Searching for the $W\gamma$ decay of a charged Higgs boson

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Based on HEL & Yongcheng Wu, arXiv:1809.09127

Outline

Introduction

$H^{\pm} \to W^{\pm}\gamma$ calculation and effective vertex

Concrete implementation: Georgi-Machacek model

LHC collider study & results

Conclusions

Introduction

Why charged Higgs:

SEVENTH INTERNATIONAL WORKSHOP
cH±arged 2018

Charged Higgs searches up to now:

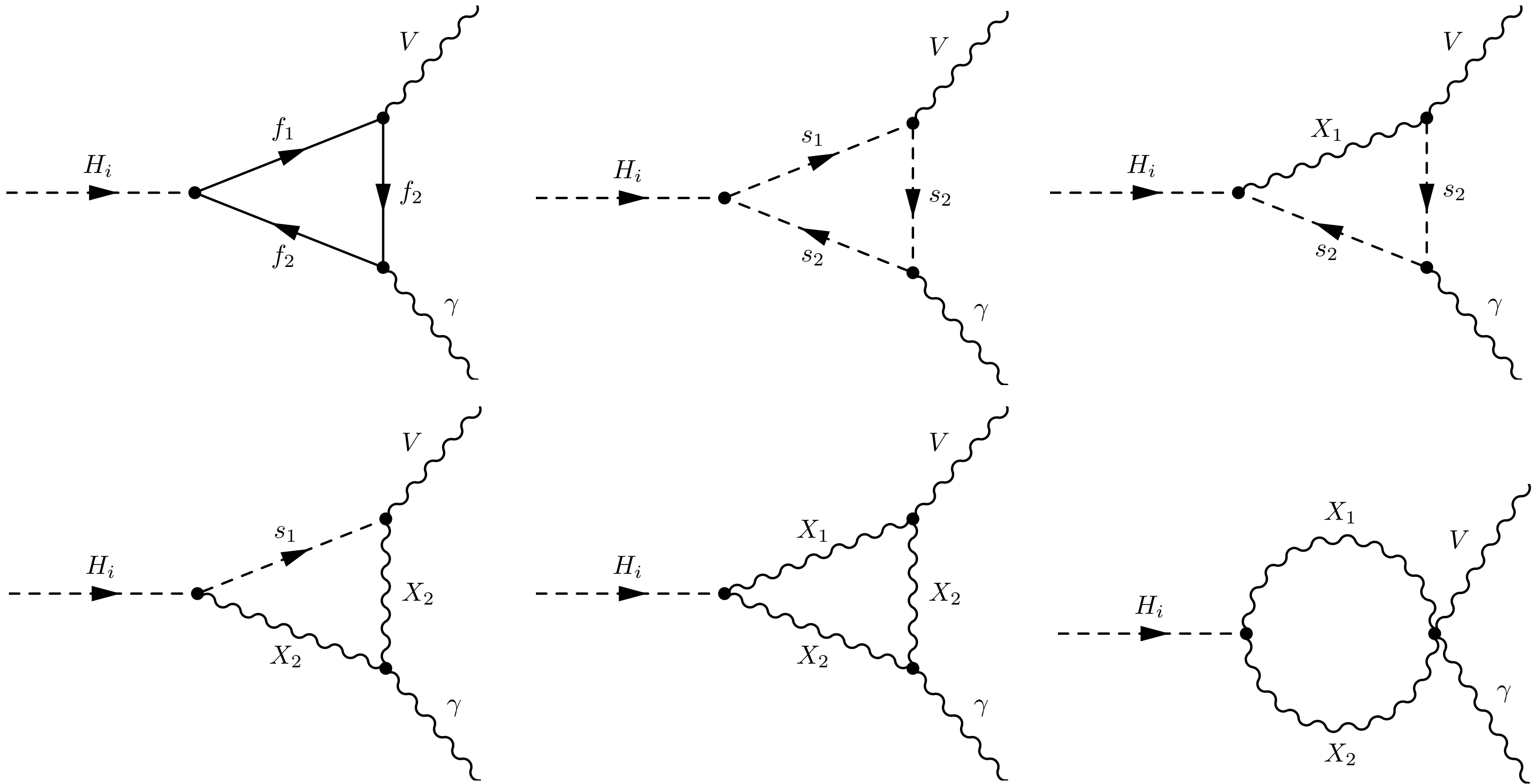
Fermiophilic:
- Production via tbH^+ coupling, decays to fermions
- Production in decays of heavier Higgs (2HDM $H/A \to H^+W^-$) (proposed)

Fermiophobic:
- VBF production of $H^\pm$, decays to $W^\pm Z$

This talk:
- Loop-induced decay $H^\pm \to W^\pm\gamma$

Loop calculations for $H^+ \to W^+\gamma$

2HDM/MSSM: Arhrib, Benbrik & Chabab, hep-ph/0607182
Stealth Doublet model: Enberg, Rathsman & Wouda, 1311.4367
Aligned 2HDM: Ilisie & Pich, 1405.6639
Georgi-Machacek model: Degrande, Hartling & HEL, 1708.08753



Most interesting when $H^\pm$ is fermiophobic and light ($< M_W + M_Z$)

One-loop effective vertex

2 form factors: S (scalar) and $\tilde{S}$ (pseudoscalar)

$\mathcal{M} = \Gamma^{\mu\nu} \varepsilon_\nu^{W*}(k) \varepsilon_\mu^{\gamma*}(q)$, $\quad \Gamma^{\mu\nu} = (g^{\mu\nu} k \cdot q - k^\mu q^\nu) S + i\epsilon^{\mu\nu\alpha\beta} k_\alpha q_\beta \tilde{S}$

In a CP-conserving theory:
S: from fermion, scalar, gauge, & mixed gauge/scalar loops
$\tilde{S}$: only from fermion loop Fermiophobic $H^\pm \Rightarrow \tilde{S} = 0$

Decay width:

$$\Gamma(H^+ \to W^+ \gamma) = \frac{m_{H^+}^3}{32\pi} \left[1 - \frac{m_W^2}{m_{H^+}^2} \right]^3 \left[|S|^2 + |\tilde{S}|^2 \right],$$

Experimentally, we'll look for $W \to \ell\nu$.

$\Rightarrow$ Information about W polarization in angular distribution of ℓ relative to γ

One-loop effective vertex & kinematic shapes

2 form factors: S (scalar) and $\tilde{S}$ (pseudoscalar)

$$\mathcal{M} = \Gamma^{\mu\nu} \varepsilon_\nu^{W*}(k) \varepsilon_\mu^{\gamma*}(q), \qquad \Gamma^{\mu\nu} = (g^{\mu\nu} k \cdot q - k^\mu q^\nu) S + i\epsilon^{\mu\nu\alpha\beta} k_\alpha q_\beta \tilde{S}$$

Differential distribution:

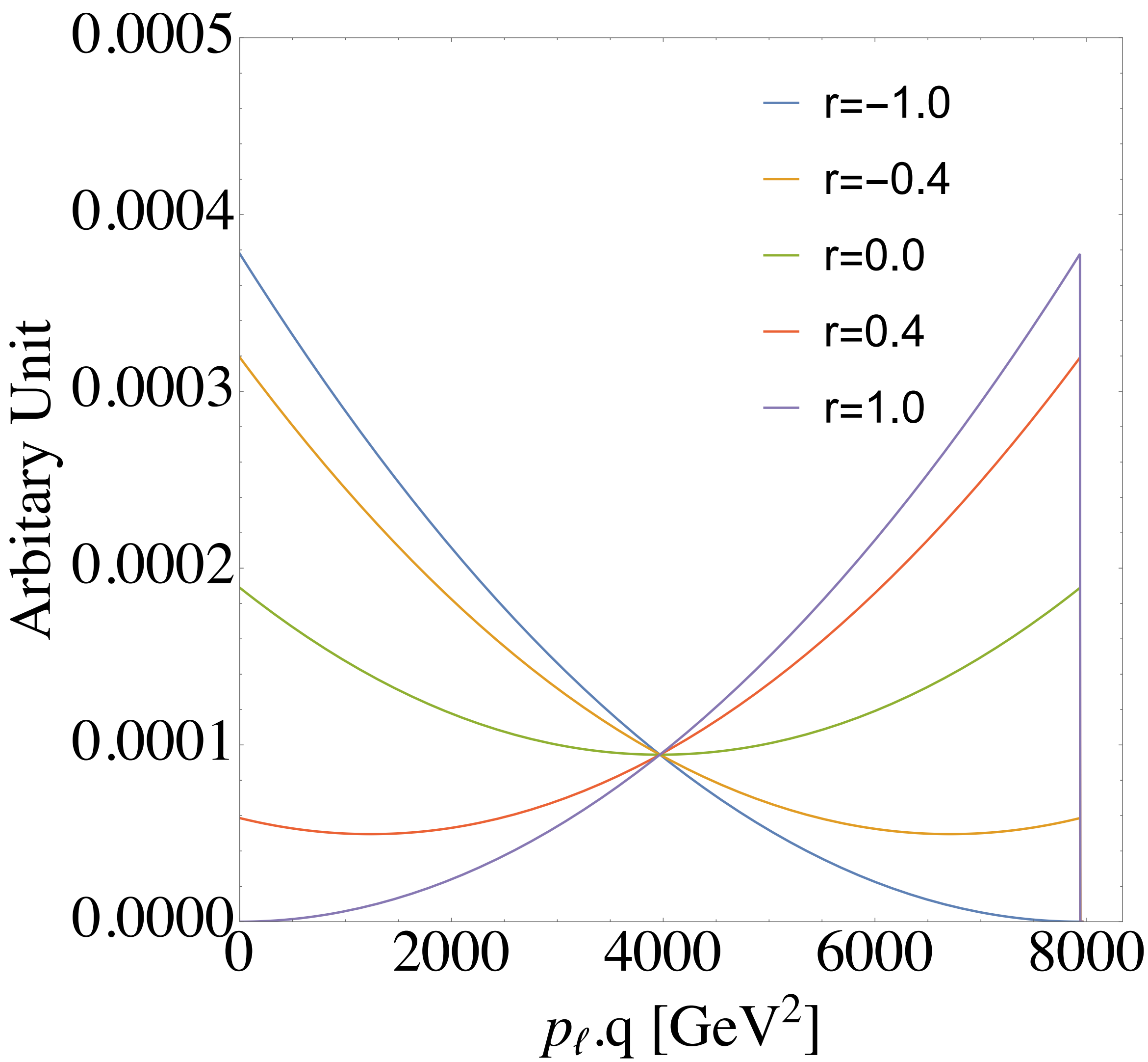
$$\begin{aligned} |\mathcal{M}|^2 &\propto \Gamma^{\mu\nu} \Gamma^{\rho\sigma*} \varepsilon_\mu^{\gamma*} \varepsilon_\rho^{\gamma} \, \textbf{Tr}(\not{p}_\nu \gamma_\sigma P_L \not{p}_\ell \gamma_\nu) \\ &= \frac{m_W^2}{2} \Big\{ 8(p_\ell \cdot q)^2 \left[|S|^2 + |\tilde{S}|^2 \right] \\ &\quad -4(p_\ell \cdot q)(m_{H+}^2 - m_W^2) \left[|S|^2 + |\tilde{S}|^2 - 2\textbf{Re}(S\tilde{S}^*) \right] \\ &\quad +(m_{H+}^2 - m_W^2)^2 \left[|S|^2 + |\tilde{S}|^2 - 2\textbf{Re}(S\tilde{S}^*) \right] \Big\} \end{aligned}$$

Define $\qquad r \equiv \dfrac{\tilde{S}}{S}, \qquad K \equiv \dfrac{p_\ell \cdot q}{(m_{H+}^2 - m_W^2)/2} \in [0,1]$

$$|\mathcal{M}|^2 \propto 2K^2 \left[1 + |r|^2 \right] + (-2K + 1) \left[1 + |r|^2 - 2\textbf{Re}(r) \right]$$

Parabola in $K \propto p_\ell \cdot q$, shape depends on r

One-loop effective vertex & kinematic shapes



$m_{H^+} = 150$ GeV

(changing m_{H^+} just rescales x axis)

Fermiophobic H^+
$\Rightarrow r = 0$

Concrete implementation: Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs (bi-)doublet + triplets $(1,0)+(1,1)$ in a bi-triplet:

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

Global $SU(2)_L \times SU(2)_R \to$ custodial symmetry $\langle \chi^0 \rangle = \langle \xi^0 \rangle \equiv v_\chi$

(ensures $\rho = 1$)

Most general scalar potential invariant under $SU(2)_L \times SU(2)_R$:

$$\begin{aligned} V(\Phi, X) = \; & \frac{\mu_2^2}{2} \mathrm{Tr}(\Phi^\dagger \Phi) + \frac{\mu_3^2}{2} \mathrm{Tr}(X^\dagger X) + \lambda_1 [\mathrm{Tr}(\Phi^\dagger \Phi)]^2 \\ & + \lambda_2 \mathrm{Tr}(\Phi^\dagger \Phi) \mathrm{Tr}(X^\dagger X) + \lambda_3 \mathrm{Tr}(X^\dagger X X^\dagger X) \\ & + \lambda_4 [\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5 \mathrm{Tr}(\Phi^\dagger \tau^a \Phi \tau^b) \mathrm{Tr}(X^\dagger t^a X t^b) \\ & - M_1 \mathrm{Tr}(\Phi^\dagger \tau^a \Phi \tau^b)(U X U^\dagger)_{ab} - M_2 \mathrm{Tr}(X^\dagger t^a X t^b)(U X U^\dagger)_{ab} \end{aligned}$$

9 parameters, 2 fixed by G_F and $m_h \to$ 7 free parameters. Aoki & Kanemura, 0712.4053

Chiang & Yagyu, 1211.2658; Chiang, Kuo & Yagyu, 1307.7526

Hartling, Kumar & HEL, 1404.2640

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Global $\text{SU}(2)_L \times \text{SU}(2)_R \to$ custodial symmetry $\langle \chi^0 \rangle = \langle \xi^0 \rangle \equiv v_\chi$

Physical spectrum:

Bi-doublet: $2 \otimes 2 \to 1 \oplus 3$ Bi-triplet: $3 \otimes 3 \to 1 \oplus 3 \oplus 5$

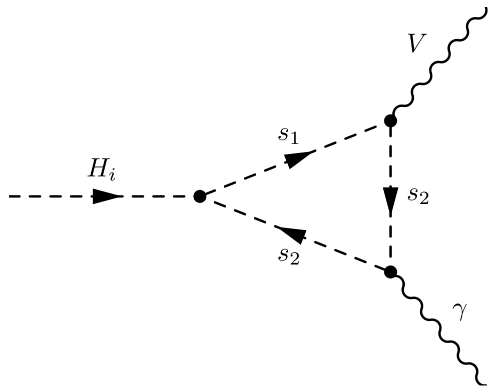
- Two custodial singlets mix $\to h^0$, H^0 m_h, m_H, angle α
  Usually identify $h^0 = h(125)$

- Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ m_3 + Goldstones
  Phenomenology very similar to $H^\pm, A^0$ in 2HDM Type I, $\tan\beta \to \cot\theta_H$

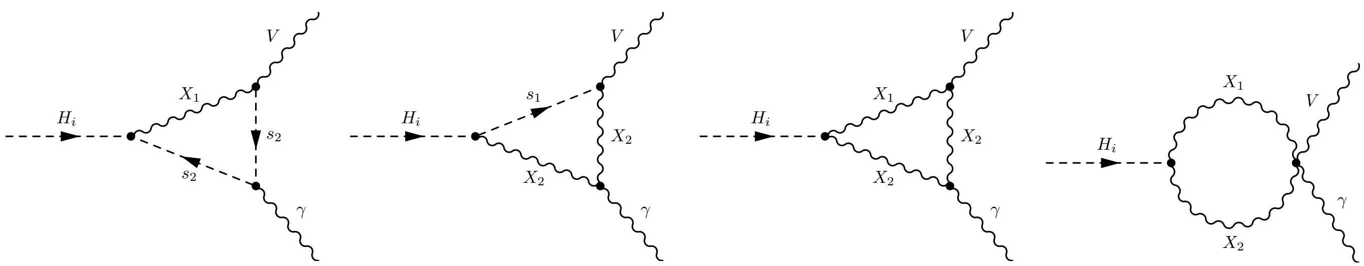
- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ m_5
  Fermiophobic! H_5VV couplings $\propto s_H \equiv \sqrt{8} v_\chi / v_{\text{SM}}$
  $s_H^2 \equiv$ exotic fraction of M_W^2, M_Z^2

$H_5^+ \to W^+\gamma$ in Georgi-Machacek model

Degrande, Hartling & HEL, 1708.08753



$\propto M_2$ when $s_H \ll 1$



$\propto s_H$

Competing decay: $H_5^+ \to W^+ Z$ coupling $\propto s_H$.

So the most interesting model parameters are m_5, s_H, and M_2.

Choice of benchmark

9 Lagrangian parameters: μ_2^2, μ_3^2, λ_1, λ_2, λ_3, λ_4, λ_5, M_1, M_2

Can re-express as: G_F, m_h, m_H, m_3, m_5, s_H, $\sin\alpha$, M_1, M_2

- Fix G_F and $m_h = 125$ GeV

- Keep m_5, s_H, and M_2 as variable parameters

- Fix the remaining 4 parameters as follows:

$$m_3^2 = m_5^2 + \delta m^2 \qquad \delta m^2 = (300 \text{ GeV})^2$$

$$m_H^2 = m_5^2 + \tfrac{3}{2}\delta m^2 + \kappa_H v^2 s_H^2 \qquad \kappa_H = -m_5/(100 \text{ GeV})$$

$$M_1 = s_H \left[\frac{\sqrt{2}}{v}\left(m_5^2 + \tfrac{3}{2}\delta m^2\right) + 3M_2 s_H + \kappa_{\lambda_3} v s_H^2\right] \qquad \kappa_{\lambda_3} = -\kappa_H^2/10$$

$$\sin\alpha = \kappa_\alpha s_H \qquad \kappa_\alpha = -0.15 - m_5/(1000 \text{ GeV})$$

Sufficient for this study: fully populates low m_5 and $s_H < 0.3$.
(Consistency with indirect & h_{125} constraints not checked yet.)

Computational tools

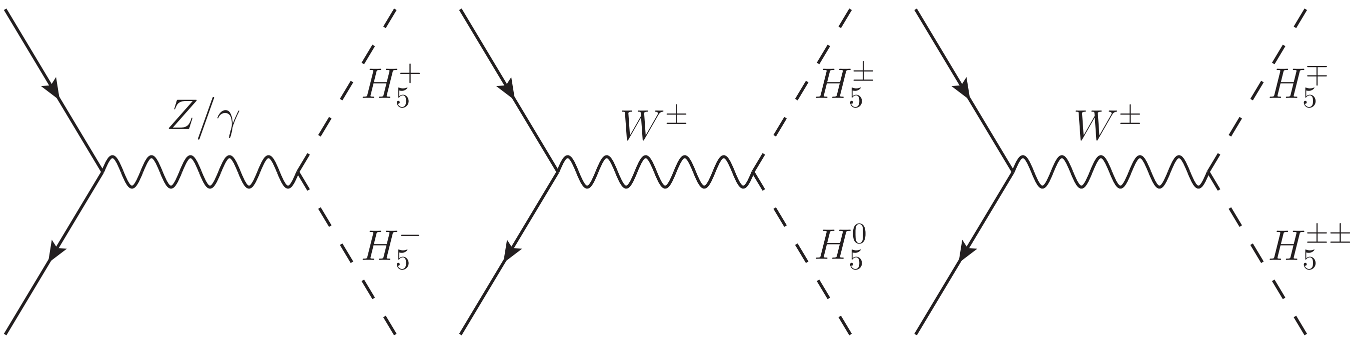
Loop-induced decays for GM model calculated in Degrande, Hartling & HEL, 1708.08753 and implemented in GMCALC 1.3.0 (uses Loop-Tools)

FeynRules implementation + UFO model file updated to include loop-induced scalar-gauge-gauge vertices in EFT approach (gg, $\gamma\gamma$, $Z\gamma$ for all neutral scalars, $W\gamma$ for all singly-charged)

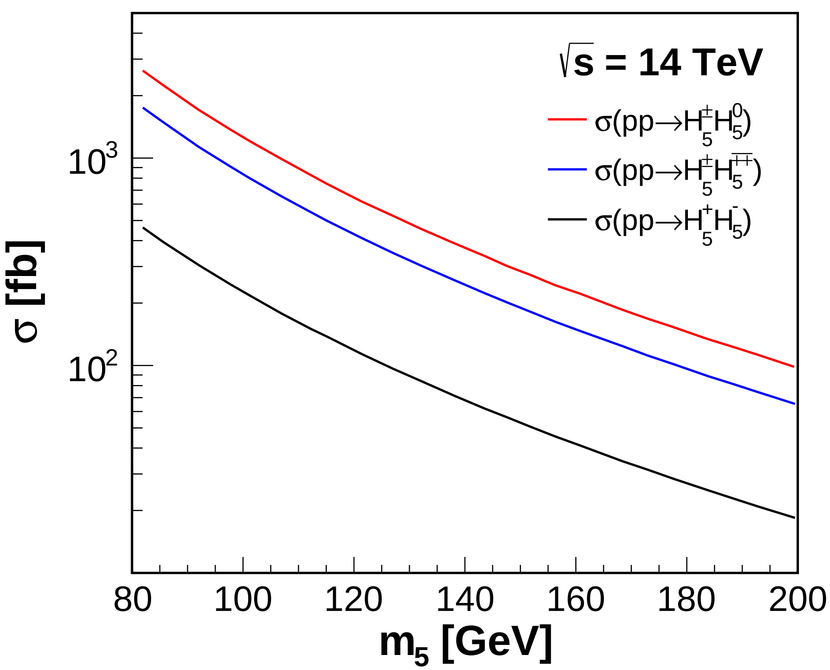
GMCALC 1.4.0: dedicated update to generate param_card.dat file including effective couplings for new EFT vertices
(also speed improvement for $H_i \to V_j^* V_k^*$, minor bug fixes)

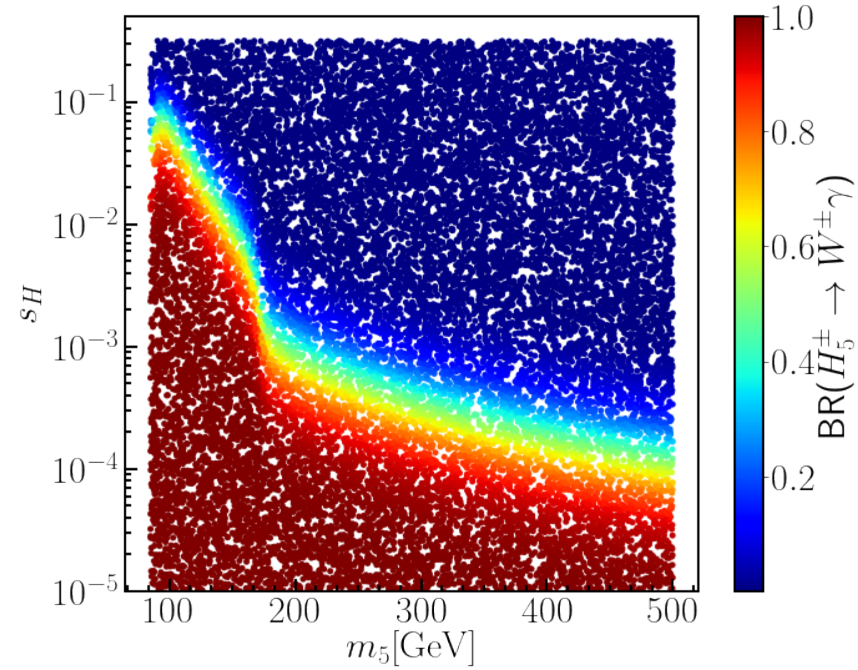
Our simulation: MadGraph5 (LO) $\to$ Pythia $\to$ Delphes

$H_5^{\pm}$ production and decays



Drell-Yan cross sections depend only on gauge couplings, m_5





LO QCD using MadGraph5, NNPDF23 $M_2 = 40$ GeV

Backgrounds:

$W^\pm\gamma$ (biggest, but killed well by cuts)

$t\bar{t}\gamma$ (biggest after cuts)

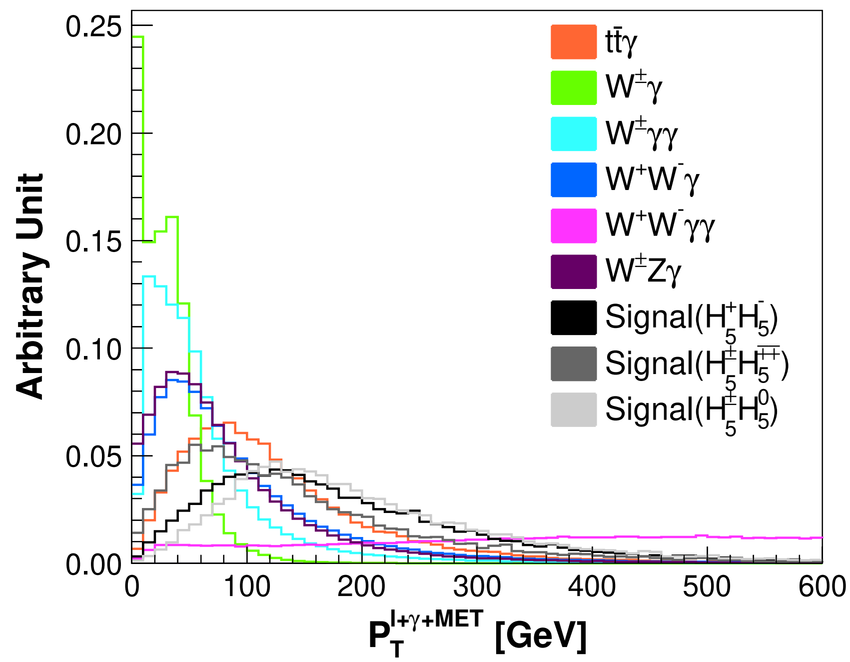
$W^+W^-\gamma$ (second biggest after cuts)

$W^+W^-\gamma\gamma$ (3rd biggest after cuts)

$W^\pm\gamma\gamma$

$W^\pm Z\gamma$

$m_5 = 150$ GeV $\rightarrow$



Cuts:

$\geq$ 1 lepton $p_T > 25$ GeV, $|\eta| < 2.5$

$\geq$ 1 photon $p_T > 25$ GeV, $|\eta| < 2.5$

$\leq$ 2 jets with $p_T > 20$ GeV

Zero jets tagged as b-jets

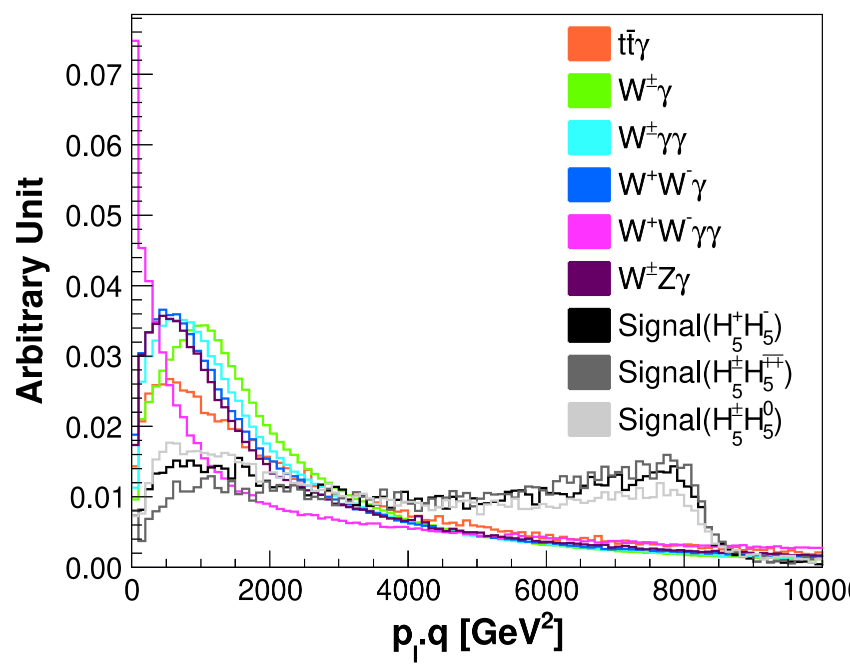
Optimize range for each mass:

MET

H_T (visible objects)

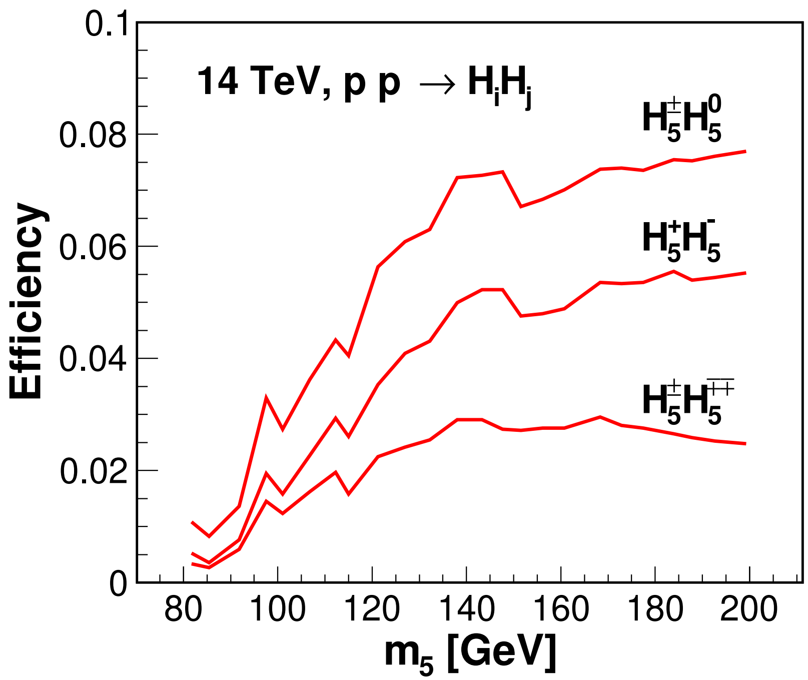
$p_T(\ell + \gamma + \text{MET})$

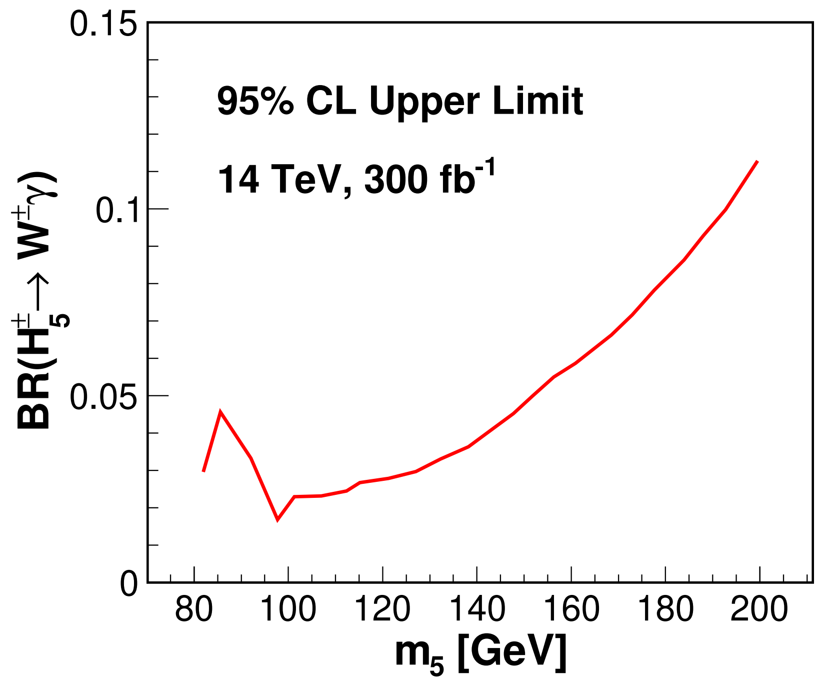
$p_\ell \cdot q$



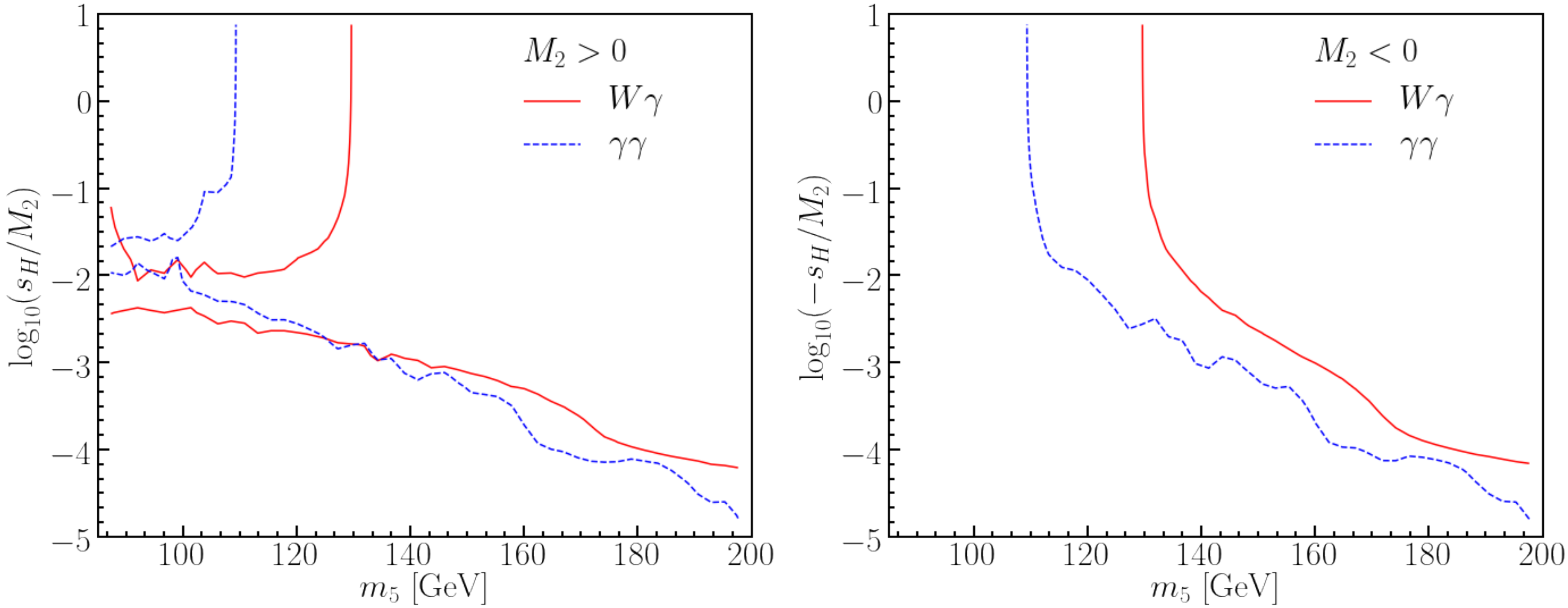
Results

$$(\sigma \times \text{BR})_{\text{Fiducial}} \equiv \epsilon_{H_5^\pm H_5^0}\sigma(pp \to H_5^\pm H_5^0)\text{BR}(H_5^\pm \to \ell^\pm \nu\gamma)$$
$$+ \epsilon_{H_5^\pm H_5^{\mp\mp}}\sigma(pp \to H_5^\pm H_5^{\mp\mp})\text{BR}(H_5^\pm \to \ell^\pm \nu\gamma)$$
$$+ \epsilon_{H_5^+ H_5^-}\sigma(pp \to H_5^+ H_5^-)\left[2\text{BR}(H_5^\pm \to \ell^\pm \nu\gamma) - \text{BR}(H_5^\pm \to \ell^\pm \nu\gamma)^2\right]$$





Results



Red: Expected 95%CL exclusion with 300 fb^{-1} at 14 TeV LHC

Note cancellation between scalar and gauge diagrams at $s_H/M_2 \sim 10^{-2}$/GeV

Blue: Existing 95%CL exclusion from diphoton resonance search

ATLAS 1407.6583, 20.3 fb^{-1} at 8 TeV

recast to constrain $pp \to H_5^0 H_5^\pm$ (LO), $H_5^0 \to \gamma\gamma$.

Conclusions

$H^\pm \to W^\pm \gamma$ is an interesting search channel for fermiophobic $H^\pm$ with mass below WZ threshold

LHC prospects are good: use distinctive $p_\ell \cdot q$ distribution.
- Exclude $m_5 \lesssim 130$ GeV for almost all s_H values with 300 fb^{-1}
- Exclude m_5 up to 200 GeV and beyond for very small s_H

Georgi-Machacek model implementation with EFT vertices for loop-induced couplings now available as UFO file for MadGraph5 (LO QCD); param_card.dat generated by GMCALC 1.4.0

Strong competition from $H^0 \to \gamma\gamma$, but only when $H^\pm$ and H^0 have the same mass (as is the case in GM model)

BACKUP SLIDES

Optimized cuts for $m_5 = 150$ GeV

72 GeV $\leq$ MET $\leq$ 220 GeV

260 GeV $< H_T <$ 620 GeV

100 GeV $< p_T(\ell + \gamma +$ MET$) <$ 420 GeV

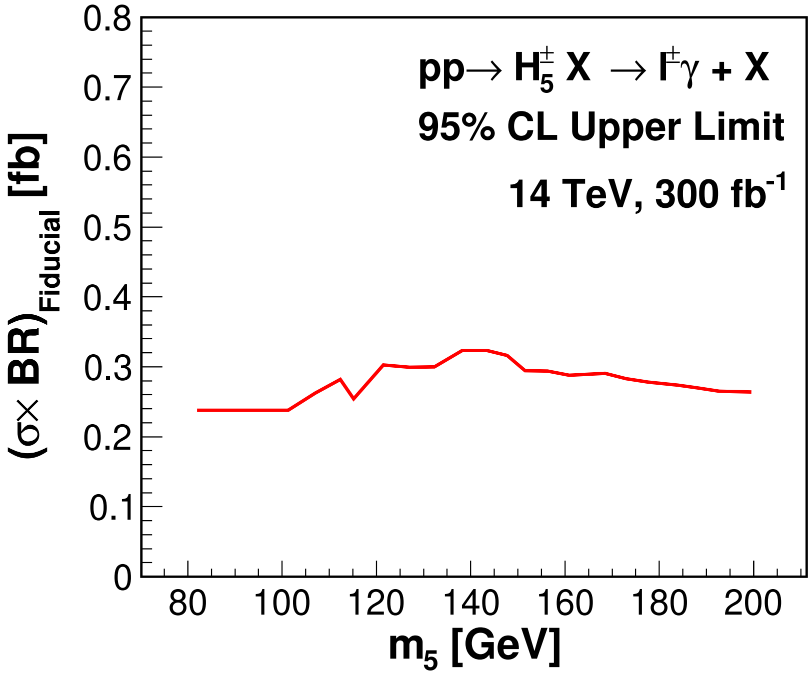
3300 GeV$^2 < p_\ell \cdot q <$ 8200 GeV^2

Signal and background cross sections before and after cuts:

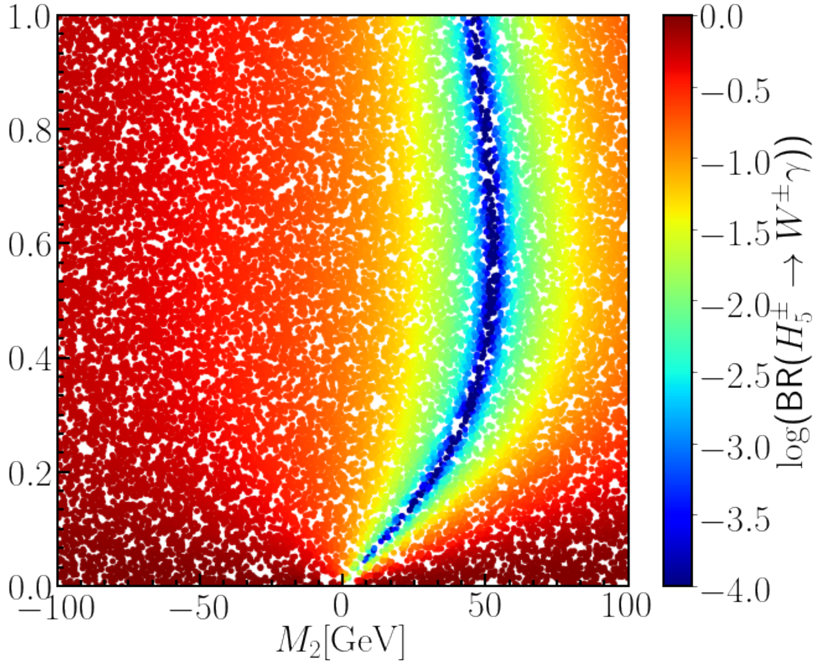
Process	$H_5^\pm H_5^0$	$H_5^\pm H_5^{\mp\mp}$	$H_5^+ H_5^-$	$t\bar{t}\gamma$	$W^\pm\gamma$	$W^\pm\gamma\gamma$	$W^+W^-\gamma$	$W^+W^-\gamma\gamma$	$W^\pm Z\gamma$
$\sigma\times$BR [fb] (before cuts)	57.29	38.19	19.07	856	23000	30	120	65	25
$\epsilon \times \sigma\times$BR [fb] (after cuts)	4.21	1.01	0.95	0.49	0.09	0.05	0.38	0.28	0.05

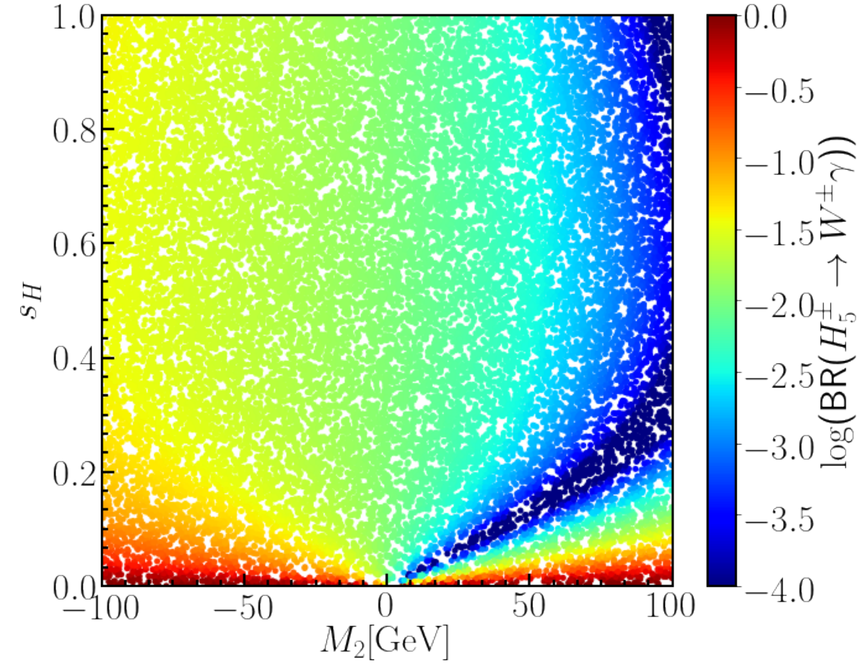
Expected upper limit on fiducial cross section

$$(\sigma \times \mathrm{BR})_{\mathrm{Fiducial}} \equiv \epsilon_{H_5^\pm H_5^0}\sigma(pp \to H_5^\pm H_5^0)\mathrm{BR}(H_5^\pm \to \ell^\pm \nu\gamma)$$
$$+ \epsilon_{H_5^\pm H_5^{\mp\mp}}\sigma(pp \to H_5^\pm H_5^{\mp\mp})\mathrm{BR}(H_5^\pm \to \ell^\pm \nu\gamma)$$
$$+ \epsilon_{H_5^+ H_5^-}\sigma(pp \to H_5^+ H_5^-)\left[2\mathrm{BR}(H_5^\pm \to \ell^\pm \nu\gamma) - \mathrm{BR}(H_5^\pm \to \ell^\pm \nu\gamma)^2\right]$$



$H_5^+ \to W^+\gamma$ branching ratio

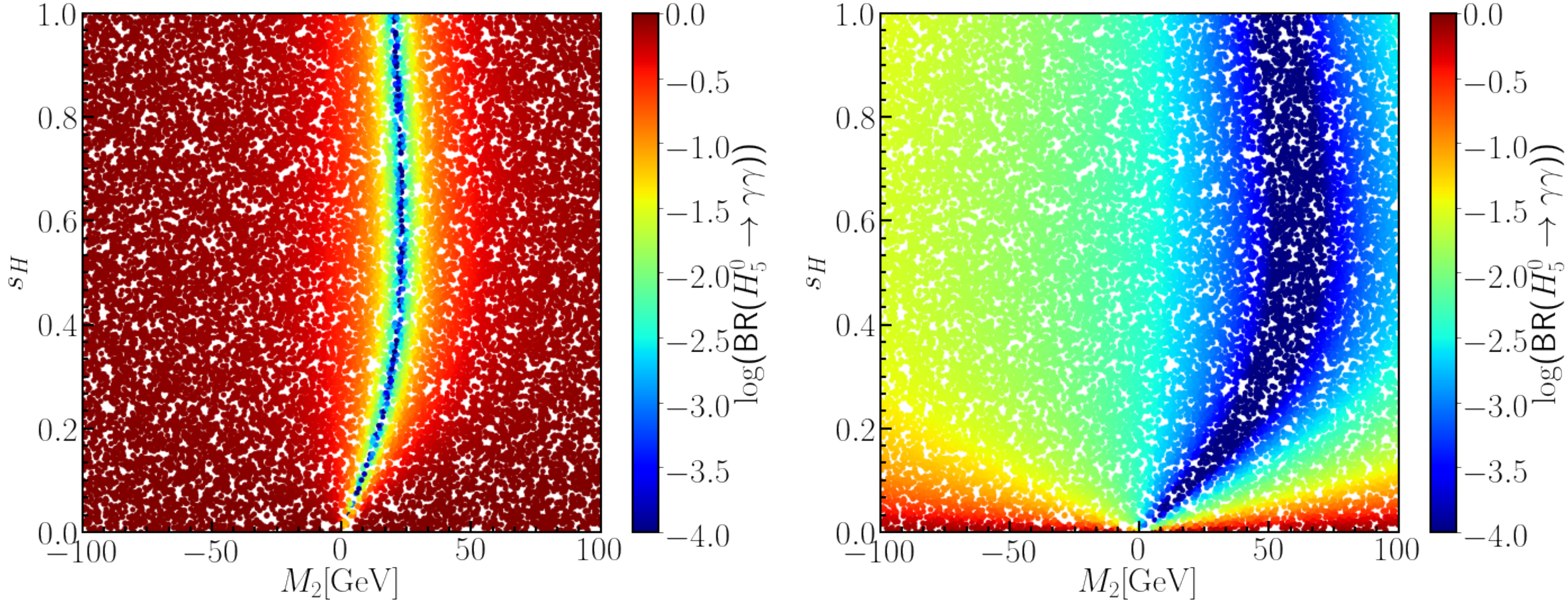




$m_5 = 100$ GeV

$m_5 = 150$ GeV

$H_5^0 \to \gamma\gamma$ branching ratio



$m_5 = 100$ GeV

$m_5 = 150$ GeV