$W^{\pm}\gamma$ Searches in Georgi-Machacek Model

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WG3 Meeting

H. Logan, Y. Wu: 18xx.xxxxx

Outline

- $H^{\pm} \rightarrow W^{\pm}\gamma$
- Benchmark scenario in GM Model
  - Implementation in UFO model files
  - GMCalc v1.4.0
- Search Prospects at the LHC
- Summary

$H^{\pm} \to W^{\pm}\gamma$

- $H^{\pm}$ Search channels:
  - $\tau\, \upsilon\, /\, c\, s\, /\, t\, b$ — Fermionphobic
  - WZ — Alignment/Low mass region
- Loop induced, effective Form:

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

- Source of S and $\tilde{S}$, particles in the loop:
  - S: Fermion, Scalar, Gauge boson
  - $\tilde{S}$: Fermion
- For Fermionphobic scalar:
  - $\tilde{S} = 0$

$H^{\pm} \to W^{\pm}\gamma$

- Effective Form:

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

- Decay Width: $\Gamma(H^+ \to W^+\gamma) = \frac{m_{H^+}^3}{32\pi}\left[1 - \frac{m_W^2}{m_{H^+}^2}\right]^3\left[|S|^2 + |\tilde{S}|^2\right]$
- Differential Distribution:
  - considering W leptonic decay: $\mathrm{H}^{\pm} \to W^{\pm}\gamma \to \gamma l^{\pm}\nu$

$$\begin{aligned}|\mathcal{M}|^2 &\propto \Gamma^{\mu\nu}\Gamma^{\rho\sigma*}\varepsilon_{\mu}^{\gamma*}\varepsilon_{\rho}^{\gamma}\ \mathbf{Tr}(\not{p}_{\nu}\gamma_{\sigma}P_L\not{p}_{\ell}\gamma_{\nu}) \\ &= \frac{m_W^2}{2}\left\{8(p_\ell\cdot q)^2\left[|S|^2+|\tilde{S}|^2\right] - 4(p_\ell\cdot q)(m_{H^+}^2 - m_W^2)\left[|S|^2+|\tilde{S}|^2 - 2\mathbf{Re}(S\tilde{S}^*)\right]\right. \\ &\quad \left. +(m_{H^+}^2 - m_W^2)^2\left[|S|^2+|\tilde{S}|^2 - 2\mathbf{Re}(S\tilde{S}^*)\right]\right\}, \qquad (2.3)\end{aligned}$$

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

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

Parabolic distribution

$H^{\pm} \to W^{\pm}\gamma$

- Effective Form:

$$\mathcal{M} = \Gamma^{\mu\nu}\varepsilon_{\nu}^{W*}(k)\varepsilon_{\mu}^{\gamma*}(q), \quad \text{witl}$$

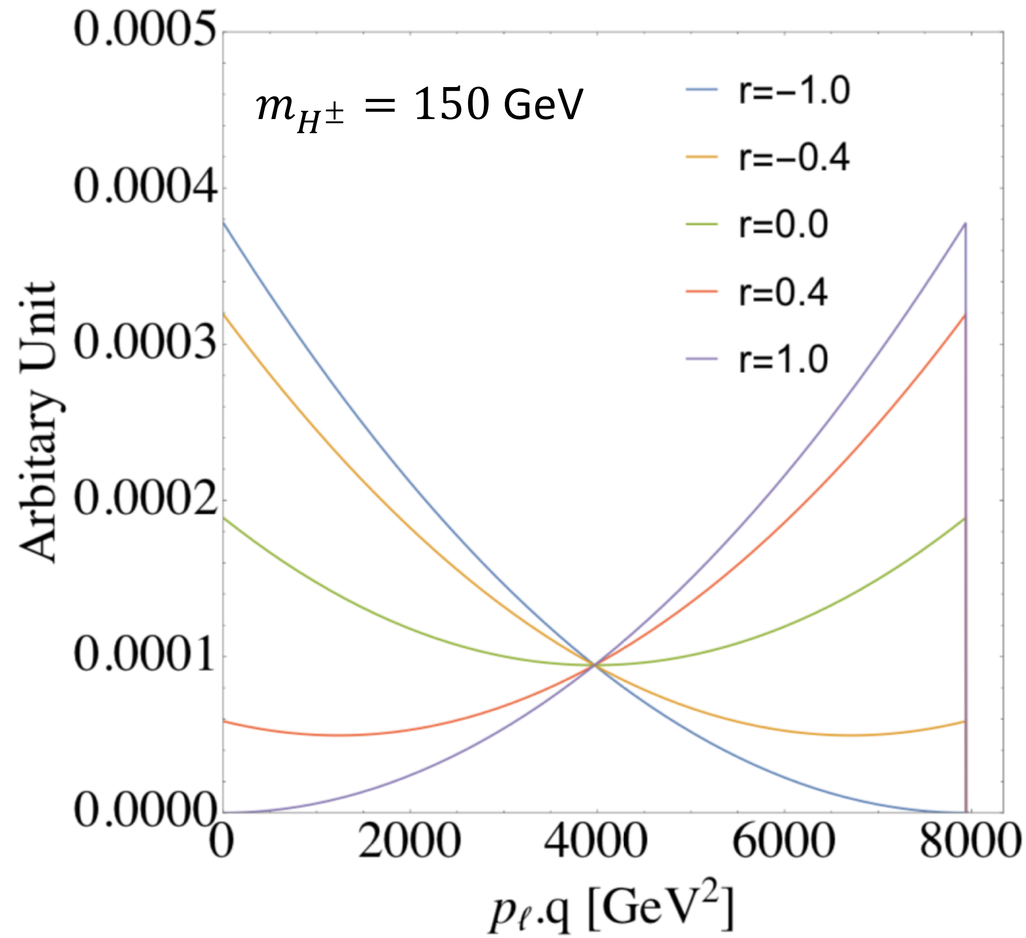
- Decay Width: $\Gamma(H^{+} -$
- Differential Distribut
  - considering W lepto

$$|\mathcal{M}|^2 \propto \Gamma^{\mu\nu}\Gamma^{\rho\sigma*}\varepsilon_{\mu}^{\gamma*}\varepsilon_{\rho}^{\gamma}\ \mathbf{Tr}(\not{p}_{\nu}\gamma_{\sigma}P_L\not{p}_{\ell}$$

$$= \frac{m_W^2}{2}\left\{8(p_\ell \cdot q)^2\left[|S|^2 + |\tilde{S}|\right.\right.$$

$$+(m_{H^+}^2 - m_W^2)^2\left[|S|^2 + |\tilde{S}\right.$$

$$r \equiv \frac{\tilde{S}}{S}, \qquad K \equiv \frac{p_\ell \cdot q}{(m_{H^+}^2 - m_W^2)/2} \in$$



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

Parabolic distribution

GM model

- One complex doublet + two Triplets:
  - One Real triplet + One Complex triplet

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

- Scalar Potential: $\mu_2^2,\ \mu_3^2,\ \lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5,\ M_1,\ M_2.$

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

$$v,\ s_H,\ \cos\alpha,\ m_h,\ m_H,\ m_3,\ m_5,\ M_1,\ M_2.$$

s_H → Similar to $tan\beta$ in SUSY/2HDM → Gauge Couplings

M_1 → Proportional to s_H

M_2 → Triple scalar coupling

GM model

- One complex doublet + two Triplets:
  - One Real triplet + One Complex triplet

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

- After EWSB, under the custodial SU(2):

Fiveplet: $H_5^{++} = \chi^{++}, \quad H_5^{+} = \frac{\chi^{+} - \xi^{+}}{\sqrt{2}}, \quad H_5^{0} = \sqrt{\frac{2}{3}}\xi^{0,r} - \sqrt{\frac{1}{3}}\chi^{0,r},$

Triplet: $H_3^{+} = -s_H\phi^{+} + c_H\frac{\chi^{+} + \xi^{+}}{\sqrt{2}}, \quad H_3^{0} = -s_H\phi^{0,i} + c_H\chi^{0,i},$

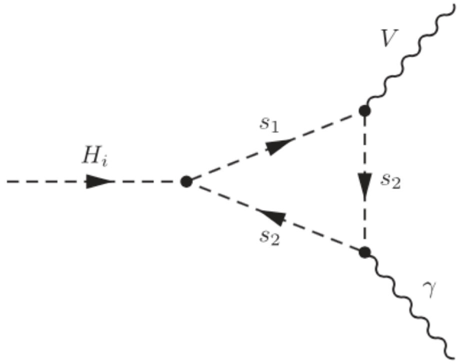
$$s_H \equiv \sin\theta_H = \frac{2\sqrt{2}v_\chi}{v},$$

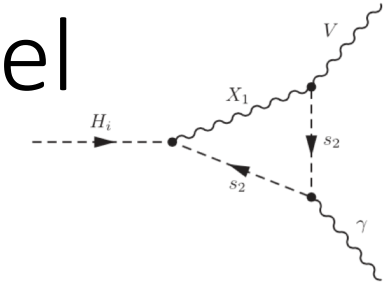
Singlets: $H_1^{0} = \phi^{0,r}, \quad H_1^{0\prime} = \sqrt{\frac{1}{3}}\xi^{0,r} + \sqrt{\frac{2}{3}}\chi^{0,r},$

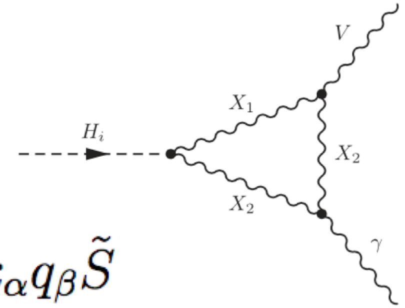
$$h = c_\alpha H_1^0 - s_\alpha H_1^{0\prime},$$
$$H = s_\alpha H_1^0 + c_\alpha H_1^{0\prime}.$$

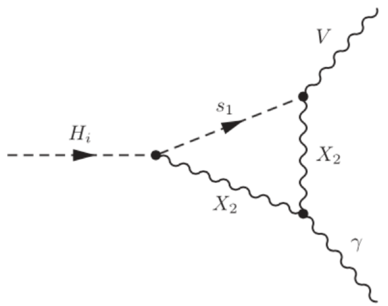
Benchmark Scenario in GM model

- $H_5^{\pm}$ Decays:
  - Tree level: H_3 Heavier Than H_5
    - $H_3^{\pm}\, H_3^0 \quad H_3^{\pm}\, Z \quad W^{\pm}\, H_3^0$
    - $W^{\pm}\, Z \quad \propto sin\theta_h$
  - Loop Induced:
    - $W^{\pm}\gamma$









$$\Gamma^{\mu\nu} = (g^{\mu\nu} k\cdot q - k^{\mu} q^{\nu}) S + i\epsilon^{\mu\nu\alpha\beta} k_{\alpha} q_{\beta} \tilde{S}$$

$$S_{H_5^{\pm}\to W^{\pm}\gamma} \xrightarrow{\sin\theta_h \to 0} -\frac{\alpha_{em}}{\pi}\frac{3\sqrt{2}}{2}\frac{M_2}{s_w}\left(\frac{I_1(\tau_5,\lambda_5)}{4m_{H_5}^2} - \frac{I_1(\tau_3,\lambda_3)}{4m_{H_3}^2}\right)$$

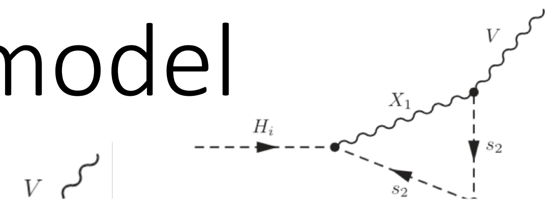
- Parameter choice in GM model:

m_5, s_H, M_2

$$m_3^2 = m_5^2 + \delta m^2,$$
$$m_H^2 = m_5^2 + \frac{3}{2}\delta m^2 + \kappa_H v^2 s_H^2,$$
$$M_1 = \frac{\sqrt{2}}{v}\left(m_5^2 + \frac{3}{2}\delta m^2\right) s_H + 3M_2 s_H^2 + \kappa_{\lambda_3} v s_H^3,$$
$$s_\alpha = \kappa_\alpha s_H,$$

$$\kappa_\alpha = -0.15 - \frac{m_5}{1000(\mathrm{GeV})},$$
$$\kappa_H = -\frac{m_5}{100(\mathrm{GeV})},$$
$$\kappa_{\lambda_3} = -\frac{\kappa_H^2}{10}.$$

Benchmark Scenario in GM model

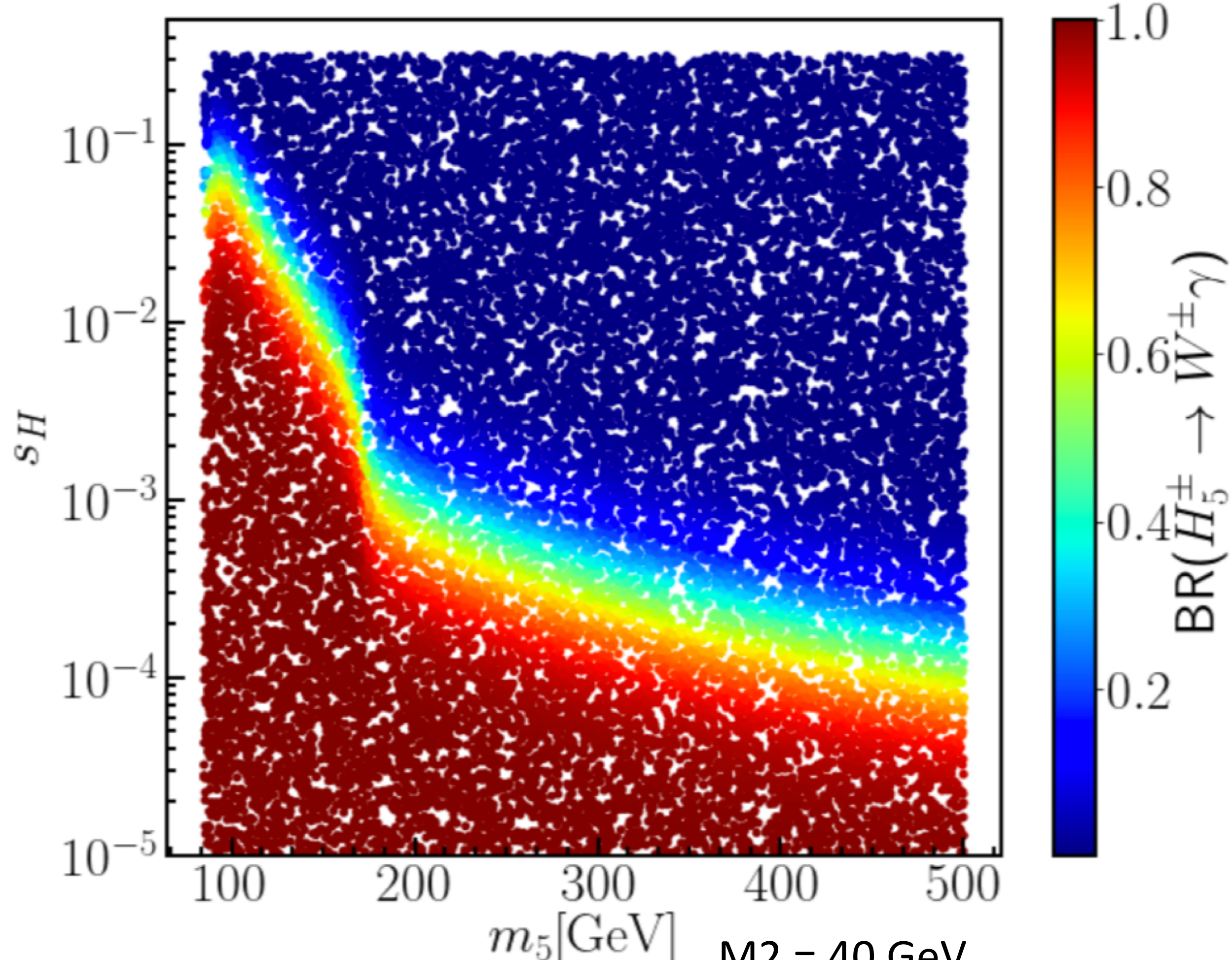


- $H_5^\pm$ Decays:
  - Tree level:
    - $H_3^\pm\ H_3^0$
    - $W^\pm Z$
  - Loop Induc
    - $W^\pm \gamma$

$$S_{H_5^\pm \to W^\pm\gamma} \xrightarrow{\sin\theta_h \to 0} -$$

- Parameter ch

m_5, s_H, M_2

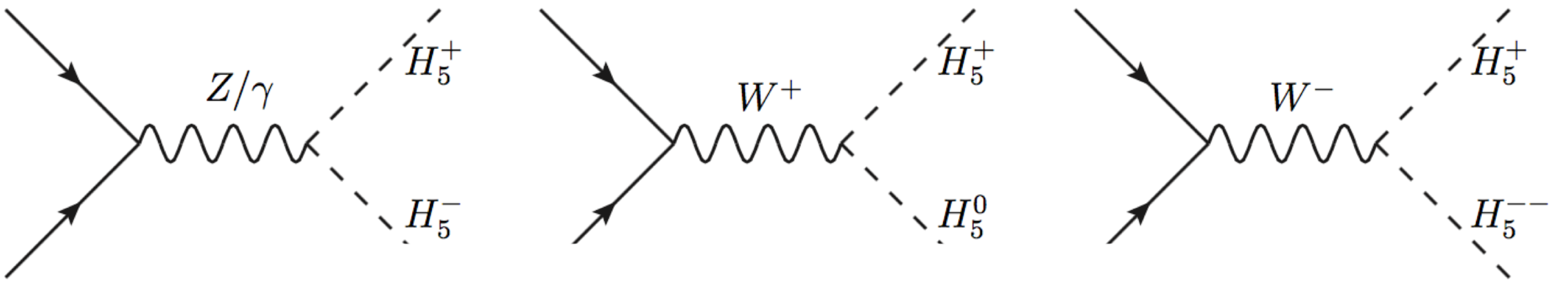


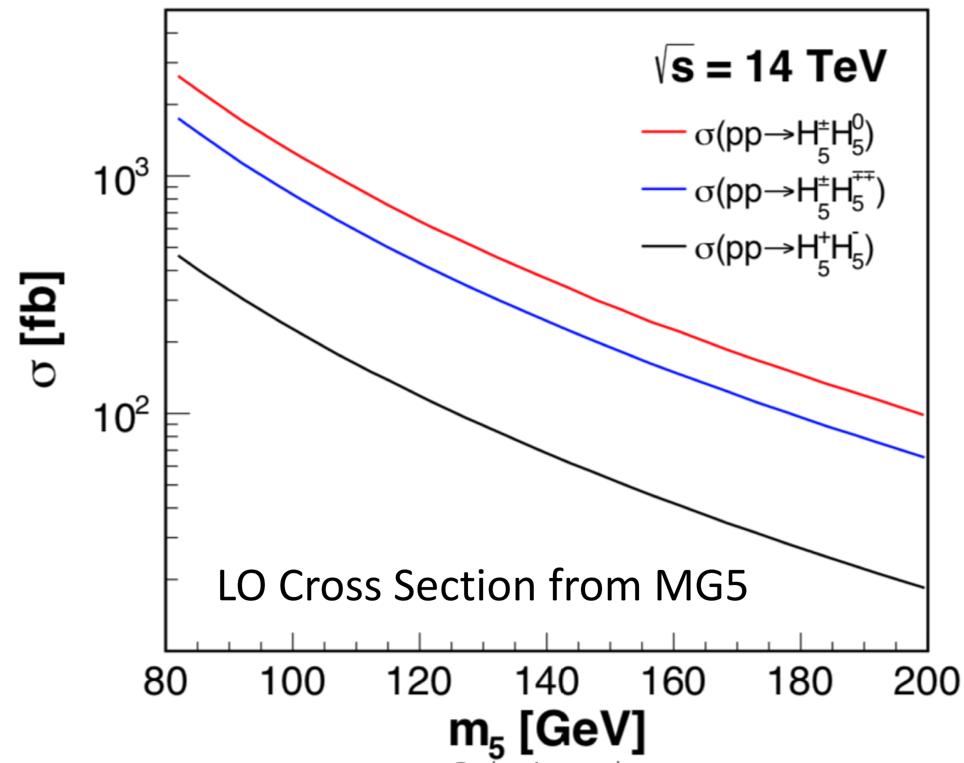
M2 = 40 GeV

$s_\alpha = \kappa_\alpha s_H,$

$H_5^{\pm}$ Production:

- Consider Small s_H region:
  - Drell-Yan dominant, only depend on Mass





Simulations:

- UFO model files: http://feynrules.irmp.ucl.ac.be/wiki/GeorgiMachacekModel

(QCD@LO+EFT/QCD@NLO +EFT available in FeynRule website)

- Loop Induced SVV couplings are included (no only $W\gamma$):

$$\Gamma^{\mu\nu} = (g^{\mu\nu} k \cdot q - k^{\mu} q^{\nu}) S + i\epsilon^{\mu\nu\alpha\beta} k_{\alpha} q_{\beta} \tilde{S}$$

- $S/\tilde{S}$ as External input (calculated by GMCalc)

```
###################################
## INFORMATION FOR NEUTRALFORMFACTORS
###################################
BLOCK NEUTRALFORMFACTORS #
      1 3.541890e-06 # h5ngaga
      2 4.899730e-06 # h5nzga
      3 3.874610e-06 # h3ngaga
      4 1.460320e-06 # h3nzga
      5 2.267160e-05 # h3ngg
      6 9.681870e-07 # hhgaga
      7 3.870980e-07 # hhzga
      8 1.949000e-05 # hhgg
      9 3.114730e-05 # hlgaga
      10 5.752290e-05 # hlzga
      11 5.099820e-05 # hlgg
```

```
###################################
## INFORMATION FOR REXCHARGEDFORMFACTORS
###################################
BLOCK REXCHARGEDFORMFACTORS #
      1 6.239490e-07 # rxh5pwga
      2 0.000000e+00 # rxh5pwgatilde(debug)
      3 2.021440e-06 # rxh3pwga
      4 2.124940e-06 # rxh3pwgatilde
###################################
## INFORMATION FOR IMXCHARGEDFORMFACTORS
###################################
BLOCK IMXCHARGEDFORMFACTORS #
      1 4.616660e-06 # ixh5pwga
      2 0.000000e+00 # ixh5pwgatilde(debug)
      3 -3.678550e-07 # ixh3pwga
      4 5.140060e-07 # ixh3pwgatilde
```

Leave for DEBUG

Calculated by GMCalc 1.4.0

Simulations:

http://people.physics.carleton.ca/~logan/gmcalc/

- GMCalc Updated accordingly (v1.4.0 available now):
  - Generating the corresponding Parameter Cards for MG5 simulation
    - Extra $S/\tilde{S}$ Block.
    - Decay Table for Scalars(h/H/H3/H5) including loop induced channels.
  - 5 different input sets.
    - INPUTSET 3 using the physical parameters
    - $m_h, m_H, m_3, m_5, s_H, s_\alpha, M_1, M_2$
  - One benchmark choice:

$$\begin{aligned} m_5 &\in [80, 200] \text{ GeV}, \\ \delta m^2 &= (300 \text{ GeV})^2, \\ M_2 &\in [-100, 100] \text{ GeV} \\ s_H &\ll 1, \end{aligned}$$

$$\begin{aligned} m_3^2 &= m_5^2 + \delta m^2, \\ m_H^2 &= m_5^2 + \frac{3}{2}\delta m^2 + \kappa_H v^2 s_H^2, \\ M_1 &= \frac{\sqrt{2}}{v}\left(m_5^2 + \frac{3}{2}\delta m^2\right) s_H + 3M_2 s_H^2 + \kappa_{\lambda_3} v s_H^3, \\ s_\alpha &= \kappa_\alpha s_H, \end{aligned}$$

$$\begin{aligned} \kappa_\alpha &= -0.15 - \frac{m_5}{1000(\text{GeV})}, \\ \kappa_H &= -\frac{m_5}{100(\text{GeV})}, \\ \kappa_{\lambda_3} &= -\frac{\kappa_H^2}{10}. \end{aligned}$$

Pheno Study at the LHC

- Signal: 1-lep + 1-photon inclusive (2-lep + 2-photon working in progress)

$$pp \to H_5^{\pm} H_5^0 \to W^{\pm}\gamma + X \to \ell\, \nu_\ell\, \gamma + X,$$
$$pp \to H_5^{\pm} H_5^{\mp\mp} \to W^{\pm}\gamma + X \to \ell\, \nu_\ell\, \gamma + X,$$
$$pp \to H_5^{+} H_5^{-} \to W^{\pm}\gamma + X \to \ell\, \nu_\ell\, \gamma + X.$$

- Assumptions:

$$\mathrm{BR}(H_5^{\pm\pm} \to W^{\pm}W^{\pm}) = 1 \text{ and } \mathrm{BR}(H_5^0 \to \gamma\gamma) = 1.$$
$$\mathrm{BR}(H_5^{\pm} \to W^{\pm}Z) = 1 - \mathrm{BR}(H_5^{\pm} \to W^{\pm}\gamma).$$

  - Loopholes:
    - Model dependences

- Backgrounds:

$$pp \to W^{\pm}\gamma \to \ell\, \nu_\ell\, \gamma,$$
$$pp \to W^{\pm}\gamma\gamma \to \ell\, \nu_\ell\, \gamma\, \gamma,$$
$$pp \to W^{+}W^{-}\gamma \to \ell\, \nu_\ell\, \gamma + X,$$
$$pp \to W^{+}W^{-}\gamma\gamma \to \ell\, \nu_\ell\, \gamma\, \gamma + X,$$
$$pp \to t\bar{t}\gamma \to \ell\, \nu_\ell\, \gamma + X,$$
$$pp \to W^{\pm}Z\gamma \to \ell\, \nu_\ell\, \gamma + X.$$

Pheno Study at the LHC

- Simulation:
  - MG5 (GM-UFO with Effective Couplings)
  - PYTHIA + Delphes
- Selection:
  - Lepton & Photon:
    - At least one lepton & one Photon
    - With PT > 25 GeV, |eta| < 2.5
  - Jets & b-Jets:
    - No more than 2 jets with PT > 20 GeV
    - No b-tagged jet
  - Other Variables:
    - MET, HT

      $p_\ell \cdot q,$

      $p_T^{\ell+\gamma+\not{E}_T}$

Fixed (Lepton & Photon; Jets & b-Jets)

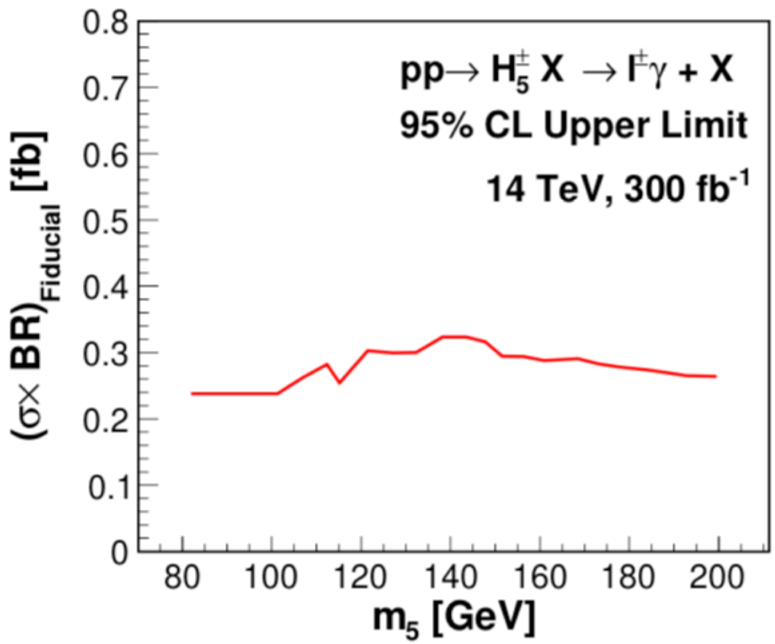
Scanned for different m5 (Other Variables)

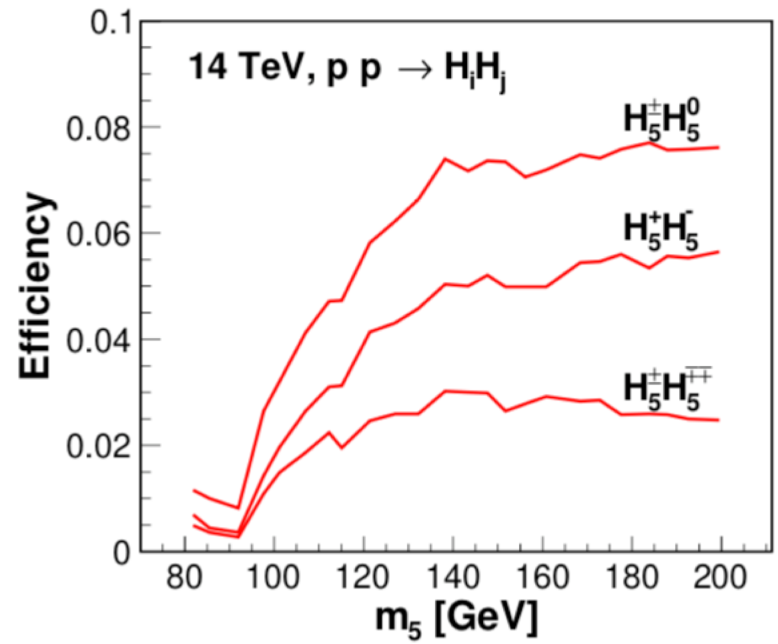
Pheno Study at the LHC

- Results:
  - Upper limits on ``Fiducial'' cross section:

inhomogeneous

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





$m_5 < 100$ GeV. Not reliable

Pheno Study at the LHC

- Results:
  - Upper limits on Branch Ratio:

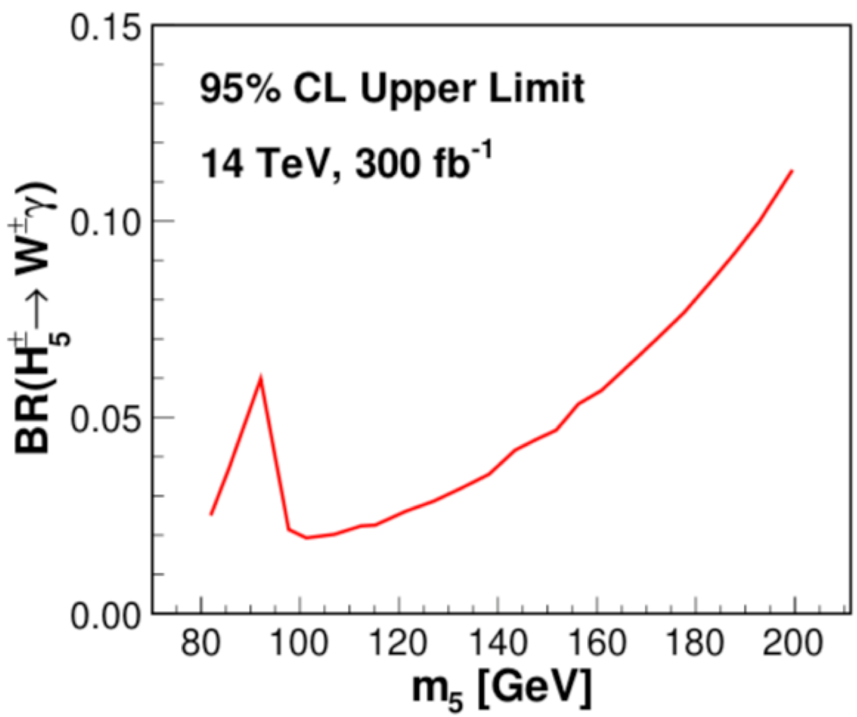
Another loophole: inhomogeneous

$$(\sigma \times \mathrm{BR})_{\mathrm{Fiducial}} \equiv \epsilon_{H_5^\pm H_5^0}\sigma(pp \to H_5^\pm H_5^0)\mathrm{BR}(H_5^\pm \to \ell^\pm \nu\gamma)$$

$$+ \epsilon_{H_5^\pm H_5^{\mp\mp}}\sigma(pp \to H_5^\pm H_5^{\mp\mp})\mathrm{BR}(H_5^\pm \to \ell^\pm \nu\gamma)$$

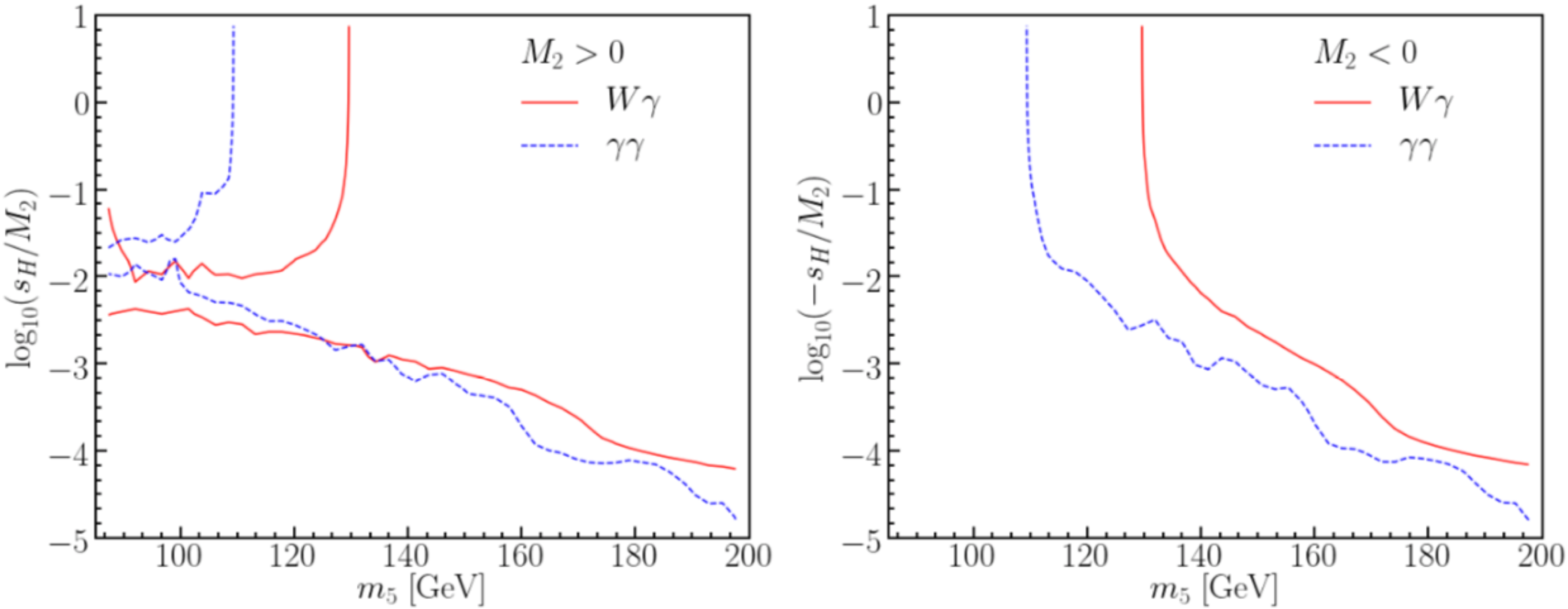
$$+ \epsilon_{H_5^+ H_5^-}\sigma(pp \to H_5^+ H_5^-)\left[2\mathrm{BR}(H_5^\pm \to \ell^\pm \nu\gamma) - \mathrm{BR}(H_5^\pm \to \ell^\pm \nu\gamma)^2\right].$$

Solving BR



Interpretation in GM model

- s_H/M_2 vs m_5



- Result for $m_5 < 100$ GeV is not good enough
- $\gamma\gamma$ results recast from 1407.6583 (ATLAS 8 TeV)

Also see 1603.00962/1805.01970 for diphoton searches in Drell-Yan production

Summary

- $W\gamma$ channel for low mass region (~100-200 GeV) and in alignment limit
- Implementation in UFO model files for simulation
- GMCalc for spectrum generation
- Prospects at the LHC
  - Exclude mass up to 130 GeV.
  - Exclude low s_H region (aligned region)

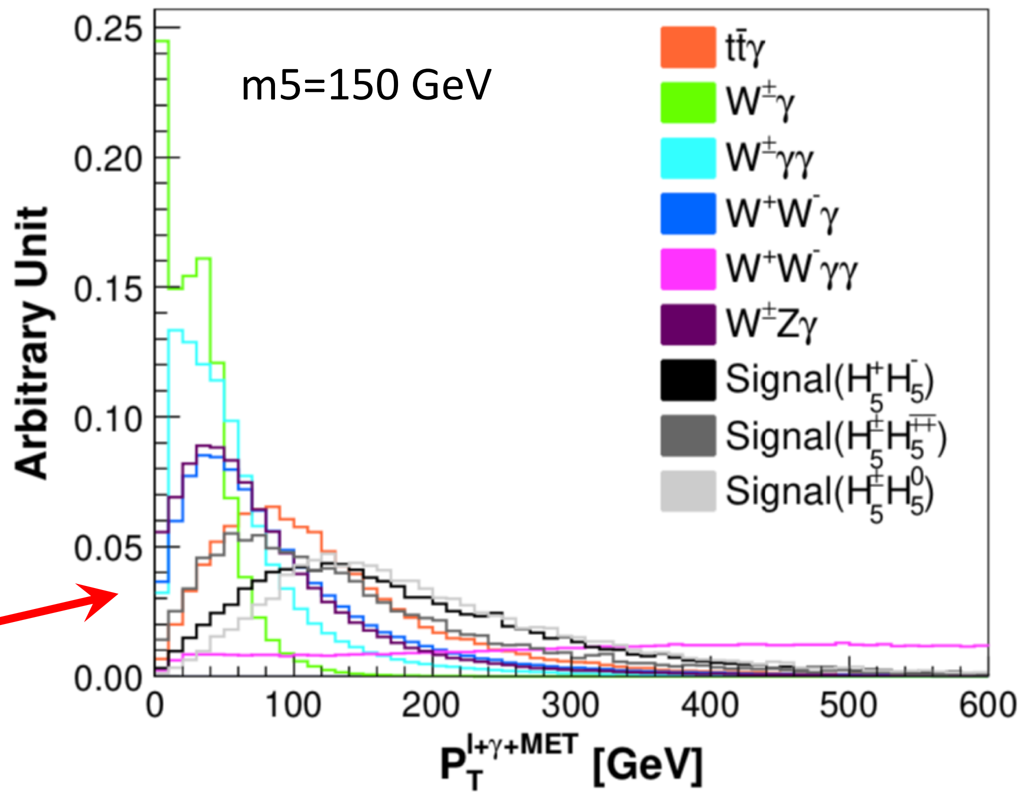
Thanks!

Pheno Study at the LHC

- Simulation:
  - MG5 (GM-UFO with Effective Couplings)
  - PYTHIA + Delphes
- Selection:
  - Lepton & Photon:
    - At least one lepton
    - With PT > 25 GeV,
  - Jets & b-Jets:
    - No more than 2 jet
    - No b-tagged jet
  - Other Variables:
    - MET, HT

$p_T^{\ell+\gamma+\not{E}_T}$

$p_\ell \cdot q,$



Pheno Study at the LHC

- Simulation:
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  - PYTHIA + Delphes
- Selection:
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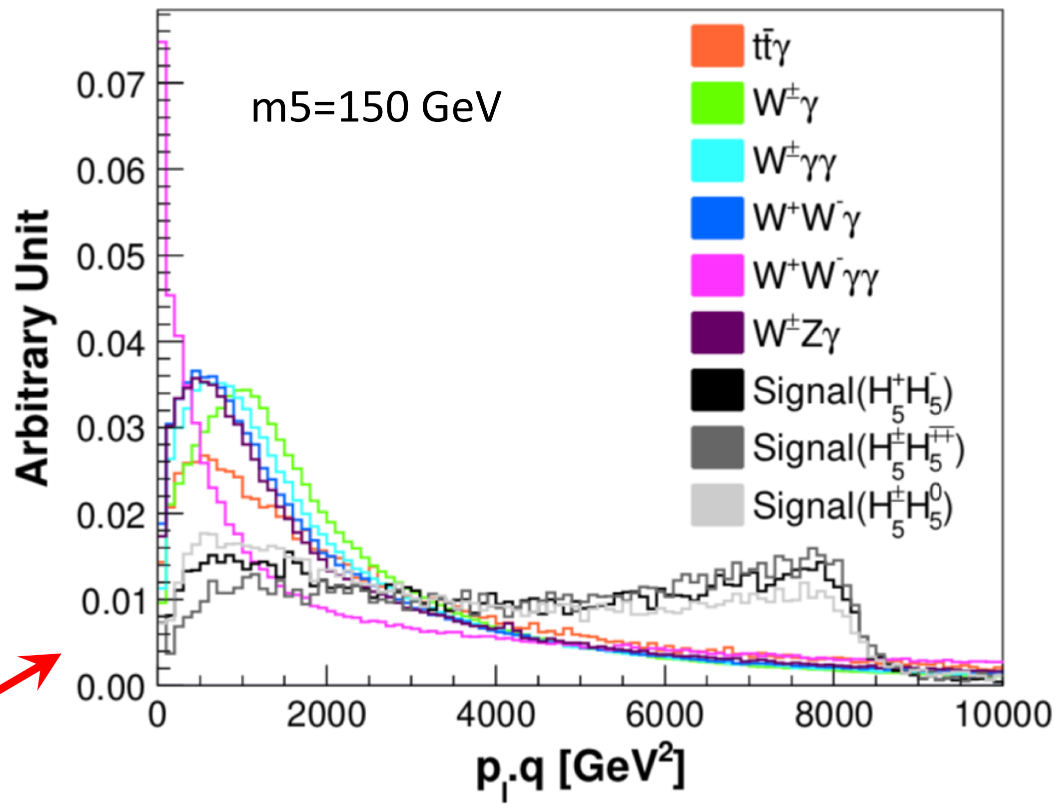
$p_T^{\ell+\gamma+\not{E}_T}$

$p_\ell \cdot q,$



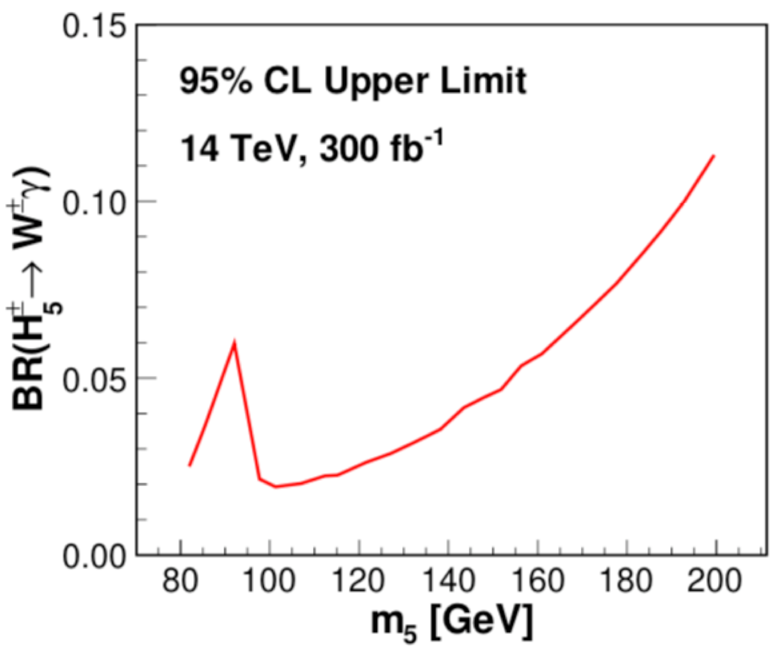
Pheno Study at the LHC

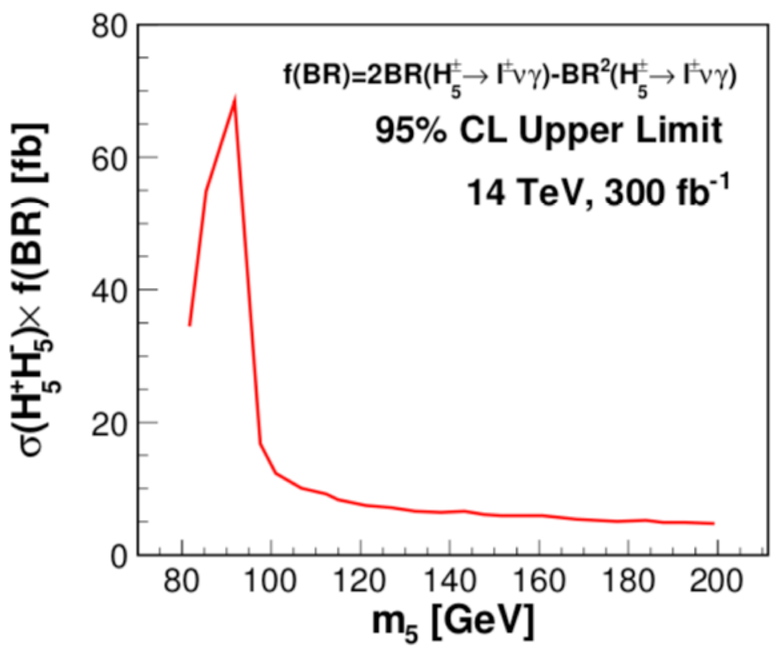
- Results:
  - Upper limits on Branch Ratio/ $H_5^+ H_5^-$ Only:

Another loophole: inhomogeneous

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

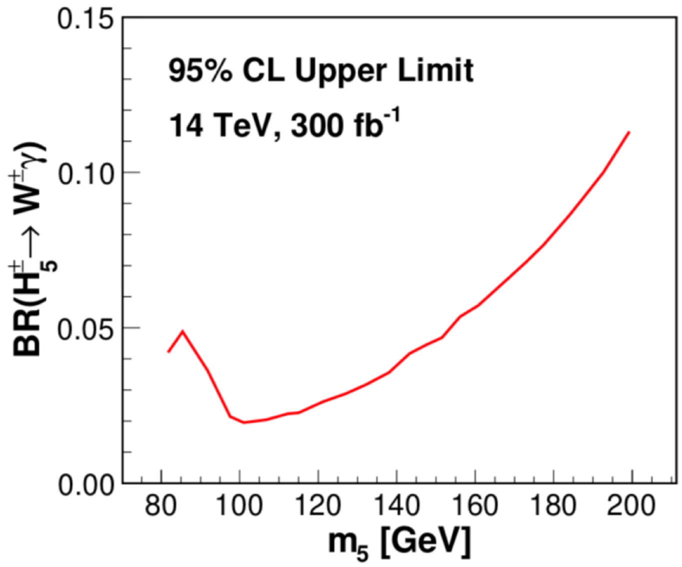
Solving BR

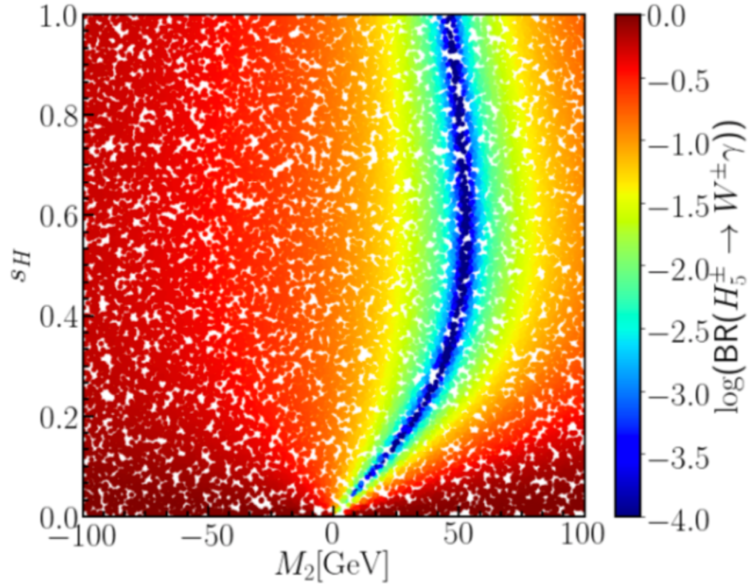




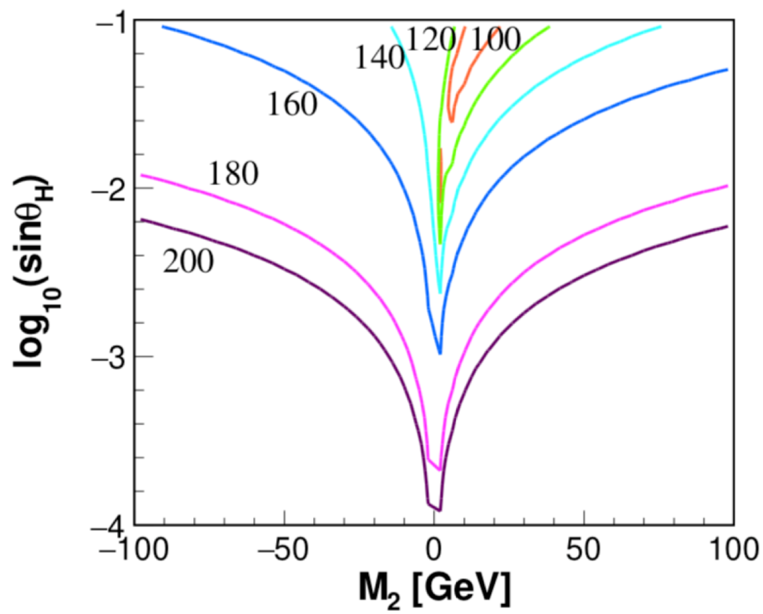
Interpretation in GM model

- s_H vs M_2 for different masses:

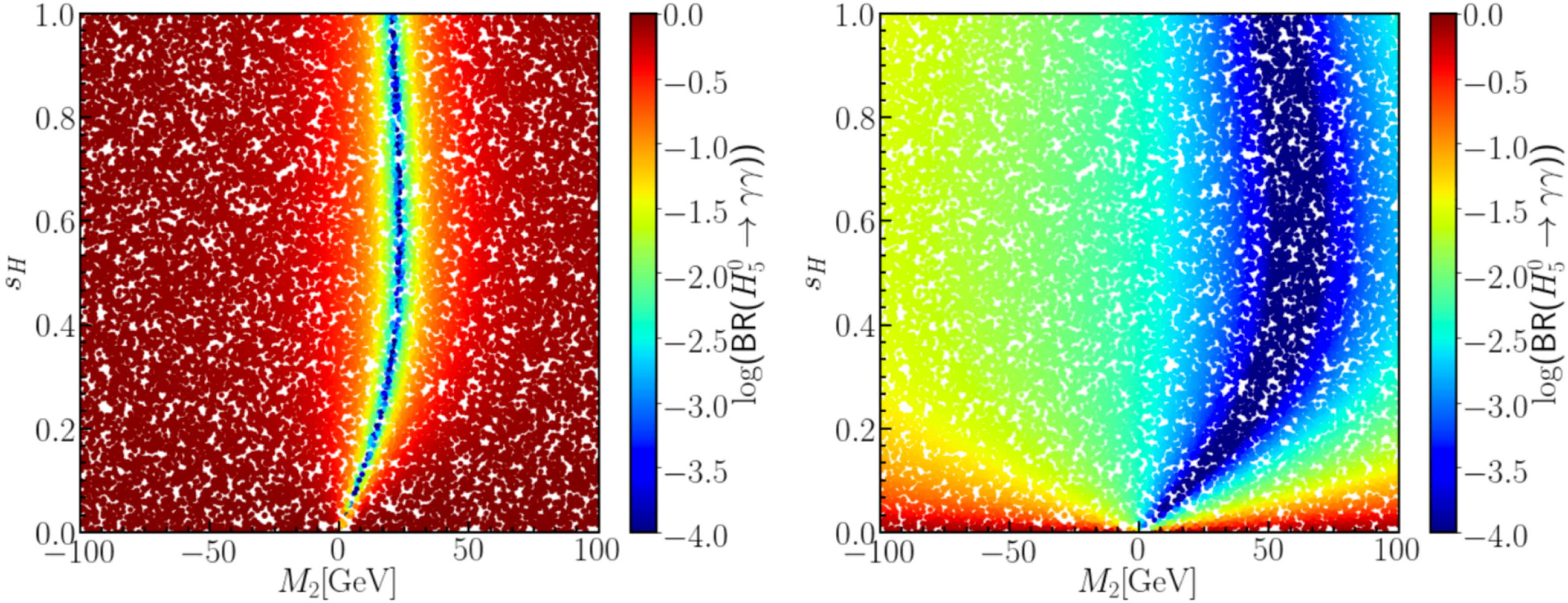




m5 = 100 GeV



$H_5^0 \to \gamma\gamma$



100 GeV

150 GeV

Recast of the diphoton results

- Consider $pp \to H_5^{\pm} H_5^0$ process
- Calculate the fiducial efficiency(as function of m5)
  - Two photon with $E_T > 22$ GeV and $|\eta| < 2.37$
  - If $m_{\gamma\gamma} > 110$ GeV:
    - $\frac{E_T^{\gamma_1}}{m_{\gamma\gamma}} > 0.4$ and $\frac{E_T^{\gamma_2}}{m_{\gamma\gamma}} > 0.3$
- Then translate the upper limit on the $\sigma \times BR$ into our own parameter plane.