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HPNP2019

Light Scalars in Georgi-Machacek Model at the LHC

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HPNP2019, Osaka, Japan

Heather Logan, YW JHEP 1811 (2018) 121

Ameen Ismail, Ben Keeshan, Heather Logan, YW: work in progress



Outline

- Georgi-Machacek Model

- Current Constraints

- Low mass benchmark

- $H^\pm \rightarrow W^\pm \gamma$ Channel

Jeonghyeon Song's talk in Wednesday about this channel in 2HDM with VLQ

- Summary

Georgi-Machacek Model

- GM Model:
 - Larger Isospin Scalars (Double charged scalar, Fermiophobic)
 - Larger Gauge interactions ($\kappa_V > 1$)
- SM + One complex Triplet + One real Triplet:

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

$\rho \approx 1$

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

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

- 9 parameters

Gauge Couplings $v, s_H, \cos \alpha, m_h, m_H, m_3, m_5, M_1, M_2$. Proportional to s_H

Georgi-Machacek Model

- SM + One complex Triplet + One real Triplet:

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

- Global $SU(2)_L \times SU(2)_R$, $\langle \chi^0 \rangle = \langle \xi^0 \rangle$ (Custodial symmetry)
- Physical Spectrum after EWSB:
 - Bi-doublet: $2 \otimes 2 \rightarrow 1 \oplus 3$, Bi-triplet: $3 \otimes 3 \rightarrow 1 \oplus 3 \oplus 5$
 - Two custodial singlets mix $\rightarrow h, H$. m_h, m_H, α
 - h as SM-like 125 GeV Higgs.
 - Two custodial triplets mix $\rightarrow (H_3^+, H_3^0, H_3^-) + \text{Goldstone } m_3$
 - Similar to H^\pm, A^0 in Type-I 2HDM, $\tan \beta \rightarrow \cot \theta_H$
 - Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$. m_5
 - Fermiophobic, $g_{H_5 VV} \propto s_H = \frac{2\sqrt{2}v_\chi}{v}$
 - Our focus

Current Searches/Constraints

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

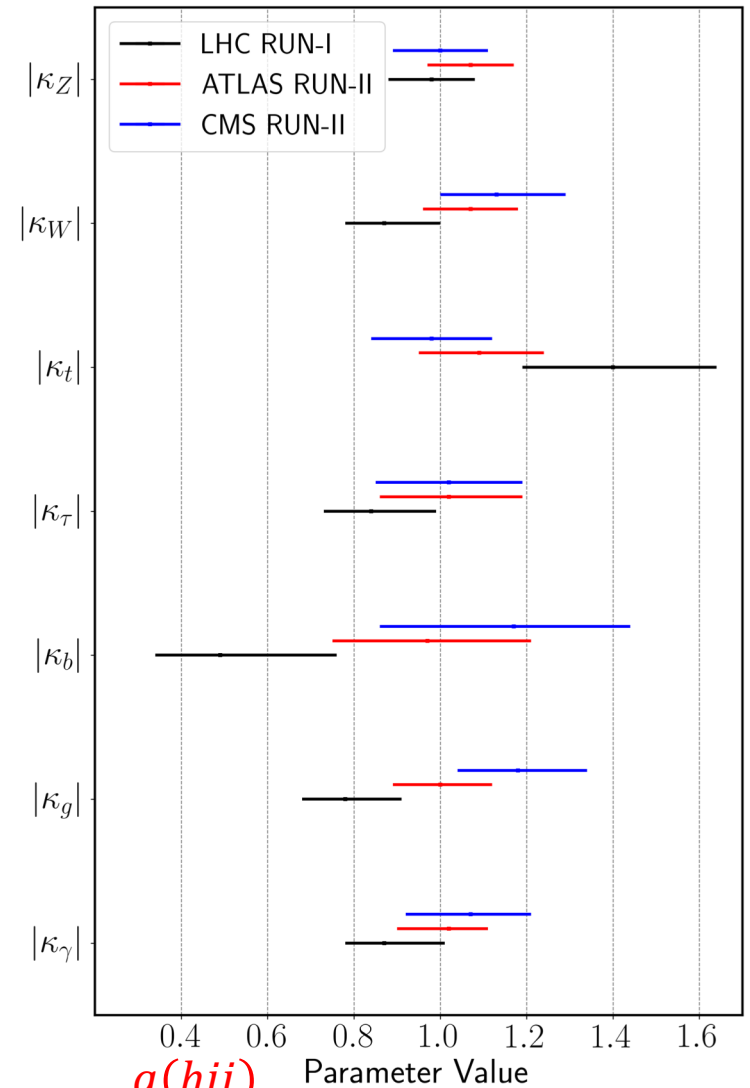
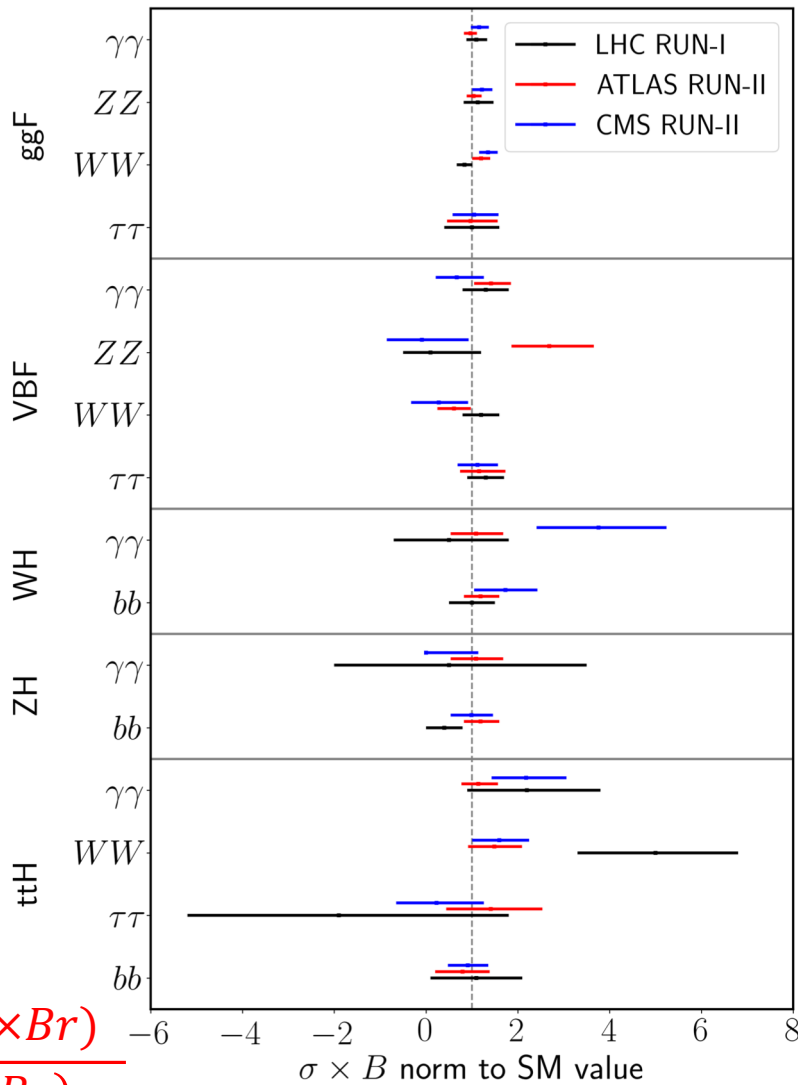
Current Searches/Constraints

1606.02266

1809.10733

ATLAS-CONF-2018-031

- Higgs Signal Strength



$$\mu_i \sim \frac{(\sigma \times Br)}{(\sigma \times Br)_{SM}}$$

$$\kappa_i \sim \frac{g(hii)}{g(hii; SM)}$$

Assume no BSM channel

Current Searches/Constraints

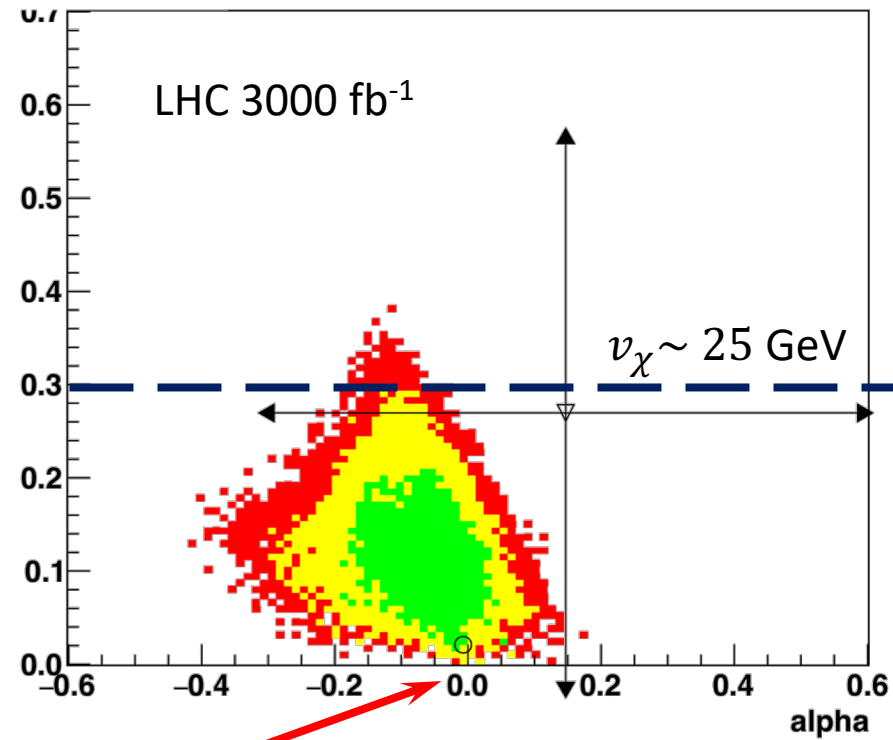
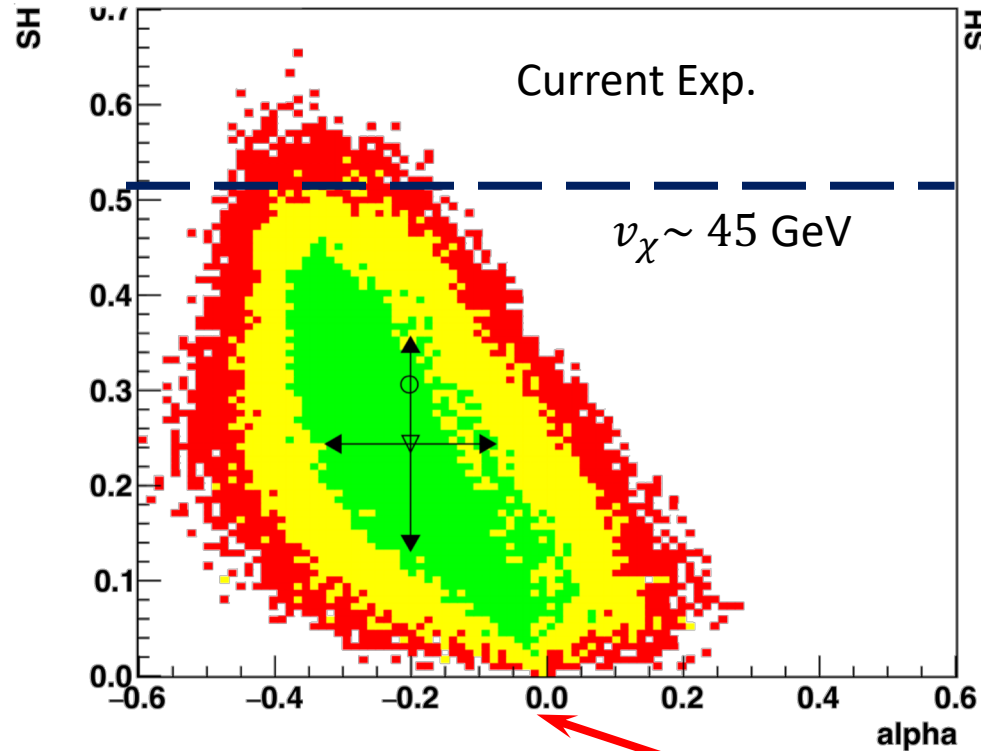
1606.02266

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- Higgs Signal Strength



Alignment Limit

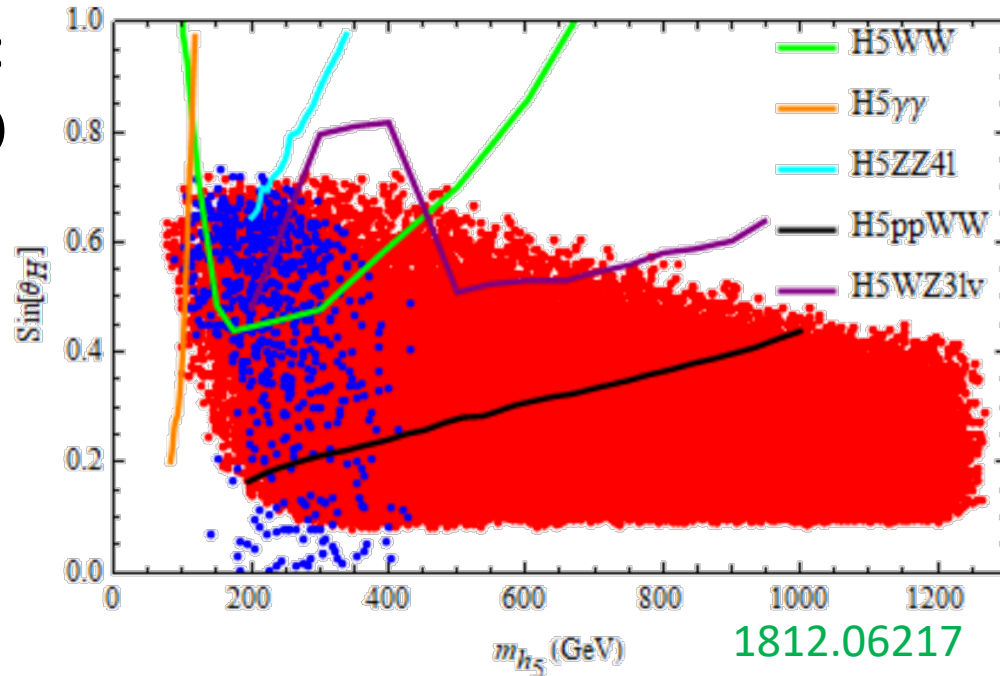
$$\kappa_f = \kappa_g = \frac{c_\alpha}{c_H}$$

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

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

Current Searches/Constraints

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



- 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

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

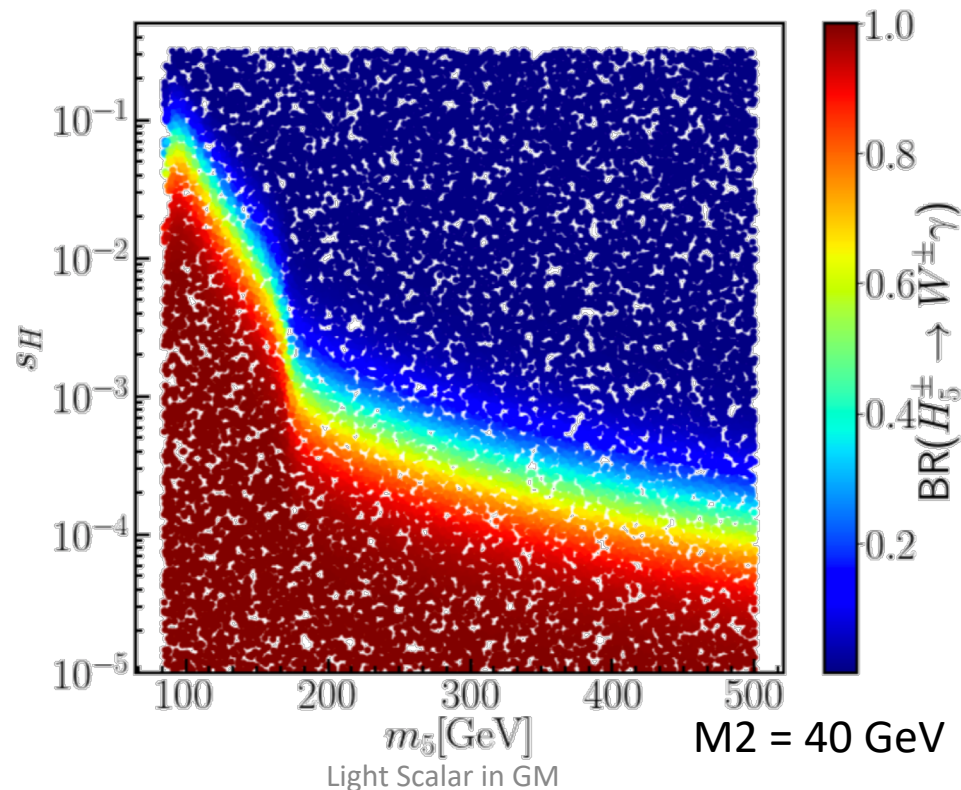
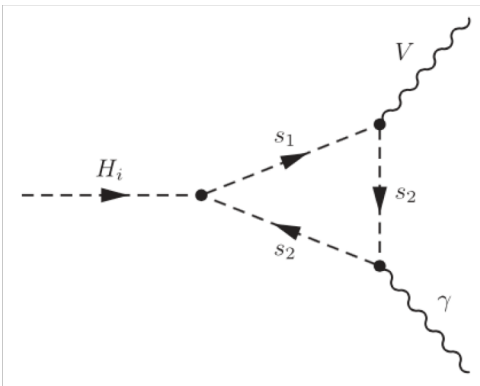
Variables	Other fixed parameters
$m_5 \in (50,550) \text{ GeV}$	$\lambda_2 = 0.08(m_5/100)$
$s_H \in (0,1)$	$\lambda_3 = -\lambda_4 = -1.5$
M_2	$\lambda_5 = -4\lambda_2$

$H^\pm \rightarrow W^\pm \gamma$ Searches

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

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

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

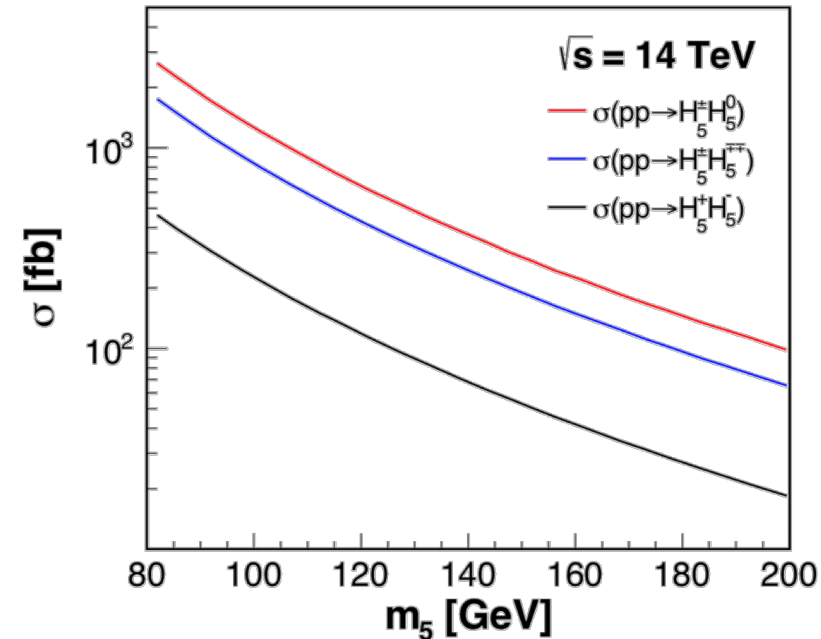


Pheno Study at the LHC

- Simulation through MG5:
 - 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/>
- Signal: 1-lep + 1-photon inclusive

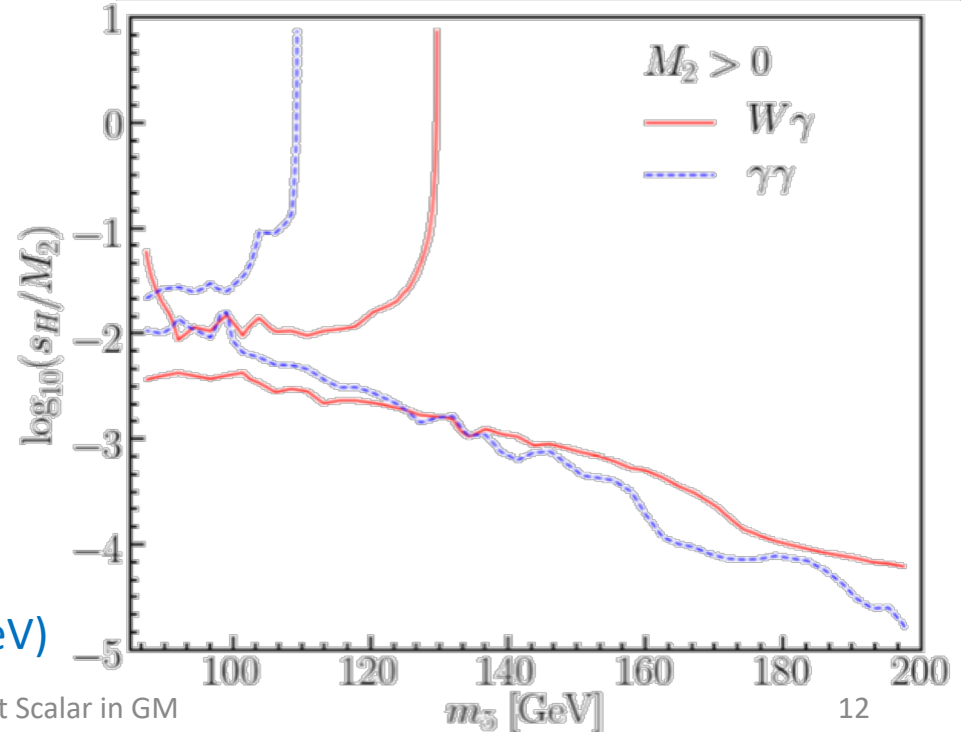
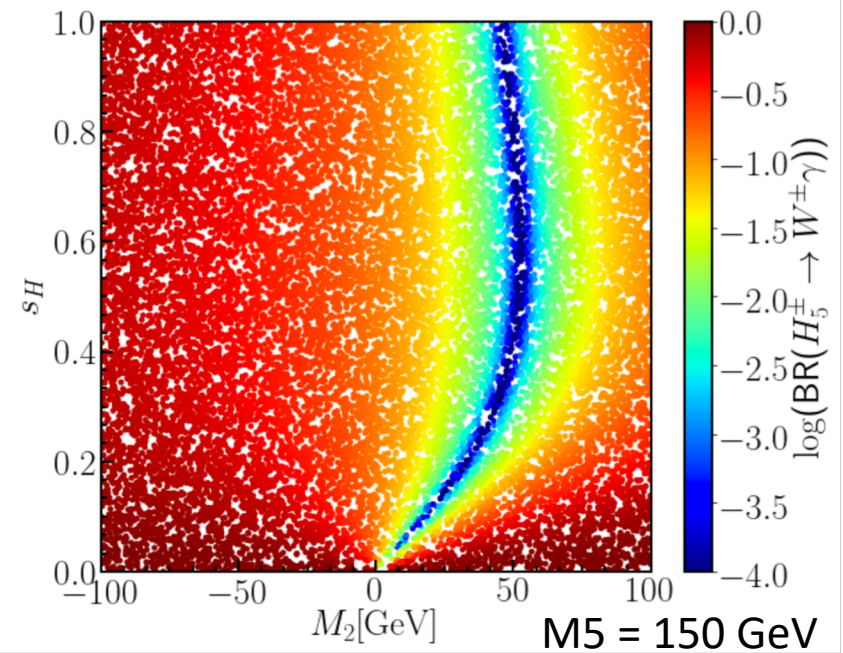
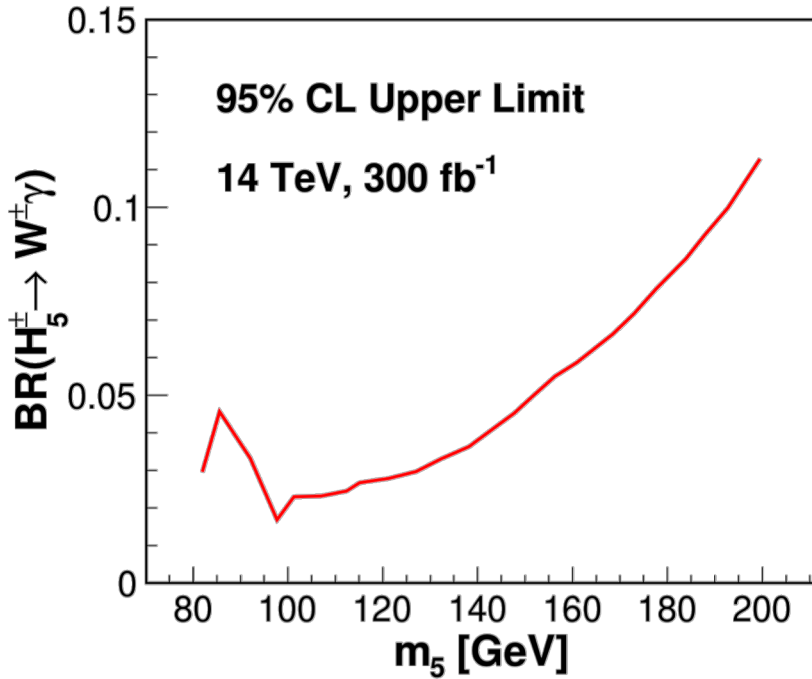
Drell-Yan

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



Results

- Upper limits on the BR:



$\gamma\gamma$ results recast from 1407.6583 (ATLAS 8 TeV)

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.
- Low mass benchmark in GM model is provided.
- $W^{\pm}\gamma$ channel is studied for low mass fermiophobic scalar, mass up to 130 GeV is excluded.



Thanks!

Backups

Current Searches/Constraints

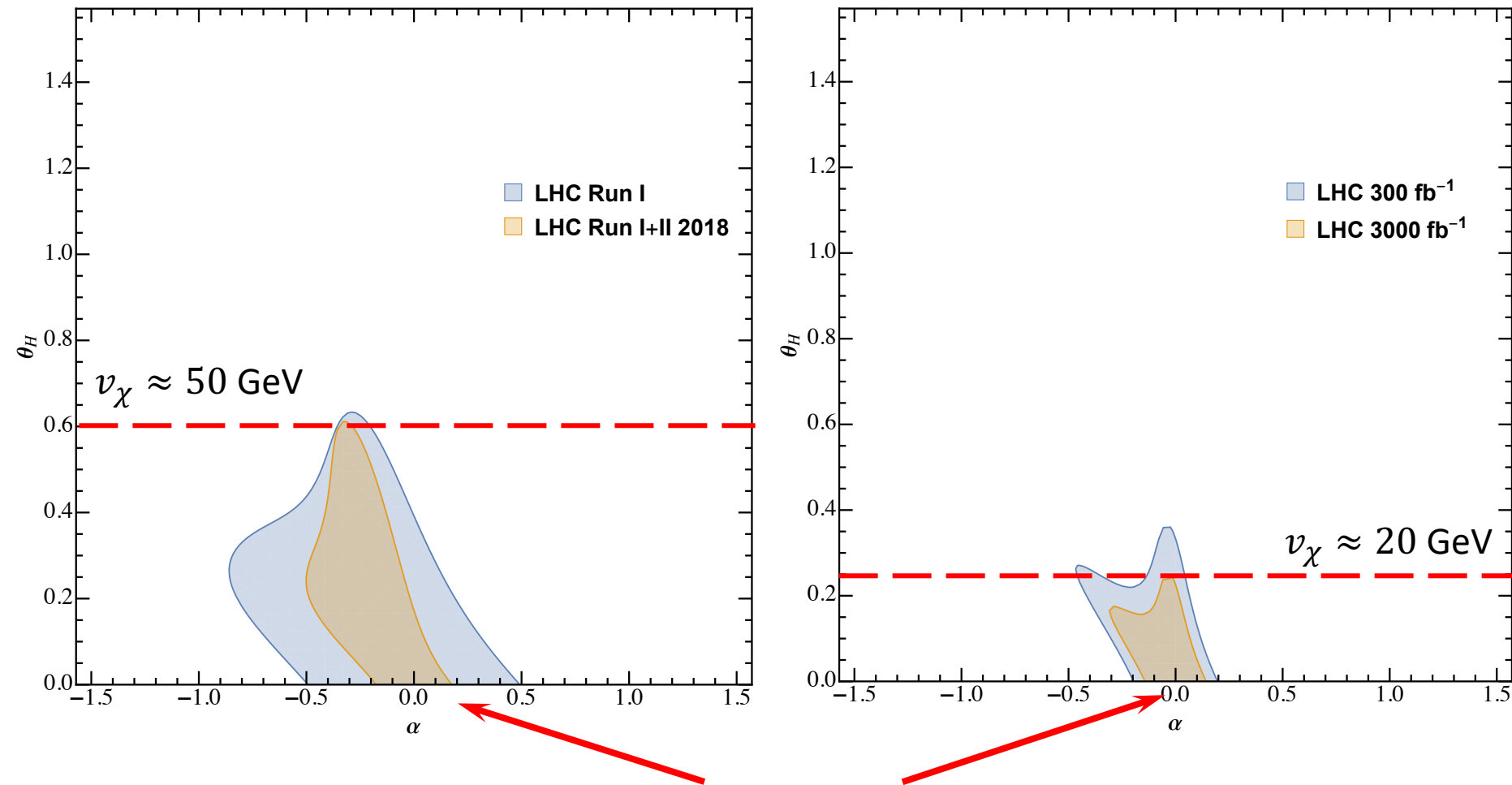
- Higgs Signal Strength

1606.02266

1809.10733

ATLAS-CONF-2018-031

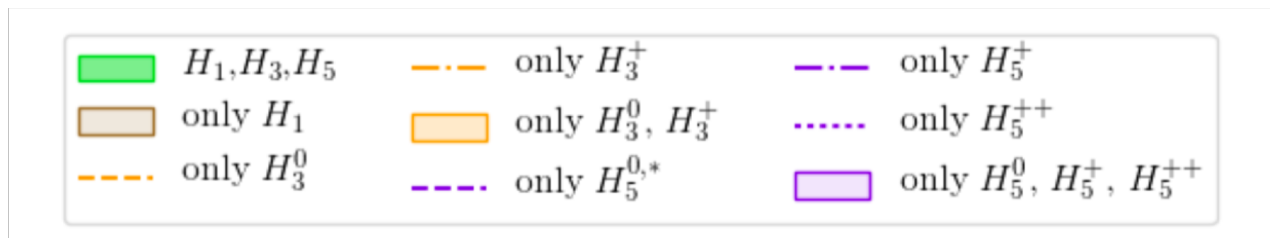
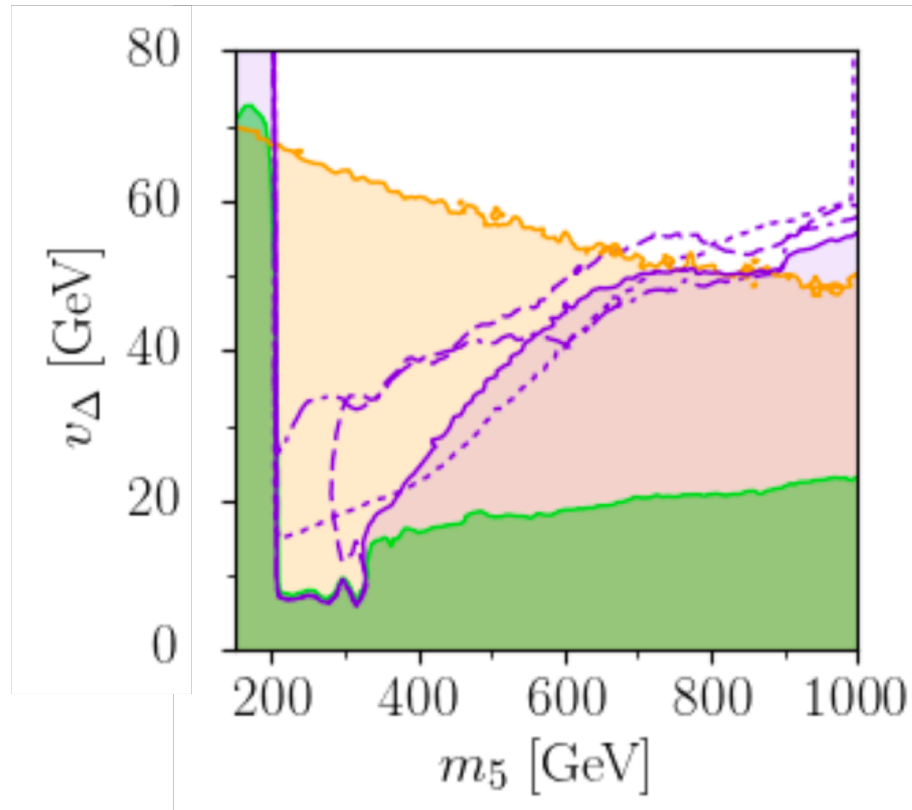
JHEP12 (2017) 153



Alignment Limit

Current Searches/Constraints

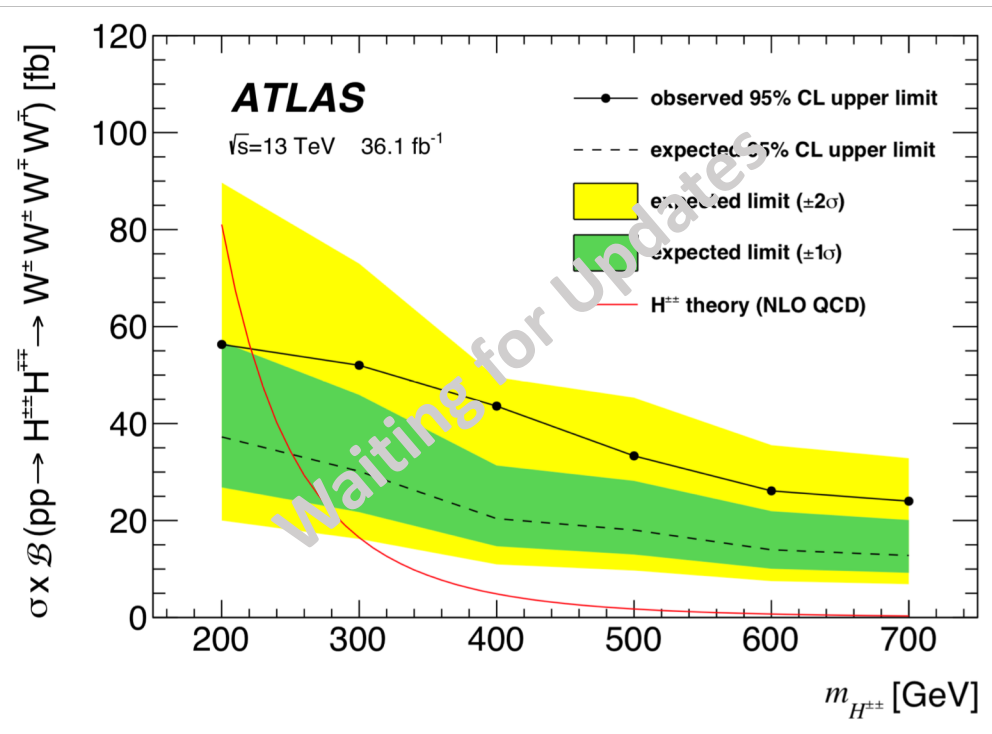
- Comprehensive Global fitting with Direct detection:



Phys.Rev. D99 (2019) no.1, 015001

Current Searches/Constraints

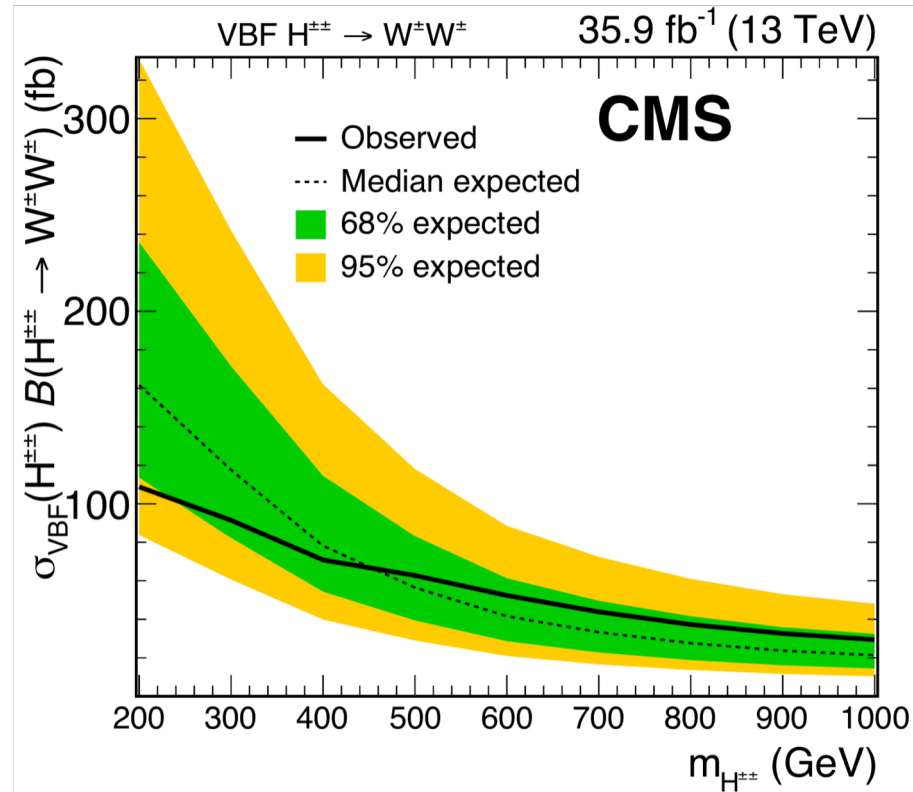
- Exotic Higgs Searches
 - Double charged scalar H_5^{++} :
 - Decay to Same sign W



2 SS lepton + 3 lepton + 4 lepton

1808.01899

Osaka Feb 2019

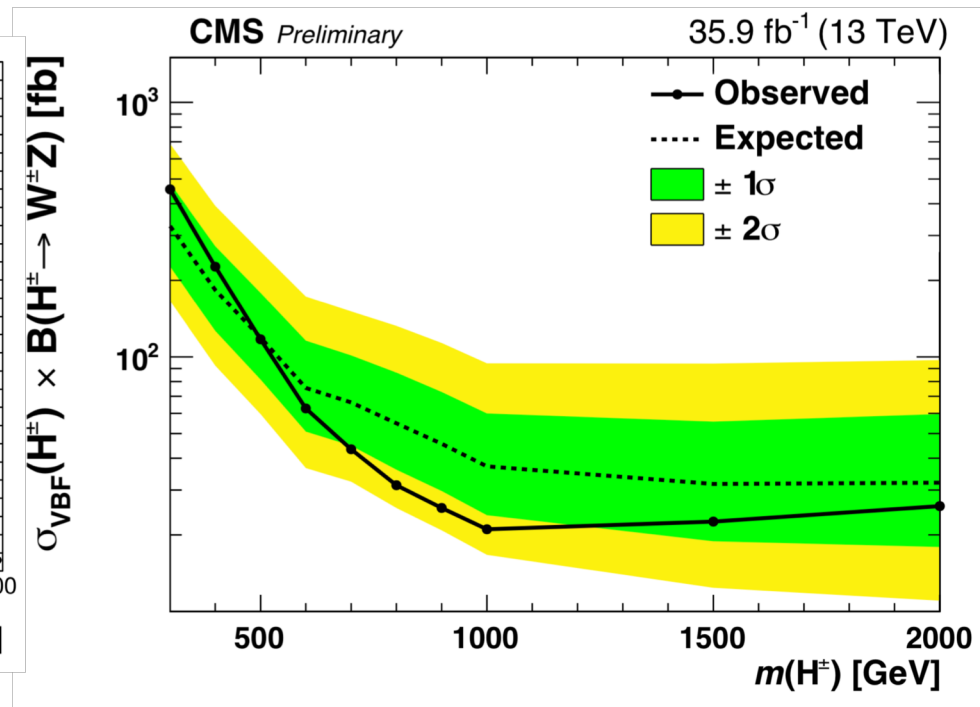
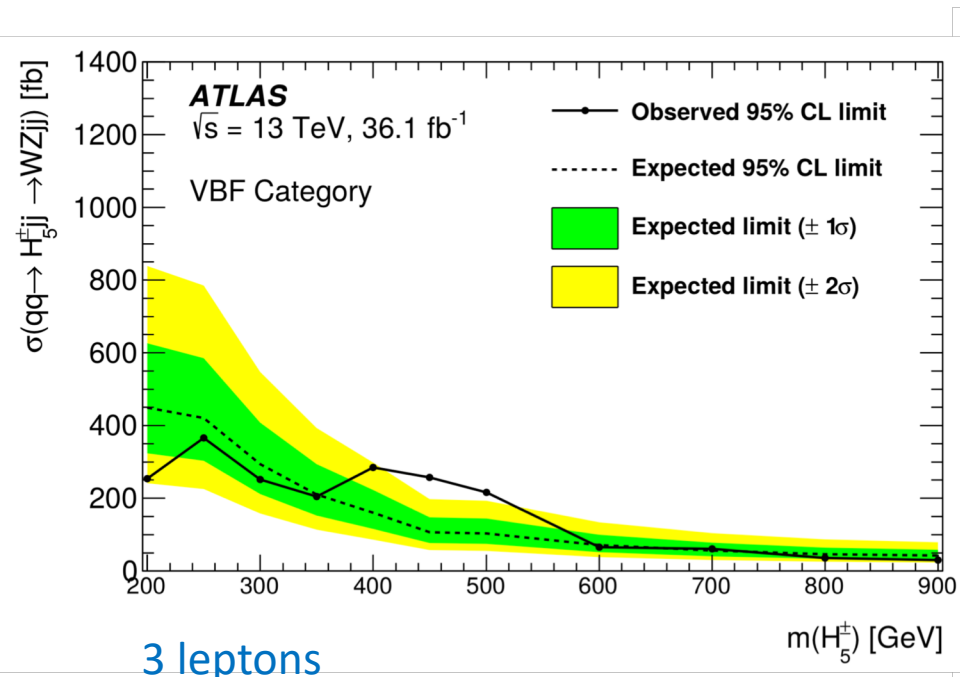


2 SS lepton

1709.05822

Current Searches/Constraints

- Exotic Higgs Searches
 - Single charged scalar H^\pm :
 - Decay to WZ

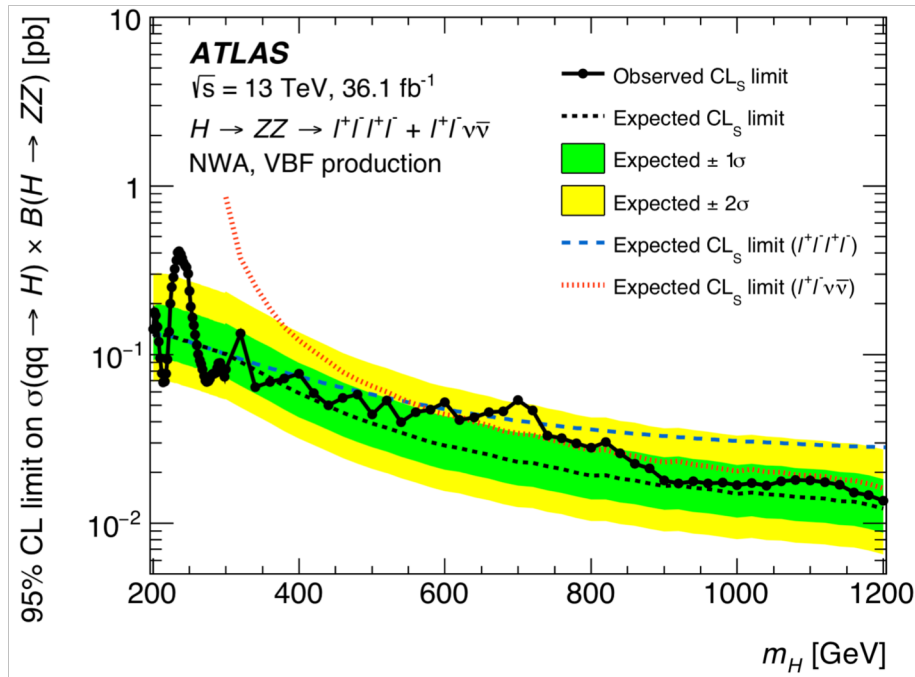


1806.01532

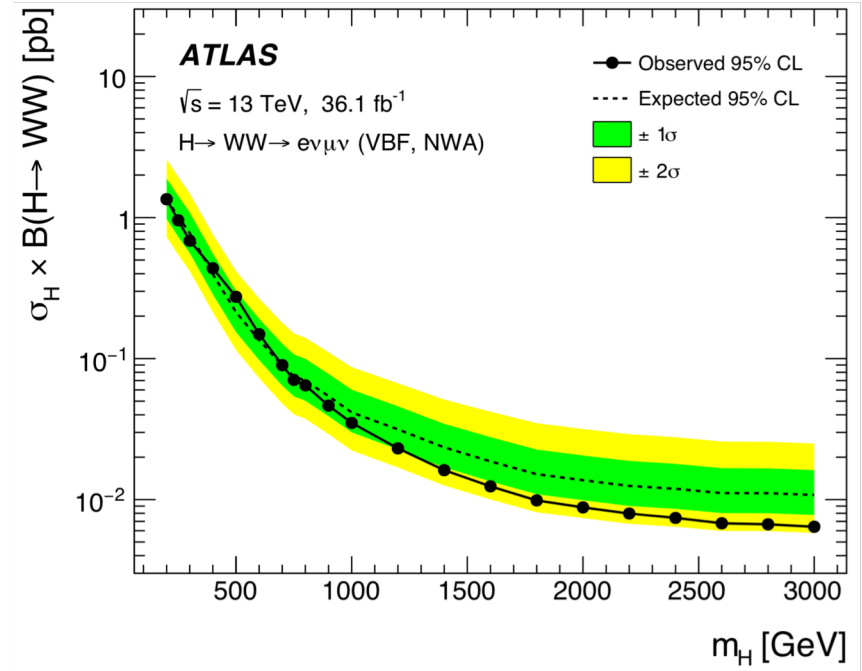
CMS-PAS-SMP-18-001

Current Searches/Constraints

- Exotic Higgs Searches
 - Neutral scalar H^0 :
 - Decay to $WW/ZZ/\gamma\gamma$

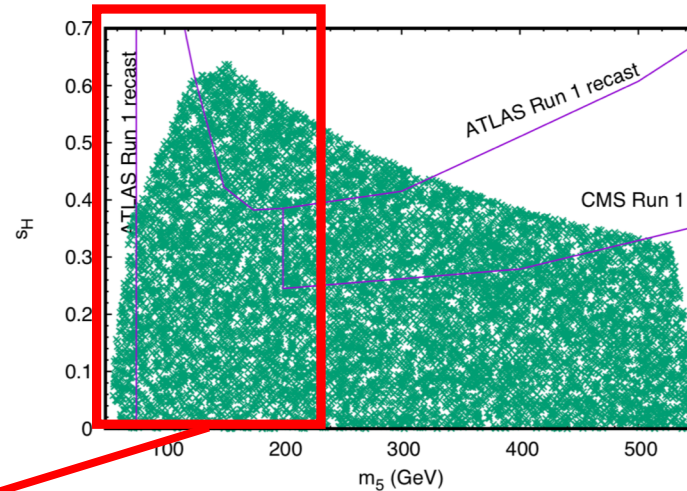
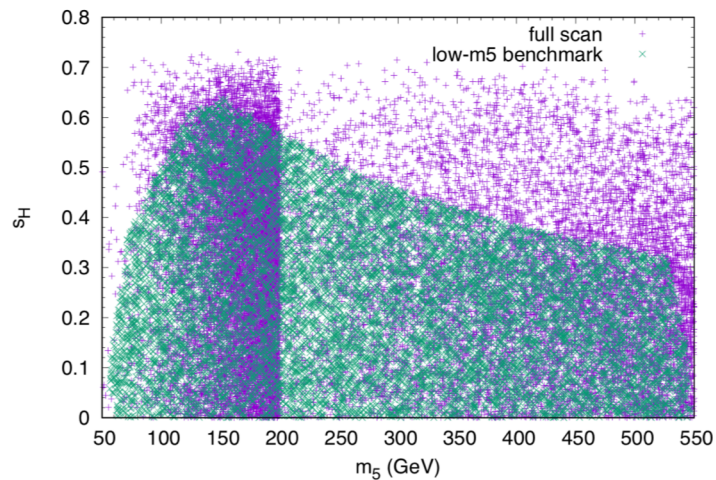


1712.06386

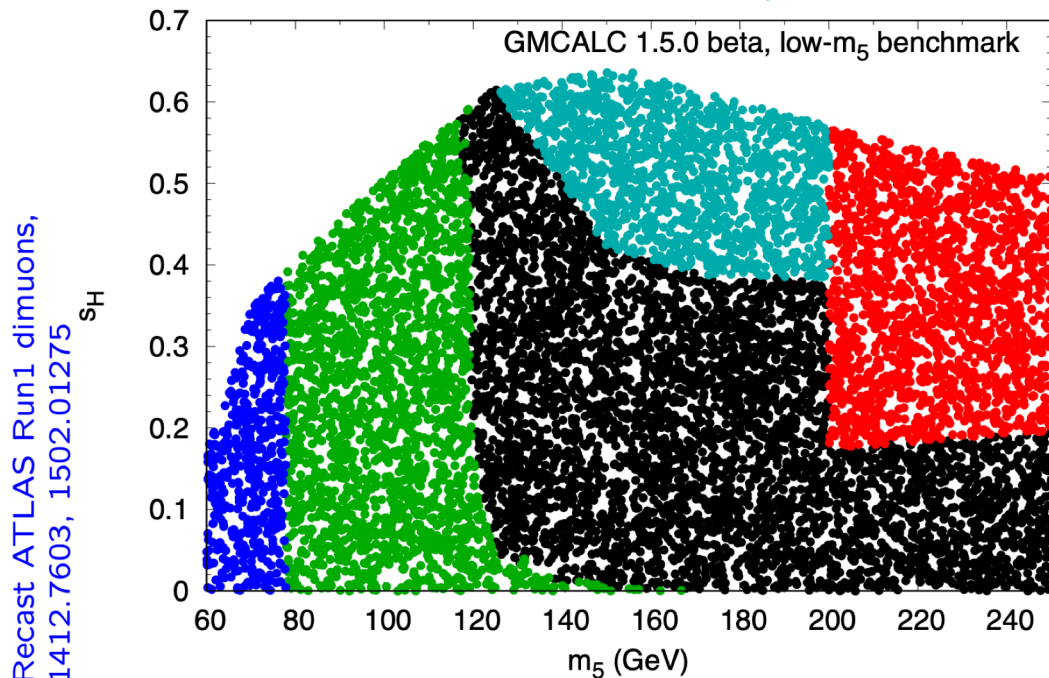


1710.01123

Low mass benchmark



Recast ATLAS Run1 VBF $\rightarrow W^+W^-$, 1407.5053



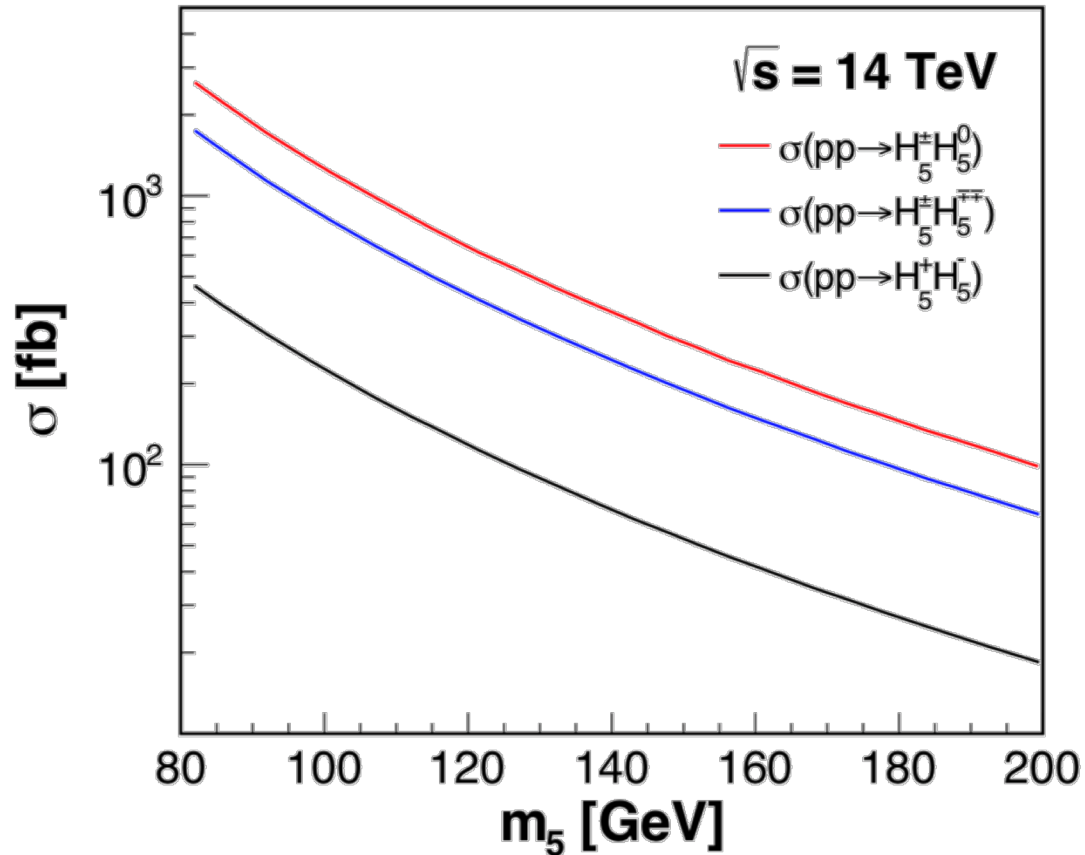
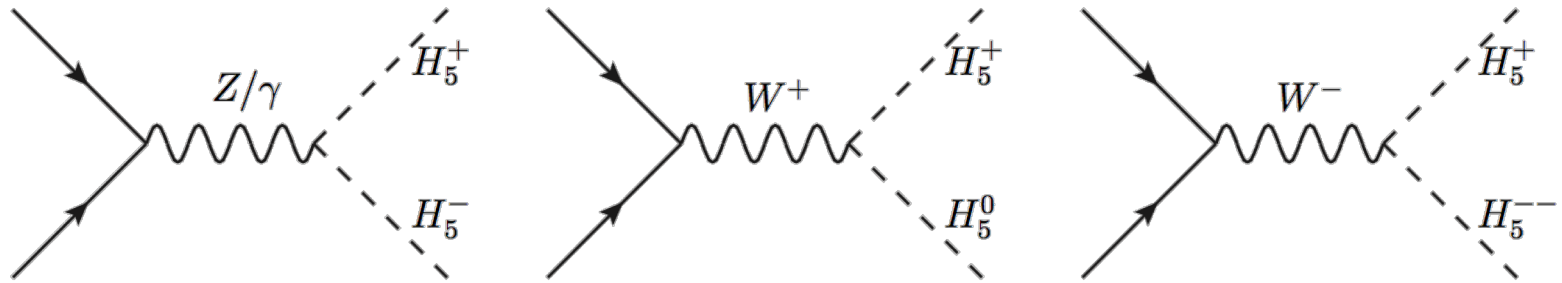
(Preliminary)

CMS VBF $\rightarrow H^{\pm\pm} \rightarrow W^+W^-$
1709.05822

Allowed

Recast ATLAS Run1 $\gamma\gamma$ resonance, GMCALC 1.5.0 beta

Drell-Yan production @ 14TeV

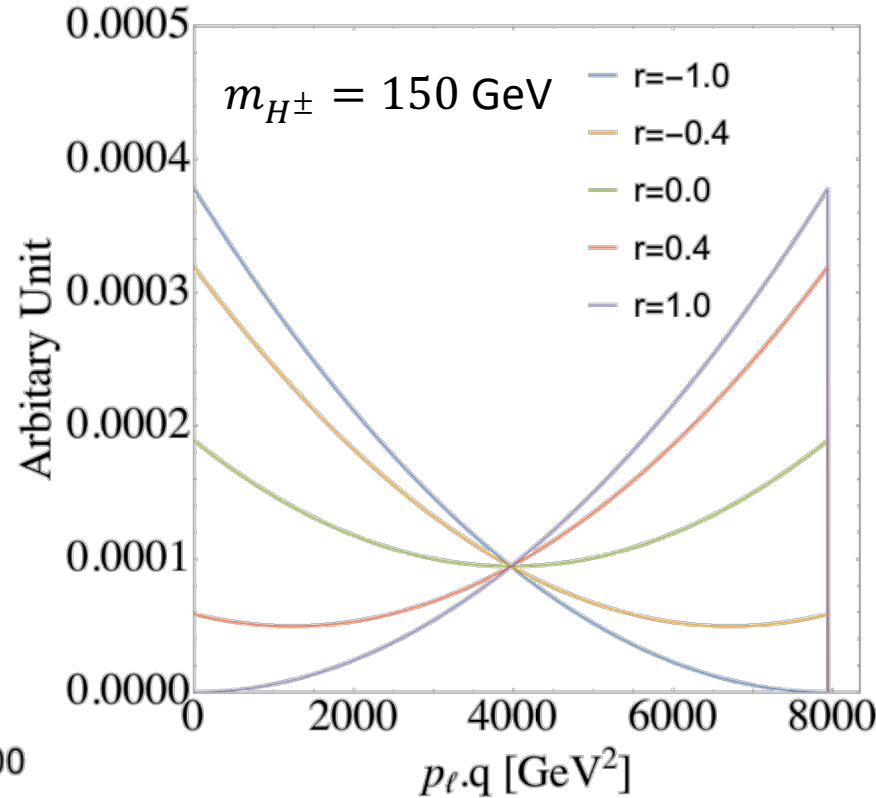
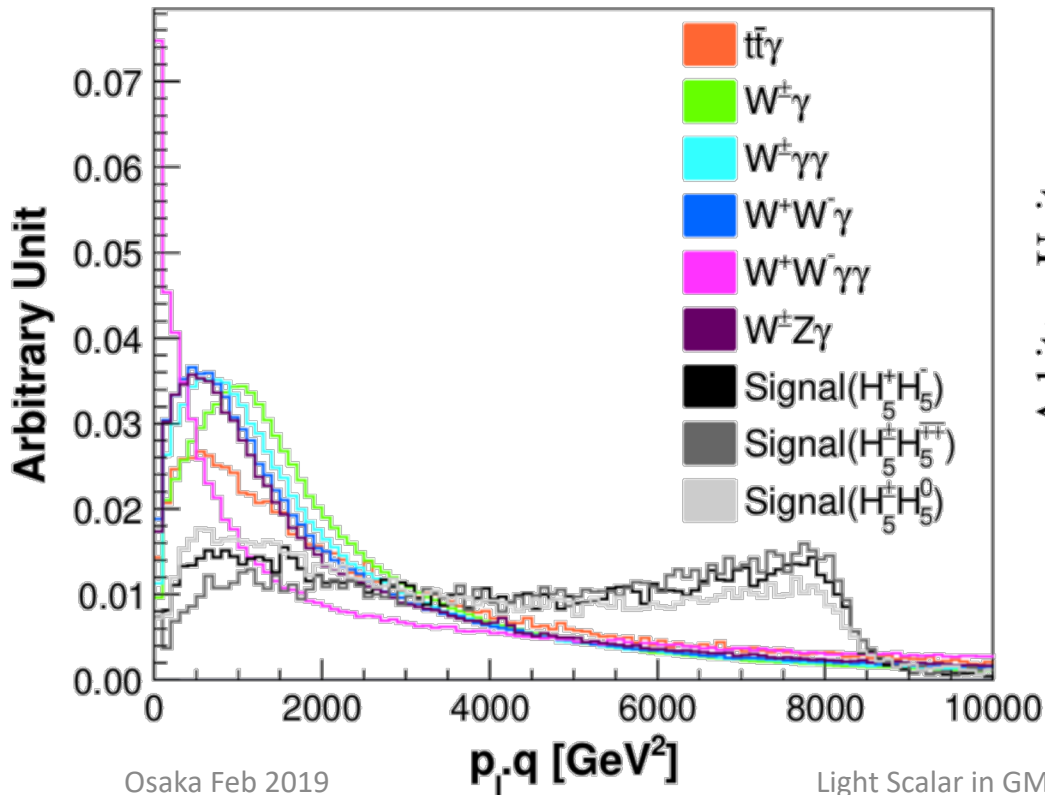


Distributions

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

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

$$r \equiv \frac{\tilde{S}}{S}, \quad K \equiv \frac{p_\ell \cdot q}{(m_{H^+}^2 - m_W^2)/2} \in [0, 1], \quad |\mathcal{M}|^2 \propto 2K^2 [1 + |r|^2] + (-2K + 1) [1 + |r|^2 - 2\text{Re}(r)].$$



Pheno Study at the LHC

- Simulation through MG5:
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 - Spectrum generated with [GMCalc](http://people.physics.carleton.ca/~logan/gmcalc/)
- Signal: 1-lep + 1-photon inclusive

Drell-Yan

$$pp \rightarrow H_5^\pm H_5^0 \rightarrow W^\pm \gamma + X \rightarrow \ell \nu_e \gamma + X,$$

$$pp \rightarrow H_5^\pm H_5^{\mp\mp} \rightarrow W^\pm \gamma + X \rightarrow \ell \nu_e \gamma + X,$$

$$pp \rightarrow H_5^+ H_5^- \rightarrow W^\pm \gamma + X \rightarrow \ell \nu_e \gamma + X.$$

- Backgrounds:

$$pp \rightarrow W^\pm \gamma \rightarrow \ell \nu_e \gamma,$$

$$pp \rightarrow W^\pm \gamma \gamma \rightarrow \ell \nu_e \gamma \gamma,$$

$$pp \rightarrow W^+ W^- \gamma \rightarrow \ell \nu_e \gamma + X,$$

$$pp \rightarrow W^+ W^- \gamma \gamma \rightarrow \ell \nu_e \gamma \gamma + X,$$

$$pp \rightarrow t\bar{t}\gamma \rightarrow \ell \nu_e \gamma + X,$$

$$pp \rightarrow W^\pm Z \gamma \rightarrow \ell \nu_e \gamma + X.$$

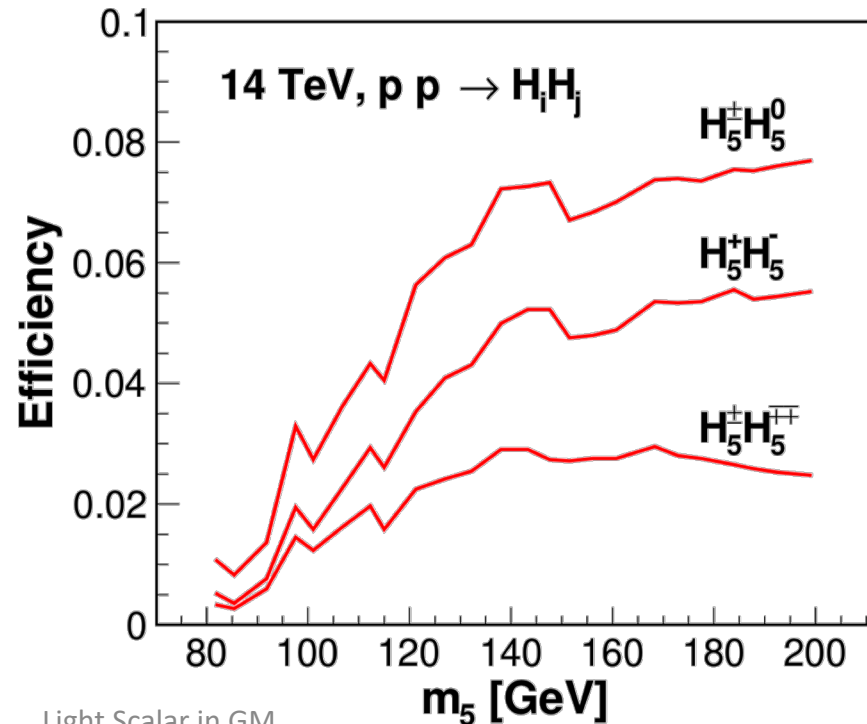
Selections and Results

- Selections:
 - Lepton & Photon:
 - At least one lepton & one Photon
 - With $p_T > 25$ GeV, $|\eta| < 2.5$
 - Jets & b-Jets:
 - No more than 2 jets with $p_T > 20$ GeV
 - No b-tagged jet
 - Other Variables:

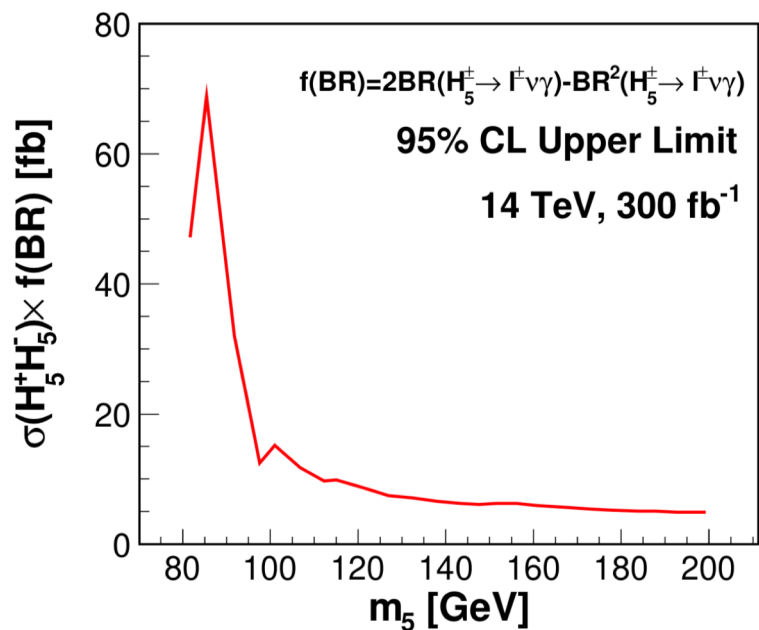
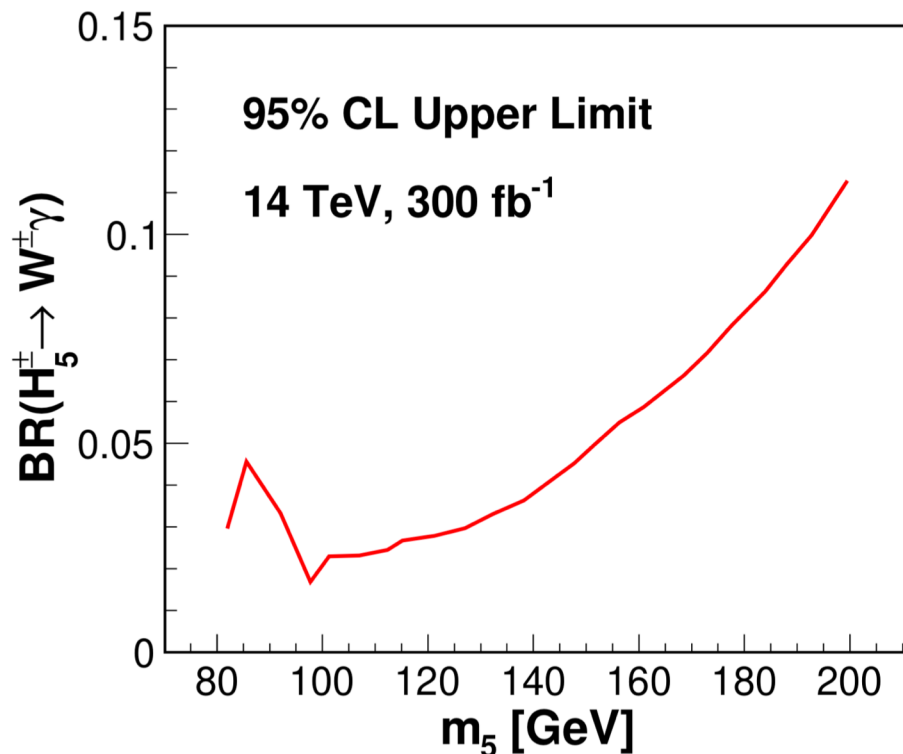
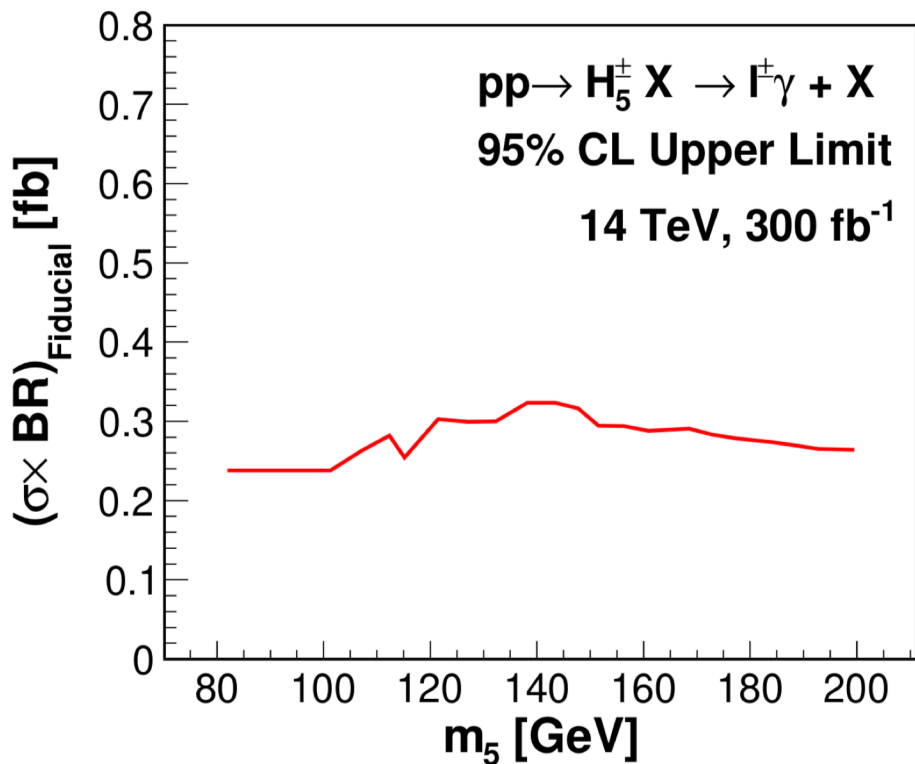
- MET, HT

$$p_\ell \cdot q,$$

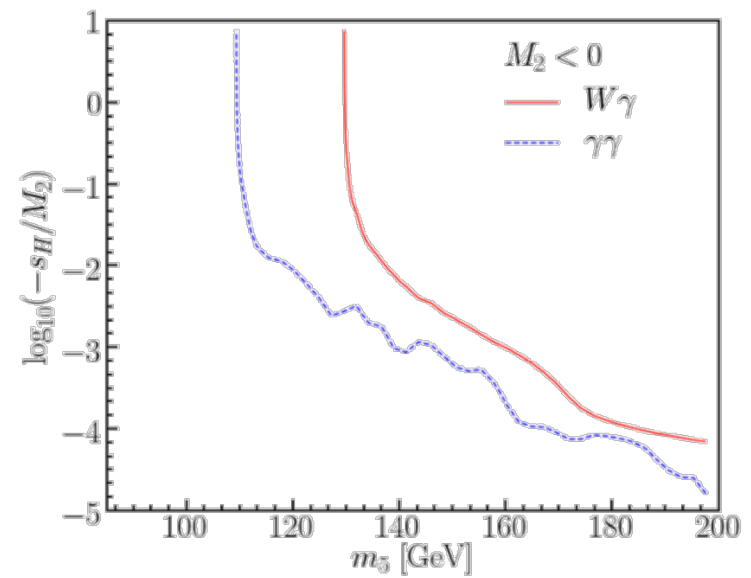
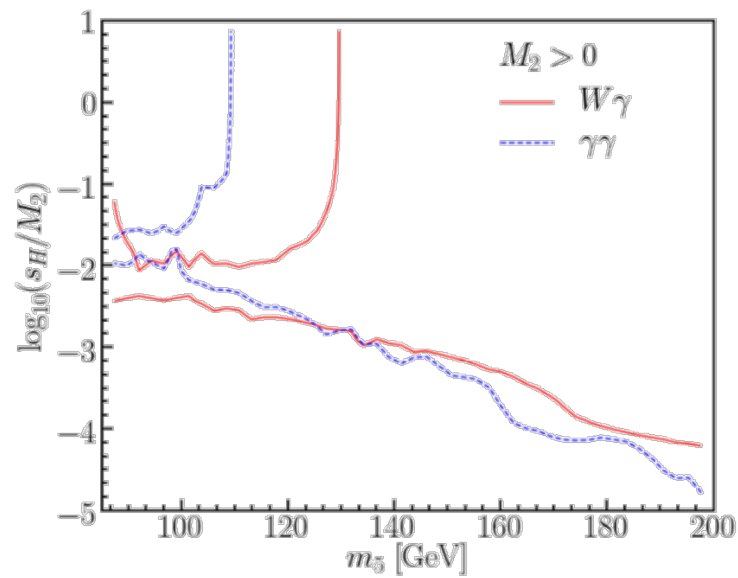
$$p_T^{\ell+\gamma+\cancel{E}_T}$$



Results



Results



$\gamma\gamma$ results recast from 1407.6583 (ATLAS 8 TeV)

Recast of the diphoton results

- Consider $pp \rightarrow H_5^\pm H_5^0$ process
- Calculate the fiducial efficiency(as function of m_5)
 - 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.