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Phenomenology of the Georgi-Machacek model at future electron-positron colliders

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Based on:

CWC, S Kanemura and K Yagyu, PRD **93** (2016) 055002 (arXiv:1510.06297 [hep-ph])

WHAT THE MODEL LOOKS LIKE

General Features

- Higgs triplet models have the following features:
  - type-II seesaw for Majorana neutrino mass, generated by the VEV of the new triplet scalar field;
  - 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/weaker couplings with weak bosons;
  - existence of a $H_5^{\pm}W^{\mp}Z$ vertex at tree level through mixing and proportional to v_Δ (only loop-induced in models such as 2HDM);
  - Georgi-Machacek model with custodial symmetry allowing a larger triplet VEV v_Δ.

Custodial SU(2) Classification

SU(2)L ⊗ SU(2)R

1 complex triplet + 1 real triplet

Δ: 3 ⊗ 3

1 complex doublet

Φ: 2 ⊗ 2

SU(2)V

5 ⊕ 3 ⊕ 1

3 ⊕ 1

mixing angle β or θ_H

mixing angle α

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

CP-even

m_{H5}

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

CP-odd

m_{H3}

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

$$H_1 \equiv \left[H_1^0\right]$$

m_{H1}

h (125 GeV)

m_h

CP-even

Verifying the Model

- To verify the model, it is crucial to find the entire H_5 family:
    (i) there are three charged states;
    (ii) they are almost degenerate in mass;
    (iii) they are CP-even;
    (iv) they have correct couplings with SM particles;
    ……

Neutral Higgs Couplings

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

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

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

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

suppressed by α

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

independent of α; proportional to v_Δ

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

Decay Pattern

CWC, Yagyu JHEP 2012

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

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

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

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

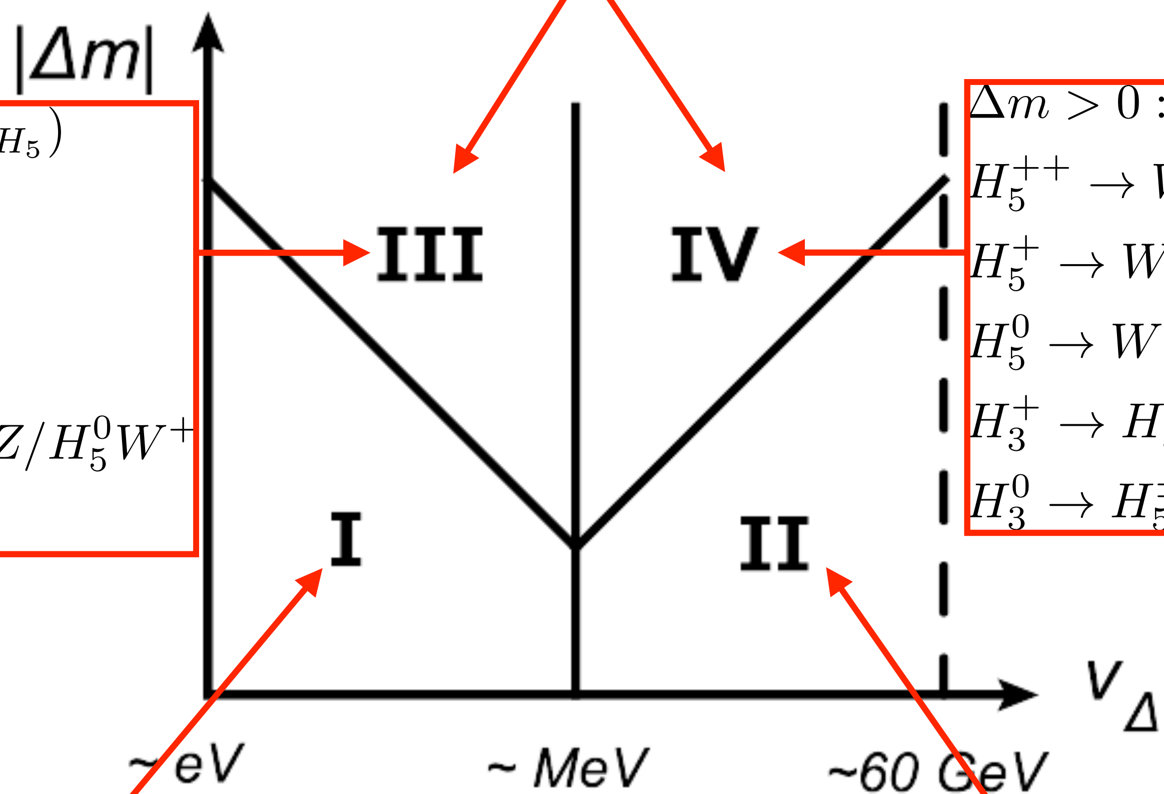
$H_5^{++} \to \ell^+ \ell^+$

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

$H_5^0 \to \nu \nu$

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

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



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

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

$H_5^+ \to W^+ Z$

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

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

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

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

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

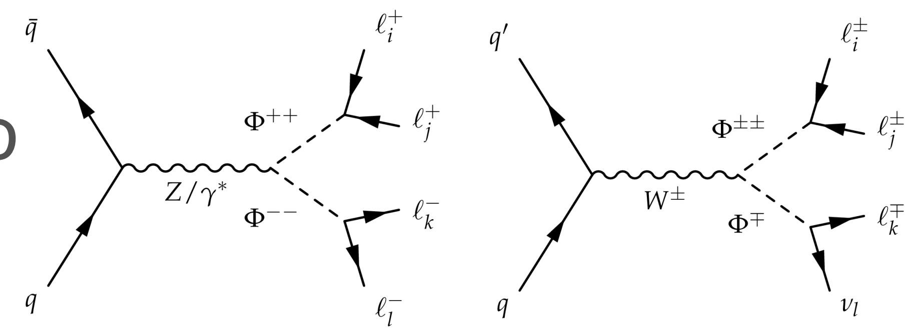
$H_5^{++} \to W^+ W^+ \ , \ H_5^+ \to W^+ Z \ , \ H_5^0 \to W^+ W^- / ZZ \ ,$

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

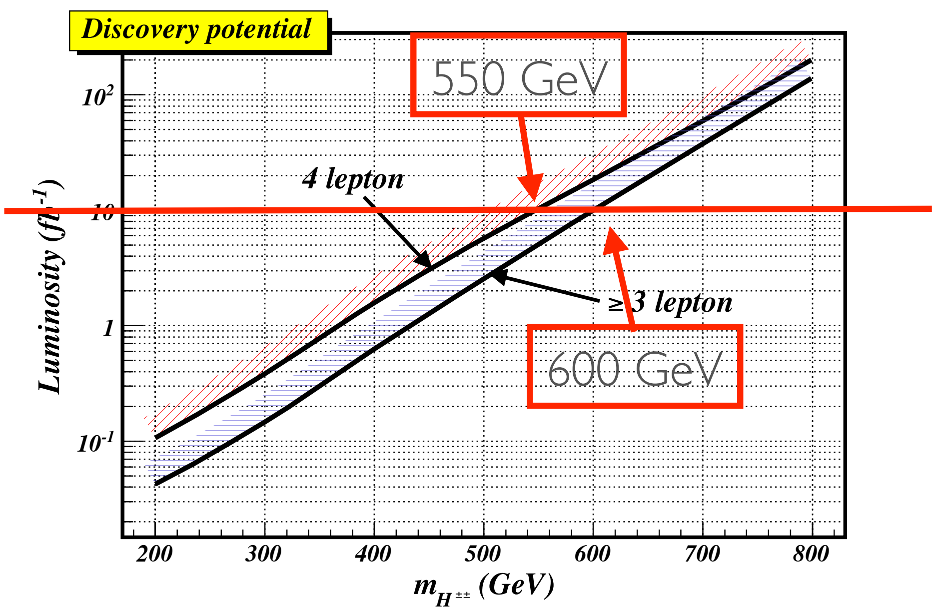
CURRENT CONSTRAINTS AND STUDIES FROM/FOR LHC

Signature for Small v_Δ

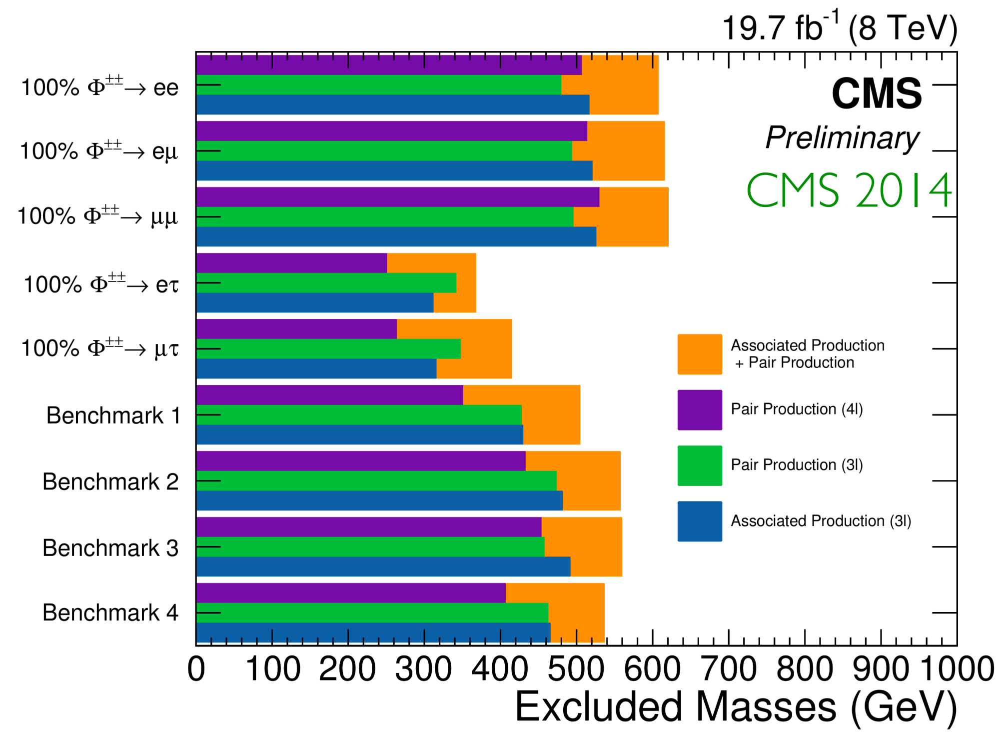
- In the case of small v_Δ, both $H^{\pm\pm}$ and $H^{\pm}$ decay primarily into leptonic final states, same as the simplest Higgs triplet model in phenomenology.



Akeroyd, CWC, Gaur JHEP 2010



14-TeV LHC



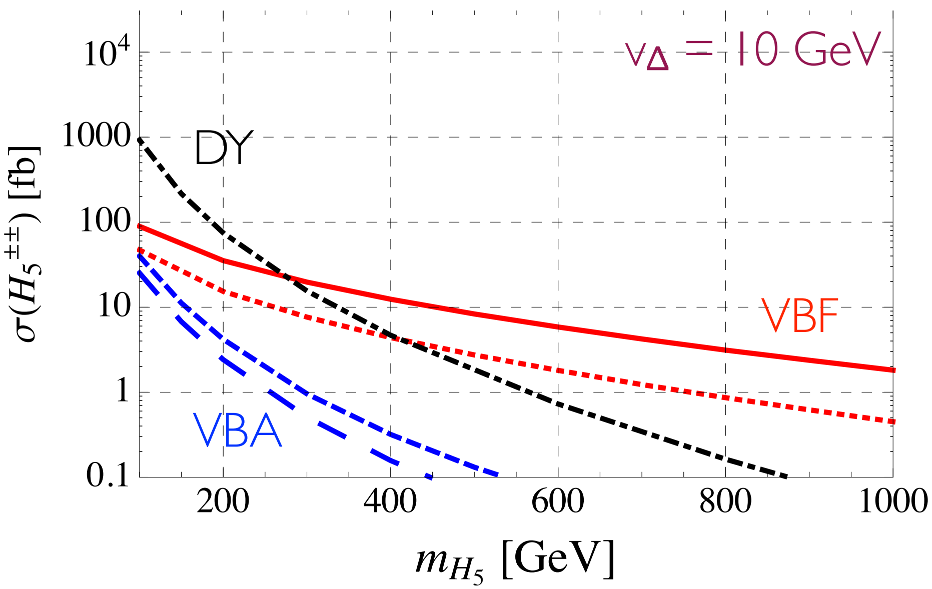
A general lower bound of 500−600 GeV is given by both ATLAS and CMS.

ATLAS 2012, 2014

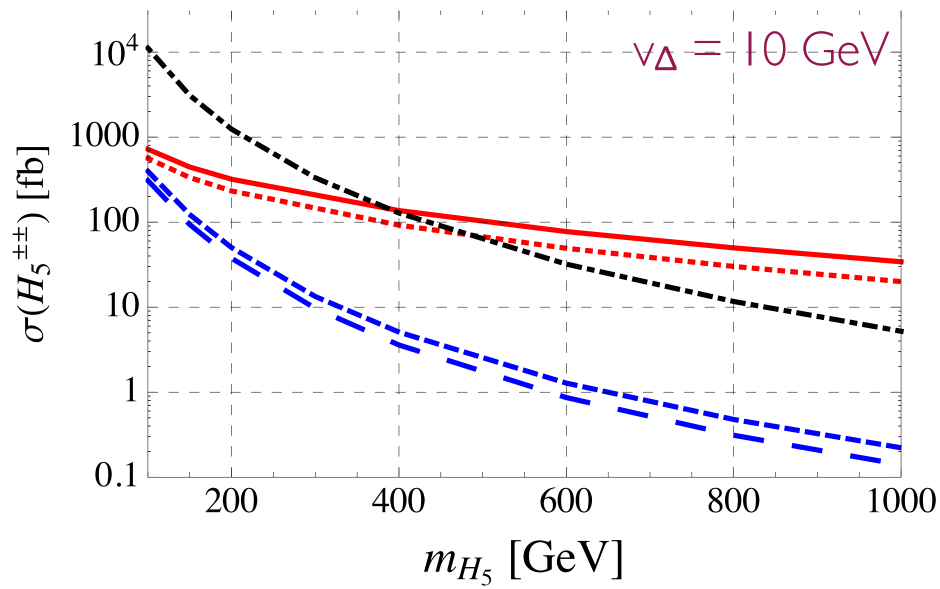
Production for Large v_Δ

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

CWC, Kuo, and Yamada JHEP 2015



14 TeV



100 TeV

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

an experimentally less explored scenario, and unique for GM

Transverse Mass Distributions

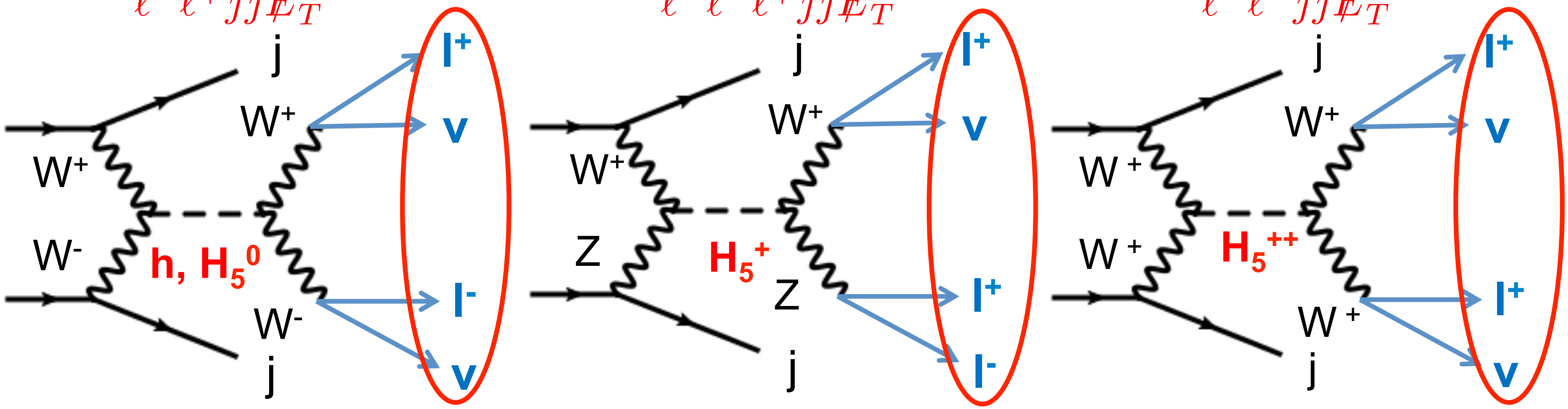
$c_{hVV} = 1.3$ with $(\theta_H, \alpha) = (40°, 55°)$ and
$M_{H5} = M_{H3} = M_{H1} = 300$ GeV ➠ no mass hierarchy

CWC, Kuo, Yagyu JHEP 2013

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

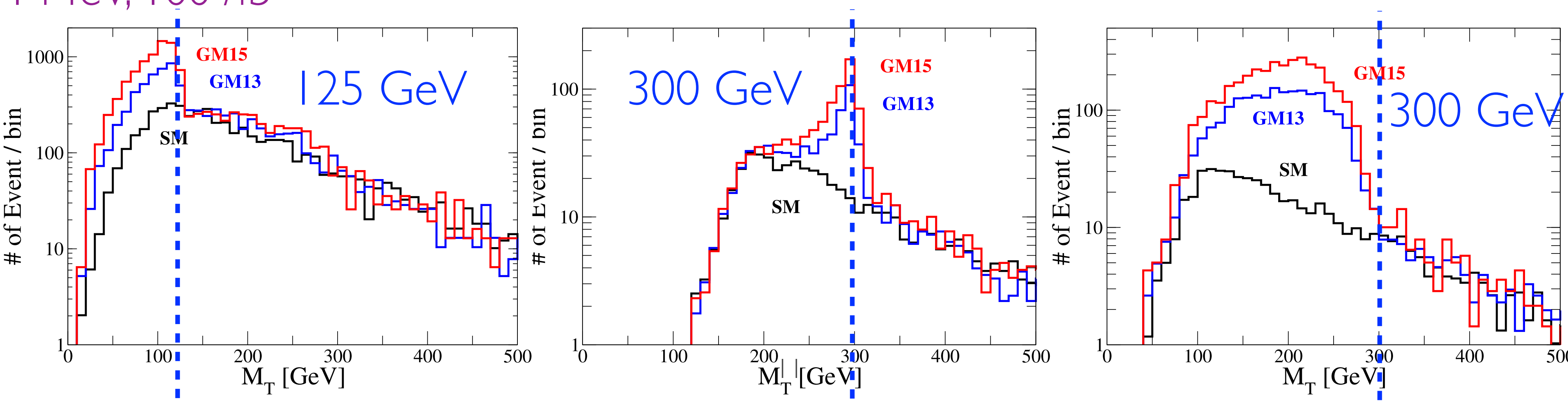
singly-charged: $\ell^\pm \ell^\pm \ell^\mp jj \not{E}_T$

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

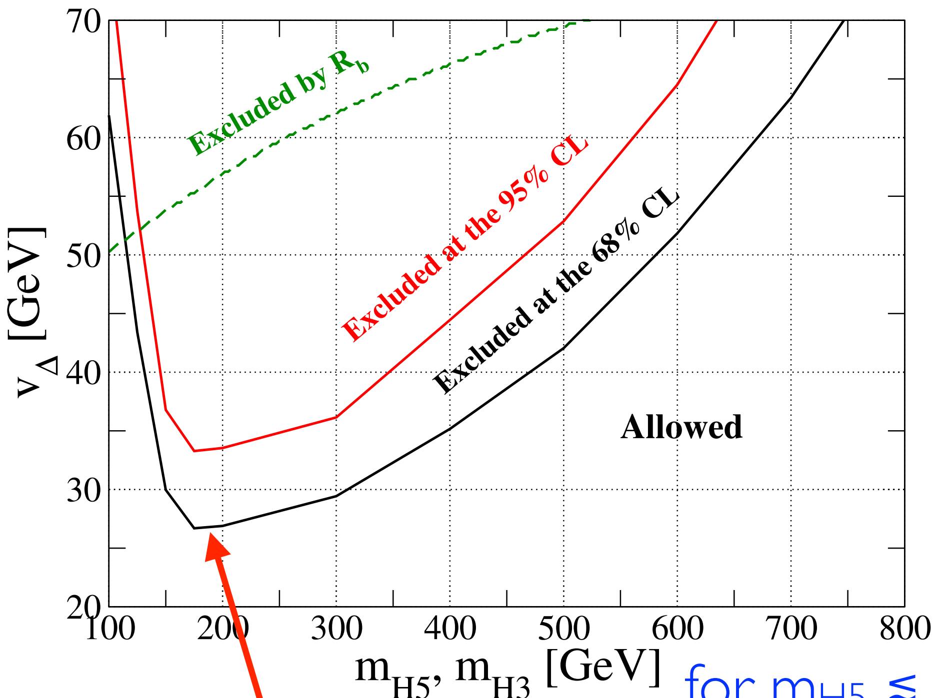


Constraint from $H_5^{\pm\pm}$

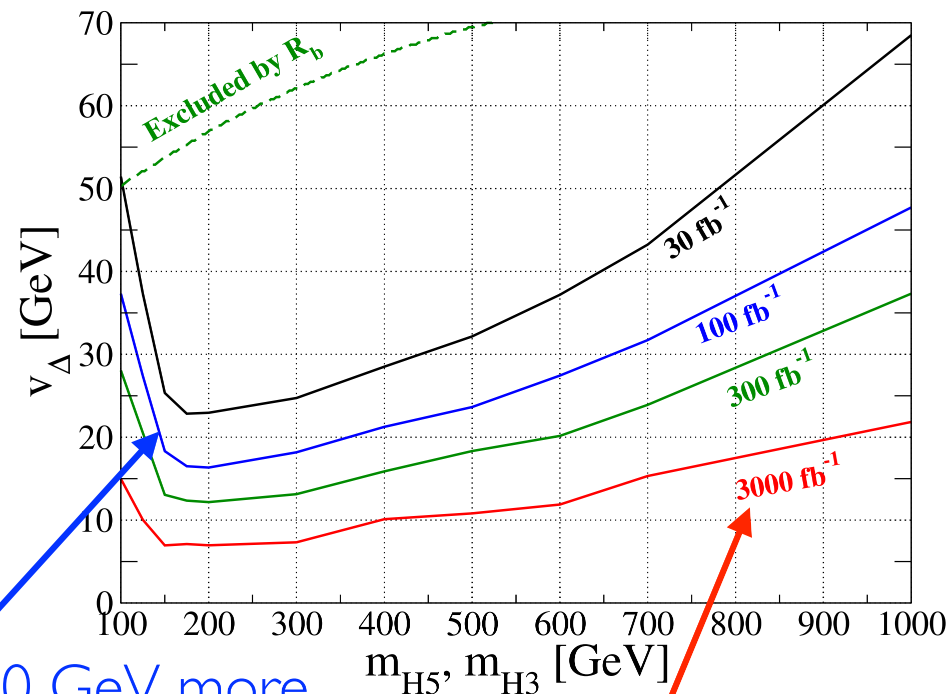
- ATLAS data of same-sign di-boson (light leptonic decays) events (20.3/fb, 8-TeV) can be used to put constraints on the v_Δ-m_{H5} plane:

ATLAS 2014

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

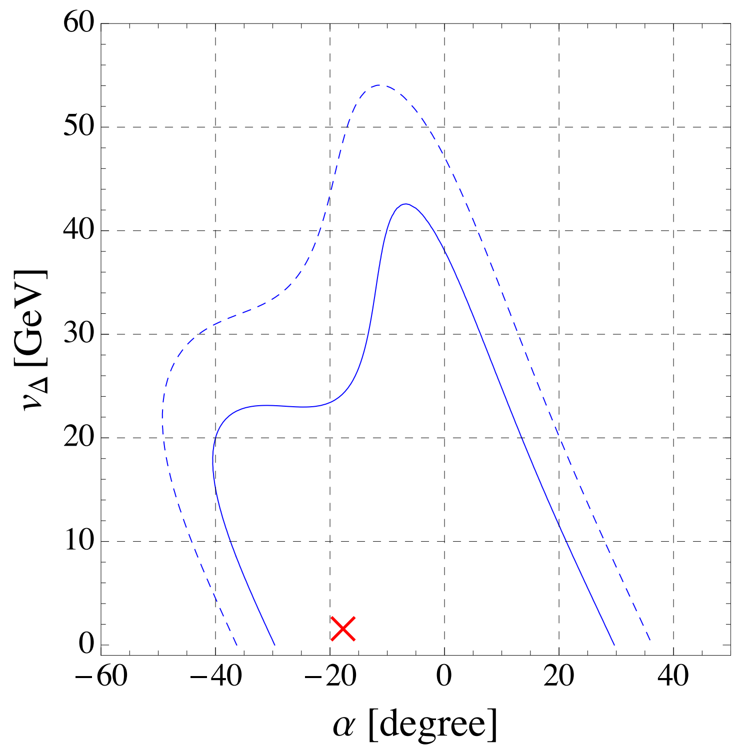
- Results are independent of α.

CWC, Kanemura, Yagyu PRD 2014

Constraints from Higgs Data

- Consider the tree-dominated Higgs decays into ZZ, WW, bb, and ττ in a chi-square fit.
- Exclude γγ to avoid uncertainties in the loop.
- Solid: 1σ contour; dashed: 2σ contour.

CWC, Kuo, and Yamada JHEP 2015



HOW LEPTON COLLIDERS CAN HELP — FOCUSING ON 5-PLETS

GM @ Lepton Collider

- Although in the case of a large triplet VEV the exotic Higgs bosons have diminishing Yukawa couplings with charged leptons, the 5-plet Higgs bosons can still be produced via productions in association with weak gauge bosons that serve as promising detection channels at lepton colliders, such as ILC, Compact LC, CEPC, or the electron-positron branch of the Future Circular Collider.

ILC
- ECFA/DESY LC Physics Working Group Collab. 2001
- Linear Collider American Working Group Collab. 2001
- Linear Collider ACFA Working Group Collab. 2001
- Moortgat-Pick et al., 2015

Compact Linear Collider
- CLIC Physics Working Group Collab. 2004

CEPC
- CEPC-SPPC Study Group Collab. 2015

GM @ Lepton Collider

- It is possible to probe this sector using the uniquely featured tree-level vertex of $H_5^{\pm}W^{\mp}Z$ at high-energy e^+e^- colliders.

Godbole, Mukhopadhyaya, Nowakowski 1995
Cheung, Phillips, Pilaftsis 1995

- Make use of the excellent energy resolution for jet systems to help tagging dijets from W and Z bosons.

Remarks about H_3's

- An important feature of H_3's is that they have no tree-level H_3VV couplings. But $H_3\bar{f}f$ couplings are allowed.
- Instead, they have Yukawa couplings that are proportional to $\tan\theta_H$ or v_Δ through mixing with the Higgs doublet ➠ their decay patterns are the same as those of the extra Higgs bosons in the Type-I 2HDM

  Gunion, Haber, Kane, Dawson 2000
  Kanemura, Yokoya, Zheng 2014
- Their possible production mechanisms at ILC are pair production $e^+e^-\to H_3^+H_3^-$ and the fermion associated processes $e^+e^-\to\bar{f}fH_3^0$ and $e^+e^-\to\bar{f}f'H_3^\pm$.
- Dedicated studies of the production and decays of H_3's at LHC has been done before.

  CWC and Yagyu 2013

H_5 Interactions

- There are three types of interactions which induce the decays of the 5-plet Higgs bosons at the tree level:
  (i) scalar-gauge-gauge interactions,
  (ii) scalar-scalar-gauge interactions, and
  (iii) scalar-scalar-scalar interactions.
- When the mass of the 5-plet Higgs bosons is smaller than the total mass of the 2-body final-state bosons, one or both of the boson must be off shell.
- In our analysis, we consider up to 3 bodies in final states.

H_5 Interactions

- Scalar-gauge-gauge interactions lead to

proportional to v_Δ

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

- Scalar-scalar-gauge interactions lead to

proportional to weak gauge coupling

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

- Scalar-scalar-scalar interactions lead to

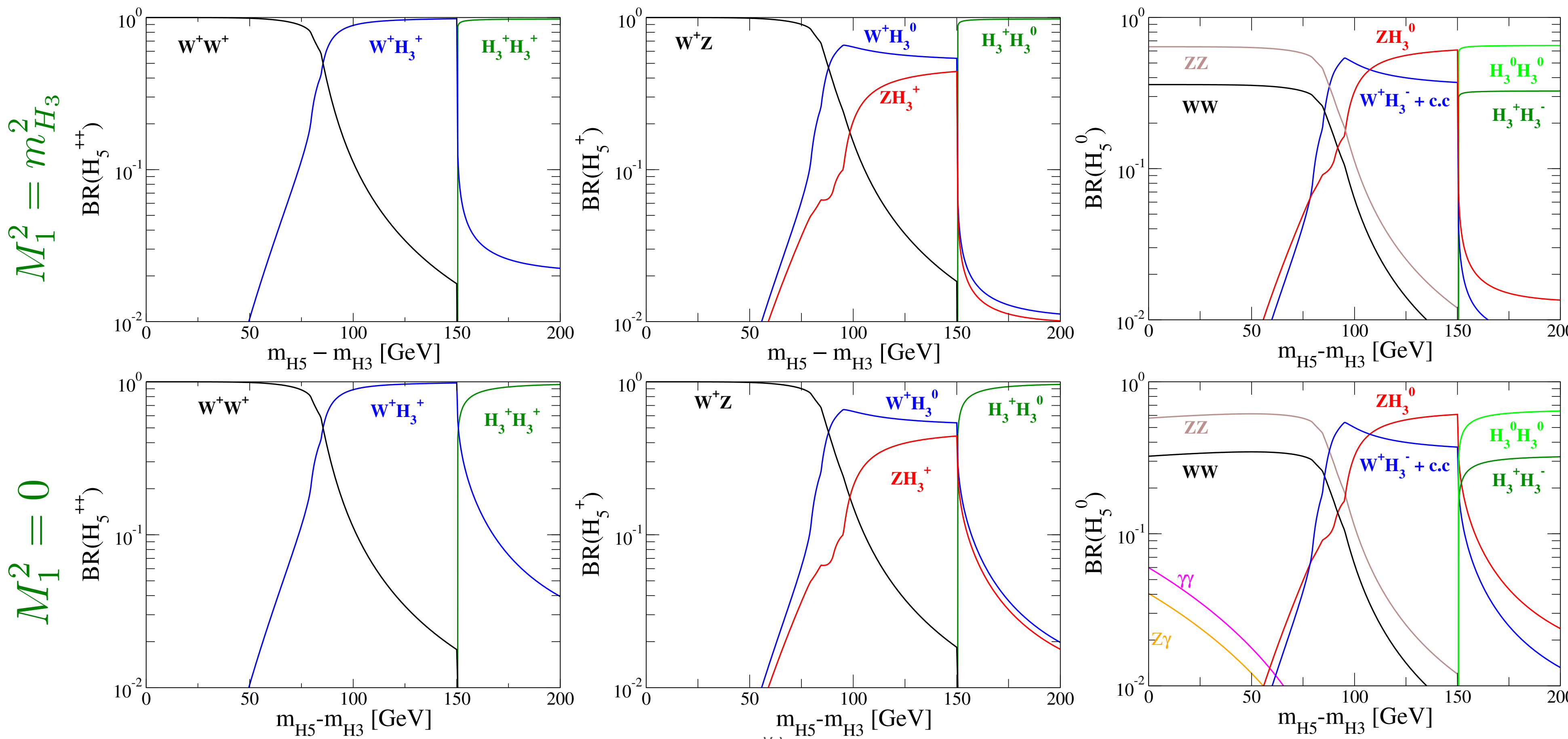
involving triple Higgs couplings

$$H_5^{\pm\pm} \to H_3^\pm H_3^\pm$$
$$H_5^{\pm} \to H_3^\pm H_3^0 / H_3^0 H_3^\pm$$
$$H_5^{0} \to H_3^\pm H_3^\mp / H_3^0 H_3^0$$

BR's of H_5

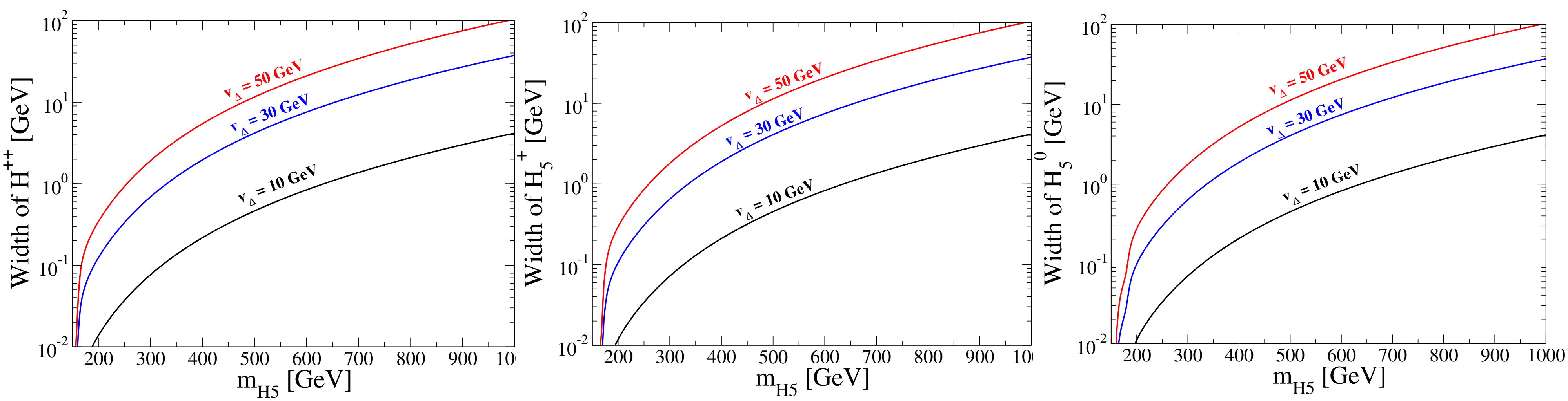
- Fix m_{H5} = 300 GeV, v_Δ = 10 GeV and $M_2^2 = 0$.
- Choice of M_1^2 results in more changes in γγ and Zγ, through the triple Higgs couplings in H_5 loops.

*M_1^2 and M_2^2 are two parameters related to ΦΦΔ and Δ^3 trilinear terms in Higgs potential.



Widths of H₅'s

- Total widths of H_5's as functions of $m_{H5} = m_{H3}$, so that only the diboson decays of H_5's are allowed.
- There is almost no difference among the H_5 widths, another evidence of custodial symmetry.
- They increase with m_{H5} and v_Δ.



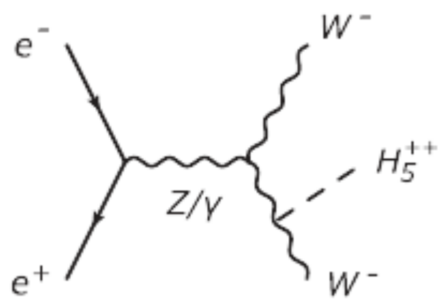
Production of H_5's at ILC

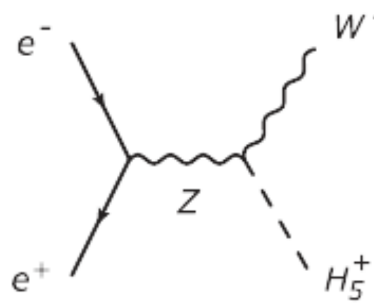
- Three types of production modes at ILC: Gunion, Vega, Wudka 1990
  - Pair production (PP) processes

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

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

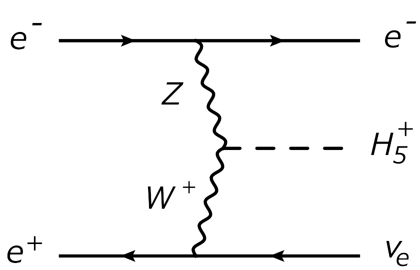
  - Vector boson associated (VBA) processes

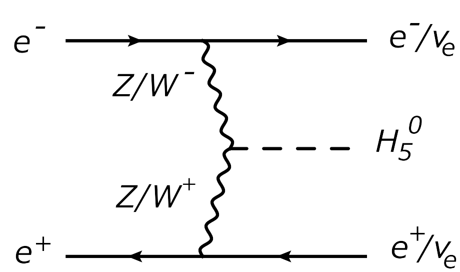




depending on v_Δ
dominant for large v_Δ and m_{H5}
up to $\sqrt{s}-M_{W,Z}$ or $\sqrt{s}-2M_{W,Z}$
involving $H_5^\pm W^\mp Z$ vertex

  - Vector boson fusion (VBF) processes

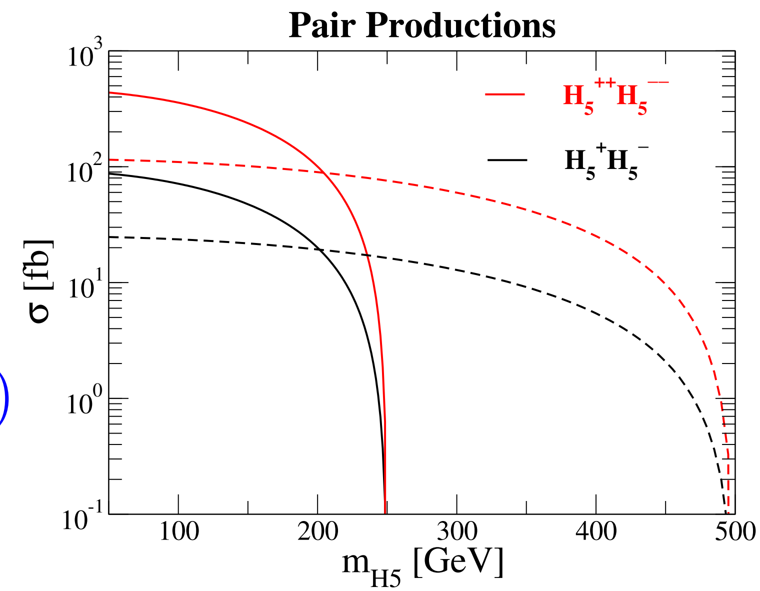




depending on v_Δ
dominant for large v_Δ and m_{H5}
up to $\sim\sqrt{s}$
involving $H_5^\pm W^\mp Z$ vertex

Cross Sections @ ILC

CWC, Kanemura, Yagyu 2016

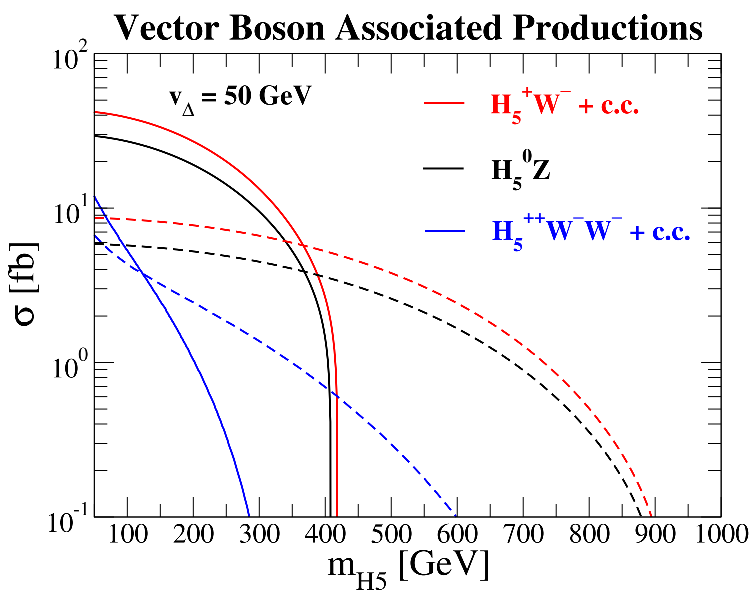


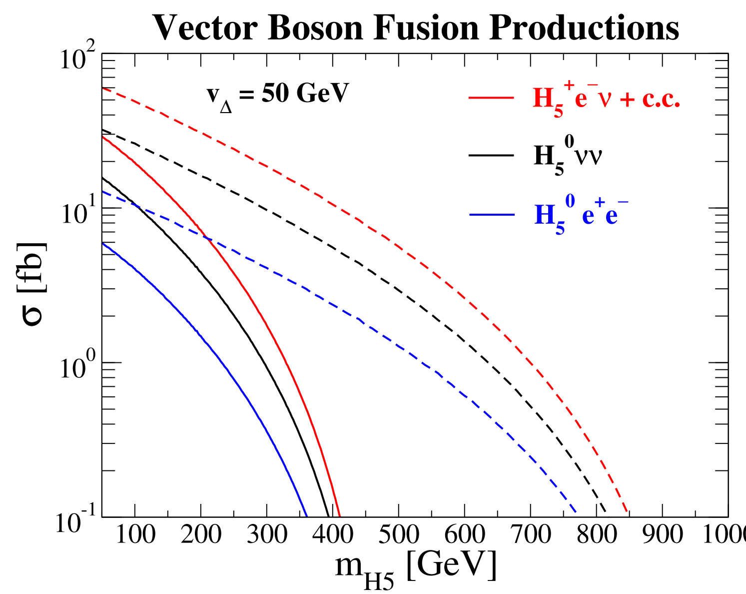
PP

$$\sqrt{s} = \begin{cases} 500\ \text{GeV (solid)} \\ 1\ \text{TeV (dashed)} \end{cases}$$

all independent of α

VBA





VBF

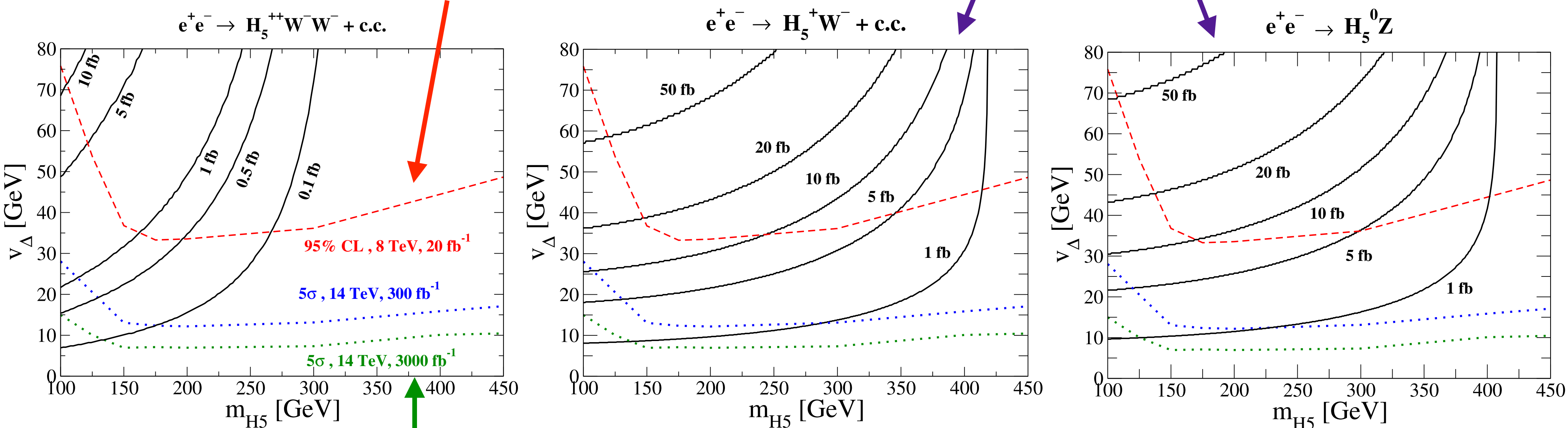
cross sections of lower two types of processes for other values of v_Δ can be obtained readily by scaling

VBA Cross Sections @ ILC

- 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.

same-sign diboson production constraint from LHC Run-I

larger cross sections

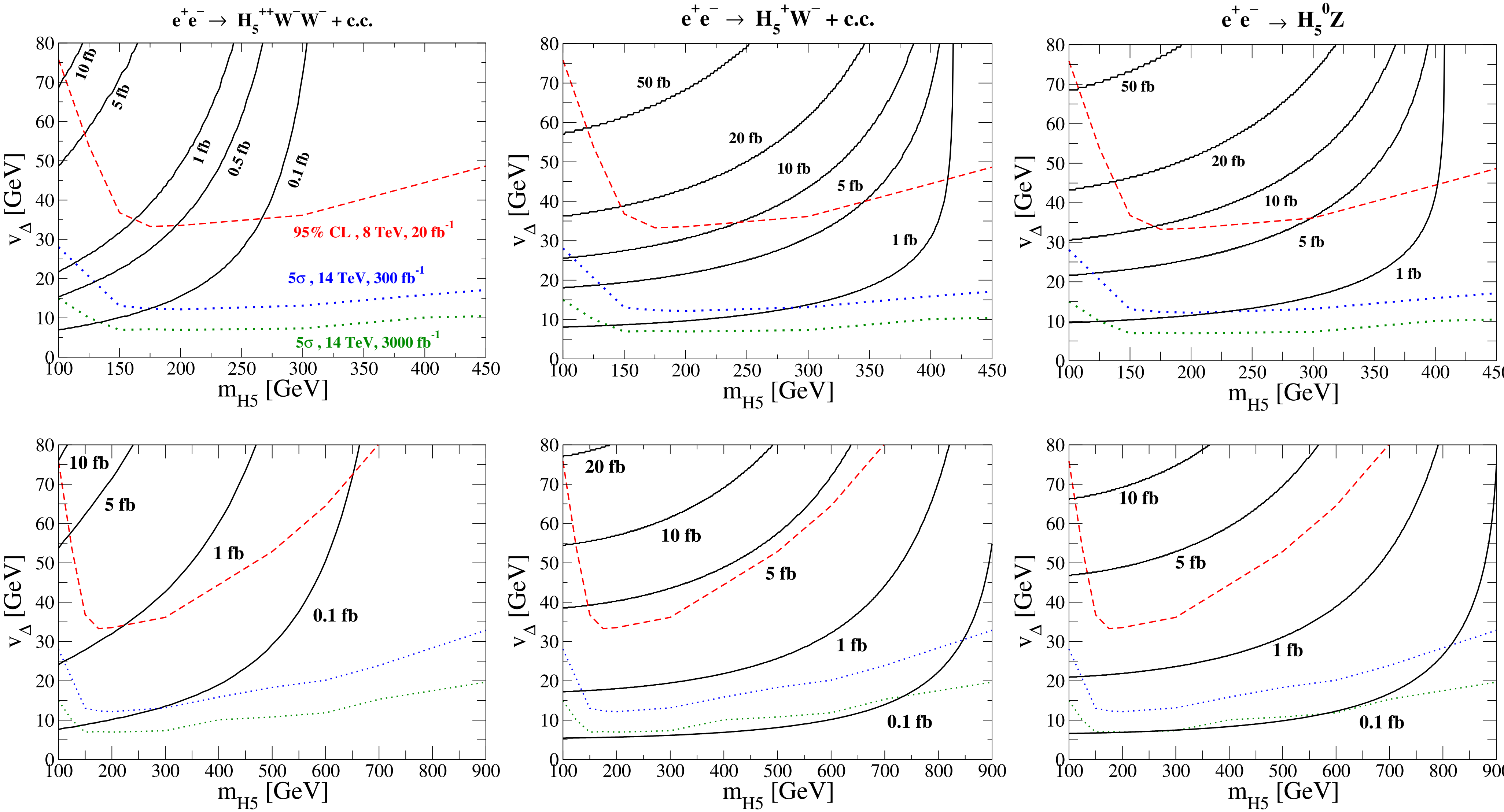


$\sqrt{s} = 500$ GeV

5σ reach of same-sign diboson excess at 14-TeV LHC with luminosities of 300 fb^{-1} and 3000 fb^{-1}

VBA Cross Sections @ ILC

$\sqrt{s} = 500\ \text{GeV}$

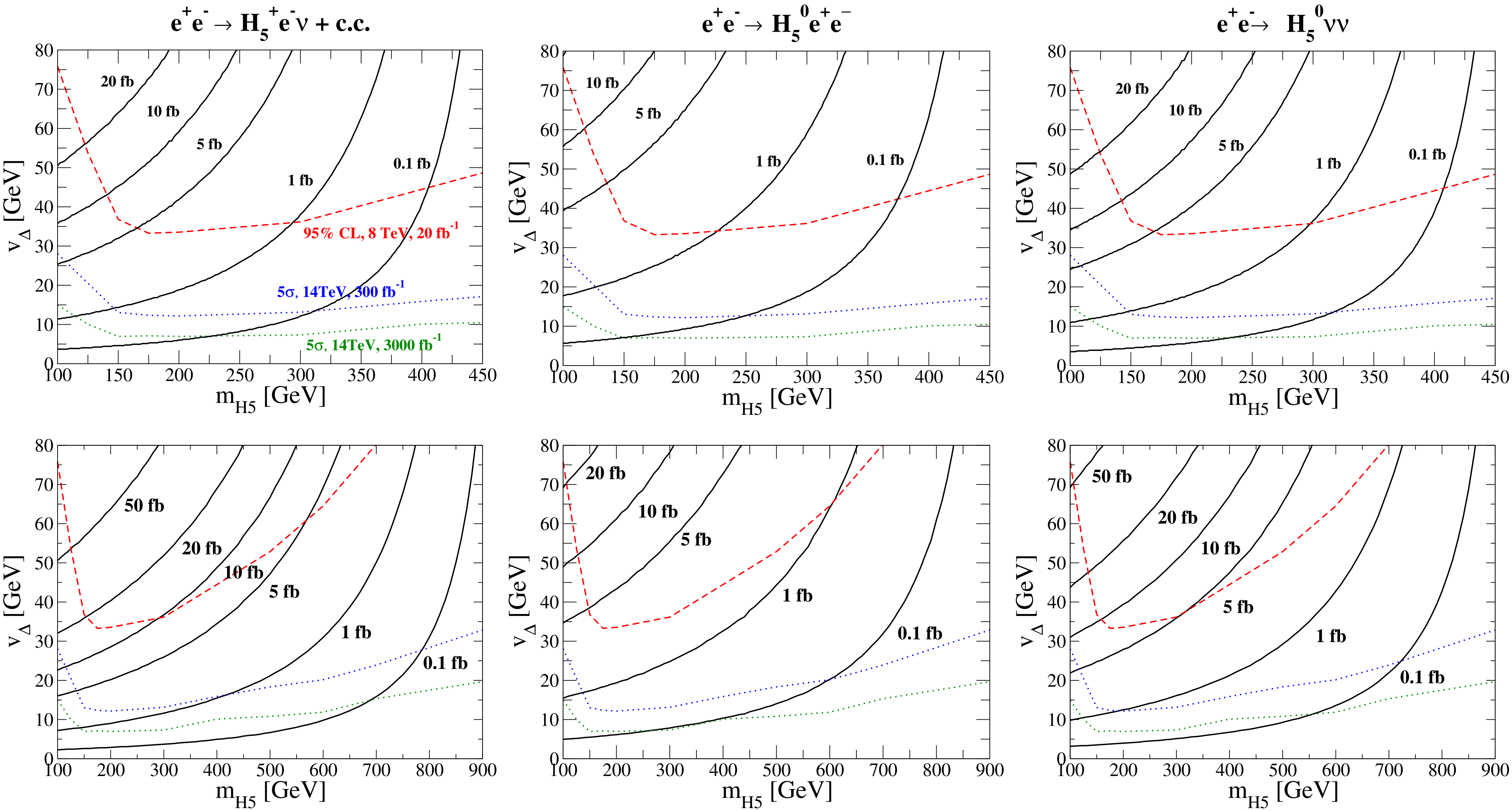


$\sqrt{s} = 1\ \text{TeV}$

mind different horizontal ranges above and below

VBF Cross Sections @ ILC

$\sqrt{s} = 500\ \text{GeV}$



mind different horizontal ranges above and below

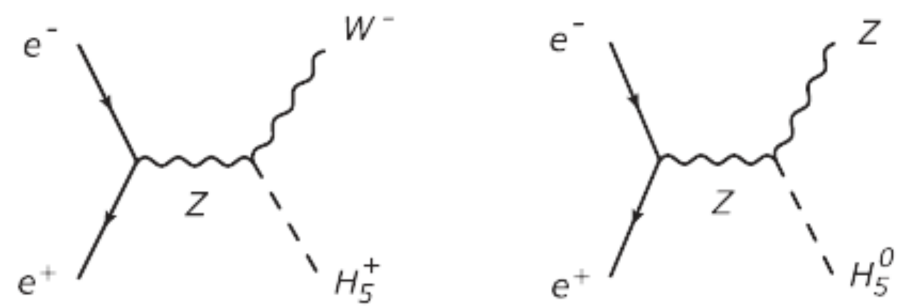
$\sqrt{s} = 1\ \text{TeV}$

Signals and Backgrounds

- Cross sections of 3- and 4-gauge final states in the SM:

$\sqrt{s}$	ZZZ	W^+W^-Z	$W^+W^-W^+W^-$	W^+W^-ZZ	$ZZZZ$
500 GeV	1.1 fb	39 fb	0.13 fb	0.036 fb	6.8×10^{-4} fb
1 TeV	0.86 fb	57 fb	0.79 fb	0.46 fb	3.0×10^{-3} fb

- Although W^+W^-Z has larger background, it also receives more contributions in GM model via the VBA diagrams.

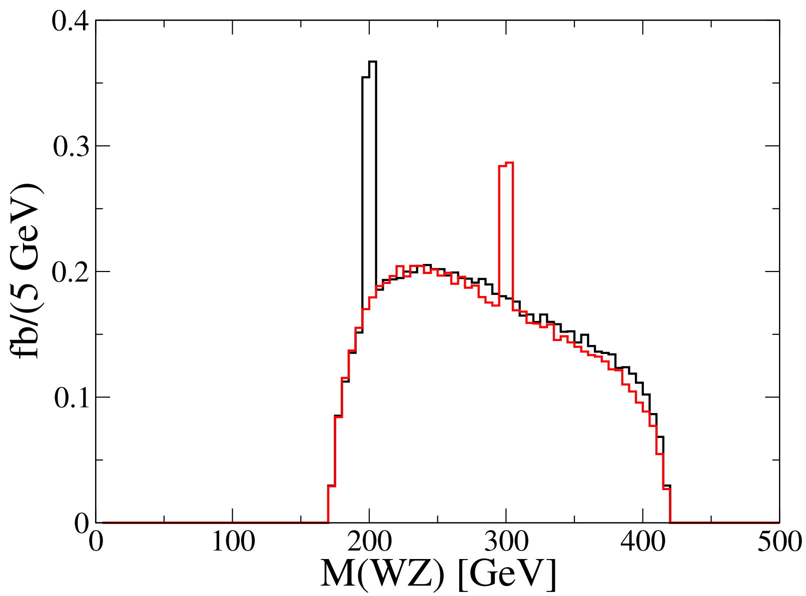


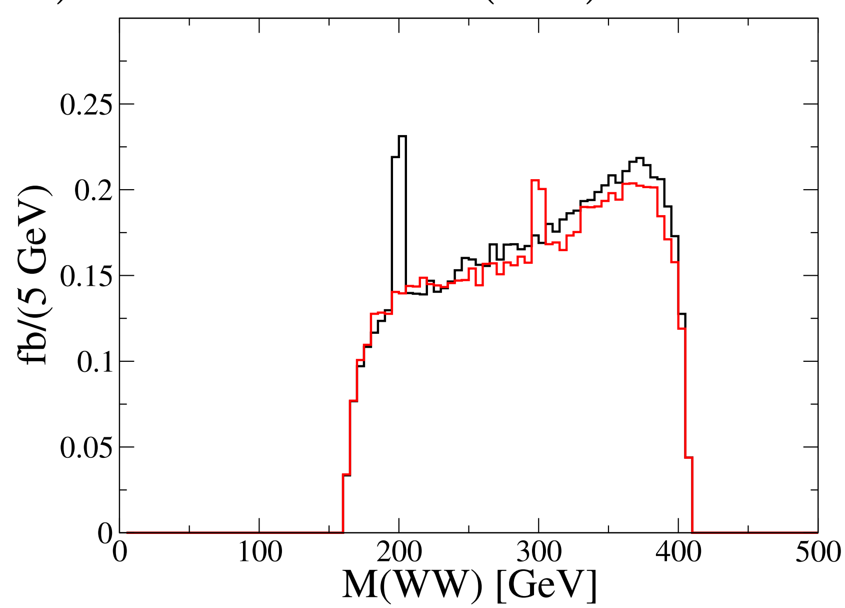
- They can be used to study properties associated with singly-charged and neutral H_5 bosons.
- Assume $m_{H5}–m_{H3} < 50$ GeV, then BR's($H_5 \to VV$) ~ 100%, because $H_5 \to V^{(*)}H_3$ and $H_5 \to H_3H_3$ are forbidden.

Invariant Mass Distributions

- Invariant mass distributions for subsystems of the $e^+e^- \to W^+W^-Z$ process, including ISR with scale set at √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.

$$\sqrt{s} = 500 \text{ GeV and } v_\Delta = 30 \text{ GeV}$$
$$m_{H_5} = 200 \text{ GeV (black) and } 300 \text{ GeV (red)}$$





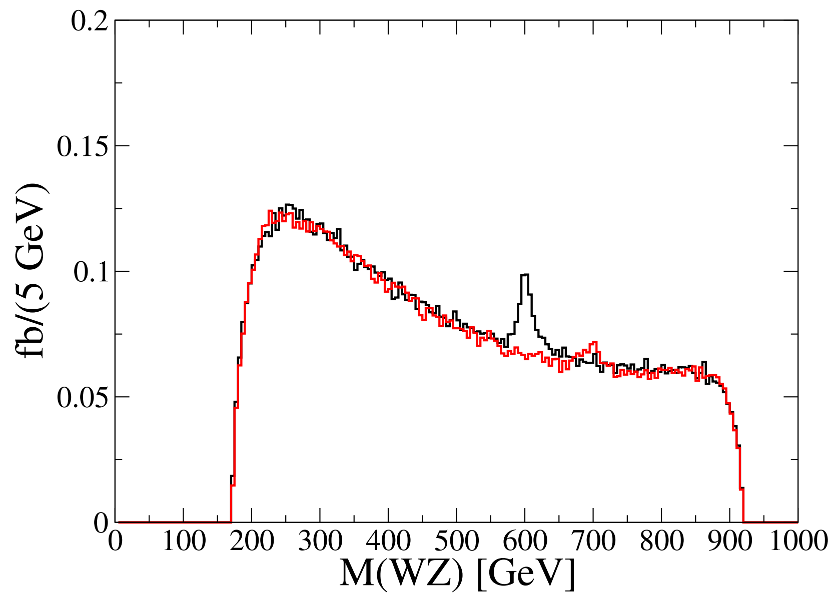
Peaks at same location in both plots serve as a test of custodial symmetry.

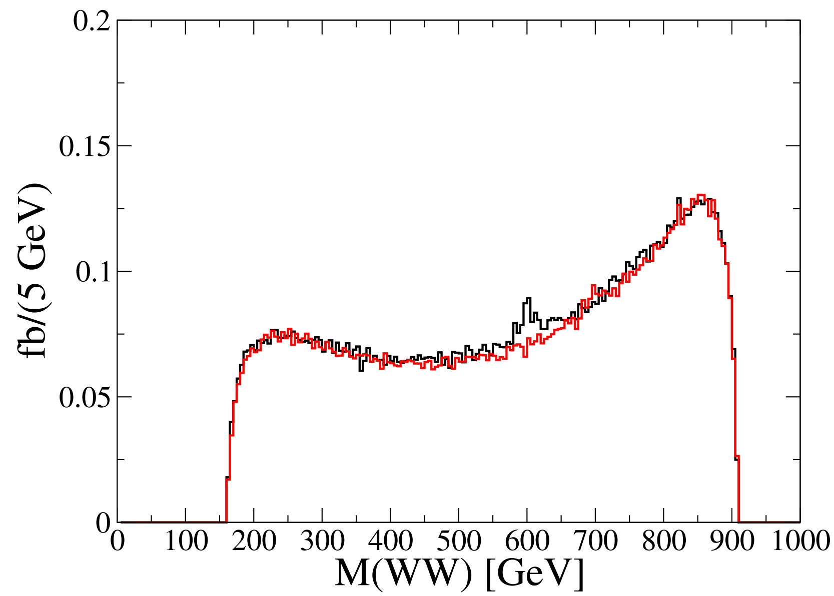
Invariant Mass Distributions

- 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.

$$\sqrt{s} = 1 \text{ TeV and } v_\Delta = 50 \text{ GeV}$$

$$m_{H_5} = 600 \text{ GeV (black) and } 700 \text{ GeV (red)}$$





For m_{H5}= 700 GeV, it is difficult to find a peak because the signal cross section is suppressed, while the widths become larger for larger m_{H5}.

Summary

- Concentrate on the study of how one can test the GM model at the ILC with proposed colliding energies of 0.5 and 1 TeV.
- Show decay BR's of the three charged states of H_5 as functions of $m_{H5} - m_{H3}$.
- With a cleaner collider environment, it is easier to determine singly-charged and neutral H_5 mass with high precision at the ILC than the LHC, using the VBA production processes with the W^+W^-Z channel.
- A synergy with LHC for the mass of doubly-charged H_5 helps verify the model, including its custodial nature.

Thank You!