Muon Yukawa couplings at the high-energy muon collider

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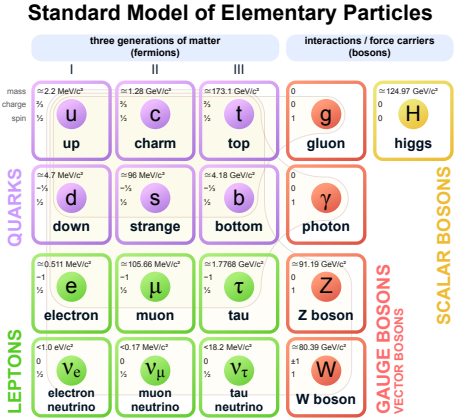
[T.Han, W.Kilian, N. Kreher, YM, J. Reuter, and K.Xie, JHEP 12 (2021) 162, 2108.05362]

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

Why Higgs?

A well understood and well tested model

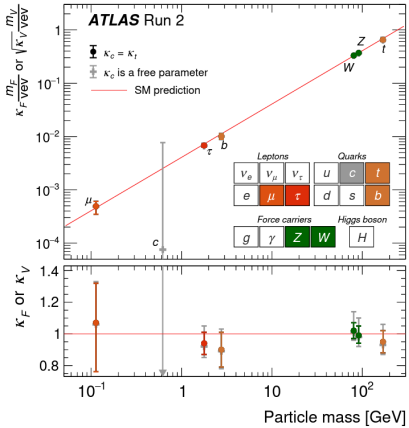


- Model doesn't make sense without Higgs or something like it
- The Higgs is a scalar particle whose interactions with other particles are predicted in terms of their masses
- It provides masses to all other elementary particles

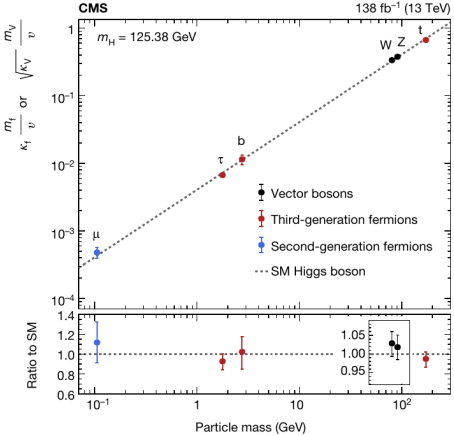
Higgs physics: A portal to new physics

- LHC has gone from discovery to precision
- A telescope to high scale physics
- Interplay of theory and experiment is important

Measure the Higgs couplings



[Nature 607 (2022) 52]



[Nature 607 (2022) 60]

The next task is to complete the above plots

Why Yukawa couplings?

Measuring the Yukawa couplings is important

- Directly test the SM Higgs mechanism that generates the masses.
- The Yukawa couplings for heavy fermions are well measured (to 5σ level)

$$y_f = \sqrt{2} m_f^{\rm SM}/v, \quad f = t, b, \tau$$

- **The next target is the second generation fermions!**

The physics motivation:

- **A naive question:** 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:** The fermion mass is not (only) generated by SM Higgs.
  $\Rightarrow$ What if the possible BSM physics modifies the $\mu\mu H$ coupling ($y_\mu = \kappa_\mu y_\mu^{\rm SM}$)?
  $\Rightarrow$ Is there new vertex, i.e. $\mu\mu H^n$ coupling?

EFT parameterizations

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

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

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, $\cdots$]

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

HEFT in the unitary gauge: the extended κ framework

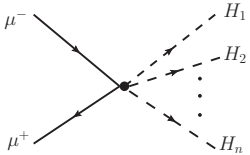
Introduce the form factors α_n, β_n

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

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

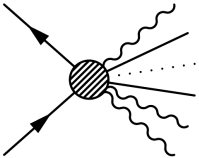


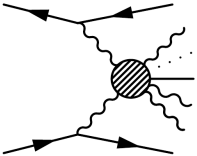
$$= \frac{n!\alpha_n m_\mu}{v^n}, \quad \alpha_1 = \kappa_\mu$$

Physics at high-energy lepton colliders: electroweak Tevatron

New phenomenology at a multi-TeV lepton collider:

1. Multi-boson production (annihilation)
2. …and vector boson fusion (**VBF**) to multi-bosons,
   leading to multi-fermion final states with resonance structure.





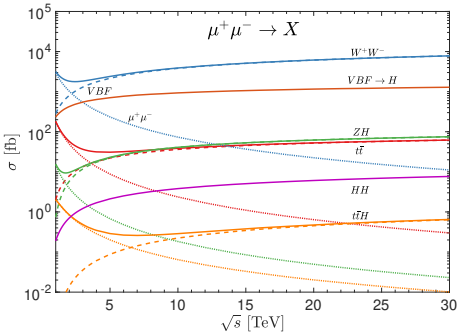
[Barger, Cheung, Han, Phillips 1995] [Boos, He, Kilian, Pukhov, Yuan, Zerwas 1998]

Task:
Measure all interactions of multiple SM particles exclusively and with precision, from threshold to up to 2 orders of magnitude above EW scale.

The full picture: Semi-inclusive processes

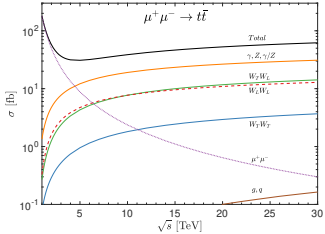
Just like in hadronic collisions:

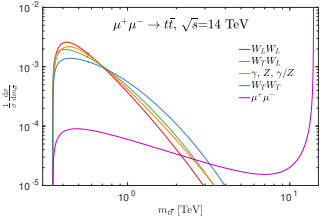
$\mu^+\mu^- \to$ exclusive particles + remnants



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

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



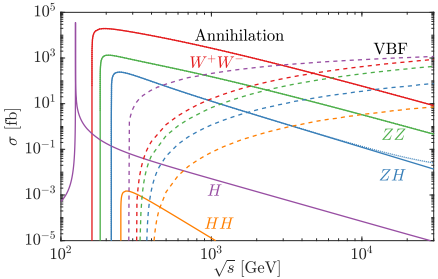


Multi-boson production and the sensitivity to new physics

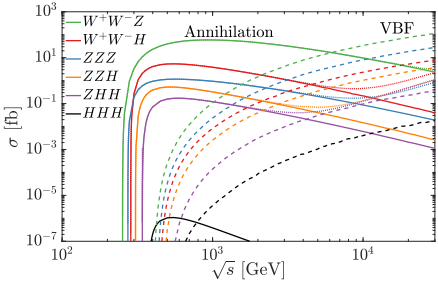
First glance: $\alpha_1 = 1$ VS $\alpha_1 = 0$

- **SM**: $\lambda(\text{Muon} - \text{Higgs}) \sim y_\mu^{\text{SM}} = \sqrt{2} m_\mu^{\text{SM}}/v$
- **Possible BSM physics**: $m_\mu = m_\mu^{\text{SM}}$, $\lambda(\text{Muon} - \text{Higgs}) \sim \alpha_1 y_\mu^{\text{SM}}$, e.g. $\alpha_1 = 0$

Two-boson final states



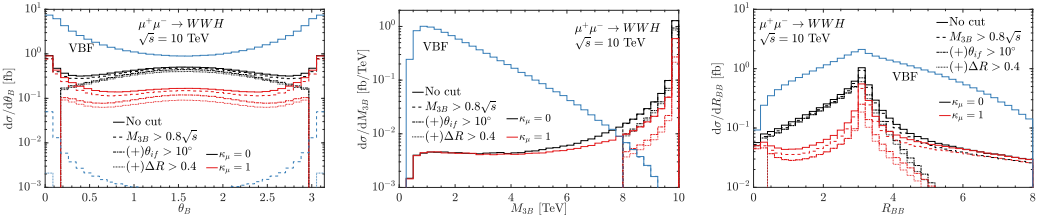
Three-boson final states



New physics signal shows up in the high energy region

[T.Han, W.Kilian, N. Kreher, YM, J. Reuter, and K.Xie, JHEP 12 (2021) 162, 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 $W \to WH$

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

WWH at a 10 TeV muon collider: Cuts

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	$5.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-2}$
$10° < \theta_B < 170°$	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.

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

Processes in consideration

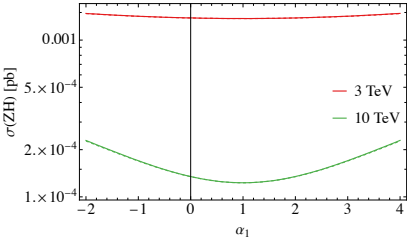
H \ V	0	1	2	3	4	5
0	-	Z	Z^2,W^2	Z^3 W^2Z	Z^4, W^4 W^2Z^2	Z^5,W^2Z^3 W^4Z
1	H	ZH	W^2H Z^2H	W^2ZH Z^3H	W^4H, Z^4H W^2Z^2H	-
2	H^2	ZH^2	W^2H^2 Z^2H^2	W^2ZH^2 Z^3H^2	-	-
3	H^3	ZH^3	W^2H^3 Z^2H^3	-	-	-
4	H^4	ZH^4	-	-	-	-
5	H^5	-	-	-	-	-

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

Measure the $\mu\mu H$ vertex

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

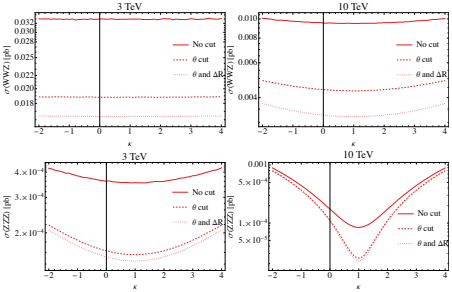
- ZH production



- 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

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

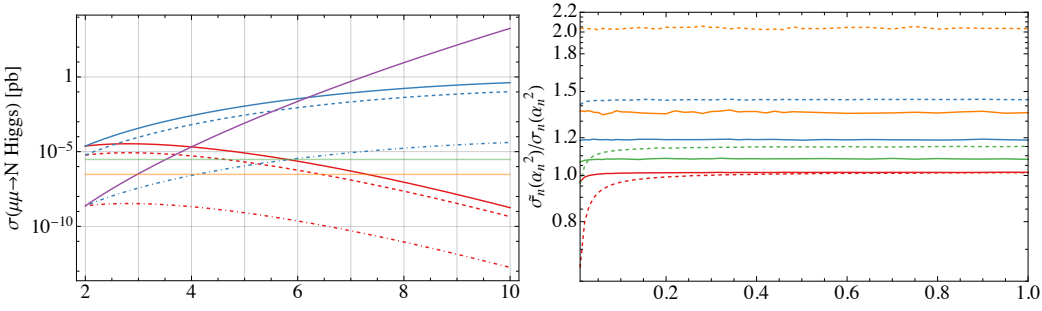
Measure the $\mu\mu H^n$ vertices: Multi-Higgs production processes

Dominant contribution from the contact diagram: $\mu\mu H^n$ vertex

$$\sigma_{\rm BSM}(\mu^+\mu^- \to H^n) = \sigma_{\rm SM}^{\rm (loop)} + \sigma_n(\alpha_n^2) + \mathcal{O}(\alpha_m,\, \alpha_n),\; m \leq n,$$

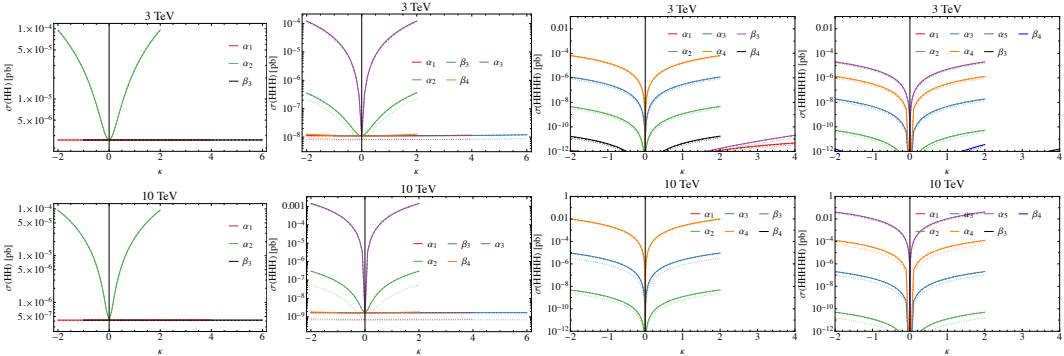
Approximate in the massless limit

$$\sigma_n(\alpha_n^2) \approx \tilde{\sigma}_n(\alpha_n^2) = \frac{n! m_\mu^2 s^{n-2} \alpha_n^2}{2^{4n-3}\pi^{2n-3} v^{2n} \Gamma(n)\Gamma(n-1)}.$$



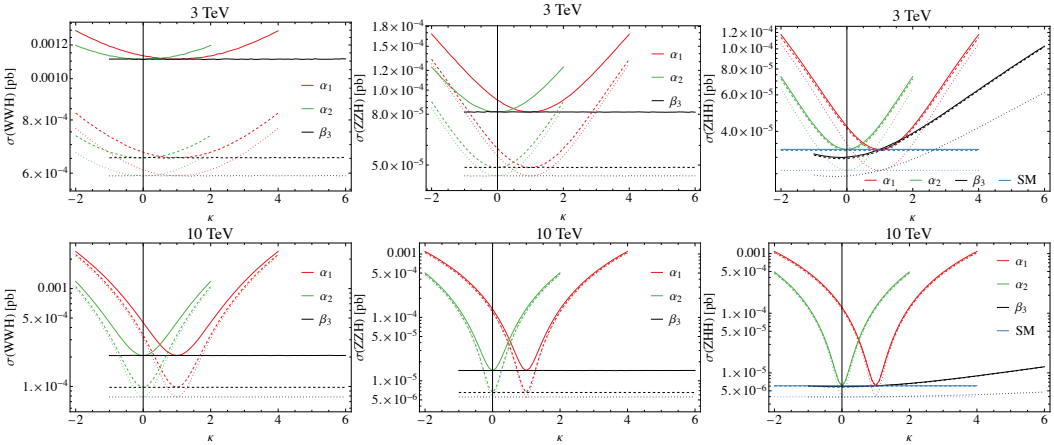
Multi-Higgs production processes: $\mu^+\mu^- \to H^n$

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

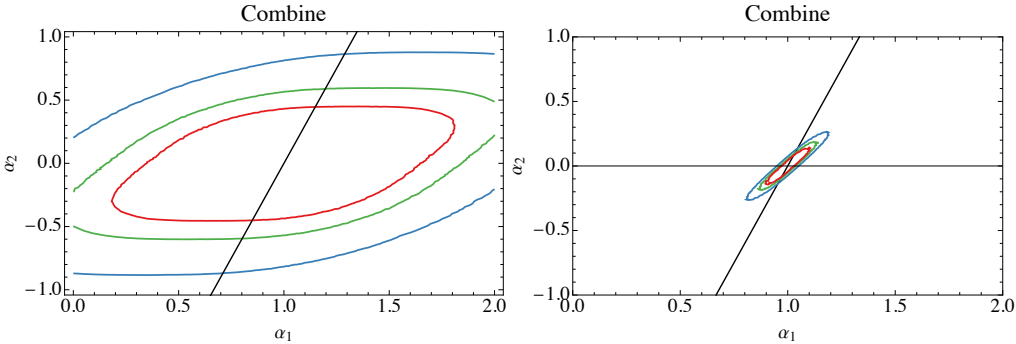


Other processes: constrain $(\alpha_1,\ \alpha_2)$ simultaneously

Example: WWH, ZZH, ZHH



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



Summary and prospects

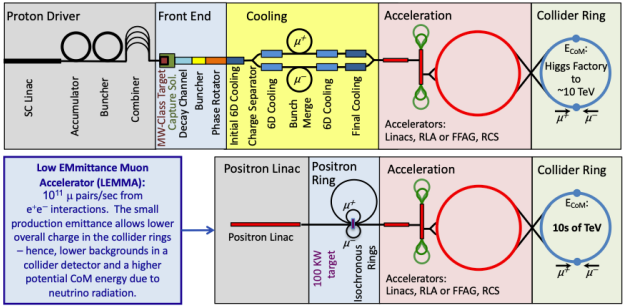
Higgs is special and important

- 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

Muon collider implementations



Muon Accelerator Program

map.fnal.gov [1901.06150,1907.08562]

- Protons → pions → muons
- 6D cooling is needed

Low EMittance Muon Accelerator

web.infn.it/LEMMA [1901.06150]

- $e^+e^- \to \mu^+\mu^-$:
  45 GeV e^+ to rest e^-
- Cooling is not a problem
- High luminosity is challenging