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Collider Phenomenology of Higgs Bosons in the Georgi-Machacek Model

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CWC and K Tsumura, JHEP 1504 (2015) 113
CWC, S Kanemura and K Yagyu, arXiv:1510.06297 [hep-ph]
CWC, AL Kuo and T Yamada, to arXiv:1511.00865 [hep-ph]

Why Higgs Triplets?

All models are wrong, but some are useful.

--- George E.P. Box

- Higgs triplet models have the following intriguing features:
  - type-II seesaw for Majorana neutrino mass, generated by the VEV of the new scalar (automatically induced by EWSB);
  - existence of a doubly-charged Higgs boson, leading to like-sign LNV and possibly even LFV processes at tree level;
    ➠ a link between neutrino and LHC physics
  - SM-like Higgs possibly having stronger couplings with weak bosons;
  - existence of a $H^{\pm}W^{\mp}Z$ vertex at tree level through mixing (only loop-induced in models such as 2HDM).

Georgi-Machacek Model

Georgi, Machacek 1985
Chanowitz, Golden 1985

- The Higgs sector includes SM doublet field ϕ (2,1/2) and triplet fields χ (3,1) and ξ (3,0)

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ \phi^{-} & \phi^{0} \end{pmatrix}, \qquad \Delta = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ \chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & \xi^{-} & \chi^{0} \end{pmatrix}$$

$SU(2)_L$

$SU(2)_R$

transformed under $SU(2)_L \times SU(2)_R$ as

$$\Phi \to U_L\, \Phi\, U_R^\dagger \quad \text{and} \quad \Delta \to U_L\, \Delta\, U_R^\dagger$$

with $U_{L,R} = \exp(i\, \theta_{L,R}^a\, T^a)$ and T^a being corresponding SU(2) generators.

Georgi-Machacek Model

Georgi, Machacek 1985
Chanowitz, Golden 1985

- The Higgs sector includes SM doublet field ϕ (2,1/2) and triplet fields χ (3,1) and ξ (3,0)

$$\Phi = \begin{pmatrix} v_\phi & \phi^+ \\ \phi^- & v_\phi \end{pmatrix}, \qquad \Delta = \begin{pmatrix} v_\Delta & \xi^+ & \chi^{++} \\ \chi^- & v_\Delta & \chi^+ \\ \chi^{--} & \xi^- & v_\Delta \end{pmatrix}$$

transformed under $SU(2)_L \times SU(2)_R$ as

$$\Phi \to U_L \, \Phi \, U_R^\dagger \quad \text{and} \quad \Delta \to U_L \, \Delta \, U_R^\dagger$$

with $U_{L,R} = \exp(i\, \theta_{L,R}^a T^a)$ and T^a being corresponding SU(2) generators.

- Take $v_\chi = v_\xi \equiv v_\Delta$ (aligned VEV).

➠ $SU(2)_L \times SU(2)_R \to$ custodial $SU(2)_V$

➠ $\rho = 1$ at tree level

Vacuum Expectation Value

- The VEV's are subject to the constraint

$$v^2 = v_\phi^2 + 8v_\Delta^2 = \frac{1}{\sqrt{2}G_F} = (246\ \text{GeV})^2$$

with two mixing angle definitions seen in the literature:

$$\tan\theta_H = \frac{2\sqrt{2}v_\Delta}{v_\phi} \quad \text{or} \quad \tan\beta = \frac{v_\phi}{2\sqrt{2}v_\Delta}$$

- One could attribute EWSB entirely to v_Δ ($\simeq$ 87 GeV) while keeping $v_\phi = 0$.

Georgi, Machacek 1985
Chanowitz, Golden 1985

- Perturbativity of top Yukawa coupling demands $v_\Delta \lesssim 80$ GeV.

➠ other constraints later

Custodial SU(2) Classification

$SU(2)_L \otimes SU(2)_R$

Δ: **3** $\otimes$ **3**

Φ: **2** $\otimes$ **2**

$SU(2)_V$

5 $\oplus$ **3** $\oplus$ **1**

3 $\oplus$ **1**

mixing angle β or θ_H

mixing angle α

$$H_5 \equiv \begin{bmatrix} H_5^{++} \\ H_5^{+} \\ H_5^{0} \\ H_5^{-} \\ H_5^{--} \end{bmatrix} m_{H5}$$

CP-even

$$H_3 \equiv \begin{bmatrix} H_3^{+} \\ H_3^{0} \\ H_3^{-} \end{bmatrix} m_{H3}$$

CP-odd

$$\Phi_3 \equiv \begin{bmatrix} w^{+} \\ z^{0} \\ w^{-} \end{bmatrix}$$

$$H_1 \equiv \left[H_1^0 \right] m_{H1}$$

h (125 GeV) m_h

CP-even

discovering entire H_5 family crucial to verify the model

mass degeneracy within each representation as a result of custodial symmetry

Neutral Higgs Couplings

- Normalize all couplings to those for SM Higgs boson (V = W,Z; F = quarks):

$$\kappa_F = \frac{g_{\varphi FF}}{g^{\rm SM}_{hFF}} \ , \ \kappa_V = \frac{g_{\varphi VV}}{g^{\rm SM}_{hVV}}$$

Higgs	κ_F	κ_V	
h	$\frac{\cos\alpha}{\sin\beta}$	$\sin\beta\cos\alpha - \sqrt{\frac{8}{3}}\cos\beta\sin\alpha$	
H_1^0	$\frac{\sin\alpha}{\sin\beta}$	$\sin\beta\sin\alpha + \sqrt{\frac{8}{3}}\cos\beta\cos\alpha$	
H_3^0	$i\eta_f\cot\beta$	0	gauge-phobic
H_5^0	0	$\kappa_W = -\frac{\cos\beta}{\sqrt{3}}$ and $\kappa_Z = \frac{2\cos\beta}{\sqrt{3}}$	quark-phobic

$\eta_f = +1$ for up-type quarks and -1 for down-type quarks and charged leptons.

group factor that makes it possible for the entire factor to be greater than 1 (mixing required)

suppressed by α

independent of α; proportional to v_Δ

Decay Pattern

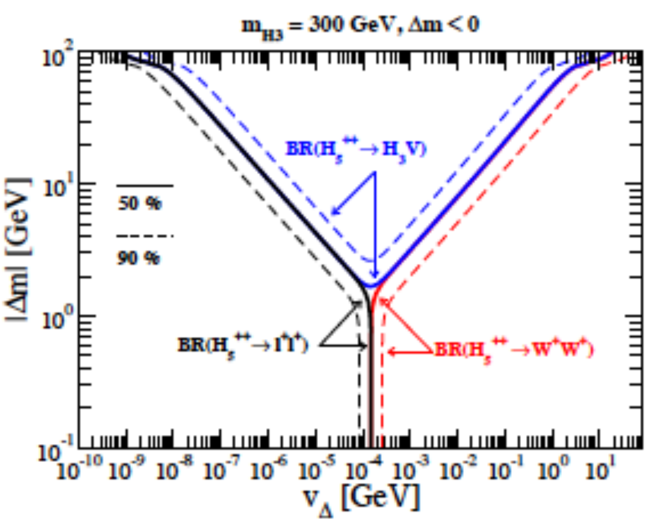
- Decay rates of new Higgs bosons generally depend on their mass hierarchy, v_Δ (or $\tan\theta_H$), and mixing angle α.
- Possible mass hierarchies in the decoupling limit:
  - $\Delta m = 0$ ➠ $m_{H5} = m_{H3} = m_{H1}$
  - $\Delta m > 0$ ➠ $m_{H1} > m_{H3} > m_{H5}$
  - $\Delta m < 0$ ➠ $m_{H5} > m_{H3} > m_{H1}$
- General mass spectra without fixing α and consistent with current Higgs data and some other theoretical and experimental constraints have recently been worked out. All six mass hierarchies are possible. CWC, Kuo, and Yamada 2015

Contour Plots for H_5 Decays

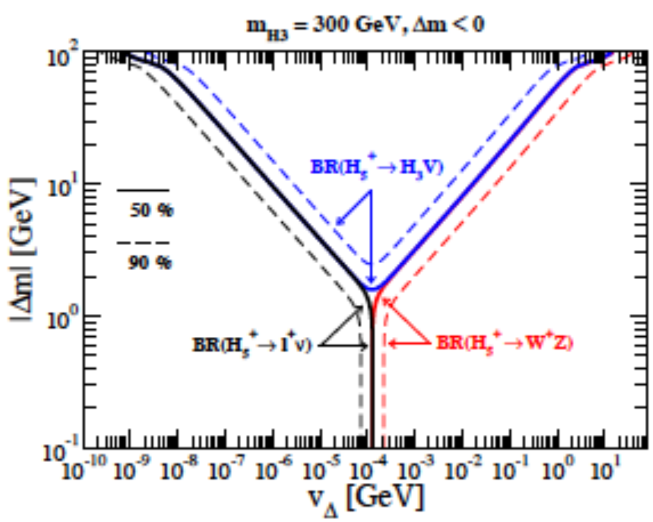
- Fix m_h = 125 GeV and $\alpha = 0$ in these plots.
- Decay rates now depend upon v_Δ, m_{H3} and the mass splitting between **5**-plet and **3**-plet:

$$\Delta m \equiv m_{H_3} - m_{H_5}$$

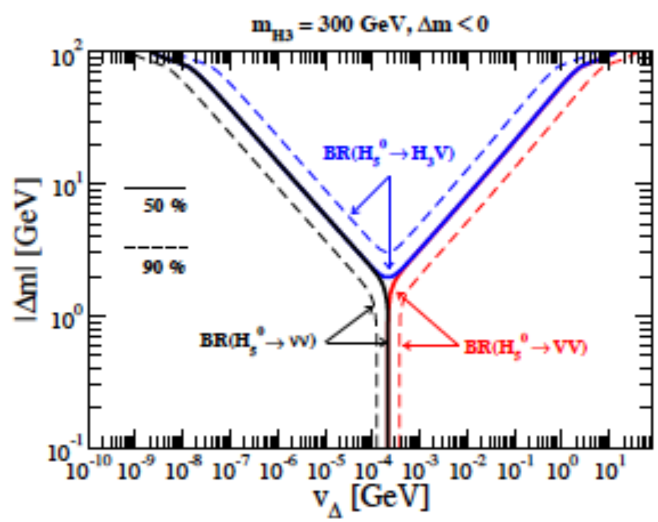
doubly-charged



singly-charged



neutral



solid: 50%; dashed: 90%

Decay Pattern

CWC, Yagyu JHEP 2012

$\Delta m < 0 \;\; (m_{H_5} > m_{H_3})$

$H_5^{++} \to H_3^+ W^+ \;,\; H_5^+ \to H_3^+ Z / H_3^0 W^+ \;,\; H_5^0 \to H_3^\pm W^\mp / H_3^0 Z$

$H_3^+ \to H_1^0 W^+ \;,\; H_3^0 \to H_1^0 Z$

$\Delta m > 0 : \;\; (m_{H_3} > m_{H_5})$

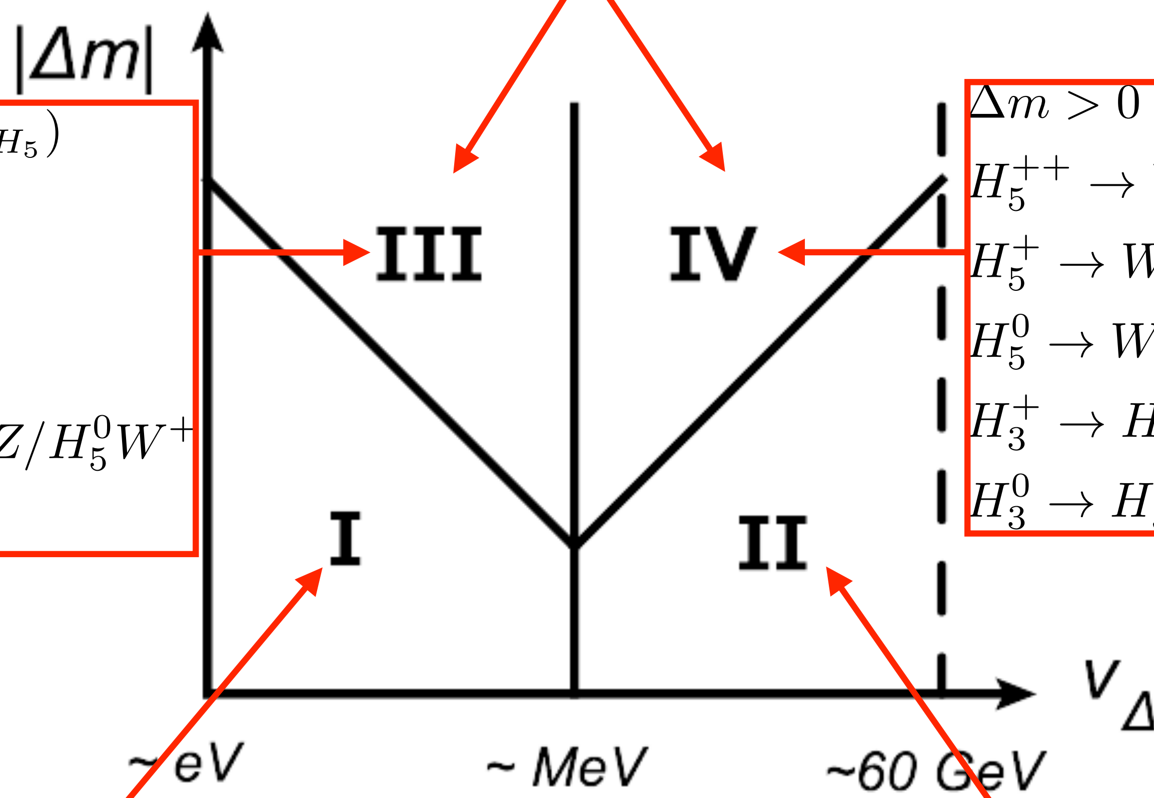
$H_5^{++} \to \ell^+ \ell^+$

$H_5^+ \to \ell^+ \nu$

$H_5^0 \to \nu\nu$

$H_3^+ \to H_5^{++} W^- / H_5^+ Z / H_5^0 W^+$

$H_3^0 \to H_5^\pm W^\mp / H_5^0 Z$



$\Delta m > 0 : \;\; (m_{H_3} > m_{H_5})$

$H_5^{++} \to W^+ W^+$

$H_5^+ \to W^+ Z$

$H_5^0 \to W^+ W^- / ZZ$

$H_3^+ \to H_5^{++} W^- / H_5^+ Z / H_5^0 W^+$

$H_3^0 \to H_5^\pm W^\mp / H_5^0 Z$

$H_5^{++} \to \ell^+ \ell^+ \;,\; H_5^+ \to \ell^+ \nu \;,\; H_5^0 \to \nu\nu \;,$

$H_3^+ \to \ell^+ \nu \;,\; H_3^0 \to \nu\nu.$

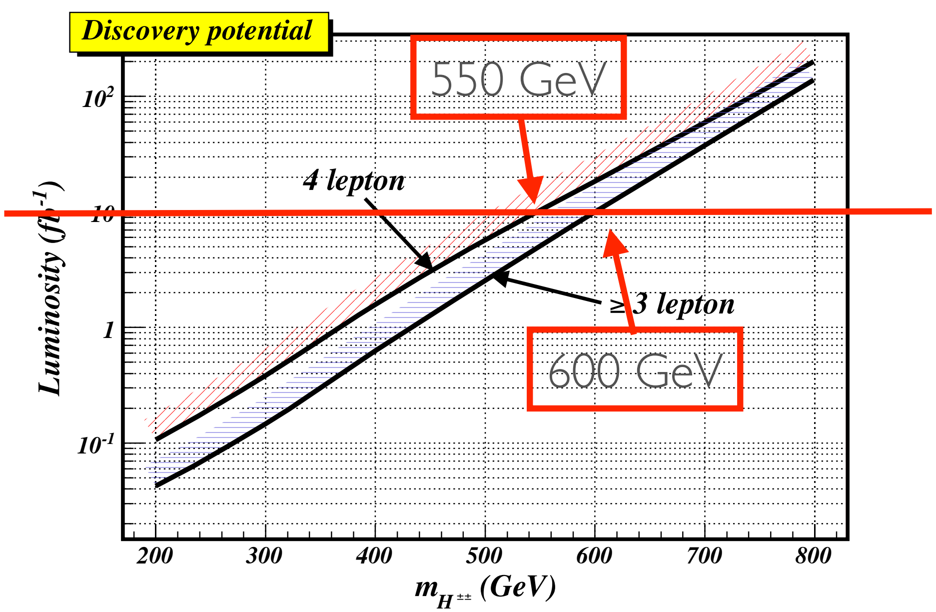
$H_5^{++} \to W^+ W^+ \;,\; H_5^+ \to W^+ Z \;,\; H_5^0 \to W^+ W^- / ZZ \;,$

$H_3^+ \to \tau^+ \nu / c\bar{s} / t\bar{b} \;,\; H_3^0 \to b\bar{b}.$

Signature for Small v_Δ

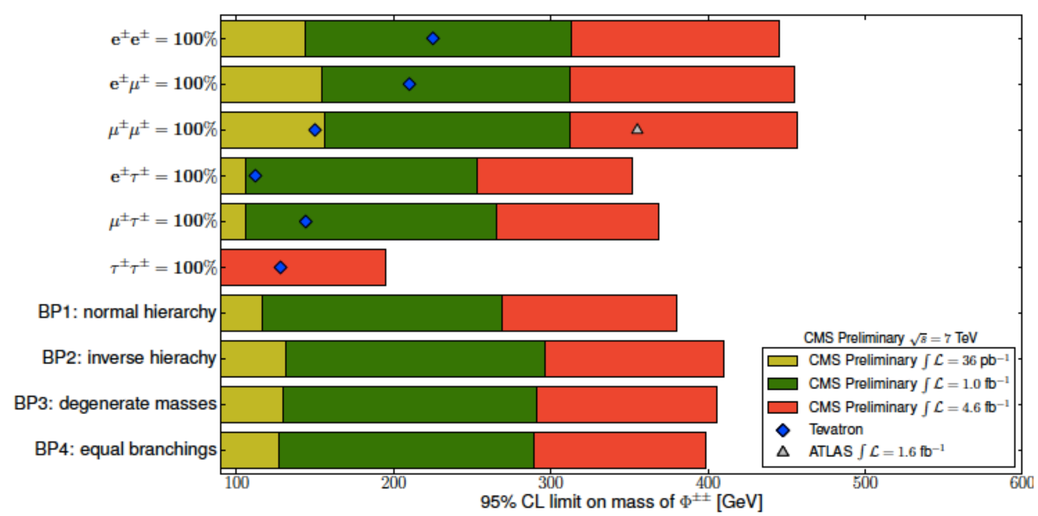
- In the case of small v_Δ, both $H^{\pm\pm}$ and $H^\pm$ decay dominantly into leptonic final states, same as the simplest Higgs triplet model in phenomenology.

Akeroyd, CWC, Gaur 2010



14-TeV LHC

CMS 2012

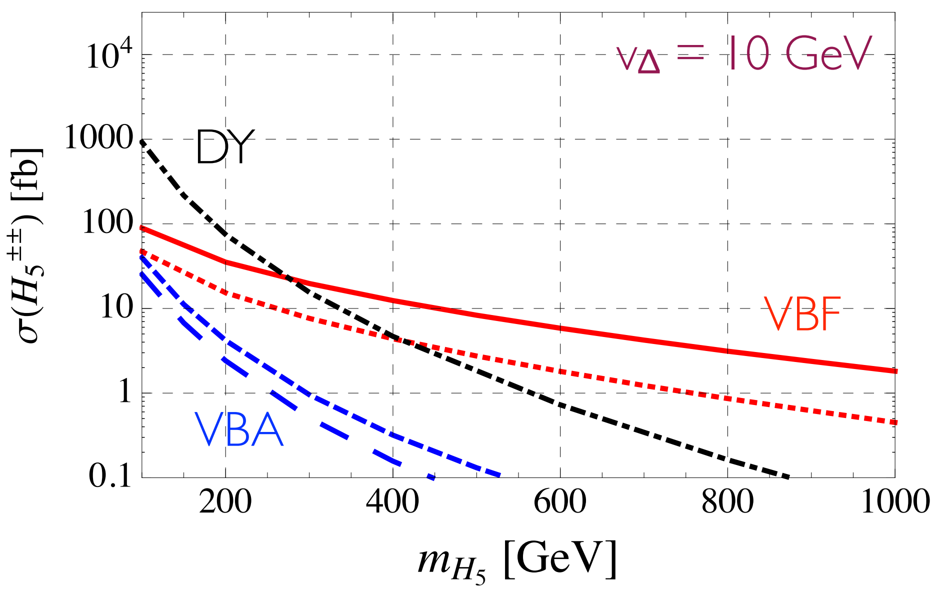


A general lower bound of 400 GeV from like-sign dilepton modes is given by both ATLAS and CMS. ATLAS 2012, 2014

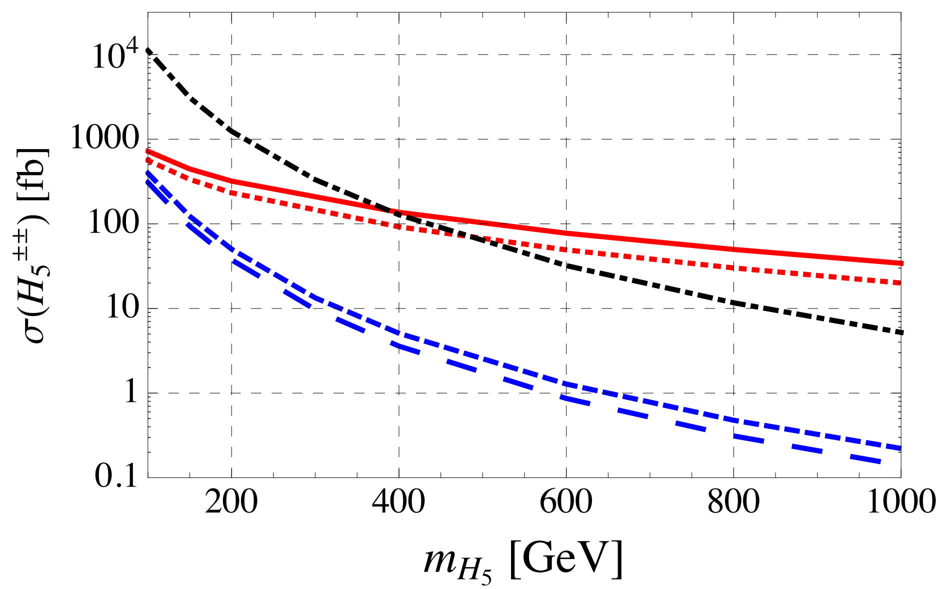
Production for Large v_Δ

- For large v_Δ, $H^{\pm\pm}$ couples dominantly to weak bosons.
- VBF as dominant production processes for sufficiently large v_Δ and sufficiently large $M_{H^{\pm\pm}}$.

CWC, Kuo, and Yamada 2015



14 TeV



100 TeV

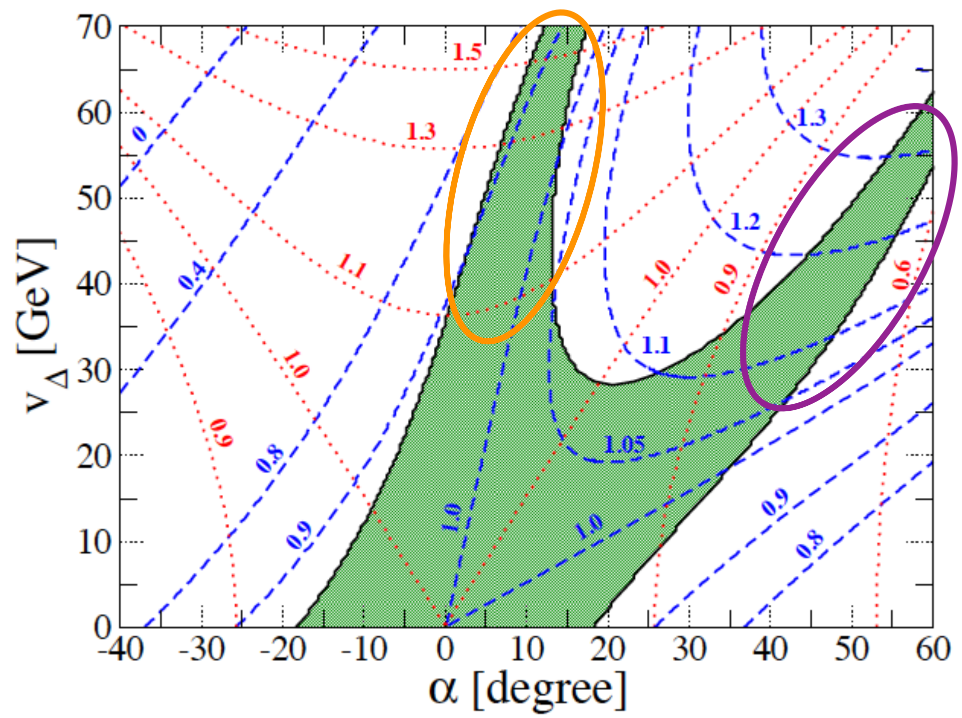
- Upper curves for ++ and lower curves for −−.

an experimentally less explored scenario, and unique for GM

Importance of VBF Processes

$\mu_{VV}^{GGF} = 1.0 \pm 0.1$ κ_V contours κ_F contours

- Enhancement (suppression) in BR($h \to VV$) due to $\kappa_V > 1$ (< 1) is compensated by suppression (enhancement) in gluon fusion cross section due to $\kappa_F < 1$ (> 1).
  ➠ importance of studying the VBF processes in GM



Transverse Mass Distributions

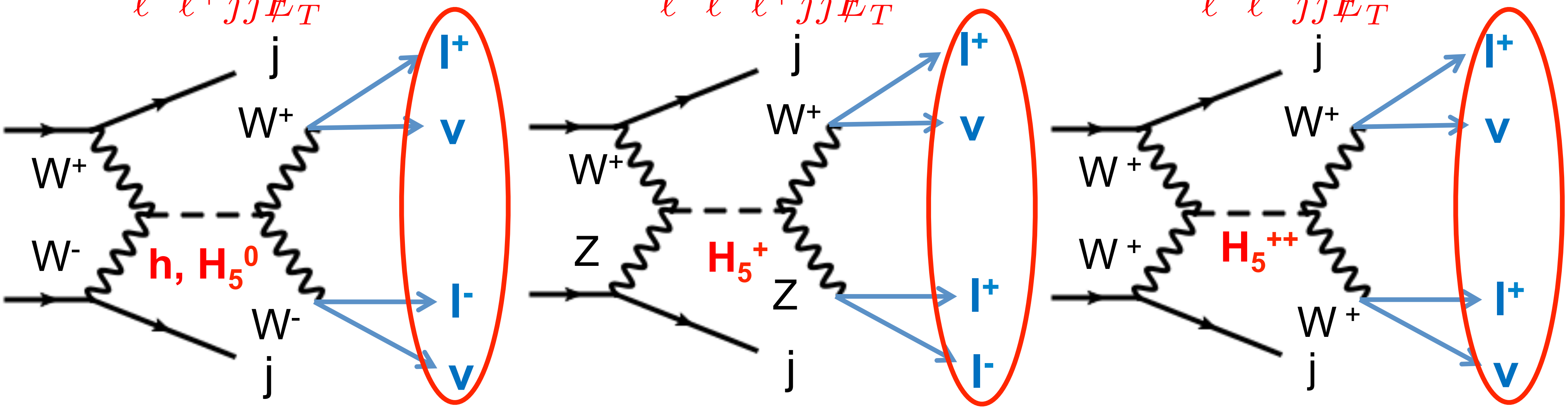
c_{hVV} = 1.3 with (θ_H,α) = (40°,55°) and
M_{H5} = M_{H3} = M_{H1} = 300 GeV ➠ no mass hierarchy

CWC, Kuo, Yagyu JHEP 2013

neutral — $\ell^\pm\ell^\mp jj\not{E}_T$

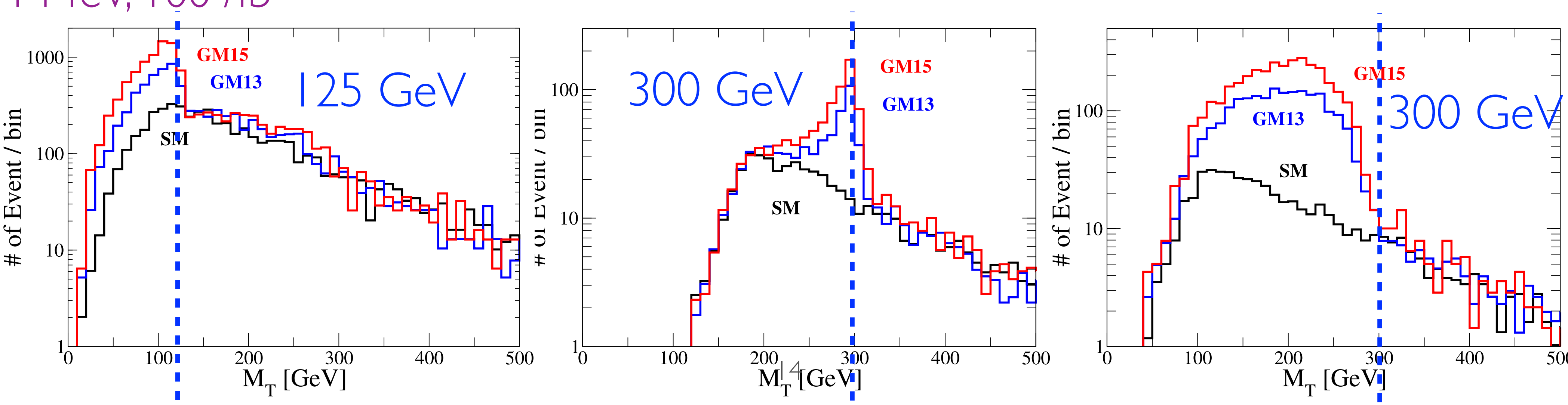
singly-charged — $\ell^\pm\ell^\pm\ell^\mp jj\not{E}_T$

doubly-charged — $\ell^\pm\ell^\pm jj\not{E}_T$



14 TeV, 100 /fb

easier to determine $H_5^{\pm\pm}$ mass than the other two

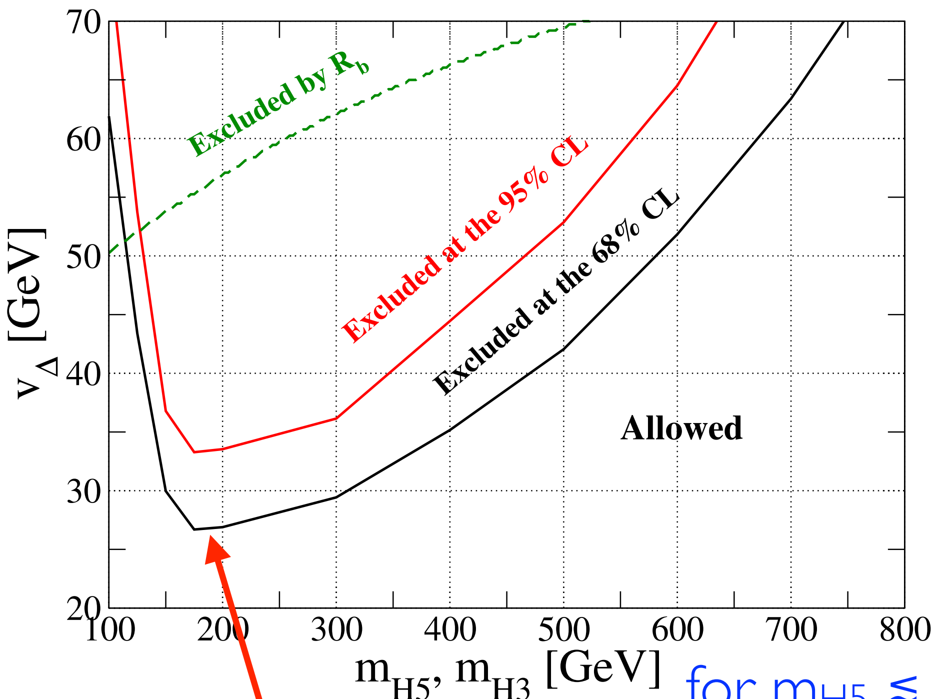


Constraint from $H_5^{\pm\pm}$

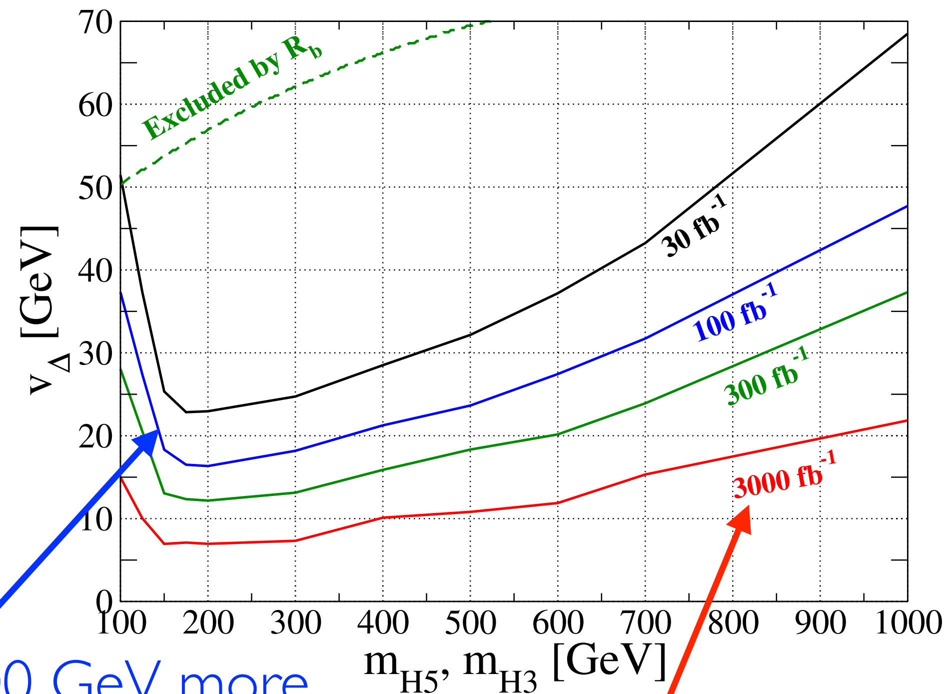
ATLAS 2014

- ATLAS data of **same-sign di-boson** events (20.3/fb, 8-TeV) can be used to limit the v_Δ-m_{H5} plane:

limit from 8-TeV LHC of 20.3 /fb



5σ reach at 14-TeV LHC



most severe bound on v_Δ at m_{H5} = 200 GeV

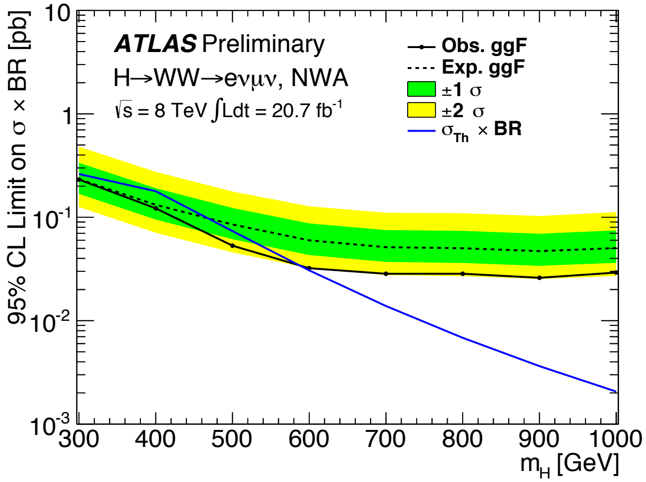
for $m_{H5} \lesssim 200$ GeV, more events from 5-plet Higgses are rejected by kinematic cuts

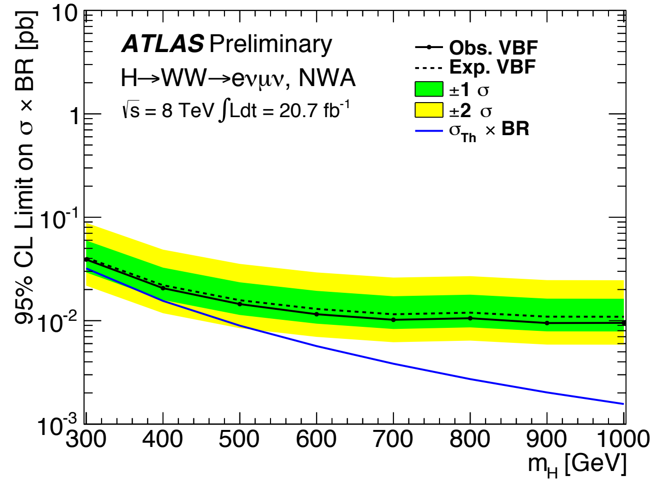
more improvement in high mass region

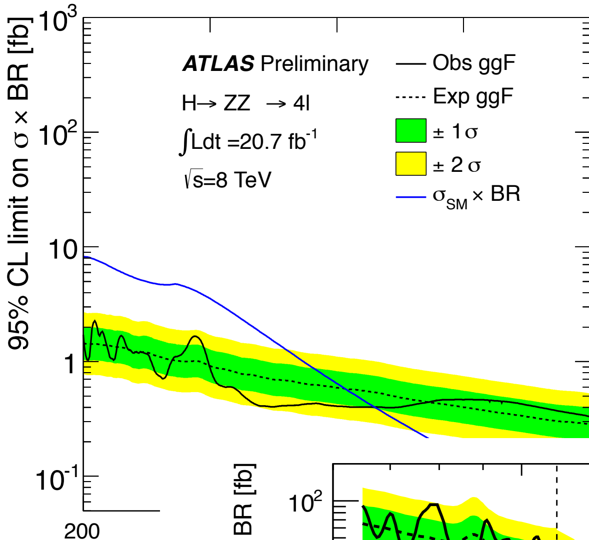
- Results are **independent of α.**

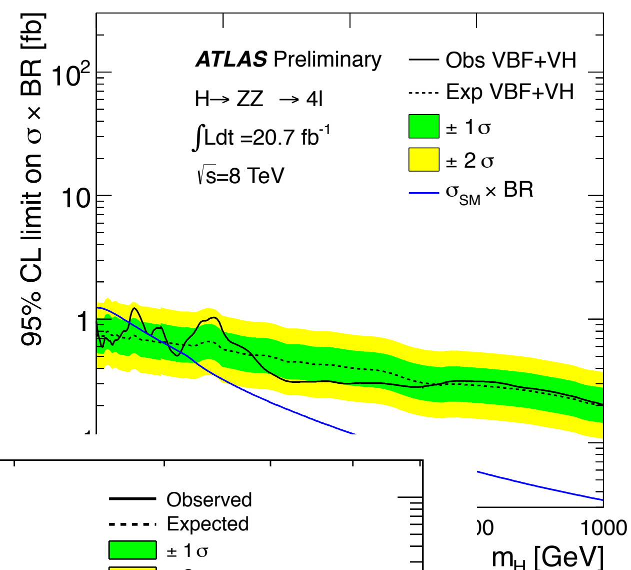
CWC, Kanemura, Yagyu PRD 2014

Searches of Other Neutral Higgses

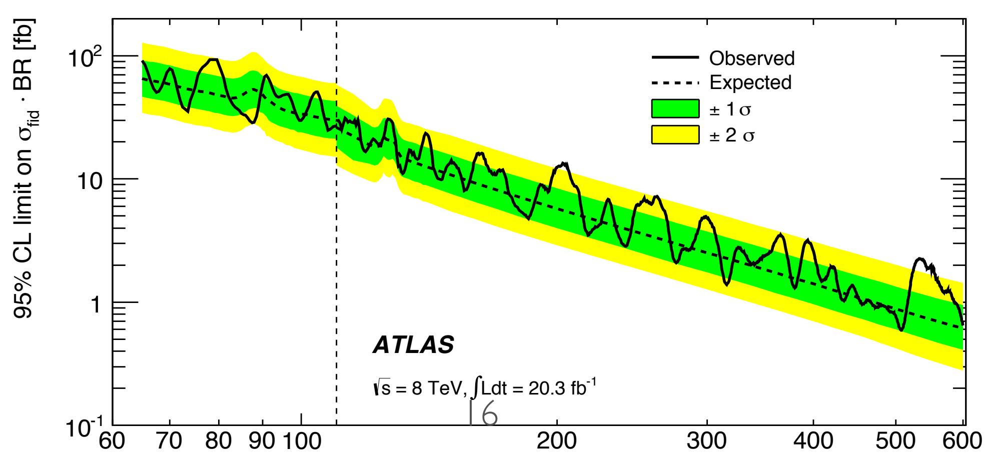








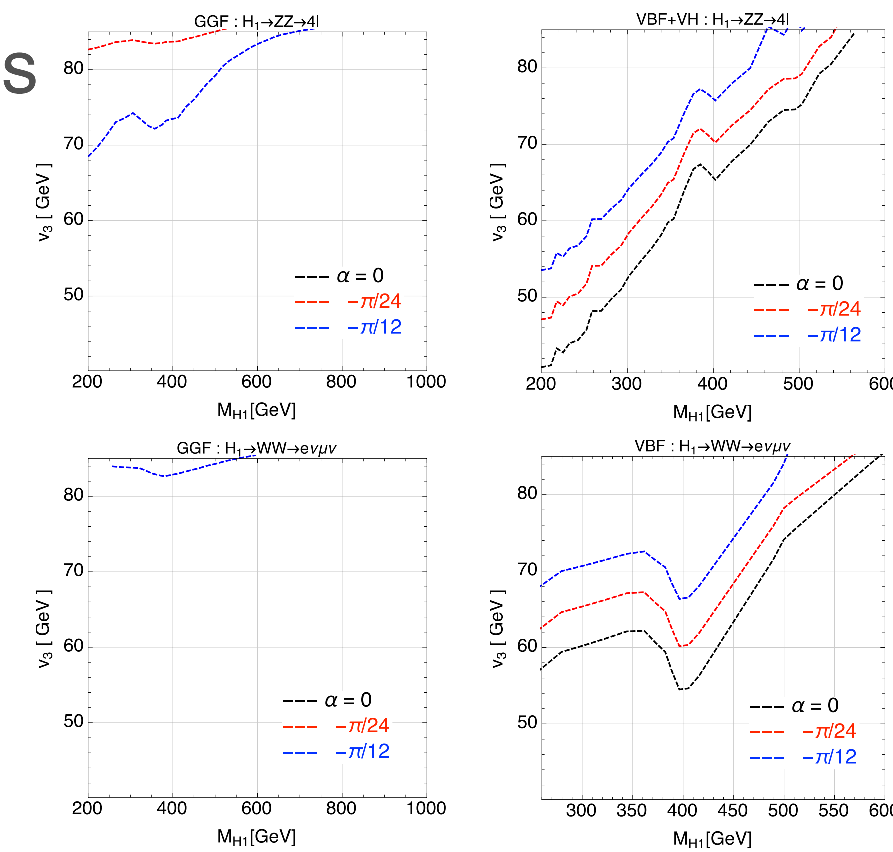
ATLAS 2014



Constraint from H_1^0

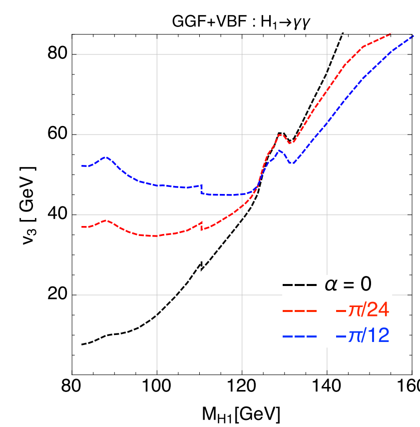
CWC and Tsumura JHEP 2015

- Constraints from VBF channels are stronger than those from GGF mechanism.



- ZZ is more constraining than WW when $M_{H1} \lesssim 375$ GeV as the former has a slightly better experimental sensitivity.

- The γγ mode (GGF+VBF) provides useful bounds on v_Δ in the low-mass regime.

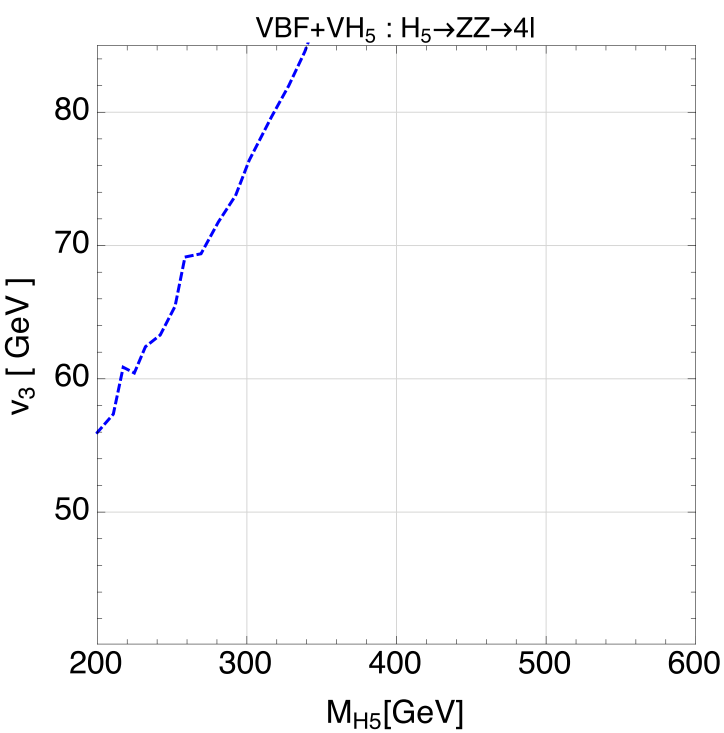


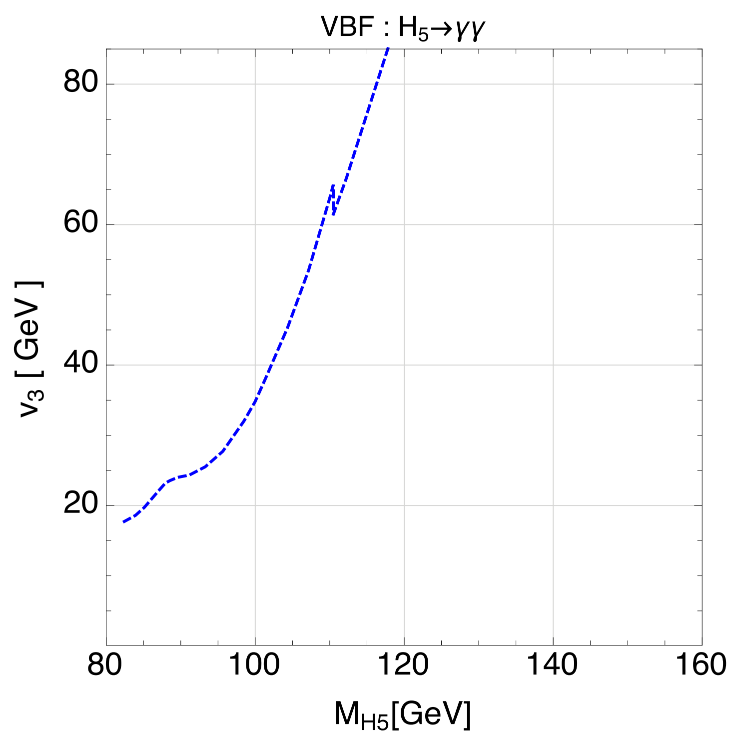
- All of them are sensitive to α.

Constraint from H_5^0

CWC and Tsumura JHEP 2015

- Since H_5 does not couple to SM quarks and charged leptons, it has only VBF ZZ, WW, and γγ channels.
- Constraints are generally weaker, but independent of α.
- The WW mode does not provide a useful constraint.





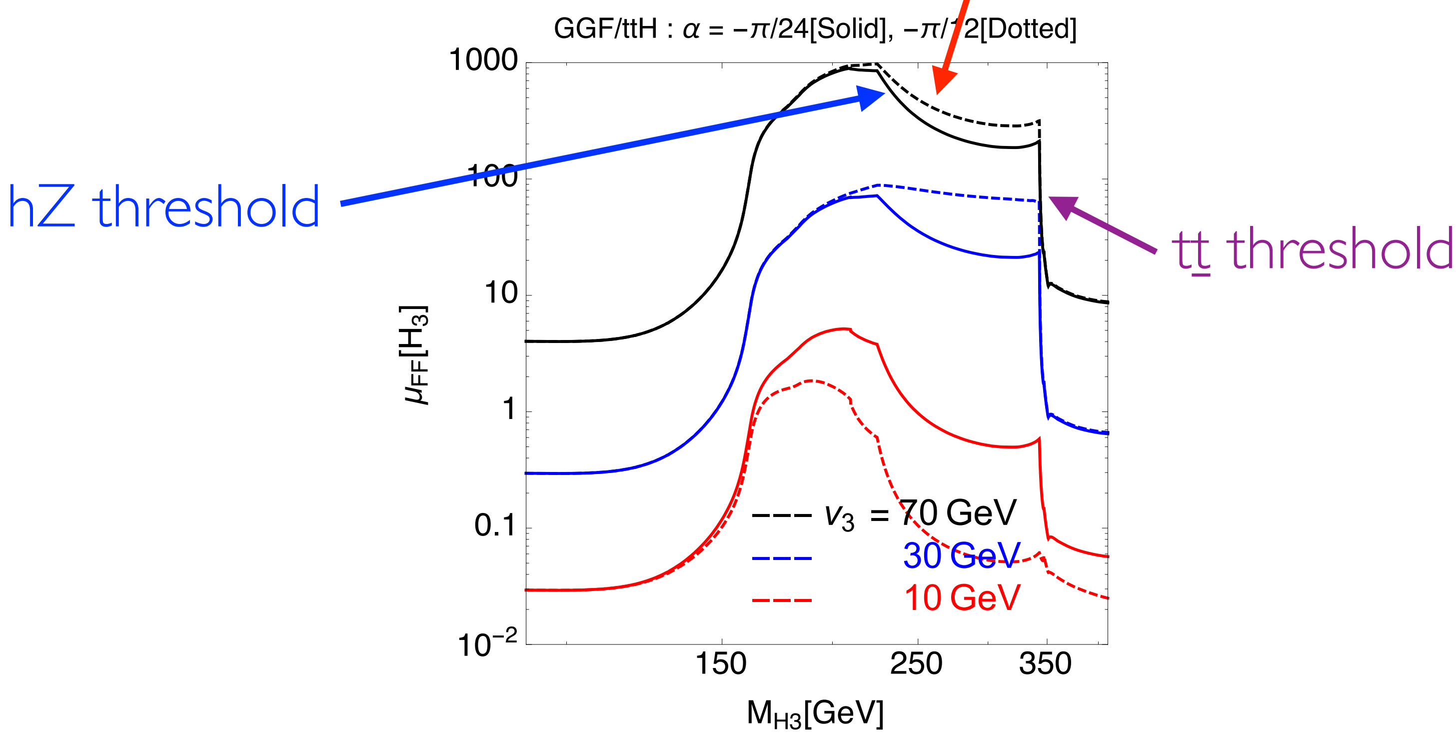
No Constraint from H_3^0 Yet

CWC and Tsumura JHEP 2015

- Signal strength of $H_3^0 \to f\bar{f}$ is significantly enhanced in the mass range **between $2M_W$ and $2M_t$**:

$$\mu_{FF}^{\rm GGF}[H_3] = (\kappa_F^{H_3})^2 \frac{F_{1/2}^A(M_{H_3})}{F_{1/2}^S(M_{H_3})} \times \frac{\mathcal{B}_F}{\mathcal{B}_F^{\rm SM}(M_{H_3})} \left(1 - \frac{4M_f^2}{M_{H_3}^2}\right)^{-1}$$

- Use these modes to search for H_3^0 or constrain the model.

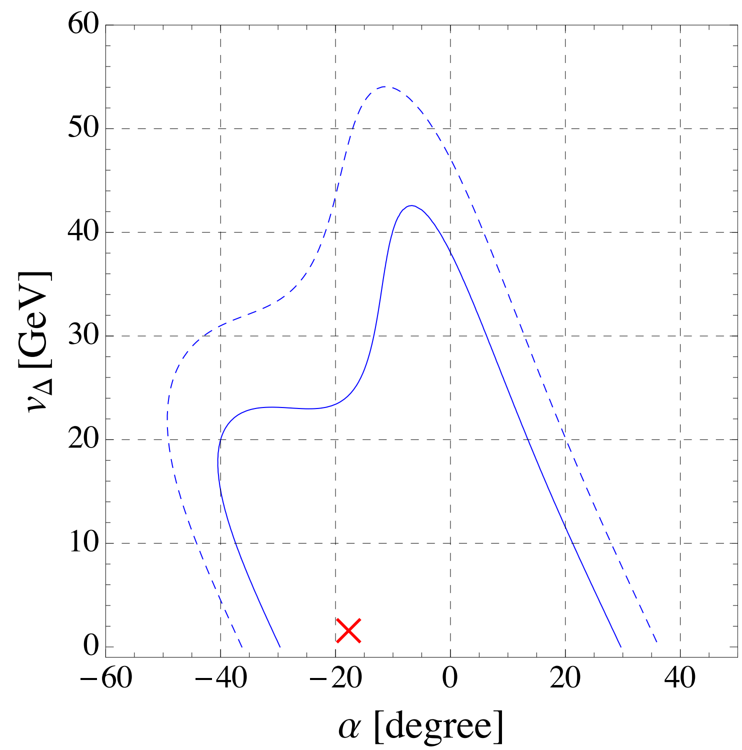


Constraints from Higgs Data

CWC, Kuo, and Yamada 2015

- Consider the tree-dominated Higgs decays into ZZ, WW, bb, and ττ in a chi-square fit.
- Do not include γγ to avoid uncertainties in the loop.
- Solid: 1σ contour; dashed: 2σ contour.

- In our work, we sample a few points in the allowed region and scan for viable mass spectra for exotic Higgs bosons.



Unitarity/Stability Bounds

- (Tree-level) perturbative unitarity bound — Aoki, Kanemura 2008

$$|\,6\lambda_1 + 7\lambda_3 + 11\lambda_2\,| + \sqrt{(6\lambda_1 - 7\lambda_3 - 11\lambda_2)^2 + 36\lambda_4^2} < 4\pi\ ,$$
$$|\,\lambda_4 - \lambda_5\,| < 2\pi\ , \qquad |\,2\lambda_3 + \lambda_2\,| < \pi\ ,$$
$$|\,2\lambda_1 - \lambda_3 + 2\lambda_2\,| + \sqrt{(2\lambda_1 + \lambda_3 - 2\lambda_2)^2 + \lambda_5^2} < 4\pi\ .$$

- (Tree-level) vacuum stability bound — Arhrib et al 2011

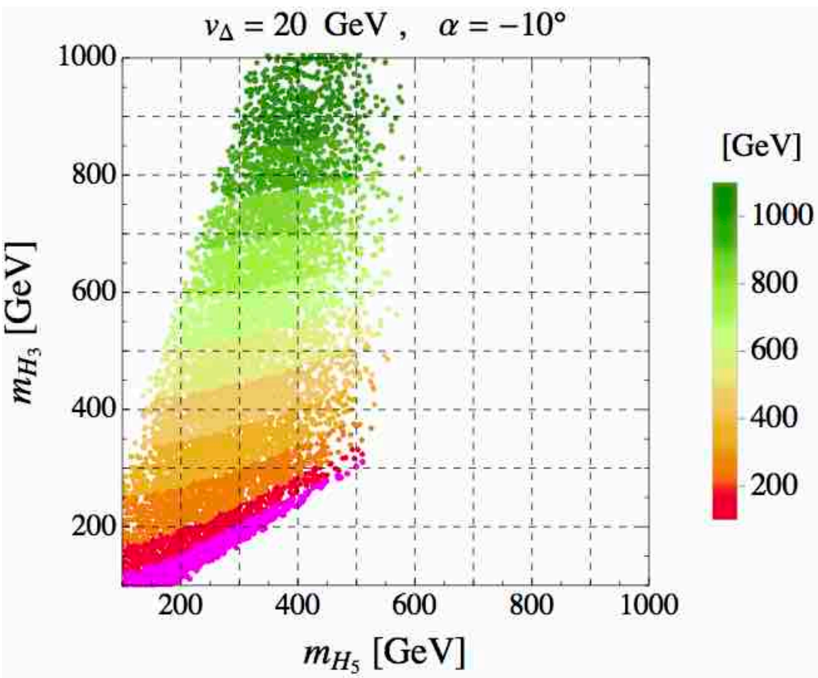
$$\lambda_1 > 0\ , \quad \lambda_2 + \lambda_3 > 0\ , \quad \lambda_2 + \frac{1}{2}\lambda_3 > 0\ ,$$
$$-|\lambda_4| + 2\sqrt{\lambda_1(\lambda_2+\lambda_3)} > 0\ , \quad \lambda_4 - \frac{1}{4}|\lambda_5| + \sqrt{2\lambda_1(2\lambda_2+\lambda_3)} > 0\ .$$

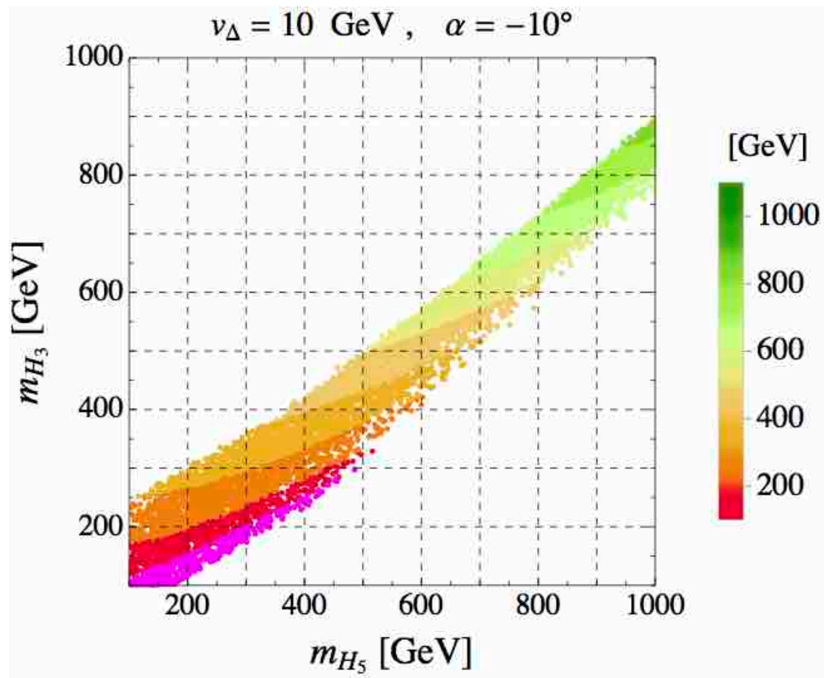
- All λ's can be written in terms of physical parameters.

Viable Mass Spectra

CWC, Kuo, and Yamada 2015

- m_{H1} on the m_{H5}-m_{H3} plane, satisfying stability and unitarity constraints and measurements of the S parameter and the Zbb coupling at 2σ level.

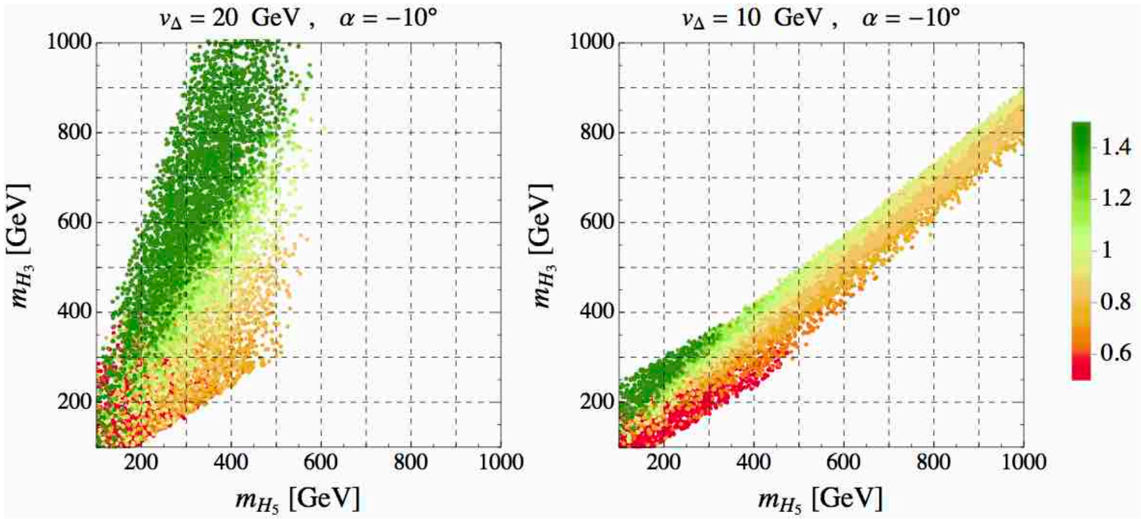




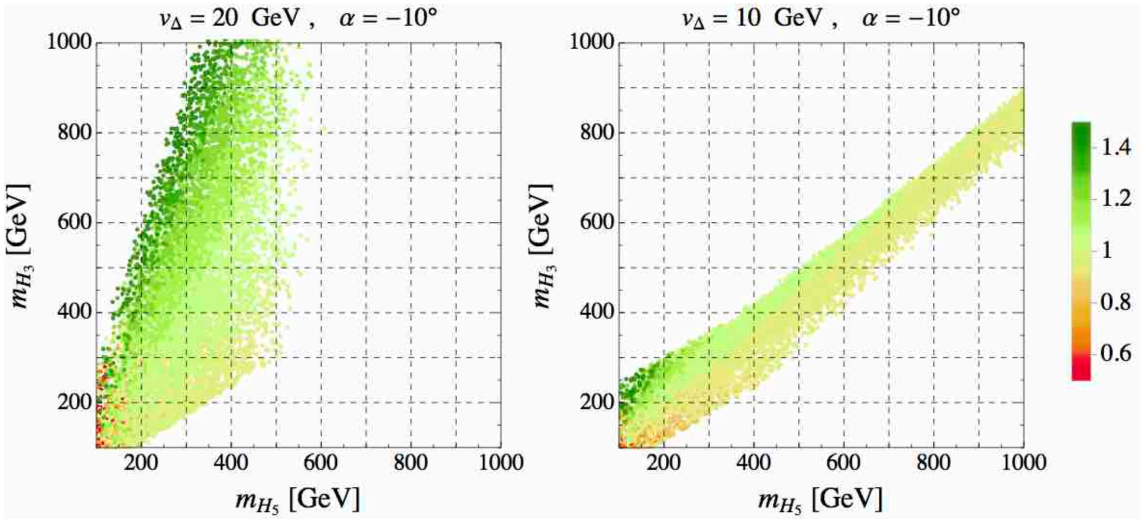
- Just two examples; more in our paper.

γγ and γZ Decays of h

- Signal strength of the γγ mode via GGF.
- LHC 7 TeV + 8 TeV data
  - ATLAS: $1.007^{+0.934}_{-1.089}$
  - CMS: 1.32±0.38

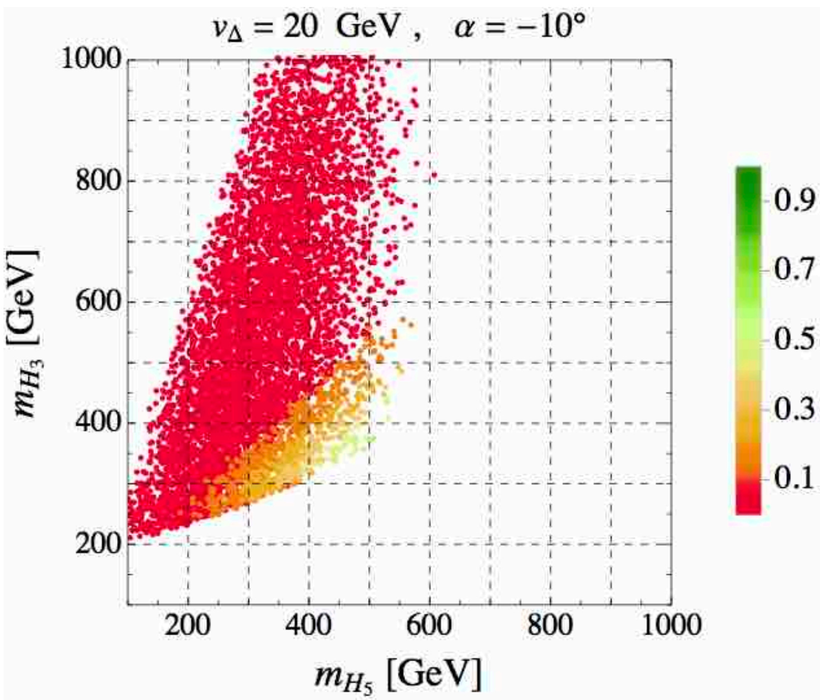


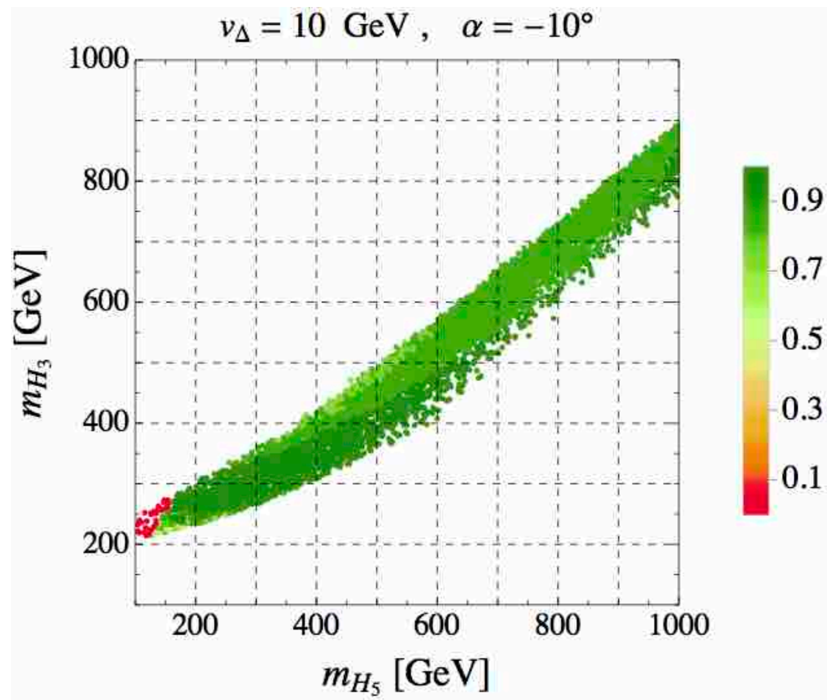
- Signal strength of the γZ mode via GGF.



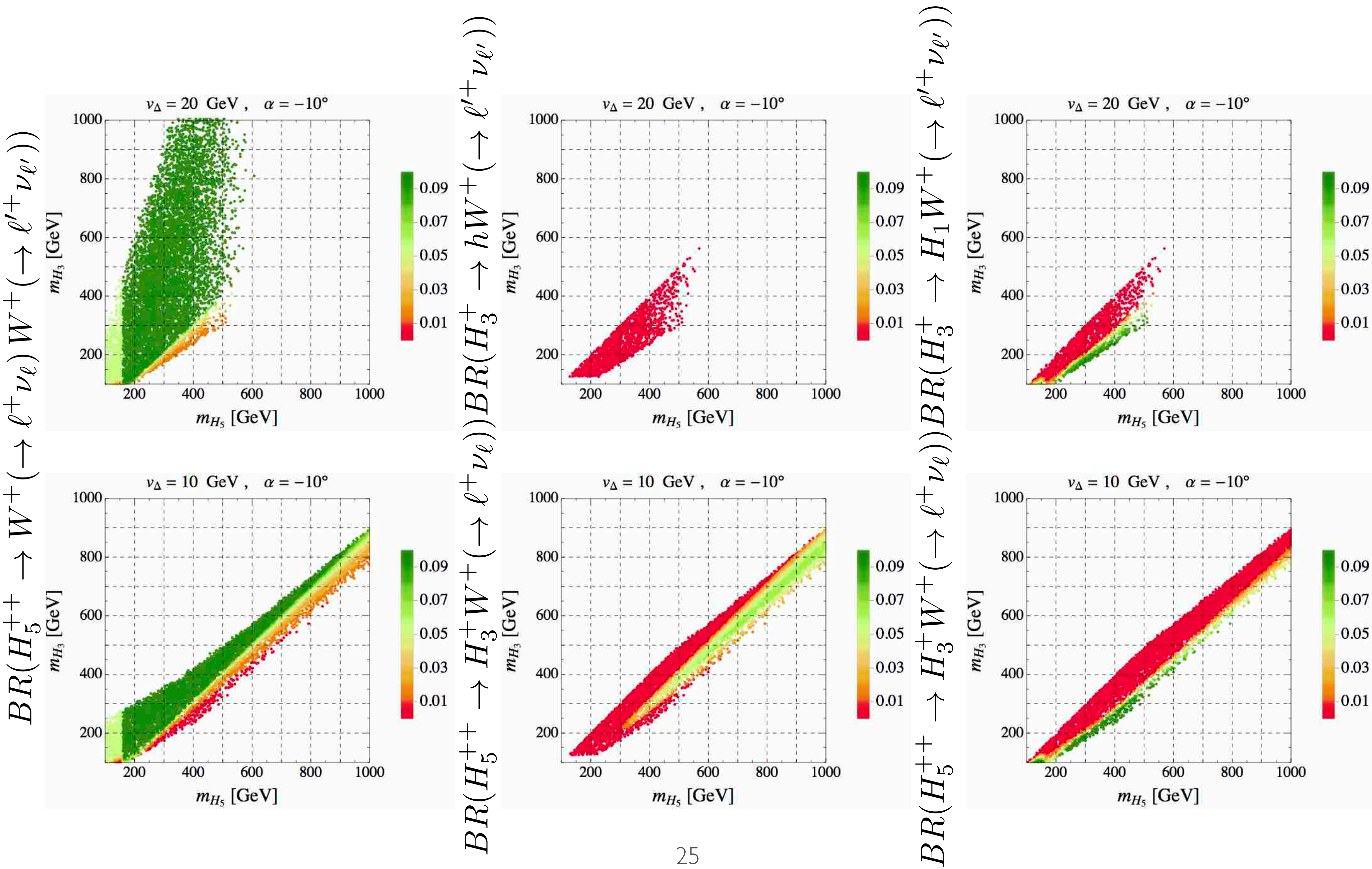
Double Higgs Decay of H_1

- When $m_{H1} > m_h$, $H_1 \to hh$ becomes possible.
- BR varies a lot.
  ➠ affecting search scheme
- In certain cases, it can be larger than 90%!





W-Pair/Cascade $H^{\pm\pm}$ Decays



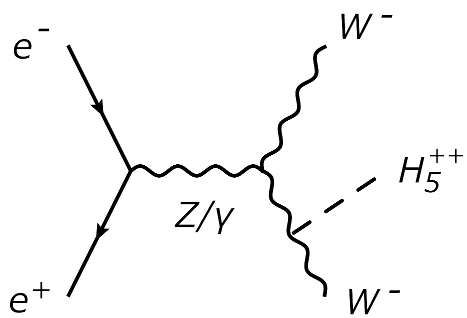
5-plet at ILC

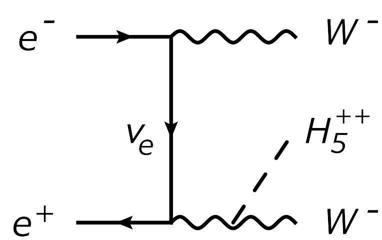
- Three types of production modes at ILC:
  - Pair production (PP) processes

$$e^+e^- \to Z^*/\gamma^* \to H_5^{++}H_5^{--}$$
$$e^+e^- \to Z^*/\gamma^* \to H_5^{+}H_5^{-}$$

independent of v_Δ
dominant for small v_Δ
kinematically limited to $\sqrt{s}/2$

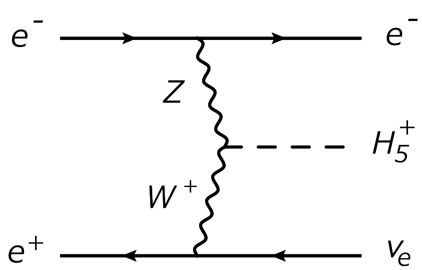
  - Vector boson associated (VBA) processes

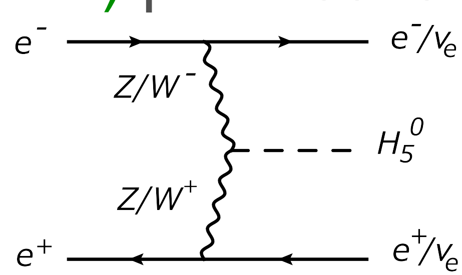




depending on v_Δ
dominant for large v_Δ and m_{H5}
up to $\sqrt{s} - M_{W,Z}$
involving $H_5^{\pm}W^{\mp}Z$ vertex

  - Vector boson fusion (VBF) processes



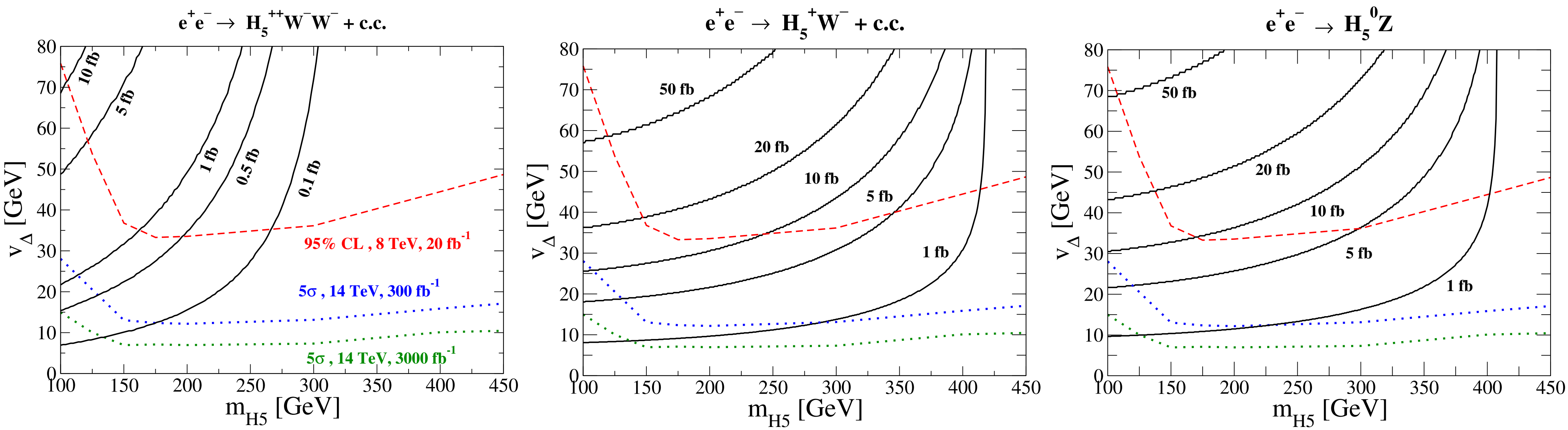


depending on v_Δ
dominant for large v_Δ and m_{H5}
up to $\sim\sqrt{s}$
involving $H_5^{\pm}W^{\mp}Z$ vertex

VBA Cross Sections @ ILC

CWC, Kanemura, Yagyu 2015

- Production rates for the neutral and singly-charged H_5 are higher than the doubly-charged one, and are ~ O(1 fb) for a wide mass range.



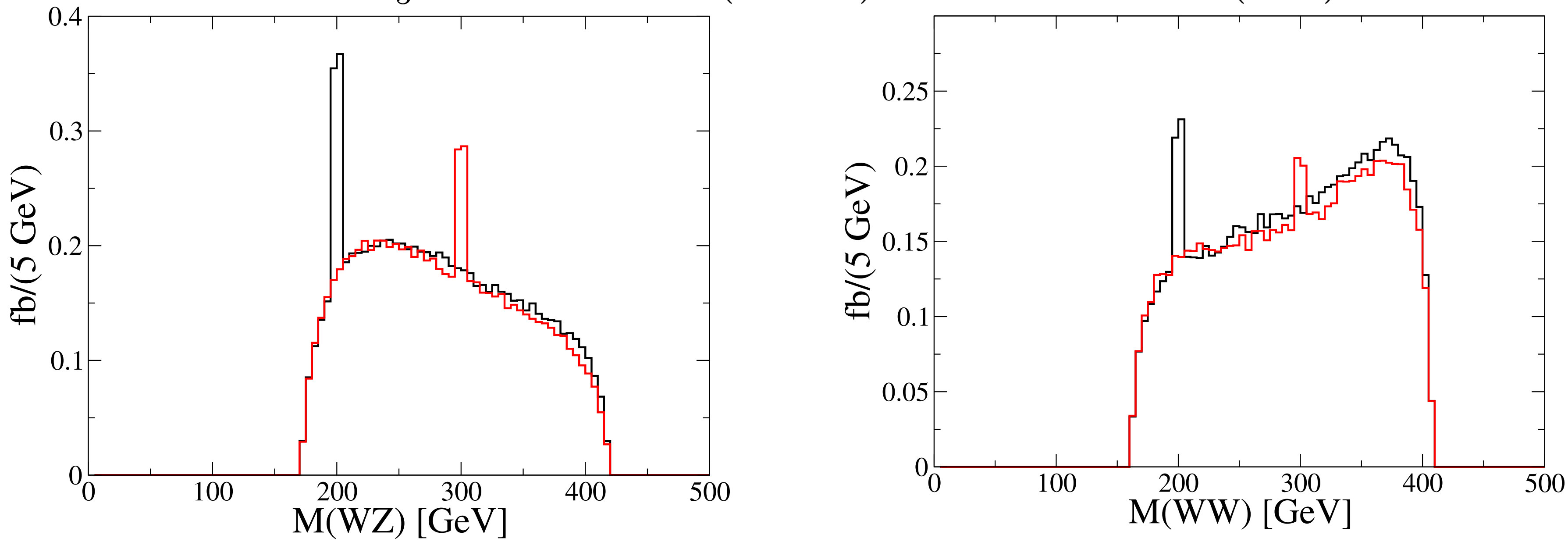
$\sqrt{s} = 500$ GeV

Invariant Mass Distributions

- Invariant mass distributions for subsystems of the $e^+e^- \to W^+W^-Z$ process, including ISR with scale set at $\sqrt{s}$.
- Narrow peaks are due to $H_5^\pm$ and H_5^0, respectively.
- Precise measurement of the $H_5^\pm W^\mp Z$ vertex is possible.

$$\sqrt{s} = 500 \text{ GeV and } v_\Delta = 30 \text{ GeV}$$

$$m_{H_5} = 200 \text{ GeV (black) and } 300 \text{ GeV (red)}$$



Summary

- With $SU(2)_L \times SU(2)_R$-symmetric Higgs potential and vacuum alignment, GM model preserves custodial symmetry, allows a large v_Δ, and possibly has hVV couplings stronger than SM's.
- There is an [approximate] mass degeneracy in each of the 3-plet, and 5-plet Higgs representations.
- For large v_Δ, VBF processes are useful for searching for exotic GM Higgs bosons, verifying their mass spectrum, and extracting hVV couplings.
- Latest LHC data are employed to put constraints on the parameter space (e.g., v_Δ vs α), and comprehensive scans are done to search for viable Higgs mass spectra.
- Synergy between searches of $H_5^\pm$ and H_5^0 at ILC and $H_5^{\pm\pm}$ at LHC will make the 5-plet study more comprehensive.

Thank You!