Multiple boson production at high-energy muon colliders to probe the Higgs-muon coupling

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Theory and Phenomenology of Fundamental Interactions

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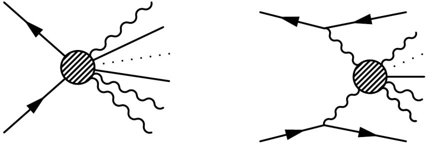
A multi-TeV lepton collider is amazing



- $\ell^+\ell^-$ annihilation **probes TeV scale directly**
- VBF **scans the new physics hints in the full spectrum**
  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!

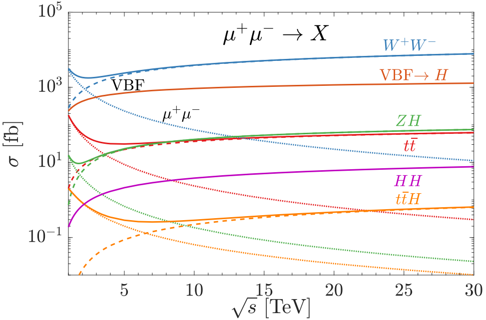
Challenges:

Be careful about the radiations!
EW NLO shall be necessary, just like the NLO QCD at LHC.

The full picture: An electroweak version of Tevatron

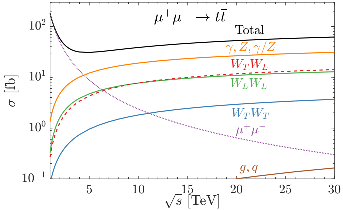
Just like in hadronic collisions:

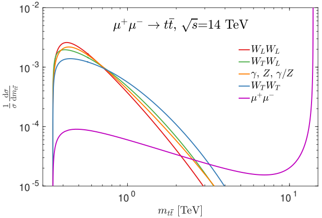
$\mu^+\mu^- \to$ exclusive particles + remnants



[T. Han, Y. Ma, K.Xie 2007.14300]

One example: $\mu^+\mu^- \to t\bar{t} + X$





Compare the “EW Tevatron” with LHC

The lepton collider is better in studying EW physics

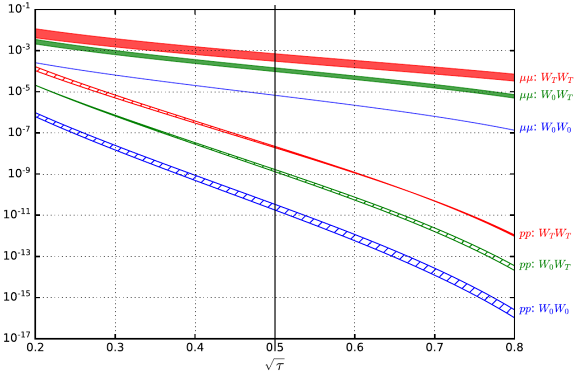
$$\mathcal{L}_{W^+_{\lambda_1} W^-_{\lambda_2}} = \int_\tau^1 \frac{\mathrm{d}\xi}{\xi} f_{W_{\lambda_1}}(\xi, \mu_f) f_{W_{\lambda_1}}(\frac{\tau}{\xi}, \mu_f)$$

Consider the two colliders in the same ring

$$\sqrt{s}_{\mu\mu} = \sqrt{s}_{pp}$$

For $2 \to 1$ processes, take a benchmark

$$\sqrt{\tau} = \frac{M}{\sqrt{s}} = \frac{1}{2}$$



The ratio $\mu\mu/pp$ is larger than 10^4!

[2005.10289]

Muon collider: Our first time to play with beams in 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, in progress]

- 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?**

EFT parameterizations

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

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

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

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

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

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

HEFT in the unitary gauge: the extended κ framework

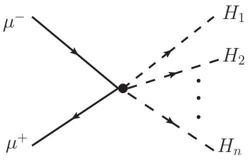
Introduce the form factors α_n, β_n

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

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 "κ framework" is extended to include more vertices



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

Relate the two EFTs

$$\alpha_1 = \frac{v}{\sqrt{2}m_\mu} y_{\ell,1} = 1 + \frac{v^3}{\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{v^5}{\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{3v^7}{4\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_2 = \frac{v}{\sqrt{2}m_\mu} y_{\ell,2} = \frac{3v^3}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{5v^5}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{21v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_3 = \frac{v}{\sqrt{2}m_\mu} y_{\ell,3} = \frac{v^3}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(6)}}{\Lambda^2} + \frac{5v^5}{2\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{35v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

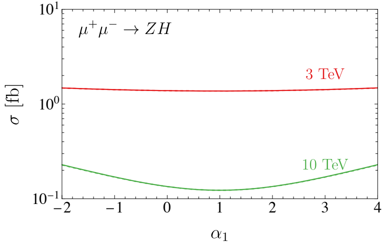
$$\alpha_4 = \frac{v}{\sqrt{2}m_\mu} y_{\ell,4} = \frac{5v^5}{4\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{35v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

$$\alpha_5 = \frac{v}{\sqrt{2}m_\mu} y_{\ell,5} = \frac{v^5}{4\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(8)}}{\Lambda^4} + \frac{21v^7}{8\sqrt{2}m_\mu}\frac{c_{\ell\phi}^{(10)}}{\Lambda^6},$$

Measure the $\mu\mu H$ vertex

There are processes that depend on only α_1: $\mu^+\mu^- \to ZH$ and $\mu^+\mu^- \to V^3$

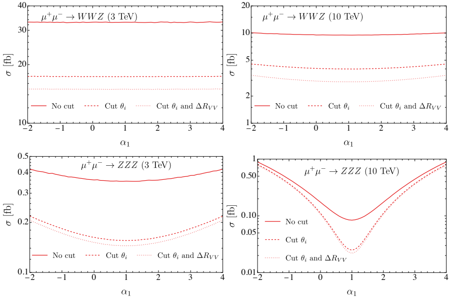
- ZH production



- Sign of Yukawa: $\alpha_1 = 1$ VS $\alpha_1 = -1$

$$\mathcal{S}^{\pm}_{3\,\mathrm{TeV}} = 1.23, \quad \mathcal{S}^{\pm}_{10\,\mathrm{TeV}} = 11.8$$
$$\mathcal{S}_{10\,\mathrm{TeV}} = 2.09, \quad |\Delta\alpha_1| \leq 0.8$$

- V^3 production



- Measure α_1 more precisely

$$\mathcal{S}^{WWZ}_{10\,\mathrm{TeV}} = 2.1, \quad |\Delta\alpha_1| \leq 0.8$$
$$\mathcal{S}^{ZZZ}_{10\,\mathrm{TeV}} = 2.2, \quad |\Delta\alpha_1| \leq 0.2.$$

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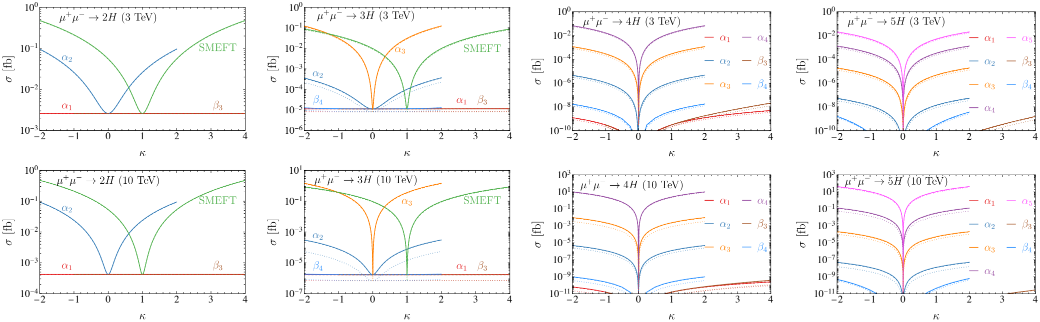
Processes in consideration

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, coming out soon]

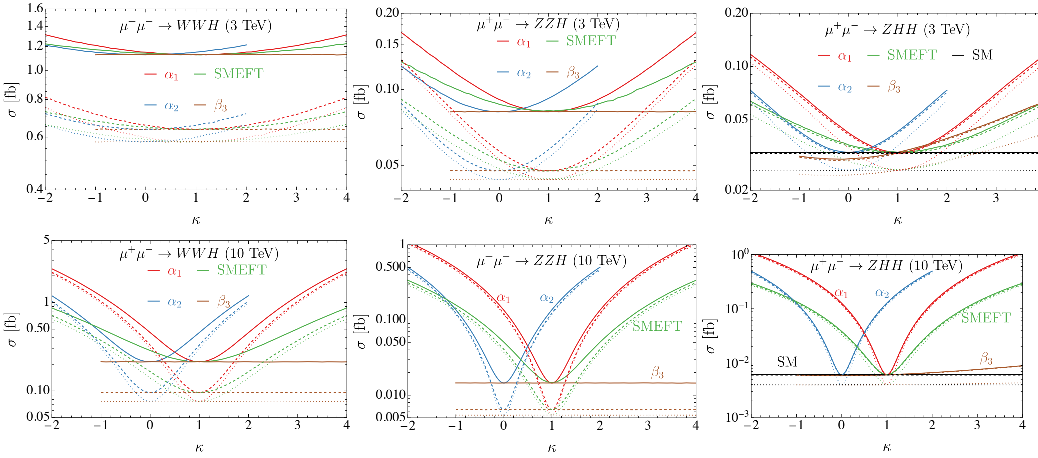
Multi-Higgs production processes: $\mu^+\mu^- \to H^n$

The cross section is solely dependent on $\alpha_n \Rightarrow$ Measure α_n directly

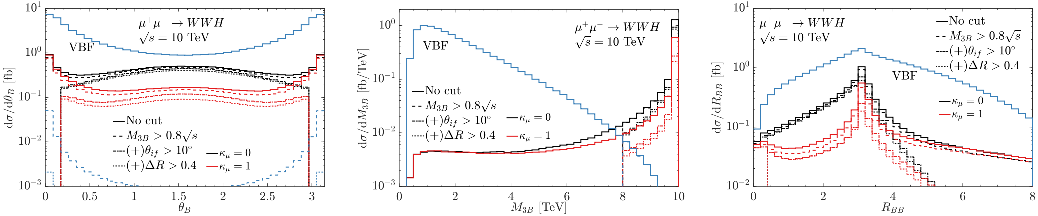


Other processes: constrain $(\alpha_1,\ \alpha_2)$ simultaneously

Example: WWH, ZZH, ZHH



Kinematics: WWH at a 10 TeV muon collider



- 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 $W \to WH$

[T.Han, W.Kilian, N. Kreher, YM, J. Reuter, and K.Xie, JHEP 12 (2021) 162, 2108.05362]

Cuts: WWH at a 10 TeV muon collider

Cut flow	$\kappa_\mu = 1$	w/o ISR	$\kappa_\mu = 0$ (2)	CVBF	NVBF
σ [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	$5.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-2}$
$10^\circ < \theta_B < 170^\circ$	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.

[T.Han, W.Kilian, N. Kreher, YM, J. Reuter, and K.Xie, JHEP 12 (2021) 162, 2108.05362]

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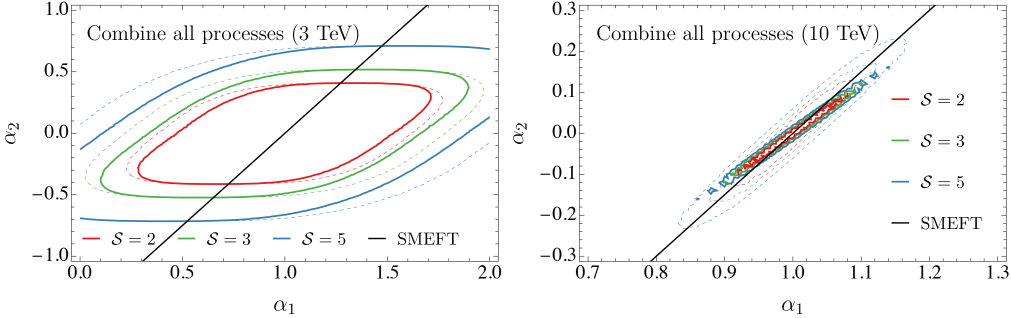
Constrains on $(\alpha_1,\ \alpha_2)$



Summary and prospects

Higgs is special and important

- The Higgs sector is the portal to new physics beyond SM.
  - Testing the SM mass generation mechanism indirectly helps BSM physics searches.
  - Measuring the vertices that do not exit in SM directly aim at BSM physics
  - The Yukawa couplings of the 3rd generation fermions are precisely measured $\Rightarrow$ The 2nd generation is the next target.

Multi-TeV muon collider is cool

- A dream machine with many physics opportunities
- Two mechanisms with different kinematic features: lepton collision and VBF
- The main background is from VBF: Introduce kinematic cuts $M_F > 80\%\sqrt{s}$
- The sign of $\mu\mu H$ can be determined via $\mu^+\mu^- \to ZH$
- The $\mu\mu H^n$ couplings can be determined via multi-boson production processes directly
- The $\mu\mu H$ and $\mu\mu H^2$ can be constrained simultaneously in the (α_1, α_2) contour plots