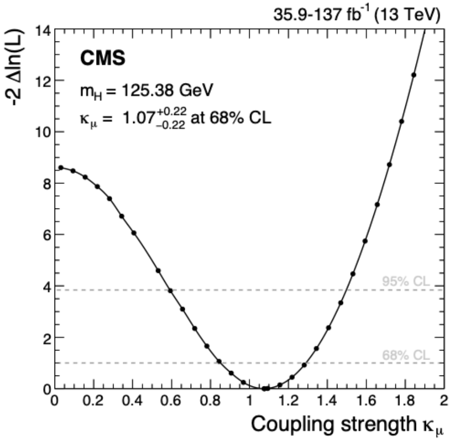

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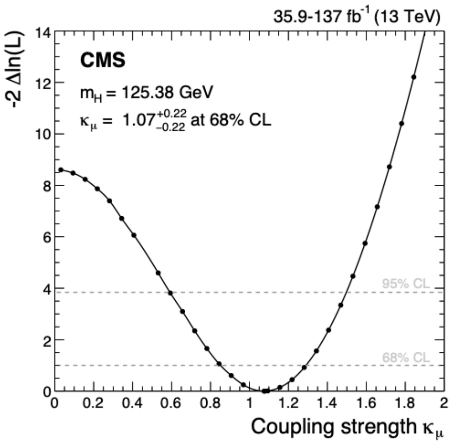

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Limits : Can't measure complex phase

For complex κ_μ, $\Delta\kappa_\mu < 2.50$

Standard Model Effective Field theory (SMEFT)

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(59 independent operators)

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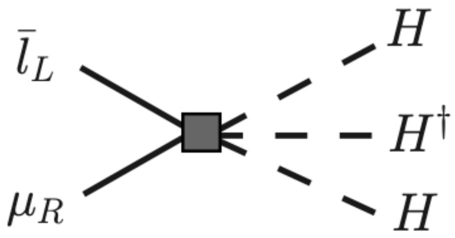
There is only one dimension 6 SMEFT operator responsible for deviation Yukawa coupling

$$\mathscr{L} \supset -C_{\mu H}\, \bar{l}_L \mu_R H \left(H^\dagger H\right) + \mathrm{h.c.}$$



Dimension 6 mass operator

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$$\Delta\kappa_\mu = 2C_{\mu H} v^3 / m_\mu$$

$$\lambda^h_{\mu\mu} = \frac{m_\mu}{v} \kappa_\mu \qquad \Delta\kappa_\mu = \kappa_\mu - 1$$

Thus we can parametrize the processes from dim 6 mass operator in terms of $\Delta\kappa_\mu$.

Dimension 6 mass operator

Di-Higgs, tri-Higgs : arXiv:2108.10950

	in terms of $\Delta\kappa_\mu$	in units of $\sigma_{\mu^+\mu^-\to hh}$
$\sigma_{\mu^+\mu^-\to hh}$	$\frac{9}{256\pi}\left(\frac{m_\mu}{v^2}\right)^2 \lvert\Delta\kappa_\mu\rvert^2$	1
$\sigma_{\mu^+\mu^-\to hZ_L}$	$\frac{1}{128\pi}\left(\frac{m_\mu}{v^2}\right)^2 \lvert\Delta\kappa_\mu\rvert^2$	$\frac{2}{9}$
$\sigma_{\mu^+\mu^-\to Z_L Z_L}$	$\frac{1}{256\pi}\left(\frac{m_\mu}{v^2}\right)^2 \lvert\Delta\kappa_\mu\rvert^2$	$\frac{1}{9}$
$\sigma_{\mu^+\mu^-\to W_L^+ W_L^-}$	$\frac{1}{128\pi}\left(\frac{m_\mu}{v^2}\right)^2 \lvert\Delta\kappa_\mu\rvert^2$	$\frac{2}{9}$

	in terms of $\Delta\kappa_\mu$	in units of $\sigma_{\mu^+\mu^-\to hhh}$
$\sigma_{\mu^+\mu^-\to hhh}$	$\frac{3s}{2^{14}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2 \lvert\Delta\kappa_\mu\rvert^2$	1
$\sigma_{\mu^+\mu^-\to hhZ_L}$	$\frac{s}{2^{14}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2 \lvert\Delta\kappa_\mu\rvert^2$	$\frac{1}{3}$
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Assuming muon and Higgs mass zero

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- Are there other dimension 6 operators that can produce same final state?

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$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
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$$\mu^+\mu^- \to W^+W^-, hZ, W^+W^-h, W^+W^-Z, Zhh, ZZZ$$

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Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$

Dipole operators

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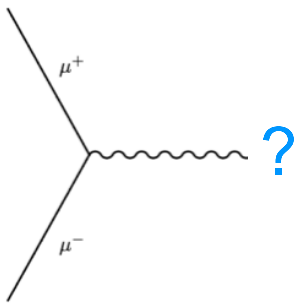
Large SM background comes from gauge boson interaction.



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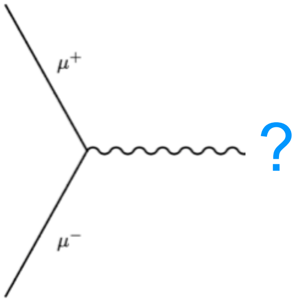

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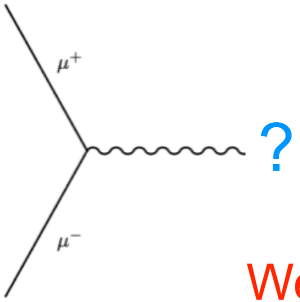
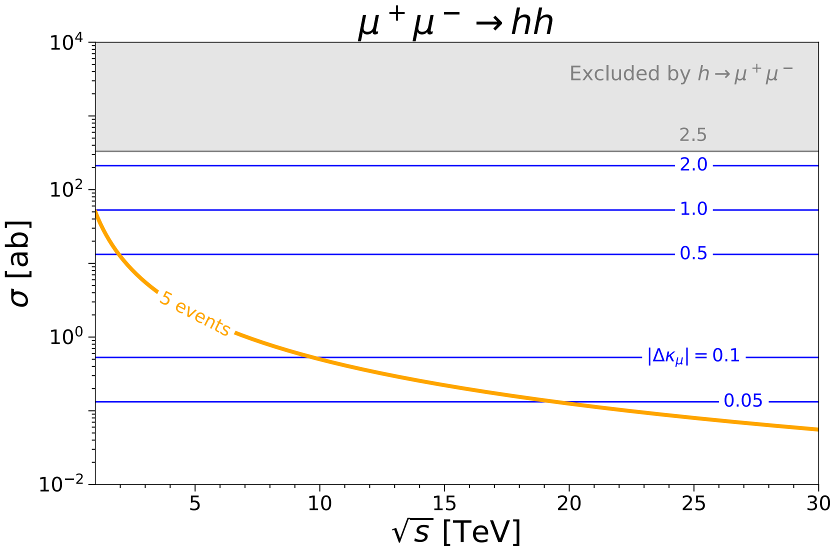
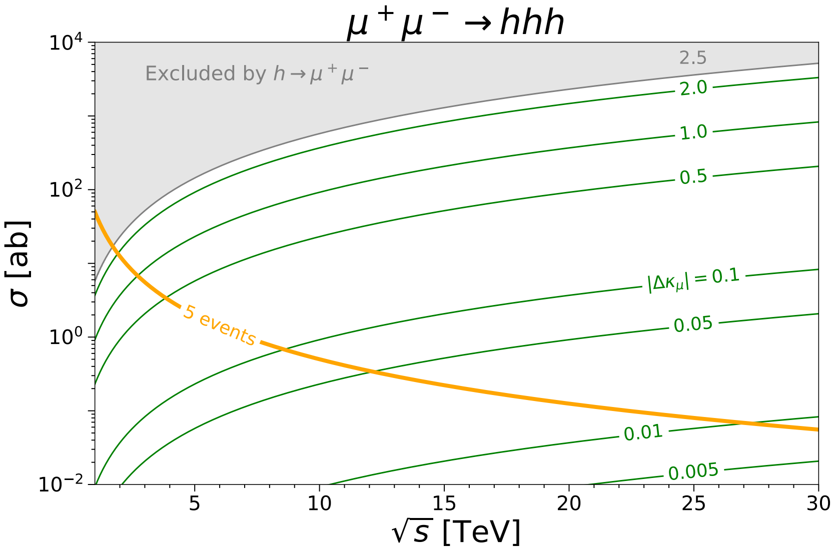


$\mu^+\mu^- \to hh, hhh$ survived.

We identify $\mu^+\mu^- \to hh, hhh$ as a golden channel for measuring deviation in muon Yukawa coupling

Dimension 6 mass operator





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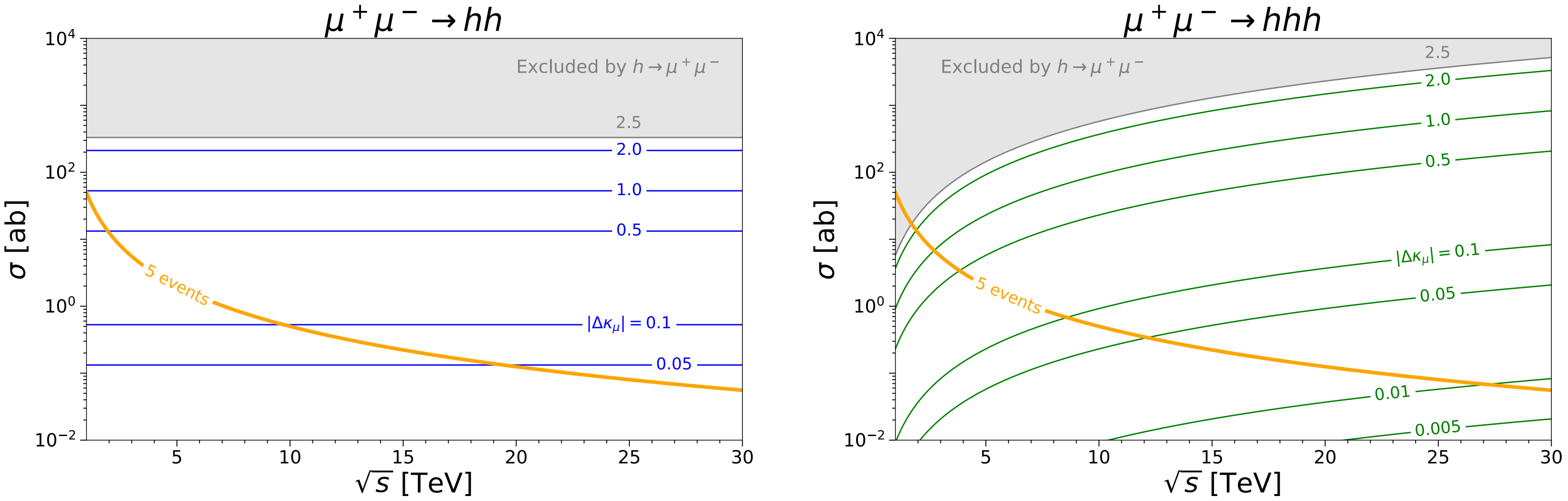
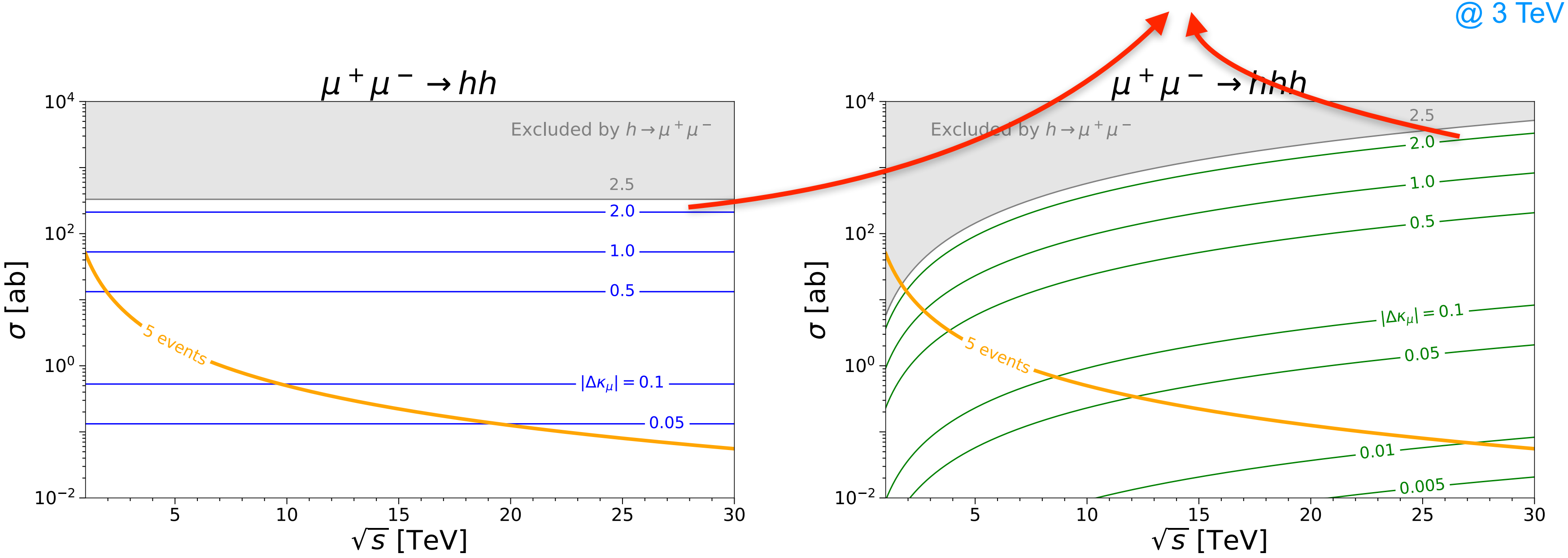


$\sigma(\mu^+\mu^- \to hh)_{SM} = 1.6 \times 10^{-4}$ ab and $\sigma(\mu^+\mu^- \to hhh)_{SM} = 2.9 \times 10^{-5}$ ab at $\sqrt{s} = 3$ TeV, and falling as $1/s^2$ and $1/s$ at larger energies.

Dimension 6 mass operator

Opposite sign Yukawa

191 di-Higgs
30 tri-Higgs
@ 3 TeV



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Extension to 2HDM type II

$$\mathcal{L} \supset -y_\mu \bar{l}_L \mu_R H_d - C_{\mu H_d} \bar{l}_L \mu_R H_d \left(H_d^\dagger H_d\right)$$
$$-C_{\mu H_u}^{(1)} \bar{l}_L \mu_R H_d \left(H_u^\dagger H_u\right) - C_{\mu H_u}^{(2)} \bar{l}_L \mu_R \cdot H_u^\dagger \left(H_d \cdot H_u\right) - C_{\mu H_u}^{(3)} \bar{l}_L \mu_R \cdot H_u^\dagger \left(H_d^\dagger \cdot H_u^\dagger\right) + \mathrm{h.c.}$$

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$$-C^{(1)}_{\mu H_u} \bar{l}_L \mu_R H_d \left(H_u^\dagger H_u \right) - C^{(2)}_{\mu H_u} \bar{l}_L \mu_R \cdot H_u^\dagger \left(H_d \cdot H_u \right) - C^{(3)}_{\mu H_u} \bar{l}_L \mu_R \cdot H_u^\dagger \left(H_d^\dagger \cdot H_u^\dagger \right) + \mathrm{h.c.}$$

1. Comes from new leptons with same quantum number as SM leptons
2. Leads to largest $\tan\beta$ enhancement to the processes.

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$$\Delta\kappa_\mu = 2 C_{\mu H_d} v_d^3 / m_\mu \qquad\qquad v_d = v \cos\beta$$

For each heavy Higgs in the process leads to $\tan^2\beta$ enhancement to the Cross section

$$H_d = (H_d^+, H_d^0)^T$$

$$H_d^\pm = \cos\beta G^\pm - \sin\beta H^\pm$$

$$H_d^0 = v\cos\beta + \frac{1}{\sqrt{2}}(h\cos\beta + H\sin\beta) + \frac{i}{\sqrt{2}}(G\cos\beta - A\sin\beta)$$

Extension to 2HDM type II

	in terms of $\Delta\kappa_\mu$
$\sigma_{\mu^+\mu^-\to hh}$	$\frac{9}{256\pi}\left(\frac{m_\mu}{v^2}\right)^2 \lvert\Delta\kappa_\mu\rvert^2$
$\sigma_{\mu^+\mu^-\to AA}$	$\frac{1}{256\pi}\left(\frac{m_\mu}{v^2}\right)^2 \lvert\Delta\kappa_\mu\rvert^2 \tan^4\beta$
$\sigma_{\mu^+\mu^-\to HH}$	$\frac{9}{256\pi}\left(\frac{m_\mu}{v^2}\right)^2 \lvert\Delta\kappa_\mu\rvert^2 \tan^4\beta$
$\sigma_{\mu^+\mu^-\to hH}$	$\frac{9}{128\pi}\left(\frac{m_\mu}{v^2}\right)^2 \lvert\Delta\kappa_\mu\rvert^2 \tan^2\beta$
$\sigma_{\mu^+\mu^-\to hA}$	$\frac{1}{128\pi}\left(\frac{m_\mu}{v^2}\right)^2 \lvert\Delta\kappa_\mu\rvert^2 \tan^2\beta$
$\sigma_{\mu^+\mu^-\to HA}$	$\frac{1}{128\pi}\left(\frac{m_\mu}{v^2}\right)^2 \lvert\Delta\kappa_\mu\rvert^2 \tan^4\beta$
$\sigma_{\mu^+\mu^-\to H^+H^-}$	$\frac{1}{128\pi}\left(\frac{m_\mu}{v^2}\right)^2 \lvert\Delta\kappa_\mu\rvert^2 \tan^4\beta$

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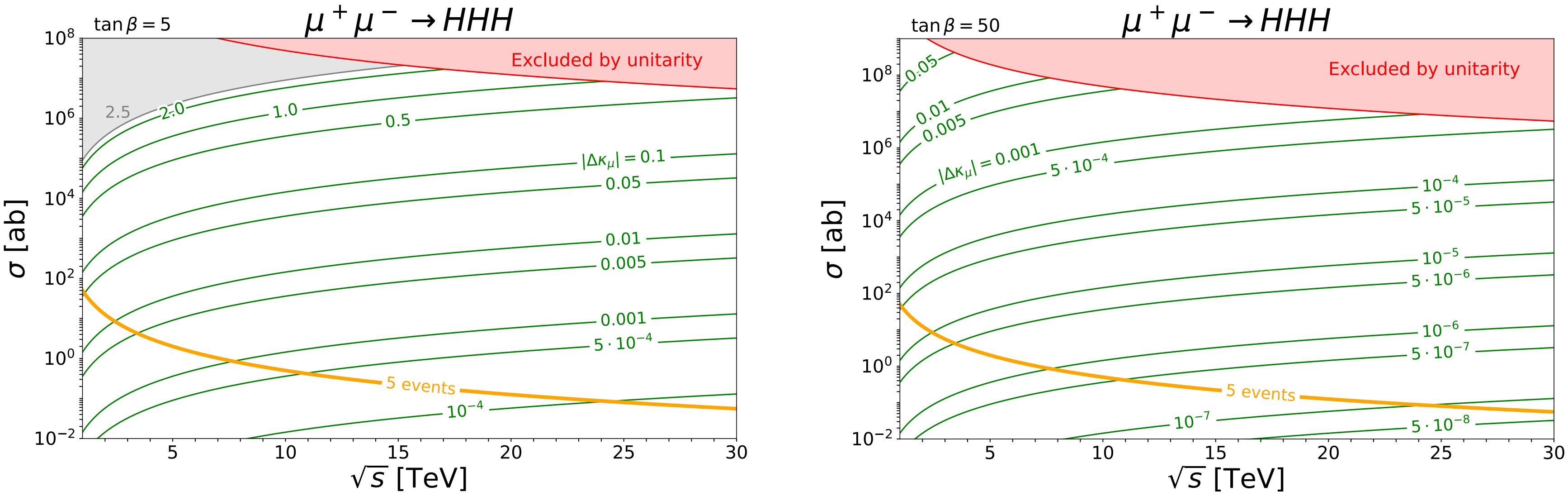
Extension to 2HDM type II



Summary

- Future muon collider is expected to probe deviation to muon Yukawa coupling up to 7% (0.8 %) at 10 TeV (30 TeV) from $\mu^+\mu^- \to hhh$
- Expected to measure opposite sign Yukawa even at low energy muon collider.
- 2HDM type II can be tested and if there are 2HDM type II present, we can probe deviation to muon Yukawa coupling up to the $\sim 10^{-6}$ (10^{-8}) level at 10 TeV (30 TeV) from $\mu^+\mu^- \to HHH$

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Thanks for listening

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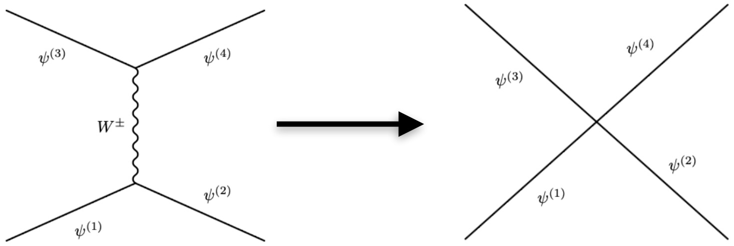
Familiar example would be Fermi theory of weak interaction

$$\mathscr{L}_F = \frac{4}{\sqrt{2}} G_F \cdot \bar{\psi}_L^{(1)} \gamma^\mu \psi_L^{(2)} \cdot \bar{\psi}_L^{(3)} \gamma_\mu \psi_L^{(4)}$$

$$G_F = \frac{\sqrt{2}}{8} \frac{e^2}{\sin^2\theta_W M_W^2}$$



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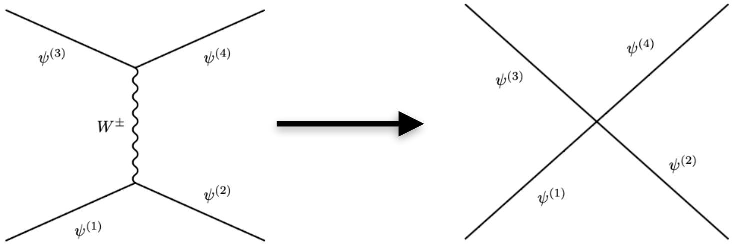
Scale of UV theory



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Thus, $\mu^+\mu^- \to HH$ and $\mu^+\mu^- \to HHH$ could be a golden channel for large $\tan\beta$

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	in terms of $\Delta\kappa_\mu$
$\sigma_{\mu^+\mu^-\to hZ_L}$	$\frac{1}{128\pi}\left(\frac{m_\mu}{v^2}\right)^2(\Delta\kappa_\mu)^2$
$\sigma_{\mu^+\mu^-\to HZ_L}$	$\frac{1}{128\pi}\left(\frac{m_\mu}{v^2}\right)^2(\Delta\kappa_\mu)^2\tan^2\beta$
$\sigma_{\mu^+\mu^-\to AZ_L}$	$\frac{1}{128\pi}\left(\frac{m_\mu}{v^2}\right)^2(\Delta\kappa_\mu)^2\tan^2\beta$
$\sigma_{\mu^+\mu^-\to Z_LZ_L}$	$\frac{1}{256\pi}\left(\frac{m_\mu}{v^2}\right)^2(\Delta\kappa_\mu)^2$
$\sigma_{\mu^+\mu^-\to H^+W_L^-/W_L^+H^-}$	$\frac{1}{128\pi}\left(\frac{m_\mu}{v^2}\right)^2(\Delta\kappa_\mu)^2\tan^2\beta$
$\sigma_{\mu^+\mu^-\to W_L^+W_L^-}$	$\frac{1}{128\pi}\left(\frac{m_\mu}{v^2}\right)^2(\Delta\kappa_\mu)^2$

	in terms of $\Delta\kappa_\mu$
$\sigma_{\mu^+\mu^-\to hhZ_L}$	$\frac{s}{2^{14}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2$
$\sigma_{\mu^+\mu^-\to hHZ_L}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^2\beta$
$\sigma_{\mu^+\mu^-\to hAZ_L}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^2\beta$
$\sigma_{\mu^+\mu^-\to HHZ_L}$	$\frac{s}{2^{14}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^4\beta$
$\sigma_{\mu^+\mu^-\to HAZ_L}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^4\beta$
$\sigma_{\mu^+\mu^-\to AAZ_L}$	$\frac{9s}{2^{14}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^4\beta$
$\sigma_{\mu^+\mu^-\to hZ_LZ_L}$	$\frac{s}{2^{14}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2$
$\sigma_{\mu^+\mu^-\to HZ_LZ_L}$	$\frac{s}{2^{14}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^2\beta$
$\sigma_{\mu^+\mu^-\to AZ_LZ_L}$	$\frac{9s}{2^{14}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^2\beta$
$\sigma_{\mu^+\mu^-\to Z_LZ_LZ_L}$	$\frac{3s}{2^{14}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2$
$\sigma_{\mu^+\mu^-\to hW_L^+W_L^-}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2$
$\sigma_{\mu^+\mu^-\to HW_L^+W_L^-}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^2\beta$
$\sigma_{\mu^+\mu^-\to AW_L^+W_L^-}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^2\beta$
$\sigma_{\mu^+\mu^-\to Z_LW_L^+W_L^-}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2$
$\sigma_{\mu^+\mu^-\to hH^+W_L^-/hW_L^+H^-}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^2\beta$
$\sigma_{\mu^+\mu^-\to HH^+W_L^-/HW_L^+H^-}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^4\beta$
$\sigma_{\mu^+\mu^-\to AH^+W_L^-/AW_L^+H^-}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^4\beta$
$\sigma_{\mu^+\mu^-\to Z_LH^+H^-}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^4\beta$
$\sigma_{\mu^+\mu^-\to Z_LH^+W_L^-/Z_LW_L^+H^-}$	$\frac{s}{2^{13}\pi^3}\left(\frac{m_\mu}{v^3}\right)^2(\Delta\kappa_\mu)^2\tan^2\beta$

$$H_d = (H_d^+, H_d^0)^T$$

$$H_d^\pm = \cos\beta G^\pm - \sin\beta H^\pm$$

$$H_d^0 = v\cos\beta + \frac{1}{\sqrt{2}}(h\cos\beta + H\sin\beta) + \frac{i}{\sqrt{2}}(G\cos\beta - A\sin\beta)$$

$$H_u = (H_u^0, H_u^-)^T$$

$$H_u^\pm = -\sin\beta G^\pm - \cos\beta H^\pm$$

$$H_u^0 = v\sin\beta + \frac{1}{\sqrt{2}}(h\sin\beta - H\cos\beta) - \frac{i}{\sqrt{2}}(G\sin\beta + A\cos\beta)$$

In alignment limit