Light Scalars in Georgi-Machacek Model at the LHC

Yongcheng Wu

Nanjing Normal University

@26th LHC mini-Workshop

H.E. Logan, YW; JHEP 11 (2018) 121

A. Ismail, B. Keeshan, H.E. Logan, YW; Phys.Rev.D 103 (2021) 095010

Georgi-Machacek Model

- SM + One Complex Triplet + One Real Triplet:

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

$\rho \approx 1$

  - Global $SU(2)_L \times SU(2)_R$, $\langle \chi^0 \rangle = \langle \xi^0 \rangle$ (Custodial symmetry)

- GM Model:
  - Larger Isospin Scalars (Double charged scalar, Fermiophobic)
  - Larger Gauge interactions ($\kappa_V > 1$)

- Most General Potential under $SU(2)_L \times SU(2)_R$:

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

  - 9 parameters

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

Gauge Couplings

Proportional to s_H

Triple scalar coupling

Georgi-Machacek Model

- SM + One Complex Triplet + One Real 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 $SU(2)_L \times SU(2)_R$, $\langle \chi^0 \rangle = \langle \xi^0 \rangle$ (Custodial symmetry)
- Physical Spectrum after EWSB

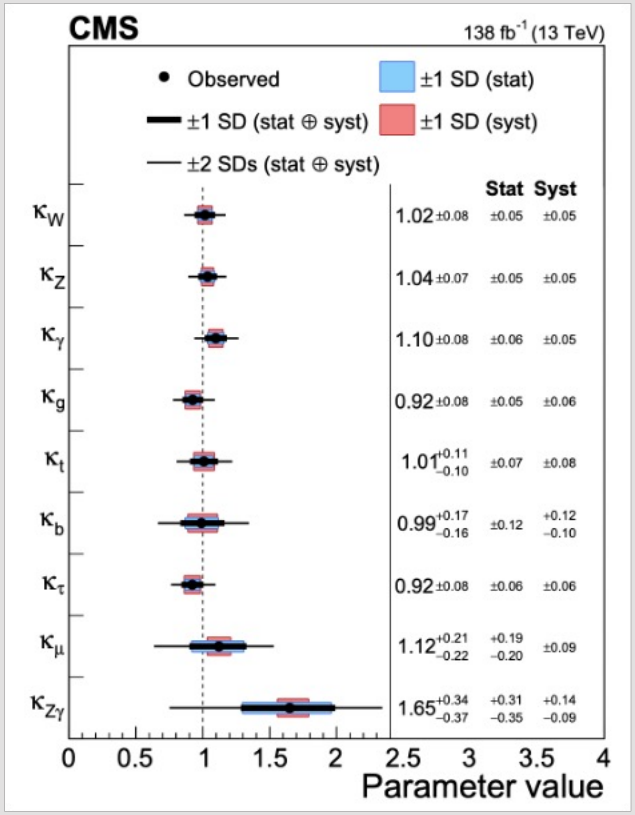
  Bi-doublet: $2 \otimes 2 \to 1 \oplus 3$, Bi-triplet: $3 \otimes 3 \to 1 \oplus 3 \oplus 5$
  - Two custodial singlets mix $\to h, H$. m_h, m_H, α
    - h as SM-like 125 GeV Higgs.
  - Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ + Goldstone m_3
    - Similar to $H^{\pm}, A^0$ in Type-I 2HDM, $\tan\beta \to \cot\theta_H$
  - Custodial fiveplet $\left(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--}\right)$. m_5
    - Fermiophobic, $g_{H_5VV} \propto s_H = \frac{2\sqrt{2}v_\chi}{v}$
    - Our focus

Current Searches/Constraints

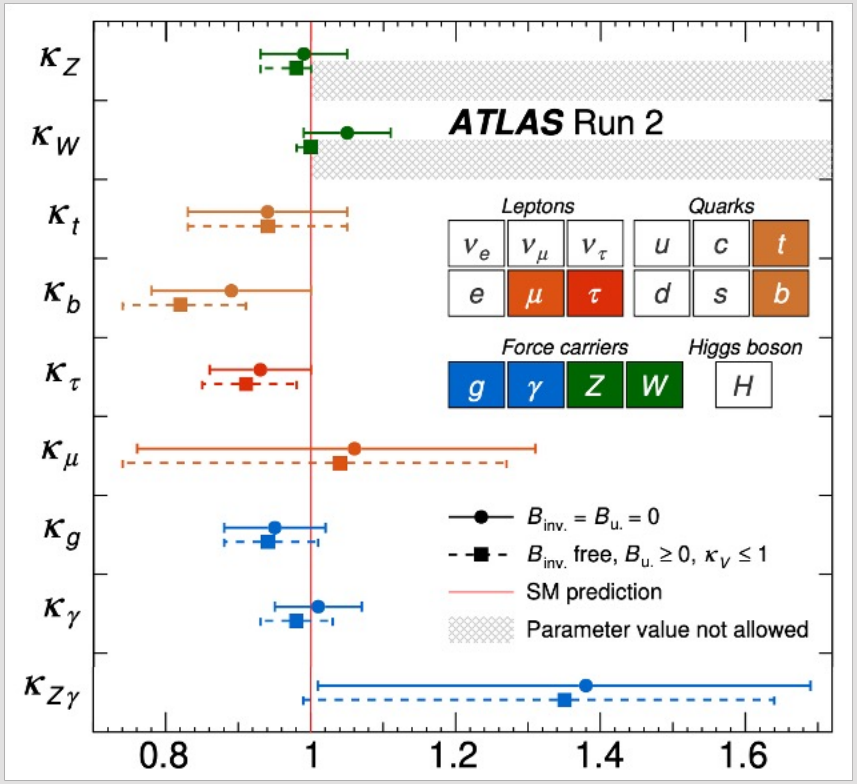
- Indirect Searches:
  - Higgs Signal Strength
- Direct Searches:
  - Double Charged Scalar
  - Single Charged Scalar
  - Neutral Scalar

Current Searches/Constraints

- Higgs Signal Strength



CMS: 2207.00043

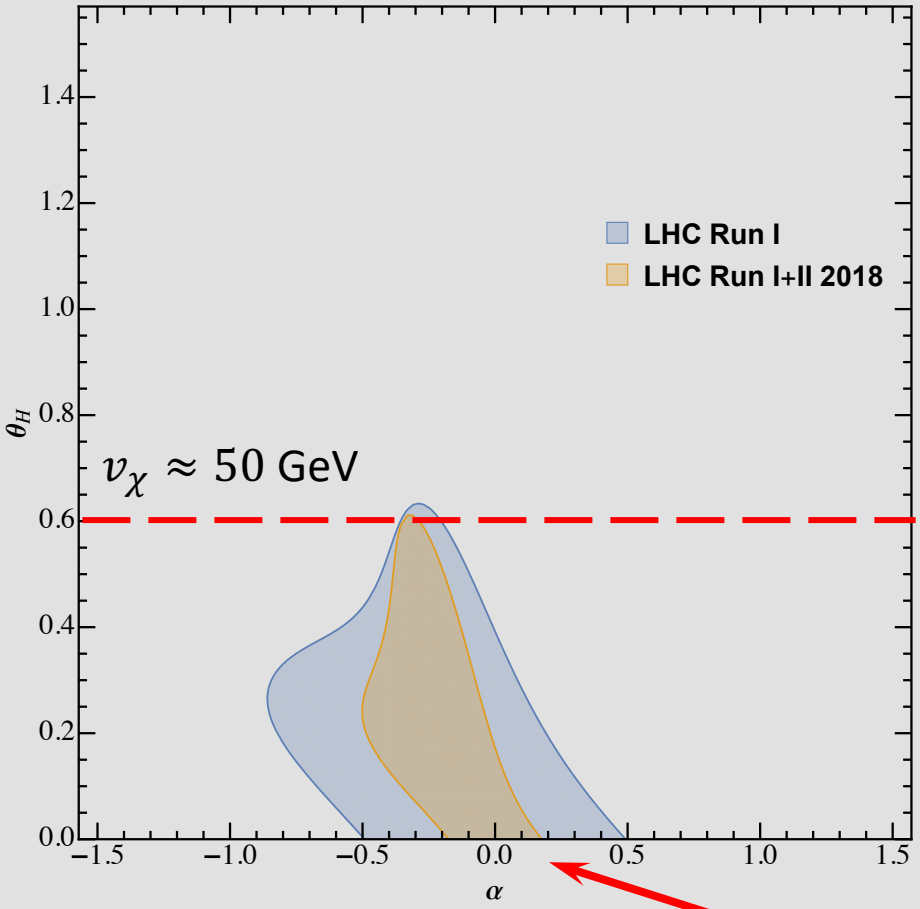


ATLAS: 2207.00092

Current Searches/Constraints

1606.02266
1809.10733
ATLAS-CONF-2018-031
JHEP12 (2017) 153

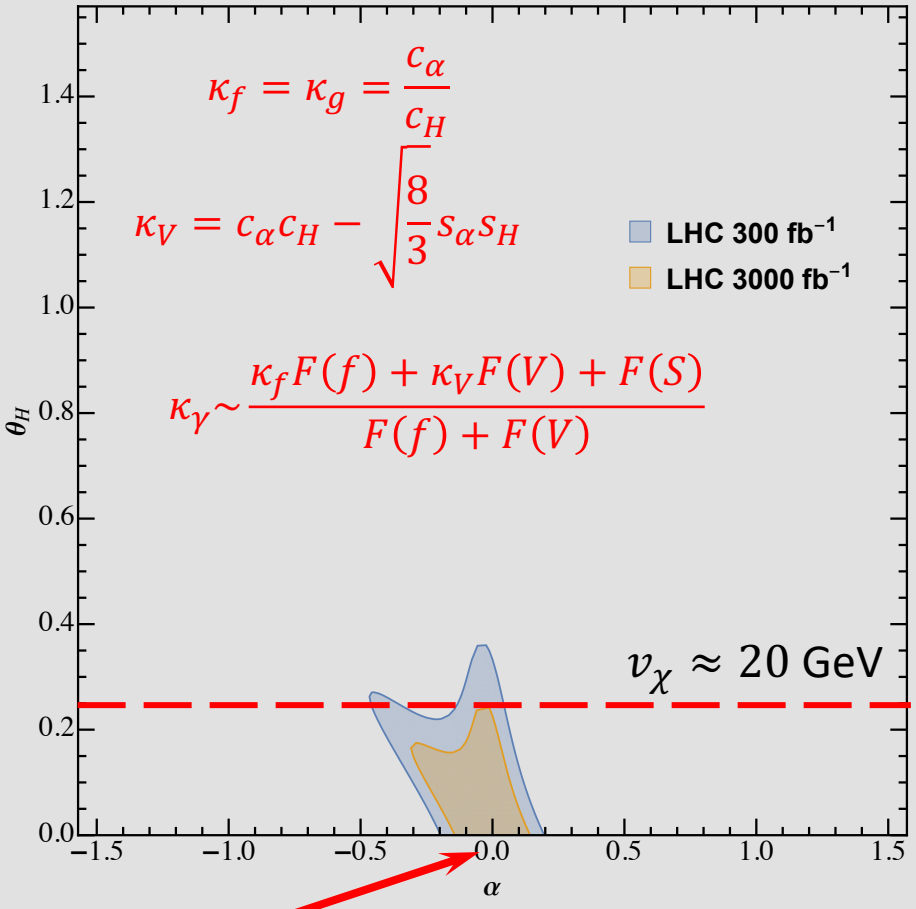
- Higgs Signal Strength



$$\kappa_f = \kappa_g = \frac{c_\alpha}{c_H}$$

$$\kappa_V = c_\alpha c_H - \sqrt{\frac{8}{3}} s_\alpha s_H$$

$$\kappa_\gamma \sim \frac{\kappa_f F(f) + \kappa_V F(V) + F(S)}{F(f) + F(V)}$$

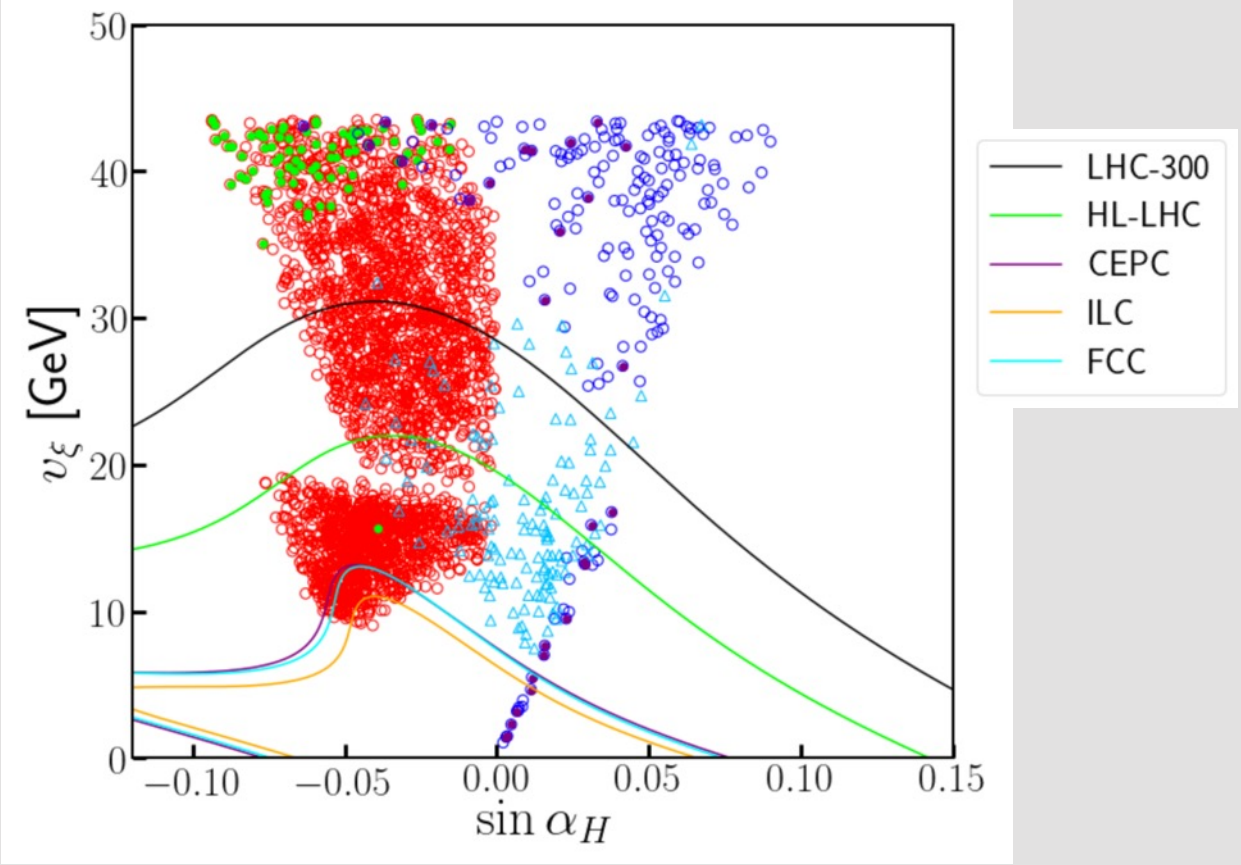


Alignment Limit

ycwu@njnu.edu.cn

Current Searches/Constraints

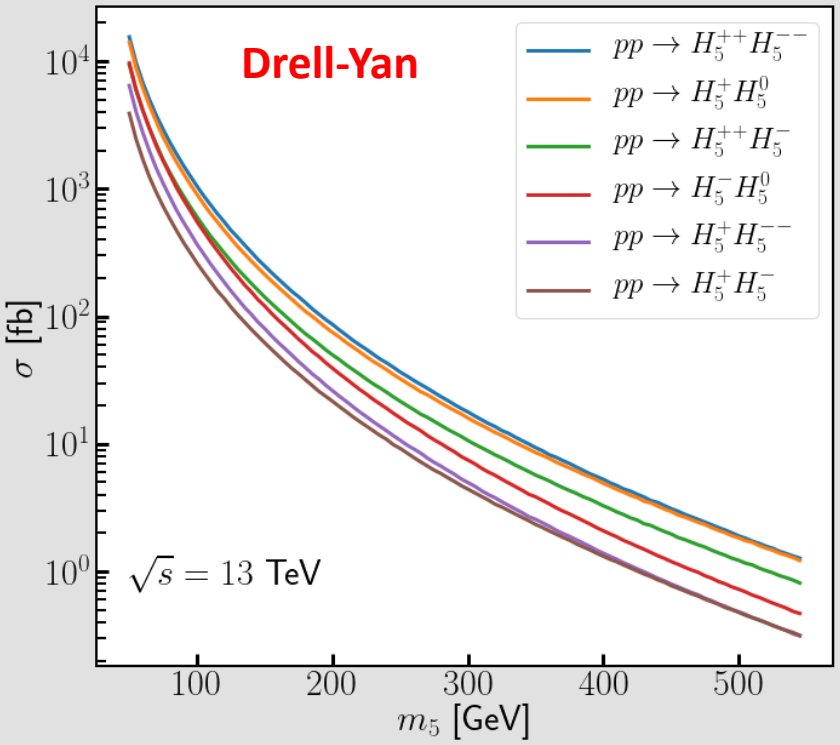
- Higgs Signal Strength

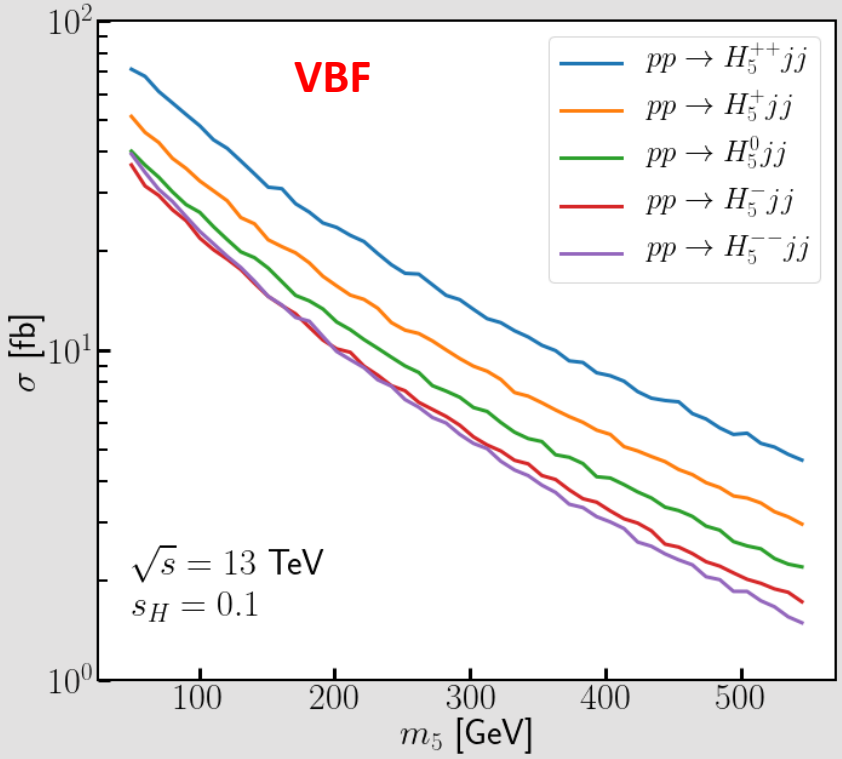


L.Bian, H.-K. Guo, YW, R. Zhou: PRD 101(2020) 035011

Current Searches/Constraints

- Exotic Higgs Searches (relevant to fermiophobic scalars)
- Productions



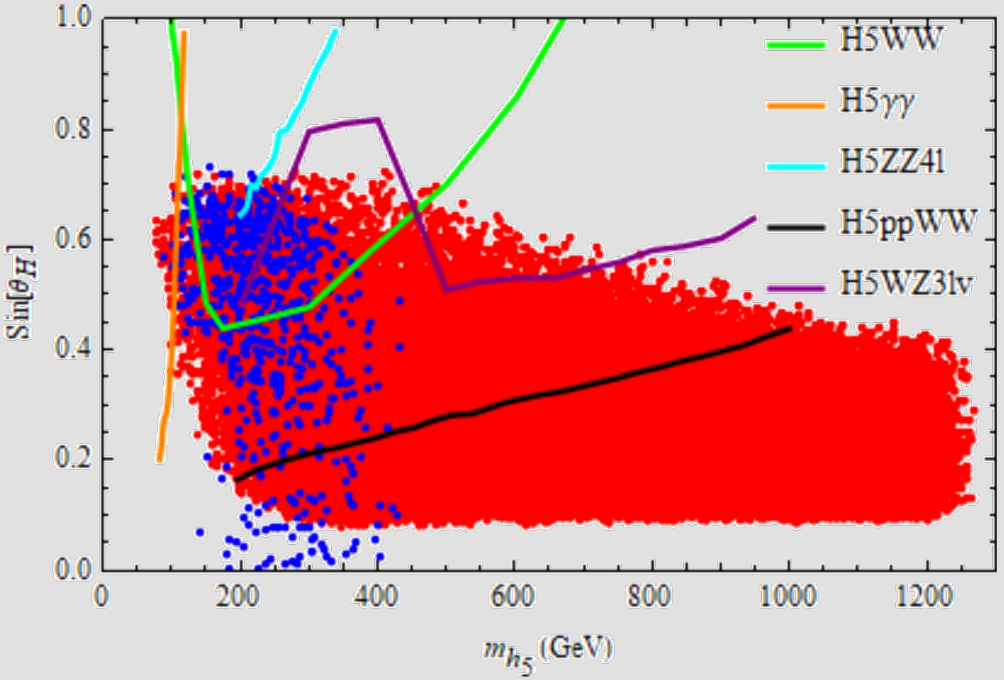


- Decays:
  - Only di-bosons
    - Tree-level $\sim s_H$
    - Loop-induced

$$g_{H_5VV} \propto s_H = \frac{2\sqrt{2}v_\chi}{v}$$

Current Searches/Constraints

- Exotic Higgs Searches (relevant to fermiophobic scalars)
  - Double Charged Scalar: 2101.11961 1808.01899 1709.05822
    - Same-sign W: 2-lep/3-lep/4-lep channel
  - Single Charged Scalar: 1901.04060 1806.01532 CMS-PAS-SMP-18-001
    - WZ channel: 3-lep
  - Neutral Scalar: 1805.01970 1712.06386 1710.01123 1603.00962 1407.6583
    - WW/ZZ/$\gamma\gamma$ channel
  - Interpret in GM model:
    - Dependence on $s_H(v_\xi)$



R. Zhou, W. Cheng, X. Deng, L. Bian, YW: JHEP 01 (2019) 216

- Strongest: double charged scalar searches
- Weak at low mass region below 200 GeV (Threshold of WW/ZZ)

More comprehensive results see:
C-W Chiang, G. Cottin, O. Eberhardt
Phys.Rev. D99 (2019) no.1, 015001

Low mass benchmark

- The benchmark for studying low mass fermiophobic scalars
  - Easy to achieve the alignment limit
    - especially for $h \to \gamma\gamma$
  - Focus on Fiveplet, avoid $H_5 \to H_3\, X$
  - Sufficiently large theoretically allowed region.
- Most relevant parameters:
  - m_5 the mass
  - s_H the mixing angle determining gauge coupling

Variables	Other fixed parameters
$m_5 \in (50,550)$ GeV	$\lambda_2 = 0.08(m_5/100)$
$s_H \in (0,1)$	$\lambda_3 = -\lambda_4 = -1.5$
M_2	$\lambda_5 = -4\lambda_2$

A. Ismail, B. Keeshan, H. Logan, YW: PRD 103 (2021) 095010

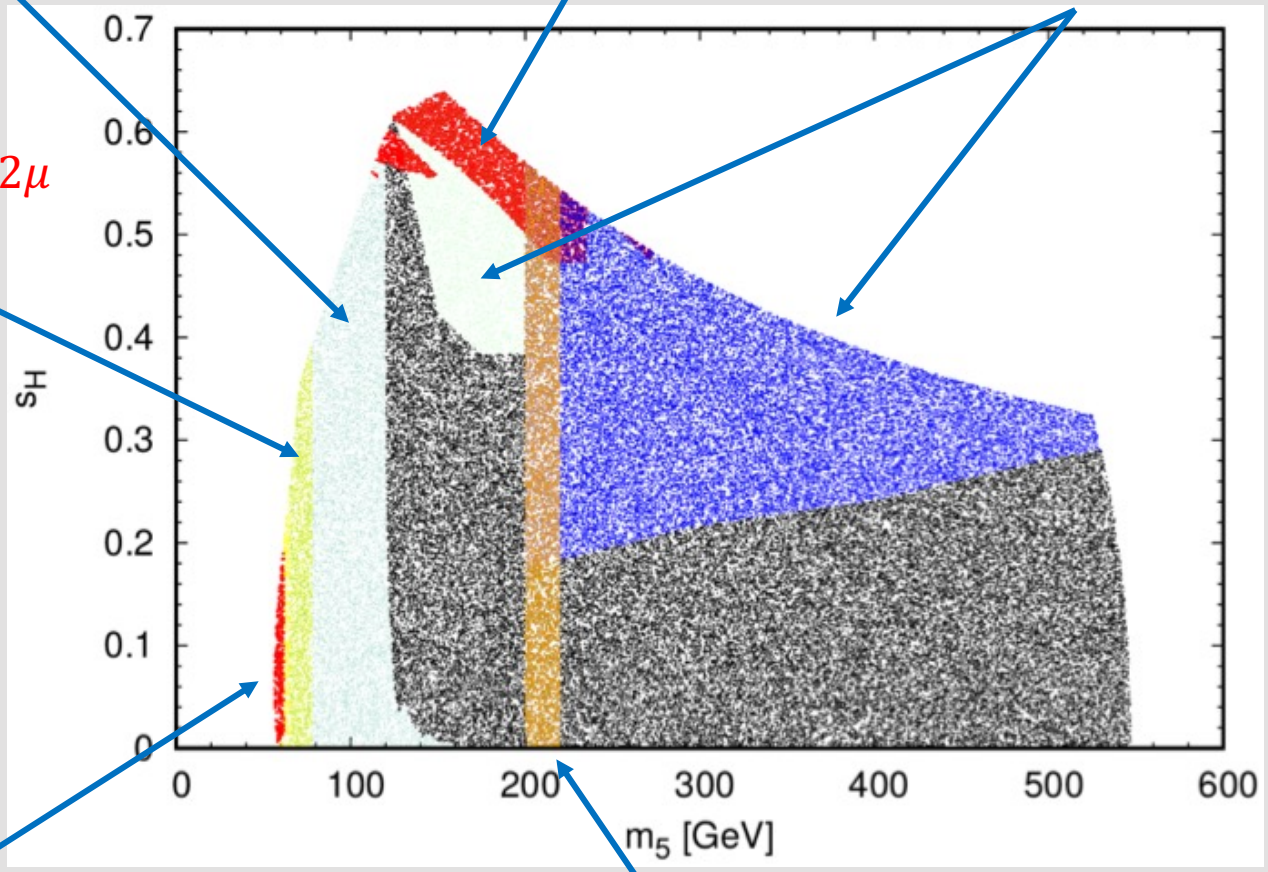
Low mass benchmark

$qq' \to W \to H_5^0 H_5^\pm, H_5^0 \to \gamma\gamma$

$H \to ZZ$

$VBF \to H_5^{\pm\pm} \to W^\pm W^\pm \to \ell^\pm \ell^\pm$

$qq \to Z \to H_5^{\pm\pm} H_5^{\mp\mp} \to 2\mu$



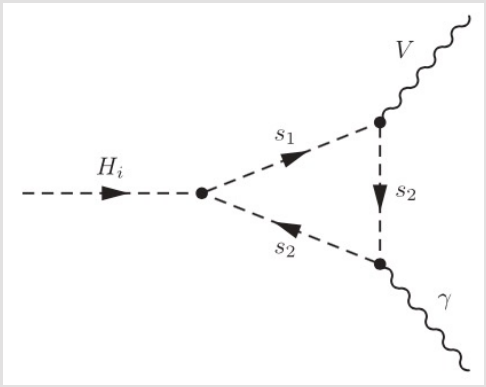
$h \to H_5^0 H_5^0 \to 4\gamma$

$qq \to Z \to H_5^{\pm\pm} H_5^{\mp\mp} \to 4W\ (2\ell, 3\ell, 4\ell)$

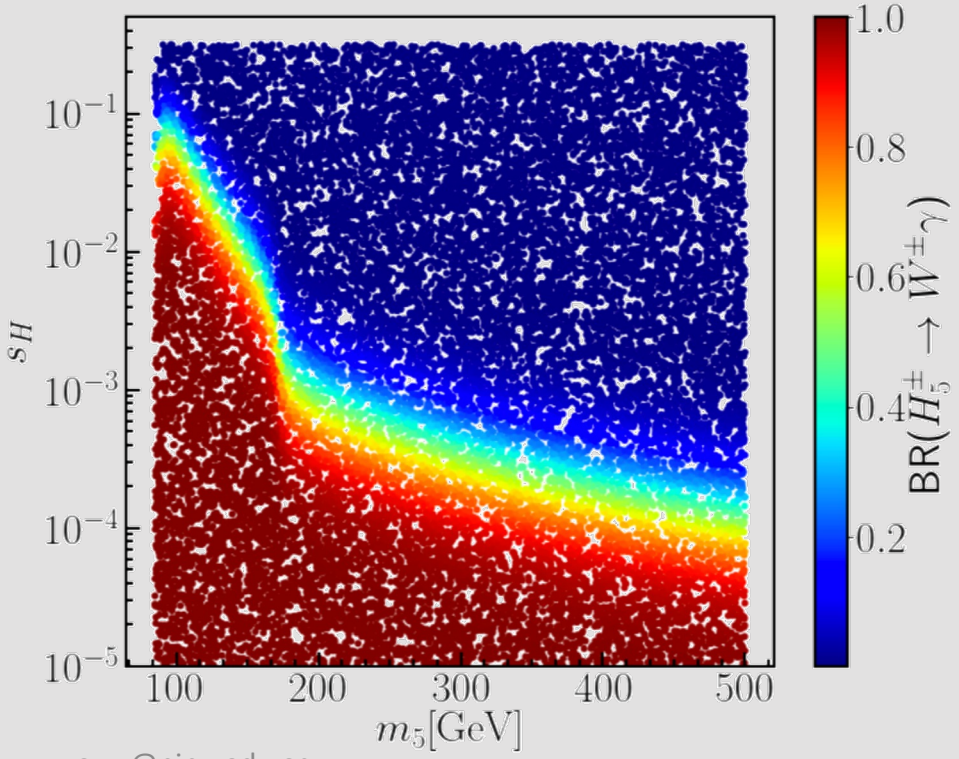
$H^{\pm} \to W^{\pm}\gamma$ Searches

- WZ channel suppressed by phase space and s_H
- Loop induced channel:

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



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

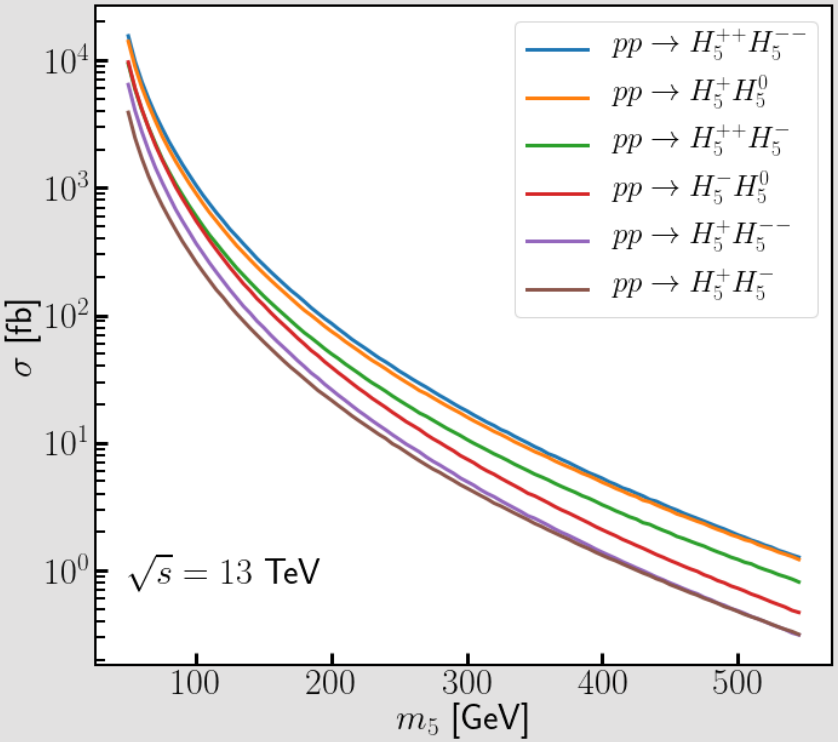


H. Logan, YW; JHEP 11 (2018) 121

Pheno Study at the LHC

- Signal: 1-lep + 1-photon inclusive
  - Production: Drell-Yan, no suppression from s_H

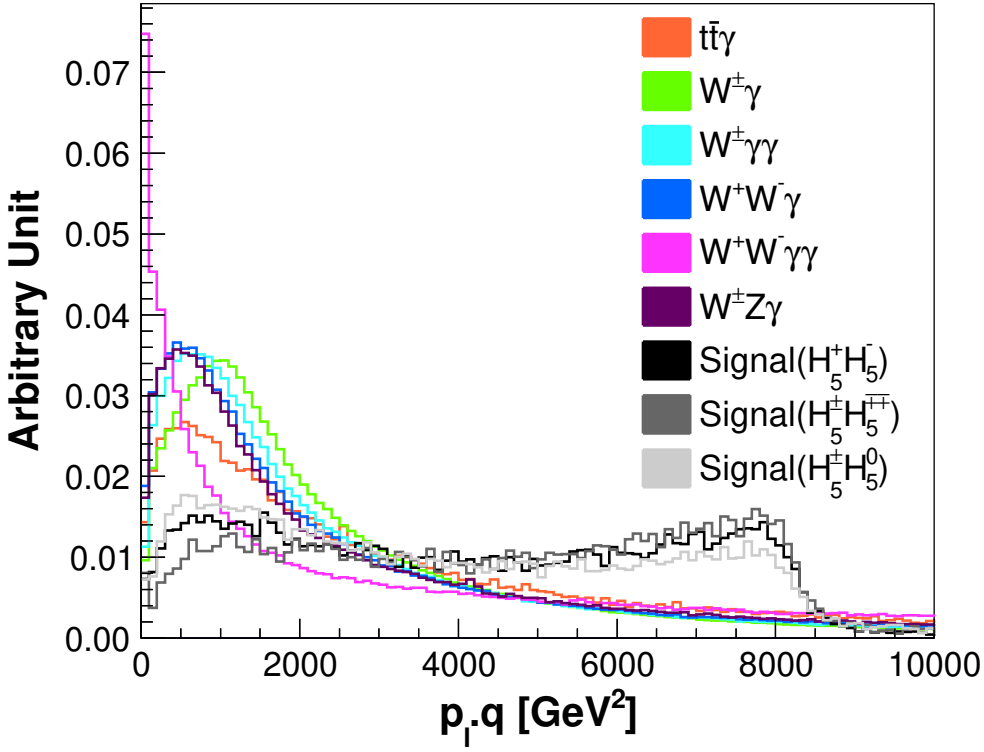
$$
\begin{aligned}
pp &\to H_5^{\pm} H_5^0 \to W^{\pm}\gamma + X \to \ell\ \nu_\ell\ \gamma + X, \\
pp &\to H_5^{\pm} H_5^{\mp\mp} \to W^{\pm}\gamma + X \to \ell\ \nu_\ell\ \gamma + X, \\
pp &\to H_5^{+} H_5^{-} \to W^{\pm}\gamma + X \to \ell\ \nu_\ell\ \gamma + X.
\end{aligned}
$$

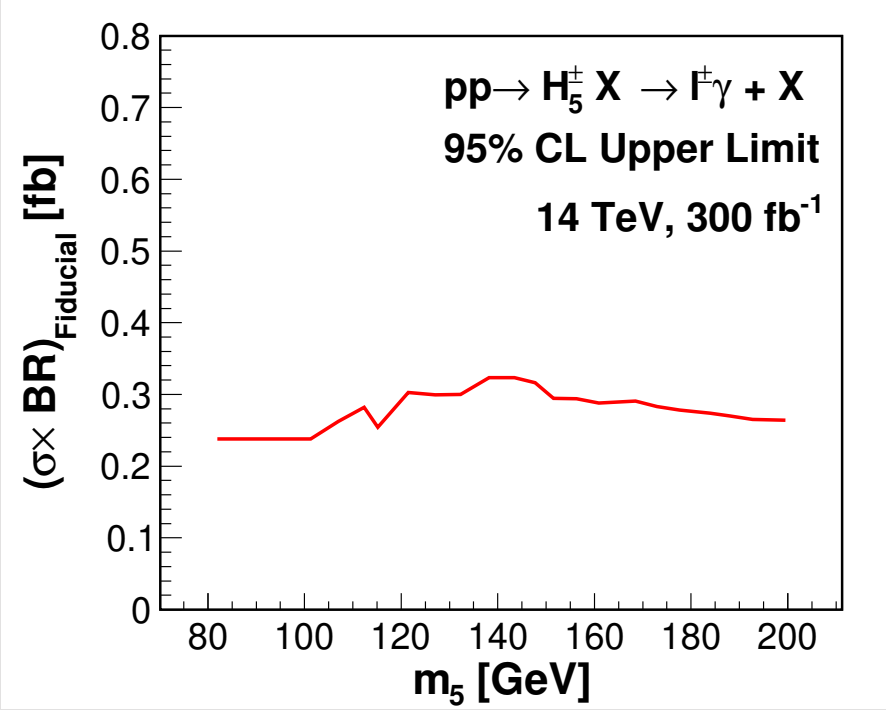


- GM model implemented with FeynRule
  http://feynrules.irmp.ucl.ac.be/wiki/GeorgiMachacekModel
- Form Factor/Spectrum generated with GMCalc
  http://people.physics.carleton.ca/~logan/gmcalc/

Pheno Study at the LHC

- Cutting Variable

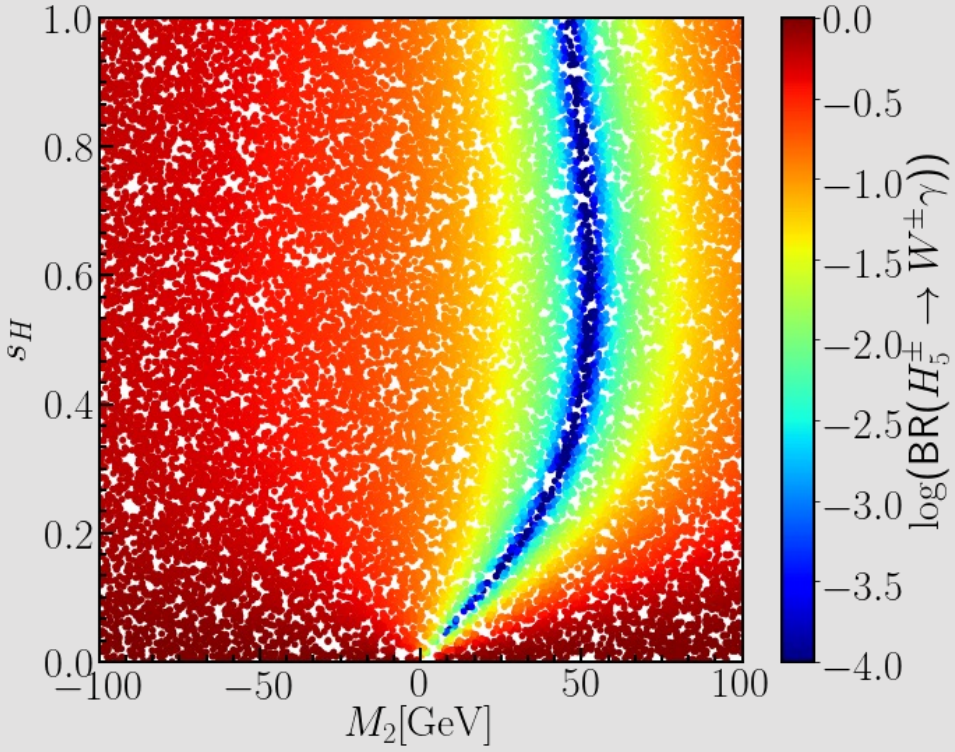




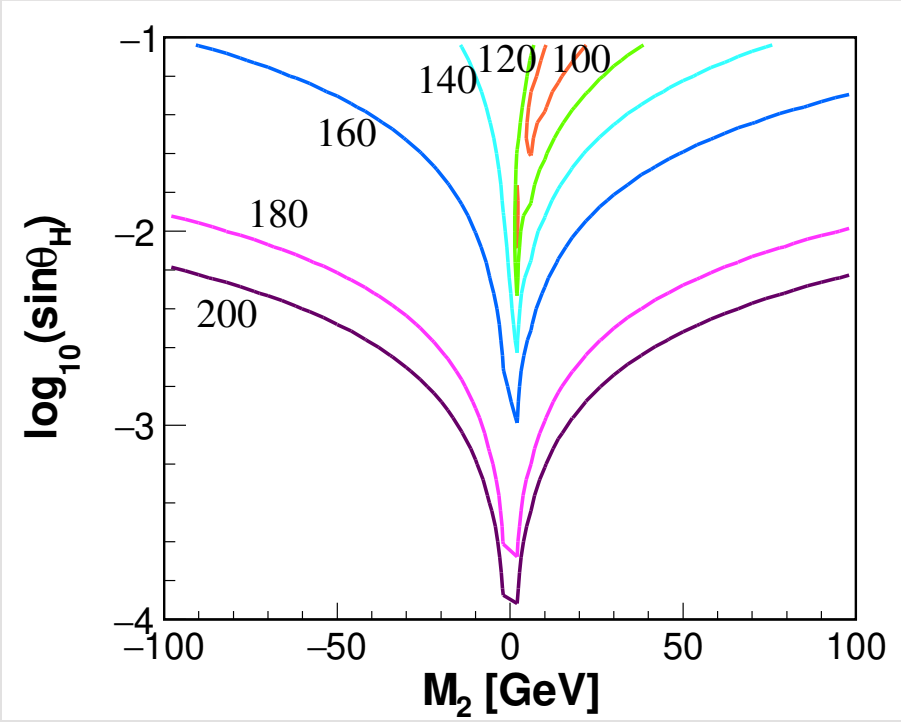
- Upper limits on $\sigma \times BR$

Constraints on GM model

- The $BR\left(H_5^{\pm} \to W^{\pm}\gamma\right)$

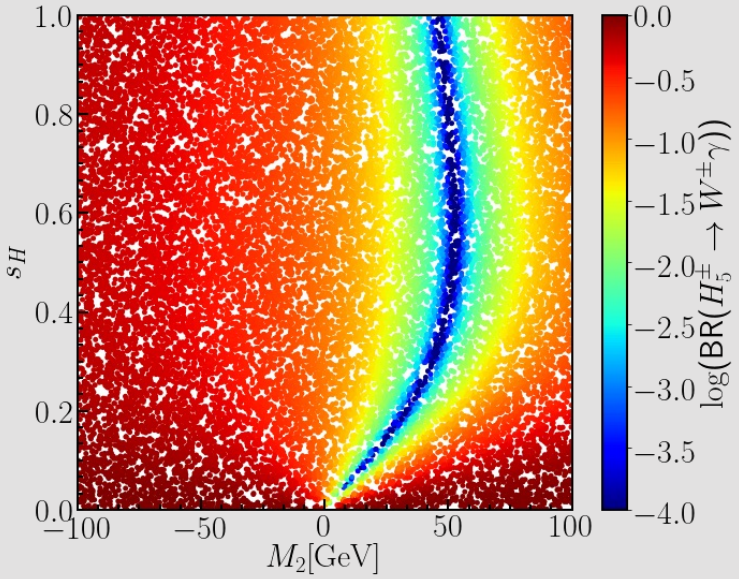


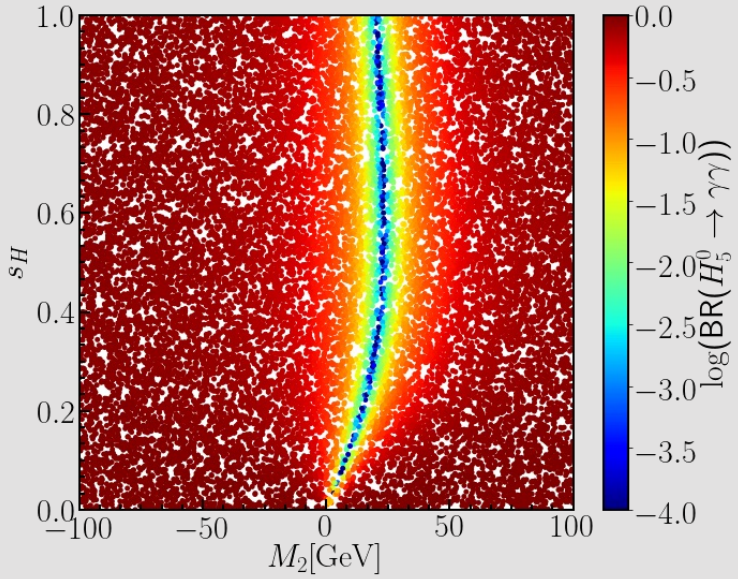
$m_5 = 100$ GeV



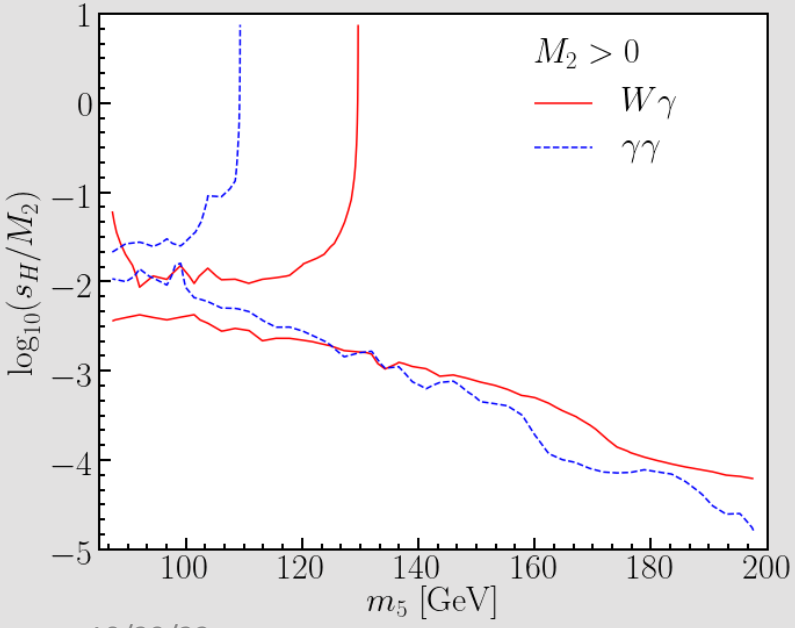
- Regions below each line (m_5) are excluded
  - Alignment Limit
  - Complementary with Higgs Signal Strength

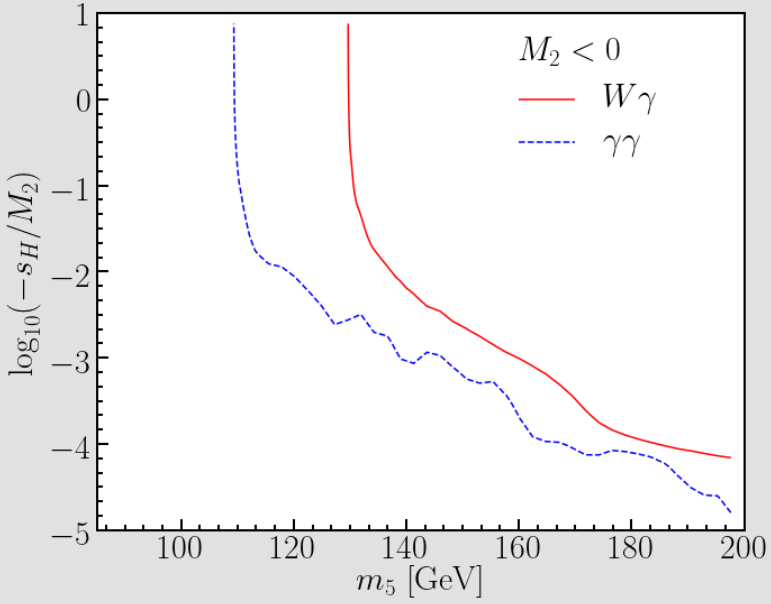
Compare with $\gamma\gamma$ searches





$m_5 = 100$ GeV



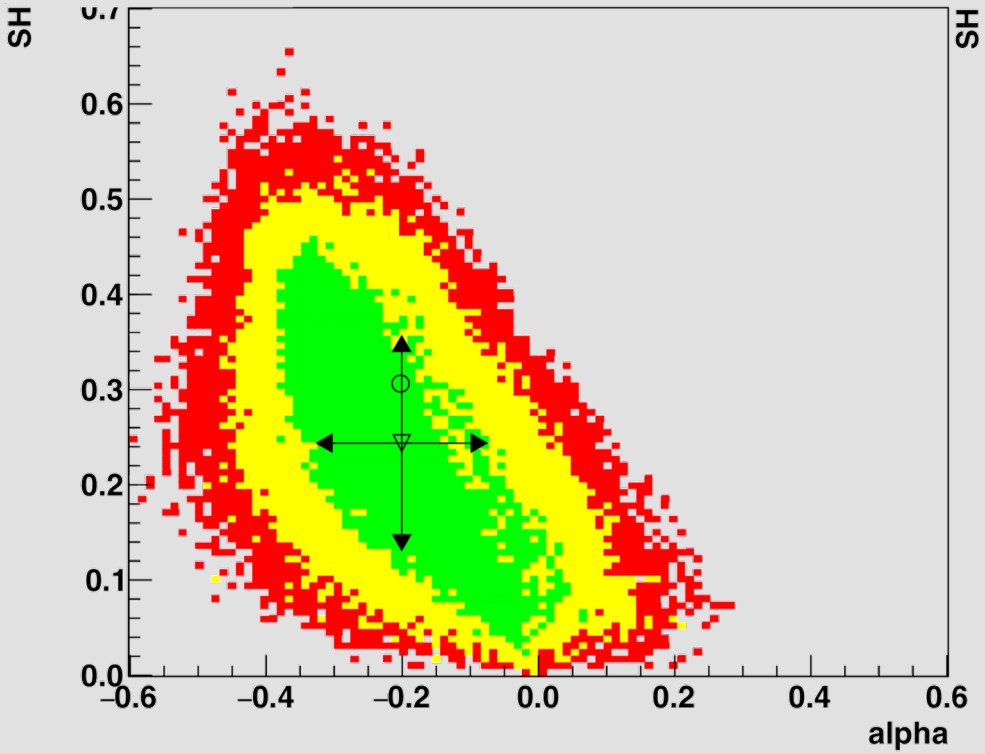


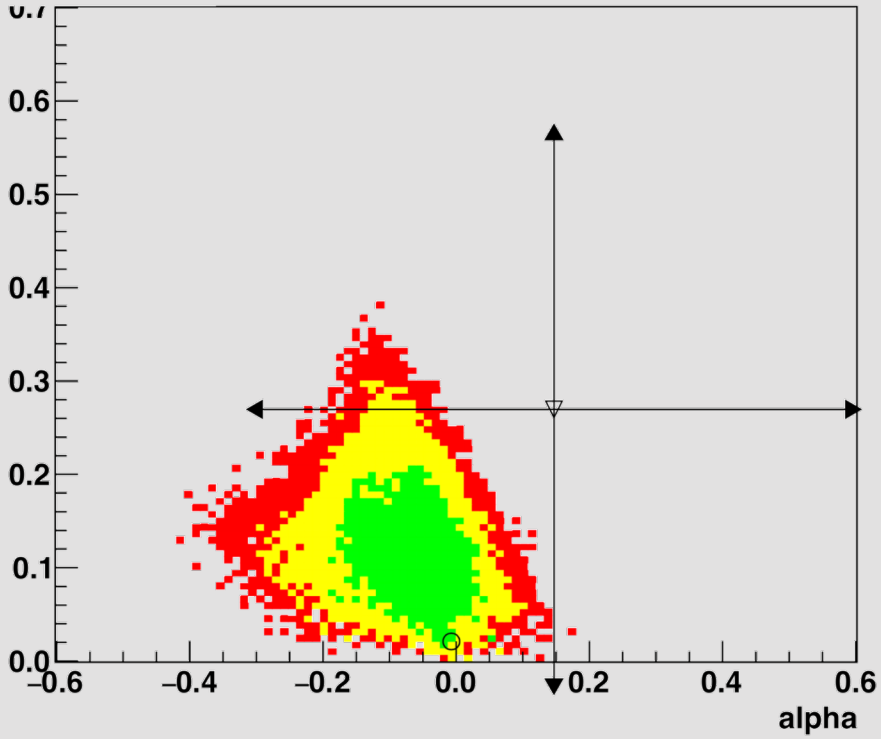
Summary

- GM model provides a concrete ground to study exotic scalars (double charged scalar, fermiophobic scalar, etc.).
- Low mass fermiophobic scalar is still an interesting scenario ($H_5^{\pm\pm} \to W^{\pm}W^{\pm}, H_5^0 \to \gamma\gamma$)
- Low mass benchmark in GM model is provided.
- $W^{\pm}\gamma$ channel is studied for low mass fermiophobic scalar
  - Cover alignment limit
  - Complementary with $\gamma\gamma$

Backup

Higgs Signal Strength, HEPfit





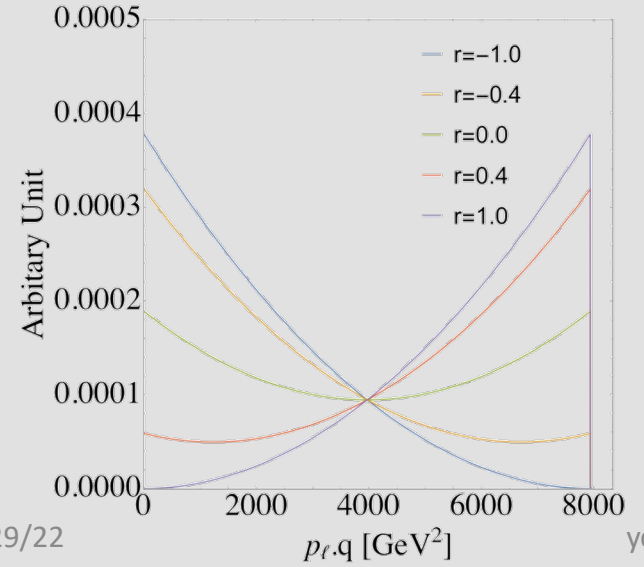
$W\gamma$ Distributions

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

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

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

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



$m_{H^\pm} = 150$ GeV

Pheno Study at the LHC

- Signal: 1-lep + 1-photon inclusive

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

- Backgrounds:

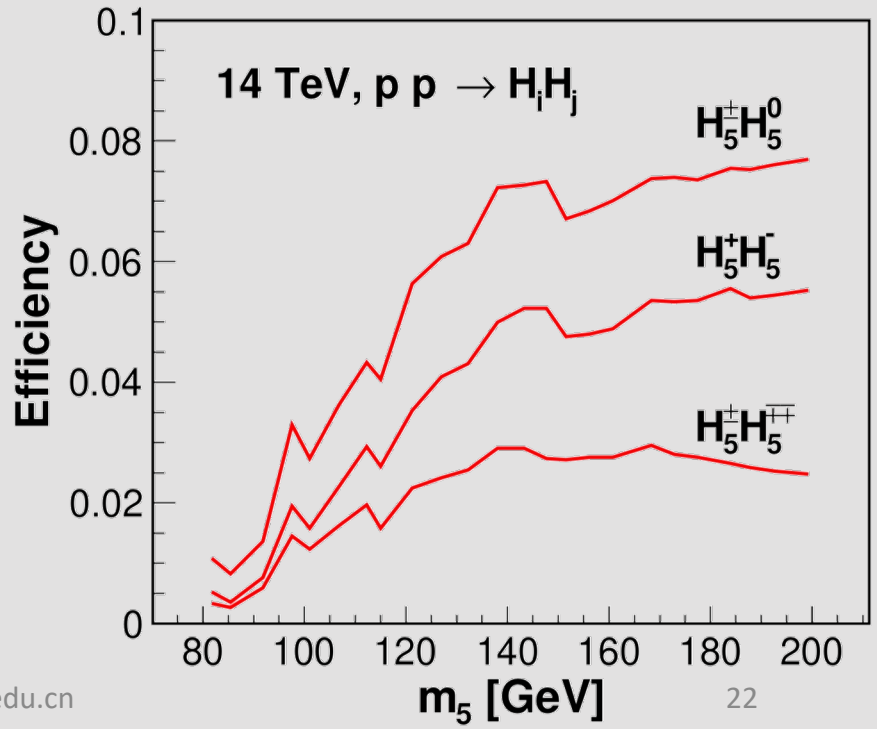
$$
\begin{aligned}
pp &\to W^{\pm}\gamma \to \ell\ \nu_\ell\ \gamma, \\
pp &\to W^{\pm}\gamma\gamma \to \ell\ \nu_\ell\ \gamma\ \gamma, \\
pp &\to W^{+}W^{-}\gamma \to \ell\ \nu_\ell\ \gamma + X, \\
pp &\to W^{+}W^{-}\gamma\gamma \to \ell\ \nu_\ell\ \gamma\ \gamma + X, \\
pp &\to t\bar{t}\gamma \to \ell\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

Selections and Results

- Selections:
  - 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

$$p_\ell \cdot q,$$

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



Recast of the $\gamma\gamma$ 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 $\frac{E_T^{\gamma 2}}{m_{\gamma\gamma}} > 0.3$