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# Phenomenology of Higgs Bosons in the Georgi-Machacek Model

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CWC and K Yagyu, JHEP 1301 (2013) 026
CWC, AL Kuo and K Yagyu, JHEP 1310 (2013) 072
CWC, S Kanemura and K Yagyu, PRD 90 (2014) 115025
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.xxxxx [hep-ph]

# Quick Overview of This Talk

- Georgi-Machacek Model
- Higgs decay pattern
- Constraints from LHC data
  - SM-like Higgs, like-sign W, extra neutral Higgs searches
- ILC phenomenology
- Summary

# 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 with 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 $\phi$ (2,1/2) and triplet fields $\chi$ (3,1) and $\xi$ (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.

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- The Higgs sector includes SM doublet field $\phi$ (2,1/2) and triplet fields $\chi$ (3,1) and $\xi$ (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

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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

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

with two mixing angle definitions seen in the literature:

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

- One could attribute EWSB entirely to $v_\Delta$ ($\simeq$ 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

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

$\Delta$: **3** $\otimes$ **3**

$\Phi$: **2** $\otimes$ **2**

$SU(2)_V$

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

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

mixing angle $\beta$ or $\theta_H$

mixing angle $\alpha$

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

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

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):

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

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

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

suppressed by α

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

independent of α

# Decay Pattern

- Decay rates of new Higgs bosons generally depend on their mass hierarchy, $v_\Delta$ (or $\tan\theta_H$), and mixing angle $\alpha$.
- Fix $m_h$ = 125 GeV and $\alpha = 0$ to be specific.
- Decay rates now depend upon $v_\Delta$, $m_{H3}$ and the mass splitting between **5**-plet and **3**-plet:

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

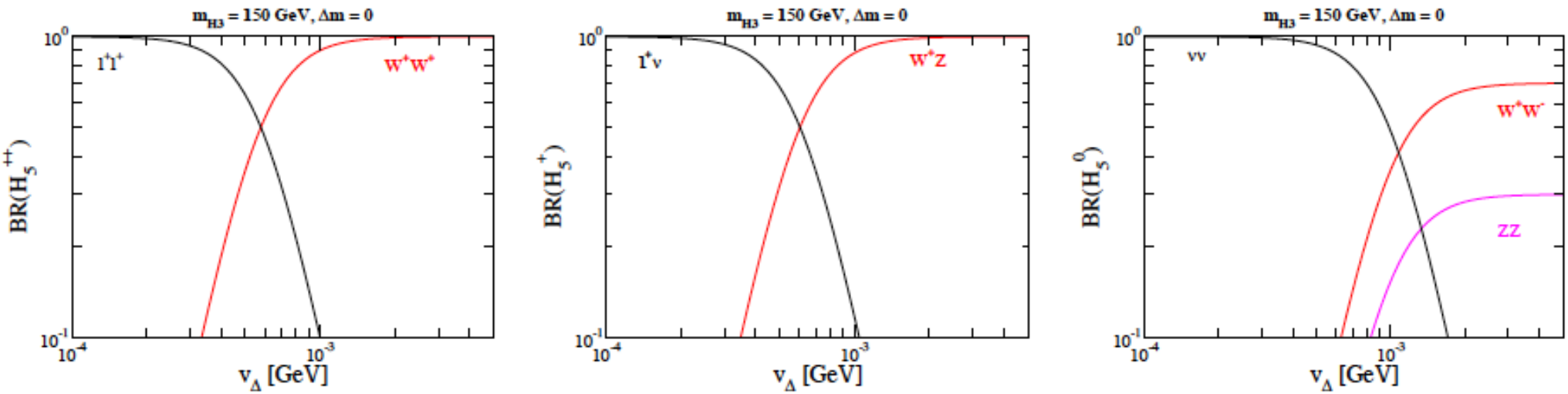
- General mass spectra without fixing $\alpha$ and consistent with current Higgs data and some other theoretical and experimental constraints have recently been worked out.

CWC, Kuo, Yamada, to appear

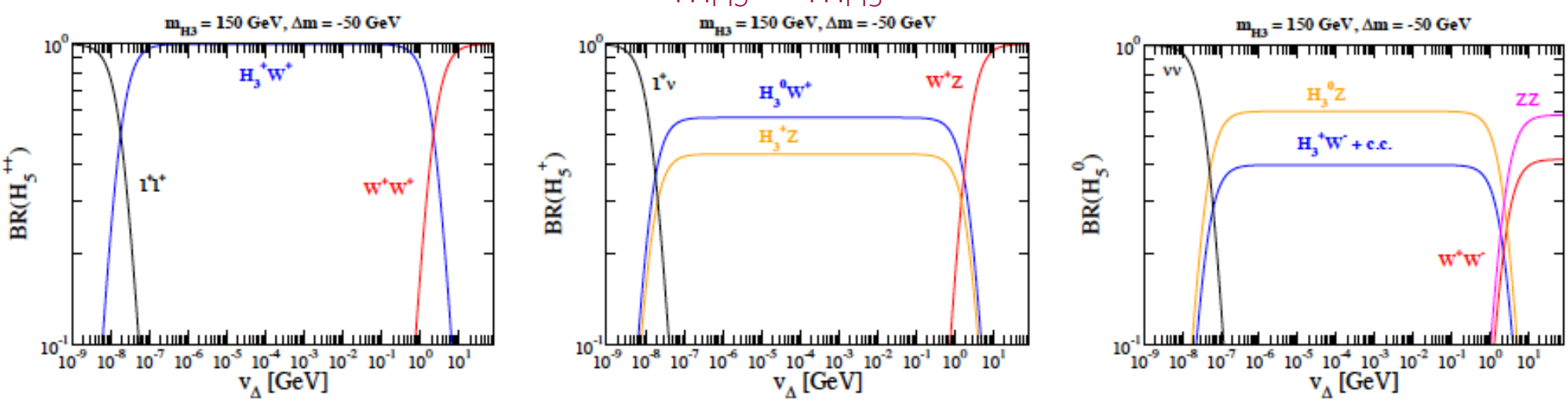
# Decays of $H_5$ Bosons

doubly-charged | singly-charged | neutral

$m_{H5} = m_{H3}$




$m_{H5} > m_{H3}$

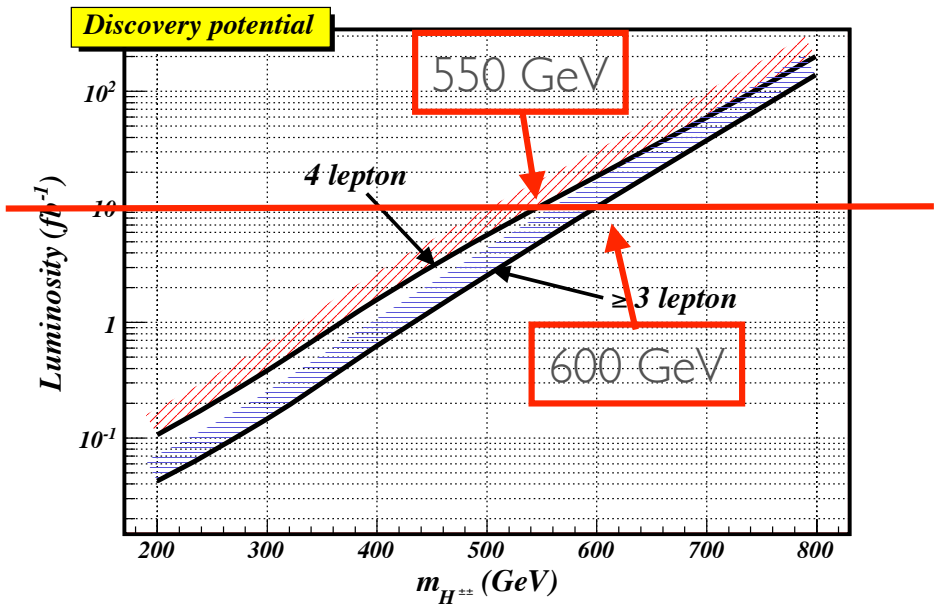



$v_\Delta$ is an important order parameter of the model.

# Signature for Small $v_\Delta$

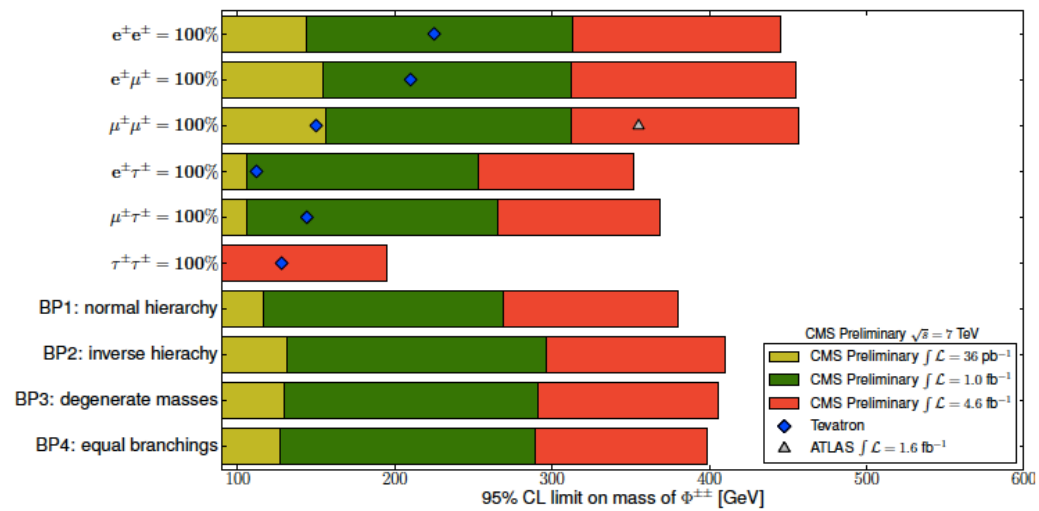
- In the case of small $v_\Delta$, both $H^{\pm\pm}$ and $H^{\pm}$ decay dominantly into leptonic final states, same as the simplest Higgs triplet model in phenomenology.

Akeroyd, CWC, Gaur 2010




14-TeV LHC

CMS 2012

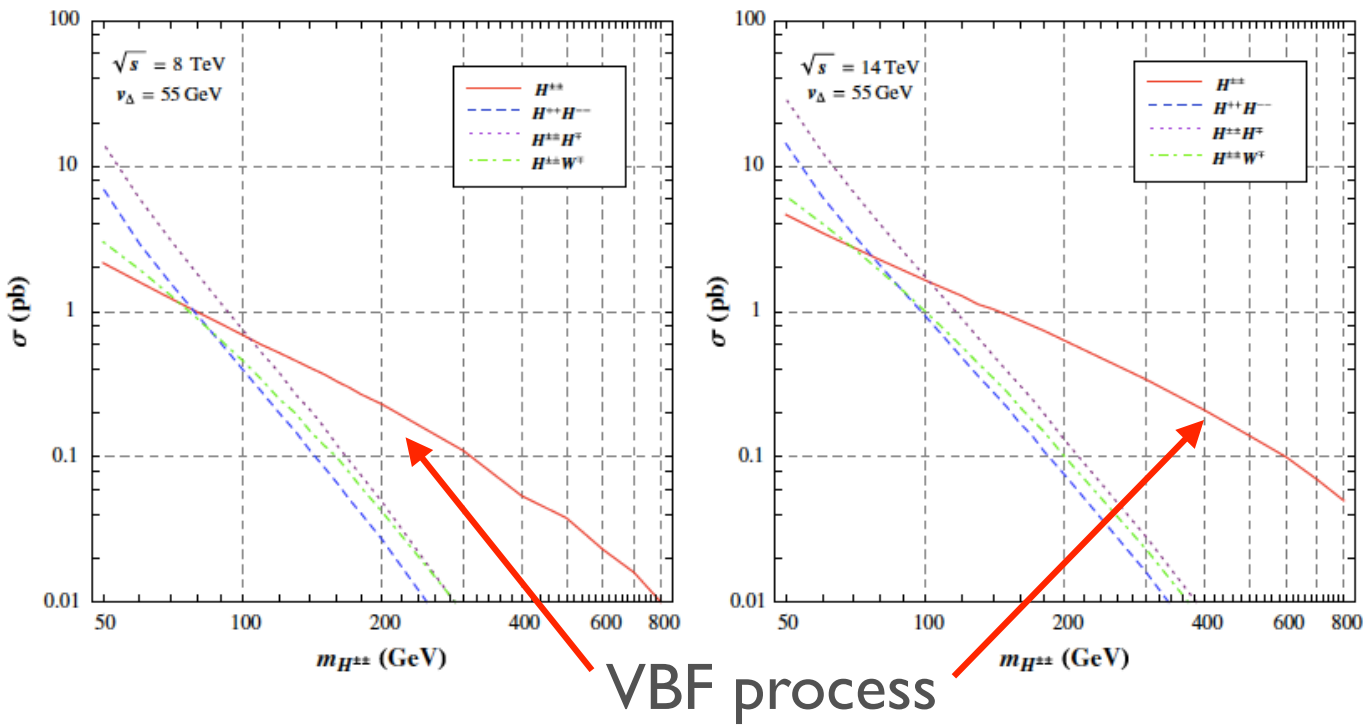



A general lower bound of 400 GeV from like-sign dilepton modes is given by both ATLAS and CMS. ATLAS 2012, 2014

# Production for Large $v_\Delta$

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

CWC, Nomura, Tsumura PRD 2012




an experimentally less explored scenario, and unique for GM

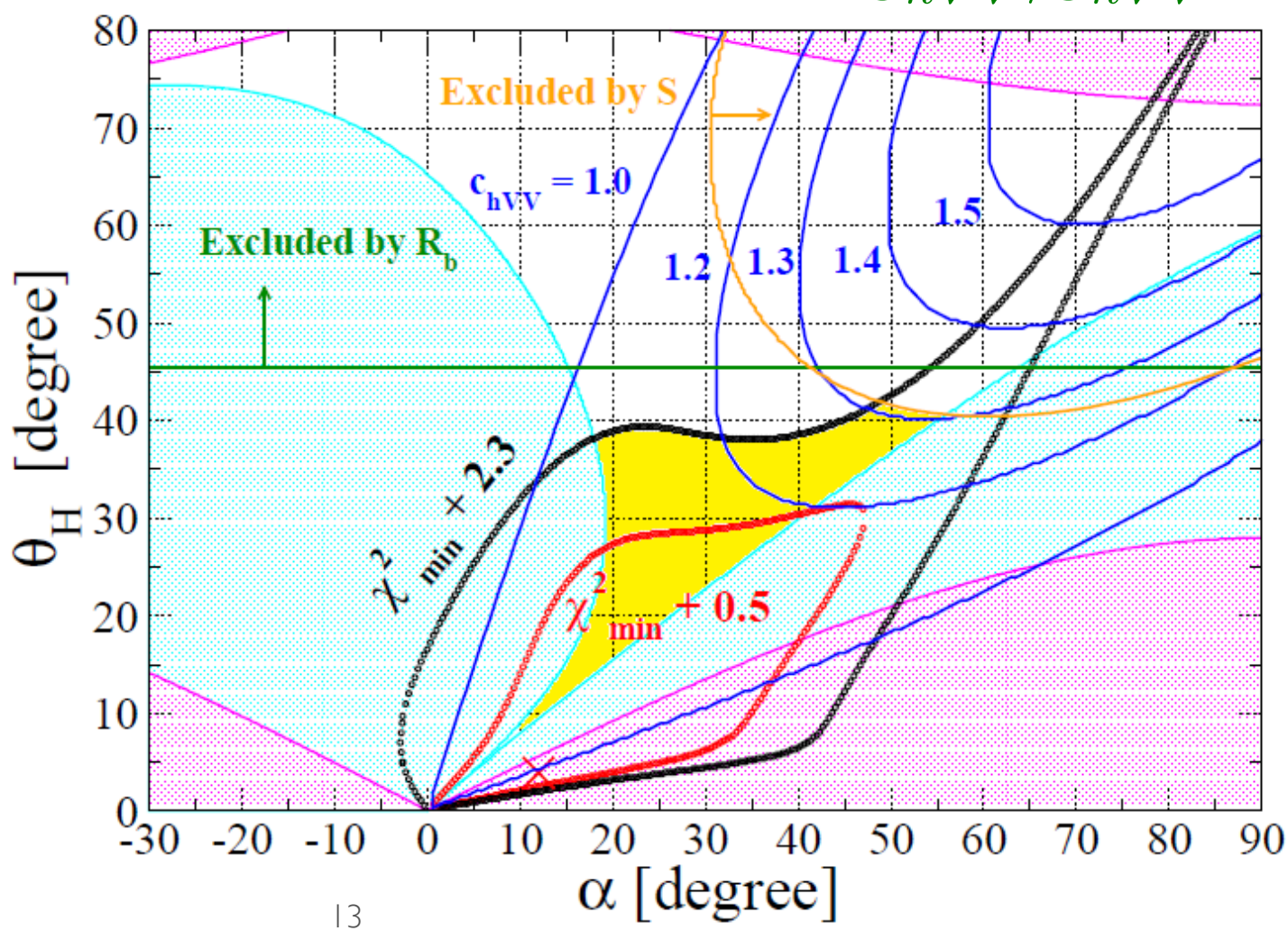
# Constraint from $H_{SM}$

CWC, Kuo, Yagyu JHEP 2013

- Take $M_{H5} = M_{H3} = M_{H1} = 300$ GeV as an example.
- Allowed region in mixing angle space

$$c_{hVV} \equiv g_{hVV}^{\rm GM}/g_{hVV}^{\rm SM}$$

- signal strengths (~2013 summer)
- unitarity
- vacuum stability
- $R_b$
- S parameter
- hVV coupling up by ~1.3 allowed

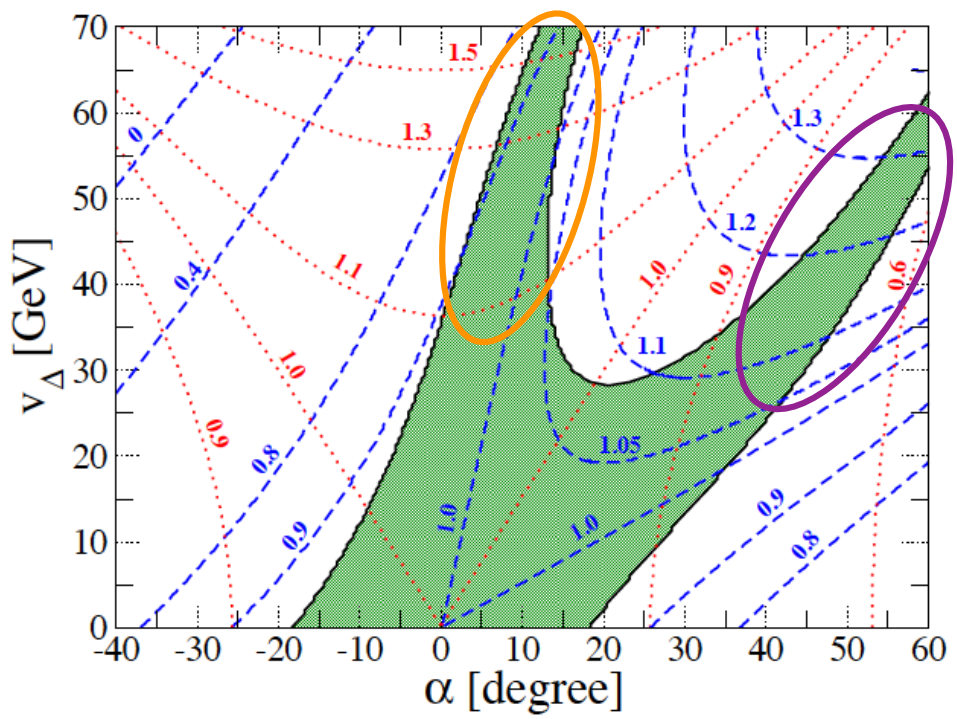


# Importance of VBF Processes

$\mu_{VV}^{GGF} = 1.0 \pm 0.1$ $\kappa_V$ contours $\kappa_F$ contours

- Enhancement (suppression) in BR(h→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



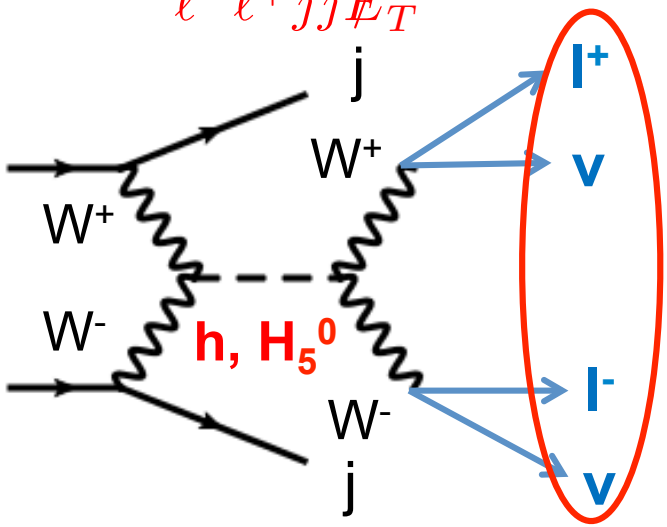
# Transverse Mass Distribution

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

CWC, Kuo, Yagyu JHEP 2013

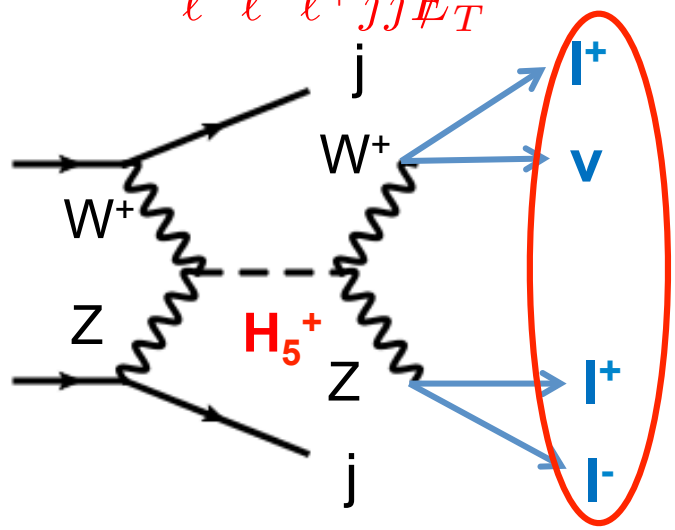
neutral

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



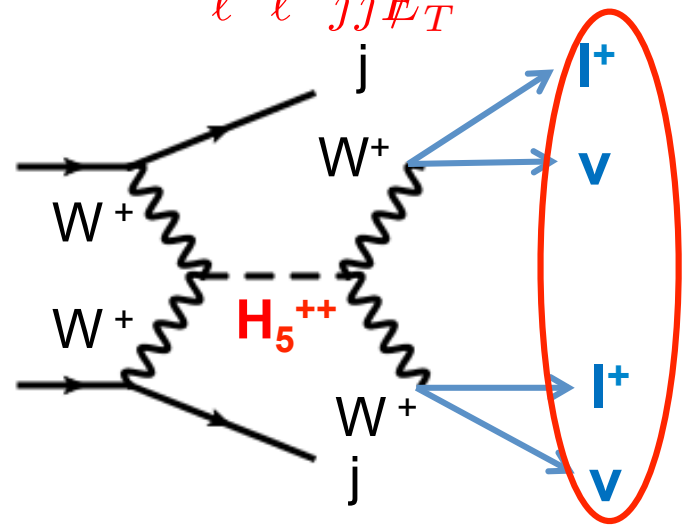

singly-charged

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



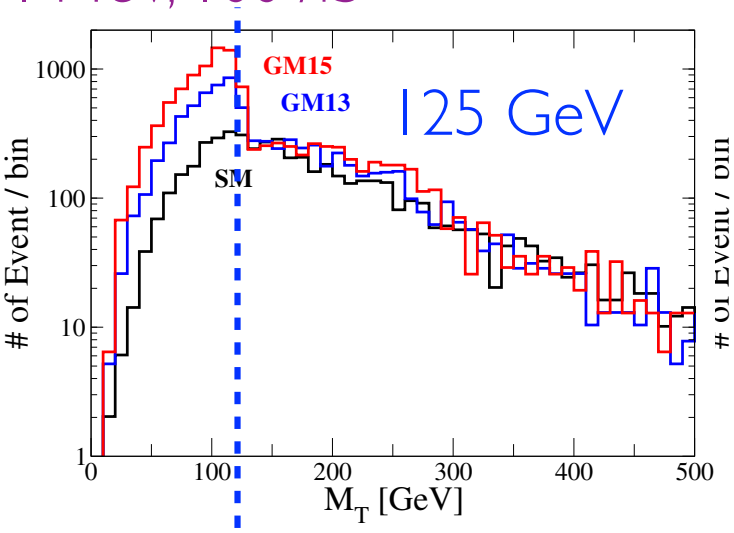

doubly-charged

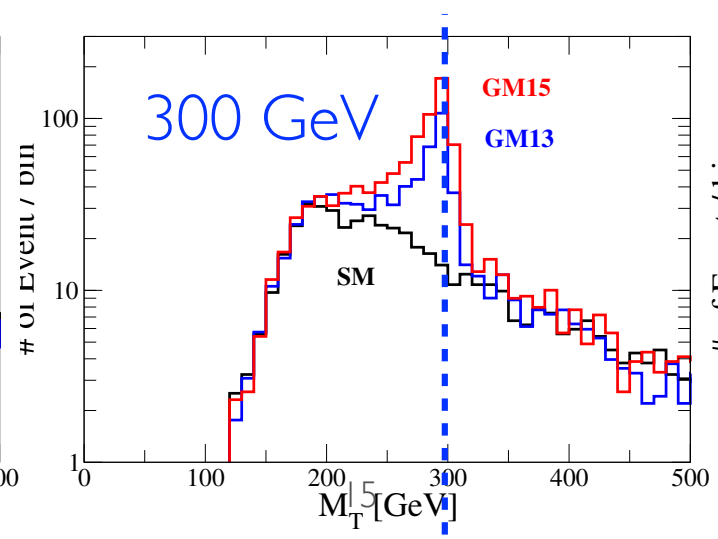
$\ell^\pm\ell^\pm jj\not{E}_T$

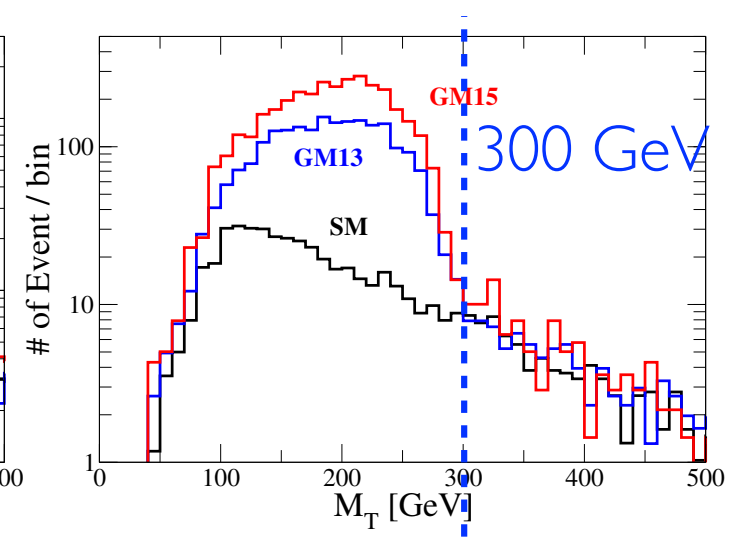



14 TeV, 100 /fb

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



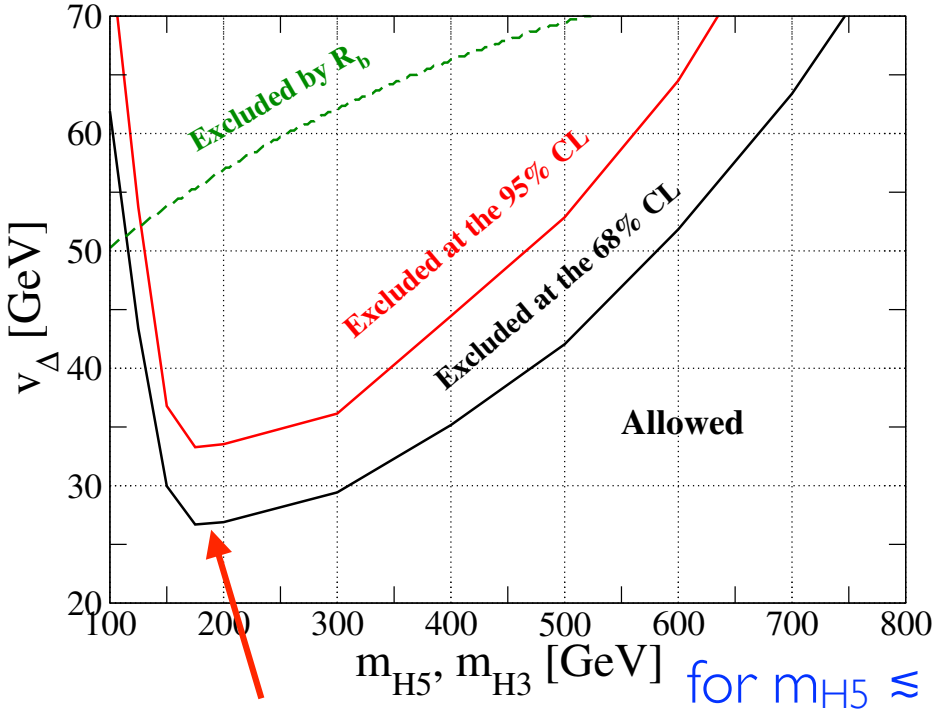



# Constraint from $H_5^{\pm\pm}$

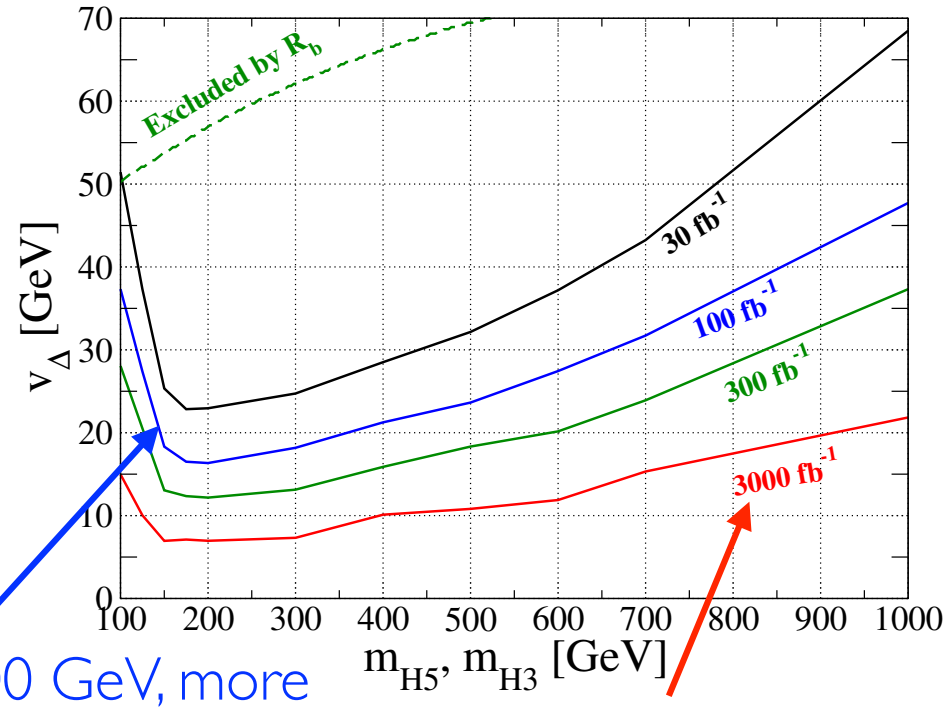
ATLAS 2014

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

limit from 8-TeV LHC of 20.3 /fb




5σ reach at 14-TeV LHC




most severe bound on $v_\Delta$ at $m_{H5}$ = 200 GeV

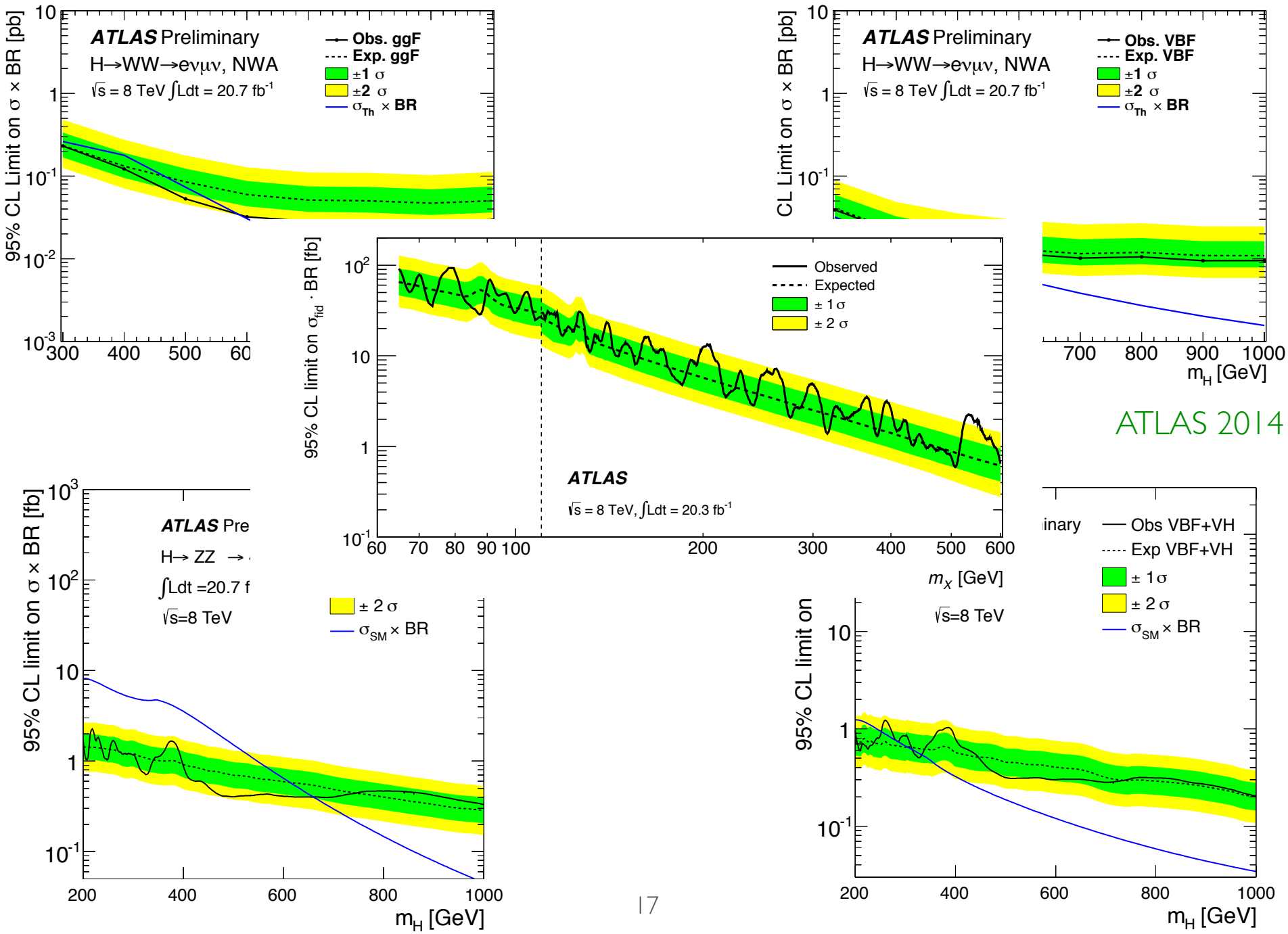
for $m_{H5} \lesssim 200$ GeV, more events from 5-plet Higgses are rejected by kinematic cuts

more improvement in high mass region

- Results are independent of α.

CWC, Kanemura, Yagyu PRD 2014

# Searches of Other Neutral Higgses

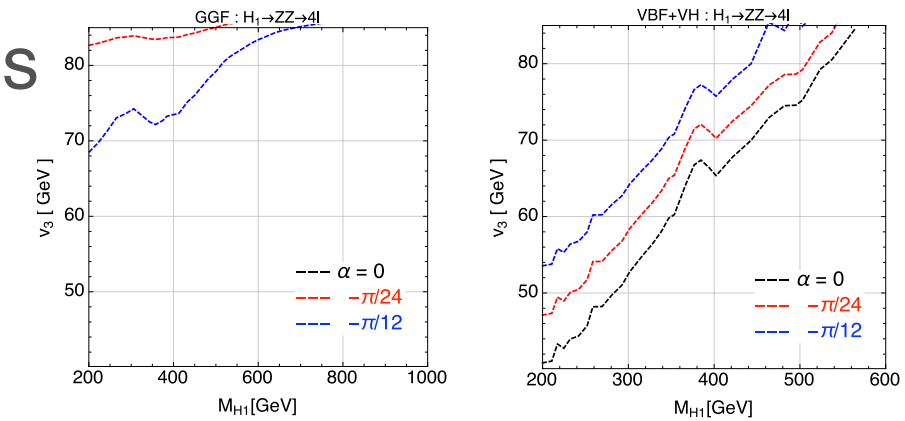



ATLAS 2014

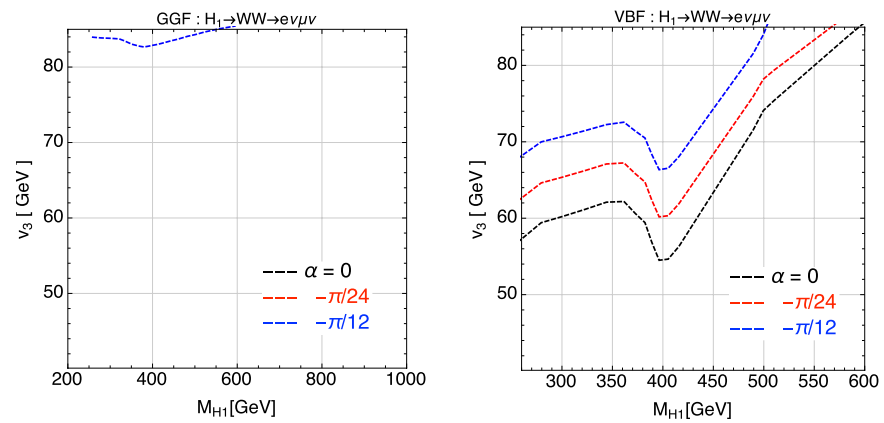
# Constraint from $H_1^0$

CWC and Tsumura JHEP 2015

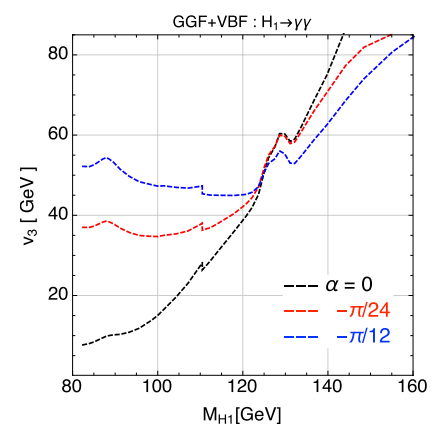
- Constraints from VBF channels are stronger than those from GGF mechanism.




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



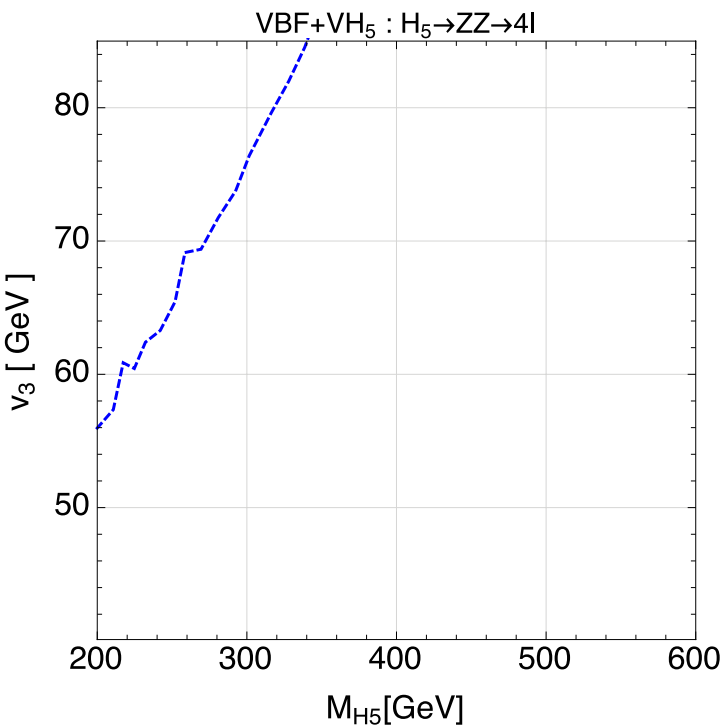

- The γγ mode (GGF+VBF) provides useful bounds on $v_\Delta$ in the low-mass regime.
- All of them are sensitive to α.

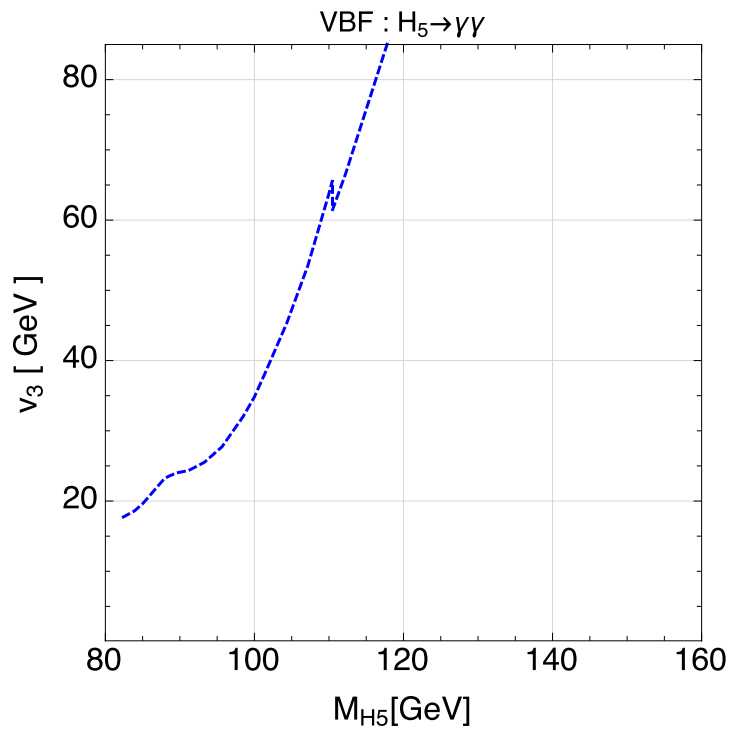


# Constraint from $H_5^0$

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.



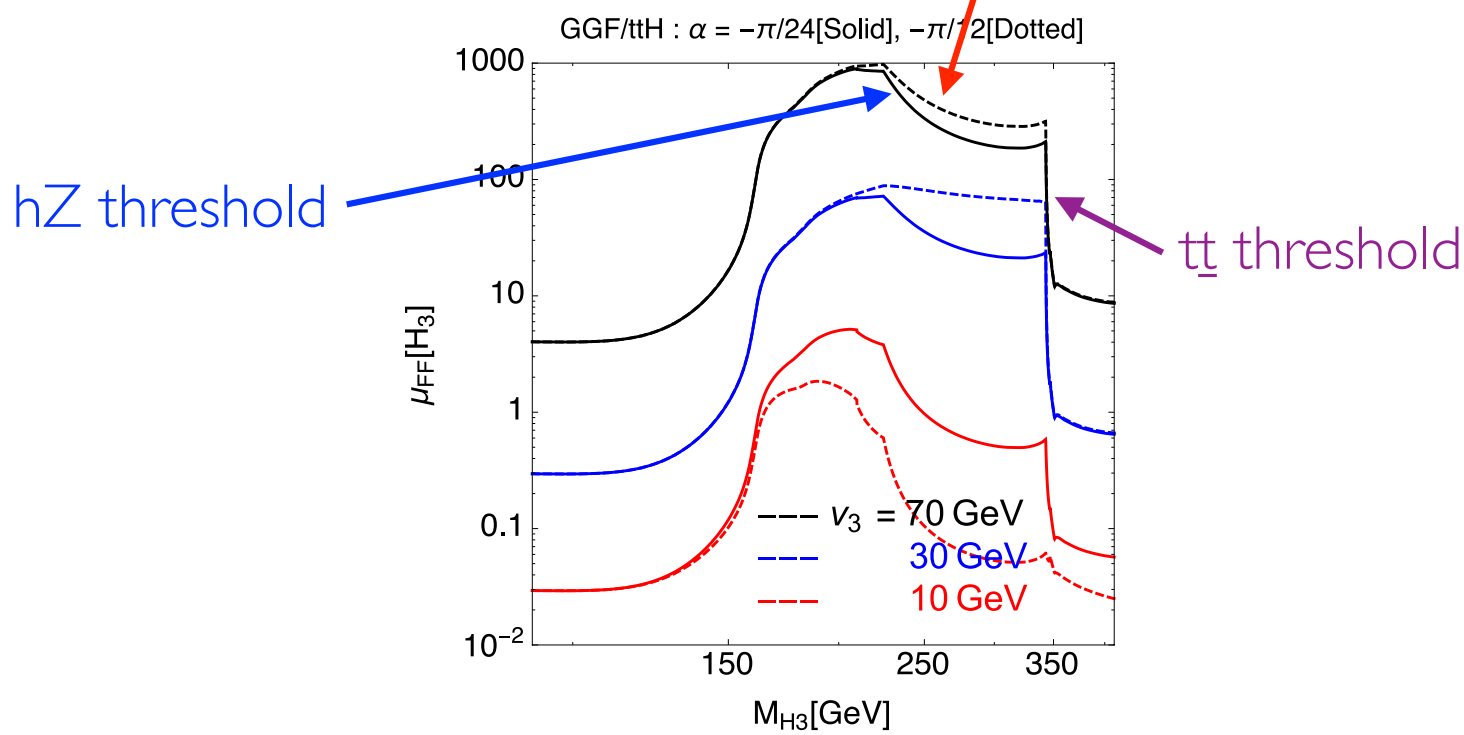
# No Constraint from $H_3^0$ yet

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.



# 5-plet at ILC

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

$$e^+e^- \to Z^*/\gamma^* \to H_5^{++}H_5^{--}$$ independent of $v_\Delta$

$$e^+e^- \to Z^*/\gamma^* \to H_5^{+}H_5^{-}$$ dominant for small $v_\Delta$; kinematically limited to $\sqrt{s}/2$

  - Vector boson associated (VBA) processes

$$e^+e^- \to Z^*/\gamma^*/\nu_e^* \to H_5^{\pm\pm}W^\mp W^\mp$$ depending on $v_\Delta$; dominant for large $v_\Delta$ and $m_{H5}$

$$e^+e^- \to Z^* \to H_5^{\pm}W^\mp \ , \ H_5^0 Z$$ up to $\sqrt{s} - M_{W,Z}$; involving $H_5^\pm W^\mp Z$ vertex

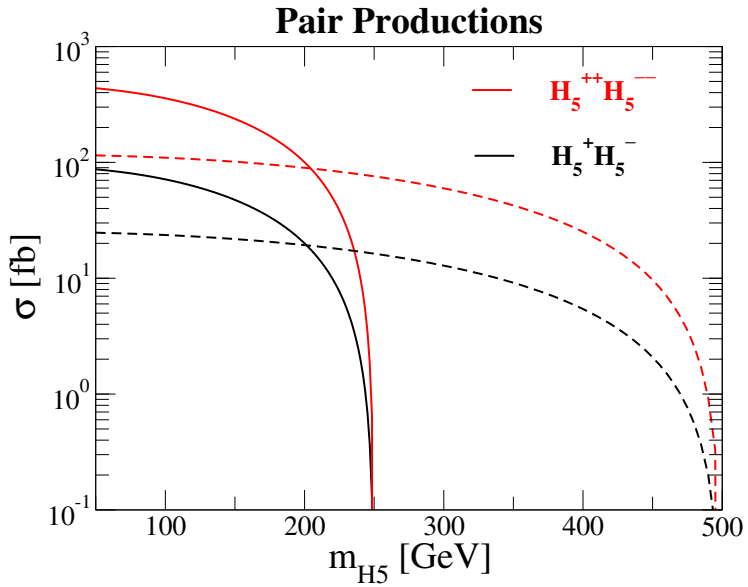
  - Vector boson fusion (VBF) processes

$$e^+e^- \to H_5^{\pm}e^\mp\nu_e$$ depending on $v_\Delta$; dominant for large $v_\Delta$ and $m_{H5}$

$$e^+e^- \to H_5^0 e^+e^- \ , \ H_5^0\nu_e\bar{\nu}_e$$ up to $\sim\sqrt{s}$; involving $H_5^\pm W^\mp Z$ vertex

# Cross Sections @ ILC

CWC, Kanemura, Yagyu 2015

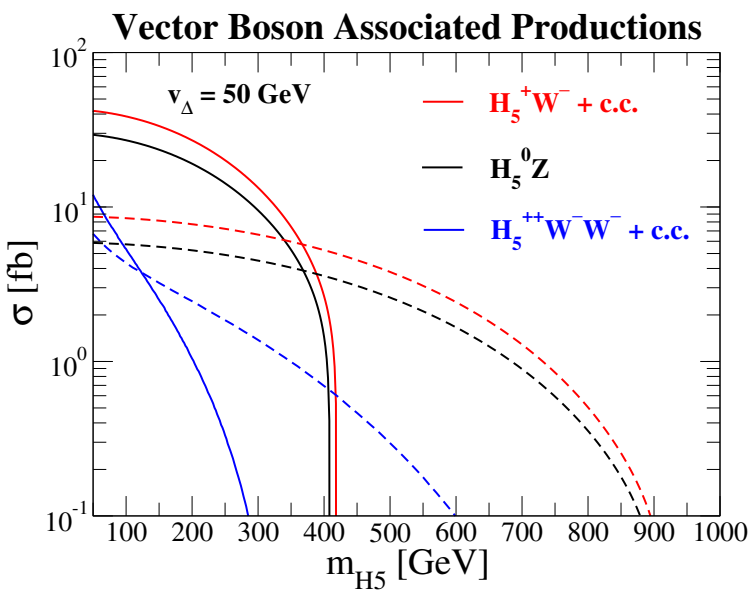


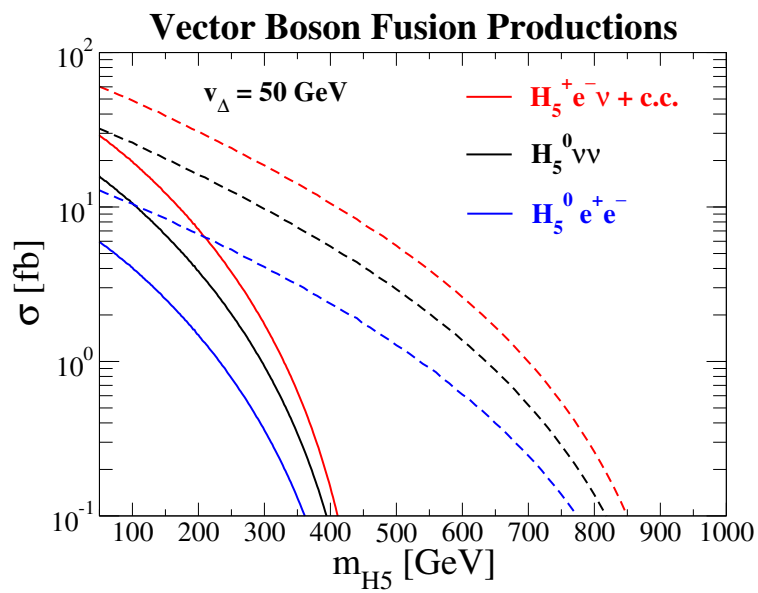

PP

independent of α

$\sqrt{s} = 500$ GeV (solid), 1 TeV (dashed)

VBA



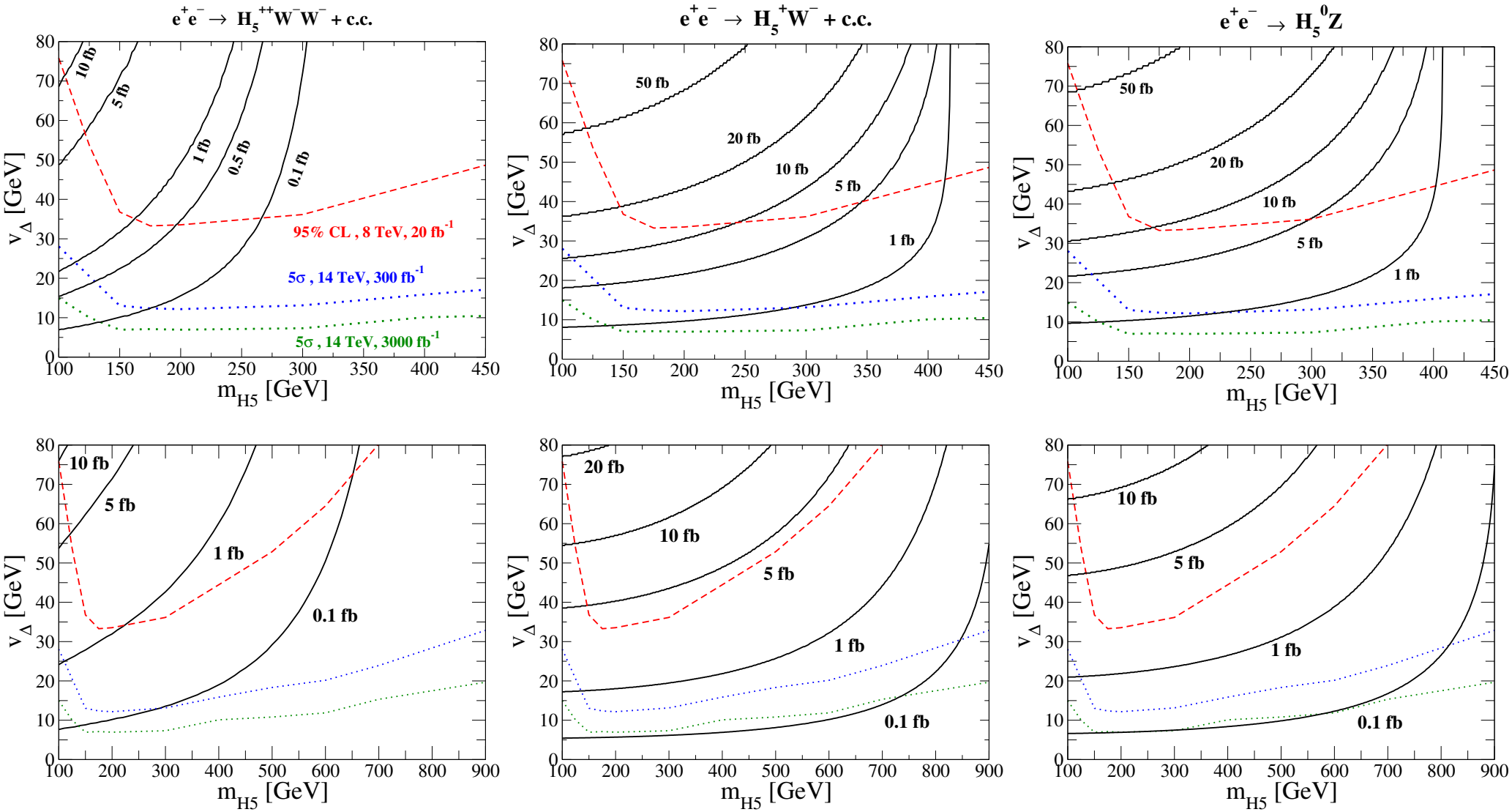




VBF

# VBA Cross Sections @ ILC

CWC, Kanemura, Yagyu 2015

$\sqrt{s} = 500$ GeV




$\sqrt{s} = 1$ TeV

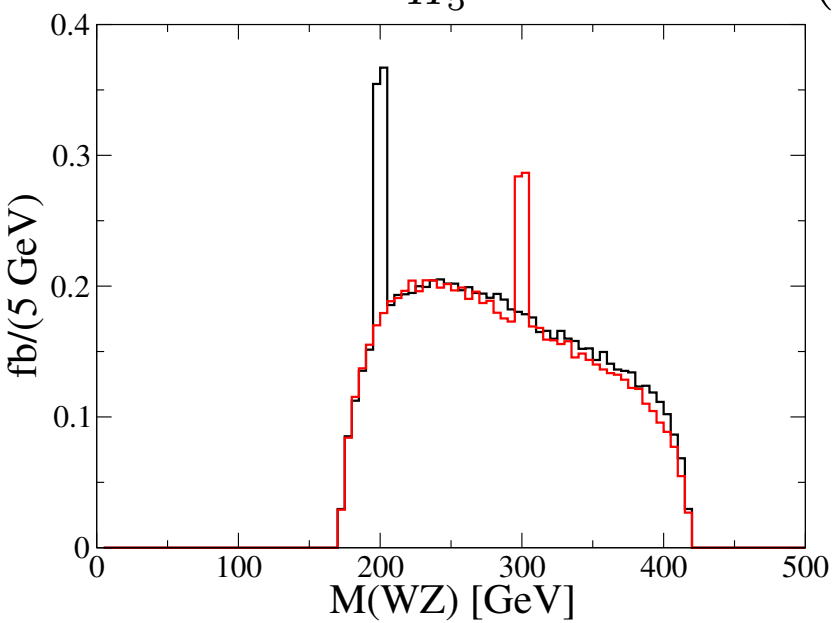
# Invariant Mass Distributions

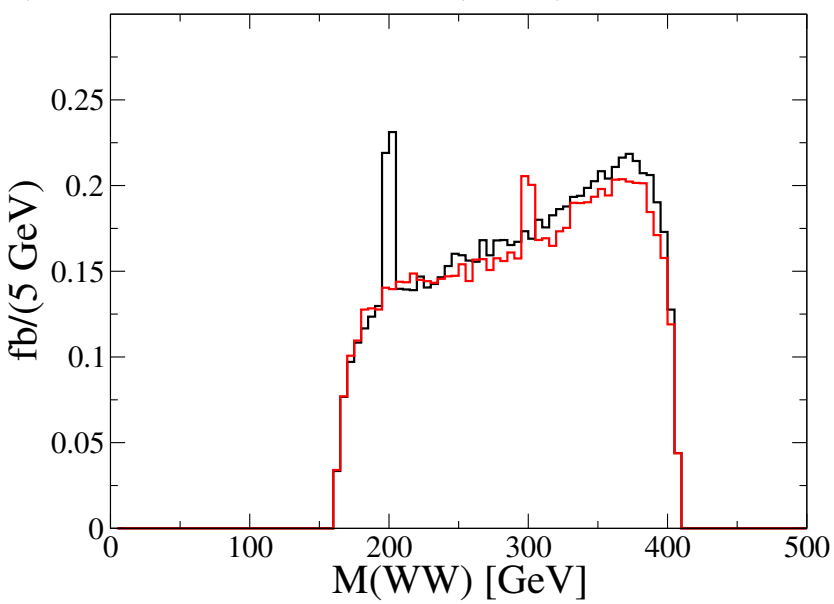
CWC, Kanemura, Yagyu 2015

- 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.

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

$m_{H_5} = 200$ GeV (black) and 300 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 $v_\Delta$, 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 $v_\Delta$, 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 ($v_\Delta$ vs $m_{H5}$ or $\alpha$).
- 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!