Higgs-muon interactions at multi-TeV muon colliders

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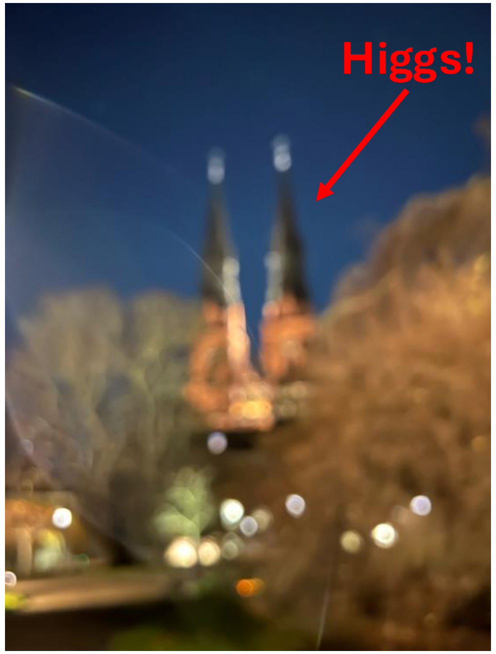
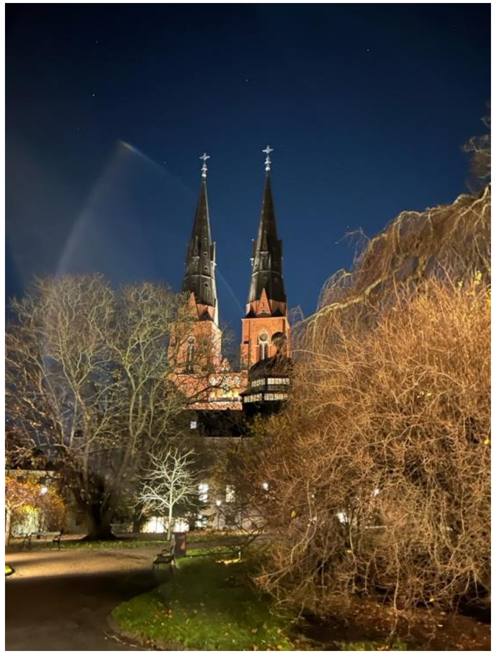
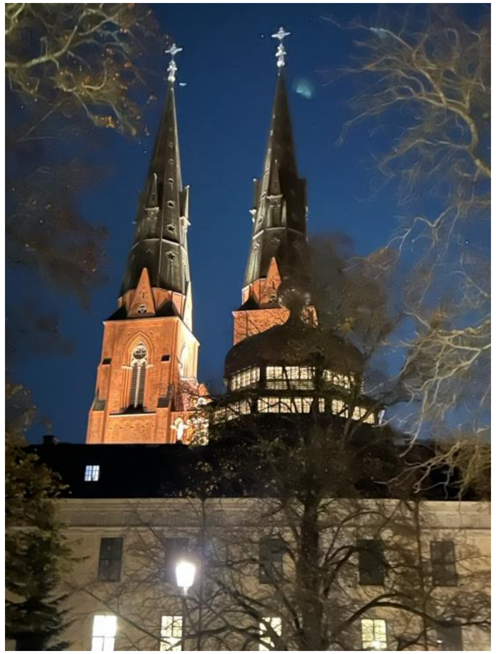
Future Colliders

LHC
(now)





HL-LHC
Near future



e+e- Higgs factory
Next step
FCCee, CEPC, CLIC, ILC, C3

Dream Machine
Far future

100 TeV FCChh
10 TeV muC

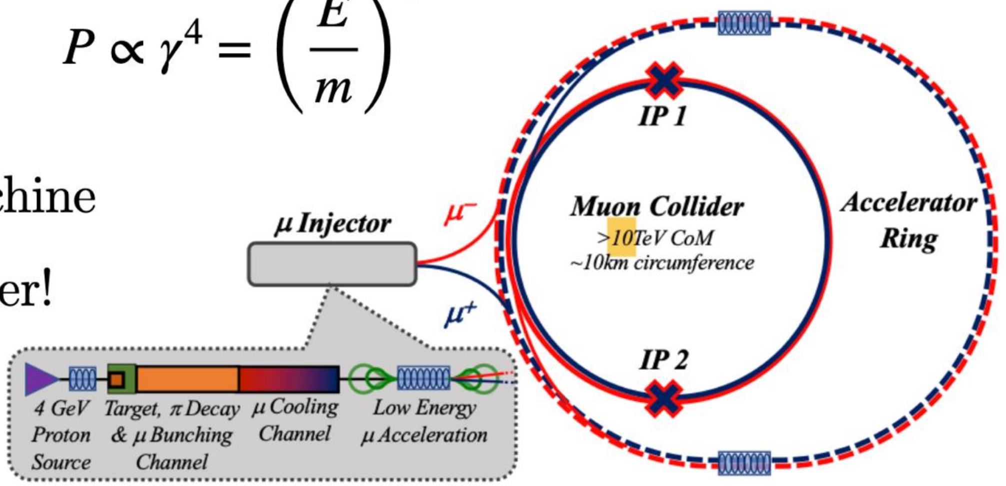
Muon Collider: main advantages

Same motivation as LHC: Muon is a “heavier electron”

Consider power losses from synchrotron radiation

$$P \propto \gamma^4 = \left(\frac{E}{m}\right)^4$$

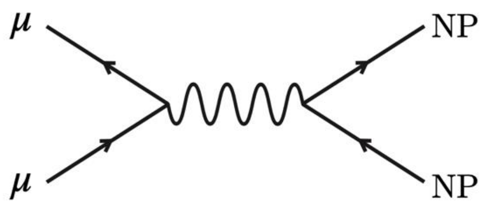
At the same energy, e^+e^- machine loses $\left(m_\mu/m_e\right)^4 \sim 10^9 \times$ power!



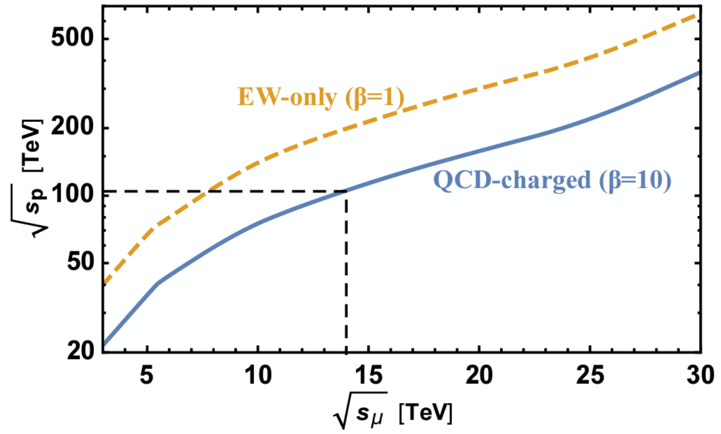
- A smaller and a circular machine is possible
- Unlike the proton as a composite particle, E_{CM} efficient in $\mu^+\mu^-$ annihilation
- Much smaller beam-energy spread: $\Delta E/E$ ~ 0.01å% - 0.001%

The exciting high-energy frontier (10 TeV)

Direct search for heavy particles



$$\sigma \sim \frac{1}{s} = \frac{1}{E^2}$$



1901.06150

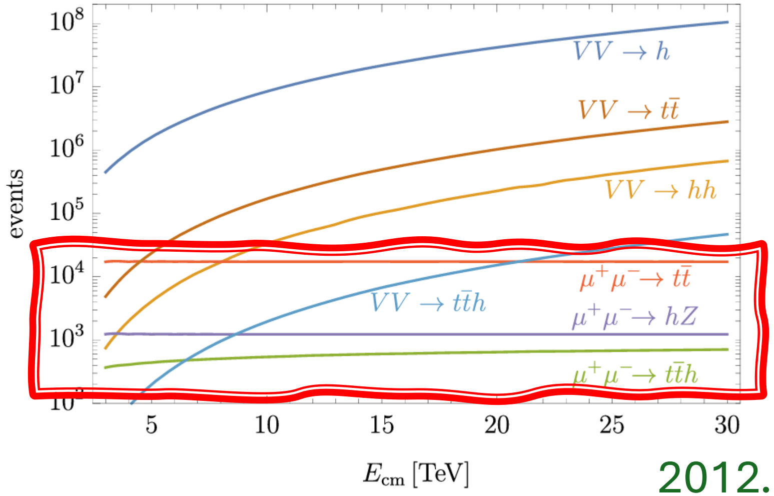
Expected luminosity

$$\mathscr{L}_{\text{int}} = 10\,\text{ab}^{-1} \times \left(\frac{E_{\text{cm}}}{10\,\text{TeV}}\right)^2$$

$$\mathscr{L} \sim E^2$$

10^4 events
$\rightarrow \mathcal{O}(1\%)$ precision

$\mathscr{L} \sim 10\ \text{fb}^{-1}$ at 10 TeV

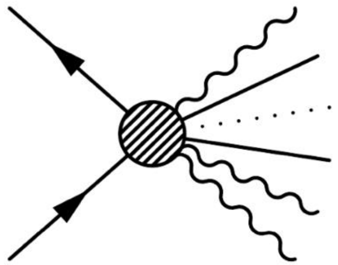


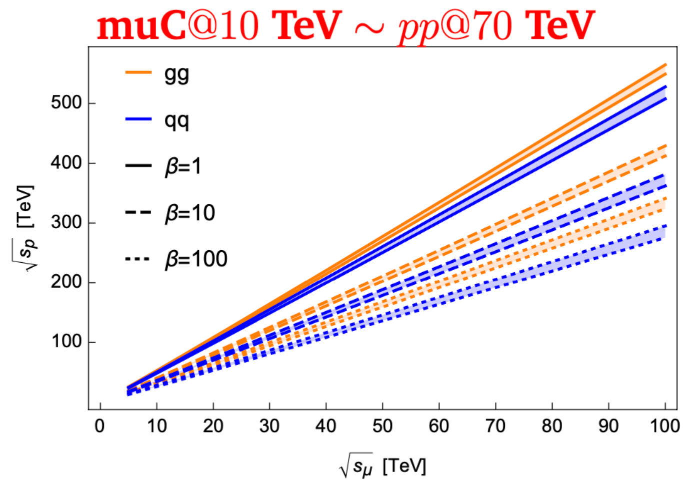
Read more in *Towards a Muon Collider*, 2303.08533

2012.11555

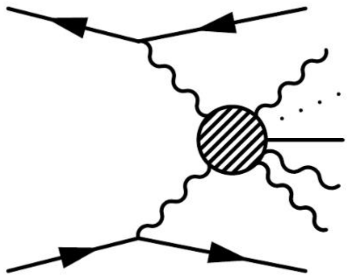
The general physics picture of muC

- Annihilation





- VBF



Take luminosity 10 ab^{-1}

10M H, 500K HH @ 10 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!

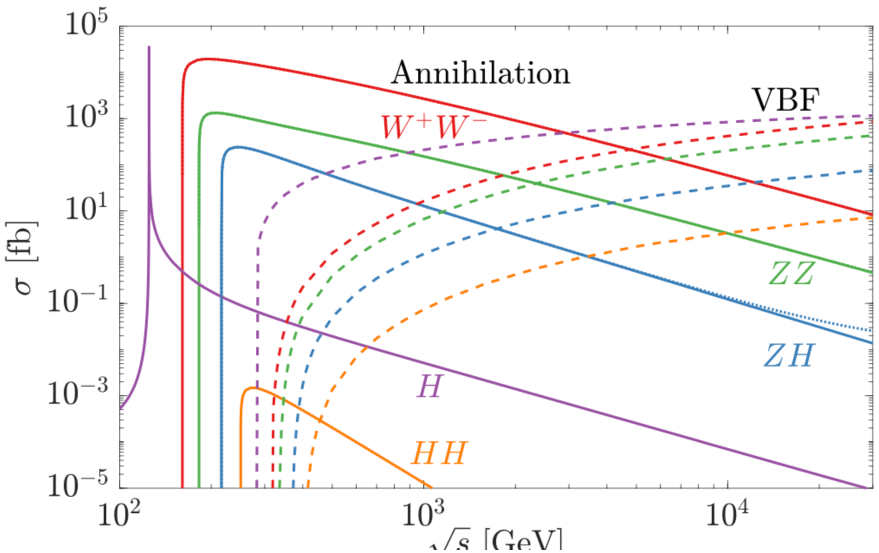
EW NLO shall be necessary, just like the NLO QCD at LHC.

Muon Yukawa in multi-boson production

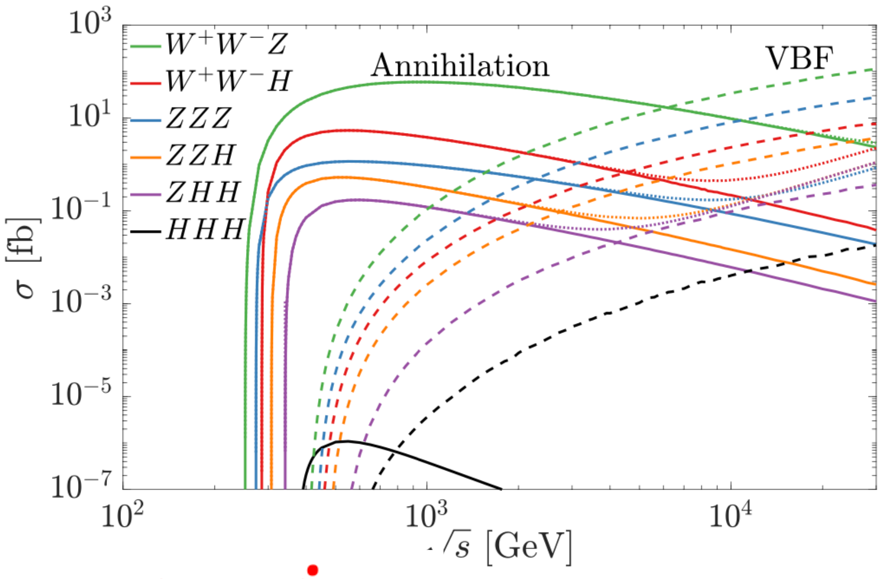
BSM muon Yukawa will break the gauge cancellation

Use $\kappa_\mu = 0$ to mimic possible BSM new physics

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

A more proper parameterization: EFT

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

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

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, · · ·]

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

Relate the EFTs

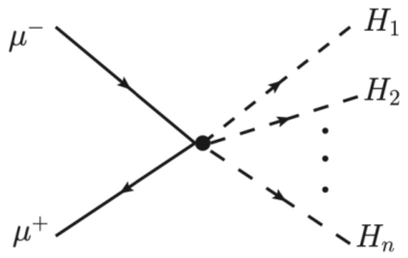
Introduce the form factors α_n, β_n

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

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



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

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

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

Processes in consideration

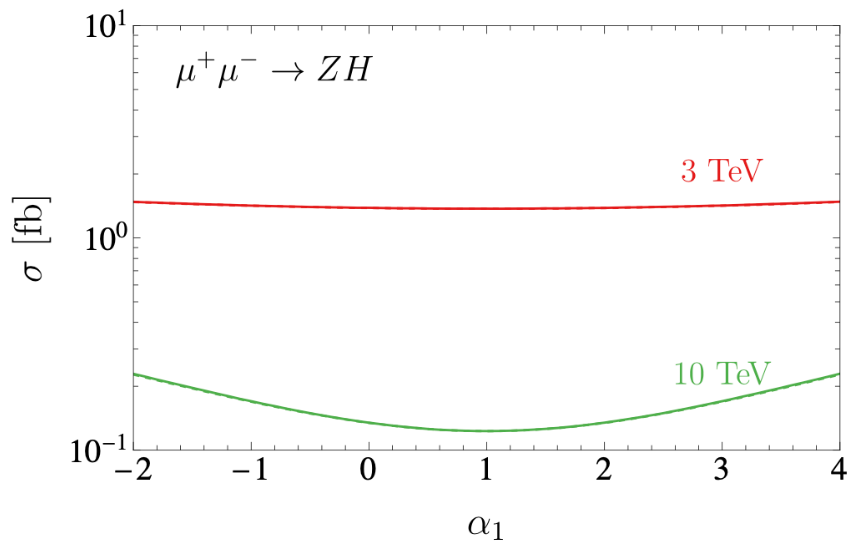
$\mu^+\mu^-$ annihilations

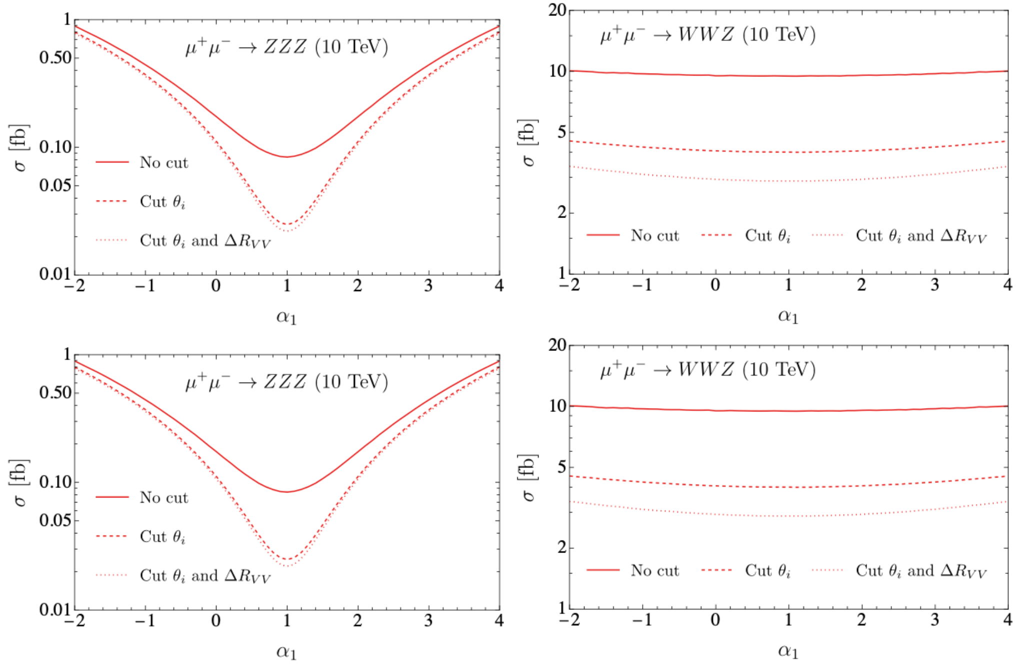
H \ V	0	1	2	3	4	5
0	-	Z	Z^2, W^2	Z^3 W^2Z	Z^4, W^4 W^2Z^2	Z^5, W^2Z^3 W^4Z
1	H	ZH	W^2H Z^2H	W^2ZH Z^3H	W^4H, Z^4H W^2Z^2H	-
2	H^2	ZH^2	W^2H^2 Z^2H^2	W^2ZH^2 Z^3H^2	-	-
3	H^3	ZH^3	W^2H^3 Z^2H^3	-	-	-
4	H^4	ZH^4	-	-	-	-
5	H^5	-	-	-	-	-

The simplest case

Processes depend on α_1 only: ZH production and $3V$ production

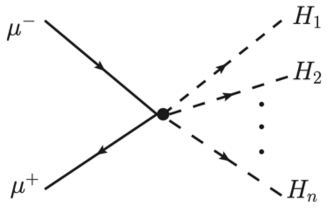
- The normal κ framework is good enough
- The sign of the muon Yukawa coupling (α_1) can be measured

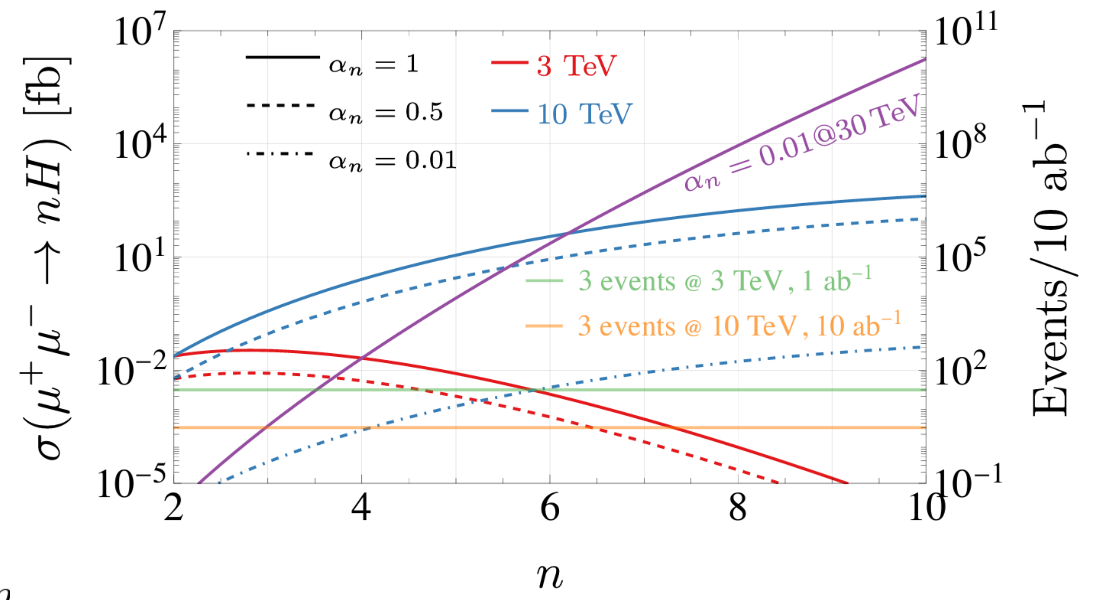




The “golden channel”

Multi-Higgs production is dominated by the contact diagrams

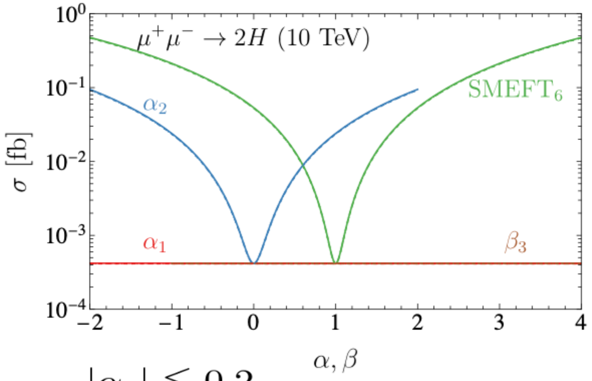




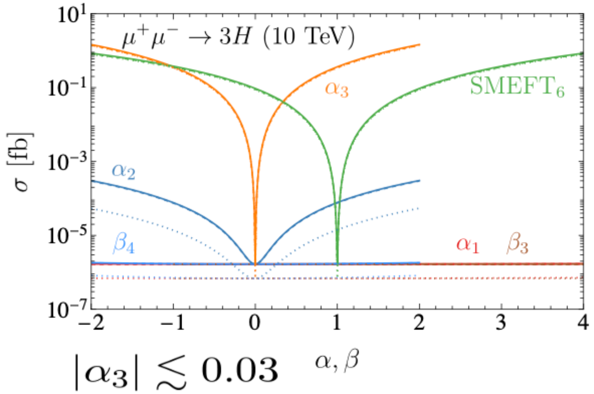
The high-energy (massless) limit $|\alpha_5| \lesssim 0.01$

$$\sigma(\mu^+\mu^- \to nH) \approx \bar{\sigma}_{X_{n00}} = \frac{n\alpha_n^2 m_\mu}{8\Gamma(n-1)(4\pi)^{2n-3}v^{2n}}$$

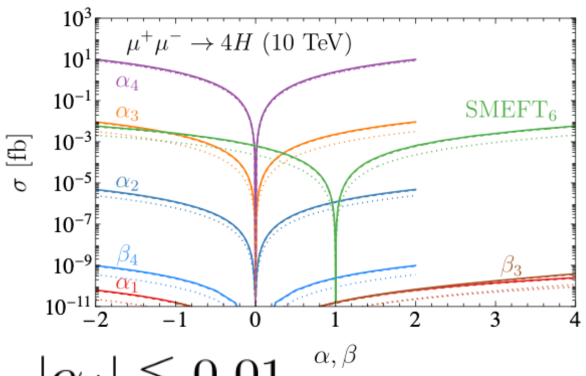
Realistic case



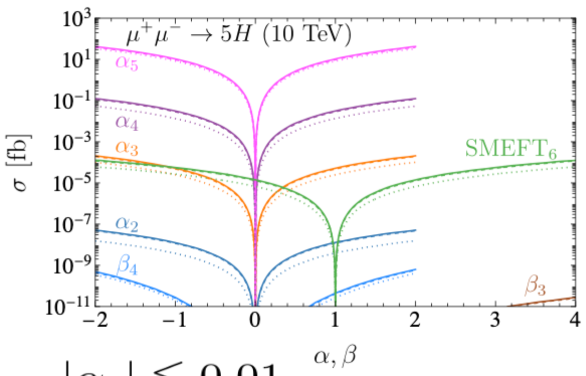
$|\alpha_2| \lesssim 0.2$



$|\alpha_3| \lesssim 0.03$



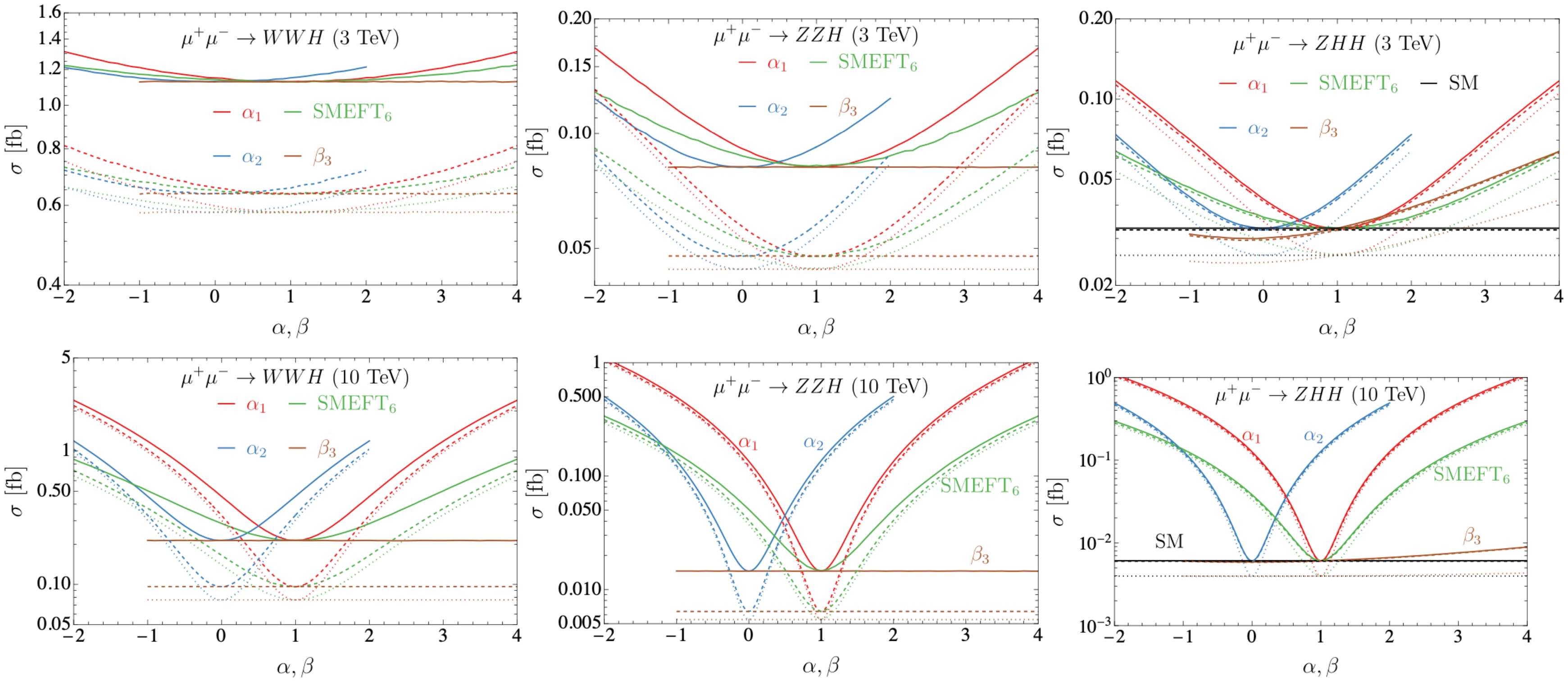
$|\alpha_4| \lesssim 0.01$



$|\alpha_5| \lesssim 0.01$

Higgs associated gauge boson production

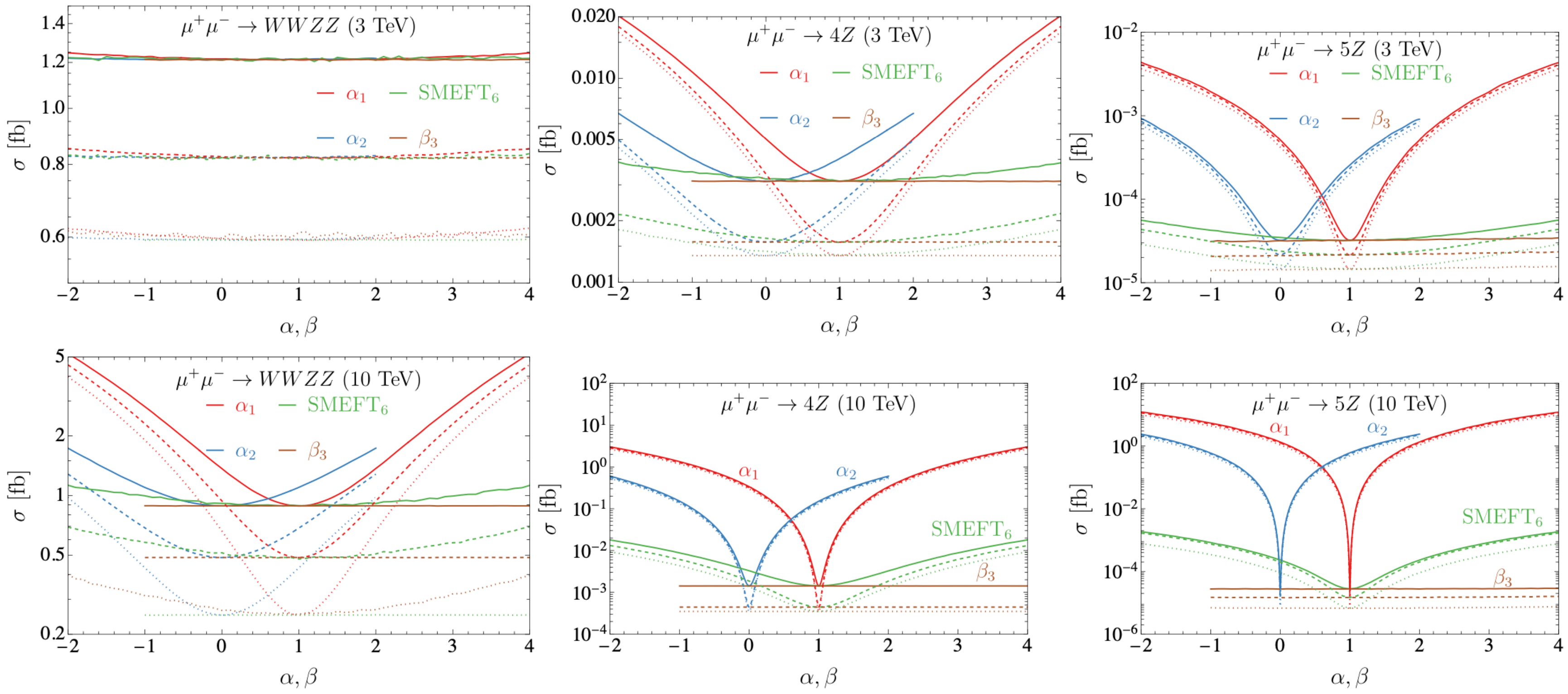
Constrain $(\alpha_1,\ \alpha_2)$ simultaneously: e.g. WWH, ZZH, ZHH



- Weak dependence on Higgs self-couplings (β_3)
- The $\alpha_{1,2}$ dependence is much stronger at 10 TeV

Multi gauge-boson production

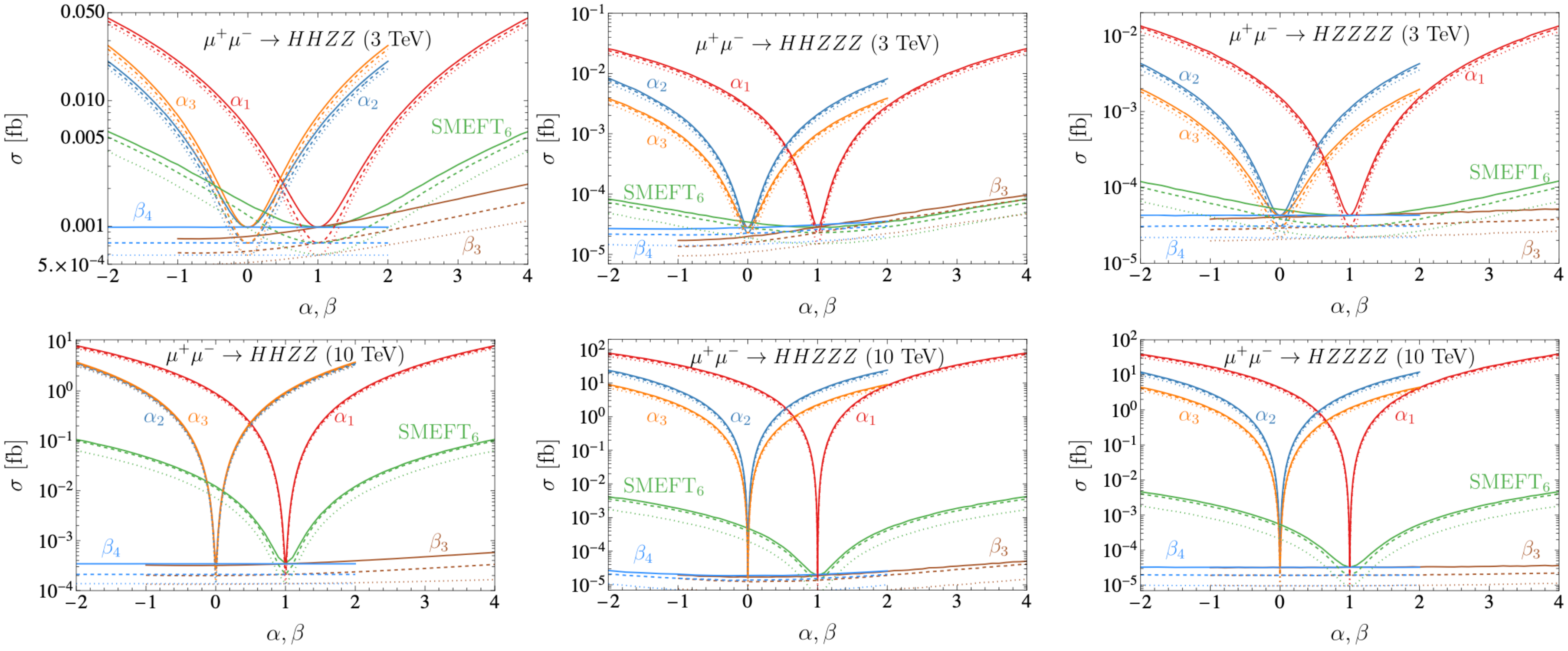
Constrain $(\alpha_1,\ \alpha_2)$ at 10 TeV : e.g. $WWZZ, 4Z, 5Z$



- Weak dependence on Higgs self-couplings (β_3)
- The $\alpha_{1,2}$ dependence is much stronger at 10 TeV

More processes

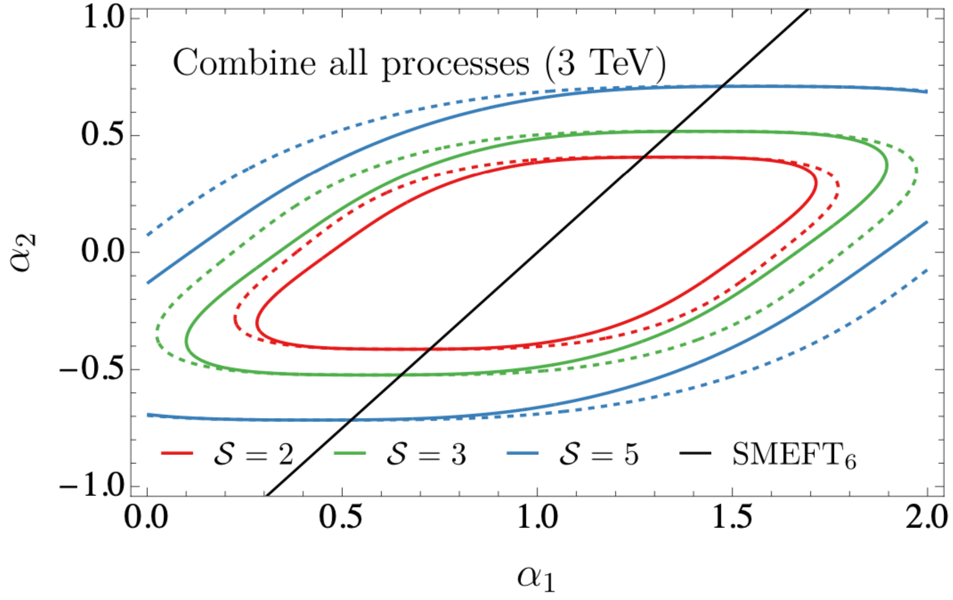
α_3 dependence also shows up: e.g. $HHZZ, HHZZZ, HZZZZ$



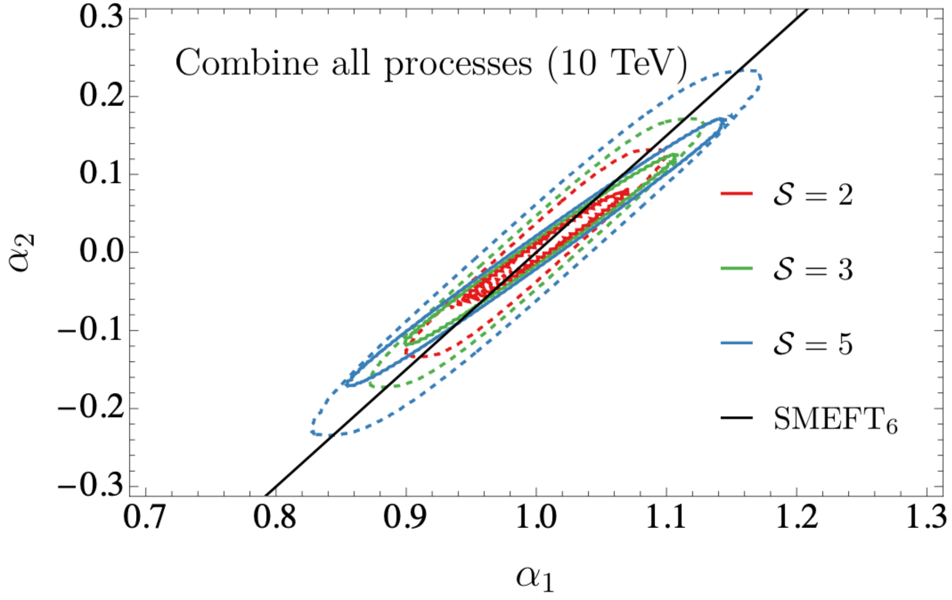
- Constrain $(\alpha_1, \alpha_2, , \alpha_3)$ simultaneously

Model-independent constraints

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



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

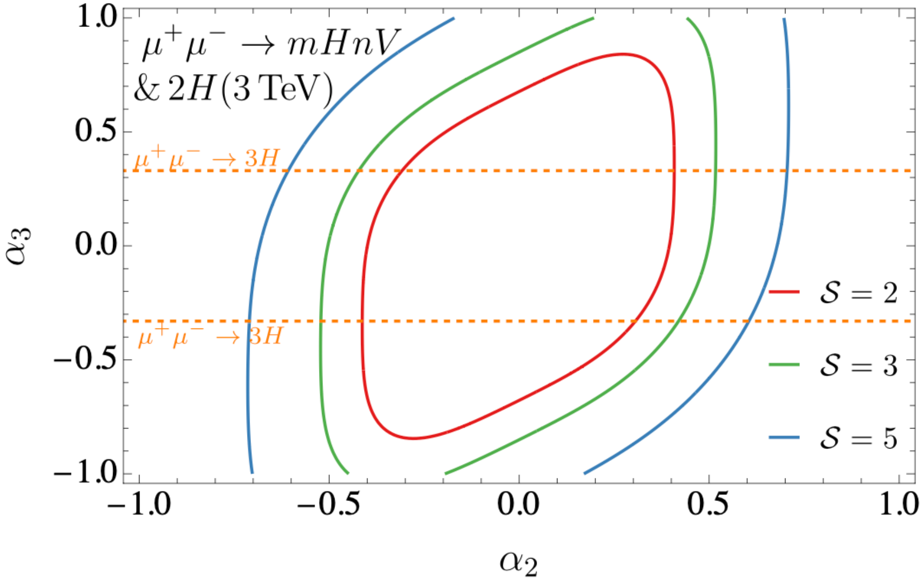


- Guaranteed to measure the sign of the muon Yukawa coupling α_1
- The 10 TeV machine can do much better than the 3 TeV machine does
- With assumption $\alpha_3 = 0$, one could further improve the measurement on α_1 and α_2.

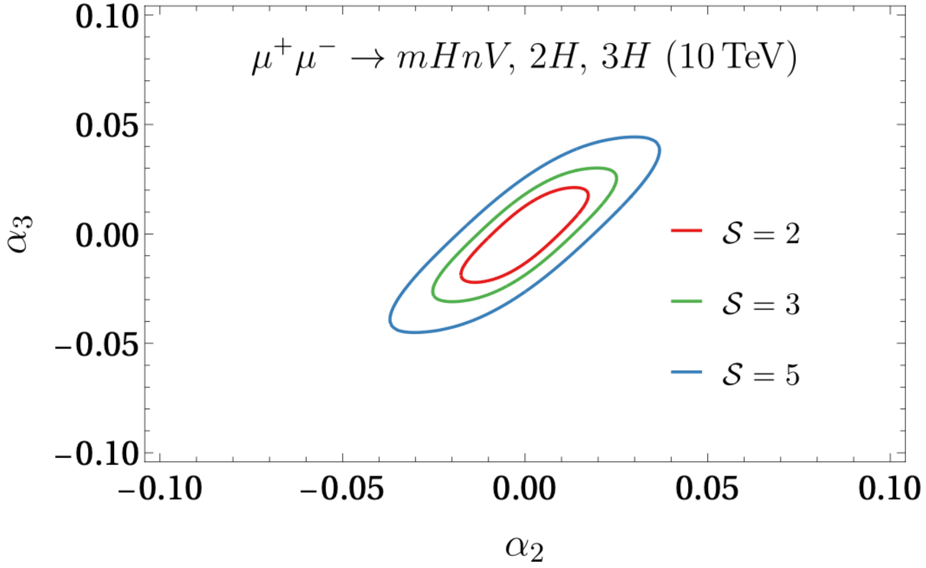
What if $\alpha_1 = 1$?

- 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

- Muon collider is cool!
  - An exciting high-energy frontier
  - A possible precision frontier
  - Our first time to play with another flavor
- Muon-Higgs interactions at muC via multi-boson production
  - Precision measurement of Higgs at the energy frontier
  - No need to assume any decay branching fractions
  - To measure the sign of muon Yukawa coupling y_μ
  - A direct probe of $\bar{\mu}\mu H^n$ via n-Higgs production
  - Constrain (α_1, α_2) together
  - 10 TeV muC works way better than the 3 TeV muC