Exploring the global symmetry structure of the Higgs potential via same-sign pair production of charged Higgs bosons

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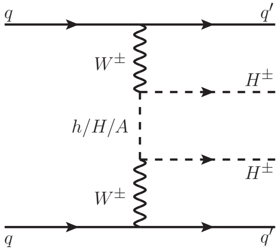
Message

$W^{\pm}W^{\pm} \to H^{\pm}H^{\pm}$ process is interesting.



By studying this process, we can explore

- Global symmetry structure of the Higgs potential
- Cutoff scale

This process can be feasible at the LHC and the future higher energy colliders.

Introduction

- Is the Higgs sector extended from SM?
  Representation and number of Higgs multiplets,
  Structure of the Higgs potential etc.

- Why important?
  Higgs sector is related to BSM physics (dark matter, tiny neutrino mass, baryon asymmetry of the universe and ect.).

- Why interesting?
  We can study this possibility by current and future collider experiment. (direct search, precision measurement)

Extended Higgs sector : 2 Higgs doublet model(2HDM)

We consider 2HDM as a concrete model.

$$V_{\rm 2HDM}(\Phi_1, \Phi_2) = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_1^\dagger\Phi_2 + h.c.) \\ + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 \\ + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + h.c.],$$

*We assume softly broken Z_2 symmetry and CP conservation for simplicity.

Scalars: CP-even h, H, CP-odd A, and $H^\pm$
We take lightest CP-even scalar h as the discovered Higgs boson.

The 2HDM often appears in new models which solve BSM phenomena.
Global symmetry in the Higgs potential characterizes new models.

Global symmetry in 2HDM

We focus on the quartic part :

$$
\begin{aligned}
V_4 = &+\frac{1}{8}c_1(|\Phi_1|^2+|\Phi_2|^2)^2 && [O(8)] \\
&+\frac{1}{8}c_2(|\Phi_1|^2-|\Phi_2|^2)^2 && [O(4)\times O(4)] \\
&+\frac{1}{4}c_3(|\Phi_1|^2+|\Phi_2|^2)(|\Phi_1|^2-|\Phi_2|^2) \\
&+\frac{1}{2}c_4(\Phi_1^\dagger\Phi_2+\Phi_2^\dagger\Phi_1)^2+\frac{1}{2}c_5(\Phi_1^\dagger\Phi_2-\Phi_2^\dagger\Phi_1)^2, && [O(4)\&SU(2)]
\end{aligned}
$$

Deshpande and Ma, Phys. Rev. D18 (1978)

where

$$
\begin{aligned}
c_1 = \lambda_1+\lambda_2+2\lambda_3,\ c_2 = \lambda_1+\lambda_2-2\lambda_3, \\
c_3 = \lambda_1-\lambda_2,\ c_4 = \lambda_4+\lambda_5,\ c_5 = \lambda_4-\lambda_5.
\end{aligned}
$$

Experimental constraints

We need to take into account experimental constraints.

- T parameter : $\lambda_4 = \lambda_5$ or $\lambda_4 = -\lambda_5$.
  Pomarol and Vega, Nucl. Phys. B413 (1994), Gerard and Herquet, Phys. Rev. Lett. 98 (2007)
- Natural alignment : $\lambda_1 = \lambda_2 = \lambda_3 + \lambda_4 + \lambda_5$
  Bhupal and Pilaftsis, J. High Energy Phys. 12 (2014)

* "Natural" means the condition of the Higgs quartic coupling ensures alignment limit.

These conditions would be approximate one. However we here use them as inputs, and try to extract essential parameters.

Symmetry of the Higgs potential

Under the previous conditions,

$$V_1 = \frac{1}{2}\left(\frac{m_h^2}{v^2} - \eta\right)(|\Phi_1|^2 + |\Phi_2|^2)^2 + \frac{1}{2}\eta(|\Phi_1|^2 - |\Phi_2|^2)^2 + \frac{1}{2}\eta(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1)^2, \qquad (\lambda_4 = \lambda_5),$$

$$V_2 = \frac{m_h^2}{2v^2}(|\Phi_1|^2 + |\Phi_2|^2)^2 + \frac{1}{2}\eta(\Phi_1^\dagger\Phi_2 - \Phi_2^\dagger\Phi_1)^2, \quad (\lambda_4 = -\lambda_5),$$

where $\eta = (m_H^2 - m_A^2)/v^2$. If $\eta = 0$,

$$V = \frac{m_h^2}{2v^2}(|\Phi_1|^2 + |\Phi_2|^2)^2 \ : \ [O(8)]$$

Mass difference closely relates to global symmetry $O(4)$ or $O(8)$.

Role of mass difference in the RGE running

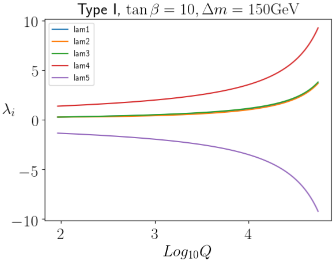
- Sizable mass difference

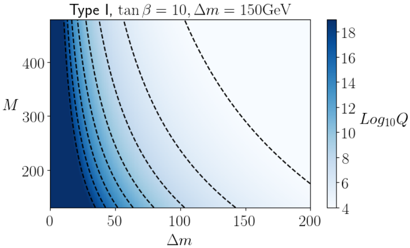
$$\eta = \frac{m_H^2 - m_A^2}{v^2}$$

  triggers the rapid growth of the Higgs quartic couplings in the RGE running.

- We can search not only the global symmetry of the Higgs potential but also the cutoff scale Λ.

Question: Can we measure η ?





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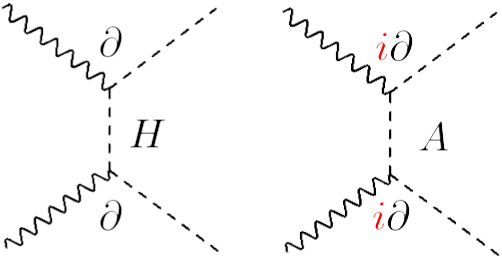
How to observe η ?

Answer: Yes, we can measure η using $W^+W^+ \to H^+H^+$.

The amplitude is

$$\mathcal{M}_{W^+W^+\to H^+H^+} \propto \eta,$$

independent of the W^+ helicity in the alignment limit. This is because diagrams mediated by H and A are destructive.



Cross section of H^+H^+ pair production

We evaluate the cross section of

$$pp \to H^+H^+jj$$

using MadGraph5_aMC@NLO.

- The bigger $\Delta m = m_A - m_H$, the bigger the cross section.
- Because of the PDF, the cross section of H^+H^+ is bigger than H^-H^-.

We assume $m_A > m_H = m_{H^\pm}$, and H^+ dominantly decays into $t\bar{b}$ or $\tau\nu$ following the Z_2 charge.

Aoki, Kanemura, Tsumura, and Yagyu, Phys. Rev. D80 (2009)

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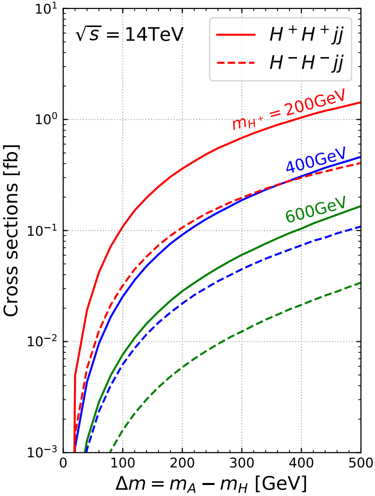

Significance of $H^+ \to t\bar{b}$

The signal

$$H^+H^+jj \to t\bar{b}t\bar{b}jj \to (b\ell^+\nu)\bar{b}(b\ell^+\nu)\bar{b}jj.$$

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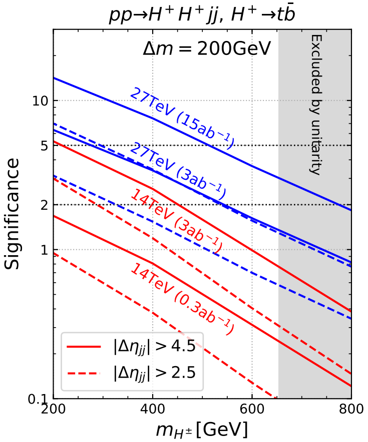

The background

$$tt\bar{t}\bar{t} \to (b\ell^+\nu)(b\ell^+\nu)(\bar{b}jj)(\bar{b}jj)$$

CMS, Eur. Phys. J. C78, (2018)

The vector boson fusion(VBF) selection

$$\Delta m_{jj} > 500\text{GeV},\ \Delta\eta_{jj} > 2.5\ (4.5)$$

efficiently suppresses the BG.

*Significance $(H^+ \to \tau\nu)$ in backup.

Summary

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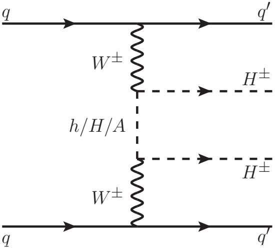

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Backup

Significance $H^+ \to \tau\nu$

The signal

$$H^+H^+jj \to \tau^+\nu\tau^+\nu jj$$

The background

$$W^+W^+jj \to \tau^+\nu\tau^+\nu jj$$

CMS, Phys. Rev. Lett. 120, (2018)

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