

Same-sign pair production of charged Higgs bosons at hadron colliders

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with Masashi Aikou and Kentarou Mawatari

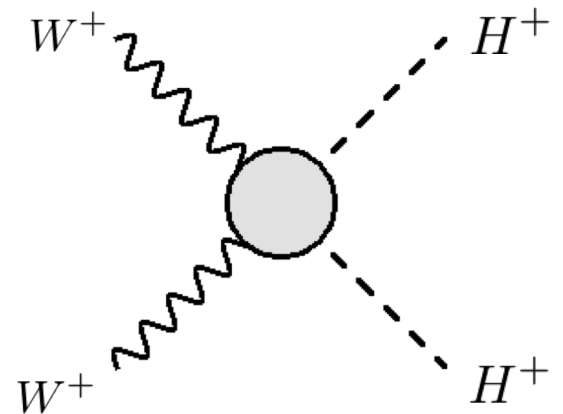
Paper in preparation

Helsinki RISE Meeting, 2019

In this talk

Symmetry structure of extended Higgs sector may be explored by H^+H^+ production via VBF

- Introduction
- Extended Higgs sectors
- Symmetry of the Higgs potential
- **VBF as a probe of the symmetry structure of the potential**
- Summary



Introduction

Standard Model

Gauge principle: Interaction

$$SU(3)_C \times SU(2)_I \times U(1)_Y$$

Color Isospin Hypercharge

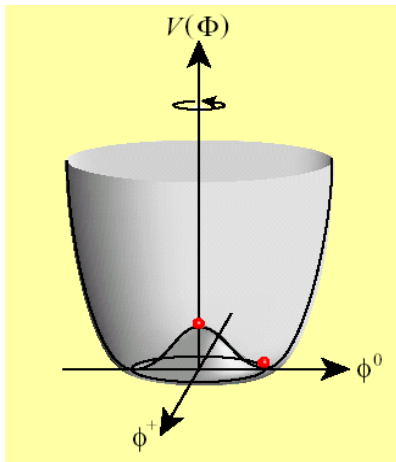
$$g_\mu^\alpha \text{ Gluon}$$

$$W_\mu^a$$

$$B_\mu$$

Spontaneous Symmetry Breaking: Mass

$$SU(2)_I \times U(1)_Y \rightarrow U(1)_{em}$$



Quarks and leptons
3-generations

Massive

	$SU(2)_L$	$U(1)_Y$
$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	2	1/3
u_R	1	4/3
d_R	1	-2/3
$l_L = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	2	-1
e_R	1	-2

Massless

$$A_\mu$$

Photon

Massive

$$W_\mu^\pm \quad Z_\mu^0$$

Weak bosons

Standard Model

Gauge principle: Interaction

$$SU(3)_C \times SU(2)_I \times U(1)_Y$$

Color Isospin Hypercharge

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Massless

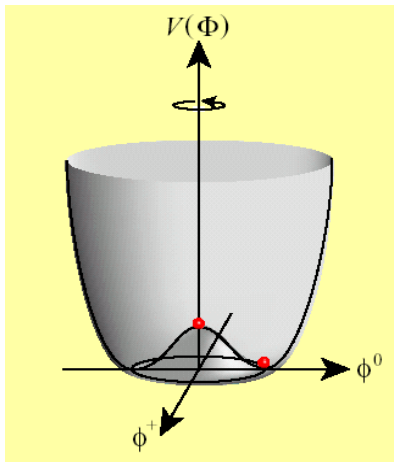
$$A_\mu$$

Photon

Massive

$$W_\mu^\pm \quad Z_\mu^0$$

Weak bosons



Tentatively introducing a scalar doublet (Higgs field)

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$V(\Phi) = +\mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

$\mu^2 < 0$

$$\phi^0 = \frac{1}{\sqrt{2}} (v + h + iz)$$

\downarrow VEV 246 GeV
 \uparrow Higgs boson

LHC experiment

ATLAS/CMS
July 2012

Discovery

Mass 125 GeV, ...

Spin, Parity 0^+

Coupling with many particles

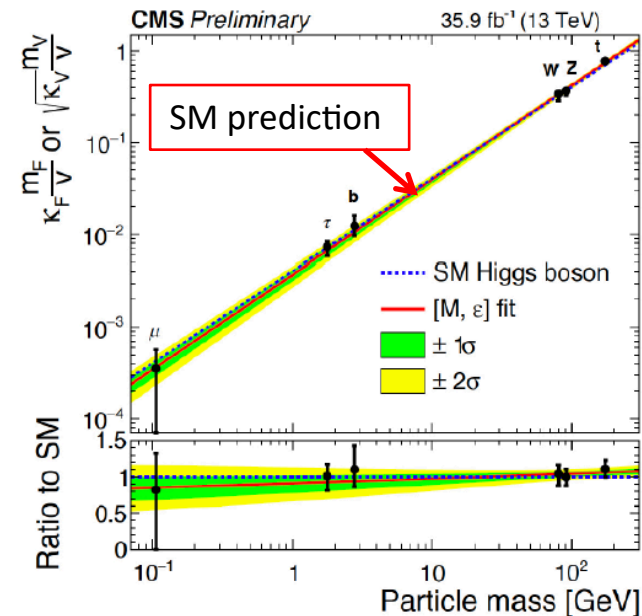
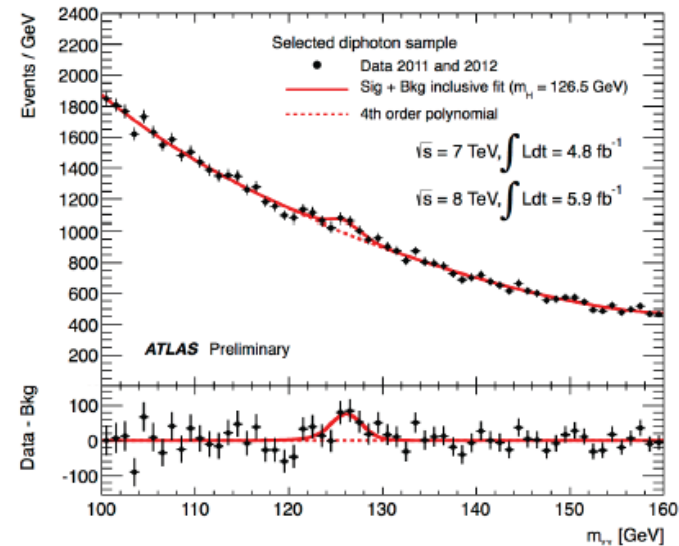
$h\gamma\gamma$, hgg , hZZ , hWW , $h\tau\tau$, htt , hbb , ...

Identified as a **Higgs boson**

Measured couplings turned out to be consistent with the SM

No BSM particle has been found

Standard Model is enough?



Beyond the **S**tandard **M**odel

Many reasons to consider New Physics beyond SM

Unification of Law

- Paradigm of Grand Unification
- Yukawa structure (flavor physics)

Problem in the SM Higgs

- Hierarchy Problem, Shape of Higgs sector, Nature, ...

BSM Phenomena

- Dark Matter
- Neutrino mass and mixing
- Baryon Asymmetry of Universe
- Inflation, Dark Energy, Gravity,...

New Physics is necessary

At which scale?

If TeV scale, they should have connection with Higgs physics

Higgs Sector

Mass Generation mechanisms

Higgs Mechanism

hWW

hZZ

Yukawa Interaction

$h\tau\tau, hbb$

htt, \dots

Dim 6 Operators

hgg

$H\gamma\gamma, hZ\gamma$

$$L_{eff} = |D_\mu \Phi|^2 - y L\Phi R - 1/v^2 |\Phi|^2 GG$$

Flavor Structure

New particle effect
in the loop

$$- V_{eff}(\Phi)$$

EW Symmetry Breaking

$hhh, hhhh$



LHC Run I, II results,

consistent with SM

But with more precision,

They may differ from SM

Higgs Sector

Mass Generation mechanisms

Higgs Mechanism

hWW

hZZ

Yukawa Interaction

$h\tau\tau, hbb$

htt, \dots

Dim 6 Operators

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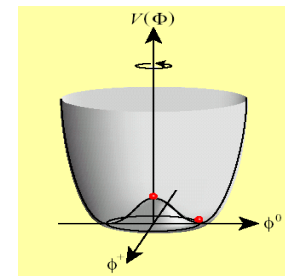
$hhh, hhhh$

Physics behind EWSB
EW Phase Transition



So little is known about
the Higgs potential

$V = 246\text{GeV}$
 $M_h = 125\text{GeV}$



Future experiments

Thorough exploration of the Higgs sector

- **Hadron Colliders** LHC, HL-LHC, 27TeV, 100TeV, ...
- **Lepton Colliders** ILC, FCCee, CEPC, CLIC, ...
- **Flavor Experiments** LHCb, Super KEKB, ...
- **Gravitational Waves** LISA, DECIGO, ...
- ...

Under such environment, the importance is getting higher to consider the possibility of **non-minimal Higgs sector** in order to explore dynamics of EWSB and BSM

Extended Higgs sectors

Extended Higgs sectors

Multiplet Structure (with additional scalars)

- Φ_{SM} +Isospin **Singlet**,
- Φ_{SM} +**Doublet** (2HDM),
- Φ_{SM} +**Triplet**, ...

Additional Symmetry

- Discrete or Continuous?
- Exact or Softly broken?

Interaction

- Weakly coupled or Strongly Coupled?

**Hint for
BSM
models**

Higgs potential in the 2HDM

$$\begin{aligned} V(\Phi_1, \Phi_2) = & \sum_{i=1}^2 m_i^2 |\Phi_i|^2 - (m_3^2 \Phi_1^\dagger \Phi_2 + h.c.) \\ & + \sum_{i=1}^2 \frac{1}{2} \lambda_i |\Phi_i|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 \\ & + \left\{ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + h.c. \right\} \end{aligned}$$

Mass terms (mass scales of new particles)

Quartic couplings (symmetries of the potential)

Major experimental constraints for the quartic coupling part

Flavor	FCNC suppression	→ At least approx. Z_2 ? <i>Glashow, Weinberg</i>
EW Precision Tests	$\rho=1$	→ global $SU(2)_V$?
SM like	$\kappa_V = \sin(\beta-\alpha) \sim 1$	→ Alignment? Decoupling?

Global Symmetries of the Higgs potential in 2HDM

Deshpande, Ma, ...

Haber, O'neil, ...

Pilaftsis, ...

Ferreira, Silva, Ivanov, ...

We here discuss very rough description

Under the Z_2 , the Custodial Symmetry and the Alignment

Symmetry of the Higgs potential

$$\begin{aligned} V_4 = & c_1(|\Phi_1|^2 + |\Phi_2|^2)^2 \\ & + c_2(|\Phi_1|^2 - |\Phi_2|^2) \\ & + c_3(|\Phi_1|^4 - |\Phi_2|^4) \\ & + c_4(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1)^2 \\ & + c_5(\Phi_1^\dagger \Phi_2 - \Phi_2^\dagger \Phi_1)^2 \end{aligned}$$

$$c_1 = \lambda_1 + \lambda_2 + 2\lambda_3$$

$$c_2 = \lambda_1 + \lambda_2 - 2\lambda_3$$

$$c_3 = \lambda_1 - \lambda_2$$

$$c_4 = \lambda_4 + \lambda_5$$

$$c_5 = \lambda_4 - \lambda_5$$

Symmetry of the Higgs potential

$$\begin{aligned} V_4 = & c_1(|\Phi_1|^2 + |\Phi_2|^2)^2 && [\leftarrow O(8)] \\ & + c_2(|\Phi_1|^2 - |\Phi_2|^2) \\ & + c_3(|\Phi_1|^4 - |\Phi_2|^4) && \left. \vphantom{\begin{aligned} V_4 = \\ + c_2 \\ + c_3 \end{aligned}} \right\} [\leftarrow O(4)_1 \times O(4)_2] \\ & + c_4(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1)^2 && [\leftarrow O(4)_2 (\simeq SU(2)_L \times SU(2)_R)] \\ & + c_5(\Phi_1^\dagger \Phi_2 - \Phi_2^\dagger \Phi_1)^2 && [\leftarrow SU(2)_L] \end{aligned}$$

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EW precision data indicate $O(4)_2 (\simeq SU(2)_L \times SU(2)_R)$

$$\rho \sim 1$$

Custodial
Symmetry

The quartic coupling part would respect the custodial symmetry

Symmetry of the Higgs potential

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Or higher symmetry would be respected

$$O(4)_1 \times O(4)_2$$

$$O(8)$$

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Symmetries and the masses

EW precision data indicate $O(4)_2 (\simeq SU(2)_L \times SU(2)_R)$

Custodial
Symmetry

LHC Higgs searches indicate $\kappa_V = \sin(\beta - \alpha) \sim 1$

Alignment

Assume that these are exact for quartic coupling part

$SU(2)_L$

no degeneracy

$$O(4)_2 (\simeq SU(2)_L \times SU(2)_R) \left\{ \begin{array}{l} \text{Case 1} \quad m_A = m_{H^\pm} \\ \text{Case 2} \quad m_H = m_{H^\pm} \end{array} \right.$$

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$$m_H = m_{H^\pm}$$

$O(4)_1 \times O(4)_2$

$$m_H = m_A = m_{H^\pm}$$

$O(8)$

$$m_h = m_H = m_A = m_{H^\pm}$$

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$O(4)_1 \times O(4)_2$

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$O(8)$

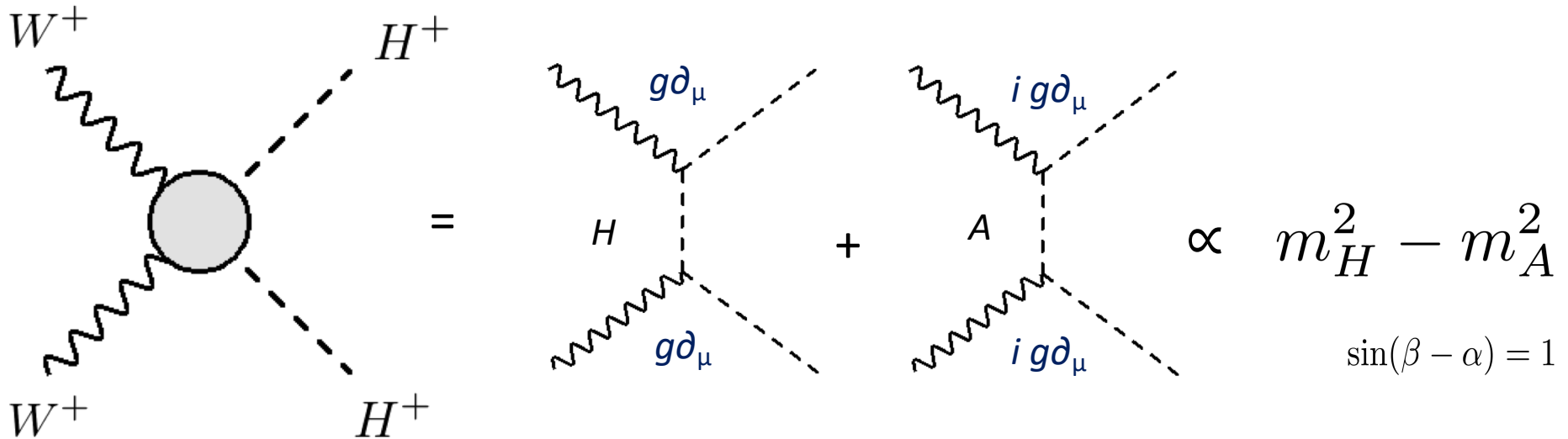
$$m_h = m_H = m_A = m_{H^\pm}$$

$\Delta m \equiv m_A - m_H$ is important for the global symmetry structure.

VBF as a probe of symmetry of the
potential

$$W^+W^+ \rightarrow H^+H^+$$

The amplitude is proportional to c_5 in alignment regime



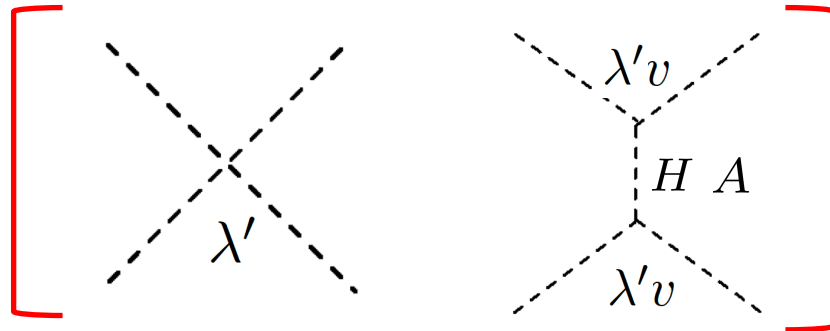
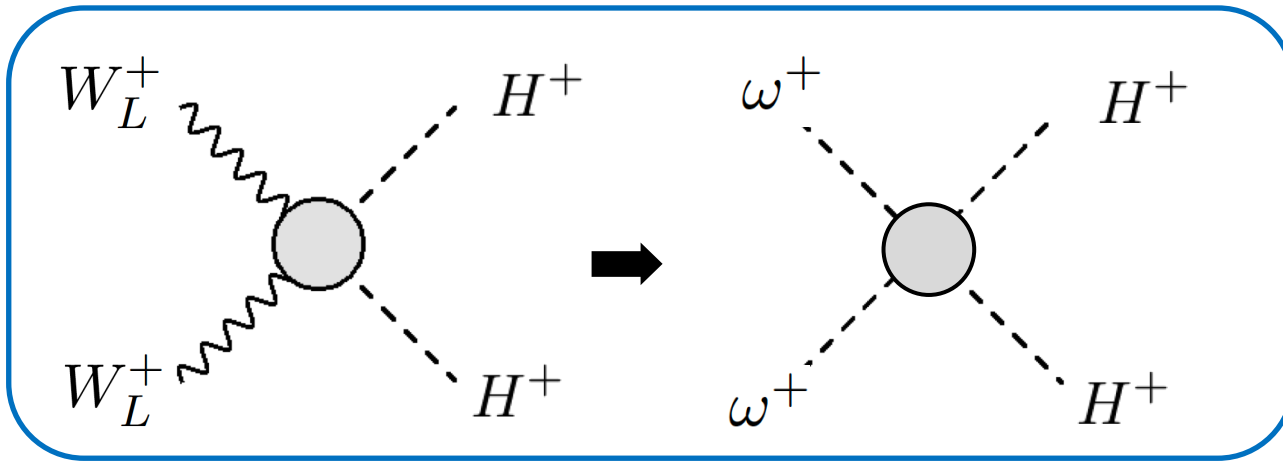
Independent of W polarization!

$$\Delta m \equiv m_A - m_H$$

Equivalence theorem

Cornwall Leven, Tiktopoulos
Lee, Quigg, Thacker

Case for the longitudinal mode

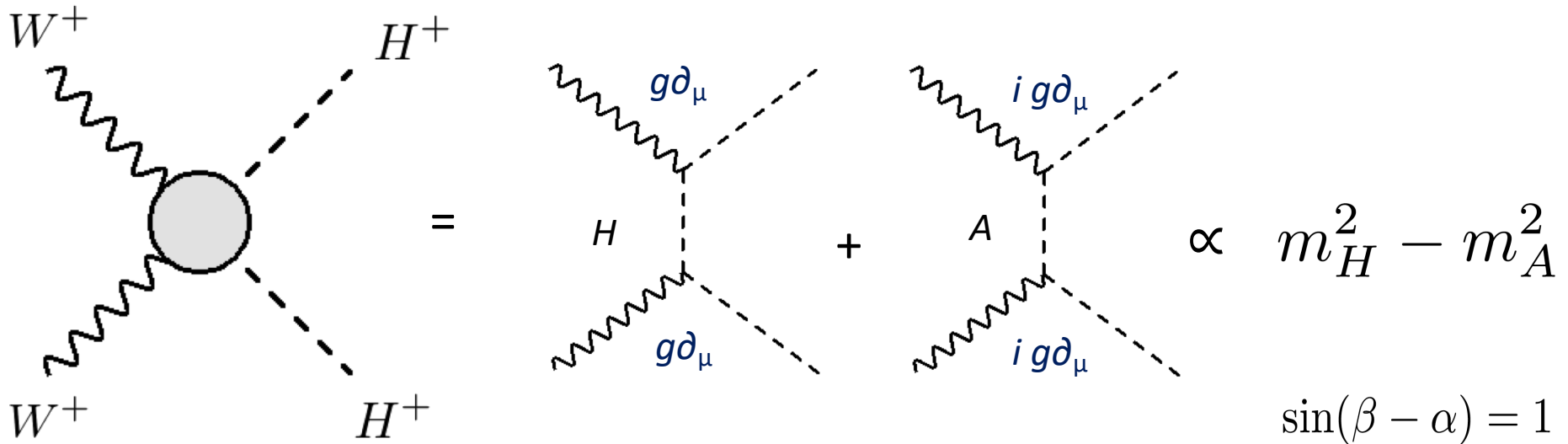


Vector Boson Fusion = Information of the Potential

$$\lambda' \equiv (m_A^2 - m_H^2)/v^2$$

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The amplitude is proportional to c_5 in alignment regime



Independent of W polarization!

$$\Delta m \equiv m_A - m_H$$

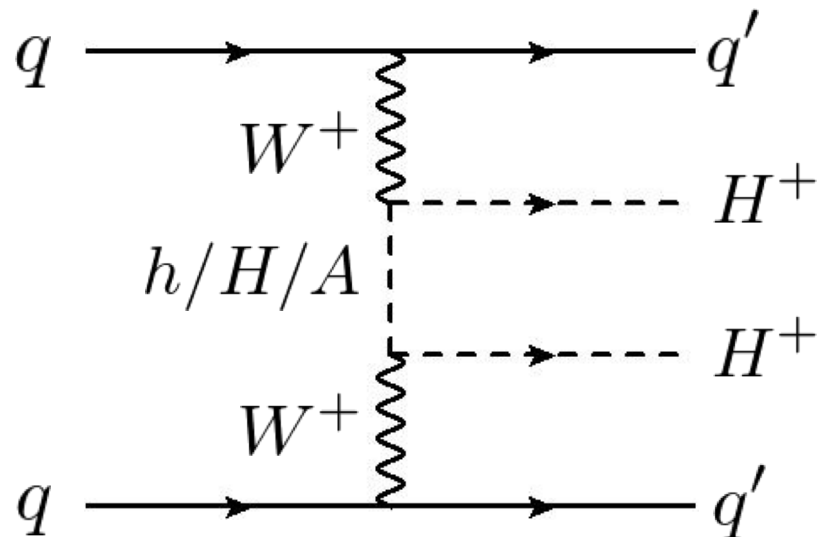
H^+H^+ via VBF

$W^+W^+ \rightarrow H^+H^+$ is proportional to Δm in alignment regime

Independent of W polarization

We may be able to explore the symmetry structure of the Higgs potential via H^+H^+ production from VBF at hadron colliders

- 1) New process
- 2) Simple structure
→ extract global symmetry of the Higgs potential
- 3) VBF, and **same sign** pair
→ less backgrounds



Same-sign vector boson scattering

W^+W^+ via VBS was observed in 2018

$$pp \rightarrow W^\pm W^\pm jj \rightarrow W^\pm W^\pm jj$$

Fiducial data

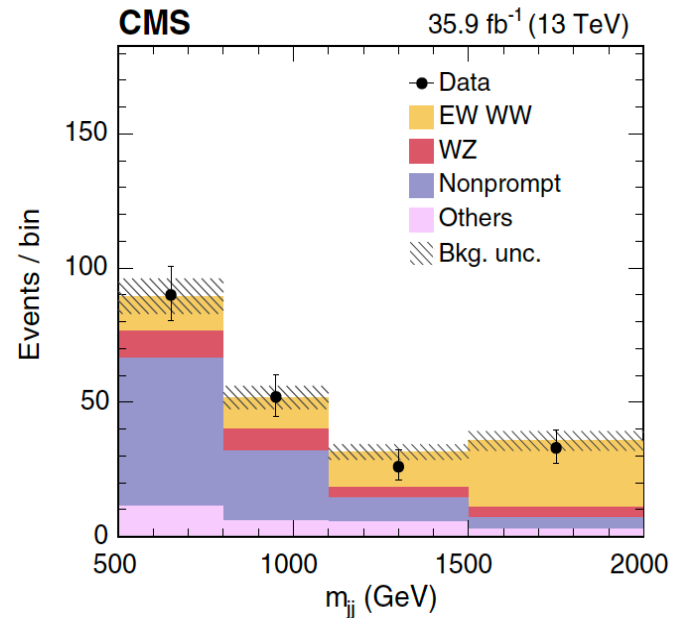
$$\sigma_{\text{fid}}(W^\pm W^\pm jj) = 3.83 \pm 0.66 \text{ (stat)} \pm 0.35 \text{ (syst) fb}$$

Predicted theoretical cross section (LO)

$$4.25 \pm 0.27 \text{ fb}$$

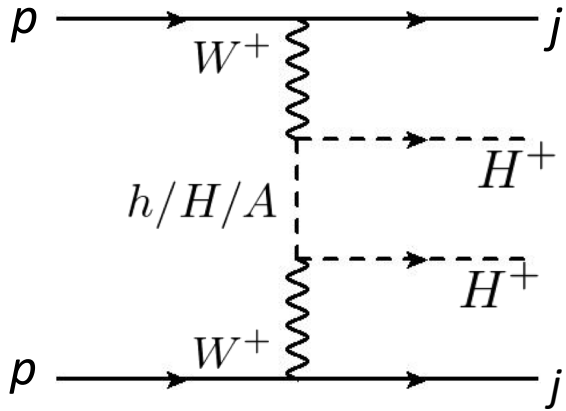
W^+Z via VBS was also observed [ATLAS 2018](#)

[Sirunyan, et al., PRL 120, 081801 \(2018\)](#)

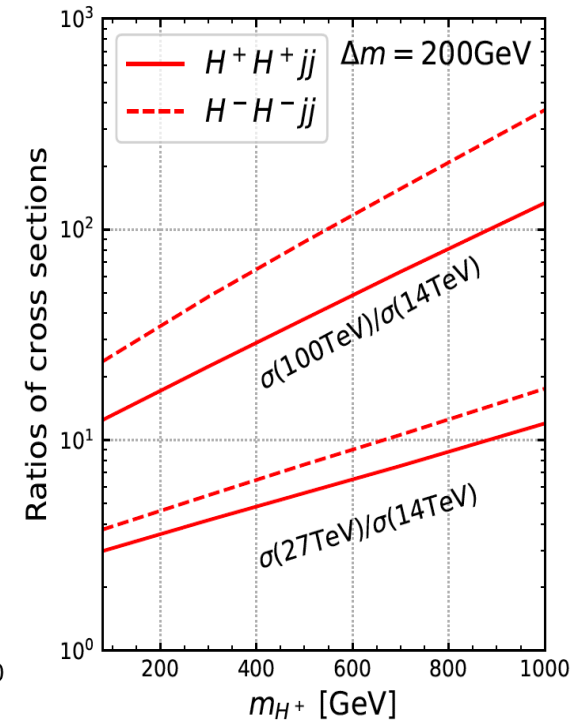
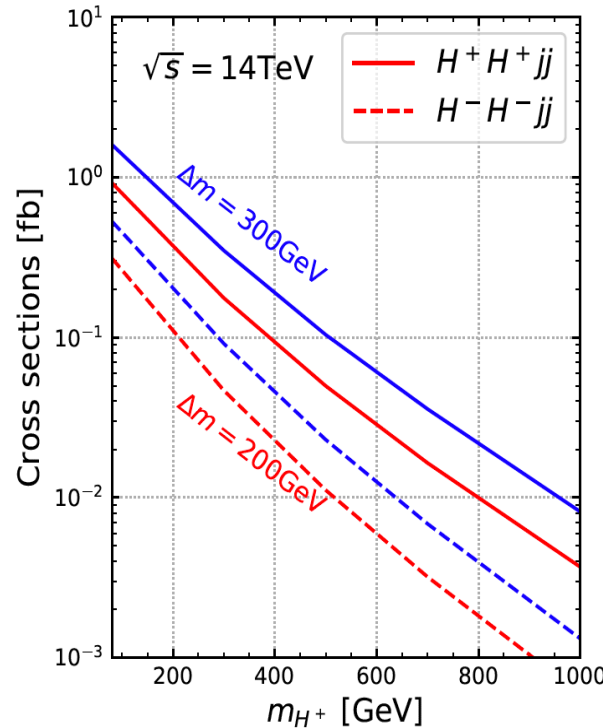


Era of BSM searches via VBS has started

$H^\pm H^\pm$ via VBF in 2HDM



Cross Sections



THDM UFO model file used
MadGraph5_AMC@NLO

At least 2 Jets requirement

$$p_T^j > 30 \text{ GeV} \quad |\eta^j| < 5$$

VBF baseline selection cuts

$$m_{jj} > 500 \text{ GeV} \quad |\Delta\eta_{jj}| > 2.5$$

$$(|\Delta\eta_{jj}| > 4.5)$$

M. Aikou, SK, K. Mawatari

$$\Delta m = m_H - m_A$$

Significance ($H^+ \rightarrow t\bar{b}$)

$$S = \sqrt{2((s+b) \ln(1+s/b) - s)}$$

$$B(H^+ \rightarrow t\bar{b}) \sim 1$$

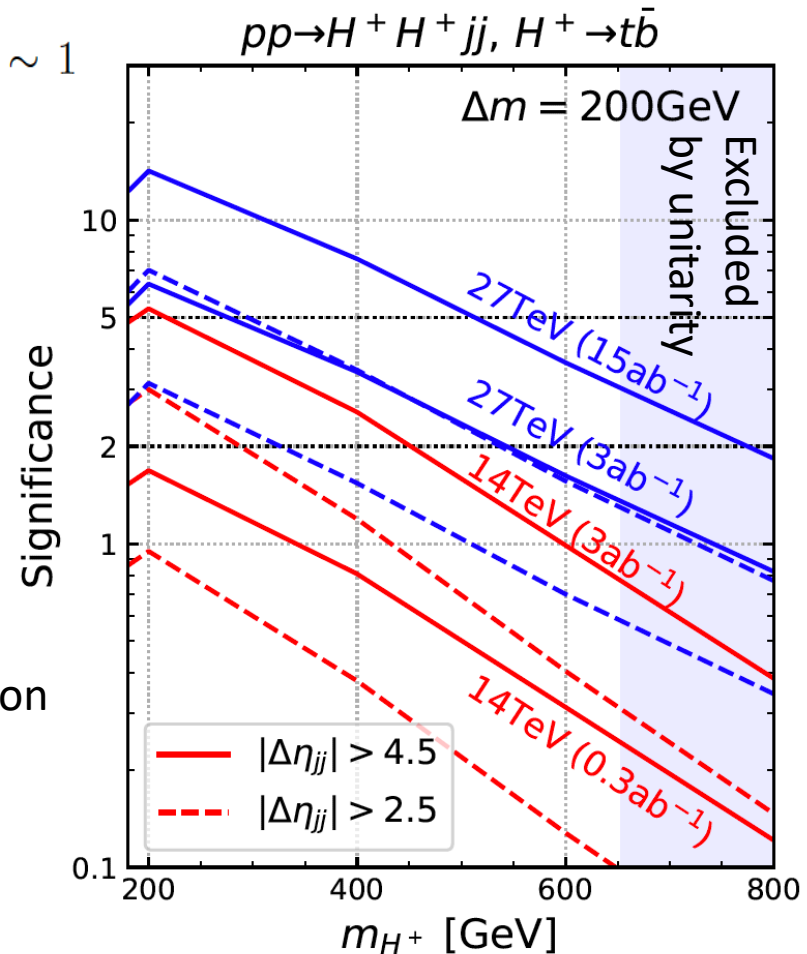
$$s = L \sigma_{\text{VBF}}(H^+ H^+ jj) \times B(H^+ \rightarrow t\bar{b})^2 B(t \rightarrow b\ell^+\nu)^2 \epsilon_{\text{sel}}^t \epsilon_b^2$$

$$b = L \sigma(pp \rightarrow t\bar{t}t\bar{t}) \times B(t \rightarrow b\ell^+\nu)^2 B(\bar{t} \rightarrow \bar{b}jj)^2 \epsilon_{\text{sel}}^t \epsilon_b^2$$

$$\epsilon_{\text{sel}}^t \left\{ \begin{array}{l} \text{Same sign two leptons with} \\ p_T^\ell > 20 \text{ GeV} \quad |\eta^\ell| < 2.5 \\ \text{To suppress BG from multi-boson production} \\ H_T > 300 \text{ GeV} \quad p_T^b > 30 \text{ GeV} \quad |\eta^b| < 2.5 \end{array} \right.$$

$$\epsilon_b = 0.65 \quad \text{b-tag efficiency}$$

M. Aikou, SK, K. Mawatari, in preparation



Significance ($H^+ \rightarrow \tau \nu$)

Corresponding to the case of Type X with $\tan\beta > 20$

$$S = \sqrt{2((s+b)\ln(1+s/b) - s)}$$

$$B(H^+ \rightarrow \tau \nu) \sim 1$$

$$s = L \sigma_{\text{VBF}}(H^\pm H^\pm jj) \times B(H^\pm \rightarrow \tau \nu)^2 \epsilon_{\text{sel}}^\tau \epsilon_\tau^2$$

$$b = L \sigma_{\text{VBF}}(W^\pm W^\pm jj) \times B(W^\pm \rightarrow \tau \nu)^2 \epsilon_{\text{sel}}^\tau \epsilon_\tau^2$$

$$\epsilon_{\text{sel}}^\tau \sim 0.8 \quad \text{Same sign tau selection efficiency}$$

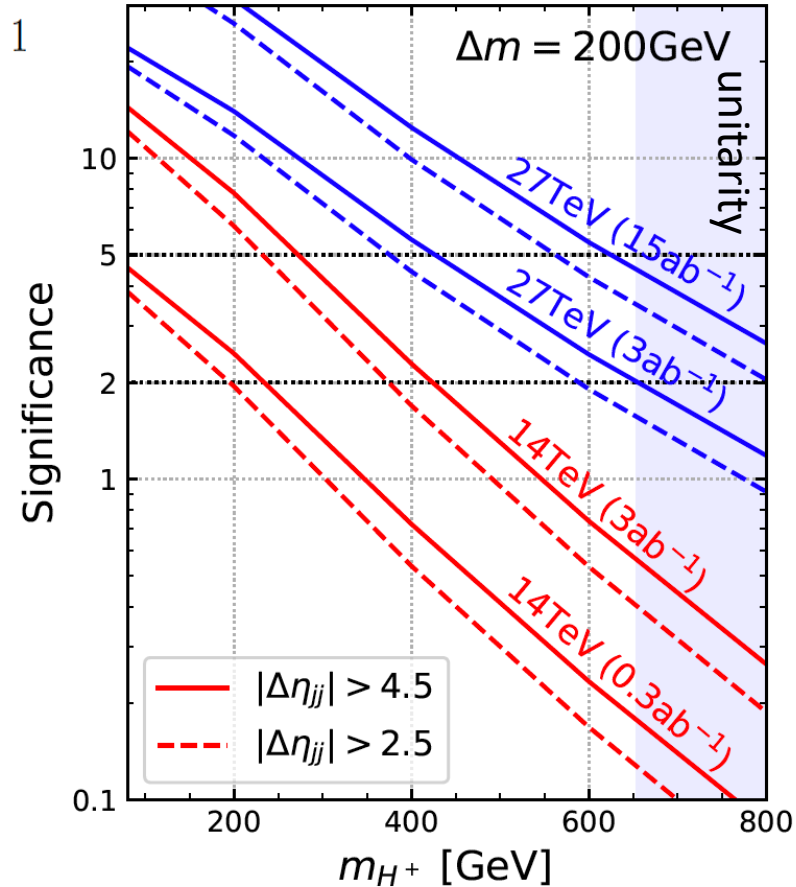
$$p_T^\tau > 20 \text{ GeV} \quad |\eta^\tau| < 2.5$$

$$\epsilon_\tau = 0.39 \quad \text{Hadronic decay branching ratio}$$

$$\text{Hadronic tau ID}$$

M. Aikou. SK. K. Mawatari. in preparation

$pp \rightarrow H^+ H^+ jj, H^+ \rightarrow \tau^+ \nu$



Summary

Characteristics of extended Higgs sector:
multiplet structures, symmetry, strength of couplings

Current data may suggest

$$O(4)_2 \simeq SU(2)_L \times SU(2)_R$$

$$m_{H^\pm} = m_A \quad \text{or} \quad m_{H^\pm} = m_H \quad \sin(\beta - \alpha) = 1$$

Possibility of larger symmetries

$$O(4)_1 \times O(4)_2 \quad \text{or} \quad O(8)$$

$$m_{H^+} = m_H = m_A = \dots$$

The global symmetry structure may be tested by searching for H^+H^+ via **VBF** at future hadron colliders

$$pp \rightarrow W^\pm W^\pm jj \rightarrow H^+ H^+ jj$$

The signal can be feasible at **HL-LHC, HE-LHC etc**, when H^+ is not too heavy and $\Delta m = (m_H - m_A)$ is not very small

Current Data

At least approx.
Custodial Symmetry
Alignment

