# Probing Higgs-Muon Interactions at Multi-TeV Collider


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March 14th, 2024

IMCC and MuCol Annual Meeting


Istituto Nazionale di Fisica Nucleare

Theory and Phenomenology of Fundamental Interactions

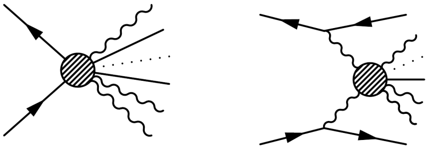
UNIVERSITY AND INFN · BOLOGNA

International MUON Collider Collaboration

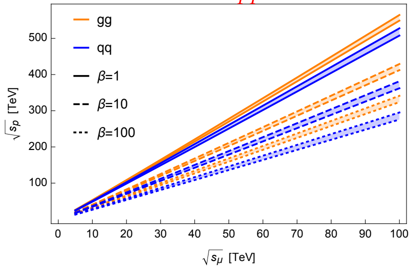
MuCol

# A possible multi-TeV lepton collider is cool!

# A multi-TeV lepton collider is amazing



**muC@10 TeV $\sim$ $pp$@70 TeV**




- $\ell^+\ell^-$ annihilation **probes TeV scale directly**
- VBF **scans physics in the full spectrum of energy**
  From the threshold to up to $2$ orders of magnitude above EW scale.
- It produces a lot of $H$, top quarks, $W/Z$, ... as **a "factory" for SM precision test**
- **An "EW jet factory"**
  In addition to QCD jets, there are $W/Z$ jet, $H$ jet, $t$ jet, neutrino jet, $\cdots$
  Even neutrino collision is not impossible!

**Challenges**:

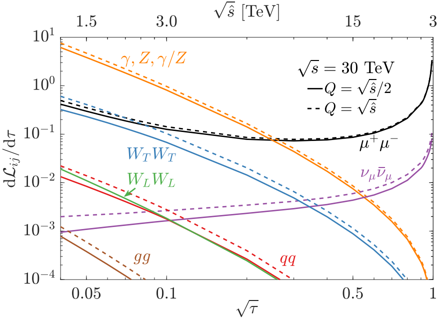
**Be careful about the radiation!**

EW NLO shall be necessary, just like the NLO QCD at LHC.

# The full picture a multi-TeV lepton collider: An electroweak LHC

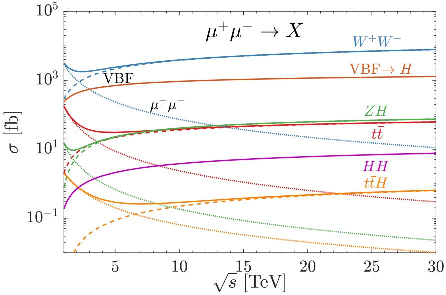
- All SM particles are partons
- We are allowed to determine the partons with their different polarizations

**The EW parton luminosities of a 30 TeV muon collider**




**Just like in hadronic collisions:**

$\mu^+\mu^- \to$ exclusive particles + remnants




[T. Han, Y. Ma and K. Xie, Phys. Rev. D 103 (2021) L031301, 2007.14300] [T. Han, Y. Ma and K. Xie, JHEP 02 (2022) 154, 2103.09844]

# It is the first time we play with another flavor

## One example in precision physics: The Muon-Higgs Coupling

[T. Han, W. Kilian, N. Kreher, YM, T. Striegl, J. Reuter, and K. Xie, 2108.05362]

[E. Celada, T. Han, W. Kilian, N. Kreher, YM, F. Maltoni, D. Pagani, T. Striegl, J. Reuter, and K. Xie, 2312.13082]

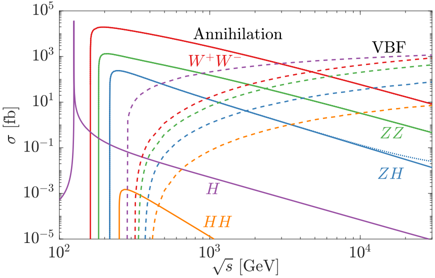
- Physics: We actually do not know whether the SM mass-generation mechanism applies just to the heavy particles, or also to the 1st/2nd generations.
- Logical possibility: Muon mass not (only) generated by SM Higgs.
  $\Rightarrow$ **Why not have an arbitrary Yukawa coupling?**

# Multi-boson final states and the Muon-Higgs coupling

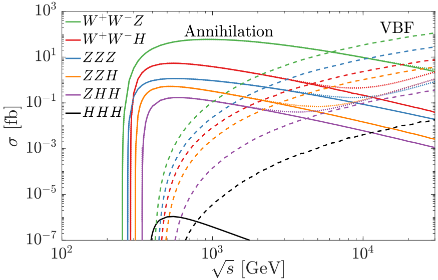
## Take a quick in the $\kappa$ framework

- **SM**: $\lambda(\mathrm{Muon}-\mathrm{Higgs}) \sim y_\mu^{\mathrm{SM}} = \sqrt{2} m_\mu^{\mathrm{SM}}/v$
- **Possible BSM physics**: $m_\mu = m_\mu^{\mathrm{SM}}$, $\lambda(\mathrm{Muon}-\mathrm{Higgs}) \sim \kappa_\mu y_\mu^{\mathrm{SM}}$, e.g. $\kappa_\mu = 0$

**Two-boson final states**



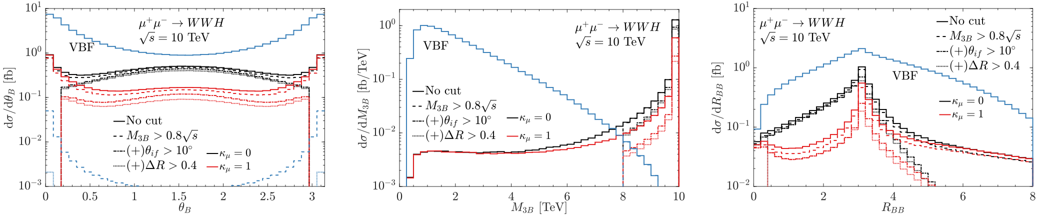

**Three-boson final states**




**New physics signal shows up in the high energy region**

[T. Han, W. Kilian, N. Kreher, YM, T. Striegl, J. Reuter, and K. Xie, 2108.05362]

# $WWH$ at a 10 TeV muon collider: Kinematics




- Background (VBF) is much larger than signal (annihilation)
- VBF events accumulate around threshold, and mostly forward
- Annihilation in the rest frame (central, and $M \sim \sqrt{s}$ spread by ISR)
- Annihilation also has forward dominance, due to the gauge splitting $W \to WH$

# $WWH$ at a 10 TeV muon collider: Cuts

| Cut flow | $\kappa_\mu = 1$ | w/o ISR | $\kappa_\mu = 0$ (2) | CVBF | NVBF |
|---|---|---|---|---|---|
| $\sigma$ [fb] | $WWH$ | | | | |
| No cut | 0.24 | 0.21 | 0.47 | 2.3 | 7.2 |
| $M_{3B} > 0.8\sqrt{s}$ | 0.20 | 0.21 | 0.42 | $5.5 \cdot 10^{-3}$ | $3.7 \cdot 10^{-2}$ |
| $10° < \theta_B < 170°$ | 0.092 | 0.096 | 0.30 | $2.5 \cdot 10^{-4}$ | $2.7 \cdot 10^{-4}$ |
| $\Delta R_{BB} > 0.4$ | 0.074 | 0.077 | 0.28 | $2.1 \cdot 10^{-4}$ | $2.4 \cdot 10^{-4}$ |
| # of events | 740 | 770 | 2800 | 2.1 | 2.4 |
| $S/B$ | 2.8 | | | | |

- Integrated luminosity $\mathcal{L} = (\sqrt{s}/10\ \text{TeV})^2 \cdot 10\,\text{ab}^{-1}$ [1901.06150]
- $S = N_{\kappa_\mu} - N_{\kappa_\mu=1}$, $B = N_{\kappa_\mu=1} + N_{\text{VBF}}$.
- VBF and ISR are mostly excluded by invariant mass cut.
- Angular cut also weaken VBF further.

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# A more proper parameterization: HEFT in the unitary gauge

[E. Celada, T. Han, W. Kilian, N. Kreher, YM, F. Maltoni, D. Pagani, T. Striegl, J. Reuter, and K. Xie, 2312.13082]

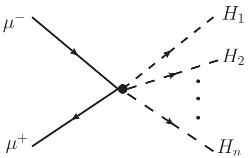
Introduce the form factors $\alpha_n, \beta_n$

$$y_{\mu,n} = \frac{\sqrt{2}m_\mu}{v}\alpha_n, \quad f_{V,n} = \beta_n \lambda$$

In the unitary gauge, the HEFT formalism can be simplified to

$$\mathcal{L} \supset -\frac{m_H^2}{2}H^2 - m_\mu \bar{\mu}\mu - \sum_{n=3}^{\infty} \beta_n \frac{\lambda}{v^{n-4}} H^n - \sum_{n=1}^{\infty} \alpha_n \frac{m_\mu}{v^n} H^n \bar{\mu}\mu$$

The regular "$\kappa$ framework" is extended to include more vertices




$$= \frac{n!\alpha_n m_\mu}{v^n}, \quad \alpha_1 = \kappa_\mu$$

# Interpret the EFT formalism: HEFT VS SMEFT

- Nonlinear HEFT gives $\kappa_\mu = \frac{v}{\sqrt{2}m_\mu} y_1$ [Coleman et al., PR1969, Weinberg, PLB1980, $\cdots$ ]

$$\mathcal{L}_{UH} = \frac{v^2}{4}\,\mathrm{Tr}\left[D_\mu U^\dagger D^\mu U\right] F_U(H) + \frac{1}{2}\partial_\mu H \partial^\mu H - V(H) - \frac{v}{2\sqrt{2}}\left[\bar{\ell}_L^i \tilde{Y}_\ell^{ij}(H) U\left(1-\tau_3\right)\ell_R^j + \text{ h.c.}\right]$$

with $F_U, V, \tilde{Y}$ expanded as

$$F_U(H) = 1 + \sum_{n\geq 1} f_{U,n}\left(\frac{H}{v}\right)^n, V(H) = v^4 \sum_{n\geq 2} f_{V,n}\left(\frac{H}{v}\right)^n, \tilde{Y}_\ell^{ij}(H) = \sum_{n\geq 0} \tilde{Y}_{\ell,n}^{ij}\left(\frac{H}{v}\right)^n$$

- Linear SMEFT [Weinberg PRL1979, Abbott & Wise PRD1980, $\cdots$ ]

$$\mathcal{L} \supset -\sum_{n=1}^{\infty} \frac{c_\varphi^{(2n+4)}}{\Lambda^{2n}}\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^{n+2} - \sum_{n=1}^{\infty} \frac{c_{\ell\varphi}^{(2n+4)}}{\Lambda^{2n}}\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^{n}\left(\bar{\ell}_L \varphi e_R + \text{ h.c.}\right)$$

# Relate the EFTs

$$
\begin{aligned}
\alpha_1 &= 1 + \frac{v^3}{\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(6)}}{\Lambda^2} + \frac{v^5}{\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(8)}}{\Lambda^4} + \frac{3v^7}{4\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(10)}}{\Lambda^6}\,, \\
\alpha_2 &= \frac{3v^3}{2\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(6)}}{\Lambda^2} + \frac{5v^5}{2\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(8)}}{\Lambda^4} + \frac{21v^7}{8\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(10)}}{\Lambda^6}\,, \\
\alpha_3 &= \frac{v^3}{2\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(6)}}{\Lambda^2} + \frac{5v^5}{2\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(8)}}{\Lambda^4} + \frac{35v^7}{8\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(10)}}{\Lambda^6} \\
\alpha_4 &= \frac{5v^5}{4\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(8)}}{\Lambda^4} + \frac{35v^7}{8\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(10)}}{\Lambda^6}\,, \\
\alpha_5 &= \frac{v^5}{4\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(8)}}{\Lambda^4} + \frac{21v^7}{8\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(10)}}{\Lambda^6}\,, \\
\alpha_6 &= \frac{7v^7}{8\sqrt{2}m_\mu}\frac{c_{l\varphi}^{(10)}}{\Lambda^6}\,, \quad \alpha_i = \frac{v}{\sqrt{2}m_\mu}y_{l,i},
\end{aligned}
$$

# Processes in consideration

$\mu^+\mu^-$ annihilations

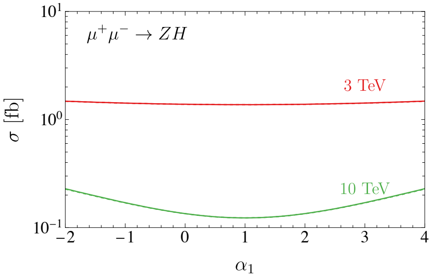
| H \ V | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 0 | - | $Z$ | $Z^2$,$W^2$ | $Z^3$ $W^2Z$ | $Z^4$, $W^4$ $W^2Z^2$ | $Z^5$,$W^2Z^3$ $W^4Z$ |
| 1 | $H$ | $ZH$ | $W^2H$ $Z^2H$ | $W^2ZH$ $Z^3H$ | $W^4H$, $Z^4H$ $W^2Z^2H$ | - |
| 2 | $H^2$ | $ZH^2$ | $W^2H^2$ $Z^2H^2$ | $W^2ZH^2$ $Z^3H^2$ | - | - |
| 3 | $H^3$ | $ZH^3$ | $W^2H^3$ $Z^2H^3$ | - | - | - |
| 4 | $H^4$ | $ZH^4$ | - | - | - | - |
| 5 | $H^5$ | - | - | - | - | - |

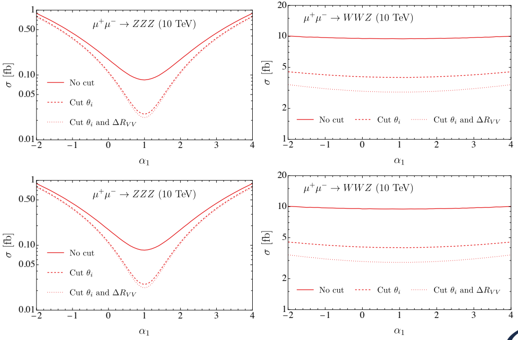
[E. Celada, T.Han, W.Kilian, N. Kreher, YM, F. Maltoni, D. Pagani, J. Reuter, T. Striegl, and K.Xie, 2312.13082 ]

# Start from the simplest

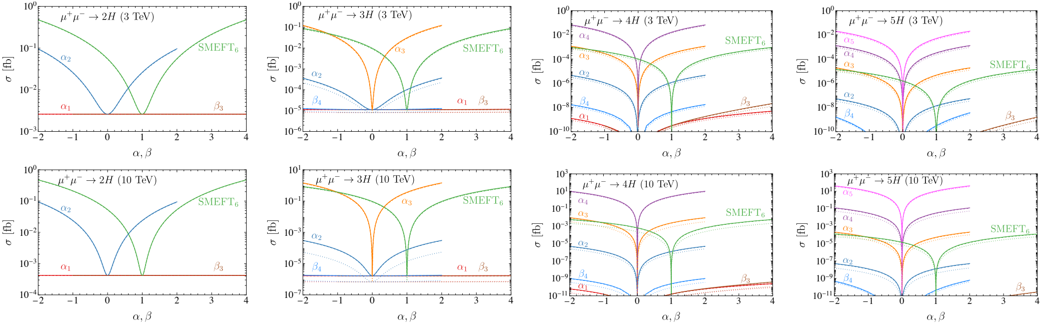
## Processes depend on $\alpha_1$ only: $ZH$ production and $3V$ production

- The normal $\kappa$ framework is good enough
- The sign of the muon Yukawa coupling ($\alpha_1$) can be measured



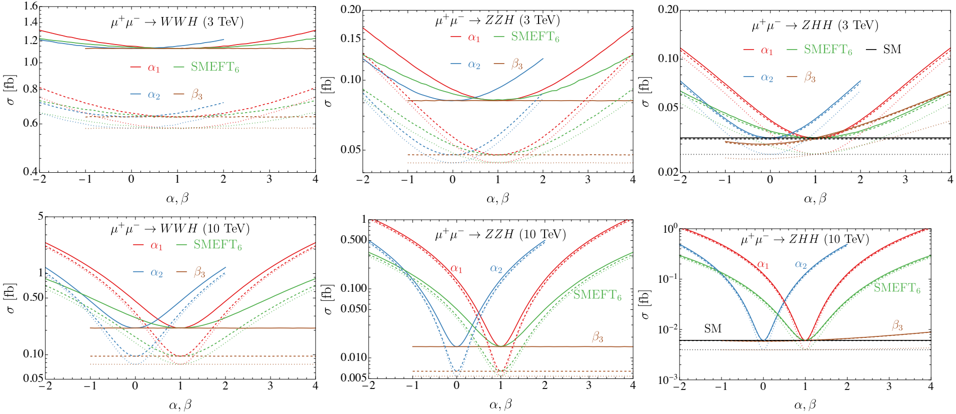
# Multi-Higgs production processes: $\mu^+\mu^- \to nH$




- The cross sections are insensitive to Higgs self-couplings ($\beta_{3,4}$).
- One could directly measure $\mu\mu nH$ vertices ($\alpha_n$) with the $n$-Higgs production
- In dim-6 SMEFT $\Delta\alpha_1 = 2\alpha_2/3 = 2\alpha_3$
  $\Rightarrow$ precisely measure $c_6/\Lambda^2$ via $2H$ $3H$ production.

# Higgs associated gauge boson production

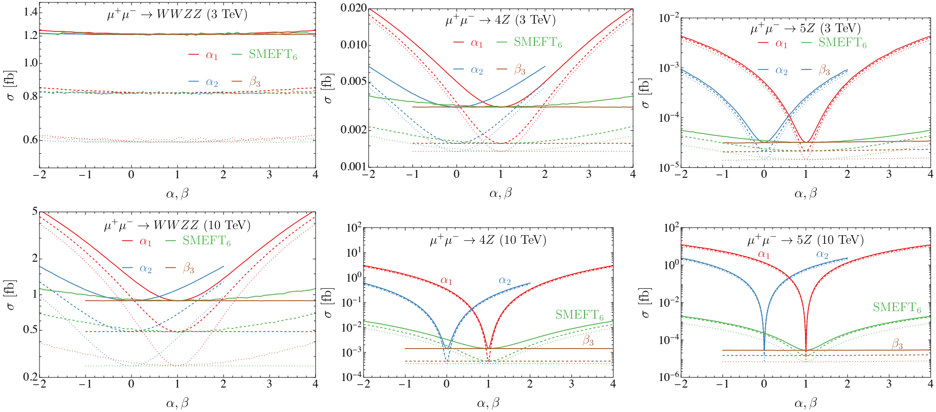
## Constrain $(\alpha_1,\ \alpha_2)$ simultaneously: e.g. $WWH, ZZH, ZHH$




- Weak dependence on Higgs self-couplings ($\beta_3$)
- The $\alpha_{1,2}$ dependence is much stronger at 10 TeV

# Multi gauge boson production

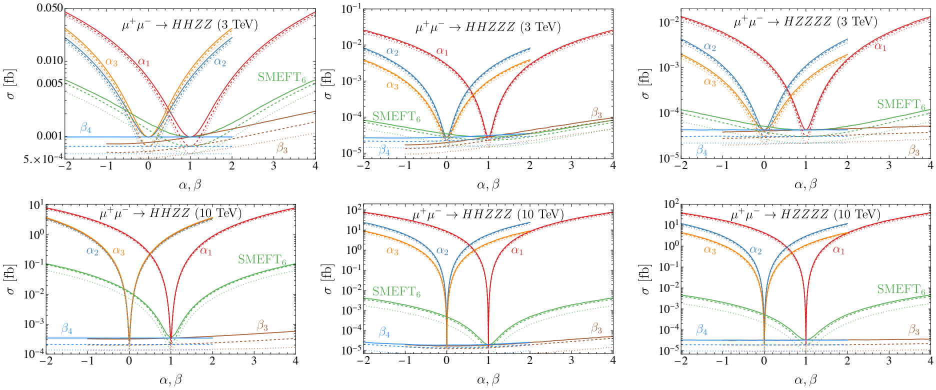
## **Constrain $(\alpha_1,\ \alpha_2)$ at 10 TeV :** e.g. $WWZZ, 4Z, 5Z$




- Weak dependence on Higgs self-couplings ($\beta_3$)
- The $\alpha_{1,2}$ dependence is much stronger at 10 TeV

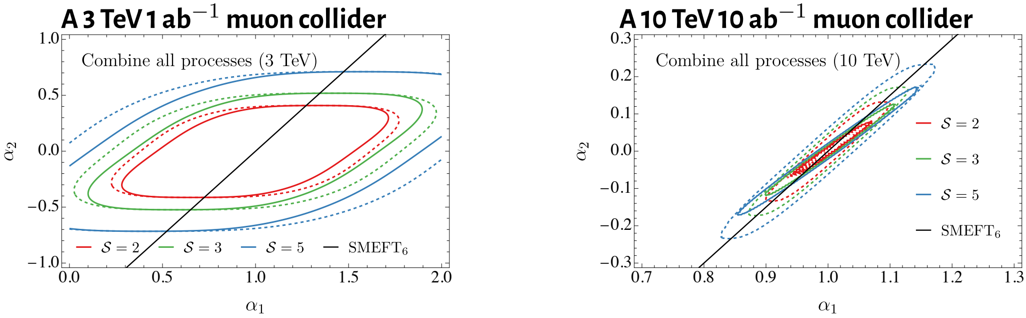
# There are more processes

## $\alpha_3$ dependence also shows up: e.g. $HHZZ, HHZZZ, HZZZZ$




- Constrain $(\alpha_1, \alpha_2, , \alpha_3)$ simultaneously

# Combine the constrains on $(\alpha_1,\ \alpha_2)$



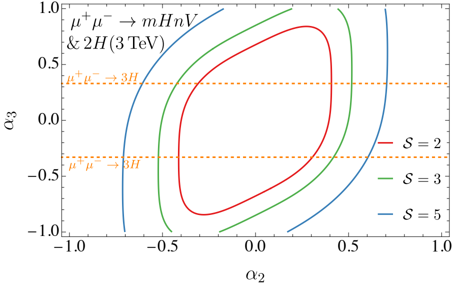

- Guaranteed to measure the sign of the muon Yukawa coupling $\alpha_1$
- The 10 TeV machine can do much better than the 3 TeV machine does
- With assumption $\alpha_3 = 0$, one could further improve the measurement on $\alpha_1$ and $\alpha_2$.

[E. Celada, T.Han, W.Kilian, N. Kreher, YM, F. Maltoni, D. Pagani, J. Reuter, T. Striegl, and K.Xie, 2312.13082 ]

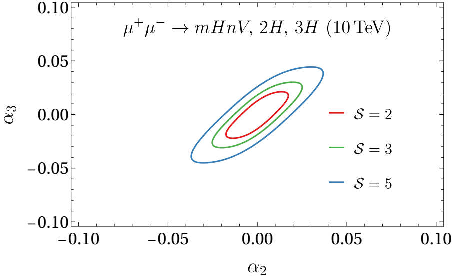
# What if $\alpha_1 = 1$?

- The $\mu\mu H$ could be measured well at other colliders , e.g. HL-LHC or FCC-ee
- We could assume $\alpha_1 = 1$ and focus on the anomalous interactions
- Note this breaks the dim-6 SMEFT

**A 3 TeV 1 ab$^{-1}$ muon collider**




**A 10 TeV 10 ab$^{-1}$ muon collider**



# Summary and prospects

- Multi-TeV lepton colliders are amazing:
  - A new energy frontier to go beyond the LHC: An EW LHC
  - Our first time to play with another flavor
- We explored the new opportunity to measure the Higgs-muon interactions at the future muon collider
  - The $\kappa$ framework is not enough, so we introduce $\alpha_n$ to denote the $\mu\mu nH$ vertices
  - The sign of the SM muon Yukawa coupling ($\alpha_1$ could be measured), which cannot be done at the other machines
  - The $n$-Higgs production processes could directly measure $\alpha_n$
  - $(\alpha_1, \alpha_2)$ dependence shows up together in most processes, we measure them simultaneously
  - With some assumptions, e.g. $\alpha_3 = 0$ or $\alpha_1 = 1$, we could further improve the constraints