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Testing Custodial Symmetry in Higgs Sector of Georgi-Machacek Model

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Plan of Talk

I. Higgs Triplet Model

II. Georgi-Machacek Model

III. Empirical Constraints

IV. GM Higgs Pheno at LHC

V. Summary

HIGGS TRIPLET MODEL

Higgs Triplet Model

Konetschny, Kummer 1977; Schechter, Valle 1980;
Cheng, Li 1980; Gelmini, Roncadelli 1981

- Introduce a triplet complex scalar field Δ: (1,3,2) in adjoint rep:

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

prediction of doubly charged Higgs boson

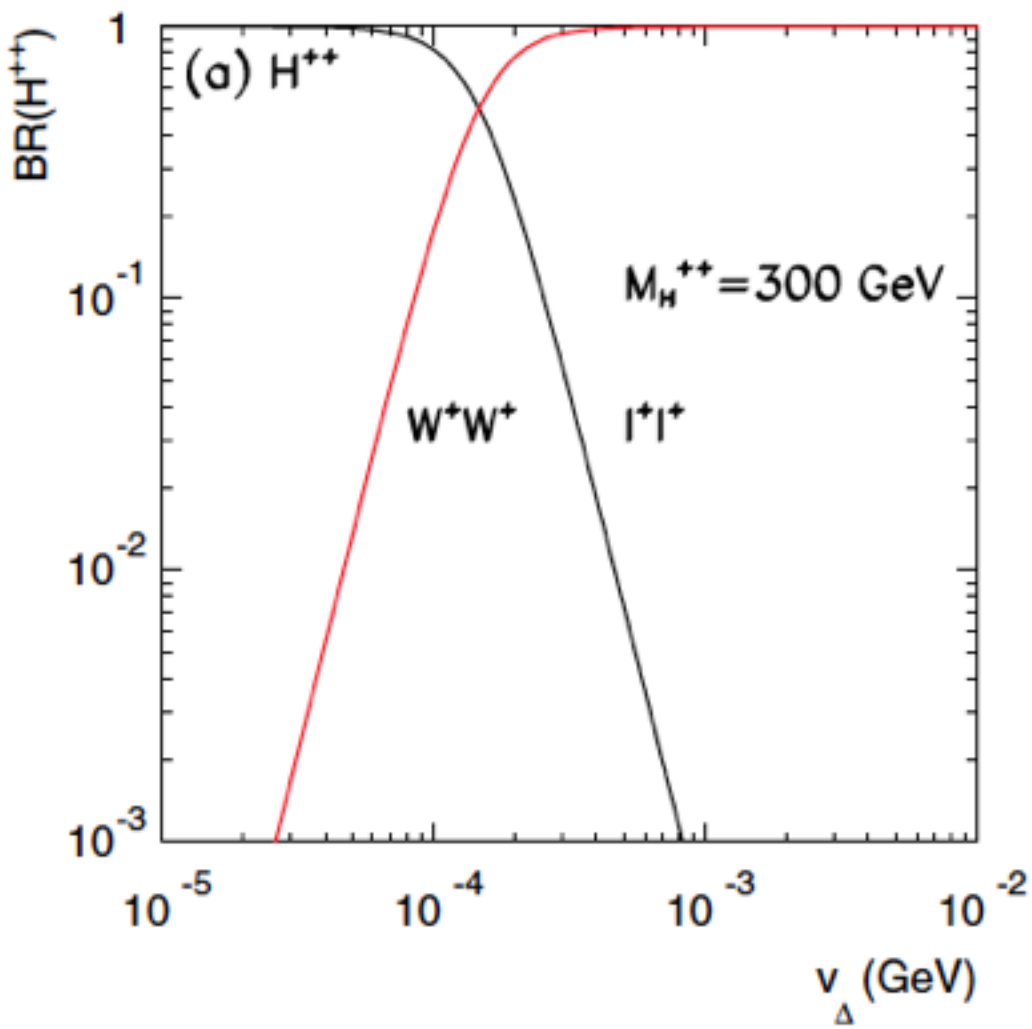
with the $SU(2)_L \times U(1)_Y$ invariant potential

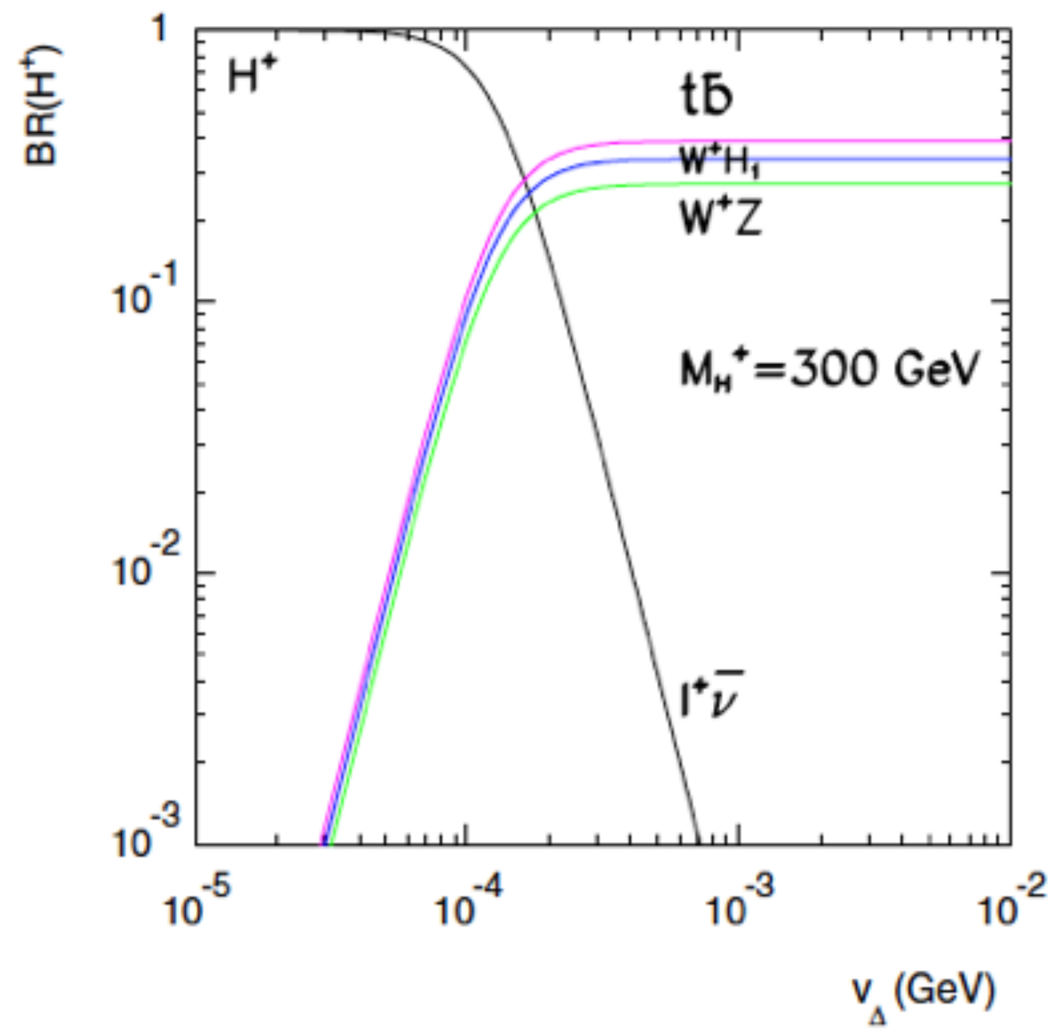
$$\begin{aligned}\mathcal{L} \quad \supset \quad & (D_\mu \Phi)^\dagger (D^\mu \Phi) - m^2 (\Phi^\dagger \Phi) - \lambda (\Phi^\dagger \Phi)^2 \\ & + \mathrm{Tr}(D_\mu \Delta)^\dagger (D^\mu \Delta) - M_\Delta^2 \mathrm{Tr}(\Delta^\dagger \Delta) - \frac{\mu}{\sqrt{2}} (\Phi^T i\sigma_2 \Delta^\dagger \Phi) \\ & - \lambda_i (\text{quartic terms}) \\ & - h_{ij} \psi_{iL}^T C i\sigma_2 \Delta \psi_{jL} + \text{h.c.}\end{aligned}$$

- All λ_i's = 0 considered by most people for simplicity.

Signature Modes

- In the case of small v_Δ, both $H^{\pm\pm}$ and $H^{\pm}$ decay dominantly into leptonic final states, desirable at hadron colliders.

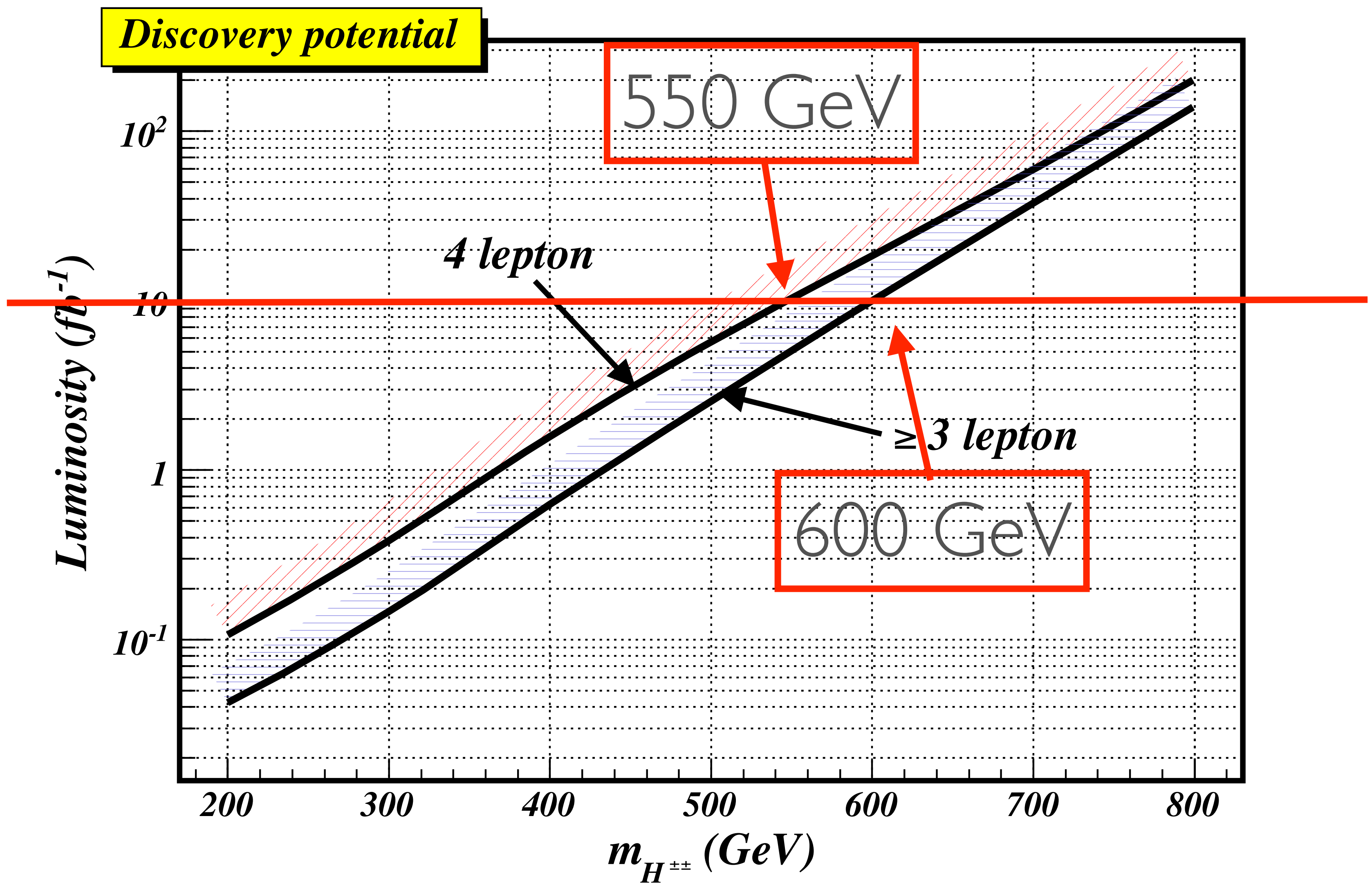




Perez et. al. 2008

5σ Discovery Potential

Akeroyd, CWC, Gaur 2010



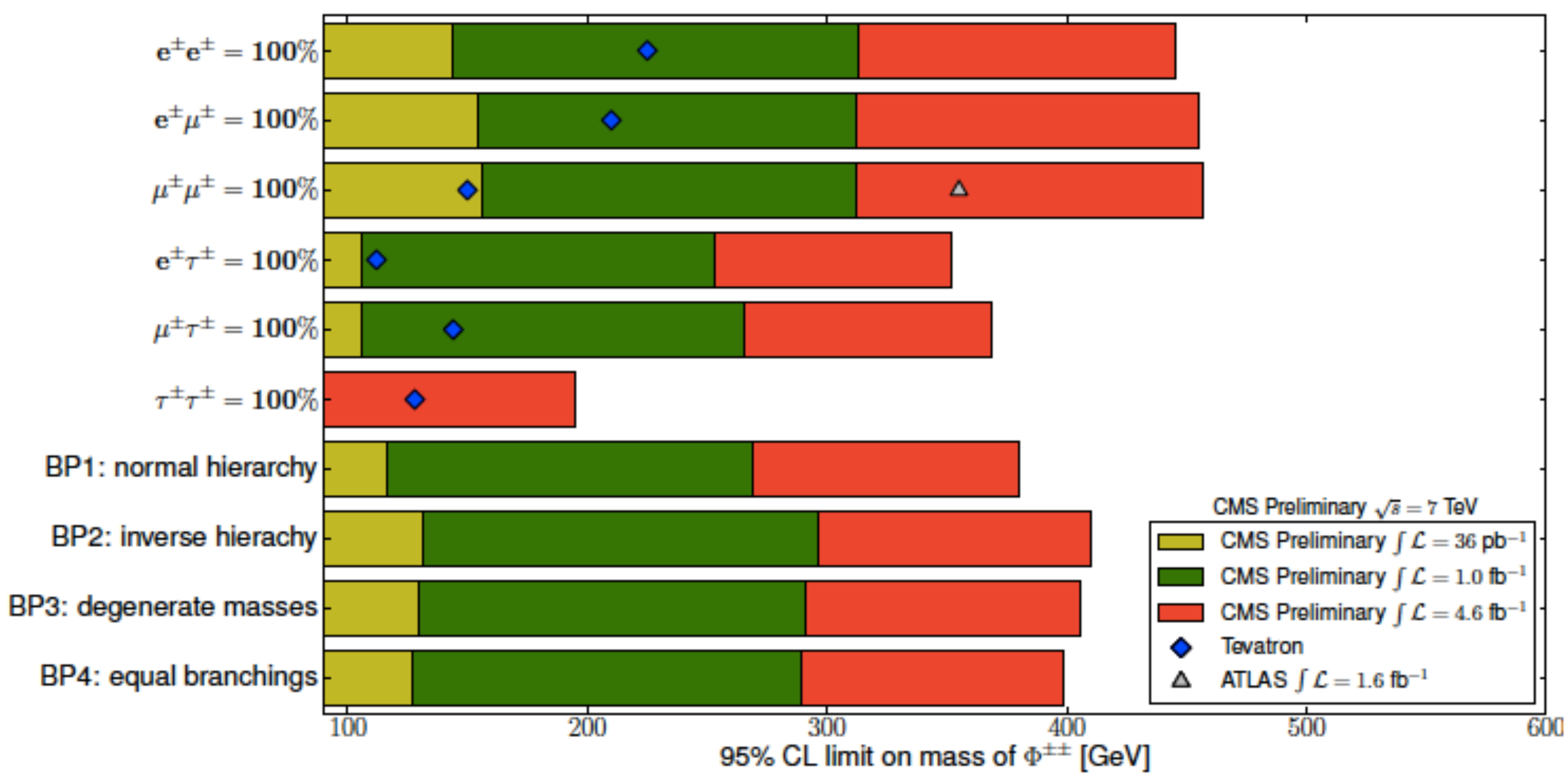
- Discovery potential for $H^{\pm\pm}$ at 14-TeV LHC through the $\geq 3\ell$ mode is significantly better than the 4ℓ mode.

CMS Search Results

- Four simple benchmark points (BP's):

CMS 2012

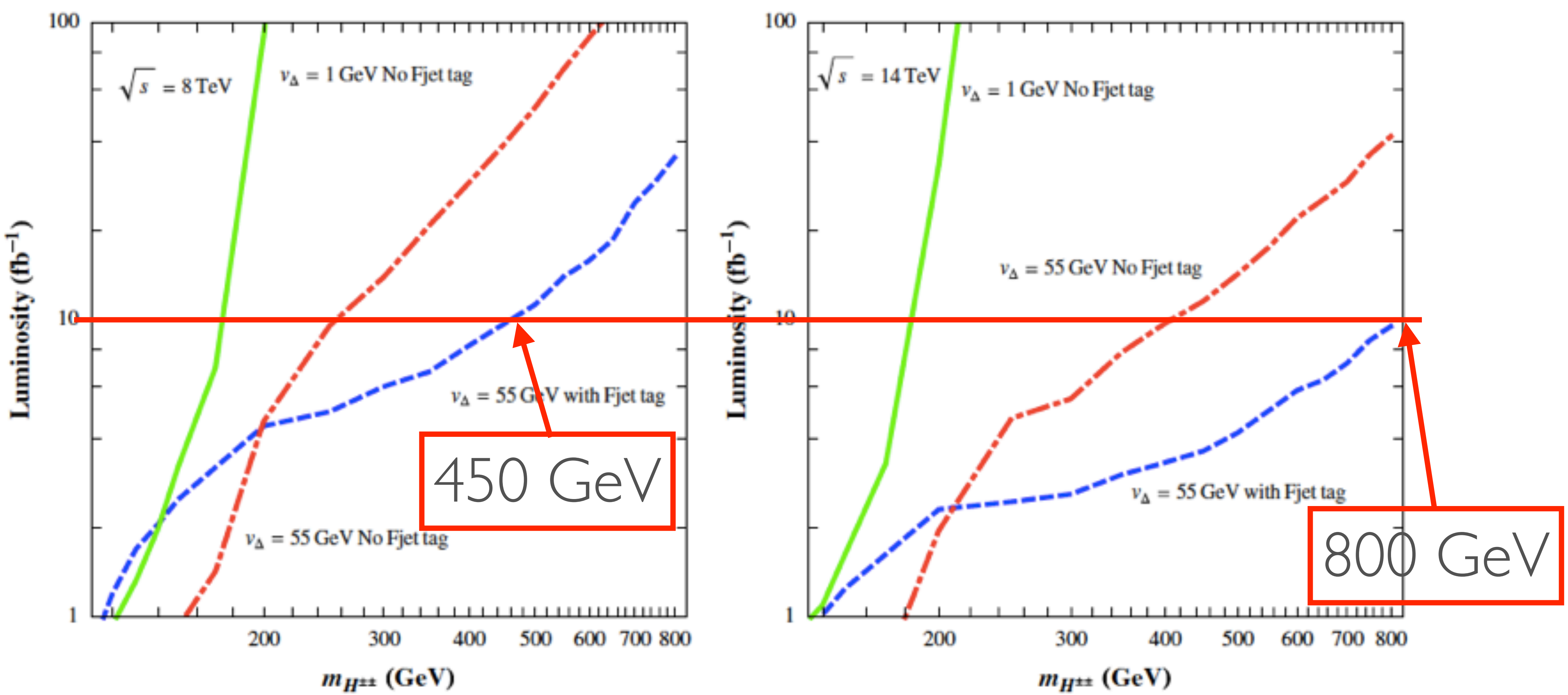
	ee	$e\mu$	$\mu\mu$	$e\tau$	$\mu\tau$	$\tau\tau$
BP1 (normal hierarchy)	0	0.01	0.3	0.01	0.38	0.3
BP2 (inverted hierarchy)	0.50	0	0.125	0	0.25	0.125
BP3 (degenerate neutrinos)	1/3	0	1/3	0	0	1/3
BP4 (equal branching ratios)	1/6	1/6	1/6	1/6	1/6	1/6



A New Direction

CWC, Nomura, Tsumura 2012

- In the case of large v_Δ, both $H^{\pm\pm}$ and $H^\pm$ couple dominantly with weak bosons instead.
- Required luminosity for a 5σ discovery of $H^{\pm\pm}$: with 10/fb, 8-TeV (14-TeV) LHC can reach up to 450 (800) GeV.



Constraint on v_Δ

- Based on realistic neutrino masses, perturbativity demands $v_\Delta \geq 1$ eV.

- Non-zero Higgs triplet VEV leads to

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} < 1$$

Current $\rho^{exp} \approx 1.0004^{+0.0008}_{-0.0004}$ requires $v_\Delta \leq$ a few GeV.

PDG 2008;
Abada et al 2007

GEORGI-MACHACEK MODEL

Higgs Field Contents

Georgi, Machacek 1985
Chanowitz, Golden 1985

- Include SM isospin doublet field ϕ: (2,1/2) and isospin triplet fields χ: (3,1) and ξ: (3,0)

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

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.

- Will 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

Higgs Potential

- Most general Higgs potential:

$$
\begin{aligned}
V_H =& m_1^2 \mathrm{tr}(\Phi^\dagger \Phi) + m_2^2 \mathrm{tr}(\Delta^\dagger \Delta) \\
&+ \lambda_1 \mathrm{tr}(\Phi^\dagger \Phi)^2 + \lambda_2 [\mathrm{tr}(\Delta^\dagger \Delta)]^2 \\
&+ \lambda_3 \mathrm{tr}[(\Delta^\dagger \Delta)^2] + \lambda_4 \mathrm{tr}(\Phi^\dagger \Phi) \mathrm{tr}(\Delta^\dagger \Delta) \\
&+ \lambda_5 \mathrm{tr}\left(\Phi^\dagger \frac{\tau^a}{2} \Phi \frac{\tau^b}{2}\right) \mathrm{tr}(\Delta^\dagger t^a \Delta t^b) \\
&+ \mu_1 \mathrm{tr}\left(\Phi^\dagger \frac{\tau^a}{2} \Phi \frac{\tau^b}{2}\right) (P^\dagger \Delta P)^{ab} \\
&+ \mu_2 \mathrm{tr}\left(\Delta^\dagger t^a \Delta t^b\right) (P^\dagger \Delta P)^{ab}
\end{aligned}
$$

self interactions

inducing triplet VEV from EWSB

$$
P = \begin{pmatrix} -1/\sqrt{2} & i/\sqrt{2} & 0 \\ 0 & 0 & 1 \\ 1/\sqrt{2} & i/\sqrt{2} & 0 \end{pmatrix}
$$

- All terms kept in our analysis

Tadpole Conditions

- Tadpole conditions give

$$m_1^2 = -v^2 \left(2c_H^2\lambda_1 + \frac{3}{8}s_H^2\lambda_4 + \frac{3}{16}s_H^2\lambda_5\right) + \frac{3}{8}s_H^2 M_1^2$$

$$m_2^2 = -v^2 \left(\frac{3}{4}s_H^2\lambda_2 + \frac{1}{4}s_H^2\lambda_3 + c_H^2\lambda_4 + \frac{1}{2}c_H^2\lambda_5\right) + \frac{1}{2}c_H^2 M_1^2 + \frac{1}{4}M_2^2$$

where $\quad M_1^2 = -\frac{v\mu_1}{\sqrt{2}s_H} \qquad M_2^2 = -3\sqrt{2}s_H v\mu_2$

$$v^2 = v_\phi^2 + 8v_\Delta^2 = \frac{1}{\sqrt{2}G_F}\ , \quad \tan\theta_H = \frac{2\sqrt{2}v_\Delta}{v_\phi}$$

$$s_H = \sin\theta_H\ ,\ c_H = \cos\theta_H$$

Custodial SU(2) Classification

- The triplet field Δ: **3**⊗**3** = **5**⊕**3**⊕**1** under $SU(2)_V$.
- The doublet field Φ: **2**⊗**2** = **3**⊕**1** under $SU(2)_V$.
- **3** of Φ can be identified as the NG bosons of the SM as long as there is no mixing between the **3**'s of Δ and Φ.
- The **5**-plet, **3**-plet and singlet originating from Δ are

$$H_5^{\pm\pm} = \chi^{\pm\pm} \ , \quad H_5^{\pm} = \frac{1}{\sqrt{2}}(\chi^{\pm} - \xi^{\pm}) \ , \quad H_5^0 = \frac{1}{\sqrt{3}}(\chi_r - \sqrt{2}\xi_r) \ ,$$

CP-even

$$\tilde{H}_3^{\pm} = \frac{1}{\sqrt{2}}(\chi^{\pm} + \xi^{\pm}) \ , \quad \tilde{H}_3^0 = \chi_i \ ,$$

CP-odd

$$\tilde{H}_1^0 = \frac{1}{\sqrt{3}}(\xi_r + \sqrt{2}\chi_r) \ .$$

CP-even

can in general mix with **3** and **1** from Higgs doublet fields

Mass Eigenstates

- Mass eigenstates are related to above fields by

$$\begin{pmatrix} \phi_i \\ \tilde{H}_3^0 \end{pmatrix} = U_{\text{CP-odd}} \begin{pmatrix} G^0 \\ H_3^0 \end{pmatrix} , \quad U_{\text{CP-odd}} = \begin{pmatrix} c_H & -s_H \\ s_H & c_H \end{pmatrix}$$

$$\begin{pmatrix} \phi^\pm \\ \tilde{H}_3^\pm \\ H_5^\pm \end{pmatrix} = U_\pm \begin{pmatrix} G^\pm \\ H_3^\pm \\ H_5^\pm \end{pmatrix} , \qquad U_\pm = \begin{pmatrix} \multicolumn{2}{c}{\multirow{2}{*}{$U_{\text{CP-odd}}$}} & 0 \\ & & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \phi_r \\ \tilde{H}_1^0 \\ H_5^0 \end{pmatrix} = U_{\text{CP-even}} \begin{pmatrix} h \\ H_1^0 \\ H_5^0 \end{pmatrix} , \quad U_{\text{CP-even}} = \begin{pmatrix} c_\alpha & -s_\alpha & 0 \\ s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$G^\pm$ and G^0 are the NG bosons for the longitudinal components of the $W^\pm$ and Z bosons.

Mass Relation

- In the decoupling limit ($v_\Delta \to 0$ or equivalently $s_H \to 0$), the mass formulae of the Higgs bosons reduce to

$$m_{H_5}^2 = -\frac{3}{2}\lambda_5 v^2 + M_1^2 + M_2^2$$

$$m_{H_3}^2 = -\frac{1}{2}\lambda_5 v^2 + M_1^2$$

$$m_{H_1}^2 = M_1^2 - \frac{1}{2}M_2^2$$

$$m_h^2 = 8\lambda_1 v^2.$$

leading to the following relation (reducing one parameter)

$$m_{H_1}^2 = \frac{3}{2}m_{H_3}^2 - \frac{1}{2}m_{H_5}^2$$

which is a good approximation even not in the limit.

Yukawa Interactions

- In scalar mass eigenstates, the Yukawa interactions between leptons of one family and Δ are

$$\mathcal{L}_\nu = \frac{2\sqrt{2}m_\nu}{s_H v} H_5^{++}\overline{e_i^c}P_L e_i - \frac{2\sqrt{2}m_\nu}{s_H v}\left(H_5^+ + c_H H_3^+ + s_H G^+\right)\overline{\nu_i^c}P_L e_i\Big]$$

$$+\frac{2m_\nu}{s_H v}\left[\frac{1}{\sqrt{3}}(H_5^0 + \sqrt{2}s_\alpha h + c_\alpha H_1^0) + i(G^0 s_H + H_3^0 c_H)\right]\overline{\nu_i^c}P_L\nu_i + \text{h.c.}$$

- Usual Yukawa interactions between fermions of one family and ϕ are

$$\mathcal{L}_Y = -\sum_{f=u,d,e}\frac{m_f}{v}\left[\frac{c_\alpha}{c_H}\bar{f}fh - \frac{s_\alpha}{c_H}\bar{f}fH_1^0 + i\text{Sign}(f)\tan\theta_H\bar{f}\gamma_5 f H_3^0\right]$$

$$-\frac{\sqrt{2}V_{ud}}{v}\left[\tan\theta_H\bar{u}(m_u P_L - m_d P_R)dH_3^+\right] + \frac{\sqrt{2}m_e}{v}\tan\theta_H\bar{\nu}P_R e H_3^+$$

$$+\text{h.c.}$$

Sign(u)=+1, Sign(d,e)=−1

$\boxed{\text{only } H_3 \text{ with quarks via mixing}}$

Gauge-Gauge-Scalar Couplings

Vertex	Coefficient	Vertex	Coefficient
$H_5^{\pm\pm}W_\mu^\mp W_\nu^\mp$	$\frac{g^2}{2\sqrt{2}}s_H v g_{\mu\nu}$	$H_1^0 Z_\mu Z_\nu$	$-\frac{g_Z^2}{12}(3s_\alpha c_H - 2\sqrt{6}c_\alpha s_H)v g_{\mu\nu}$
$H_5^\pm W_\mu^\mp Z_\nu$	$\mp\frac{g g_Z}{2}s_H v g_{\mu\nu}$	$hW_\mu^+ W_\nu^-$	$\frac{g^2}{6}(3c_\alpha c_H + 2\sqrt{6}s_\alpha s_H)v g_{\mu\nu}$
$H_5^0 W_\mu^+ W_\nu^-$	$-\frac{g^2}{2\sqrt{3}}s_H v g_{\mu\nu}$	$hZ_\mu Z_\nu$	$\frac{g_Z^2}{12}(3c_\alpha c_H + 2\sqrt{6}s_\alpha s_H)v g_{\mu\nu}$
$H_5^0 Z_\mu Z_\nu$	$\frac{g_Z^2}{2\sqrt{3}}s_H v g_{\mu\nu}$	$G^\pm W_\mu^\mp A_\nu$	$\pm e m_W g_{\mu\nu}$
$H_1^0 W_\mu^+ W_\nu^-$	$-\frac{g^2}{6}(3s_\alpha c_H - 2\sqrt{6}c_\alpha s_H)v g_{\mu\nu}$	$G^\pm W_\mu^\mp Z_\nu$	$\mp e s_W m_Z g_{\mu\nu}$

TABLE III: Gauge-Gauge-Scalar vertices and the associated coefficients.

- No H_3 bosons are involved.
- In models with $\rho = 1$ at tree level and having $H^\pm$ bosons (e.g., 2HDM), the $H^\pm W^\mp Z$ vertex is usually absent at tree level and can only be induced at loop levels. Grifols, Mendez 1980
- This vertex can be used to discriminate models with singly-charged Higgs bosons.

Asakawa, Kanemura 2005
Kanemura, Yagyu, Tanase 2011

CONSTRAINTS ON GEORGI-MACHACEK MODEL

Unitarity/Stability Bounds

- Perturbative unitarity bound for the GM model has been studied before to be

Aoki, Kanemura 2008

$$\left| 12\lambda_1 + 22\lambda_2 + 14\lambda_3 \pm \sqrt{(12\lambda_1 - 22\lambda_2 - 14\lambda_3)^2 + 144\lambda_4^2} \right| < 16\pi$$

- Vacuum stability condition gives

$$\lambda_1 > 0\ , \quad \lambda_2 + \lambda_3 > 0\ , \quad \lambda_2 + \frac{1}{2}\lambda_3 > 0\ ,$$

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

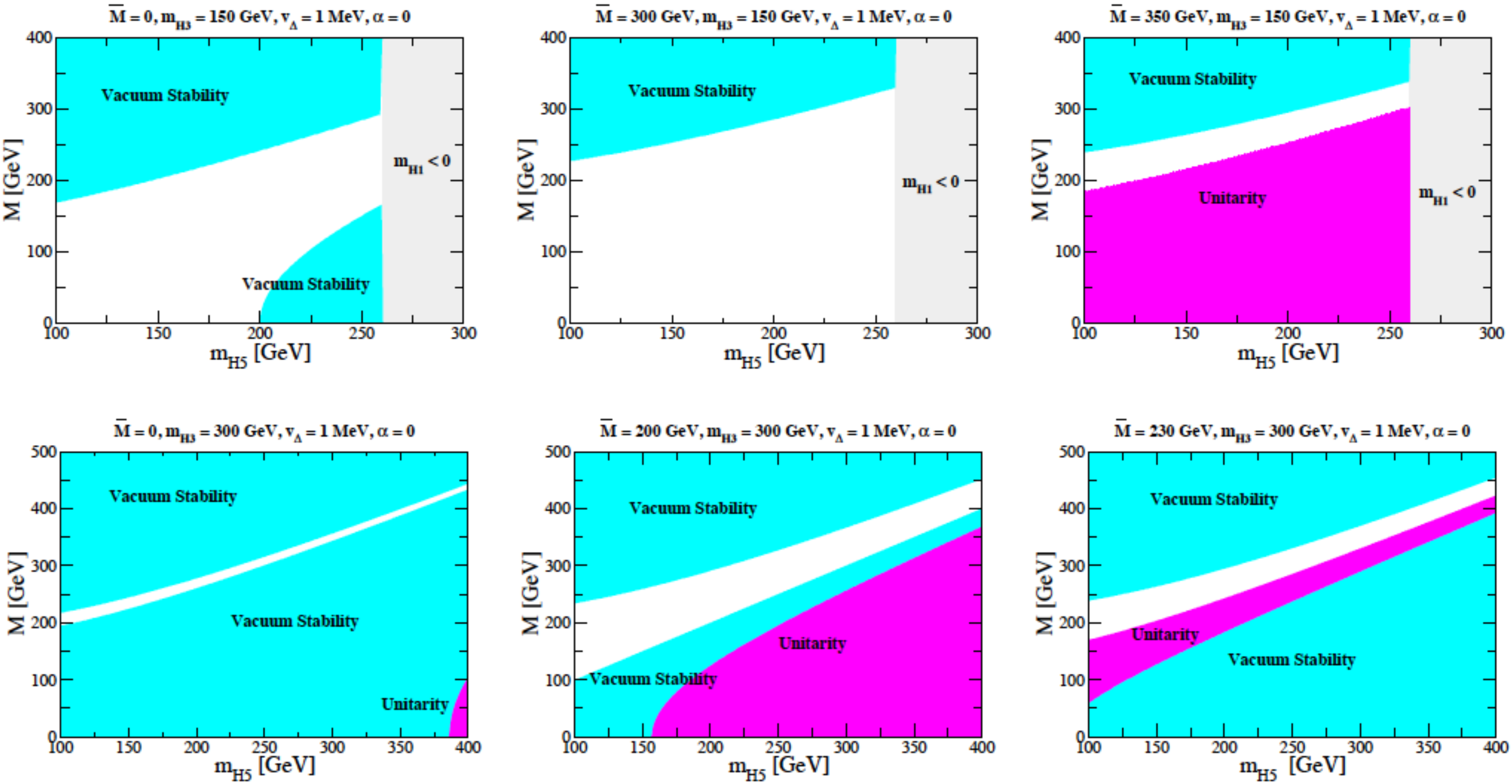
- For $\alpha = 0$ (no mixing between Φ and Δ),

$$\lambda_1 = \frac{m_h^2}{8v^2 c_H^2}\ , \quad \lambda_2 = \frac{m_{H_3}^2 - m_{H_5}^2 + M^2 + \bar{M}^2}{2v^2}\ , \quad \lambda_3 = \frac{m_{H_5}^2 - M^2}{v^2},$$

$$\lambda_4 = \frac{m_{H_3}^2 + m_{H_5}^2 - M^2}{4v^2}\ , \quad \lambda_5 = \frac{m_{H_3}^2 - m_{H_5}^2 + M^2}{v^2}\ .$$

Unitarity/Stability Bounds

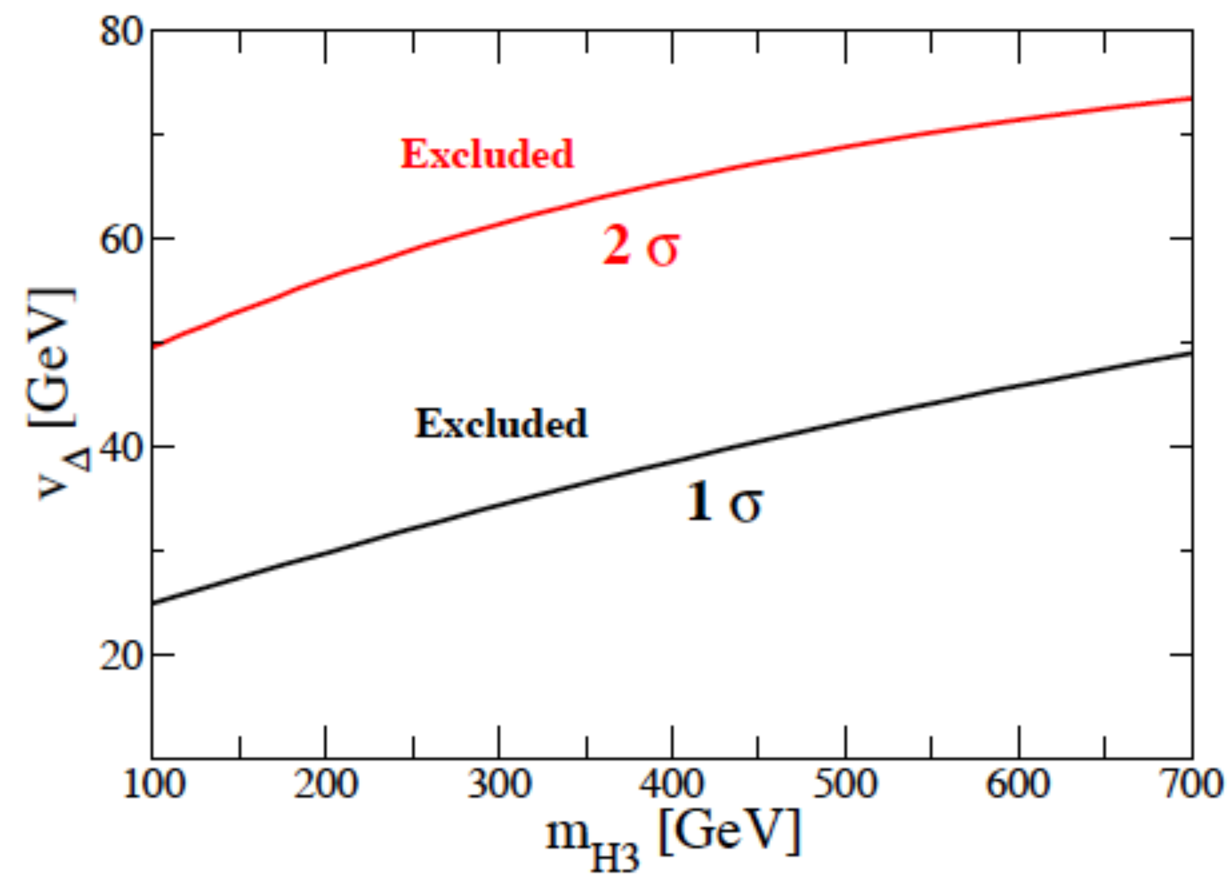
- Constraints to be imposed on later analyses.



Bounds from Z Pole Data

- Excluded parameter space in the m_{H3}-v_Δ plane using the $R_b^{exp} = 0.21629 \pm 0.00066$.

PDG 2010



- Upper bound on v_Δ increases monotonically with m_{H3} .
- The 2σ bound is about 25 GeV more relaxed than 1σ bound.
- Constraint from the $b \to s\gamma$ data for the GM model is similar to that in the Type-I 2HDM and is milder than the R_b constraint.

Barger, Hewett, Phillips 1990
Aoki, Kanemura, Tsumura, Yagyu 2009

HIGGS DECAYS

General Remarks

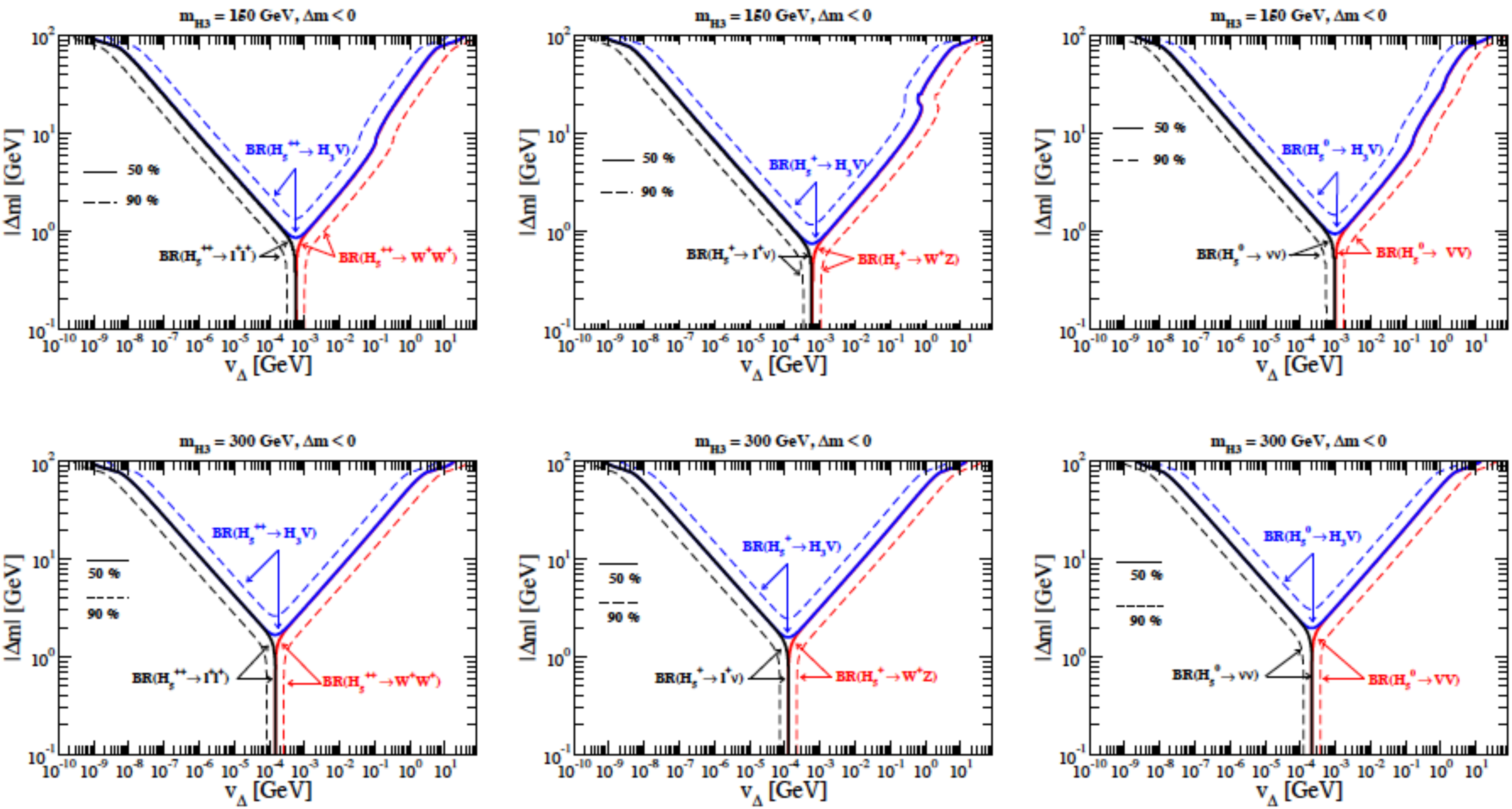
- Decay rates of new Higgs bosons generally depend on m_{H5} , m_{H3} and m_{H1} (related by approximate mass relation), v_Δ, and mixing angle α.
- Fix m_h = 125 GeV and α = 0 to be specific.
- Decay rates now depend upon v_Δ , m_{H3} and mass splitting between **5**-plet and **3**-plet:

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

- Possible mass spectra:
  - $\Delta m = 0 \Rightarrow m_{H5} = m_{H3} = m_{H1}$
  - $\Delta m > 0 \Rightarrow m_{H1} > m_{H3} > m_{H5}$
  - $\Delta m < 0 \Rightarrow m_{H5} > m_{H3} > m_{H1}$

Contour Plots for H_5 Decays

doubly charged | singly charged | neutral

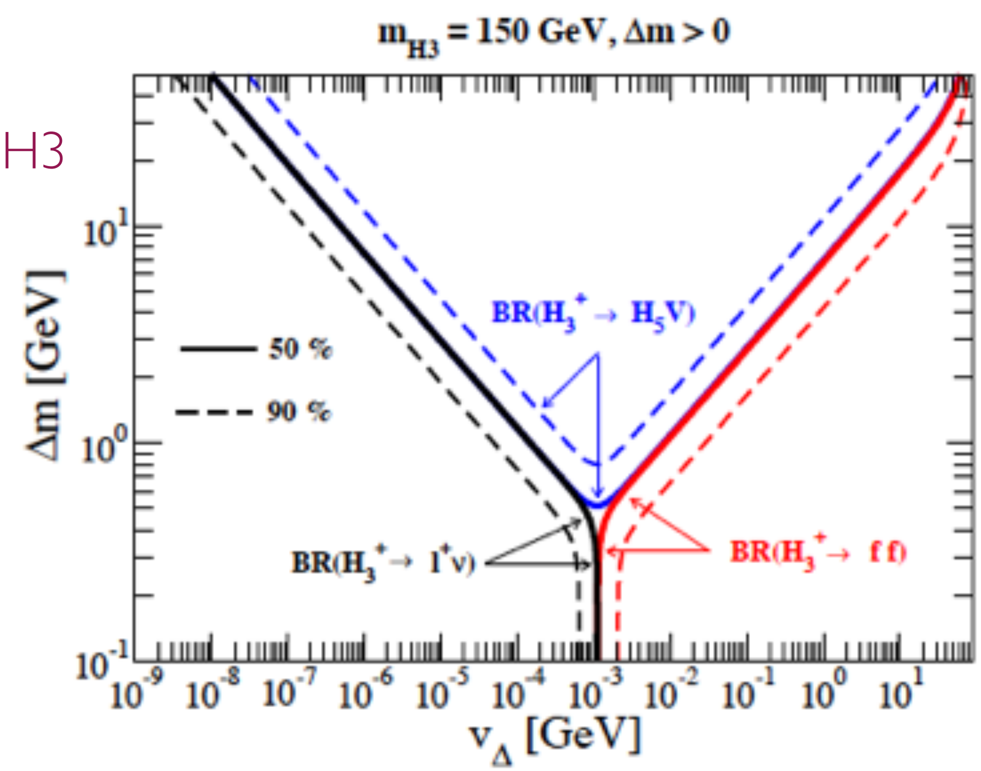


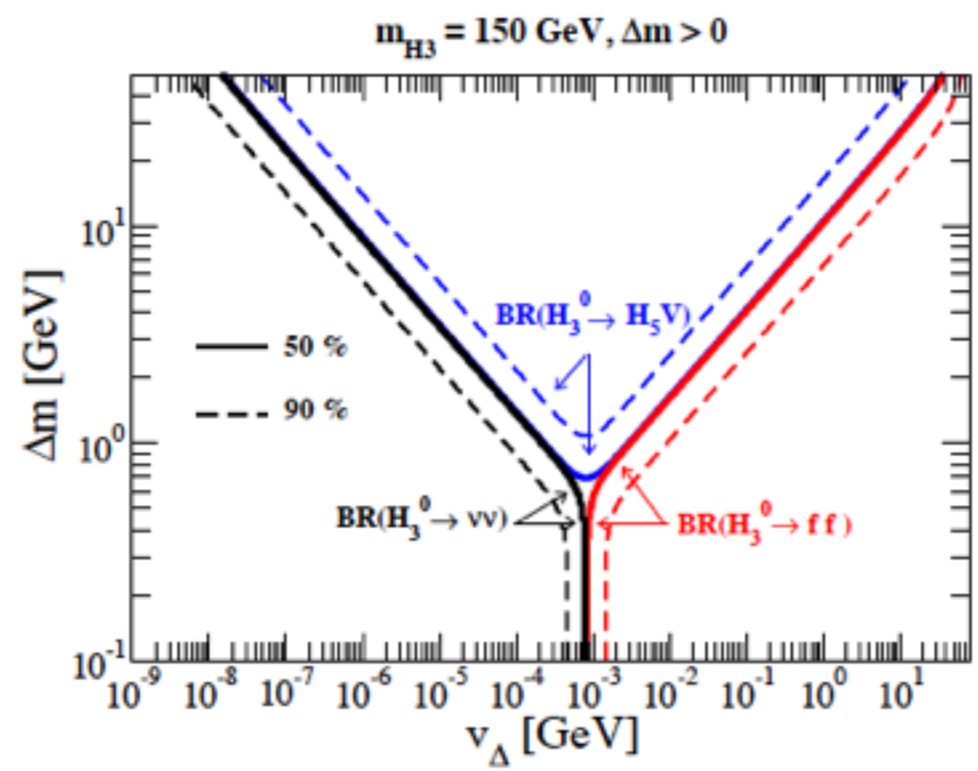
$m_{H5} > m_{H3}$

solid: 50%; dashed: 90%

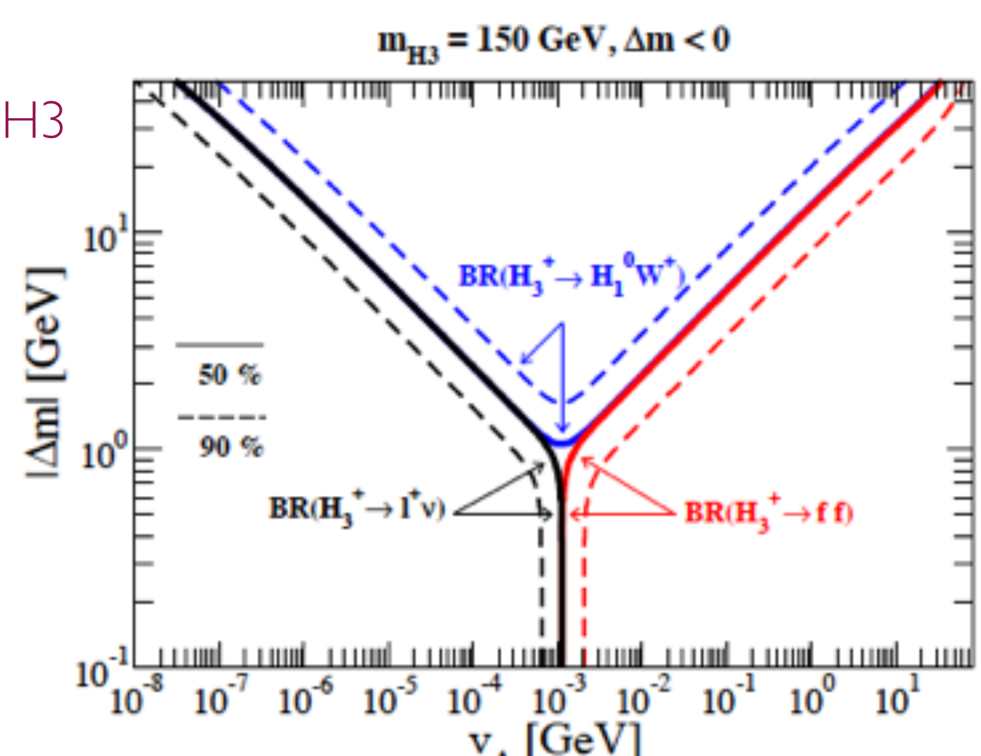
Contour Plots for H_3 Decays

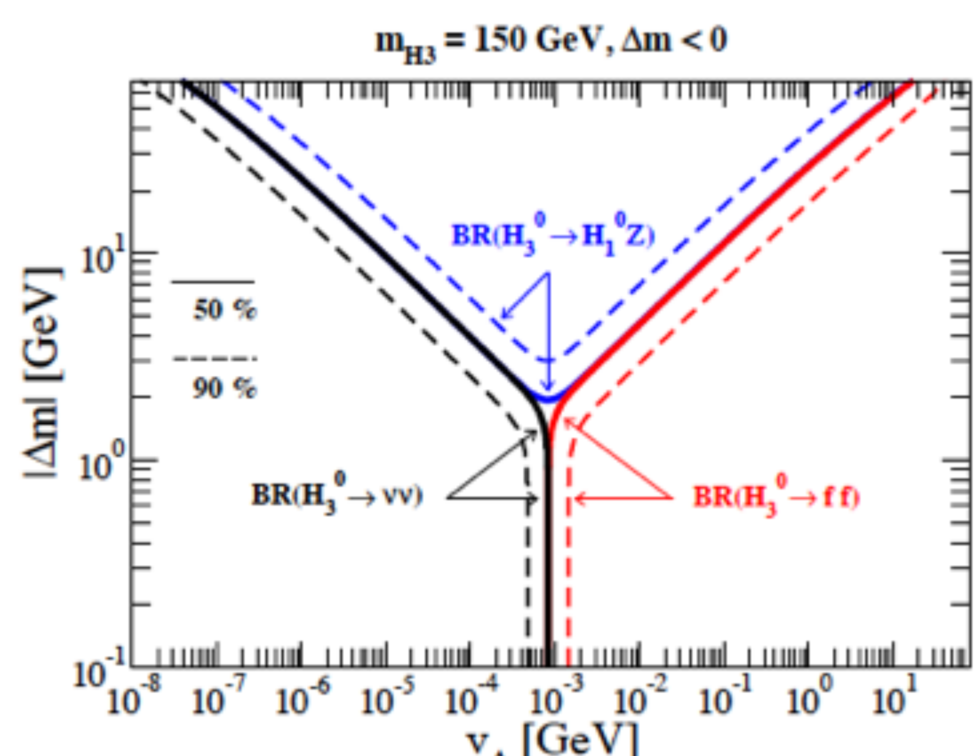
$m_{H5} < m_{H3}$





$m_{H5} > m_{H3}$





solid: 50%; dashed: 90%

In Short

$\Delta m < 0$

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

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

$\Delta m > 0 :$

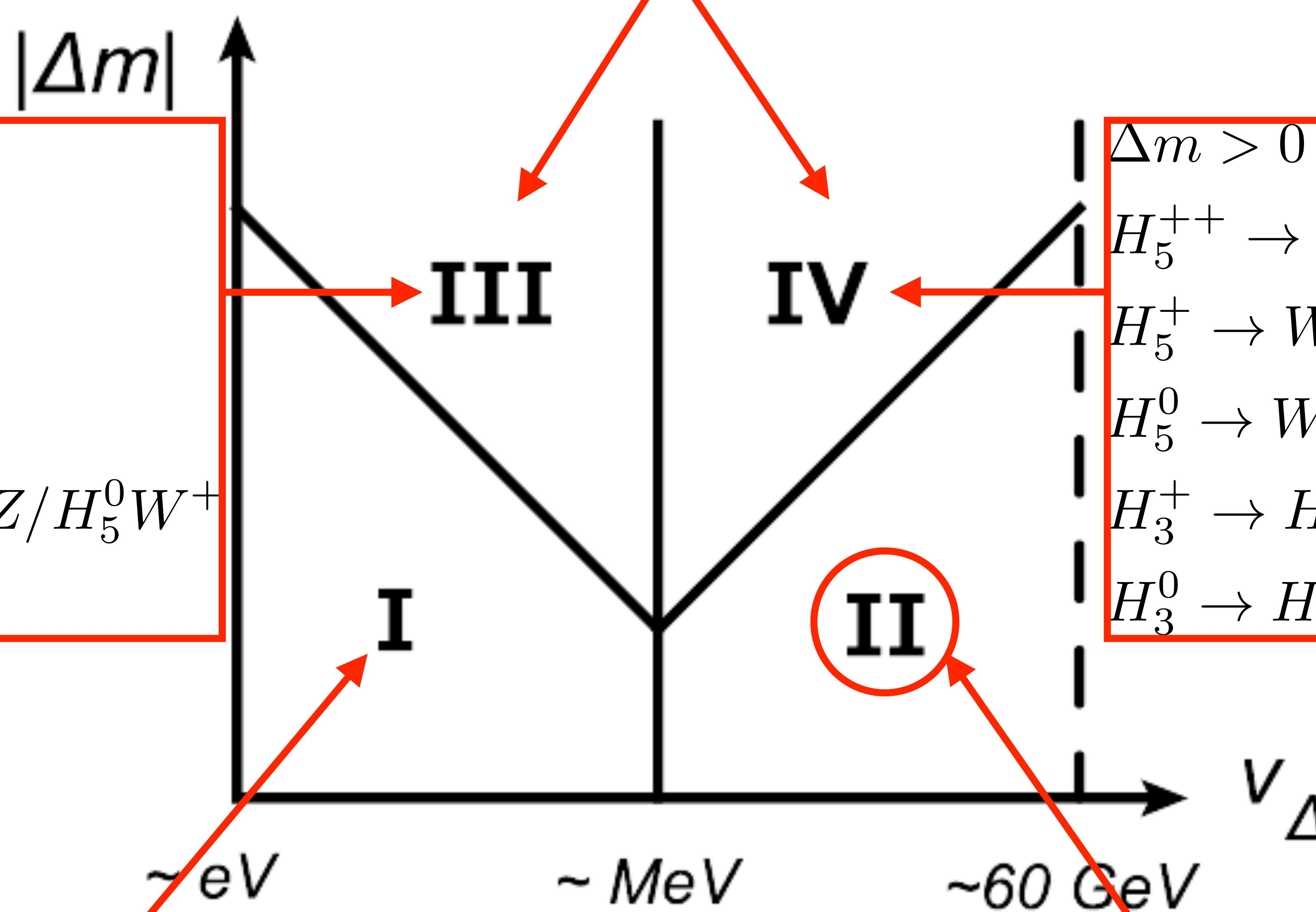
$H_5^{++} \to \ell^+ \ell^+$

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

$H_5^0 \to \nu\nu$

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

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



$\Delta m > 0 :$

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

$H_5^+ \to W^+ Z$

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

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

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

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

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

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

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

HIGGS PHENOMENOLOGY AT LHC

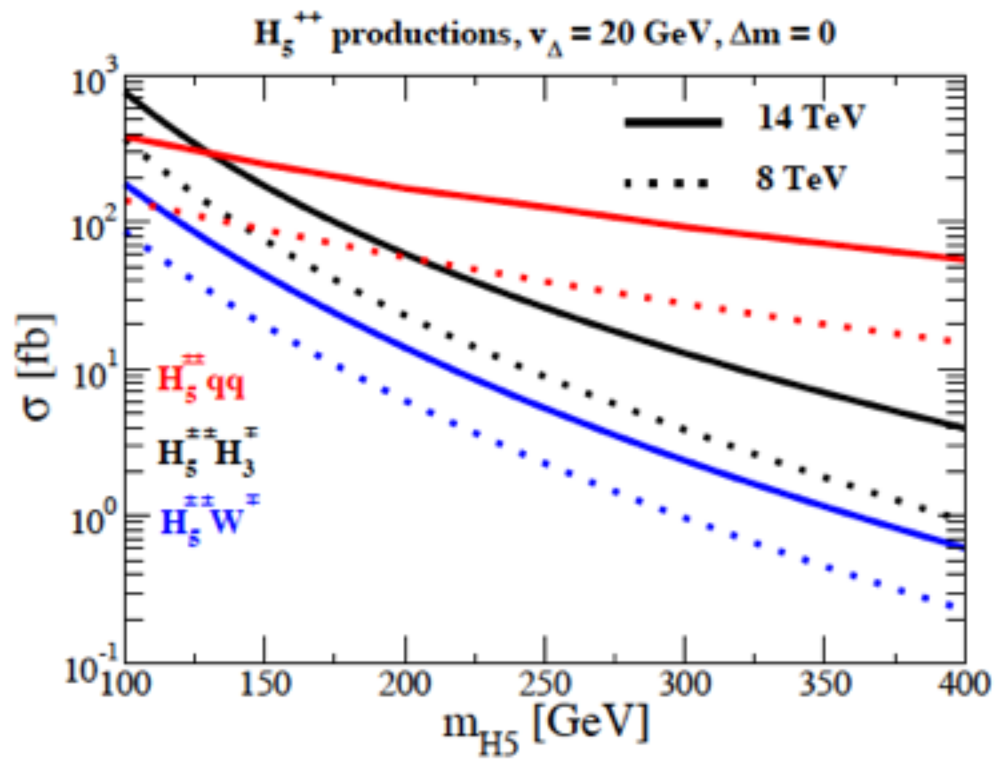
Production Channels

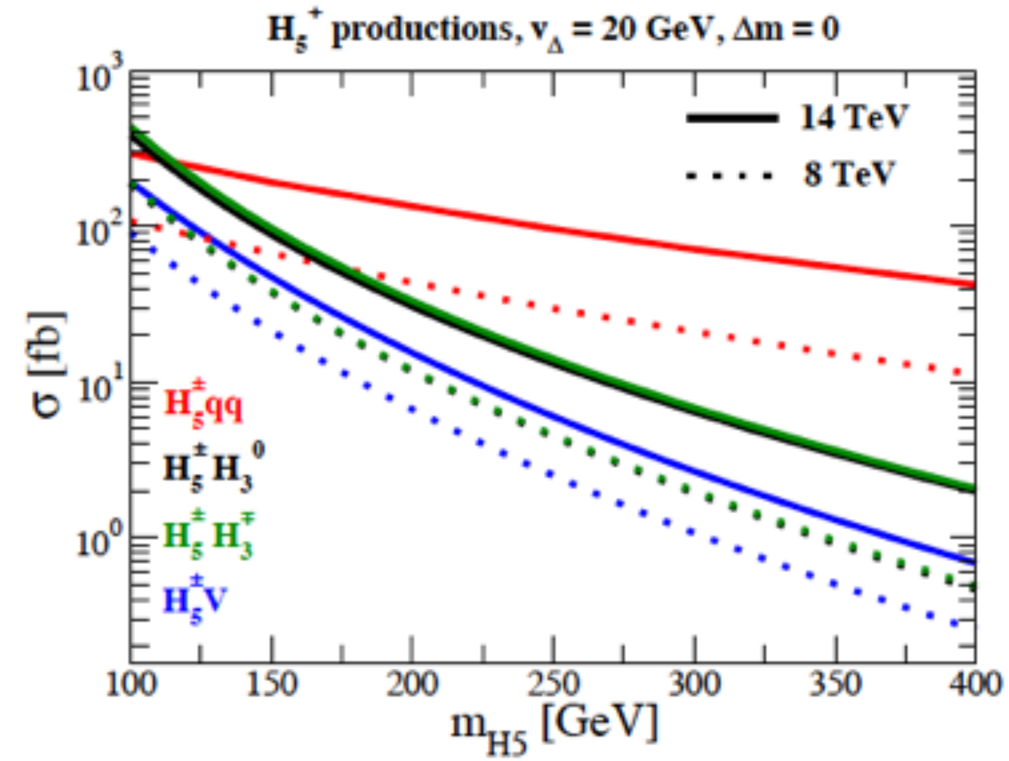
- Drell-Yan (DY) process
  - H_5, H_3 produced in pairs via γ and Z, e.g., $pp \to H_5H_5$ and H_3H_3. Cross section determined by the gauge coupling, m_{H5} and m_{H3} , independent of the value of v_Δ.
- Mixed Drell-Yan (mDY) process
  - H_5, H_3 produced at the same time, e.g., $pp \to H_5H_3$. Cross section proportional to $\cos 2\theta_H$, relatively suppressed than DY process, especially for large v_Δ.
- Weak vector boson fusion (VBF) process
  - Single production of H_5 via $qQ \to H_5$ process. Cross section proportional to v_Δ^2 , thus important for large v_Δ.
- Weak vector boson associated (associated VBF) process
  - H_5 also produced in association with a weak gauge boson, e.g., $qQ' \to H_5V$. Cross sections proportional to v_Δ too, thus also important when VBF process is important.
- Yukawa process
  - H_3 produced via Yukawa interactions as $gg \to H_3^0$ via gluon fusion. t-channel $H_3^\pm$ and H_3^0 modes: $gb \to tH_3^-$ and $gb \to bH_3^0$. Cross sections proportional to $\tan^2\theta_H$.
- Top quark decay
  - For $m_{H3} < m_t$, $H_3^\pm$ produced from the top quark decay. Decay rate of $t \to bH_3^\pm$ depending on $\tan^2\theta_H$.

VBF and associated VBF

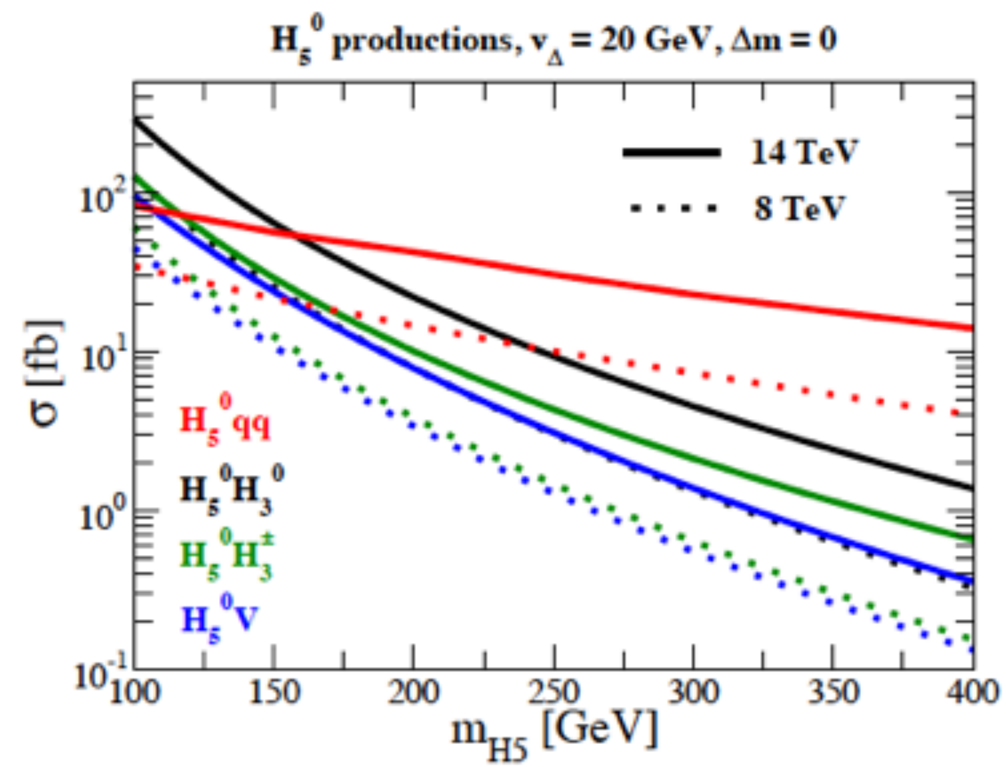
- VBF and associated VBF can be useful to discriminate the GM model from others with doubly-charged Higgs bosons and to test the mass degeneracy of H_5.
  - In HTM, VBF and associated VBF productions of $H_5^{\pm\pm}$ are much suppressed due to tiny triplet VEV.
  - In GM model, $v_\Delta \sim O(10\text{ GeV})$ possibly, so that these production processes become useful.
- mDY process is also a unique feature of the GM model because H_5 and H_3 having different decay properties (Region II in particular) are produced at the same time.
  - This process is useful not only to test mass degeneracy of H_3 but also to distinguish the model from others that also have $H^{\pm\pm}$ and/or $H^\pm$ bosons.

Production of $H_{5,3}$ Bosons





red: VBF
black/green: mDY
blue: associated VBF



Dominant production mechanism is the VBF process for a sufficiently large m_{H5}.

One Benchmark Point

- Consider as an example: m_{H3} = 150 GeV, Δm = 10 GeV (i.e., m_{H5} = 140 GeV) and v_Δ = 20 GeV in Region II.
- **5**-plet Higgs bosons decay into gauge boson pairs ~100%; BR's of $H_5^0 \to W^+W^-$ and ZZ are 2/3 and 1/3 by Clebsch.
- $H_3^\pm$ decays to $\tau^\pm\nu$ at 66% and cs at 29%, and H_3^0 decays to bb at 89%.
- BR of $t \to H_3^+ b$ is ~0.4%, consistent with upper limit of 2-3% for m_{H3} between 80 and 160 GeV, assuming that the charged Higgs boson decays to $\tau\nu$ at 100%. CMS 2012
- Will use VBF and associated VBF to fix H_5; and use mDY to fix H_3.

Signal Events

- For **5**-plet bosons, VBF's are

$$qQ \to H_5^{\pm\pm} q'Q' \to W^\pm W^\pm jj,$$
$$qQ \to H_5^{\pm} q'Q' \to W^\pm Z jj,$$
$$qQ \to H_5^{0} q'Q' \to W^\pm W^\mp jj/ZZjj$$

- Associated VBF's are

$$q\bar{q}' \to H_5^{\pm\pm} W^\mp \to W^\pm W^\pm jj$$
$$q\bar{q} \to H_5^{\pm} W^\mp \to W^\pm Z jj, \quad q\bar{q}' \to H_5^{\pm} Z \to W^\pm Z jj,$$
$$q\bar{q} \to H_5^{0} Z \to W^+ W^- jj/ZZjj,$$
$$q\bar{q}' \to H_5^{0} W^\pm \to W^+ W^- jj/ZZjj,$$

where associated weak gauge bosons are assumed to decay hadronically to have same final states as VBF.

Signal/Background Events

- Consider further that the weak gauge bosons produced from the decay of H_5 decay leptonically:

$$\begin{aligned} H_5^{\pm\pm} &: \quad \ell^\pm \ell^\pm jj \not{E}_T \\ H_5^{\pm} &: \quad \ell^\pm \ell^\pm \ell^\mp jj \not{E}_T \\ H_5^{0} &: \quad \ell^\pm \ell^\mp jj \not{E}_T \end{aligned}$$

- $\ell^\pm$ denotes collectively light leptons $e^\pm$ and $\mu^\pm$.

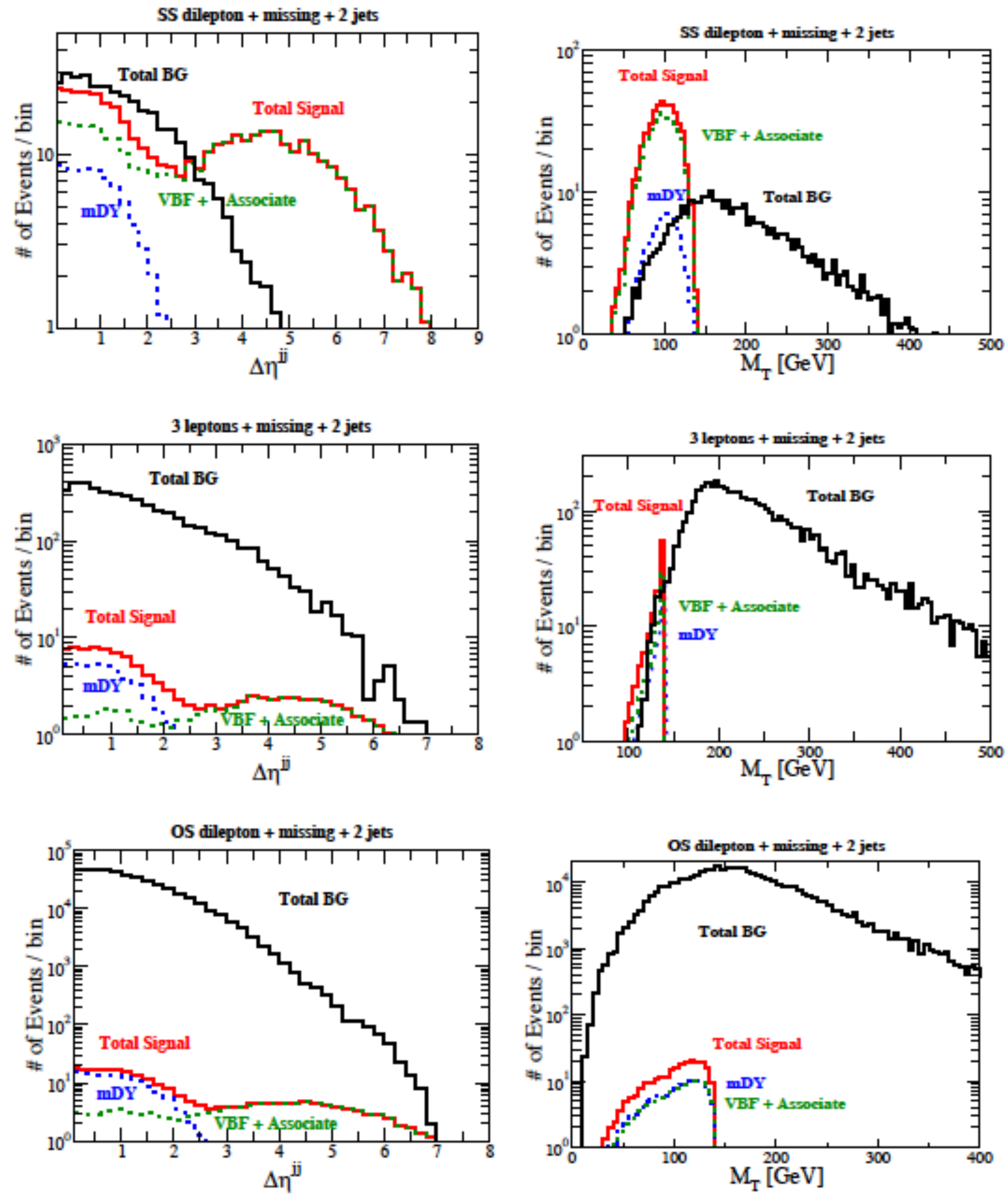
- Corresponding background events for these signal events are from the $W^\pm W^\pm jj$ for the $H_5^{\pm\pm}$, $W^\pm Zjj$ for the $H_5^\pm$, and tt, $W^\pm W^\mp jj$ and $ZZjj$ for H_5^0.

Distributions

$$H_5^{\pm\pm}: \quad \ell^\pm \ell^\pm jj \not{E}_T$$

$$H_5^{\pm}: \quad \ell^\pm \ell^\pm \ell^\mp jj \not{E}_T$$

$$H_5^{0}: \quad \ell^\pm \ell^\mp jj \not{E}_T$$



Kinematic Cuts

- Basic cuts:

$$p_T^j > 20 \text{ GeV}, \quad p_T^\ell > 10 \text{ GeV},$$
$$|\eta^j| < 5, \quad |\eta^\ell| < 2.5, \quad \Delta R^{jj} > 0.4$$

- Additional cuts:

$$\Delta\eta^{jj} > 3.5 \ \ (> 4.0 \ \text{ for } \ \ell^\pm \ell^\mp jj \not{E}_T) \ ,$$
$$50 < M_T < 150 \text{ GeV}$$

Significance Improvements

	$\ell^\pm\ell^\pm jj\not{E}_T$			$\ell^\pm\ell^\pm\ell^\mp jj\not{E}_T$			$\ell^\pm\ell^\mp jj\not{E}_T$		
Cuts	$H_5^{\pm\pm}jj$	$W^\pm W^\pm jj$	$\mathcal{S}$	$H_5^\pm jj$	$W^\pm Zjj$	$\mathcal{S}$	$H_5^0 jj$	$t\bar{t}/VVjj$	$\mathcal{S}$
Basic	3.71 (8.72)	3.48 (8.13)	13.8 (21.2)	0.61 (1.60)	45.9 (1.39×10^2)	0.89 (1.35)	1.15 (2.76)	4.39×10^3 (1.77×10^4)	0.17 (0.21)
$\Delta\eta^{jj}$	1.82 (5.68)	0.20 (0.65)	12.8 (22.6)	0.33 (0.98)	4.42 (15.6)	1.51 (2.41)	0.51 (1.42)	30.7 (1.99×10^2)	0.91 (1.00)
M_T	1.80 (5.58)	0.05 (0.12)	13.2 (23.4)	0.33 (0.98)	0.07 (0.46)	5.22 (8.17)	0.48 (1.36)	11.4 (67.4)	1.39 (1.64)
b-jet veto	- -	- -	- -	- -	- -	- -	0.48 (1.36)	1.82 (10.8)	3.16 (3.90)

100 /fb
8 TeV
(14 TeV)

TABLE I: Signal and background cross sections in units of fb after each kinematic cut, along with the significance $\mathcal{S}$ defined by Eq. (48) based on an integrated luminosity of 100 fb^{-1}. The numbers without (with) parentheses correspond to the case with a CM energy of 8 TeV (14 TeV). The signal cross section includes contributions from both the VBF production and the vactor boson associated production processes. For the $\ell^\pm\ell^\mp jj\not{E}_T$ events, we further impose the requirement of the b-jet veto for each jet to reduce the background, where the b-tagging efficiency is take to be 0.6 | ATLAS 2011

Production of H_3 Bosons

- Consider mDY processes:

$$pp \to H_5^{\pm\pm} H_3^{\mp} \to W^{\pm} W^{\pm} cs$$

$$pp \to H_5^{\pm} H_3^{\mp} \to W^{\pm} Z cs$$

$$pp \to H_5^{\pm} H_3^{0} \to W^{\pm} Z b\bar{b}$$

$$pp \to H_5^{0} H_3^{\pm} \to W^{+} W^{-} cs/ZZcs$$

$$pp \to H_5^{0} H_3^{0} \to W^{+} W^{-} b\bar{b}/ZZb\bar{b}$$

where leptonic decays of the weak gauge bosons from the H_5 decays are also assumed in this analysis.

➠ same final states as VBF and associated VBF

Distributions

- Difference between mDY and VBF is in $\Delta\eta_{jj}$ distribution.
  - In mDY process, dijets in the final state come from **3**-plet Higgs boson decays, not the external quark jets.
  - Events from mDY process concentrates in the $\Delta\eta_{jj} < 2.5$ region for all three cases.

- M_T distributions from mDY process and VBF + associated VBF are almost the same.
  $\because$ leptons plus missing transverse energy system come from the decays of H_5 in both processes
  ➠ use same M_T cut, but not $\Delta\eta_{jj}$ cut

Significance Improvements

	$\ell^\pm\ell^\pm jj\not{E}_T$				$\ell^\pm\ell^\pm\ell^\mp jj\not{E}_T$			
Cuts	$H_5^{\pm\pm}jj$	$H_5^{\pm\pm}H_3^\mp$	$W^\pm W^\pm jj$	$\mathcal{S}$	$H_5^\pm jj$	$H_5^\pm H_3^{\mp,0}$	$W^\pm Zjj$	$\mathcal{S}$
Basic	3.71 (8.72)	0.72 (1.63)	3.48 (8.13)	15.8 (24.1)	0.61 (1.60)	0.53 (1.21)	45.9 (1.39×10^2)	1.66 (2.36)
M_T	3.65 (8.57)	0.71 (1.60)	1.02 (2.20)	18.8 (28.9)	0.61 (1.60)	0.53 (1.21)	1.16 (3.42)	7.52 (11.3)

TABLE II: Signal and background cross sections in units of fb after each kinematic cut, along with the significance based on an integrated luminosity of 100 fb^{-1}. The numbers without (with) parentheses correspond to the case with a CM energy of 8 TeV (14 TeV).

100 /fb
8 TeV
(14 TeV)

- BR's of $H_3^\pm \to cs$ and $H_3^0 \to bb$ are ~30% and 90%, respectively.
  ➠ trilepton events mainly come from $H_5^\pm H_3^0$ production

Dijet Invariant Mass

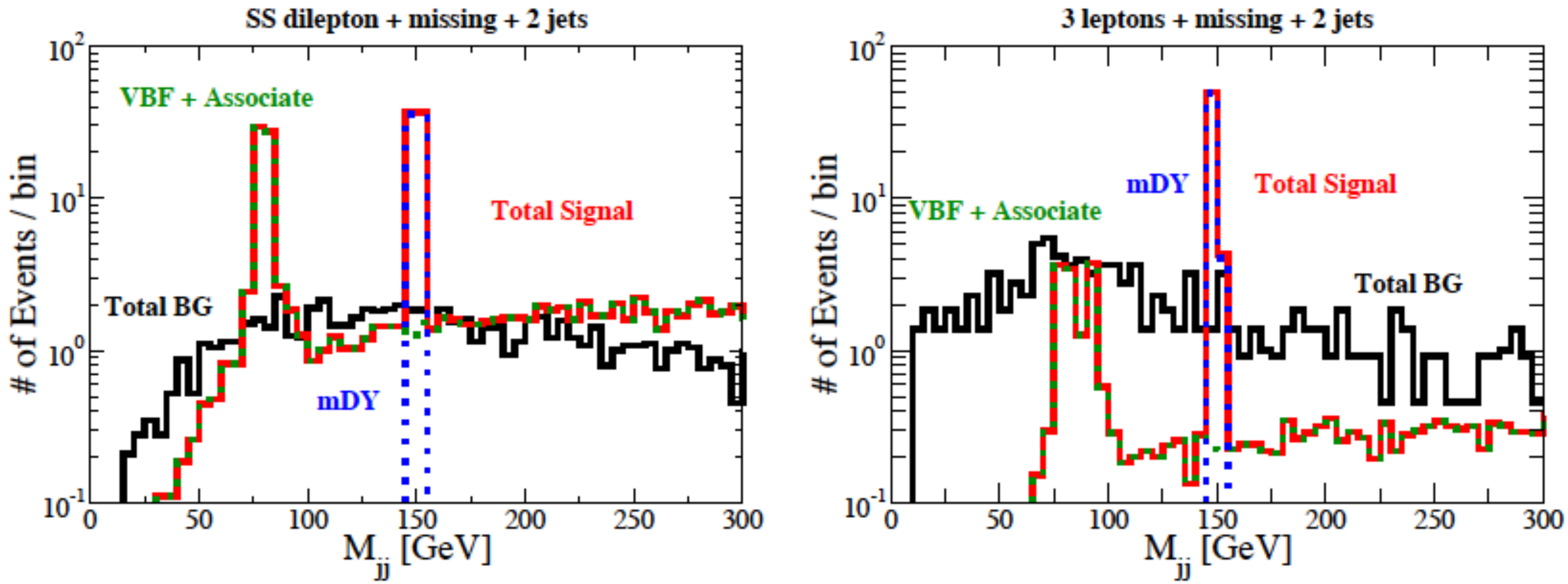
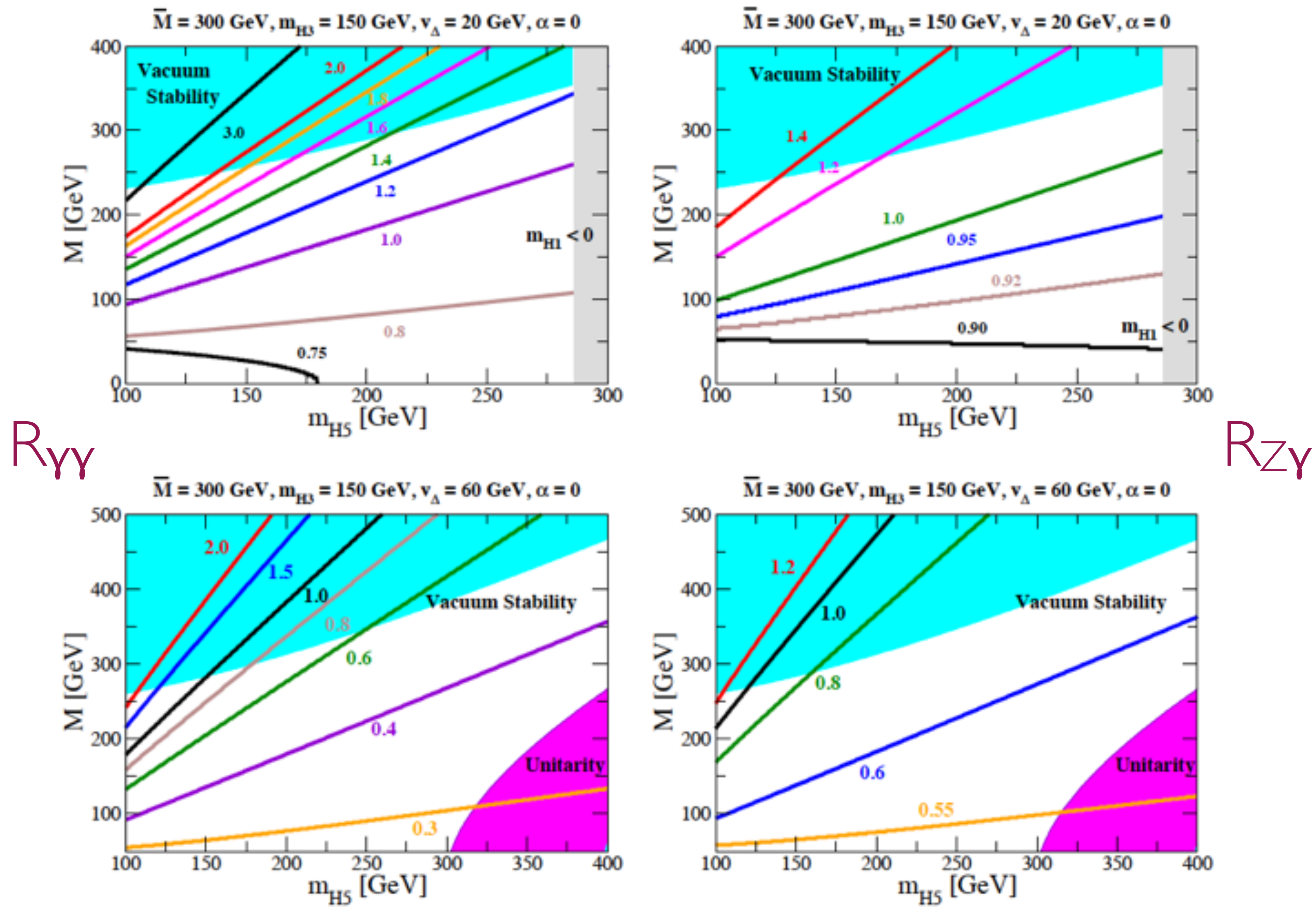


FIG. 14: Invariant mass distribution for the dijets system. The bin size in this distribution is 5 GeV. The distributions for the signal events are divided into those from the VBF process and vector boson associated process (green dashed curve), the mDY process (blue dashed curve) and the sum of them (red solid curve). The integrated luminosity and the CM energy are assumed to be 100 fb^{-1} and 8 TeV, respectively.

- Mass degeneracy between $H_3^{\pm}$ and H_3^0 can be readily established from the mDY process.

$$R_{\gamma\gamma,Z\gamma} = \frac{\sigma(gg \to h)_{\mathrm{GM}} \times BR(h \to \gamma\gamma, Z\gamma)_{\mathrm{GM}}}{\sigma(gg \to h)_{\mathrm{SM}} \times BR(h \to \gamma\gamma, Z\gamma)_{\mathrm{SM}}}$$

- For larger v_Δ, $R_{\gamma\gamma,Z\gamma}$ tend to have smaller values because the hW^+W^- coupling gets smaller.



Summary

- At LHC, the GM model with custodial symmetry can be tested by observing:
  - SM-like h, a pair of $H^{\pm\pm}$, two pairs of $H^{\pm}$, one CP-odd A and three CP-even H's
  - Mass degeneracy among same $SU(2)_V$ multiplet, subject to small EM corrections at O(100 MeV)
  - **5**-plet and singlet H's couple to weak boson pairs, but not fermion pairs via usual Yukawa couplings at tree level; **3**-plet H's couple to fermion pairs, but not weak boson pairs
  - Isospin triplet VEV ~ O(10 GeV) possible
- VBF, associated VBF and mDY processes are useful for discovering and determining Higgs masses at LHC.
- Predictions for $h \to \gamma\gamma$ and $Z\gamma$ rates are estimated.