Global fitting with LHC Higgs signals in the 2HDMs

Yun Jiang

2013 LHC-TI Fellow
Univ. of California, Davis

with J.F. Gunion, S. Kraml and B. Dumont, arXiv. 1309.XXXX

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July 4th, 2012–A HISTORIC moment in science.

It is a privilege to witness the Higgs discovery.


国际新闻
INTERNATIONAL NEWS
新快报
A29

天哪！这真是“上帝粒子”吗？

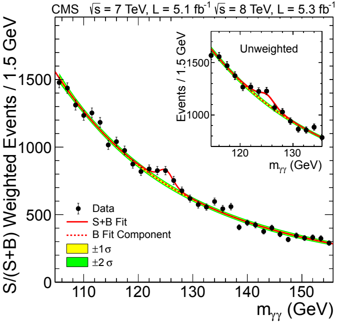
欧洲核子中心激动宣布可能发现希格斯－玻色子：“我们对宇宙的理解，将要改变！”

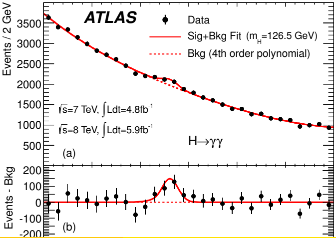
网友围观：好像很牛 但是不懂

83岁希格斯：未想过有生之年等到

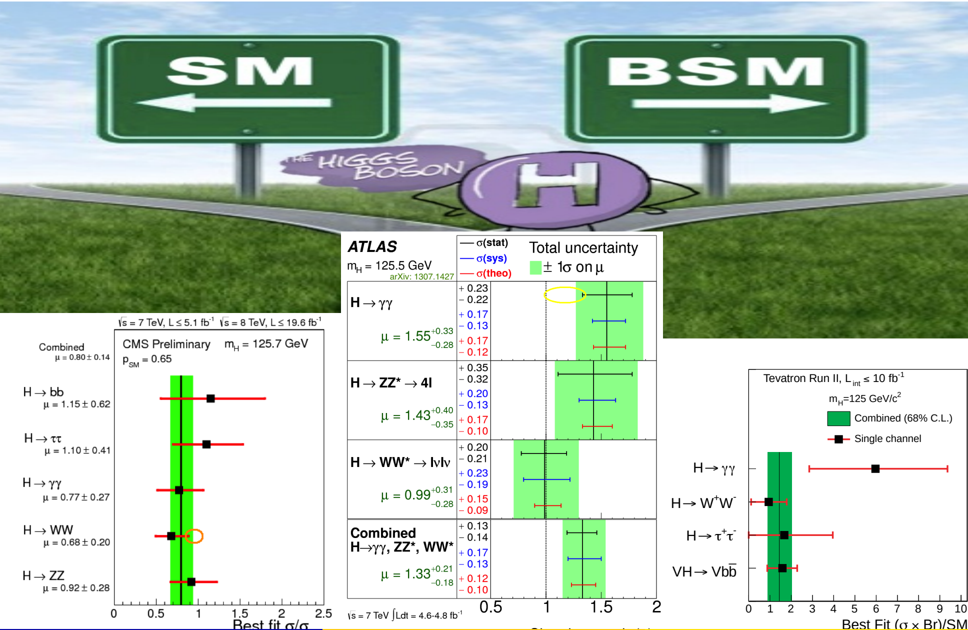
“这该死的粒子！”

希格斯－玻色子是个啥？





Whether or not it *is* the SM Higgs?



What's the naive extension?

Two Higgs Doublet Model

1. The simplest non-trivial extension on the Higgs sector beyond the SM.
   - Duplicate a complex $SU(2)_L$ Higgs doublet with the same hypercharge $Y = +1$.
   - More physical Higgs states.
2. Type II realized in the MSSM.
3. Existence of the charged Higgs boson $H^{\pm}$?

2HDM Higgs sector

$$
\begin{aligned}
\mathcal{V} =& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \\
&+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) \\
&+ \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.} \right\}
\end{aligned}
$$

The models we studied

1. NO explicit $\mathcal{CP}$ violation: all λ_i and m_{12}^2 are assumed to be real.
2. NO spontaneous $\mathcal{CP}$ breaking: take $\xi = 0$.
3. **"soft"** Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$) breaking: $m_{12}^2 \neq 0$; $\lambda_6 = \lambda_7 = 0$.

2HDM Higgs sector

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.} \right]$$
$$+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$
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free parameters: $\tan\beta, m_{12}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$

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free parameters: $\tan\beta$, $m_{12}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$

Electroweak symmetry breaking

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v\cos\beta + \rho_1 + i\eta_1)/\sqrt{2} \end{pmatrix}$$
$$\Phi_2 = \begin{pmatrix} \phi_2^+ \\ (e^{i\xi} v\sin\beta + \rho_2 + i\eta_2)/\sqrt{2} \end{pmatrix}$$

2 CP-even neutral scalars: $h = -\rho_1\sin\alpha + \rho_2\cos\alpha$
$H = \rho_1\cos\alpha + \rho_2\sin\alpha$

1 CP-odd neutral pseudoscalar: $A = -\eta_1\sin\beta + \eta_2\cos\beta$

2 charged scalars: $H^\pm$

2HDM Higgs sector

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.} \right]$$
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our inputs: $m_h, m_H, m_A, m_{H^+}, \tan\beta, \sin\alpha, m_{12}^2$

Electroweak symmetry breaking

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2 charged scalars: $H^\pm$

2HDM Yukawa sector

$$\mathcal{L} = y^1_{ij}\bar{\psi}_i\psi_j\Phi_1 + y^2_{ij}\bar{\psi}_i\psi_j\Phi_2$$

We consider the Type I and Type II models, in which tree level FCNC are completely absent due to some symmetry. [1]

Model	u_R^i	d_R^i	e_R^i	Realization
Type I	Φ_2	Φ_2	Φ_2	$\Phi_1 \to -\Phi_1$
Type II	Φ_2	Φ_1	Φ_1	$\Phi_1 \to -\Phi_1, d_R^i \to -d_R^i$

$$\begin{aligned}\mathcal{L}^{\mathbf{2HDM}}_{\mathbf{Yukawa}} &= -\sum_{f=u,d,\ell}\frac{m_f}{v}\left(C_f^h\bar{f}fh + C_f^H\bar{f}fH - iC_f^A\bar{f}\gamma_5 fA\right)\\ &\quad -\left\{\frac{\sqrt{2}V_{ud}}{v}\,\bar{u}\left(m_u C_u^A \mathrm{P}_L + m_d C_d^A \mathrm{P}_R\right)dH^+ + \frac{\sqrt{2}m_\ell C_\ell^A}{v}\,\overline{\nu_L}\ell_R H^{\mathbf{1}} + \mathrm{h.c.}\right\}\end{aligned}$$

	C_V^h	C_u^h	$C_{d,\ell}^h$	C_V^H	C_u^H	$C_{d,\ell}^H$	C_V^A	C_u^A	$C_{d,\ell}^A$
Type I	$\sin(\beta-\alpha)$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\cos(\beta-\alpha)$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	0	$\cot\beta$	$-\cot\beta$
Type II	$\sin(\beta-\alpha)$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\cos(\beta-\alpha)$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	0	$\cot\beta$	$\tan\beta$

$$(C_V^h)^2 + (C_V^H)^2 + (C_V^A)^2 = 1$$

[1] *Paschos-Glashow-Weinberg theorem: if all fermions with the same quantum numbers couple to the same Higgs multiplet, then FCNC will be absent.*

Theoretical Constraints on the 2HDMs

- Theoretically, (denoted jointly as SUP)
  1. **Vacuum stability** N.G. Deshpande and E. Ma, PRD18(1978)2574
     The potential must be bounded from below (positivity).

$$
\begin{aligned}
\lambda_1 &> 0 \\
\lambda_2 &> 0 \\
\lambda_3 &> -\sqrt{\lambda_1 \lambda_2} \\
\lambda_3 + \lambda_4 - |\lambda_5| &> -\sqrt{\lambda_1 \lambda_2} \qquad \text{if } \lambda_6 = \lambda_7 = 0
\end{aligned}
$$

  2. **Unitarity**
     Requiring the largest eigenvalue for the tree-level for full multi-state scattering matrix in (h, H, A) space to be less than the upper limit 16π.
  3. **Perturbativity**
     All self couplings among the mass eigenstates and Yukawa coupling must be finite, $|\Lambda_i| < 4\pi$.

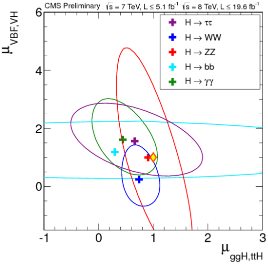
Experimental constraints: what we consider ...

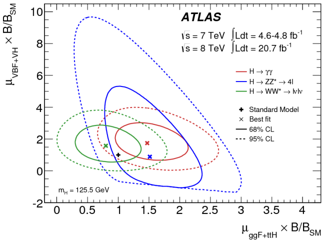
- preLHC: SUP, STU, B-physics, $(g-2)_\mu$, LEP (applied for some scenarios)
- SMHlimit:
  - $H \to ZZ* \to 4\ell$ for heavier Higgs up to 1 TeV
  - $gg \to H \to \tau\tau$ and $gg \to bbH$ with $H \to \tau\tau$ for heavier Higgs up tp 500 GeV
- postLHC: additionally, $\gamma\gamma$, ZZ, WW, bb, $\tau\tau$ signals for 125 GeV Higgs

$$\mu^H_Y(X) \equiv \frac{\sigma(Y \to H) BR(H \to X)}{\sigma(Y \to h_{\rm SM}) BR(h_{\rm SM} \to X)}$$

	$\hat{\mu}^{\rm ggF}$	$\hat{\mu}^{\rm VBF}$
$\gamma\gamma$	0.98 ± 0.28	1.72 ± 0.59
VV	0.91 ± 0.16	1.01 ± 0.49
$b\bar{b}/\tau\tau$	0.98 ± 0.63	0.97 ± 0.32
$b\bar{b}$	-0.23 ± 2.86	0.97 ± 0.38
$\tau\tau$	1.07 ± 0.71	0.94 ± 0.65

G.Belanger, B.Dumont, U. Ellwanger, J.F. Gunion & S. Kraml, arXiv:1306.2941

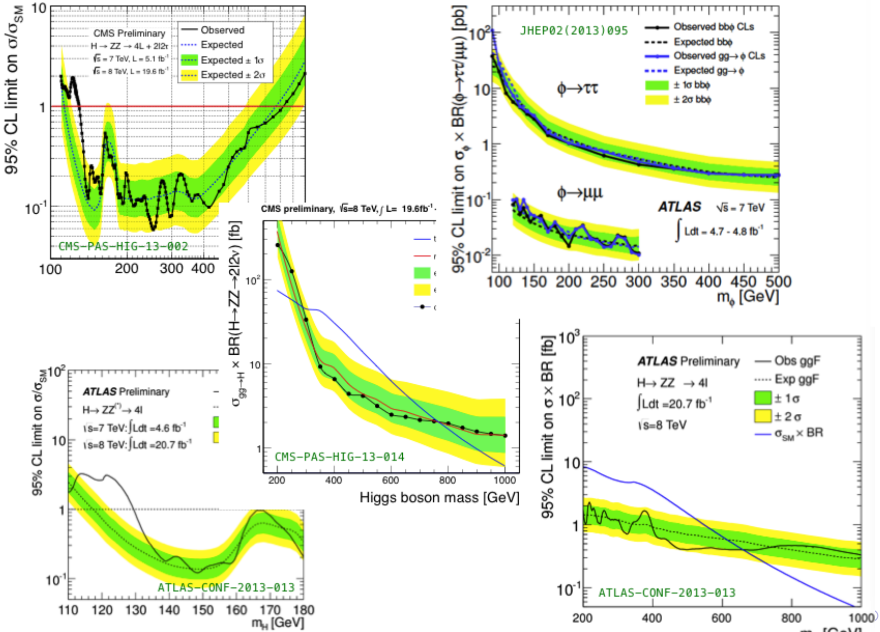




Jack et. al ...

1. not individually but corporately treat CMS and ATLAS data.
2. take the ggF,ttH–VBF,VH 2D correlation into consideration.

Search limits on the heavier Higgs bosons



2HDM scan

vacuum) [18]. We scan over the following ranges [1]:

$$\sin\alpha \in [-1,1]\,, \quad \tan\beta \in [0.5, 60]\,, \quad m_{12}^2 \in [-(2\ \text{TeV})^2, (2\ \text{TeV})^2]\,,$$
$$m_A \in [5\ \text{GeV}, 2\ \text{TeV}]\,, \quad m_{H^\pm} \in [m^*, 2\ \text{TeV}]\,, \tag{1}$$

where m^* is the lowest value of $m_{H^\pm}$ allowed by B physics constraints. These lower bounds as a function of $\tan\beta$ are as shown in Fig. 15 of [19] in the case of the Type II model (roughly $m^* \sim 300$ GeV in this case) and as shown in Fig. 18 of [19] in the case of the Type I model. For the physical Higgs masses, we consider

$$m_h \in [123\ \text{GeV}, 128\ \text{GeV}]\,, \quad m_H \in]128\ \text{GeV}, 2\ \text{TeV}]\,, \tag{2}$$

for the case that h is the observed state near 125.5 GeV, or

$$m_H \in [123\ \text{GeV}, 128\ \text{GeV}]\,, \quad m_h \in [10\ \text{GeV}, 123\ \text{GeV}[\,, \tag{3}$$

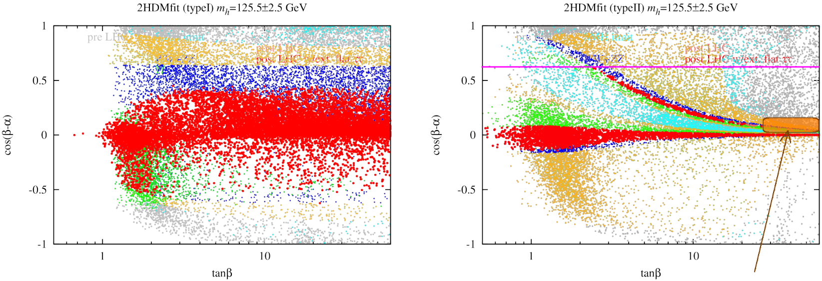
for the case that H is the observed state near 125.5 GeV. Moreover, we separately investigate degenerate scenarios, where two states (h and H, h and A, or H and A) or all three neutral Higgses fall into the 123–128 GeV mass window. The window of 125.5±2.5 GeV is adopted to account for theoretical uncertainties and to facilitate the study of near-degenerate scenarios.

[1] The lower bound on $\tan\beta$ is chosen to ensure the top Yukawa coupling within the perturbativity region. Unlike Z_2 symmetric 2HDM which constrains $\tan\beta \lesssim 7$ [ref], high $\tan\beta$ up to 100 is allowed when Z_2 symmetry is softly broken.

Single Higgs Scenarios

- h or H either lies at 125 GeV.

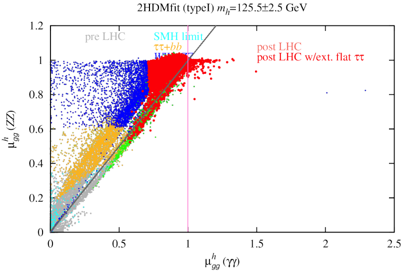
Most important $\cos(\beta-\alpha)$ vs. $\tan\beta$

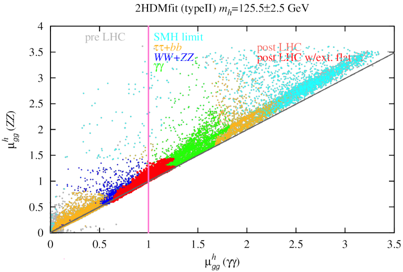


- Generally, for the lightest Higgs boson h be SM like, $C_V^h \sim \sin(\beta-\alpha) \sim 1$.
- However, there are **two branches** present in Type II model. In addition to the trivial one, the upper strip extends to $C_V^h \sim 0.7$ and also terminates at large $\tan\beta$ due to too large $\tau\tau$ rate.

$h \sim 125$-Higgs signals

Two most precisely measured $\mu^h_{gg}(ZZ)$ vs. $\mu^h_{gg}(\gamma\gamma)$





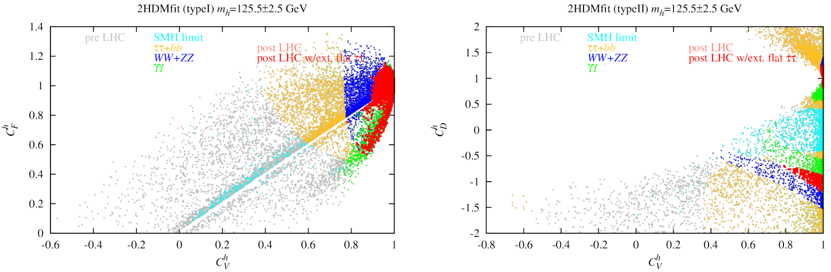
Type I

- **not too much above 1** because that gluon fusion production cannot be much enhanced (universal up and down type couplings).
- $\frac{\mu^h_{gg}(ZZ)}{\mu^h_{gg}(\gamma\gamma)} < 1$ for enhanced $\mu^h_{gg}(\gamma\gamma)$ rate.

Type II

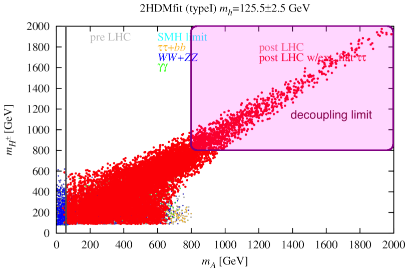
- **easy realization of substantial enhancement**.
- $\mu^h_{gg}(ZZ)$ is strictly larger than $\mu^h_{gg}(\gamma\gamma)$ for enhanced $\mu^h_{gg}(\gamma\gamma)$ rate.

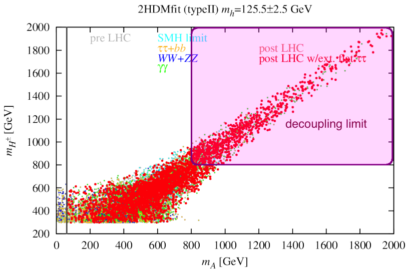
$h \sim 125$-Coupling fits C_D vs. C_V



- Remarkably, the coupling C_V^h **prefers to be $+1$ or so**.
- Type I: C_F^h and C_V^h have a moderate spread near the SM limit.
- Type II: in addition to a very SM-like region, there is another region where the deviation in the C_V^h is **at most 20%** from its SM value, and the C_D^h is slightly smaller in magnitude and have **the opposite sign** to its SM values.

$h \sim 125$-Constraints on the other Higgs bosons





- Perturbativity set bound on m_A for a certain $m_{H\pm}$.

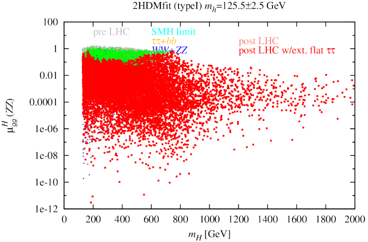
$$m_A^2 - m_{H\pm}^2 = \frac{v^2}{2}(\lambda_4 - \lambda_5)$$

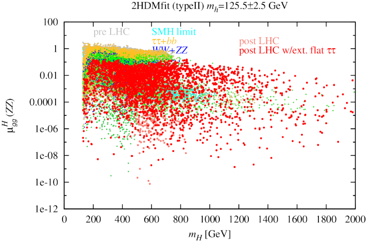
- $m_{H\pm} > 80$ GeV in Type I and $m_{H\pm} > 295$ GeV in Type II.
- **No** strong correlation away from the decoupling limit ($m_H > 800$ GeV).
- The lowest $m_A \approxeq 40$ GeV. However, if $m_A < \frac{m_h}{2}$, rare decay $h \to AA$ open. $BR(h \to AA)$ **at most** 10%, otherwise it results in the suppression in the WW and ZZ to escape the LHC signals.

Whether is the Higgs boson(s) other than 125 GeV observable or not?

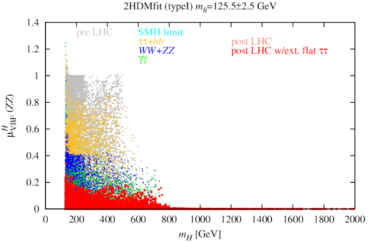
$h \sim 125$-Heavier Higgs boson H search

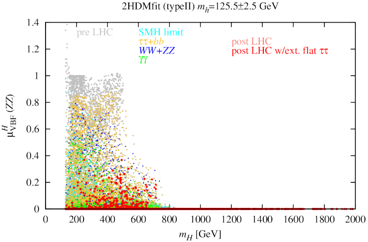
$\mu^H_{gg}(ZZ)$





$\mu^H_{VBF}(ZZ)$



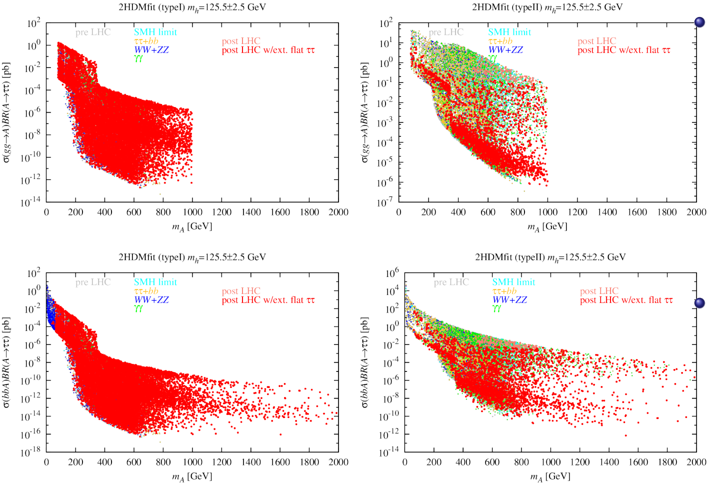


For heavier CP-even Higgs boson H, easier to access are $\mu_{gg}(ZZ)$ and $\mu_{VBF}(ZZ)$, about 0.2. This level of signal would eventually accessible in light of much smaller width [a].

[a] We correct for the width difference by rescaling the observed limits on $\sigma \times \mathrm{BR}$ by $f = \sqrt{\frac{\Gamma_H^2 + (4\ \mathrm{GeV})^2}{\Gamma_{h_{SM}}^2 + (4\ \mathrm{GeV})^2}}$.

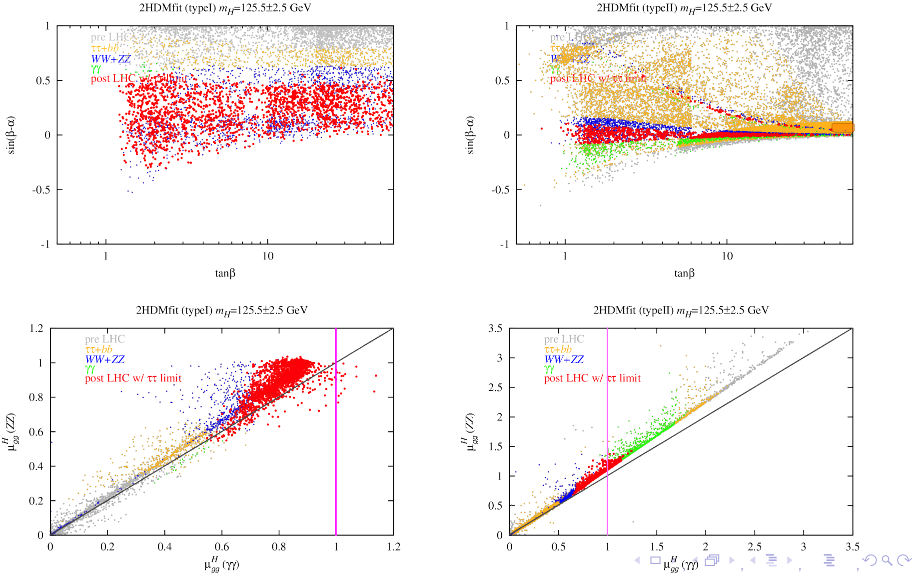
$h \sim 125$-Heavier Higgs boson A search

For heavier CP-odd Higgs boson A, the potential interest are $gg \to A \to \tau\tau$ and the bottom quark associated processes: $gg \to bbA$ with $A \to \tau\tau$.

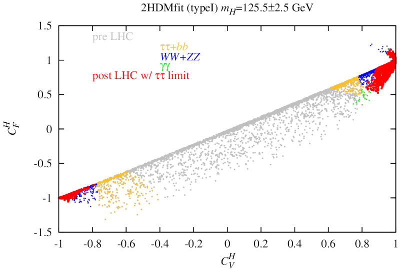


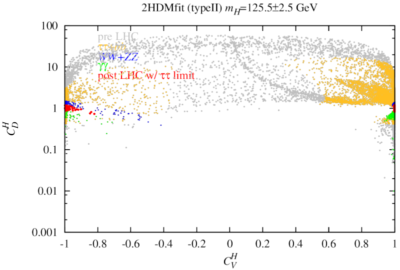
- Overall speaking, heavy Higgs boson searches has NO impact on the LHC favored points in the Type I as $\sigma < 10^{-2}$pb for b-associated production.
- But exclude a few points in Type II for $m_A \sim 500 - 1000$ GeV b.c. C_τ^A can be very large at high $\tan\beta$.

For H be SM like, $C_V^H \sim \cos(\beta - \alpha) \sim 1$, that is, $\cos(\beta - \alpha) \rightarrow \sin(\beta - \alpha) \sim 0$.



$H \sim 125$-Coupling fits C_D vs. C_V

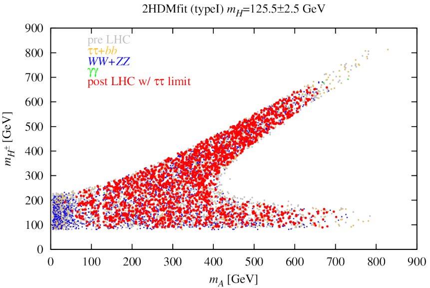


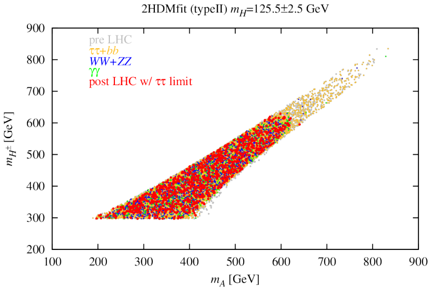


In the contrast to the case of $m_h \sim 125$ GeV,

- The coupling C_V^H could be both -1 and $+1$.
- C_F^H has about 10% derivation from $+1$ in Type I whereas C_D^H is strictly constrained near $+1$ in Type II.

$H \sim 125$-Constraints on the other Higgs bosons

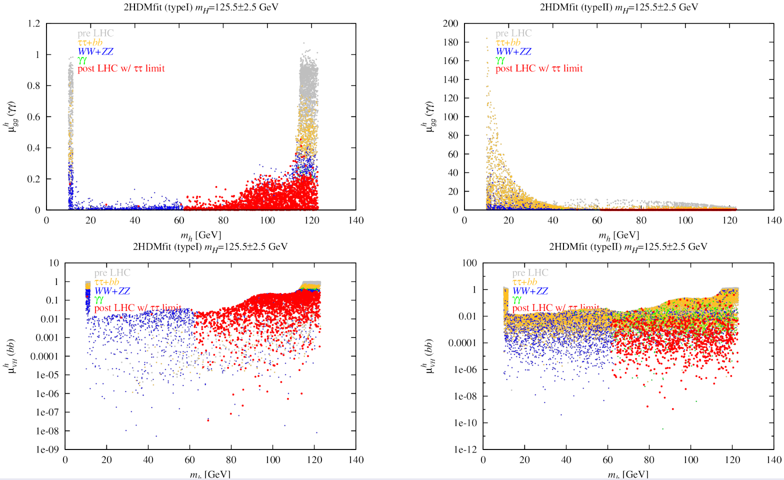




SAME pattern but the decoupling limit does NOT apply.

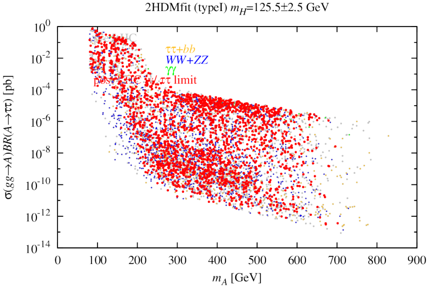
$\mu^h_{gg}(\gamma\gamma)$

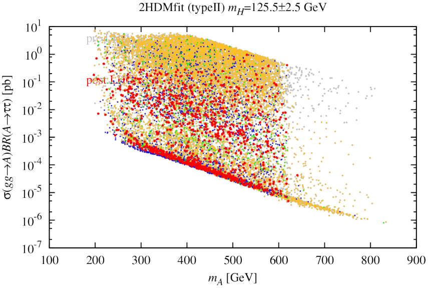
$\mu^h_{VH}(bb)$

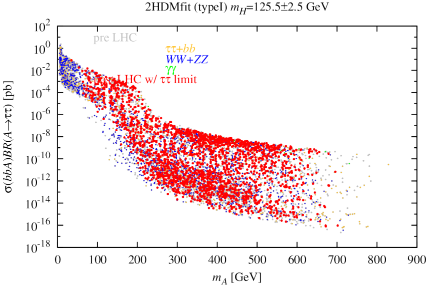


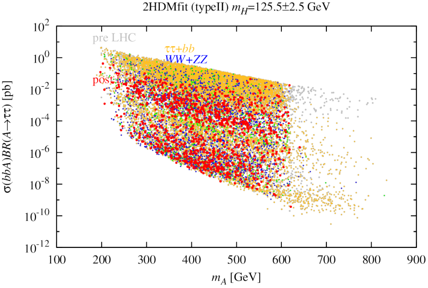
- $m_h \geq 60$ GeV with a few exception in which $H \to hh$ decay opens. $BR(H \to hh)$ at most 20 (10)% in Type I (II) to fit the LHC signals.
- Expected rates for most points are obviously too small to allow the detection of the h.
- But there are also **allowed** parameter choices for which detection in the $\gamma\gamma$ final state and, especially, the $Vh(bb)$ might prove possible with HL-LHC.

$H \sim 125$-Heavier Higgs boson A search





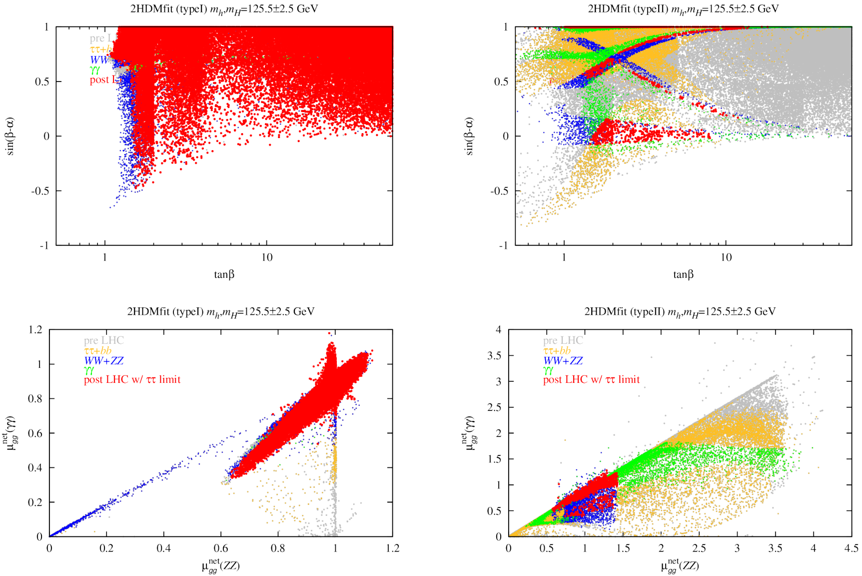




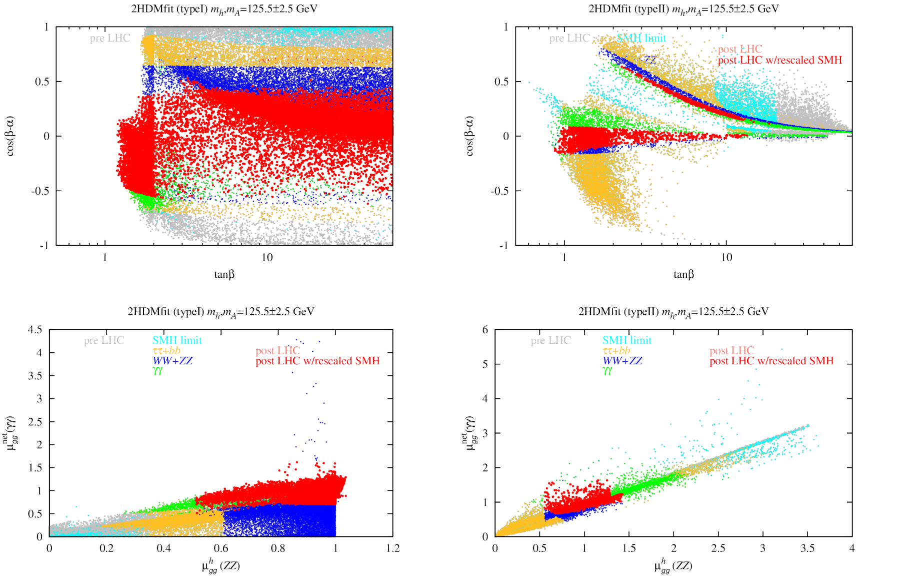
Is it possible that the excess in the Higgs $\to \gamma\gamma$ is due to two 2HDMs degenerate states?

Yes, the signal at 125 GeV cannot be pure A since at the tree level the A does not couple to ZZ, a final state that is definitely present at 125 GeV.

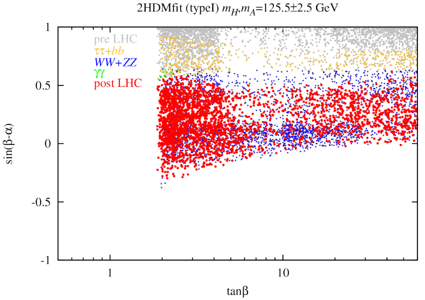
$h, H \sim 125$-Parameter and Signals

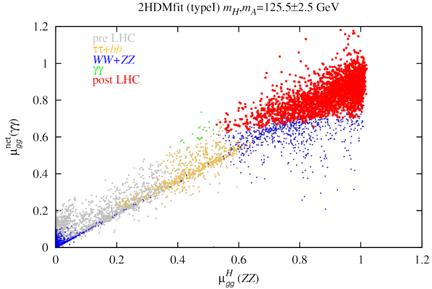


$h, A \sim 125$-Parameter and Signals



$H, A \sim 125$-Parameter and Signals





Conclusions

1. The latest Higgs data from LHC clearly favors a fairly SM-like Higgs boson with mass of 125.5 GeV.
2. There is consistent descriptions with the LHC Higgs signal in the both Type I and Type II 2HDMs. The ratio $\frac{\mu_{gg}(ZZ)}{\mu_{gg}(\gamma\gamma)}$ might be a possible signature to examine the Type I and II 2HDM if the diphoton rate is confirmed to be very SM-like or a bit enhanced in the future.
3. The search associated with other (heavier) Higgs bosons is awaiting.
4. More interesting conclusions about Higgs self-interactions is being studied, please stay tuned.
5. 2HDM+singlet with a dark matter candidate is a natural extension which we (with Bohdan, Jack and Ola) are now working in progress.

Thank you

To me, 2012 was a productive year.

It is just the start of my research career, wish your staying tuned.

Back Up

Stability condition in the 2HDM

Apparently, A matrix reduces to 4×4 in the 2HDM for real λ_5 and $\lambda_6 = \lambda_7 = 0$. In the basis $a = H_1^\dagger H_1$, $b = H_2^\dagger H_2$, $c = \mathrm{Re}(H_1^\dagger H_2)$, $d = \mathrm{Im}(H_1^\dagger H_2)$,

$$A = \begin{pmatrix} \frac{\lambda_1}{2} & \frac{\lambda_3}{2} & 0 & 0 \\ \frac{\lambda_3}{2} & \frac{\lambda_2}{2} & 0 & 0 \\ 0 & 0 & \lambda_4 + \lambda_5 & 0 \\ 0 & 0 & 0 & \lambda_4 - \lambda_5 \end{pmatrix} \tag{6}$$

Using the positivity condition on the root of a quadratic polynomial equation for upper left block, we obtain the conditions requiring all eigenvalues positive are

$$\begin{aligned} \lambda_1 + \lambda_2 &> 0 \\ \lambda_1\lambda_2 - \lambda_3^2 &> 0 \\ \lambda_4 + \lambda_5 &> 0 \\ \lambda_4 - \lambda_5 &> 0 \end{aligned} \tag{7}$$

Or essentially,

$$\begin{aligned} \lambda_1, \lambda_2 > 0 \\ -\sqrt{\lambda_1\lambda_2} < \lambda_3 < \sqrt{\lambda_1\lambda_2} \\ \lambda_4 > |\lambda_5| \end{aligned} \tag{8}$$

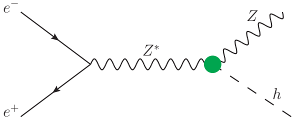
This combination seems to be a bit more strict than the ones adopted in most 2HDM papers.

$$\begin{aligned} \lambda_1 &> 0 \\ \lambda_2 &> 0 \\ \lambda_3 &> -\sqrt{\lambda_1\lambda_2} \\ \lambda_3 + \lambda_4 - |\lambda_5| &> -\sqrt{\lambda_1\lambda_2} \end{aligned} \tag{9}$$

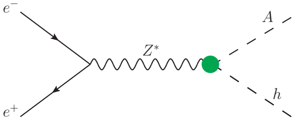
Here λ_5 is assumed to be real.

Basic Constraints – LEP

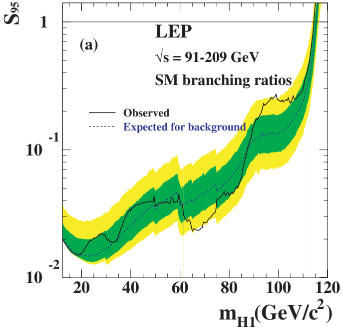
LEP constraints on Higgs mass limits

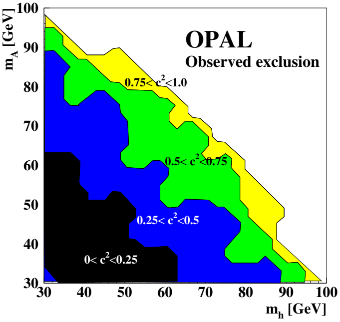


$$\frac{\sigma(e^+e^- \to Z\,h)}{\sigma(e^+e^- \to Z\,h_{\rm SM})} \sim \sin^2(\alpha-\beta)$$



$$\frac{\sigma(e^+e^- \to A\,h)}{\sigma(e^+e^- \to Z\,h_{\rm SM})} \sim \cos^2(\alpha-\beta)$$

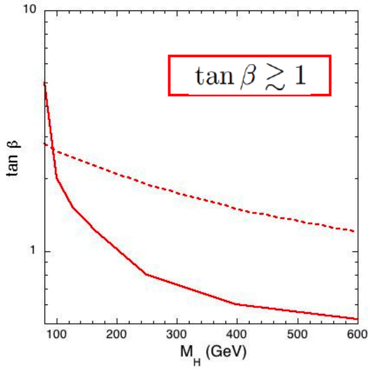




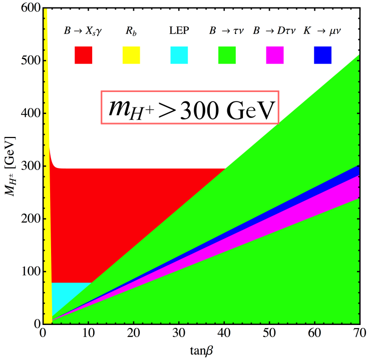
Basic Constraints – B-physics

B-physics constraints ($\mathrm{BR}(B_s \to X_s\gamma)$, R_b, ΔM_{B_s}, ϵ_K, $\mathrm{BR}(B^+ \to \tau^+\nu_\tau)$ and $\mathrm{BR}(B^+ \to D\tau^+\nu_\tau)$): set up lower bound on $m_{H^\pm}$.

Type I



Type II



Solid: R_b for $Z \to b\bar{b}$, ϵ_K and Δm_{B_s}
Dash: $\bar{B} \to X_s\gamma$ in models with FCNC

G. C. Branco et. al. Phys. Rept. **516** (2012) 1

$\gamma\gamma - ZZ$ Correlation Analysis

A. Drozd, B. Grzadkowski, J. F. Gunion and YJ, JHEP 05(2013)072

$$r_s \equiv \frac{R^s_{gg}(\gamma\gamma)}{R^s_{gg}(ZZ)} = \frac{\Gamma(s \to \gamma\gamma)/\Gamma(h_{\rm SM} \to \gamma\gamma)}{\Gamma(s \to ZZ)/\Gamma(h_{\rm SM} \to ZZ)}$$

$$r_s \simeq \frac{(C^s_{WW})^2}{(C^s_{ZZ})^2}\left(\frac{\mathcal{A}^{SM}_W - \frac{C^s_{t\bar{t}}}{C^s_{WW}}\mathcal{A}^{SM}_t + \mathcal{A}_{H^\pm}\,\text{term}}{\mathcal{A}^{SM}_W - \mathcal{A}^{SM}_t}\right)^2 = \left(\frac{\mathcal{A}^{SM}_W - \frac{C^s_{t\bar{t}}}{C^s_{WW}}\mathcal{A}^{SM}_t}{\mathcal{A}^{SM}_W - \mathcal{A}^{SM}_t}\right)^2$$

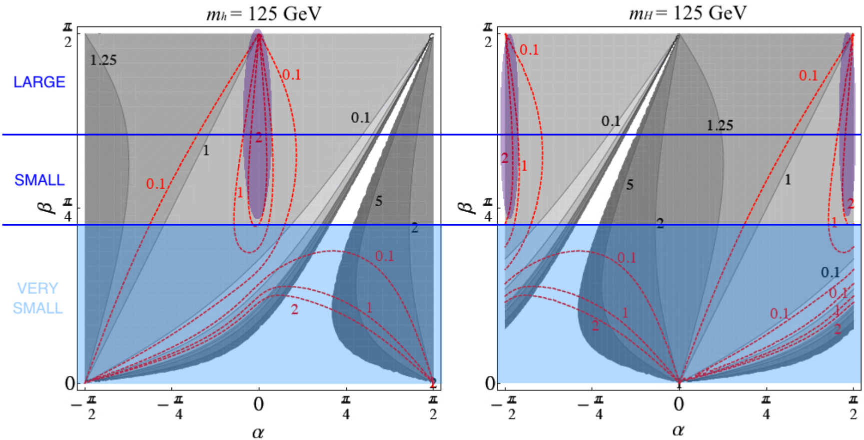
$$\boxed{r_s < 1 \Longrightarrow 1 < \frac{C^s_{t\bar{t}}}{C^s_{WW}} < 2\frac{\mathcal{A}^{SM}_W}{\mathcal{A}^{SM}_t} - 1 \simeq 9}$$

When $C^s_{t\bar{t}}/C^s_{WW}$ is outside of the above interval then $r_s > 1$.

$\gamma\gamma - ZZ$ Correlation Analysis (in Type II 2HDM)

A. Drozd, B. Grzadkowski, J. F. Gunion and YJ, JHEP 05(2013)072

$$\frac{C^h_{t\bar{t}}}{C^h_{WW}} = \frac{\cos\alpha}{\sin\beta\,\sin(\beta-\alpha)} \qquad \frac{C^H_{t\bar{t}}}{C^H_{WW}} = \frac{\sin\alpha}{\sin\beta\,\cos(\beta-\alpha)}$$



Red numbers give values of $R^s_{gg}(\gamma\gamma)$ while black ones show constant r_s values.

The white region correspond to $r_s > 10.75$.