Scalar decays to $\gamma\gamma$, $Z\gamma$, and $W^\pm\gamma$ in the Georgi-Machacek model

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C. Degrande, K. Hartling, & H.E.L., to appear

Introduction

Question: How can we probe/constrain contributions to W & Z masses from vevs of higher-isospin scalars (triplets or larger)?

- Need a scalar doublet to give fermion masses
- Impose custodial symmetry to avoid ρ parameter constraints

Write $v_{\rm SM}^2 = v_\phi^2 + A v_{\rm exotic}^2 = \frac{4M_W^2}{g^2} = \frac{4M_Z^2}{g^2+g'^2}$

Doublet contrib'n to $M_{W,Z}^2$: $\cos^2\theta_H \equiv c_H^2 = v_\phi^2/v_{\rm SM}^2$
Exotic contrib'n to $M_{W,Z}^2$: $\sin^2\theta_H \equiv s_H^2 = A v_{\rm exotic}^2/v_{\rm SM}^2$
Experimental goal is to constrain s_H.

Higher-isospin scalars + custodial symmetry $\Rightarrow$ custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ required to unitarize longitudinal $VV \to VV$ scattering.

Falkowski, Rychkov & Urbano, 1202.1532 (see also Higgs Hunter's Guide)

Benchmark for higher-isospin contributions to $M_{W,Z}$:

Georgi-Machacek model   Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs bidoublet + two isospin-triplets in a bitriplet:

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

Global SU(2)$_L \times$SU(2)$_R$ $\rightarrow$ preserves custodial symmetry (for $\rho = 1$)

Physical spectrum:

Bidoublet: $2 \times 2 \rightarrow 3 + 1$ Bitriplet: $3 \times 3 \rightarrow 5 + 3 + 1$

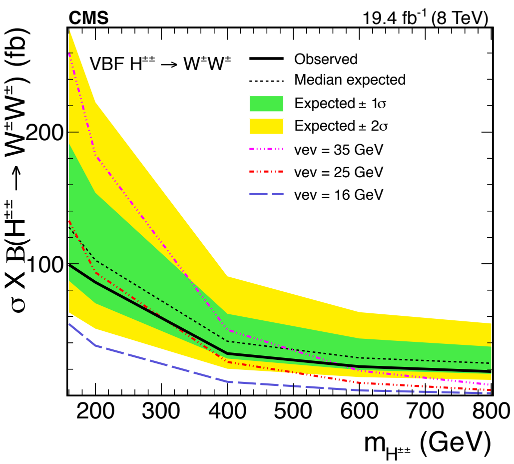
- Two custodial singlets mix $\rightarrow$ h^0, H^0
  Usually $h^0 = h(125)$

- Two custodial triplets mix $\rightarrow$ (H_3^+, H_3^0, H_3^-) + Goldstones
  Phenomenology very similar to $H^\pm, A^0$ in 2HDM Type I, $\tan\beta \rightarrow \cot\theta_H$

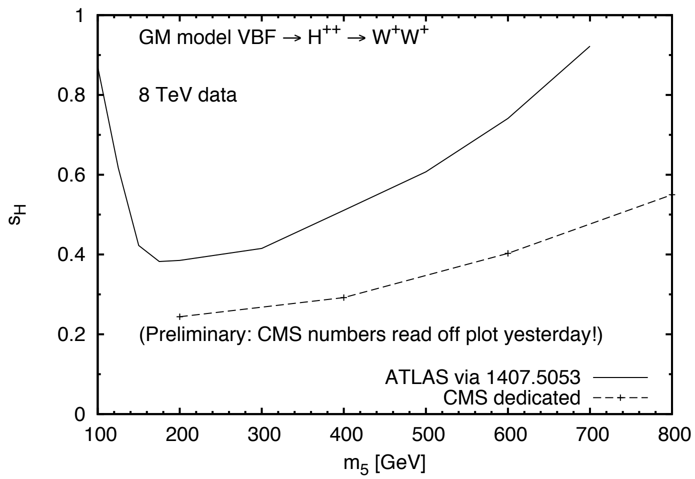
- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$
  Fermiophobic; H_5VV couplings $\propto s_H \equiv \sqrt{8} v_\chi / v_{SM}$

Constraints from direct searches in VBF:

VBF $H_5^{\pm\pm} \to W^\pm W^\pm \to \ell^\pm \ell^\pm$ + MET:

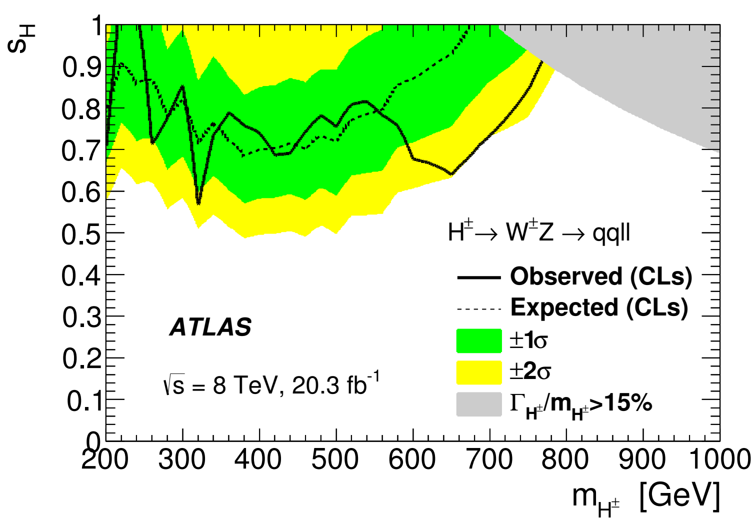


CERN-PH-EP-2014-250

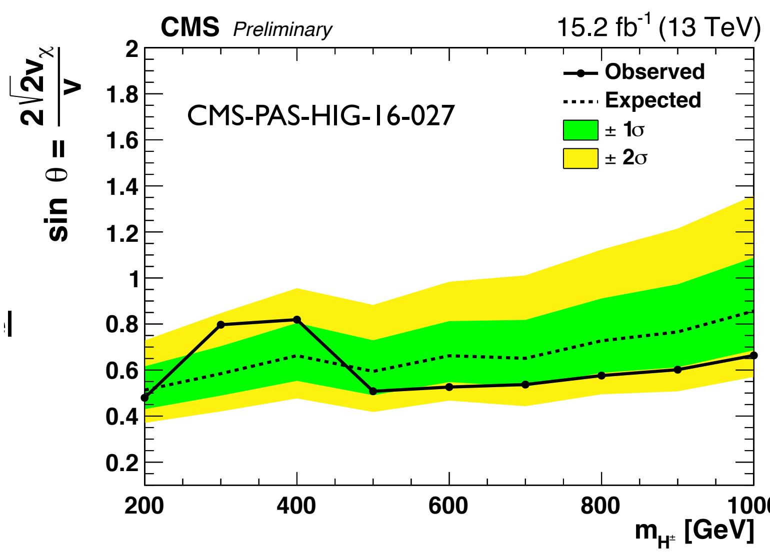


ATLAS 1405.6241 8 TeV VBF $\to W^\pm W^\pm$ xsec, theorist recast by Chiang, Kanemura, Yagyu, 1407.5053

VBF $H_5^\pm \to W^\pm Z \to qq\ell\ell$ (ATLAS), 3ℓ + MET (CMS)



ATLAS 1503.04233



CMS-PAS-HIG-16-027

Constraints from direct searches in pair production:

Constraint on $pp \to H^{\pm\pm}H^{\mp\mp} + H^{\pm\pm}H^{\mp}$ in Higgs Triplet Model from recasting ATLAS like-sign dimuons search ATLAS, 1412.0237

Kanemura, Kikuchi, Yagyu & Yokoya, 1412.7603

Adapt to GM model using cross section relations:

$\Rightarrow$ $m_5 > 76$ GeV, independent of s_H HEL & Rentala, 1502.01275

assuming no decays $H_5^{\pm\pm} \to H_3^{\pm}W^{\pm}$

Constraint on $e^+e^- \to H_3^+H_3^-$ in Type-I 2HDM LEP, hep-ex/0107031

$m_3 > 78.6$ GeV assuming no decays $H_3 \to H_5 V$

$\Rightarrow$ take $m_3 > 76$ GeV also ($m_5 > 76$ GeV guarantees no competing decays)

For H_5 masses below VV threshold:

- Tree-level decays are kinematically suppressed.
- H_5 is fermiophobic so $H_5 \to f\bar{f}$ is absent.

$\to$ Loop decays involving photon(s) can become important.

$H_5^0 \to \gamma\gamma, Z\gamma$ Nice clean signatures!

$H_5^0 \to \gamma\gamma$: constraint from LEP at low mass!

$H_5^\pm \to W^\pm\gamma$ $\to$ Want accurate prediction of BRs.

($H_5^{\pm\pm} \to W^\pm W^\pm$ always due to charge conservation)

The calculation:

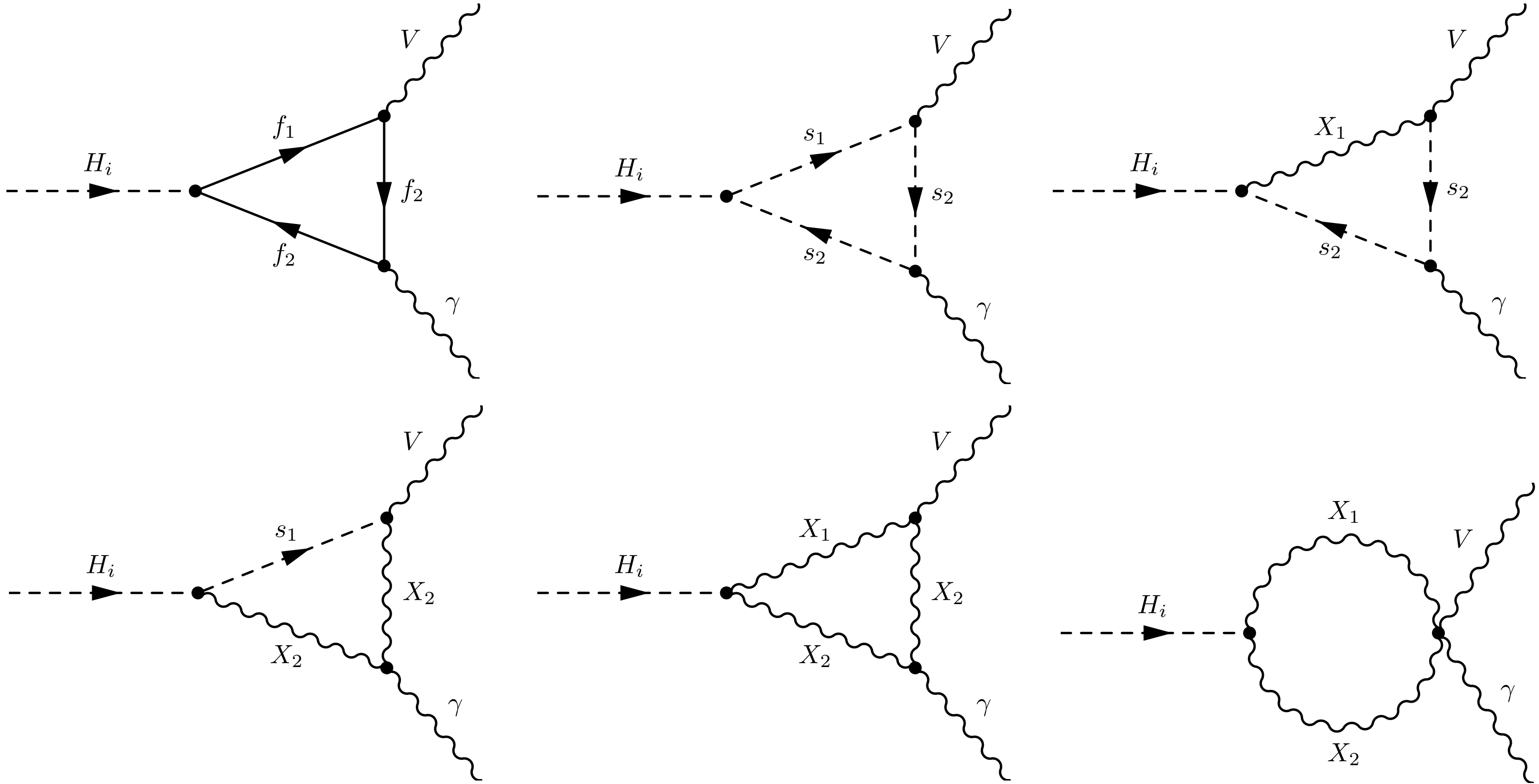
- $H_5^0 \to \gamma\gamma$ is completely standard (due to EM gauge invariance)
- $H^\pm \to W^\pm\gamma$ was calculated in 2HDM by Ilisie & Pich, 1405.6639

- In GM model there are new contributions to $H_5^0 \to Z\gamma$ and $H_5^\pm \to W^\pm\gamma$ that have not appeared in the literature.

Differences are due to tree-level H_5VV vertex and $m_3 \neq m_5$.

Need $H_5^0 \to Z\gamma$ calculation to ensure correct BR($H_5^0 \to \gamma\gamma$).

Feynman diagrams:



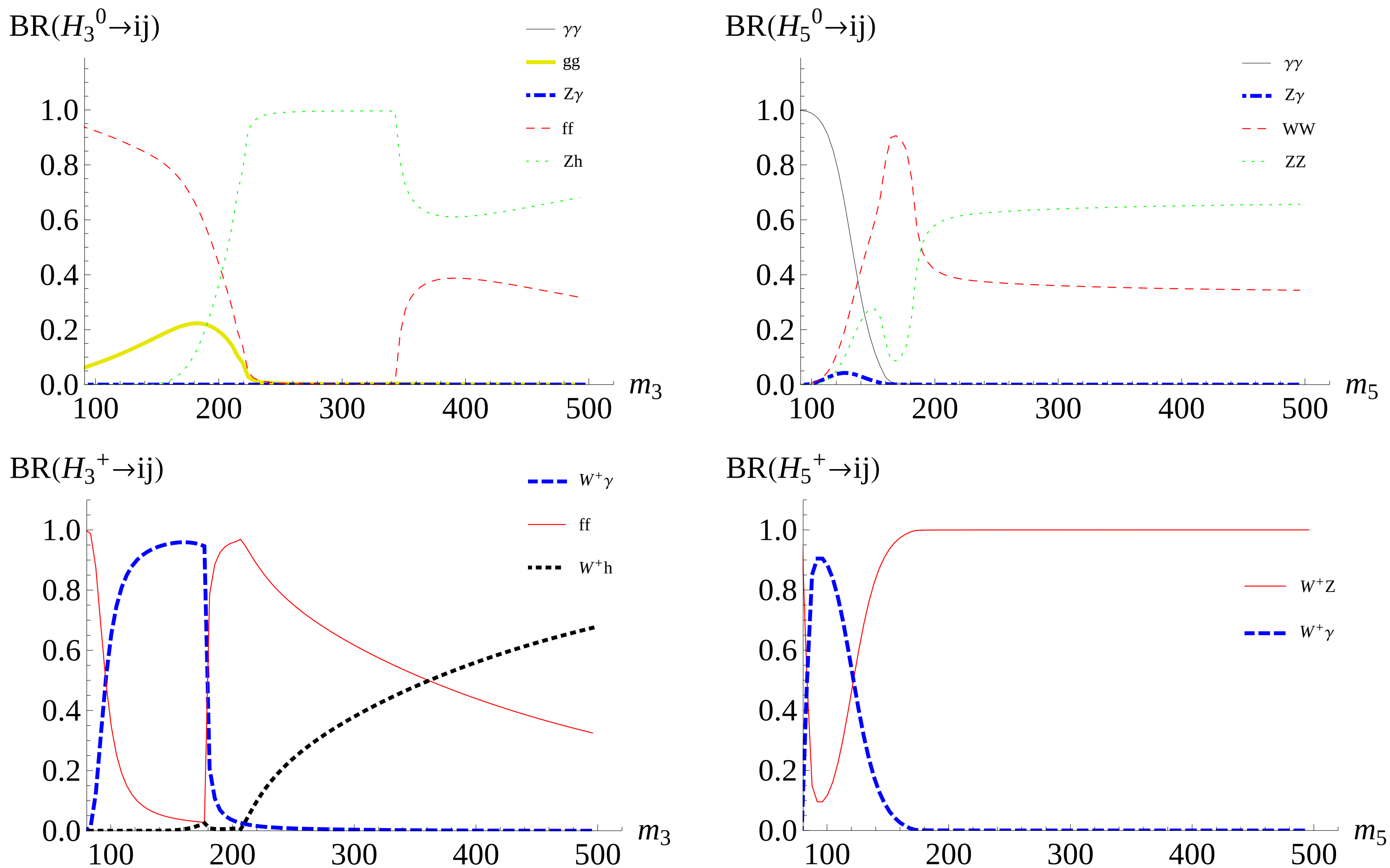
Calculated in Ilisie & Pich: 1st diagram; 2nd for $m_{H_i} = m_{s_2}$; 4th for $M_{X_2} = M_V$

We computed these in two ways:

- By hand in Unitarity gauge, then did the Feynman parameter integrals numerically in Mathematica;
- By hand in 't Hooft-Feynman gauge, then expressed results in terms of LoopTools functions and implemented in Fortran.

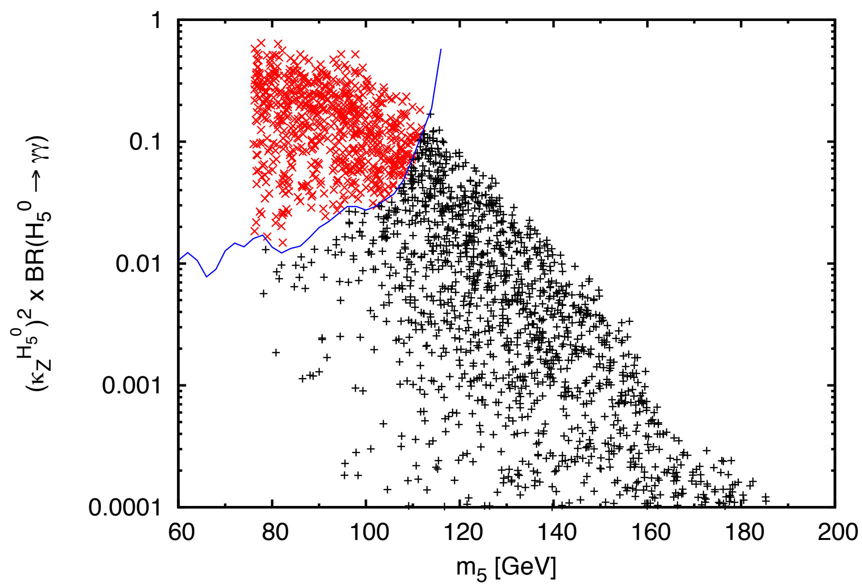
LoopTools: Hahn & Perez-Victoria, hep-ph/9807565

Results: branching ratios for two benchmark lines



Varying m_3 or m_5 while holding all other masses and relevant couplings fixed: $s_H = 0.069$, other new-scalar masses ≈500 GeV.

Results: Exclusion from LEP fermiophobic Higgs $\to \gamma\gamma$ search



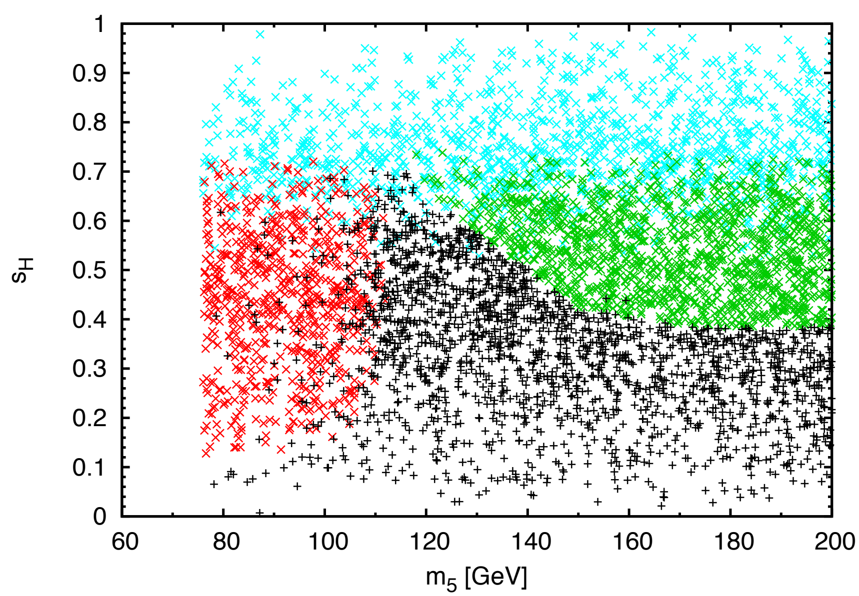
Limit on $e^+e^- \to ZH_5^0$, $H_5^0 \to \gamma\gamma$

LHWG Note 2002-02,

excl from HiggsBounds 4.2.0

Bechtle et al, 1507.06706

(red points excluded)



Exclusion in m_5–s_H plane:

cyan by $b \to s\gamma$ SuperIso + 2HDMC,

green by $H_5^{\pm\pm} \to W^\pm W^\pm$ ATLAS,

red by LEP $H_5^0 \to \gamma\gamma$.

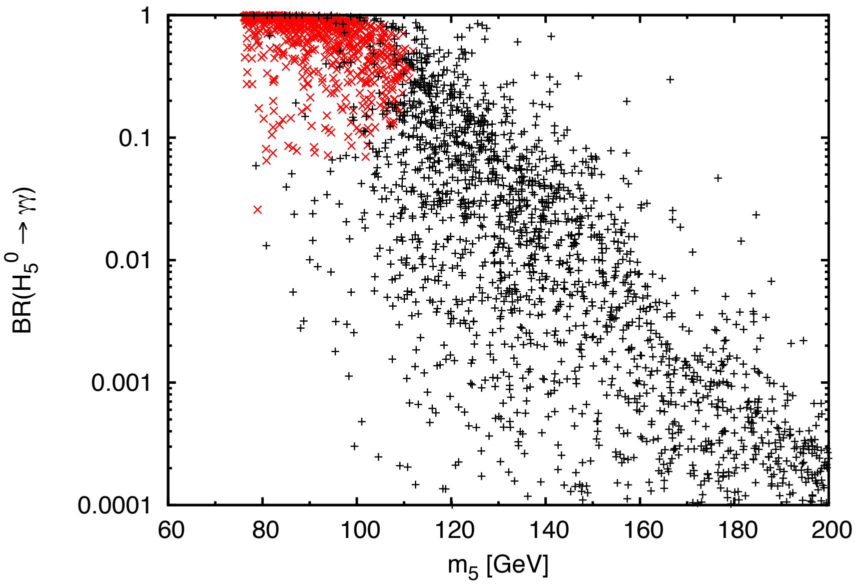
Black points are allowed.

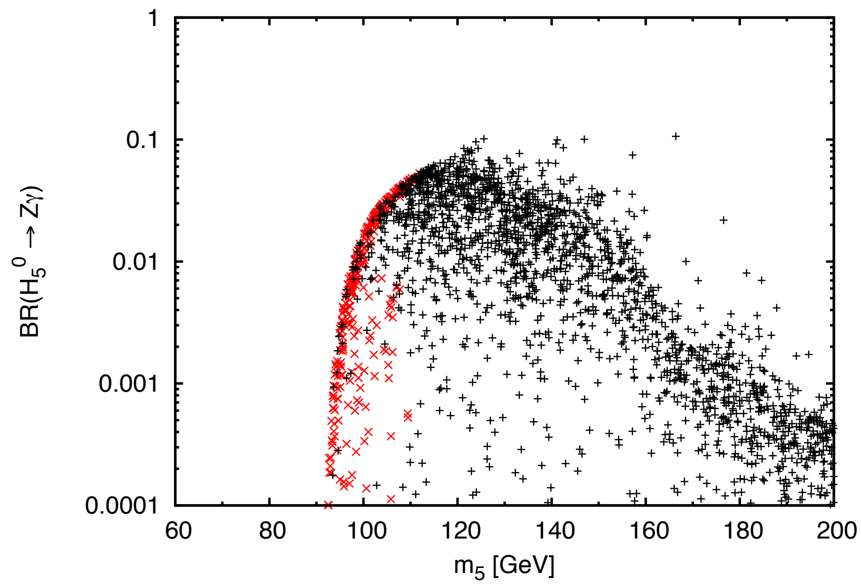
Scans based on GMCALC 1.2.0

Hartling, Kumar & HEL, 1412.7387

Results: Remaining allowed BR($H_5^0 \to \gamma\gamma, Z\gamma$)

Red points excluded by LEP $e^+e^- \to ZH_5^0$, $H_5^0 \to \gamma\gamma$

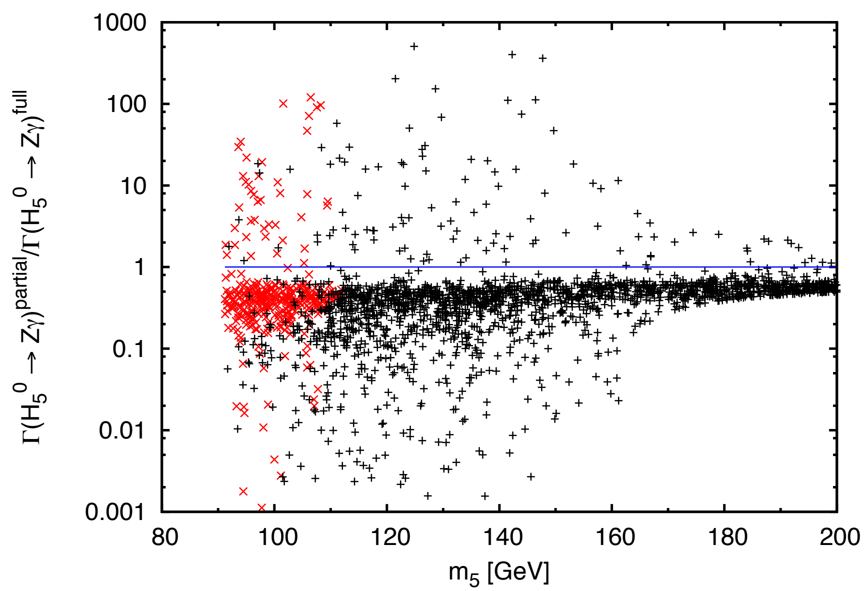




For $m_5 \sim$ 110–160 GeV:

$\gamma\gamma$: BR>10% possible, >1% likely

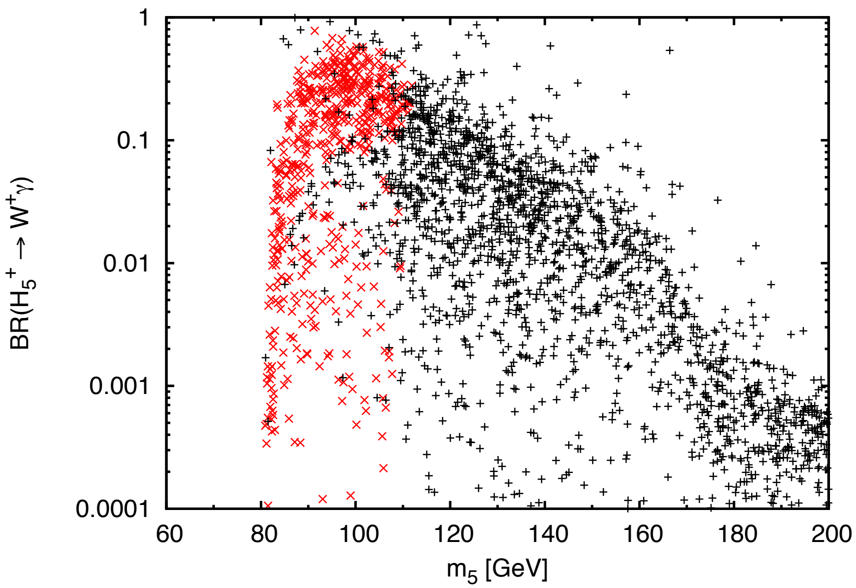
$Z\gamma$: BR>1% likely



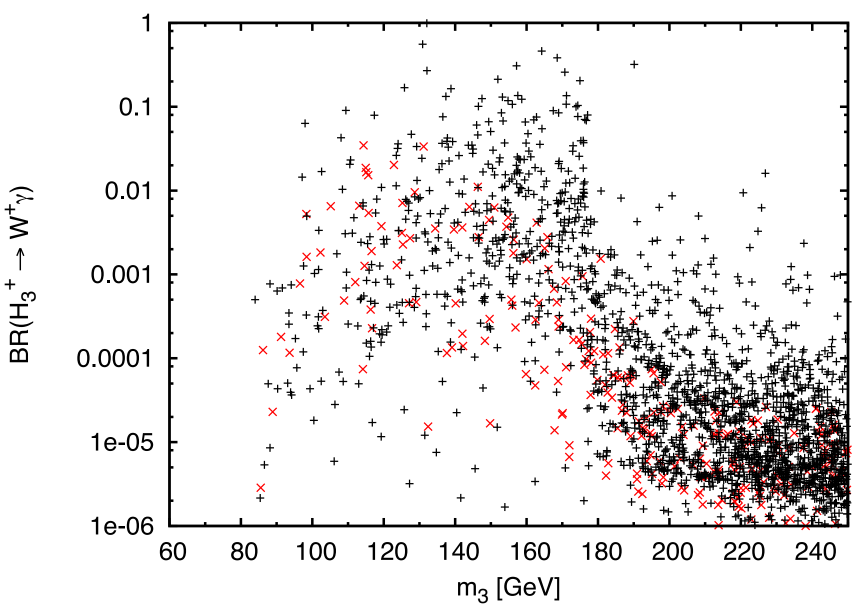
New diagrams important for accurate $\Gamma(H_5^0 \to Z\gamma)$ calculation!

Results: Remaining allowed BR($H^{\pm}_{5,3} \to W^{\pm}\gamma$)

Red points excluded by LEP $e^+e^- \to ZH^0_5$, $H^0_5 \to \gamma\gamma$



$H^{\pm}_5 \to W^{\pm}\gamma$:
lots of points with BR>1%
below WZ threshold
($m_5 \sim$ 110–170 GeV).



$H^{\pm}_3 \to W^{\pm}\gamma$: generally small BR
due to competition with $\bar{f}f$.
A few points with BR $\gtrsim$ 1%.

Summary & Outlook

We computed $H_i \to V\gamma$ in the Georgi-Machacek model.
- This involved evaluating some new 1-loop diagrams.
- Results will be given in terms of LoopTools functions.
- Results will be implemented in a future release of GMCALC.

Useful for experimental searches for H_5^0 and $H_5^\pm$ for masses below ~160 GeV in $\gamma\gamma$, $Z\gamma$ and $W^\pm\gamma$ modes.

Need $H_5^0 \to Z\gamma$ calculation to ensure correct BR($H_5^0 \to \gamma\gamma$)

Interesting production modes: VBF $\to H_5$; $pp \to H_5 H_5$

$pp \to H_5 H_5$ xsec depends on gauge couplings only; no s_H suppression.

BACKUP

Probe of contribution to EWSB from isospin triplets or larger:
Custodial fiveplet $H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--}$

Same phenomenology for higher-isospin custodial-sym models

HEL & V. Rentala, 1502.01275

H_5VV couplings:

$$H_5^0 W_\mu^+ W_\nu^- : \qquad -i\frac{2M_W^2}{v_{SM}}\frac{s_H}{\sqrt{3}}g_{\mu\nu},$$

$$H_5^0 Z_\mu Z_\nu : \qquad i\frac{2M_Z^2}{v_{SM}}\frac{2}{\sqrt{3}}s_H g_{\mu\nu},$$

$$H_5^+ W_\mu^- Z_\nu : \qquad -i\frac{2M_W M_Z}{v_{SM}}s_H g_{\mu\nu},$$

$$H_5^{++} W_\mu^- W_\nu^- : \qquad i\frac{2M_W^2}{v_{SM}}\sqrt{2}s_H g_{\mu\nu},$$

H_5VV couplings fixed by $VV \to VV$ unitarization sum rule:

$$(\kappa_V^h)^2 + (\kappa_V^H)^2 - \frac{5}{3}s_H^2 = 1$$

Falkowski, Rychkov & Urbano, 1202.1532 (see also Higgs Hunter's Guide)

(relies on custodial symmetry in scalar sector)