Probes of a SM-like and Fermiophobic Higgs Boson

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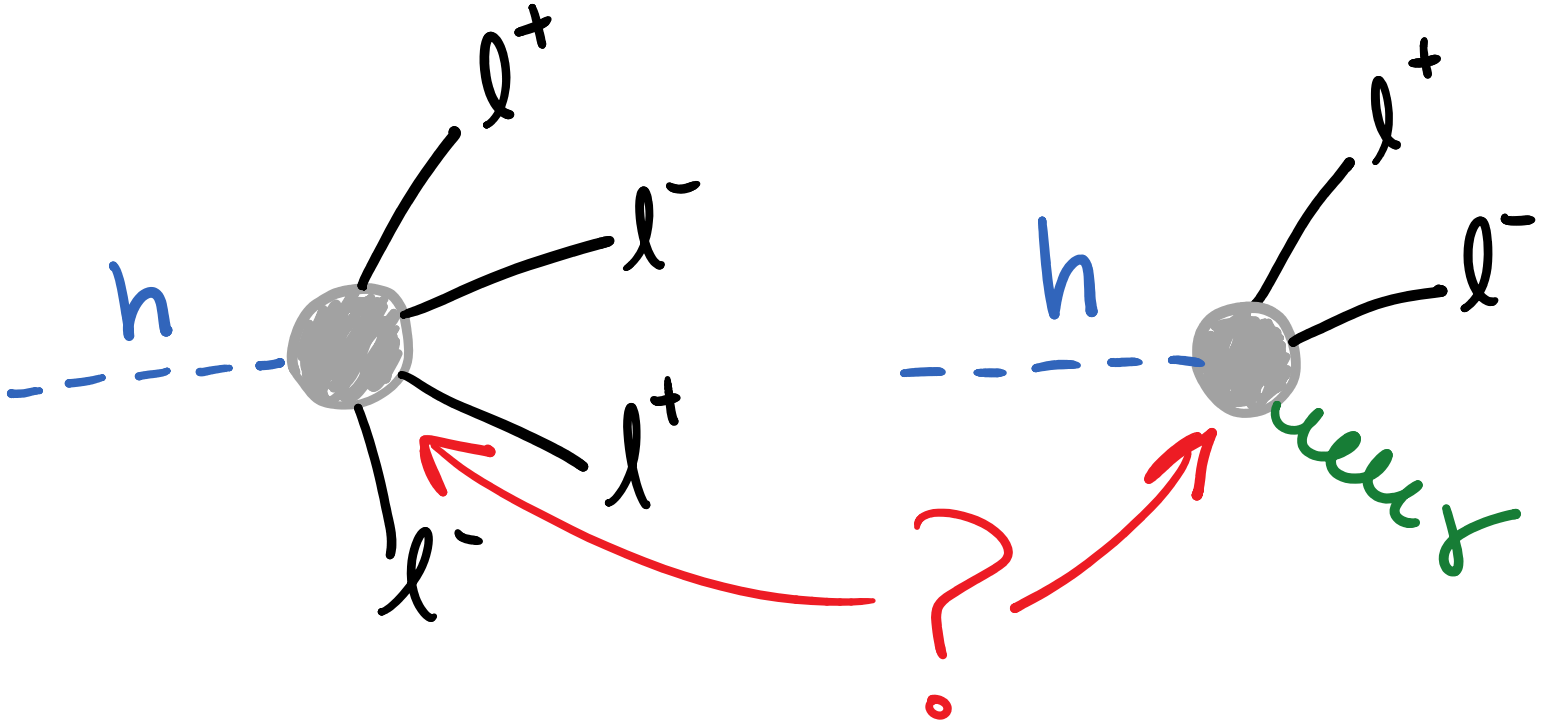
In collaboration with many...

The Higgs Boson in $h \to 4\ell$ and $h \to 2\ell\gamma$



In collaboration with: Adam Falkowski, Roni Harnik, Ian Low, Joe Lykken, Daniel Stolarski

and experimentalists Yi Chen, Emanuele DiMarco, Maria Spiropulu, Si Xie

Physics Possibilities in $h \to 4\ell$ and $h \to 2\ell\gamma$

- Hypothesis testing and multi-parameter extraction at LHC
- Probing Higgs CP properties $\Rightarrow$ searching for CP violation
- Measuring/constraining effective hVV Couplings

  (Y. Chen, RVM + others: 1211.1959, 1310.2893, 1404.1336, 1410.4817, 1411.3441, 1503.05855)
- New Observables for CP violation in Higgs decays

  (Y. Chen, A. Falkowski, I. Low, RVM: 1405.6723)
- Exotic Higgs decays

  (A. Falkowski, RVM: arXiv:1404.1095)
- Probing top Yukawa CP properties

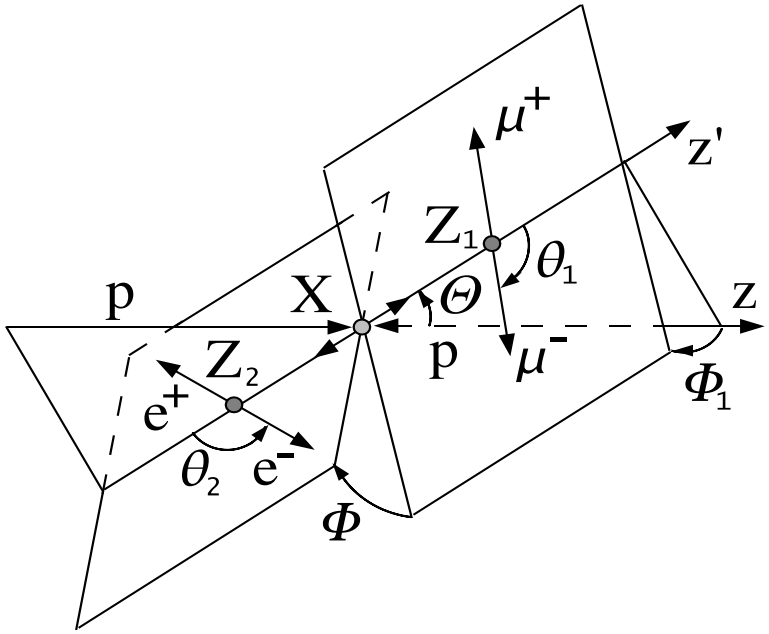
  (Y. Chen, D. Stolarski, RVM: 1505:01168)
- Testing $SU(2)_L \otimes U(1)_Y$ gauge invariance and EFT

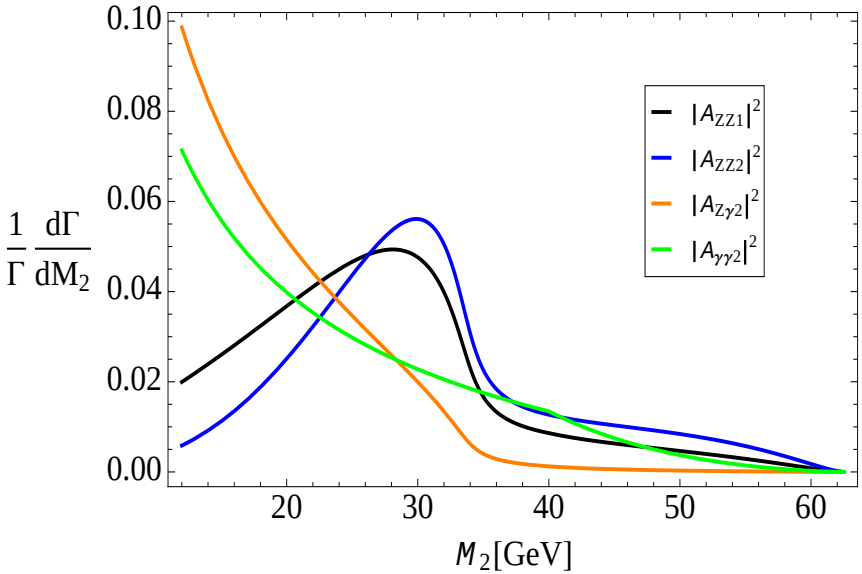
  (Y. Chen, A. Falkowski, R. Harnik RVM: Ongoing)
- Testing Custodial symmetry

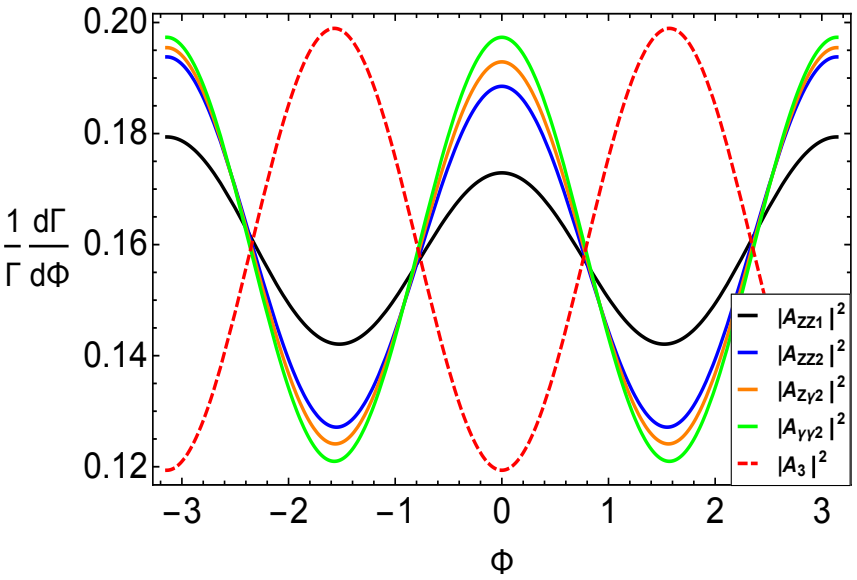
  (Y. Chen, J. Lykken, M. Spiropulu D. Stolarski, RVM: Ongoing)

ID-ing the Higgs with Kinematic Distributions

- Sensitivity to Higgs couplings and underlying loop effects comes from the many kinematic differential distributions and their correlations
- They contain information about CP properties and tensor structure of Higgs couplings







Constructing a MEM Likelihood Analysis

- A likelihood can be formed out of probability density functions (*pdfs*) using some set of observables as follows

$$L(\vec{A}) = \prod_{\mathcal{O}}^{N} \mathcal{P}(\mathcal{O}|\vec{A})$$

(where $\mathcal{O}$ is set of observables and $\vec{A}$ a set of undetermined parameters)

- For $pp \to h \to 4\ell$ we construct the pdf from the differential cxn:

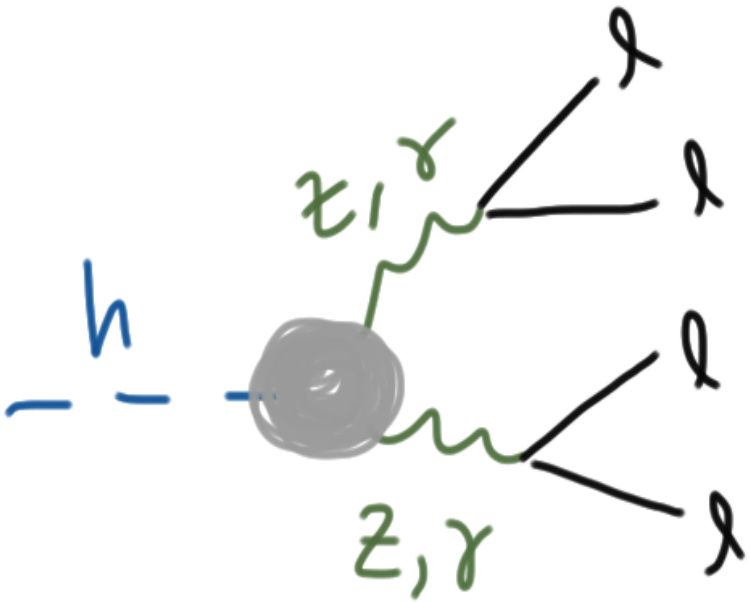
$$P(\vec{p}_T, Y, \phi, \hat{s}, M_1, M_2, \vec{\Omega}|\vec{A}) =$$

$$W_{\text{prod}}(\vec{p}_T, Y, \phi, \hat{s}) \times \frac{d\sigma_{4\ell}(\hat{s}, M_1, M_2, \vec{\Omega}|\vec{A})}{dM_1^2 dM_2^2 d\vec{\Omega}}$$

- Construct ratios $\Lambda = L(A_a)/L(A_b) \Rightarrow$ hypothesis testing
- Perform parameter extraction via maximization of the likelihood

$$\frac{\partial L(\vec{A})}{\partial \vec{A}}\Big|_{\vec{A}=\hat{A}} = 0$$

Anomalous Higgs Couplings in $h \to 4\ell$



- We consider $h \to VV \to 4\ell$ where $4\ell \equiv 2e2\mu, 4e, 4\mu$ and $VV = ZZ, Z\gamma, \gamma\gamma$
- Can parametrize the hVV couplings with an effective Lagrangian (up to D = 5)

$$\mathcal{L} = \frac{h}{4v}\Big(2m_Z^2 A_1^{ZZ} Z_\mu Z^\mu$$

Background

$$+ A_2^{ZZ} Z_{\mu\nu} Z^{\mu\nu} + A_3^{ZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

Signal

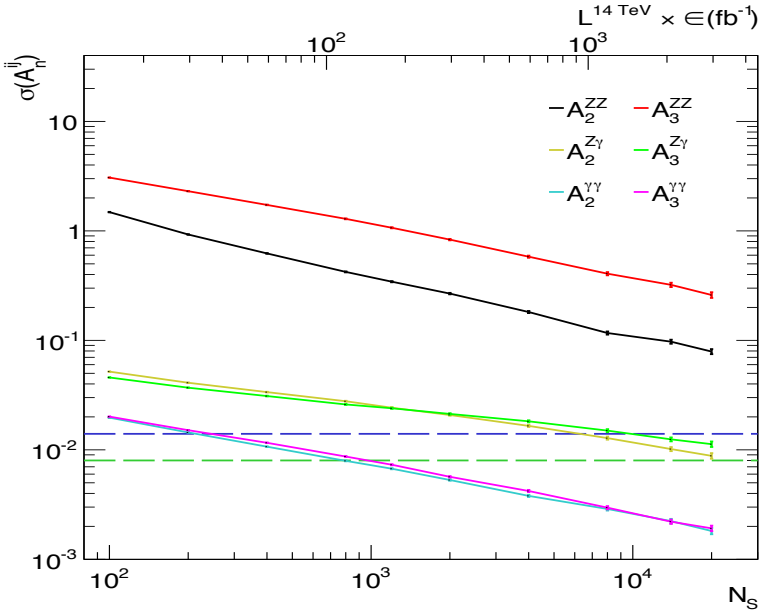
$$+ A_2^{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} + A_3^{\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$+ 2A_2^{Z\gamma} Z_{\mu\nu} F^{\mu\nu} + 2A_3^{Z\gamma} Z_{\mu\nu} \tilde{F}^{\mu\nu}\Big)$$

Many studies of $h \to 4\ell$ and $h \to 2\ell\gamma$ decays before and after discovery...

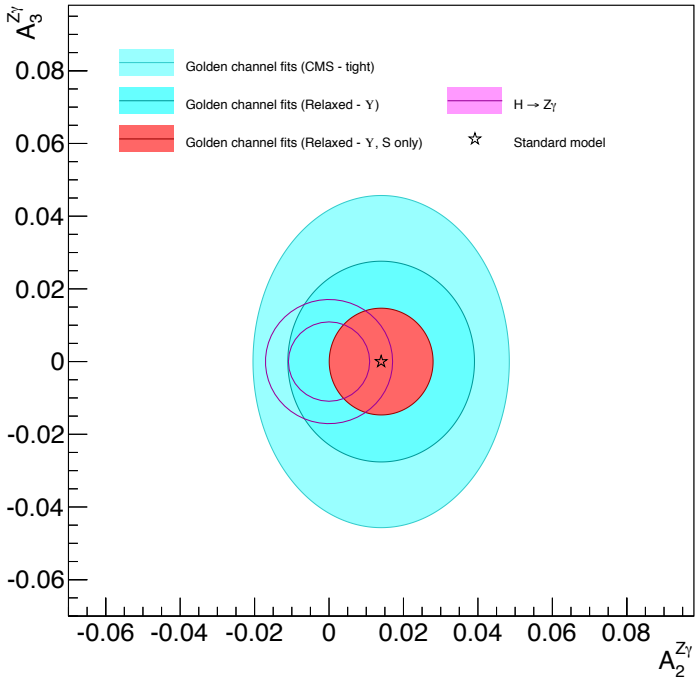
R. M. Godbole, D. Miller, M. Muhlleitner: **0708.0458**
Q. Cao, C. Jackson, W.Y. Keung, I. Low: **0911.3398**
Y. Gao, A. V. Gritsan, Z. Guo, K. Melnikov, M. Schulze, et. al: **1001.3396**
A. De Rujula, J. Lykken, M. Pierini, C. Rogan, M. Spiropulu: **1001.5300**
J. Gainer, K. Kumar, I. Low, RVM: **1108.2274**
S. Bolognesi, Y. Gao, A. V. Gritsan, K. Melnikov, et. al: **1208.4018**
R. Boughezal, T. LeCompte, F. Petriello: **1208.4311**
Avery, Bourilkov, Chen, Cheng, Drozdetskiy, et. al: **1210.0896**
J.M. Cambell, W.T. Giele, C. Williams: **1205.3434**
J.M. Cambell, W.T. Giele, C. Williams: **1204.4424**
J. Gainer, J. Lykken, et. al.: **1304.4936**
P. Artoisenet, P. de Aquino, F. Demartin, F. Maltoni, et. al: **1306.6464**
Sun, Yi and Wang, Xian-Fu and Gao, Dao-Neng: **1309.4171**
Anderson, S. Bolognesi, F. Caola, Y. Gao, A. V. Gritsan, et al.: **1309.4819**
T. Chen, J. Gainer, et. al.: **1310.1397**
Gonzales-Alonso, Isidori: **1403.2648**
J. Gainer, J. Lykken, K. T. Matchev, S. Mrenna, M. Park: **1403.4951**
M. Beneke, D. Boito, Y. Wang: **1406.1361**
M. Gonzalez-Alonso, A. Greljo, G. Isidori, D. Marzocca**1412.6038**
M. Gonzalez-Alonso, A. Greljo, G. Isidori, and D. Marzocca: **1504.04018**
M. Bordone, A. Greljo, G. Isidori, D. Marzocca, A. Pattori: **1507.02555**
+ **many others** as well as **various ATLAS and CMS studies**

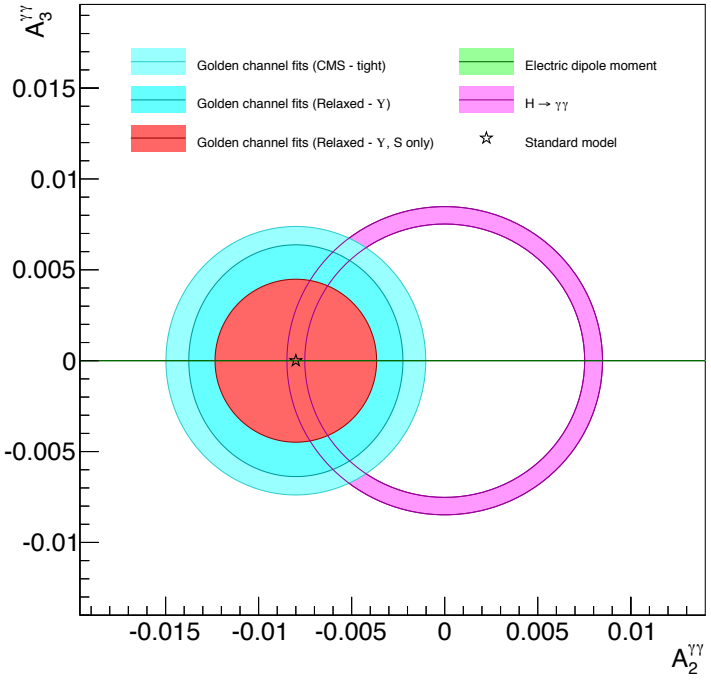
Probing Anomalous Couplings in $h \to 4\ell$ at LHC



(Y. Chen, R. Harnik, RVM: 1503.05855)

- Perform 6D fit to $ZZ, Z\gamma, \gamma\gamma$ 'anomalous' Higgs couplings
- Stronger sensitivity to $Z\gamma$ and $\gamma\gamma$ effective couplings
- Can probe $Z\gamma$ and $\gamma\gamma$ CP properties at HL-LHC





Framework in CMS Analysis

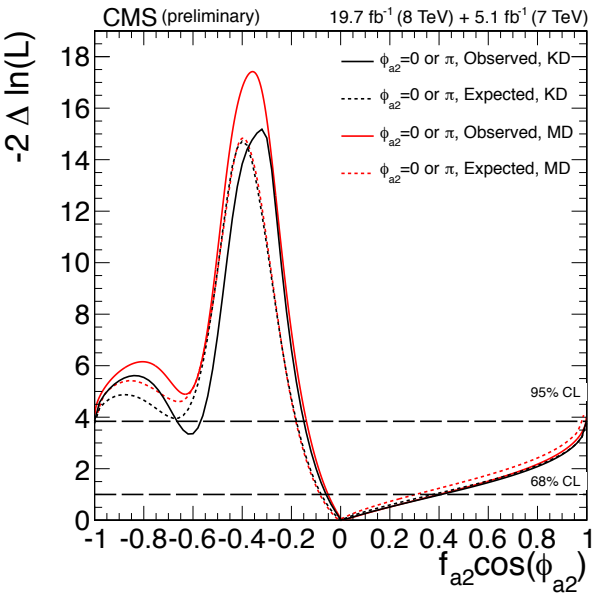
CMS PAS HIG-14-014, arXiv: 1411.3441

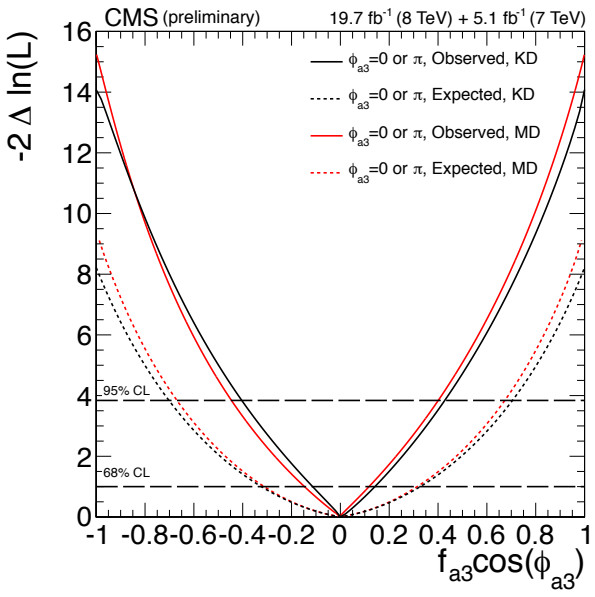
- A multi-dimensional Higgs couplings extraction framework

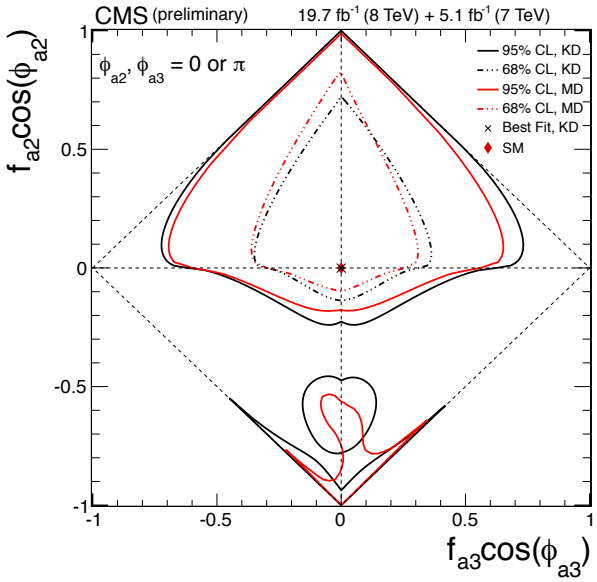
  Y. Chen, N. Tran, RVM: arXiv:1211.1959, Y. Chen, RVM: arXiv:1310.2893,

  Y. Chen, E. DiMarco, J. Lykken, M. Spiropulu, RVM, S. Xie: arXiv:1401.2077, arXiv:1410.4817

- Used in recent CMS study of anomalous hVV couplings in $h \to 4\ell$



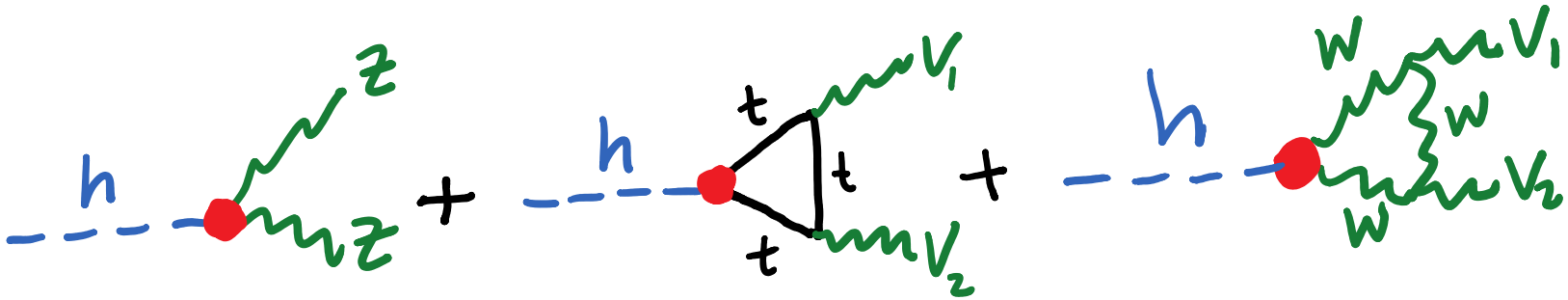




- Used in a limited scope and validated with other frameworks
- Can begin utilizing full power of framework in future LHC studies

Probing top and W Loop Effects in $h \to 4\ell$

- The W and top loops contribute to effective hVV couplings



- Can study the nature of the top and W couplings to the Higgs

$$\mathcal{L}_{ZW} \supset \frac{h}{v}\left(g_Z m_Z^2 Z^\mu Z_\mu + 2 g_W m_W^2 W^{\mu+} W_\mu^-\right)$$

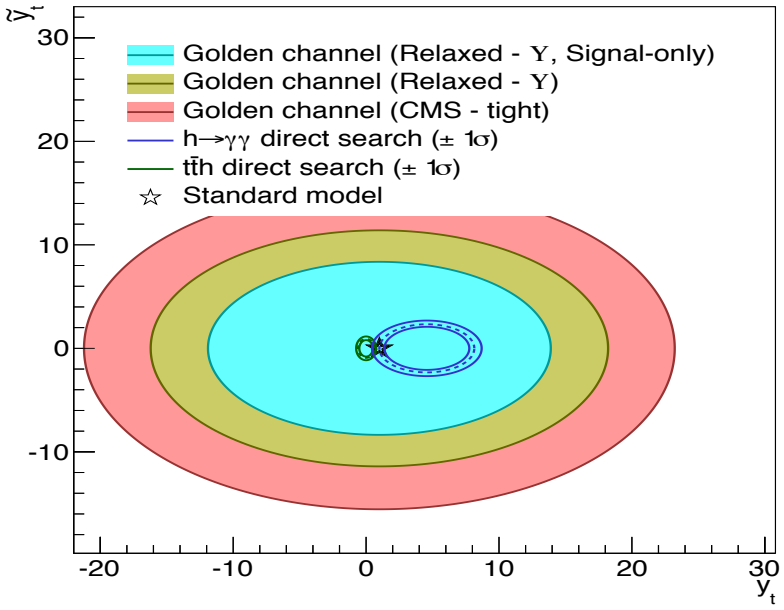
$$\mathcal{L}_t \supset \frac{m_t}{v} h \bar{t}(y_t + i\tilde{y}_t \gamma^5) t$$

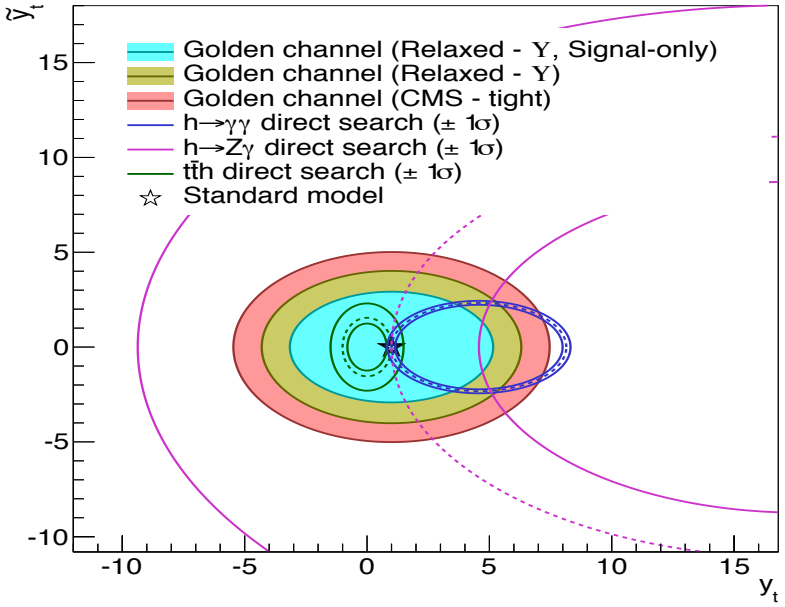
- Interference between tree level hZZ amplitude and top loop diagram allows us to probe top CP properties and searching for CP violation

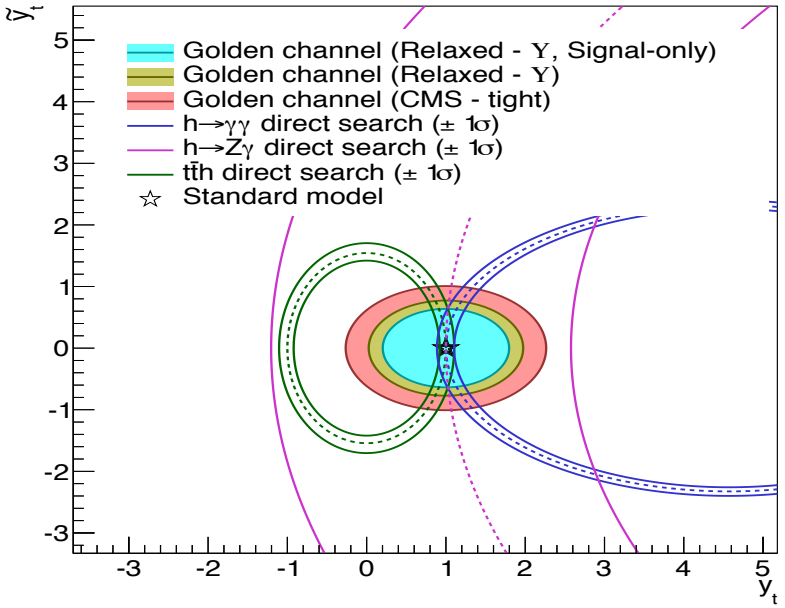
Probing Top Yukawa CP Properties in $h \to 4\ell$

- Compare with other probes such as $h \to \gamma\gamma$, $h \to Z\gamma$, and tth
- Qualitatively different probe of the top Yukawa CP properties

(Y. Chen, D. Stolarski, RVM: 1505.01168)







- Not yet sensitive, but should become at high luminosity LHC

The Custodial Nature of the Higgs Boson

- To a very good approximation, we have at tree level:

$$\rho_{tree} \equiv \frac{m_W^2}{c_W^2 m_Z^2} = 1$$

- Implies a 'custodial' global $SU(2)_C$ symmetry of the EW gauge boson mass matrix and Higgs scalar sector (P. Sikivie, L. Susskind, et. al (1980))
- Restricts possible values of $\lambda_{WZ} = g_W/g_Z$ to two possibilities:

(I. Low, J. Lykken, arXiv: 1005.0872)

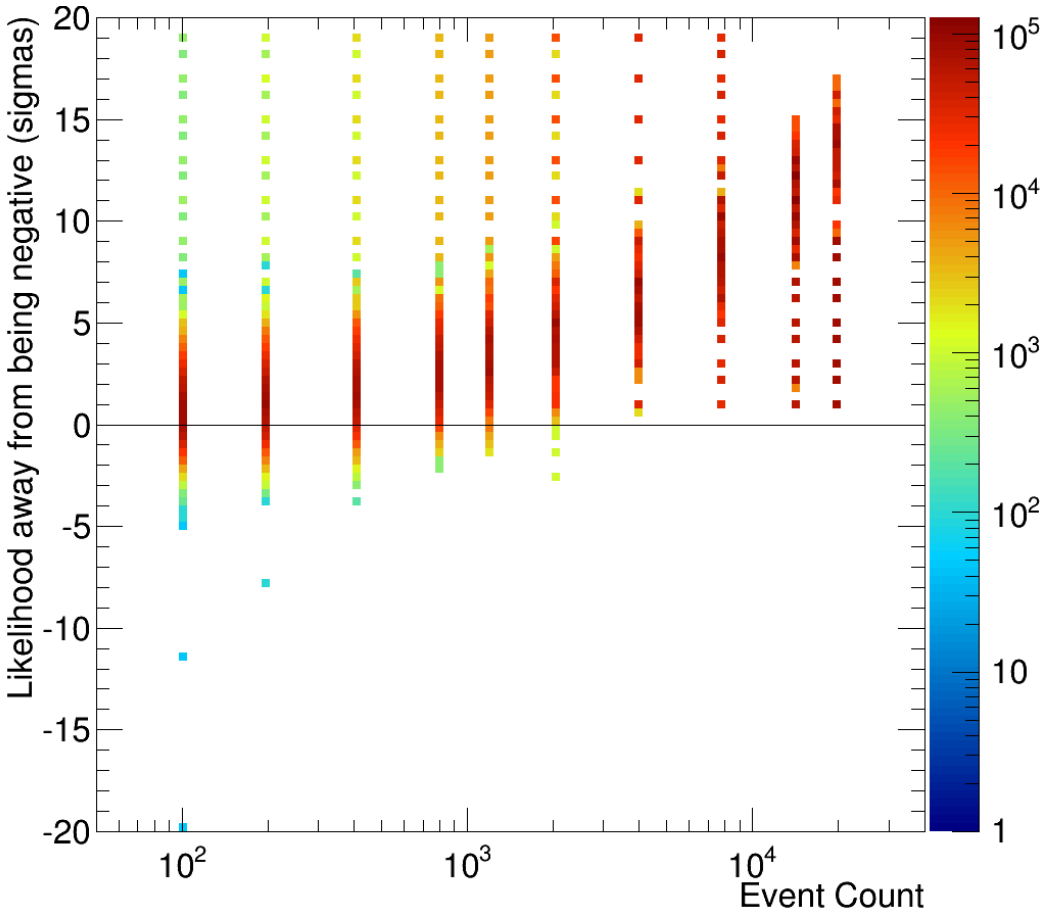
$$\lambda_{WZ} = +1 \quad (singlet)$$
$$\lambda_{WZ} = -1/2 \quad (fiveplet)$$

- In models with EW doublets only have custodial singlets
- Custodial fiveplet can be found in custodial Higgs triplet models

(H. Georgi and M. Machacek (1985), S. Gori, M. Quiros, RVM, et.al., arXiv: 1308.4025, 1409.5737)

Pinning the Sign Down at the LHC

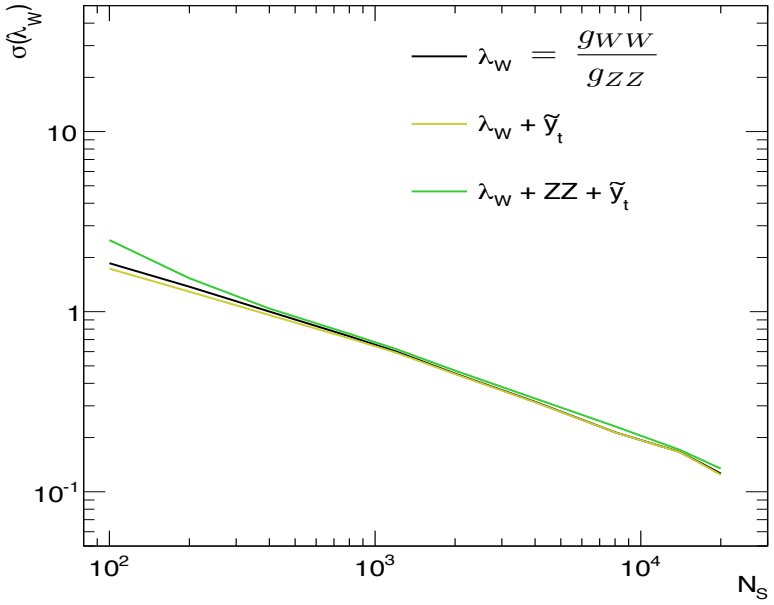
- Custodialy violating and NLO effects too small to generate $\mathcal{O}(1)$ corrections needed to change sign from the custodial prediction
- Thus simply establishing the overall sign effectively tells us the Higgs' custodial nature **(Y. Chen, D. Stolarski, RVM: PRELIMINARY)**



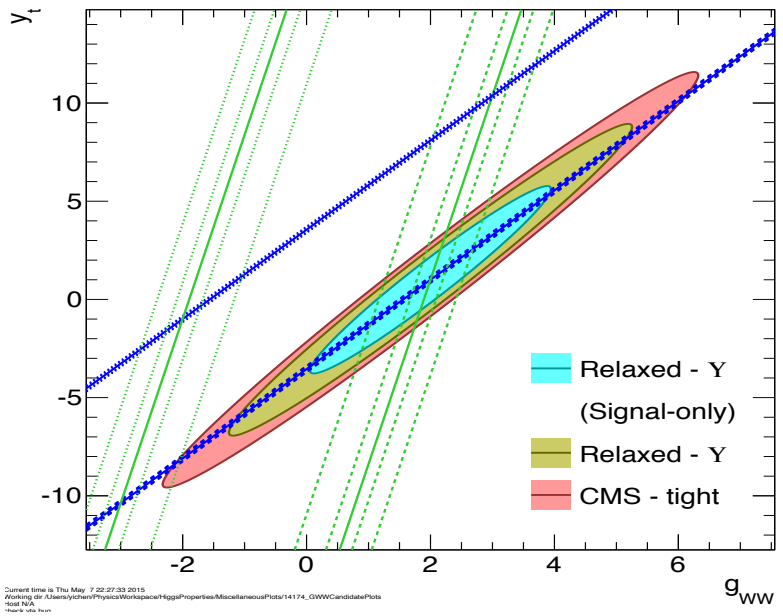
Custodial Symmetry *and* Top CP Properties

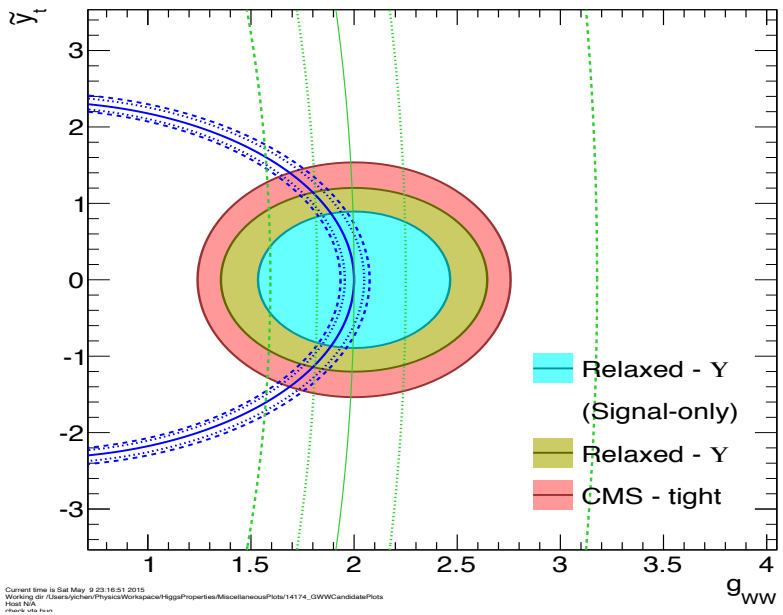
- Can also directly extract the ratio of couplings $\lambda_W = g_W/g_Z$

(Y. Chen, D. Stolarski, RVM: PRELIMINARY)

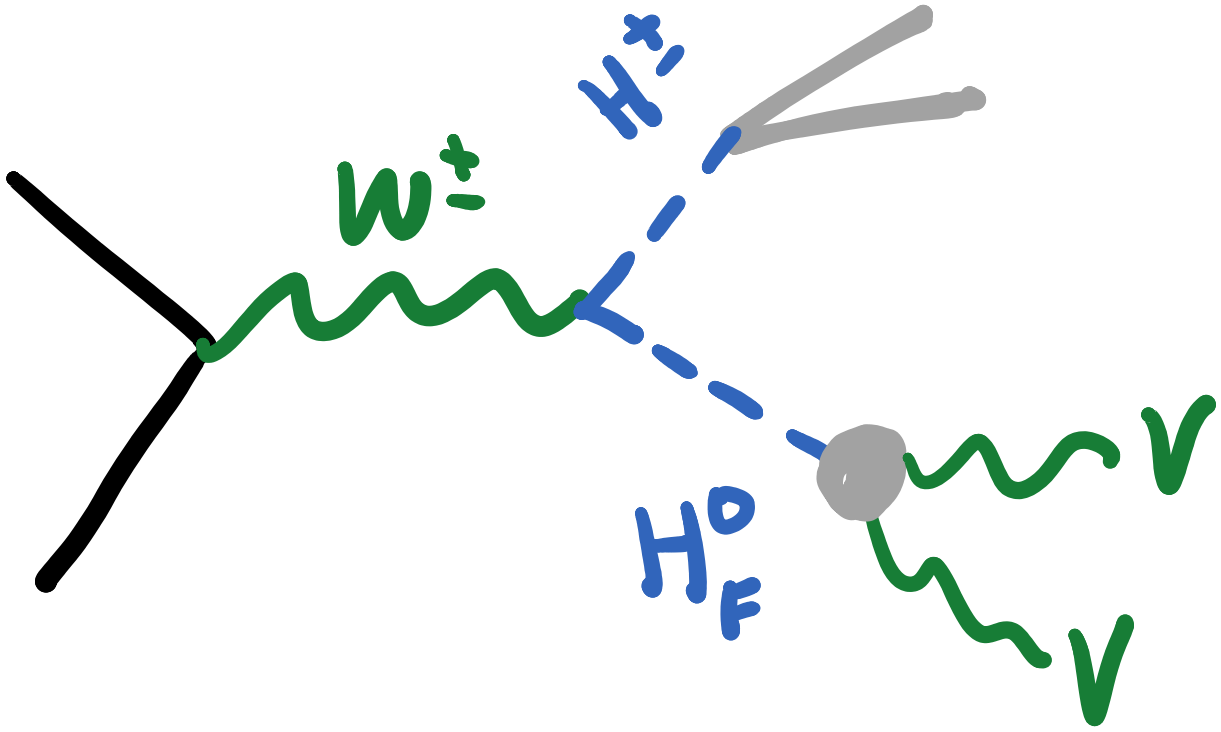


- Examining possibility of probing custodial symmetry and top CP quark properties simultaneously





Diphoton and Diboson Probes of Fermiophobic Higgs Bosons at the LHC

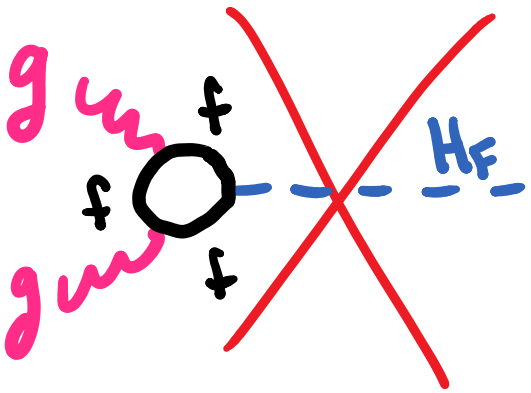


Based on work found in arXiv: 1603.00962 and in collaboration with:

Antonio Delgado, Mateo Garcia-Pepin, Mariano Quiros, Jose Santiago

Fermiophobic Higgs Bosons

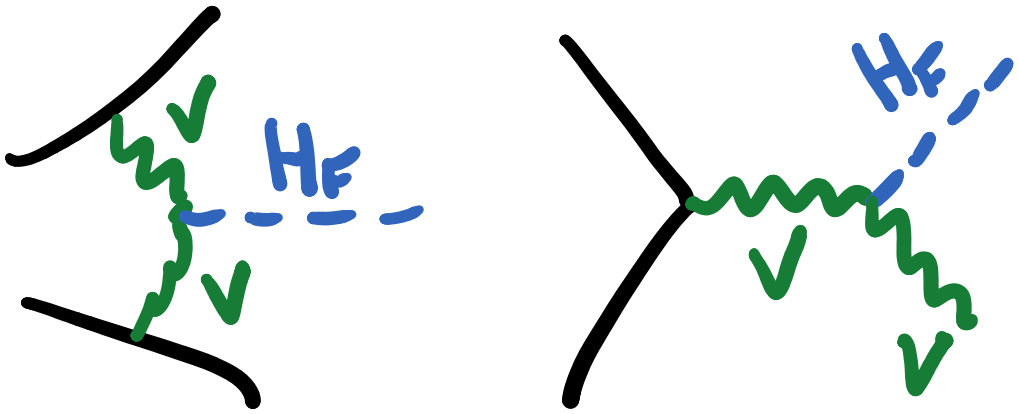
- EW charged scalars contributing to EWSB
- Do not couple (atleast approximatly) to Standard Model quarks and leptons
- Cannot be produced via gluon fusion



- Appear in many models with extended Higgs sectors (e.g. certain 2HDM and HTM as well as custodial Higgs triplet models such as the Georgi-Macacheck model)

Typical Searches for Higgs Bosons

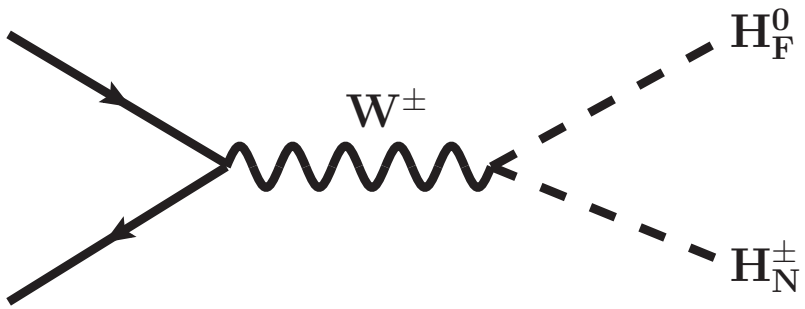
- Experimental searches have thus relied on VBF and VH production mechanisms



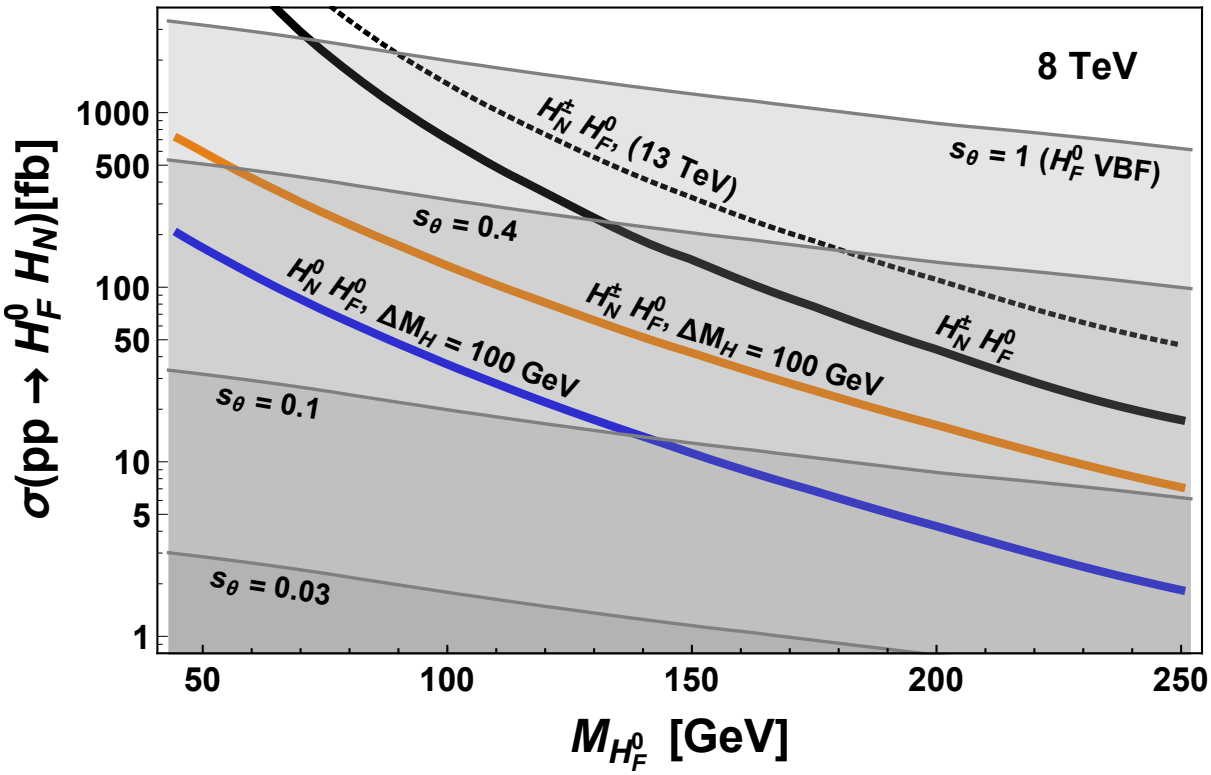
- Proportional to the *exotic* Higgs vev
- Discovery of the SM-like 125 GeV Higgs boson constrains these vevs to be small
- Implies VBF and VH are suppressed making these searches (except one) obsolete

Fermiophobic Higgs Production

- Unlike in SM there is a DY Higgs pair production mechanism

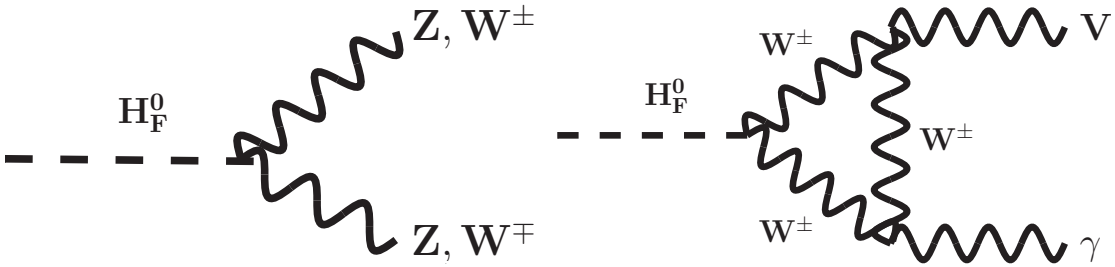


- For small vev it is the dominant production mechanism

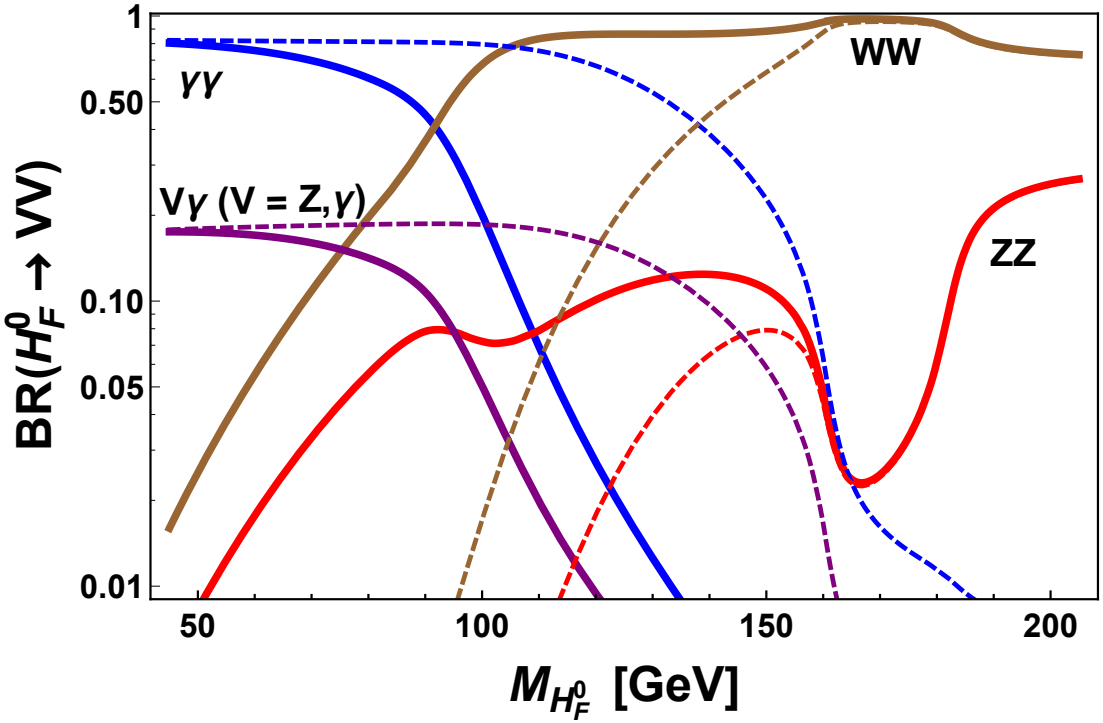


Fermiophobic Higgs Decays

- No $b\bar{b}$ (or gg) decays $\Rightarrow$ large BR into $\gamma\gamma$, VV possible



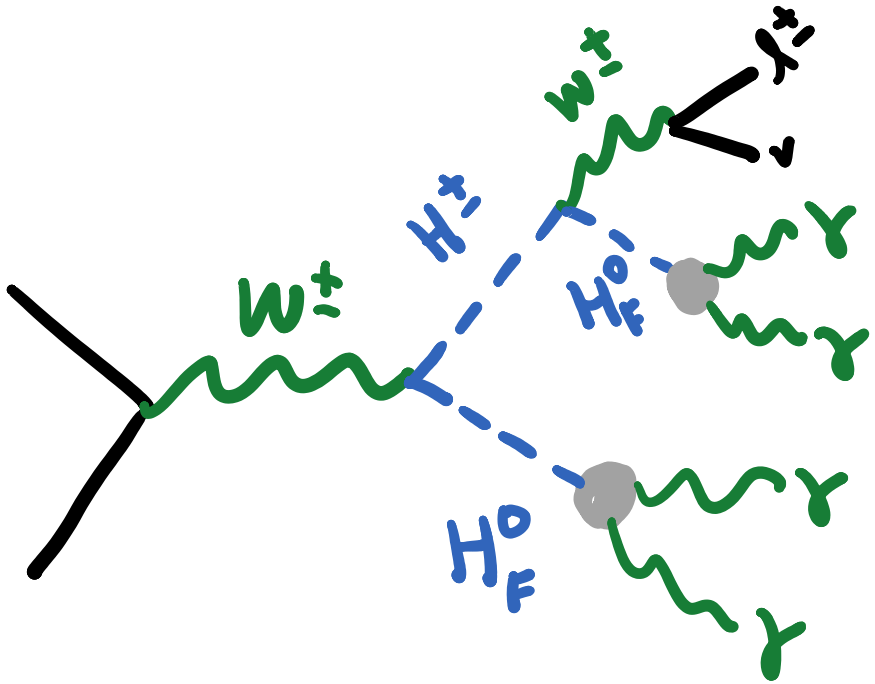
- At low masses $\gamma\gamma$ dominates while at high masses WW/ZZ



CDF Multiphoton ($4\gamma + X$) Searches

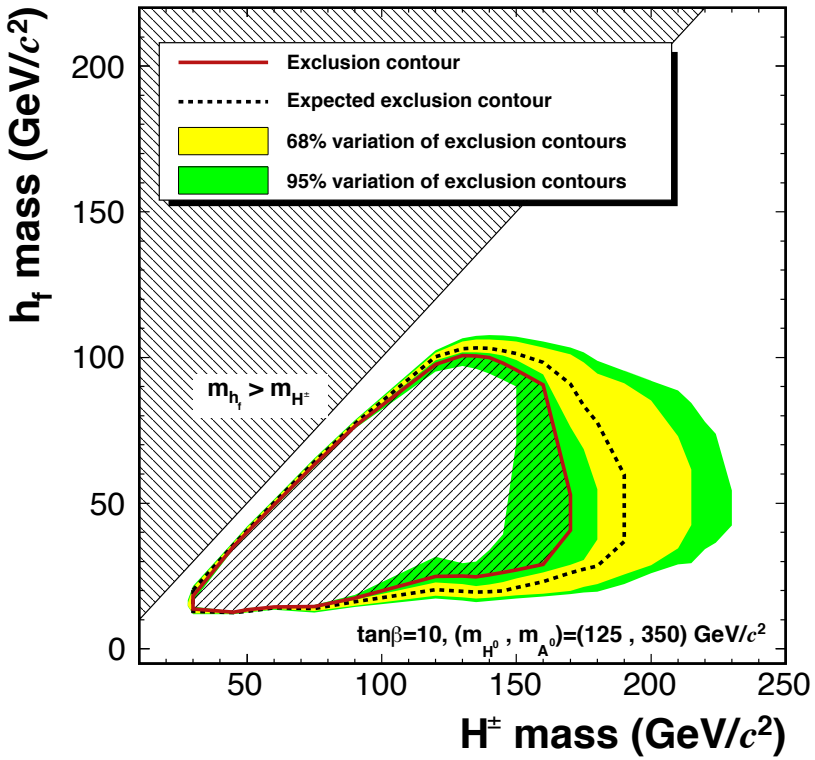
(CDF Collaboration: arXiv:1601.00401)

- Lone direct constraint is very recent CDF $4\gamma + \ell^{\pm}\nu$ search



- Clearly relies on $M_{H_F^{\pm}} > M_{H_F^0}$ and large BR for $H^{\pm} \to H_F^0 W^{\pm}$

- Can be used to set limits on $M_{H_F^{\pm}} - M_{H_F^0}$ 2D plane

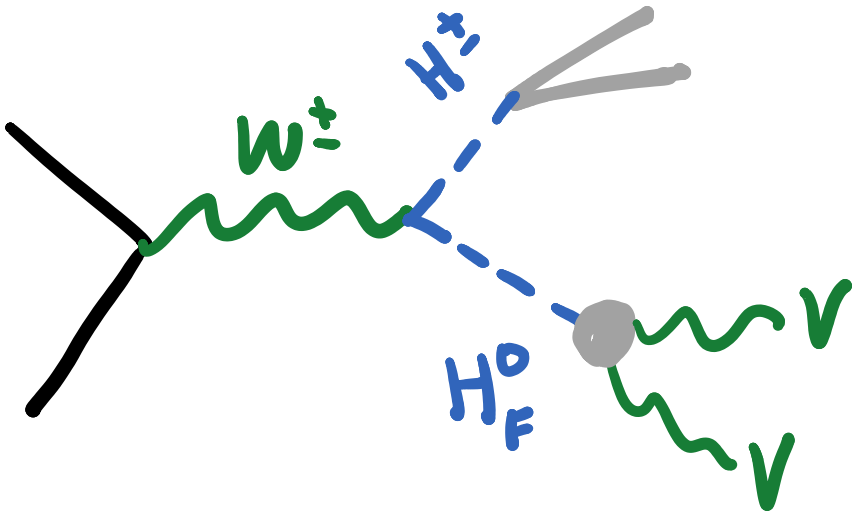


- Not applicable to cases with custodial symmetry ($M_{H_F^{\pm}} \approx M_{H_F^0}$)

Diphoton and Diboson Probes

(A. Delgado, M. Garcia-Pepin, M. Quiros, J. Santiago, RVM: 1603.00962)

- Diphoton and Diboson searches can be recast to search for H_F^0



- Applies independently of $H_F^\pm$ decay: less model dependent
- Requires large enough DY Higgs pair production to compensate for worse S/B

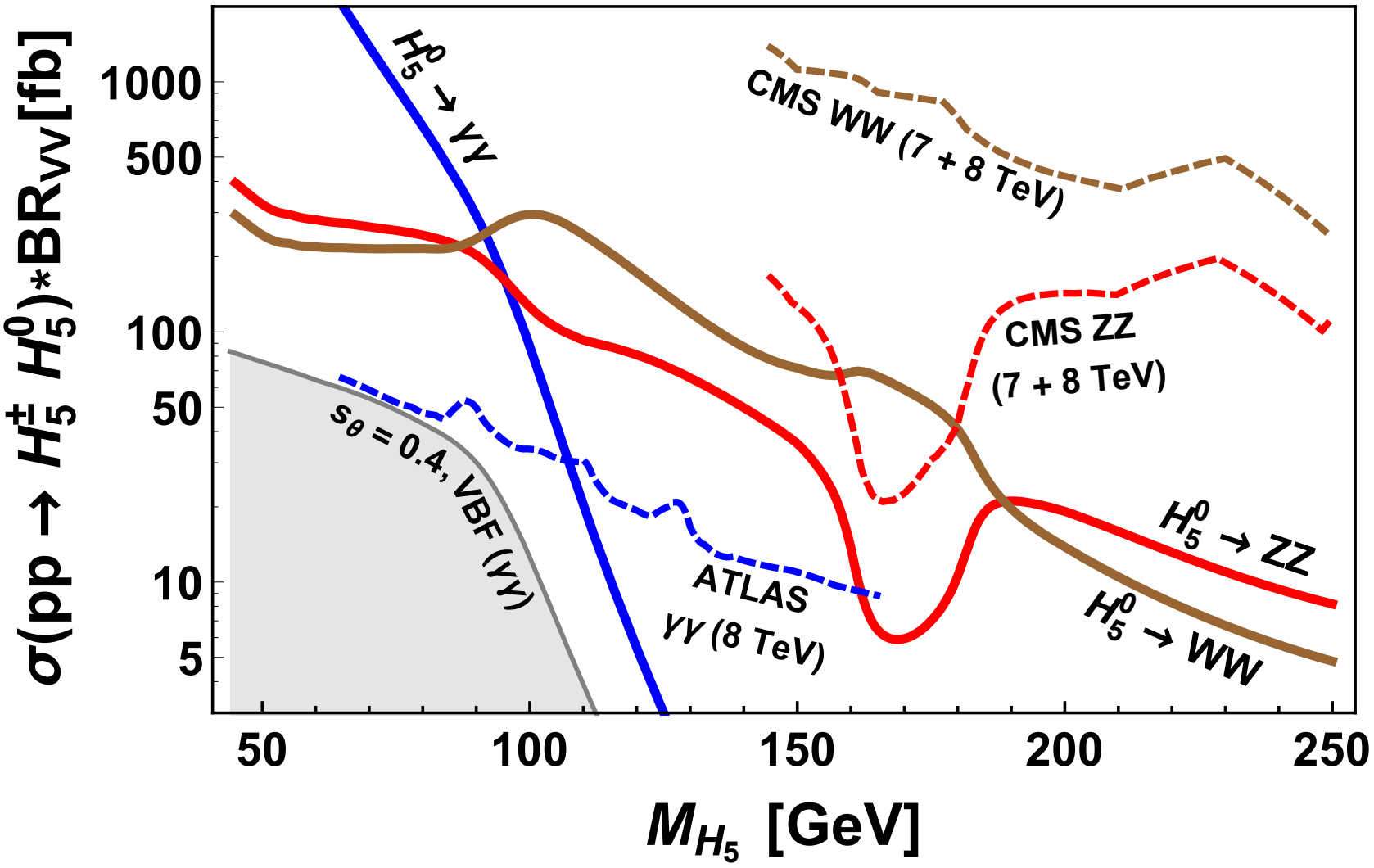
- Tevatron diphoton searches at are not quite sensitive
- Optimized searches such as CDF 4γ are needed at TEV
- Larger production cross sections at LHC allow us to use $\gamma\gamma$ and VV searches
- Can probe larger masses than CDF searches
- Applicable even if $(M_{H_F^\pm} \approx M_{H_F^0})$

Custodial Fiveplet Scalars

- Well known example of a fermiophobic Higgs boson is the custodial fiveplet found in custodial Higgs triplet models
- Can be found in non-SUSY models such as the famous Georgi-Macacheck model and its supersymmetric cousins
  (M. Garcia-Pepin, M. Quiros, RVM, et. al. arXiv:1409.5737 + others)
- In all cases a 'custodial' $SU(2)_C$ fiveplet scalar with no couplings to SM fermions and no mixing to SM-like Higgs is present
- Other possibilities for fermiophobic Higgs' are considered in:
  (A. Delgado, M. Garcia-Pepin, M. Quiros, J. Santiago, RVM: 1603.00962)

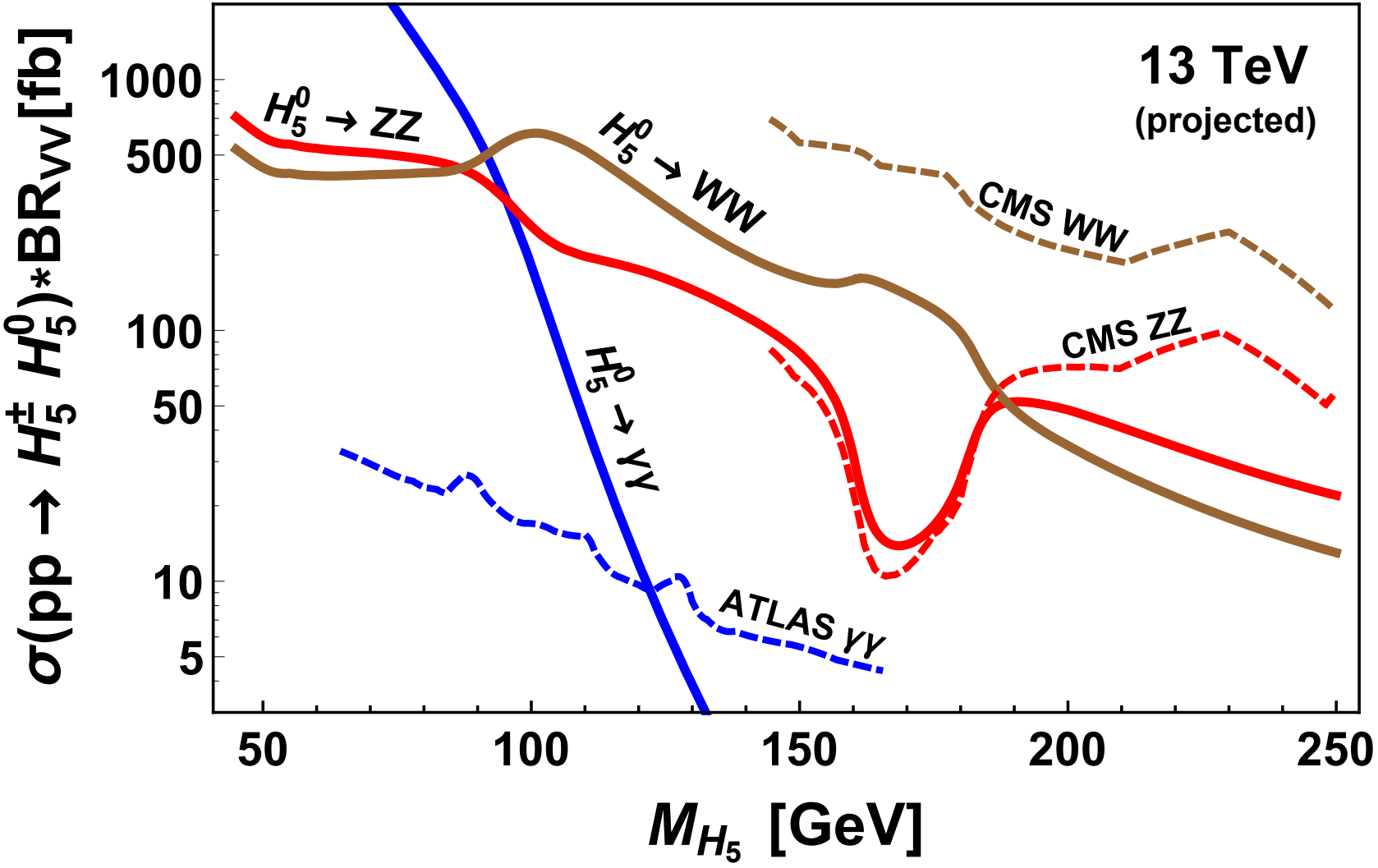
Closing Fiveplet Window at 8 TeV LHC

(A. Delgado, M. Garcia-Pepin, M. Quiros, J. Santiago, RVM: 1603.00962)



Probing Custodial Fiveplets with 13 TeV

(A. Delgado, M. Garcia-Pepin, M. Quiros, J. Santiago, RVM: Les Houches Proceedings)



THANKS!