Single 2HDM Scalar Production at a Muon Collider

Juhun Kwak & Tao Han

05.12.26.

University of Pittsburgh, PACC

The Standard Model and 2HDMs

Some outstanding questions in the SM:

- Naturalness -> SUSY?
- Baryogenesis
- Dark Matter?

The Model - Scalar Potential

Extend the SM with an additional scalar doublet

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \rho_i + i\eta_i)/\sqrt{2} \end{pmatrix}, \quad i = 1, 2$$

such that the scalar potential is

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2\right]$$

CP invariance and softly broken $\mathbb{Z}_2$!

See T. D. Lee (1973), C. Hill Thesis (1977), arXiv:1106.0034.

The Model - Parameters and Physical States

Gives fives physical scalar state:

- h (identified as the SM Higgs)
- H (heavy scalar)
- A (heavy psuedoscalar)
- $H^{\pm}$ (charged scalars)

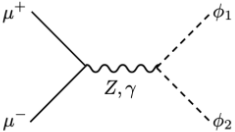
with the constraint:

$$v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}, \quad \tan\beta = \frac{v_1}{v_2}, \quad \cos(\beta - \alpha) \to 0$$

α diagonalizes h, H mass matrix; β diagonalizes A, $H^{\pm}$ mass matrix.

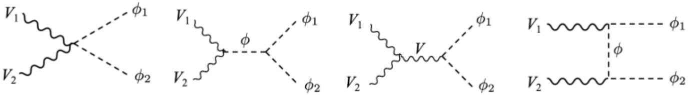
Collider Physics - Maximizing Cross-Sections

Maximum cross-section given by (Phys. Rev. D 104, 055029 (2021)):



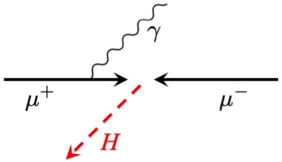
There are recent studies of 1-loop vertex correction to the above channel (arXiv: 2505.02092, 2509.23877).

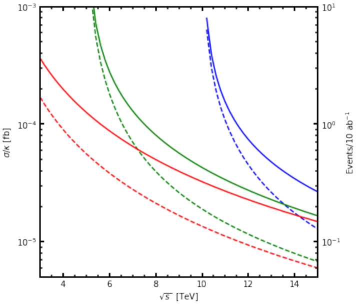
VBF channels are also important:



Radiative Return

What if $2m_\Phi > s$?

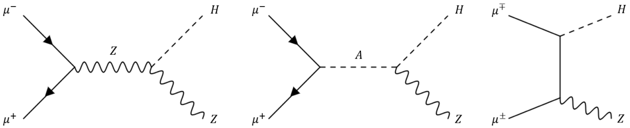




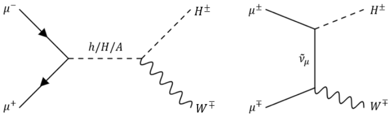
Dashed lines are $2 \to 2$ scattering with $10° < \theta < 170°$; solid lines are radiative return curves. Red: $m_\Phi = 1$ TeV, Green: $m_\Phi = 5$ TeV, Red: $m_\Phi = 10$ TeV.

A Heavy Scalar & An EW Boson

For the HZ or AZ final state:

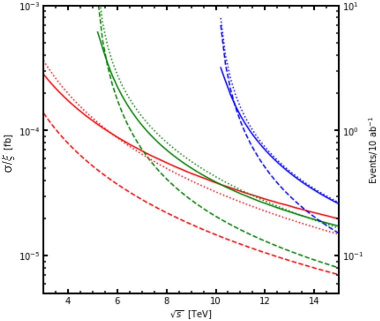


For the charged Higgs-W final state:



Note the presence of both s- and t-channel diagrams!

$H^{\pm}W^{\mp}$ Cross-Sections



Solid curves are the total cross-sections; dashed curves are the contribution from the radiative return mechanism. The vertical axis is scaled by $\xi = \tan^2\beta$ or $\cot^2\beta$. Red: $m_\Phi = 1$ TeV, Green: $m_\Phi = 5$ TeV, Red: $m_\Phi = 10$ TeV.

Yukawa Coupling & Model Distinguishability

$$\mathcal{L}_{\text{Yuk}} \supset -\sum_{f=u,d,l} \frac{m_f}{v}\left(\xi_{Hff}\bar{f}fH - i\xi_{Aff}\bar{f}\gamma_5 fA\right) - \left[\frac{\sqrt{2}\,V_{ij}}{v}\bar{u}_i(m_{u_i}\xi_{Auu}P_L + m_{d_j}\xi_{Add}P_R)d_jH^+ + \frac{\sqrt{2}m_l\xi_{All}}{v}\bar{\nu}_L l_R H^+ + \text{h.c.}\right]$$

$$\begin{aligned}
\text{I:}\quad & \xi_{Huu} = \xi_{Auu} = \cot\beta, \quad \xi_{Hdd} = -\xi_{Add} = \cot\beta, \quad \xi_{Hll} = -\xi_{All} = \cot\beta; \\
\text{II:}\quad & \xi_{Huu} = \xi_{Auu} = \cot\beta, \quad -\xi_{Hdd} = \xi_{Add} = \tan\beta, \quad -\xi_{Hll} = \xi_{All} = \tan\beta; \\
\text{L:}\quad & \xi_{Huu} = \xi_{Auu} = \cot\beta, \quad \xi_{Hdd} = -\xi_{Add} = \cot\beta, \quad -\xi_{Hll} = \xi_{All} = \tan\beta; \\
\text{F:}\quad & \xi_{Huu} = \xi_{Auu} = \cot\beta, \quad -\xi_{Hdd} = \xi_{Add} = \tan\beta, \quad \xi_{Hll} = -\xi_{All} = \cot\beta.
\end{aligned}$$

Conclusion

- A multi-TeV muon collider is a great venue for studying 2HDMs;
- Single 2HDM Higgs production is important in case the heavy Higgs pair production threshold is higher than the collider energy;
- The radiative return mechanism and the associated production are complementary to one another for single 2HDM Higgs production with an EW gauge boson, yielding preceptible signals in many cases.