Distinguishing the 125 GeV Higgs Mimickers

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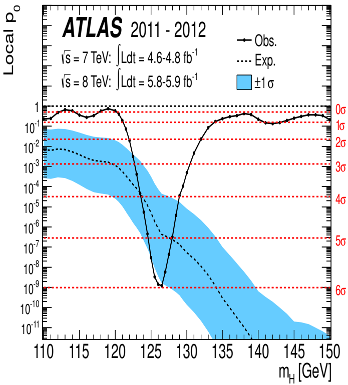
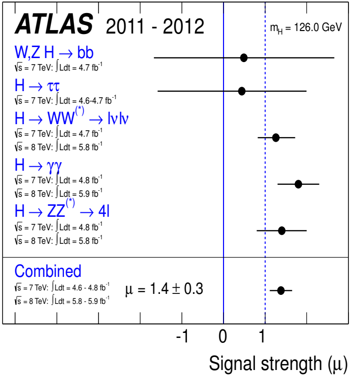
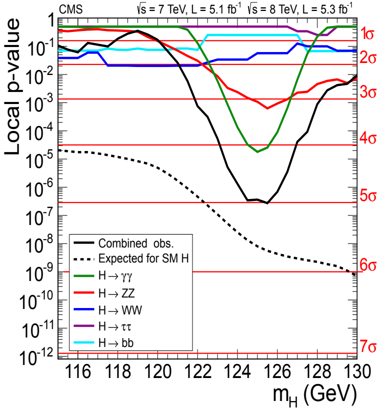
Outline

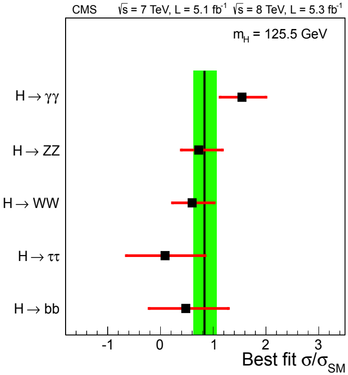
- Introduction
- Brief review of various models for the observed 125 GeV boson with the enhanced $\gamma\gamma$ rate
  - Fermiophobic Higgs
  - 2HDM and its variants
  - MSSM and its variants
  - Radion/Dilaton
- Vector Boson Fusion (VBF) to distinguish models
- Summary



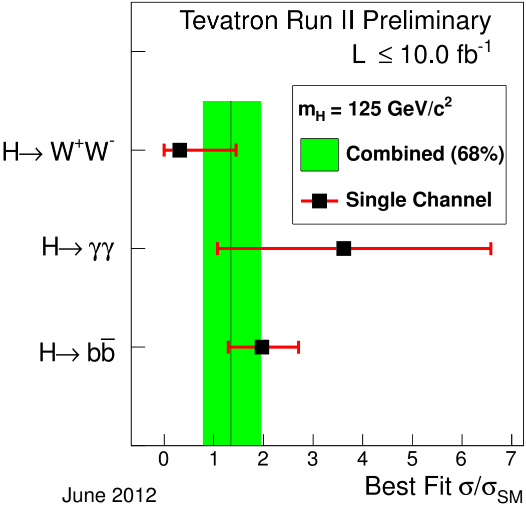


ATLAS 1207.7214





CMS 1207.7235


Tevatron Run II Preliminary
L ≤ 10.0 fb^{-1}
m_H = 125 GeV/c^2
Combined (68%)
Single Channel
H→ W$^+$W$^-$
H→ γγ
H→ b$\bar{b}$
0
1
2
3
4
5
6
7
Best Fit σ/σ$_{SM}$
June 2012

CDF, DØ

- A new particle around $125 - 126$ GeV is found, consistent with the SM Higgs boson. The fermionic modes ($\tau^- \tau^+$, $b\bar{b}$) need more data. The $WW^{(*)}, ZZ^{(*)}$ modes are consistent with SM. The $\gamma\gamma$ mode is outstanding with $1.1 - 2$ times that of the SM.
- The excesses are accumulated at $125 - 126$ GeV.
- Spin 1 is impossible by Landau-Yang theorem. $0^{\pm}$ and $2^{\pm}$ are next possibilities. Spin 0 consistent with data.
- J^P Determination: [S. Y. Choi's Talk]
  (1) the angular distributions in the 4-fermion modes from $\gamma\gamma$, $WW^{(*)}$, and $ZZ^{(*)}$. (Note: For pseudoscalar, no tree level AVV couplings.
  (2) invariant mass distribution in Higgs-strahlung.

- Within uncertainties, most obvious and natural one is SM Higgs. 2 photon excess due to QCD uncertainties [Baglio, Djouadi, Godbole 1207.1451].
- MSSM – SUSY predicts a light CP-even Higgs boson. But such a light 125 GeV Higgs puts a tight constraint on the stop mass sector, and not easy to enhance the $\gamma\gamma$ rate. [Jae Sik Lee's Talk]
- NMSSM: easier to obtain a 125 GeV Higgs boson, and not difficult to achieve enhanced $\gamma\gamma$ rate.
- Other extended MSSM.
- 2HDM and its variants. [S. K. Kang's Talk]
- Inert Higgs doublet model (IHDM).
- RS Radion/Dilaton: the anomaly couplings to gg and $\gamma\gamma$ easily enhance the diphoton rate.
- Fermiophobic Higgs boson. No free parameter. Yukawas are induced by renormalization.

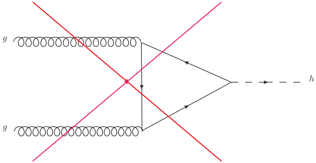
Fermiophobic Higgs

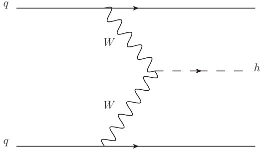
Gabrielli, Mele, Raidal 1202.1796
Berger, Sullivan, Zhang 1203.6645
Gabrielli, Kannike, Mele, Racioppi, Raidal 1204.0080

- Fermiophobic (FP) Higgs boson couples to gauge bosons only. Yukawa couplings / fermion masses are generated by some other mechanisms, e.g. technicolor. The coupling strength is the same as the SM Higgs:

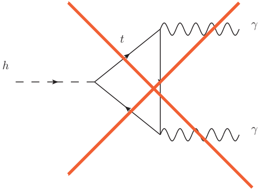
$$\mathcal{L}_{\rm FP} = -g m_W h_{\rm FP} W^+_\mu W^{-\mu} - \frac{g m_Z}{2\cos\theta_W} h_{\rm FP} Z_\mu Z^\mu \; .$$

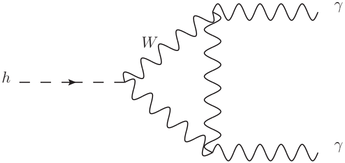
- Since it does not couple to quarks, it cannot be produced by gluon fusion but by VBF or associated production with W/Z. Production cross section at the LHC is about 10^{-1} of the SM Higgs.





- However, it would not decay into $f\bar{f}$. No interference with from top quark loop. The branching ratio of $\gamma\gamma$ can be as large as $\approx 10^{-2}$.

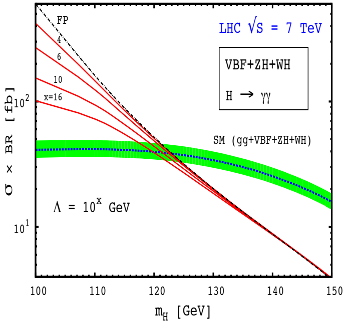


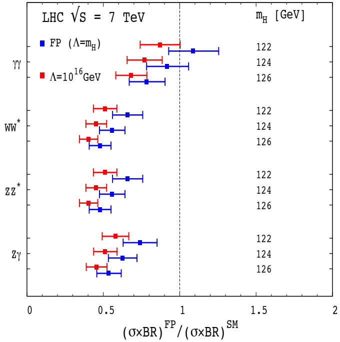


- The inclusive diphoton production rate (signal strength parameter)

$$\mu = \frac{\sigma(pp \to h_{\rm FP}) \times B(h_{\rm FP} \to \gamma\gamma)}{\sigma(pp \to h_{\rm SM}) \times B(h_{\rm SM} \to \gamma\gamma)} \approx 0.8 - 1.1$$

- Signals for WW^*, ZZ^* and $Z\gamma$ are somewhat smaller, favored by CMS.





2HDM - Type II

Ferreira, Santos, Sher, Silva 1112.3277, 1201.0019; Burdman, Haluch, Matheus 1112.3961; Chen, He 1202.3072; Arhrib, Benbrik, Chen 1205.5536; Cheon, Kang 1207.1083; Chang, Kang, Lee, Lee, Park, Song 1210.3439; ... ...

- In Type II, one doublet couples only to down-type quarks and another doublet couples to the up-type quarks. No tree level FCNC.
- The electroweak symmetry is broken when the two Higgs doublet fields develop VEVs:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \; H_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix} \longrightarrow \langle H_u \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix}, \; \langle H_d \rangle = \begin{pmatrix} 0 \\ v_d \end{pmatrix}$$

- After EWSB, there are two CP-even, one CP-odd, and a pair of charged Higgs bosons.

- The 6 parameters of the model in the CP-conserving case include

$$m_h,\ m_H,\ m_A,\ m_{H^+},\ \tan\beta \equiv \frac{v_u}{v_d},\ \alpha$$

- Couplings of the Higgs bosons to fermions:

	$t\bar{t}$	$b\bar{b}$	$\tau^-\tau^+$
h:	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
H:	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$
A:	$-i\cot\beta\,\gamma_5$	$-i\tan\beta\,\gamma_5$	$-i\tan\beta\,\gamma_5$

Those to the gauge bosons:

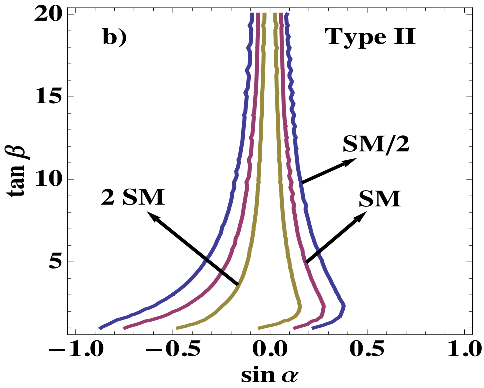
$$\begin{aligned} hW^+W^- &: \quad ig\, m_W \sin(\beta-\alpha)\, g^{\mu\nu} \\ hZZ &: \quad ig\, m_Z \frac{\sin(\beta-\alpha)}{\cos\theta_W}\, g^{\mu\nu}\,. \end{aligned}$$

- Production via gluon fusion can be enhanced at large $\tan\beta$ with the bottom contribution.
- Decay width into $\gamma\gamma$ receives contributions from W, t, and H^+ loops. Since W loop dominates, we want to make the hWW coupling as large as possible. So along

$$\alpha \approx 0 \quad \text{and} \quad \text{moderately large } \tan\beta$$

  can achieve enhancement to $\gamma\gamma$ width.
- For other 2HDM of Type I, X, and Y, see Chang et al 1210.3439 and Kang's Talk.

Contour for the ratio $\frac{N_{2\text{HDM}}}{N_{\text{SM}}}|_{\gamma\gamma} = 0.5, 1, 2$ in the $(\tan\beta, \sin\alpha)$ plane.



Ferreira, Santos, Sher, Silva 1112.3277

IDHM - Deshpande and Ma (1978)

Arhrib, Benbrik, Gaur 1201.2644
Wang, Han 1203.4477

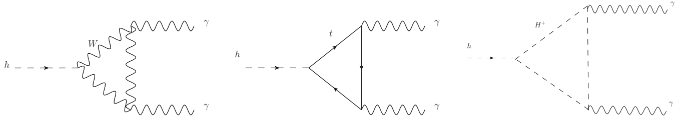
- IHDM is a special case of 2HDM. One of the doublets entirely decouples from fermions and gauge bosons. The other one works as the SM Higgs boson.
- The Higgs potential

$$\begin{aligned} V &= \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 \\ &+ \frac{\lambda_5}{2}\left\{\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right\} \end{aligned}$$

- The electroweak symmetry is broken by just one VEV from H_1:

$$H_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v}{\sqrt{2}} + \frac{h+i\chi}{\sqrt{2}} \end{pmatrix} \to \langle H_1 \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix},\ H_2 = \begin{pmatrix} \phi_2^+ \\ \frac{S+iA}{\sqrt{2}} \end{pmatrix} \to \langle H_2 \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

- The model has an Z_2 symmetry. The particles in the second doublet are odd, all the others are even. The lightest Z_2-odd particle is the DM candidate.
- No mixing between the two doublets. 2 CP-even scalars (h, S), 1 CP-odd scalar (A), and a pair of charged Higgs $(H^{\pm})$.
- 7 - 1 = 6 Parameters: $m_h, m_S, m_A, m_{H^{\pm}}, \mu_2$, and λ_2.
- Production via gluon fusion and VBF is the same as the SM.
- Decay into $\gamma\gamma$ receives extra contribution from H^+:



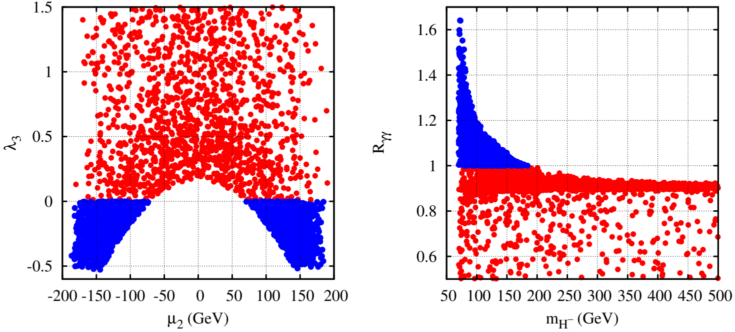
- The coupling between the charged Higgs boson and the Higgs boson is completely fixed by λ_3

$$g_{hH^+H^-} = -i\frac{e\lambda_3 v^2}{2m_W \sin\theta_W}\ , \quad \lambda_3 = \frac{2}{v^2}(m^2_{H^\pm} - \mu_2^2)\ .$$

When $m^2_{H^\pm} < \mu_2^2$ (negative λ_3!) the diphoton branching ratio is enhanced.

- Together with other theoretical constraints (e.g. perturbativity, vacuum stability, unitarity, S and T) and experimental constraints from direct searches from ATLAS and CMS, we will scan

$$|\mu_2| \approx 100 - 200 \text{ GeV} \quad \text{and} \quad m_{H^\pm} < |\mu_2|$$



Arhrib, Benbrik, Gaur 1201.2644

MSSM

Baer et al. 1112.3017; Heinemeyer et al. 1112.3026; Arbey et al. 1112.3028; Draper et al. 1112.3068; Carena et al. 1112.3336; Akula et al. 1112.3645; Kadastik et al. 1112.3647; Cao et al. 1112.4391; Christensen, Han and Su 1203.3207; Carena et al. 1205.5842; Feng and Sanford 1205.2372; Cao et al. 1202.5821; Li et al. 1112.3024; Hagiwara, Lee, Nakamura 1207.0802; Barger, Ishida, Keung 1207.0779; Akula, Nath, Peim 1207.1839; Nath 1210.0520; ... ...

- Two requirements to satisfy the data:
  (i) $m_h \approx 125$ GeV,
  (ii) Signal Strength Parameter $\mu = \frac{\sigma(gg \to h) \times B(h \to \gamma\gamma)}{\sigma(gg \to h_{\rm SM}) \times B(h_{\rm SM} \to \gamma\gamma)} > 1.$
- For $m_H \approx 125$ GeV, see Hagiwara, Lee, Nakamura 1207.0802

- Higgs mass requires a large radiative correction from the top-stop sector:

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^2}{4\pi^2 v^2}\left[\frac{1}{2}X_t + t + \frac{1}{16\pi^2}\left(\frac{3m_t^2}{2v^2} - 32\pi\alpha_s\right)(X_t t + t^2)\right]$$

  where

$$X_t = \frac{2(A_t - \mu\cot\beta)^2}{M_{\rm SUSY}^2}\left(1 - \frac{(A_t - \mu\cot\beta)^2}{12M_{\rm SUSY}^2}\right)$$

  A large A_t is needed. Following Carena et al. 1205.5842, we use $m_{Q_3} = m_{U_3} = 850$ GeV, $A_t = 1.4$ TeV, $m_A = 1$ TeV, and $\tan\beta = 60$.

- To enhance the diphoton rate one also needs to push one of the staus ($\tilde{\tau}$s) to be light enough, just above the LEP limit. Following Carena et al. 1205.5842, we scan

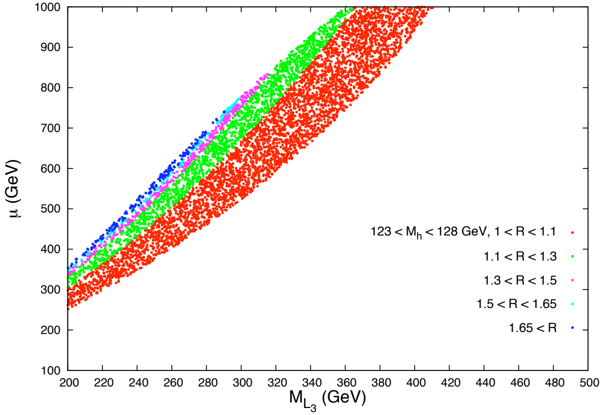
$$m_{L_3} = m_{E_3} = 200 - 450 \text{ GeV} \qquad \text{and} \qquad \mu = 200 - 1000 \text{ GeV},$$

  for diphoton rate > 1.

Chang, Cheung, Tseng, Yuan 1206.5853

$$m_{Q_3} = m_{U_3} = 850 \text{ GeV}, \; A_t = 1.4 \text{ TeV}, \; m_A = 1 \text{ TeV}, \; \tan\beta = 60$$

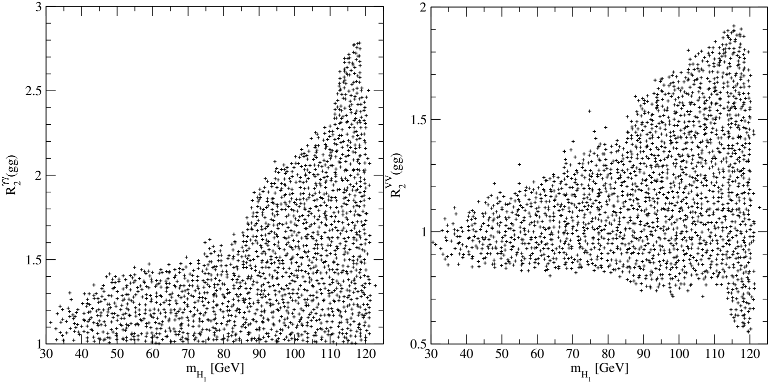
(Following Carena et al 1205.5842)



NMSSM

Gunion, Jiang, Kraml 1201.0982; 1207.1545; Ellwanger 1112.3548; King, Muhlleitner, Nevzorov 1201.2671; Ellwanger and Hugonie 1203.5048; Cao, Heng, Yang, Zhang, Zhu 1202.5821; Cao, Heng, Yang, Zhu 1207.3698; Vasquez et al. 1203.3446

- NMSSM:
$$W_{\rm NMSSM} = \lambda S H_u H_d + \frac{\kappa}{3} S^3 + W_{\rm MSSM}$$
with $\mu_{\rm eff} = \lambda v_s/\sqrt{2}$. 3 CP-even Higgs bosons and the SM-like could be the lightest or the second lightest.
- It was found that the second Higgs H_2 can be in the mass range $124 - 127$ GeV and with an enhanced $\gamma\gamma$ branching ratio.
- This is made possible because of the reduction into $b\bar{b}$ width, by a large singlet-doublet mixing.
- So $R_2^{\gamma\gamma} \equiv \sigma^{\gamma\gamma}(H_2)/\sigma^{\gamma\gamma}(h_{\rm SM})$ is enhanced, and potentially R_2^{VV} too, but the $R_2^{\tau\tau}$ is reduced.



Ellwanger, Hugonie 1203.5048

Other extended MSSM

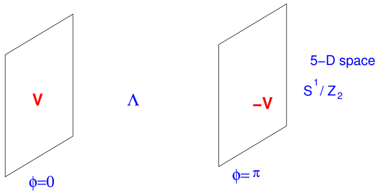
UMSSM – Chang, Cheung, Tseng, Yuan 1202.0054
$U(1)_{B-L} \times U(1)_R$ – Hirsch, Porod, Reichert, Staub 1206.3516
$U(1)_{\mathrm{PQ}}$ MSSM – An, Liu, Wang 1207.2473
pMSSM – Cahill-Rowley, Hewett, Ismail, Rizzo 1206.5800
Exceptional MSSM – Athron et al. 1206.5028
PQ-NMSSM – Jeong, Shoji, Yamaguchi 1205.2386
BMSSM – Boudjema, La Rochelle 1203.3141
BLMSSM – Perez 1201.1501

... ...

Radion

Cheung and Yuan 1112.4146
Barger, Ishida, Keung 1111.4473; 1111.2580
Grzadkowski, Gunion, Toharia 1202.5017
Tang 1204.6145
Matsuzaki and Yamawaki 1201.4722

de Sandes and Rosenfeld 1111.2006



RS I

- RS model used a nonfactorizable metric for the S^1/Z_2 orbifold
$$ds^2 = e^{-2kr_c|\varphi|}\,\eta_{\mu\nu}dx^\mu\,dx^\nu - r_c^2 d\varphi^2$$
$\overline{M_5}$ is the 5D fundamental Planck scale, k is curvature of the AdS space.
$$\overline{M_{\rm Pl}}^2 = \overline{M_5}/k$$
The scale $\Lambda_\pi \equiv \overline{M_{\rm Pl}}\,e^{-kr_c\pi}$ describes the scale of physical processes on the TeV brane with a desired value of kr_c around 12.
- Has a 4D massless scalar, the radion. No potential leads to unstable extra dimension.
- A stabilization mechanism (Goldberger and Wise) using a bulk scalar field to generate a potential.
$$ds^2 = e^{-2k\varphi T(x)}g_{\mu\nu}(x)\,dx^\mu dx^\nu - T^2(x)d\varphi^2$$
$T(x)$ is the modulus field describing the distance between the two branes. The radion ϕ (lowest excitation of the modulus field) acquires a $O(0.1-1TeV)$ mass with a coupling strength $1/$TeV.

- Interactions of the radion

$$\mathcal{L}_{\rm int} = \frac{\phi}{\Lambda_\phi}\, T^\mu_\mu(\mathrm{SM}) \,,$$

where $\Lambda_\phi = \langle \phi \rangle$ is of order TeV and

$$T^\mu_\mu(\mathrm{SM}) = \sum_f m_f \bar{f} f - 2 m_W^2 W^+_\mu W^{-\mu} - m_Z^2 Z_\mu Z^\mu + (2 m_h^2 h^2 - \partial_\mu h \partial^\mu h) + \ldots \,,$$

- Coupling of the radion to a pair of gluons and photons are anomalous!

$$T^\mu_\mu(\mathrm{SM})^{\rm anom} = \sum_a \frac{\beta_a(g_a)}{2 g_a} F^a_{\mu\nu} F^{a\mu\nu} \,.$$

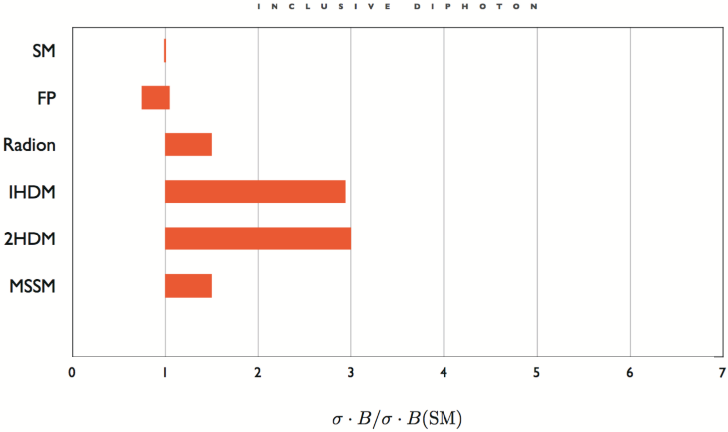
where $\beta_{\rm QCD}/2g_s = -(\alpha_s/8\pi) b_{\rm QCD}$ and $b_{\rm QCD} = 11 - 2n_f/3$.

- The diphoton production rate

$$R_{\gamma\gamma} = \frac{\sigma(gg \to \phi) \times B(\phi \to \gamma\gamma)}{\sigma(gg \to h_{\rm SM}) \times B(h_{\rm SM} \to \gamma\gamma)}$$

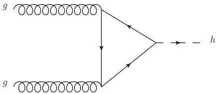
can be $1 - 1.5$ for $\Lambda_\phi = 1 - 0.8$ TeV.

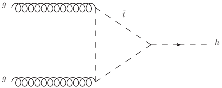
Summary of Inclusive diphoton production

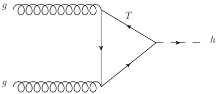


Except for FP Higgs, the inclusive dominated by gluon fusion

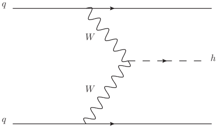
- For most models, except for the FP Higgs, gluon fusion is the dominant production mechanism ($\sigma_{gg\to h_{\rm SM}} \approx 20$ pb for 125 GeV Higgs at LHC8). But the gluon fusion can involve other exotic colored particles:







- VBF is the cleanest channel to probe the EWSB sector via the hWW/hZZ couplings:



- VBF additionally gives two energetic forward jets, which experimentally can be identified.
- Before kinematical cuts, VBF cross section is $\approx$ 8% of gluon fusion for 125 GeV Higgs at LHC8, while Higgs-strahlung is $\approx$ 5%.

- Two classes of events:

  (i) *Inclusive* diphoton events $\gamma\gamma X$ receives contributions from gluon fusion, VBF, associated production with $W/Z/t\bar{t}$.

  (ii) *Exclusive* $jj\gamma\gamma$ events receives contributions from VBF and associated production. We use the forward jet-tag to suppress the associated production.

- By combining the measurements of *inclusive* $\gamma\gamma X$ production and *exclusive* $jj\gamma\gamma$ VBF production we can obtain useful information about the models.

VBF

- The most distinguished feature of VBF at hadronic colliders is the appearance of two energetic forward jets separated by a large $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. We impose

$$E_{T_j} > 30 \text{ GeV}, \quad |\eta_j| < 4.7, \quad \Delta R_{jj} > 3.5 \,,$$

and

$$\begin{array}{lll} \text{(Ejcut)} & E_{j_1} > 500 \text{ GeV} & \text{or} \\ \text{(Mjjcut)} & M_{jj} > 350 \text{ GeV} & \end{array}$$

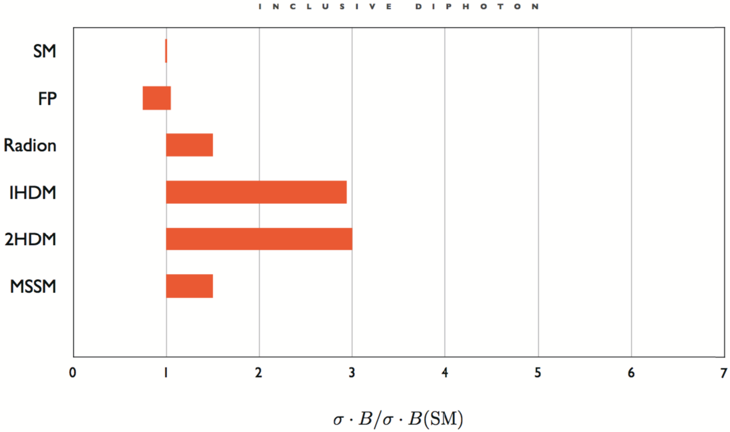
The high M_{jj} or E_j cut put away $W(Z)h \to (jj)h$ associated production ($M_{jj}^{Vh} \approx m_V$). The subscript "1" denotes the most energetic jet.

Strategies

- Current evidence comes mainly from inclusive $\gamma\gamma X$ production, because of large event rates.
- First find the parameter space of each model that can give
  (i) $m_h \sim 125$ GeV, and
  (ii) inclusive diphoton production rate larger than or equal to the SM Higgs.
- In that parameter space, we calculate the VBF cross sections and compare to the SM VBF.

	Parameter Space		$B(h \to \gamma\gamma)$
SM			2.3×10^{-3}
FP			1.5×10^{-2}
Radion	$\Lambda_\phi = 0.8 - 1$ TeV		0.57×10^{-3}
	μ_2 (GeV)	$m_{H^\pm}$ (GeV)	
IHDM1	200	70	6.7×10^{-3}
IHDM2	200	100	3.3×10^{-3}
IHDM3	200	150	2.5×10^{-3}
IHDM4	200	200	2.3×10^{-3}
IHDM5	150	70	4.2×10^{-3}
IHDM10	100	90	2.4×10^{-3}
	$\sin\alpha$	$\tan\beta$	
2HDM1	0	1.5	3.8×10^{-3}
2HDM2	0	5	6.5×10^{-3}
2HDM3	0	10	6.8×10^{-3}
2HDM4	0	20	6.9×10^{-3}

MSSM					
	$m_{L_3} = m_{E_3}$	μ	m_h	$B(h \to \gamma\gamma)$	$\frac{\sigma(gg\to h)B(h\to\gamma\gamma)}{\sigma(gg\to h_{SM})B(h_{SM}\to\gamma\gamma)}$
BP1	250	400	127.0	2.4×10^{-3}	1.02
BP2	250	500	126.2	2.9×10^{-3}	1.19
BP3	250	536	125.4	3.6×10^{-3}	1.45
BP4	300	536	126.8	2.4×10^{-3}	1.005
BP5	300	700	125.4	2.8×10^{-3}	1.15
BP6	300	763	123.7	3.4×10^{-3}	1.38
BP7	350	700	126.6	2.4×10^{-3}	0.999
BP8	350	800	125.8	2.5×10^{-3}	1.03
BP9	350	927	123.9	2.7×10^{-3}	1.11


INCLUSIVE DIPHOTON
SM
FP
Radion
IHDM
2HDM
MSSM
0
1
2
3
4
5
6
7
$\sigma \cdot B/\sigma \cdot B(\mathrm{SM})$

- Once again, we are calculating the VBF with the following cuts on the photons and the forward jets:

$$E_{T_\gamma} > 30 \text{ GeV}, \qquad |\eta_\gamma| < 2.5, \qquad |m_{\gamma\gamma} - m_h| < 3.5 \text{ GeV} .$$

$$E_{T_j} > 30 \text{ GeV}, \quad |\eta_j| < 4.7, \quad \Delta R_{jj} > 3.5 ,$$

$$\begin{array}{lll} \text{(Ejcut)} & E_{j_1} > 500 \text{ GeV} & \text{or} \\ \text{(Mjjcut)} & M_{jj} > 350 \text{ GeV} & \end{array}$$

- Use PYTHIA for parton showering and hadronization, with PGS for detector simulation. $0.2/\sqrt{E}$ and $0.8/\sqrt{E}$ for EM and hadronic calorimeter resolutions, jet cone size $\Delta R_{\rm cone} = 0.5$, ...
- We calculate the signal strength parameter for VBF

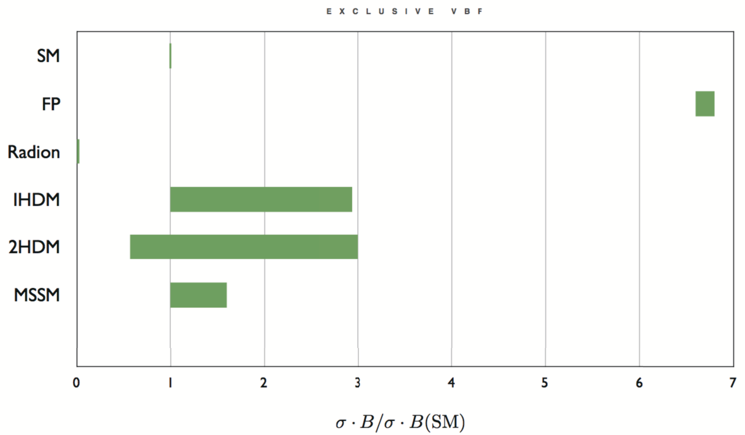
$$\mu = \frac{\sigma(pp \to jjX) \times B(X \to \gamma\gamma)}{\sigma(pp \to jjh_{\rm SM}) \times B(h_{\rm SM} \to \gamma\gamma)}$$

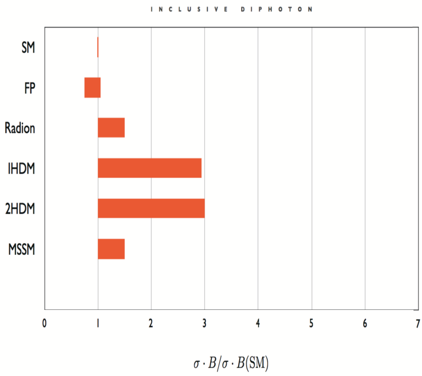
Production rates $\sigma \cdot B$ in fb at PGS level for $pp \to jjX \to jj\gamma\gamma$ at LHC-7,(-8,-14)

	w/ photon cuts and Ejcut	w/ photon cuts and Mjjcut
SM	$0.15\ (0.19, 0.61)$	$0.33\ (0.41, 1.1)$
FP	$1.03\ (1.27, 4.12)$	$2.24\ (2.78, 7.35)$
Radion	$0.0038\ (0.0047, 0.014)$	$0.0076\ (0.0095, 0.026)$
IDHM1	$0.44\ (0.56, 1.79)$	$0.97\ (1.21, 3.23)$
IDHM2	$0.22\ (0.28, 0.88)$	$0.48\ (0.59, 1.59)$
IDHM3	$0.16\ (0.21, 0.67)$	$0.36\ (0.45, 1.21)$
IDHM4	$0.15\ (0.19, 0.62)$	$0.33\ (0.41, 1.11)$
IDHM5	$0.28\ (0.35, 1.12)$	$0.61\ (0.76, 2.03)$
IDHM10	$0.16\ (0.20, 0.64)$	$0.35\ (0.43, 1.16)$
2HDM1	$0.17\ (0.22, 0.70)$	$0.38\ (0.47, 1.25)$
2HDM2	$0.41\ (0.52, 1.66)$	$0.90\ (1.11, 2.99)$
2HDM3	$0.44\ (0.56, 1.79)$	$0.97\ (1.20, 3.23)$
2HDM4	$0.45\ (0.58, 1.85)$	$1.00\ (1.24, 3.33)$

Production rates $\sigma \cdot B$ in fb at PGS level for $pp \to jjX \to jj\gamma\gamma$ at LHC-7,(-8,-14)

MSSM BP	w/ photon cuts and Ejcut	w/ photon cuts and Mjjcut
BP1	$0.19\ (0.28, 0.83)$	$0.44\ (0.57, 1.47)$
BP2	$0.22\ (0.33, 0.97)$	$0.52\ (0.66, 1.76)$
BP3	$0.29\ (0.40, 1.18)$	$0.63\ (0.82, 2.10)$
BP4	$0.19\ (0.28, 0.85)$	$0.43\ (0.56, 1.46)$
BP5	$0.22\ (0.32, 0.92)$	$0.50\ (0.65, 1.65)$
BP6	$0.27\ (0.38, 1.07)$	$0.61\ (0.75, 1.90)$
BP7	$0.20\ (0.26, 0.85)$	$0.43\ (0.53, 1.47)$
BP8	$0.21\ (0.29, 0.85)$	$0.44\ (0.59, 1.48)$
BP9	$0.22\ (0.30, 0.92)$	$0.49\ (0.59, 1.66)$


EXCLUSIVE VBF
SM
FP
Radion
IHDM
2HDM
MSSM
0
1
2
3
4
5
6
7
$\sigma \cdot B/\sigma \cdot B(\mathrm{SM})$


INCLUSIVE DIPHOTON
SM
FP
Radion
IHDM
2HDM
MSSM
0
1
2
3
4
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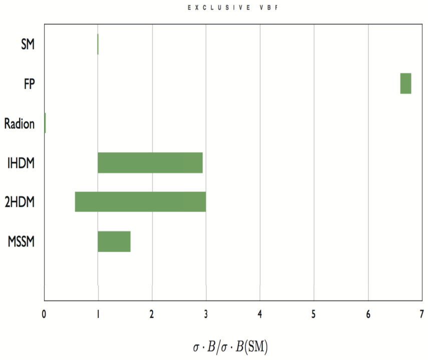
$\sigma \cdot B / \sigma \cdot B(\mathrm{SM})$


EXCLUSIVE VBF
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7
$\sigma \cdot B / \sigma \cdot B(\mathrm{SM})$

Combining Inclusive $\gamma\gamma X$ and Exclusive $\gamma\gamma jj$ VBF Production Rates

- If a similar inclusive rate, but a large excess in exclusive $jj\gamma\gamma$ rate, it would be a FP Higgs boson. Technicolor at higher scale?
- If a similar rate or excess is seen in inclusive production but a negligible exclusive VBF production rate, it would be the RS radion. Extra dimension?
- If moderate excess is seen in both inclusive production and exclusive VBF production, it could be the Higgs boson of the IHDM, 2HDM (Type II, Y), or the MSSM (and its many variants). However, if the excess is over 60% the MSSM would be very difficult to explain.

Summary

- Observation of the 125 GeV boson implies the new LHC era has arrived!
- Currently, the excess seen is believed coming from gluon fusion.
- On the decay side, for a 125 GeV Higgs, many interesting channels can be studied by experimentalists. *Nature has been very generous.*
- On the production side, vector boson fusion is the next thing to be studied in detail. It directly probes the EWSB sector.
- Combining gluon fusion and vector boson fusion, more information of the different Higgs models can be obtained.
- Associated production with W/Z and $t\bar{t}$ are important too.
- All Higgs mimickers are welcome! More data needed to distinguish them. More excitements are ahead of us. Stay tuned!