



Higgs precision (Higgcision) era begins

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JHEP 05(2013)134, arXiv:[hep-ph] 1302.3794

Outline

- Introduction
- Formalism
- Higgs data
- CP conserving fits
- CP violating fits
- Summary

Introduction

Introduction

The Nobel Prize in Physics 2013

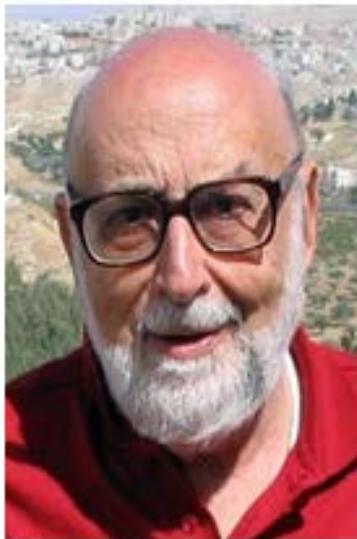


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François Englert

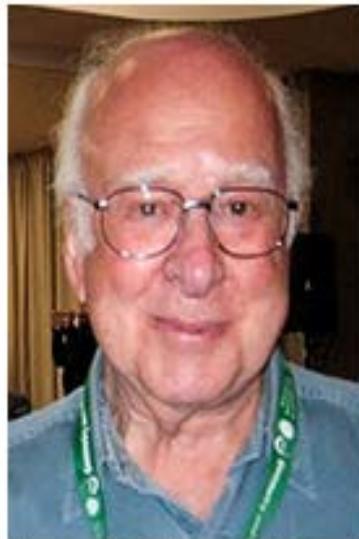


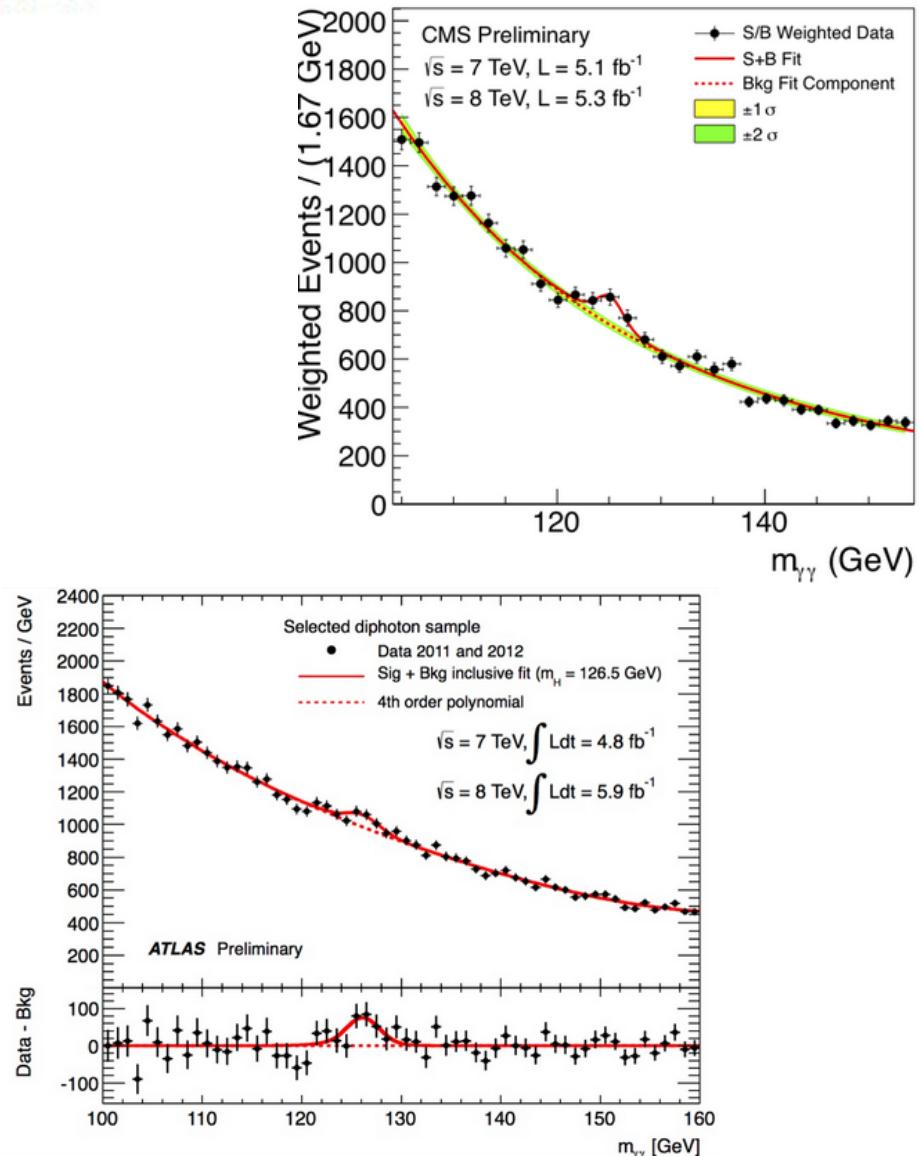
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Peter W. Higgs

R. Brout, G. Guralnik,
C.R.Hagen, Tom Kibble

3.

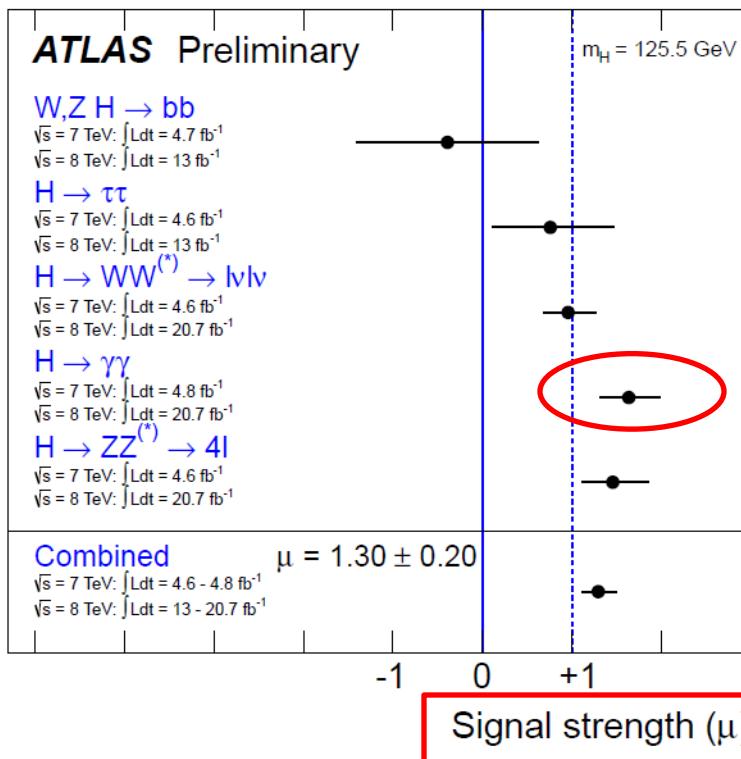
July 2012, CMS, ATLAS



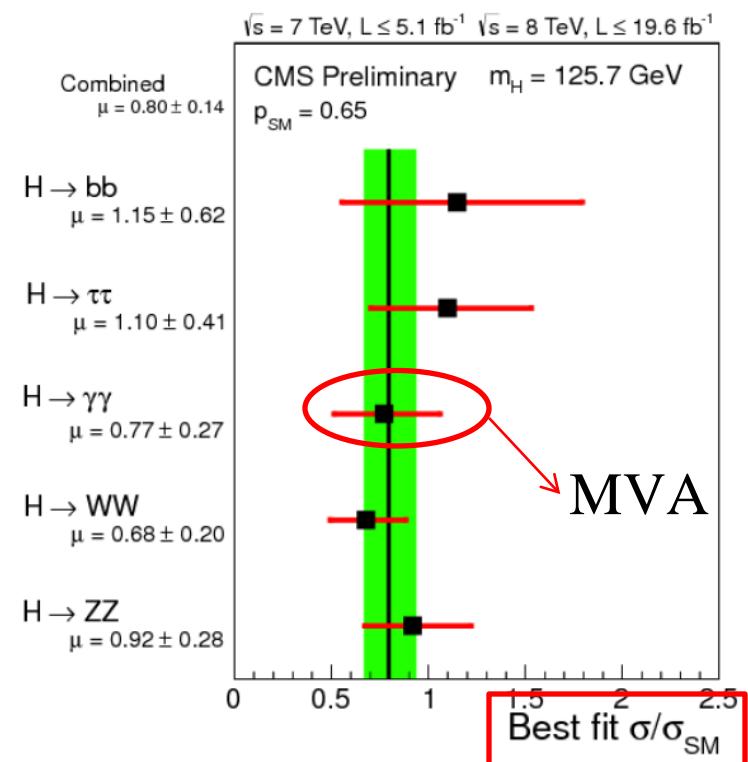
Introduction

- The diphoton production rate *after Moriond*:
ATLAS is higher than SM by a factor of **1.6**.
CMS is smaller than SM by a factor of **0.8**.

ATLAS-CONF-2013-034



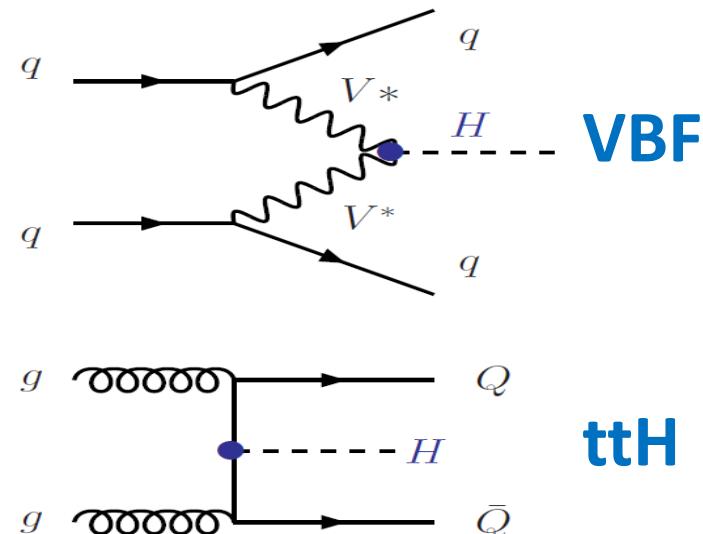
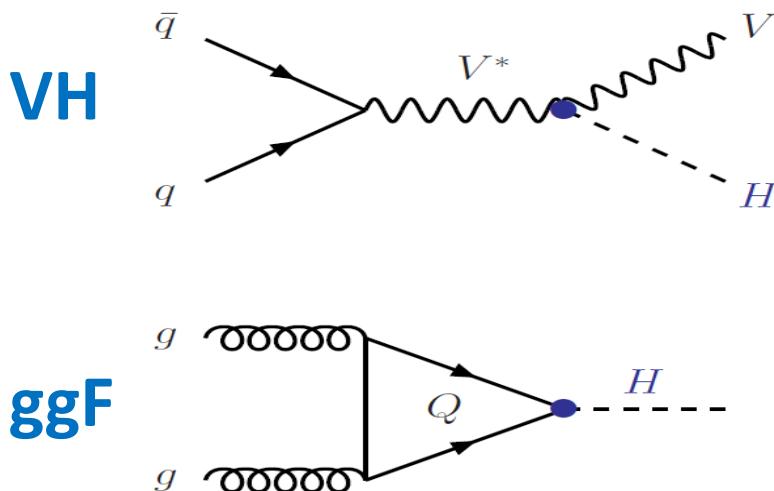
CMS PAS HIG-13-005



Introduction

- We can extract the couplings of Higgs and SM particles from the present data.
- Higgs production modes: gluon fusion (**ggF**), vector-boson fusion (**VBF**), associated production (**VH**) and (**ttH**).
- At the experimental side, these production modes usually mix together.

A Djouadi, Phys.Rept.457 (2008)1-216



Introduction : Higgs Data

- Current Higgs data focus on a few decay channels of the Higgs boson.

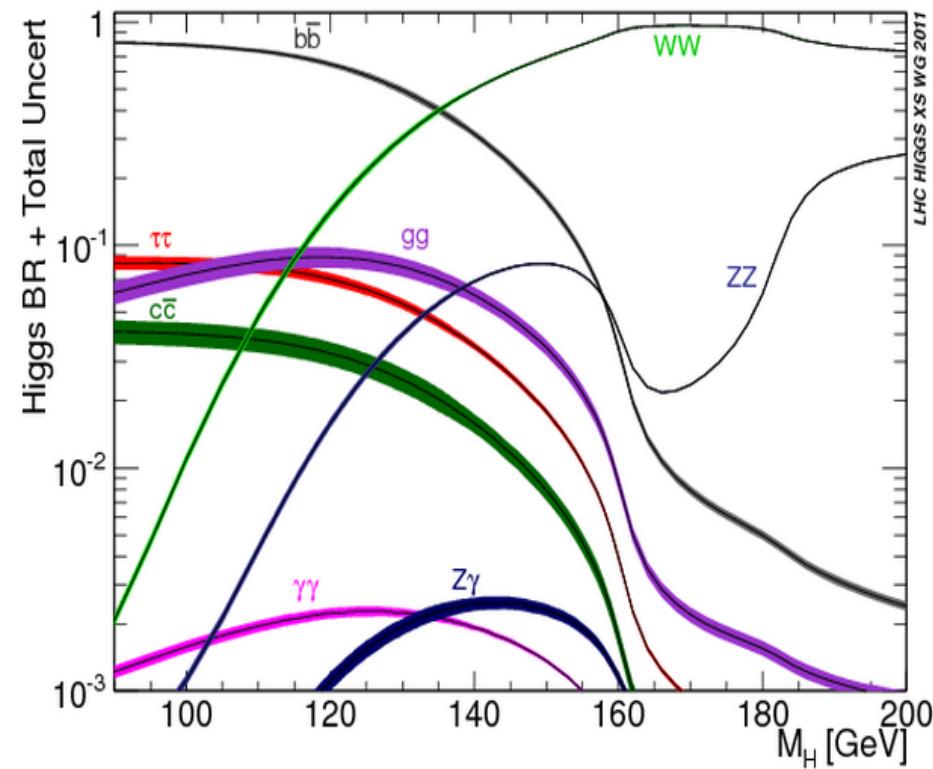
$$h \rightarrow \gamma\gamma$$

$$h \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$$

$$h \rightarrow WW^* \rightarrow l^+\bar{\nu}l^-\nu$$

$$h \rightarrow b\bar{b}$$

$$h \rightarrow \tau^+\tau^-$$



<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsTheoryPlots>

Introduction : Higgs Data

- Data on signal strength of $H \rightarrow \gamma\gamma$.

Channel	Signal strength μ		M_H (GeV)	Production mode				χ^2_{SM} (each)	
	<i>Before</i>	<i>After</i>		ggF	VBF	VH	ttH	<i>Before</i>	<i>After</i>
ATLAS (4.8fb^{-1} at 7TeV + 13.0 (20.7) fb^{-1} at 8TeV): [9, 25]									
$\mu_{ggH+ttH}$	1.8 ± 0.49	1.6 ± 0.4	126.8	100%	-	-	-	2.67	2.25
μ_{VBF}	2.0 ± 1.4	1.7 ± 0.9	126.8	-	100%	-	-	0.53	0.60
μ_{VH}	1.9 ± 2.6	$1.8^{+1.5}_{-1.3}$	126.8	-	-	100%	-	0.12	0.38
CMS (5.1fb^{-1} at 7TeV + 5.3 (19.6) fb^{-1} at 8TeV) [13, 27]									
untagged	$1.42^{+0.55}_{-0.49}$	$0.78^{+0.28}_{-0.26}$	125	87.5%	7.1%	4.9%	0.5%	0.73	0.62
VBF tagged	$2.25^{+1.34}_{-1.04}$	$2.25^{+1.34}_{-1.04}$	125.8	17%	83%	-	-	1.44	1.44
Tevatron (10.0fb^{-1} at 1.96TeV): [7]									
Combined	$6.14^{+3.25}_{-3.19}$	$6.14^{+3.25}_{-3.19}$	125	78%	5%	17%	-	2.60	2.60
							subtot:	8.09	7.89

Introduction

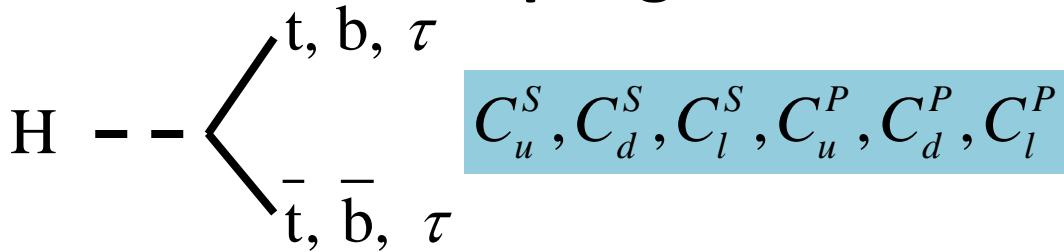
- Because the dramatically changing of the diphoton rate from **CMS** *before* and *after* **Moriond**, we will show our results with data *before* and *after* **Moriond**.

Formalism

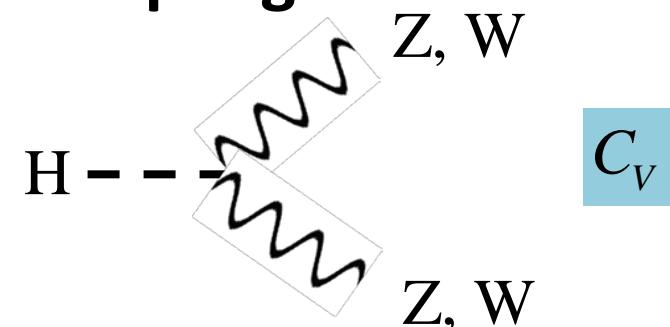
Formalism: Higgs Couplings

- We follow the conventions of **CPsuperH** for the general **CP-mixed Higgs** couplings to SM particles.

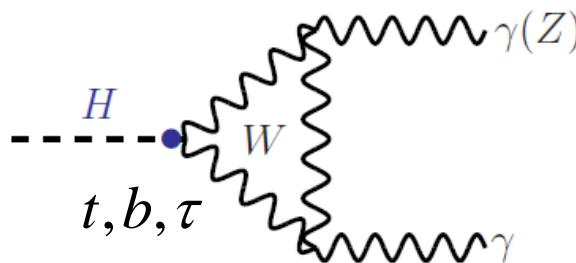
- Yukawa couplings:**



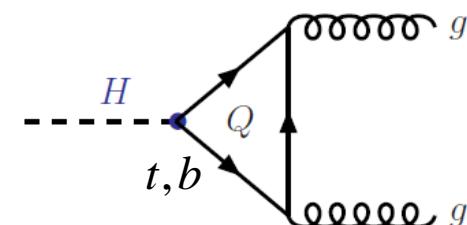
- HVV couplings:**



- Higgs-diphoton:**



- Higgs-two-gluon:**



$$\text{CP even : } S^\gamma = (b, t, \tau) - (W) + \Delta S^\gamma$$

$$\text{CP odd : } P^\gamma = (b, t, \tau) + \Delta P^\gamma$$

$$S^g = (b, t) + \Delta S^g$$

$$P^g = (b, t) + \Delta P^g$$

Formalism: Higgs Couplings

- We defined the ratios of the effective Higgs couplings to $gg, \gamma\gamma, Z\gamma$ relative to SM ones:

$$C_g \equiv \sqrt{\frac{|S^g|^2 + |P^g|^2}{|S_{\text{SM}}^g|^2}}; \quad C_\gamma \equiv \sqrt{\frac{|S^\gamma|^2 + |P^\gamma|^2}{|S_{\text{SM}}^\gamma|^2}}; \quad C_{Z\gamma} \equiv \sqrt{\frac{|S^{Z\gamma}|^2 + |P^{Z\gamma}|^2}{|S_{\text{SM}}^{Z\gamma}|^2}}$$

- Note, the ratios of decay rates relative to the SM are

$$|C_g|^2, |C_\gamma|^2, |C_{Z\gamma}|^2$$

Formalism: Higgs Couplings

- The scalar-type couplings:

$$C_u^S, C_d^S, C_l^S; \quad C_V; \quad \Delta S^g, \Delta S^\gamma, \Delta \Gamma_{\text{tot}}$$

custodial symmetry new particles invisible decay

- The pseudoscalar-type couplings:

$$C_u^P, C_d^P, C_l^P; \quad \Delta P^g, \Delta P^\gamma$$

- SM: $C_u^S = C_d^S = C_l^S = C_V = 1; \quad \Delta S^g = \Delta S^\gamma = \Delta \Gamma_{\text{tot}} = 0$
 $C_u^P = C_d^P = C_l^P = 0; \quad \Delta P^g = \Delta P^\gamma = 0$

CP Conserving Fits

CP Conserving Fits

- In CP conserving fits:

$$\begin{cases} \text{fixed: } & C_{u,d,l}^P = \Delta P^{g,\gamma} = 0 \\ \text{varying: } & C_{u,d,l}^S, \quad C_v, \quad \Delta S^{g,\gamma}, \quad \Delta \Gamma_{\text{tot}} \end{cases}$$

- Under this, implement following 5 fits:

	varying	fixed
A. SM fit		$C_{u,d,l}^S = C_v = 1, \Delta S^{g,\gamma} = \Delta \Gamma_{\text{tot}} = 0$
B. 1-parameter	$\Delta \Gamma_{\text{tot}}$	$C_{u,d,l}^S = C_v = 1, \Delta S^{g,\gamma} = 0$
C. 2/3-parameter	$\Delta S^{g,\gamma}$ without/with $\Delta \Gamma_{\text{tot}}$	$C_{u,d,l}^S = C_v = 1$
D. 4-parameter	$C_{u,d,l}^S, C_v$	$\Delta S^{g,\gamma} = \Delta \Gamma_{\text{tot}} = 0$
E. 6-parameter	$C_{u,d,l}^S, C_v, \Delta S^{g,\gamma}$	$\Delta \Gamma_{\text{tot}} = 0$

CP Conserving Fits: SM & 1-parameter

- *after* : **SM fit** gives: $\chi^2 / dof = 18.94 / 22 = 0.86$
SM is good fit to the Higgs data.
- **1-parameter fit:**
$$\begin{cases} \text{varying:} & \Delta\Gamma_{\text{tot}} \\ \text{fixed:} & C_u^S = C_d^S = C_l^S = C_\nu = 1, \Delta S^\gamma, \Delta S^g = 0 \end{cases}$$
- *after* : The 95% CL upper limit for $\Delta\Gamma_{\text{tot}}$ is 1.2 MeV.
Note the $\Gamma_{\text{tot}}^{\text{SM}} \approx 4.1 \text{ MeV}$ for $M_H = 125.5 \text{ GeV}$. The 95% CL upper limit for the nonstandard branching ratio of the Higgs boson is about 22%.

CP Conserving Fits: 4-parameter

- **4-parameter fits:**

{ varying: $C_u^S, C_d^S, C_\ell^S, C_v$
fixed: $\Delta S^\gamma = \Delta S^g = 0, \Delta \Gamma_{\text{tot}} = 0$

- This is motivated by **no new particles** running in the triangle loop of $H\gamma\gamma$ and Hgg , but only modification of the **Yukawa couplings**.
- **2HDM with heavy charged Higgs boson** and modification of the Yukawa couplings in terms of the mixing angle α and $\tan\beta$.

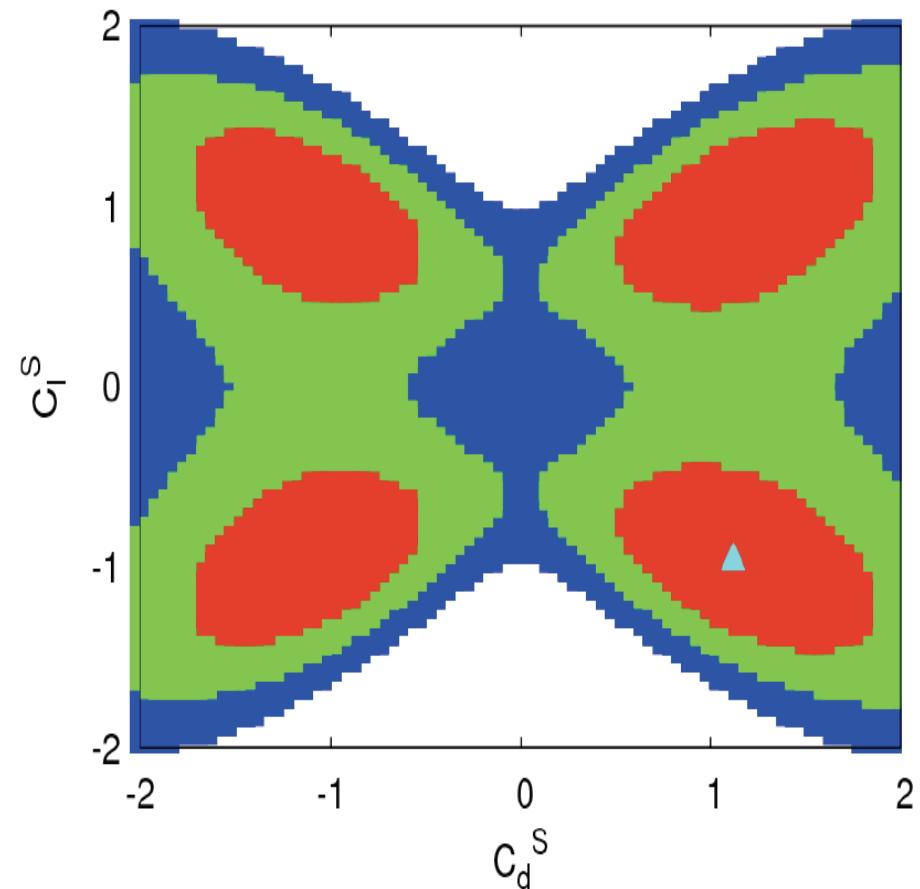
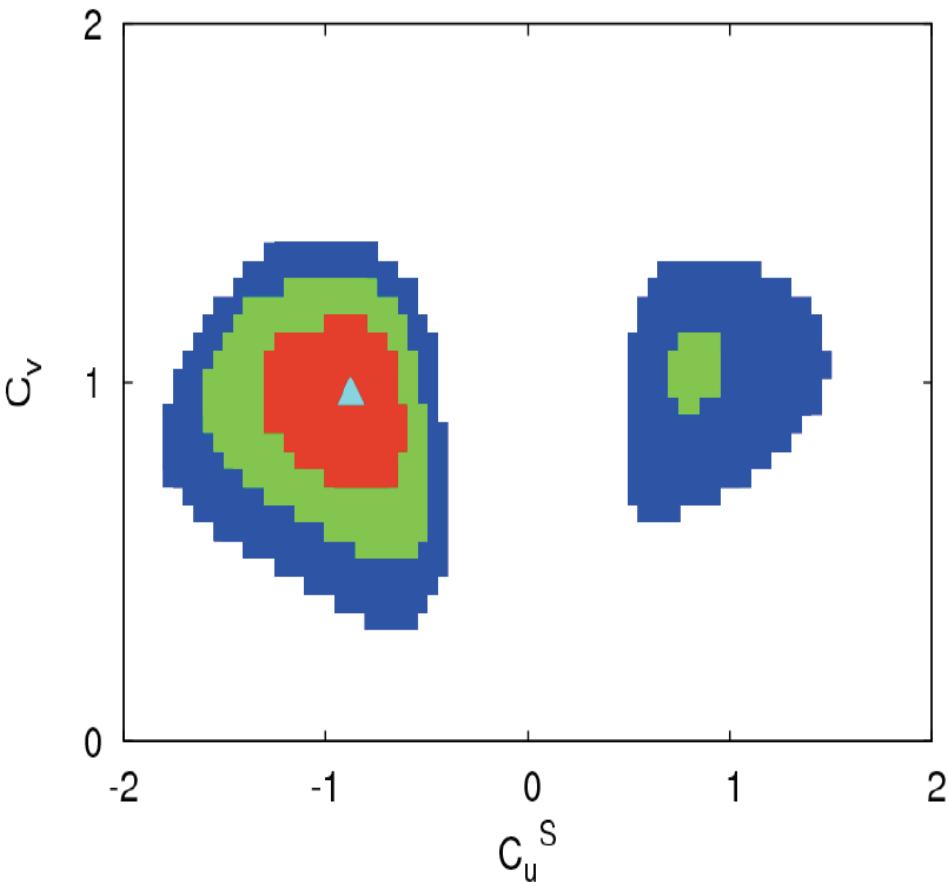
$$C_u^S = \frac{\cos \alpha}{\sin \beta}, \quad C_d^S = C_\ell^S = -\frac{\sin \alpha}{\cos \beta}, \quad C_v = \sin(\beta - \alpha)$$

CP Conserving Fits: 4-parameter

- In the loop coupling of $H\gamma\gamma$ and Hgg , since the bottom-quark and charged-lepton only have minor effects, we expect these are an approximate symmetry of $C_d^S \leftrightarrow -C_d^S$ or $C_l^S \leftrightarrow -C_l^S$.
- **Top-quark and W-boson** give the dominate contribution to $H\gamma\gamma$ with the **opposite sign**. Therefore by flipping the sign of top-quark $C_u^S \leftrightarrow -C_u^S$, it can **enhance** the $H\gamma\gamma$ vertex (*before*).

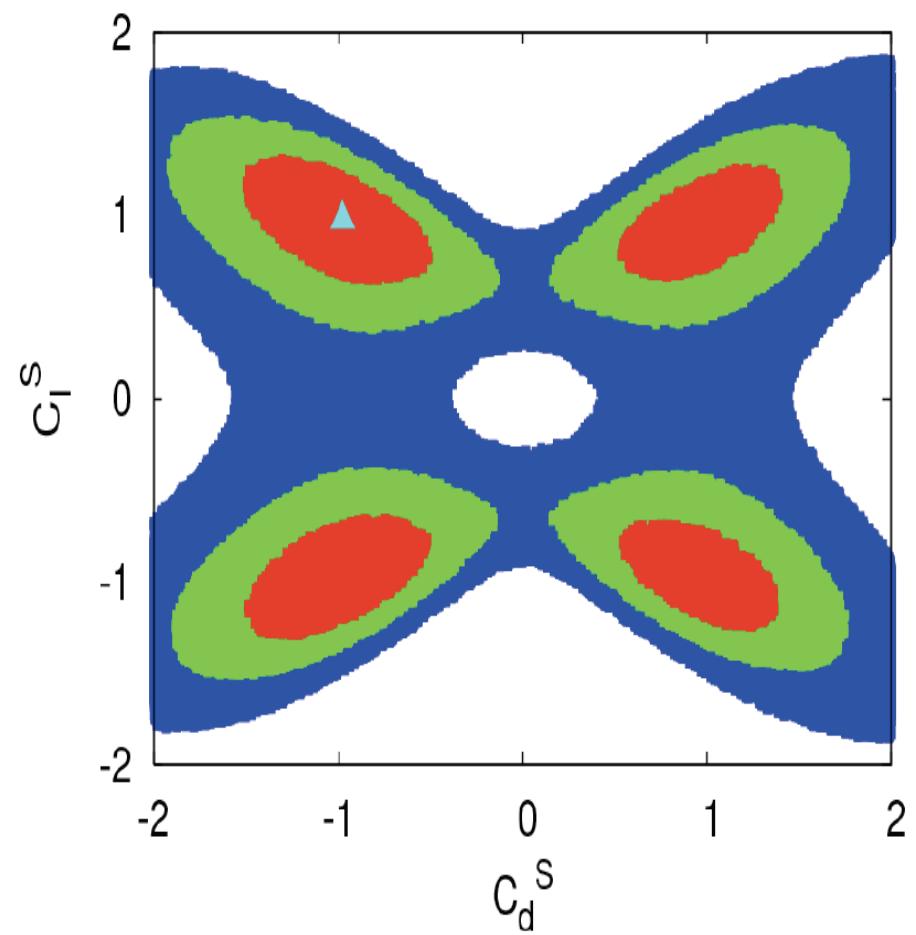
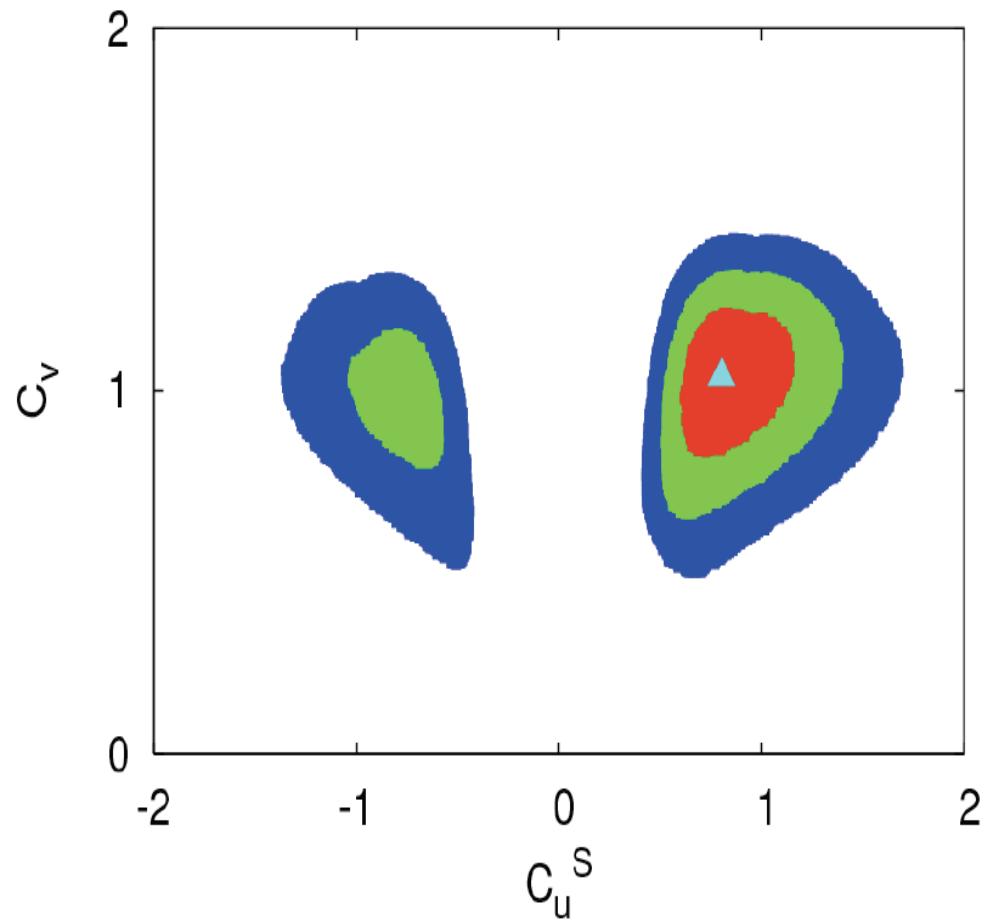
CP Conserving Fits: 4-parameter

- The 2-dim contours for the correlations of any 2 parameters of C_u^S, C_d^S, C_l^S, C_v . *before:*



CP Conserving Fits: 4-parameter

- The 2-dim contours for the correlations of any 2 parameters of C_u^S, C_d^S, C_l^S, C_v . *after:*



CP Conserving Fits: 2HDM

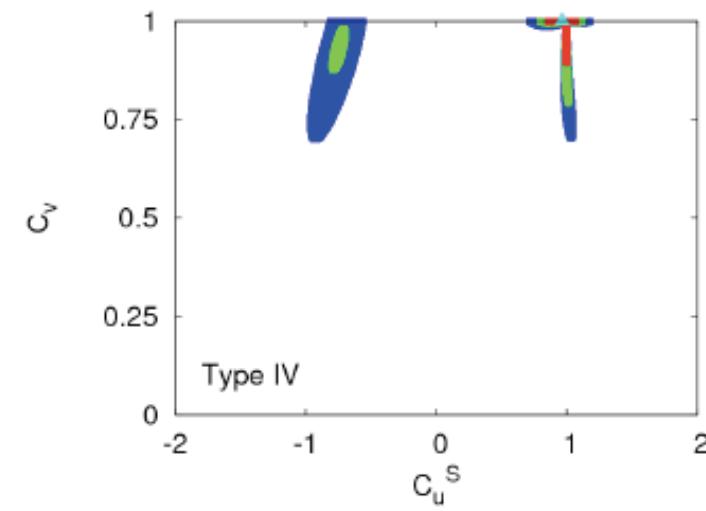
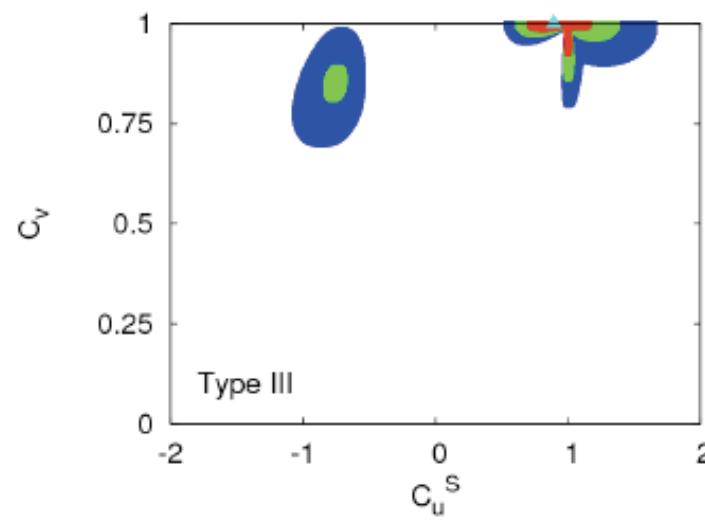
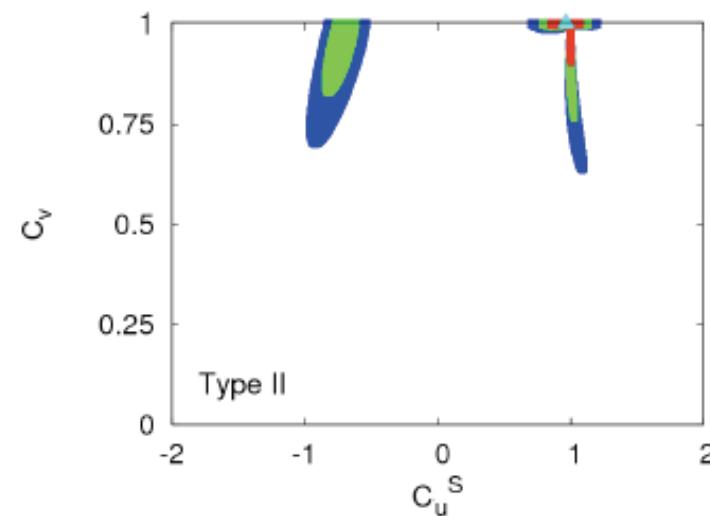
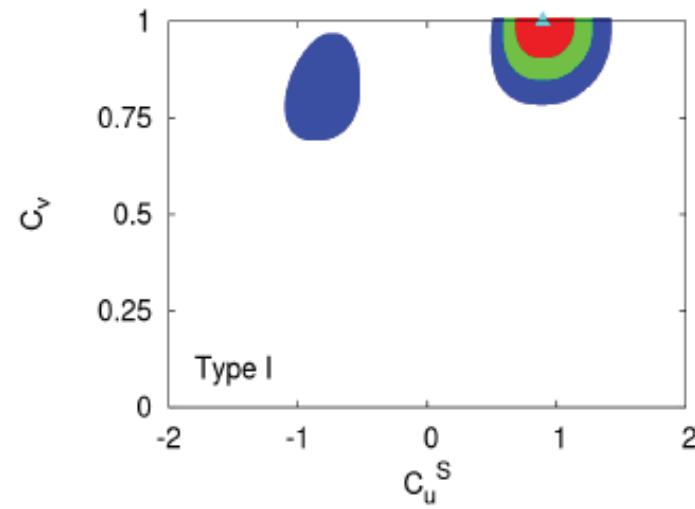
- In **2HDM** with heavy charge Higgs, only **3** parameters are needed C_u^S, C_u^P, C_V .
- Yukawa couplings:

2HDM I	$C_d^S = C_u^S$	$C_l^S = C_u^S$	$C_d^P = -C_u^P$	$C_l^P = -C_u^P$
2HDM II	$C_d^S = \pm \frac{[1-s_\beta^2(C_u^S)^2-t_\beta^2(C_u^P)^2]^{1/2}}{c_\beta}$	$C_l^S = \pm \frac{[1-s_\beta^2(C_u^S)^2-t_\beta^2(C_u^P)^2]^{1/2}}{c_\beta}$	$C_d^P = t_\beta^2 C_u^P$	$C_l^P = t_\beta^2 C_u^P$
2HDM III	$C_d^S = C_u^S$	$C_l^S = \pm \frac{[1-s_\beta^2(C_u^S)^2-t_\beta^2(C_u^P)^2]^{1/2}}{c_\beta}$	$C_d^P = -C_u^P$	$C_l^P = t_\beta^2 C_u^P$
2HDM IV	$C_d^S = \pm \frac{[1-s_\beta^2(C_u^S)^2-t_\beta^2(C_u^P)^2]^{1/2}}{c_\beta}$	$C_l^S = C_u^S$	$C_d^P = t_\beta^2 C_u^P$	$C_l^P = -C_u^P$

- $\tan\beta$ Angle of the VEV:

$$s_\beta^2 = \frac{1 - C_v^2}{1 + (C_u^S)^2 + (C_u^P)^2 - 2C_v C_u^S}$$

CP Conserving Fits: 2HDM



K. Cheung, J.S. Lee, P.Y. Tseng, arXiv:1310.3937

21. $\Delta\chi^2 = 2.3(\text{red}), 5.99(\text{green}), 11.83(\text{blue}) \Rightarrow \text{CL}=68.3\%, 95\%, 99.7\%$

CP Conserving Fits: 2HDM

- Notice: SM p-value = 0.65

Type	χ^2	χ^2/dof	p-value
I	18.39	0.920	0.562
II	18.68	0.934	0.543
III	18.44	0.922	0.558
IV	18.66	0.933	0.544

K. Cheung, J.S. Lee, P.Y. Tseng, arXiv:1310.3937

- We demonstrated that the current Higgs boson data have **NO** preference for any of the four types of **2HDM**.

CP Violating Fits

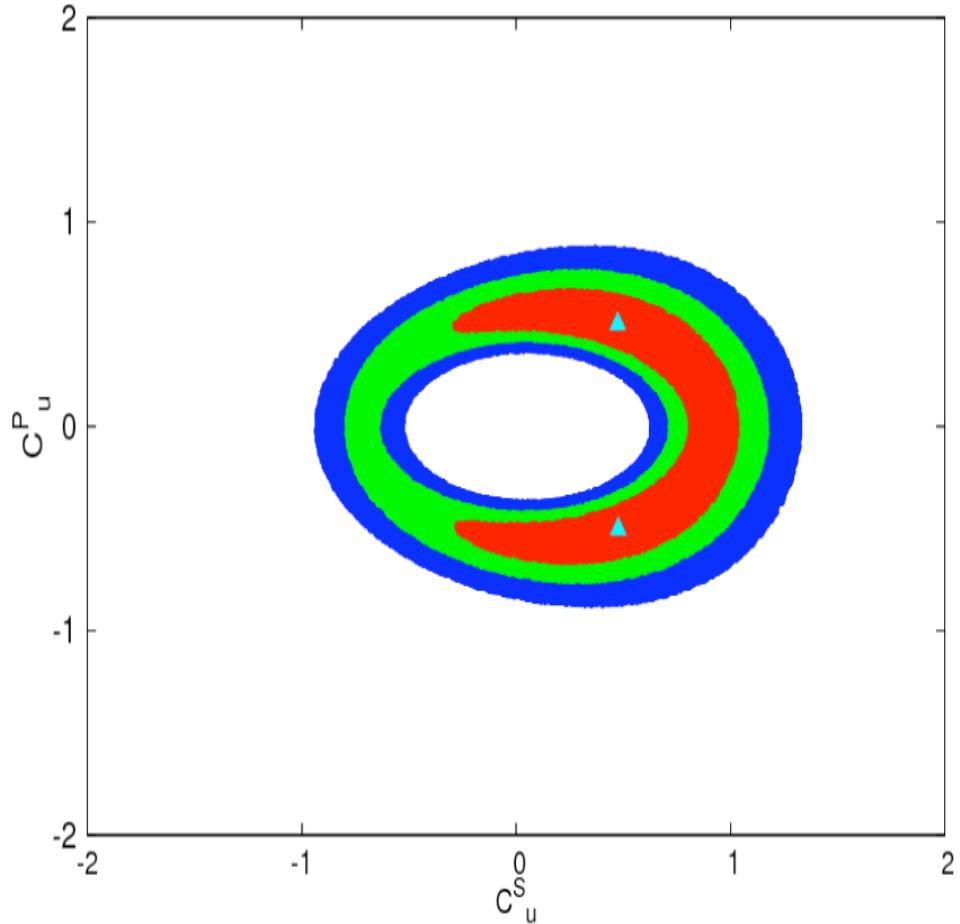
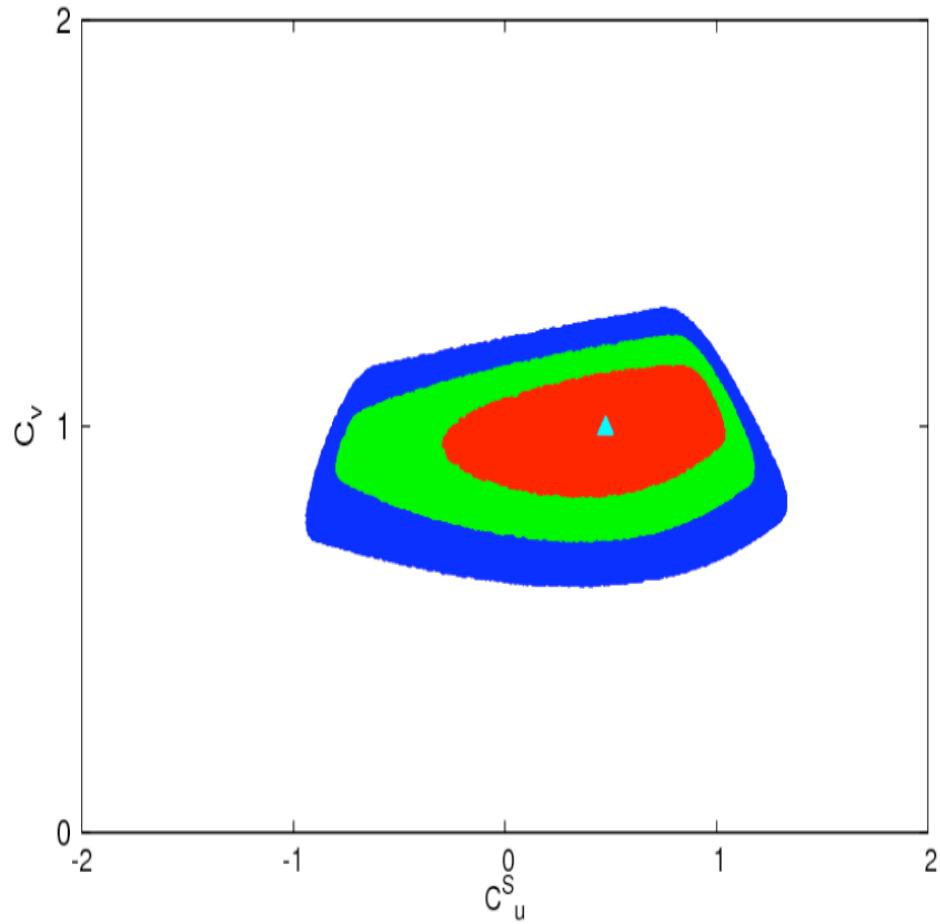
CP Violating Fits: B.

- Without loss of generality we consider the up-type scalar Yukawa couplings C_u^S and pseudoscalar C_u^P and C_v in this fit.

$$\left\{ \begin{array}{ll} \text{varying:} & C_u^S, C_u^P, C_v \\ \text{fixed:} & C_d^S = C_l^S = 1, \quad C_d^P = C_l^P = 0, \\ & \Delta S^\gamma = \Delta S^g = \Delta P^\gamma = \Delta P^g = 0, \quad \Delta \Gamma_{\text{tot}} = 0 \end{array} \right.$$

CP Violating Fits: B.

- The confidence-level regions of the fit: *after*



CP Violating Fits: B.

- The total chi-square is $\chi^2 = 17.17$, slightly better than the total chi-square $\chi^2 = 17.82$ of the **4-parameter fit** $C_u^S, C_d^S, C_l^S, C_\nu$.
- The current **signal strength** cannot rule out the combination of scalar and pseudoscalar Yukawa couplings.

Summary

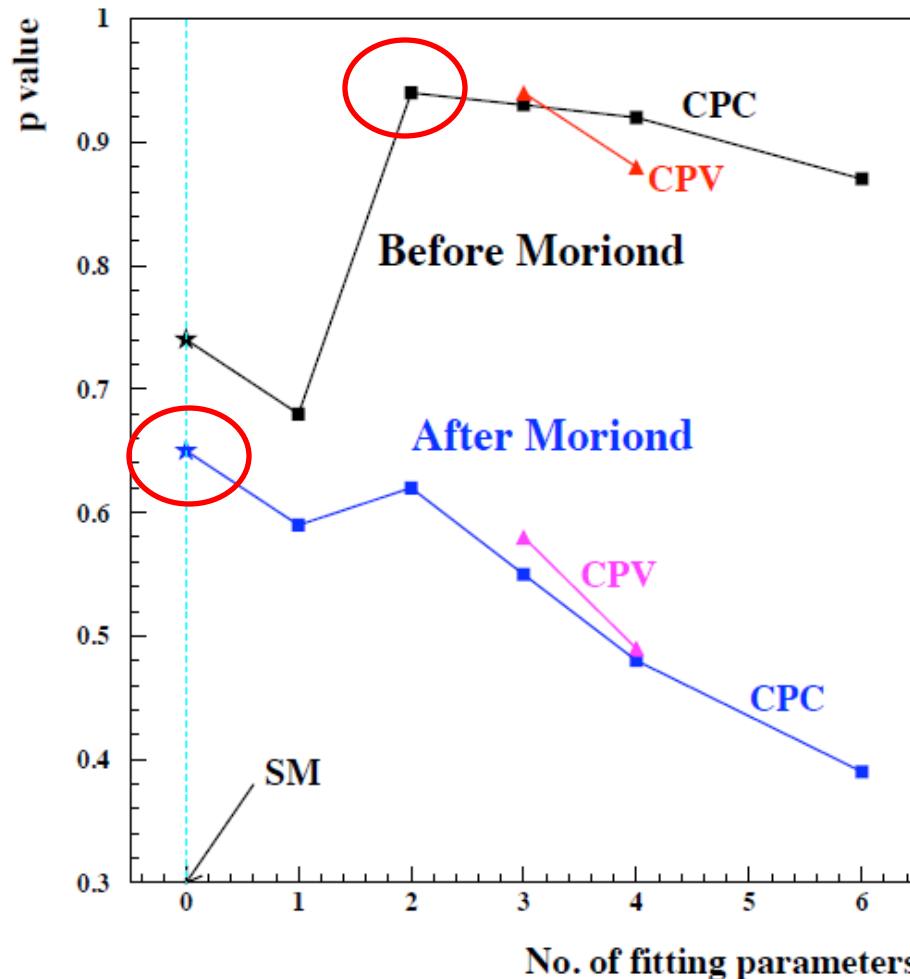
Summary

- In this work, we established a model-independent framework to analysis the observed Higgs boson signal strength and extract the Higgs boson couplings with fermions, W/Z , $\gamma\gamma$, gg . We also perform the fit to Higgs data *before* and *after* Moriond meeting.
- We assume the **Higgs boson** is a generalized **CP-mixed** state **without** carrying any definite **CP-parity**.

- Our finding are:
 - Both *before* and *after*. **SM** give the good fit $\chi^2 / dof = 0.86$ to the data.
 - If only the total Higgs width are allowed to vary. The 95% CL upper limit of the nonstandard decay branching ratio is **22%**. This improve the previous estimate 40%.

Discussion

➤ *before* The most efficient way to fit the Higgs data is to effect the $H\gamma\gamma$, Hgg vertices. *After* No optimal set of parameters can reduce χ^2 effectively.



$$(\Delta S^\gamma, \Delta S^g):$$
$$\chi^2 / dof = 0.56$$
$$p - \text{value} = 0.94$$

Discussion

- Both *before* and *after*.

The relative HVV coupling $C_v = 1.01^{+0.13}_{-0.14}$ in **6-parameter fit** (similar in **4-parameter fit**) implies the observed Higgs boson accounts for most of EWSB.

- Both *before* and *after*.

The Higgs data do not rule out the pseudoscalar contribution to $H\gamma\gamma$, Hgg nor the pseudoscalar Yukawa couplings. However, they do not improve the fit either.

Thank you !

Back Up

Introduction

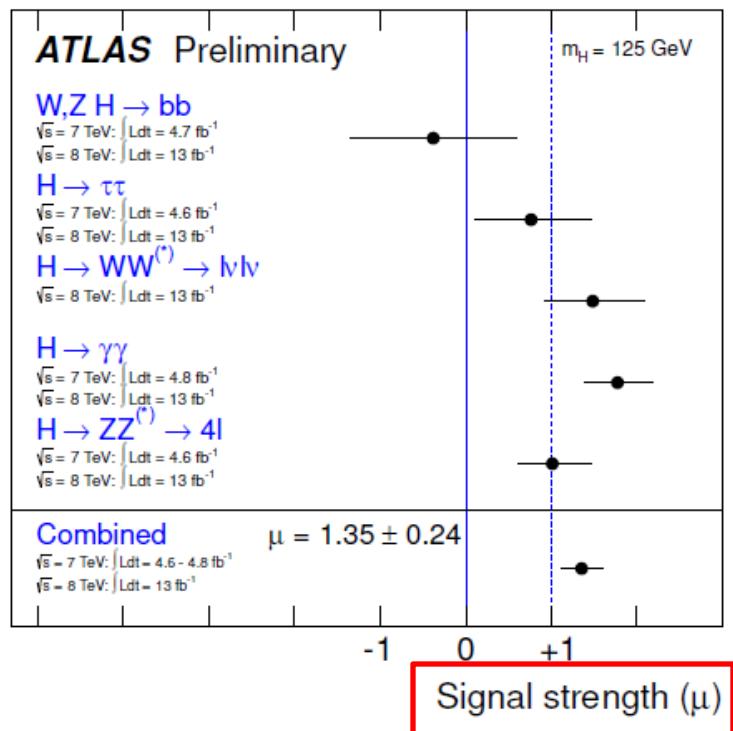
- In July 2012, ATLAS and CMS announced the discovery of the Higgs boson candidate by looking into decay modes of

$$\left\{ \begin{array}{l} H \rightarrow \gamma\gamma \\ H \rightarrow WW^* \rightarrow l^+\nu l^-\bar{\nu} \\ H \rightarrow ZZ^* \rightarrow 4l \\ H \rightarrow b\bar{b} \\ H \rightarrow \tau^+\tau^- \end{array} \right.$$

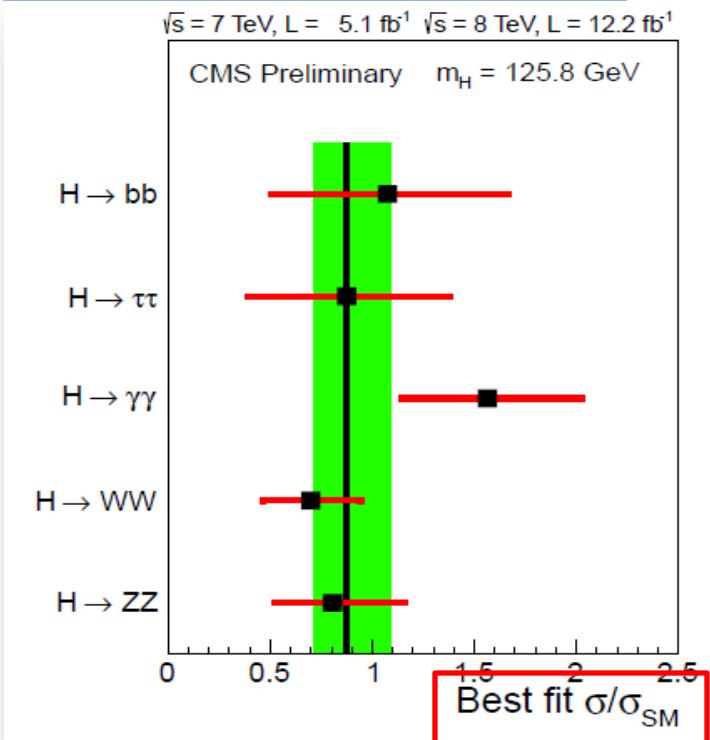
Introduction

- The diphoton production rate is higher than SM by a factor of 1.4 to 1.8. Only about 1 or 2 σ .

ATLAS-CONF-2012-170



CMS PAS HIG-12-045



Introduction

- The ggH coupling depends on $H\bar{t}t$ and $H\bar{b}b$. VBF, VH and the Higgs decays into WW, ZZ depend on coupling of $H\bar{V}V$. Higgs decays into $\bar{b}b$ and $\tau^+\tau^-$ depend on $H\bar{b}b$ and $H\tau\tau$. Higgs decays to $\gamma\gamma$ depends on all the above couplings.
- A global analysis of all the Higgs couplings using all the data is useful to identify the observed Higgs boson.
- Once we disentangle each of the Higgs coupling, we can use the results to compare with models.

Formalism: Higgs Couplings

- We follow the conventions of **CPsuperH** for the general **CP-mixed** Higgs couplings to SM particles.
- Higgs couplings to fermions:

$$\mathcal{L}_{H\bar{f}f} = - \sum_{f=u,d,l} \frac{gm_f}{2M_W} \sum_{i=1}^3 H \bar{f} \left(g_{H\bar{f}f}^S + ig_{H\bar{f}f}^P \gamma_5 \right) f$$

scalar pseudoscalar

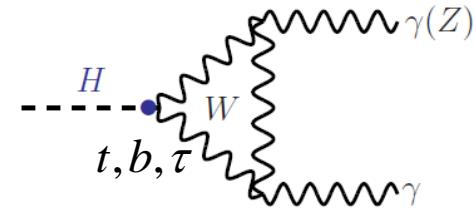
For SM couplings $g_{H\bar{f}f}^S = 1$ and $g_{H\bar{f}f}^P = 0$.

- Higgs couplings to massive vector bosons:

$$\mathcal{L}_{HVV} = g M_W \left(g_{HWW} W_\mu^+ W^{-\mu} + g_{HZZ} \frac{1}{2c_W^2} Z_\mu Z^\mu \right) H$$

For SM couplings $g_{HWW} = g_{HZZ} \equiv g_{HVV} = 1$, custodial.

Formalism: Higgs Couplings



A Djouadi, Hep-
ph:0503172

- Higgs couplings to two photons:

The amplitude for the decay $H \rightarrow \gamma\gamma$ is

$$\mathcal{M}_{\gamma\gamma H} = -\frac{\alpha M_H^2}{4\pi v} \left\{ S^\gamma(M_H) (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*) - P^\gamma(M_H) \frac{2}{M_H^2} \langle \epsilon_1^* \epsilon_2^* k_1 k_2 \rangle \right\}$$


scalar

pseudoscalar

- The decay rate of $H \rightarrow \gamma\gamma$ is proportional to $|S^\gamma|^2 + |P^\gamma|^2$

$$S^\gamma(M_H) = 2 \sum_{f=b,t,\tau} \boxed{N_C Q_f^2 g_{H\bar{f}f}^S F_{sf}(\tau_f) - g_{HWW} F_1(\tau_W)} + \underline{\Delta S^\gamma},$$

$$P^\gamma(M_H) = 2 \sum_{f=b,t,\tau} N_C Q_f^2 g_{H\bar{f}f}^P F_{pf}(\tau_f) + \Delta P^\gamma,$$

from new charged particles

from SM particle with changing Yukawa

Formalism: Higgs Couplings

- Higgs couplings to two gluons:

The amplitude for the decay $H \rightarrow gg$ is

$$\mathcal{M}_{ggH} = -\frac{\alpha_s M_H^2 \delta^{ab}}{4\pi v} \left\{ S^g(M_H) (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*) - P^g(M_H) \frac{2}{M_H^2} \langle \epsilon_1^* \epsilon_2^* k_1 k_2 \rangle \right\}$$

- The decay rate of $H \rightarrow gg$ is proportional to $|S^g|^2 + |P^g|^2$

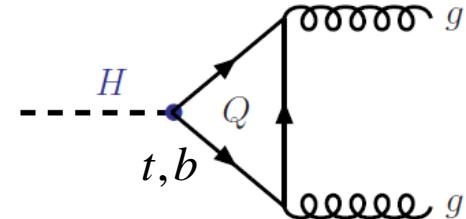
$$S^g(M_H) = \sum_{f=b,t} g_{H\bar{f}f}^S F_{sf}(\tau_f) + \Delta S^g$$

$$P^g(M_H) = \sum_{f=b,t} g_{H\bar{f}f}^P F_{pf}(\tau_f) + \Delta P^g$$

- Higgs couplings to Z and γ :

new colored particles

$$\mathcal{M}_{Z\gamma H} = -\frac{\alpha}{2\pi v} \left\{ S^{Z\gamma}(M_H) [k_1 \cdot k_2 \epsilon_1^* \cdot \epsilon_2^* - k_1 \cdot \epsilon_2^* k_2 \cdot \epsilon_1^*] - P^{Z\gamma}(M_H) \langle \epsilon_1^* \epsilon_2^* k_1 k_2 \rangle \right\}$$



A Djouadi, Hep-ph:0503172

Formalism: Signal Strengths

- The theoretical signal strength is product:

$$\hat{\mu}(\mathcal{P}, \mathcal{D}) \simeq \hat{\mu}(\mathcal{P}) \hat{\mu}(\mathcal{D})$$

where $\mathcal{P} = \text{ggF, VBF, VH, ttH}$ is the production modes
and $\mathcal{D} = \gamma\gamma, ZZ, WW, b\bar{b}, \tau\bar{\tau}$ the decay modes.

$$\hat{\mu}(\text{ggF}) = \frac{|S^g(M_H)|^2 + |P^g(M_H)|^2}{|S_{\text{SM}}^g(M_H)|^2},$$

$$\hat{\mu}(\text{VBF}) = g_{_{HWW,HZZ}}^2,$$

$$\hat{\mu}(\text{VH}) = g_{_{HWW,HZZ}}^2,$$

$$\hat{\mu}(\text{ttH}) = \left(g_{H\bar{t}t}^S\right)^2 + \left(g_{H\bar{t}t}^P\right)^2;$$

Formalism: Signal Strengths

- The decay parts:

$$\hat{\mu}(\mathcal{D}) = \frac{B(H \rightarrow \mathcal{D})}{B(H_{\text{SM}} \rightarrow \mathcal{D})}$$

with

$$B(H \rightarrow \mathcal{D}) = \frac{\Gamma(H \rightarrow \mathcal{D})}{\Gamma_{\text{tot}}(H) + \boxed{\Delta\Gamma_{\text{tot}}}}$$

where $\Delta\Gamma_{\text{tot}}$ is the non-SM contribution to the total decay width.

Formalism: Signal Strengths

- The experimentally observed signal strength should be compared to the theoretical one summed over all production modes:

$$\mu(Q, \mathcal{D}) = \sum_{\mathcal{P}=\text{ggF, VBF, VH, ttH}} C_{Q\mathcal{P}} \hat{\mu}(\mathcal{P}, \mathcal{D})$$

A red arrow points from the label "defined channel" to the term $\sum_{\mathcal{P}}$. Another red arrow points from the label "decomposition coefficients of production modes" to the term $C_{Q\mathcal{P}}$.

- The χ^2 associated with an observable is:

$$\chi^2(Q, D) = \frac{[\mu(Q, D) - \mu^{\text{EXP}}(Q, D)]^2}{[\sigma^{\text{EXP}}(Q, D)]^2}$$

experimental error

experimental data

Formalism: 2-Higgs Doublet Model

- Our parameter can cover several models.
- 2HDM:

$$H_u = (H_u^+ H_u^0)^T \text{ and } H_d = (H_d^+ H_d^0)^T$$

- After EWSB and for CP-conserving case:

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

- For Type-II. The couplings of the lighter CP-even Higgs boson h are:

	$\tau^- \tau^+$	$b\bar{b}$	$t\bar{t}$	$W^+ W^- / ZZ$
h :	$-\sin \alpha / \cos \beta$	$-\sin \alpha / \cos \beta$	$\cos \alpha / \sin \beta$	$\sin(\beta - \alpha)$

Formalism: 2-Higgs Doublet Model

- Therefore, the fitting parameters would be:

$$C_u^S = \frac{\cos \alpha}{\sin \beta}, \quad C_d^S = C_\ell^S = -\frac{\sin \alpha}{\cos \beta}, \quad C_v = \sin(\beta - \alpha)$$

- The charged Higgs boson H^+ will run in the triangle loop of $H\gamma\gamma$. There are no new particle added in the triangle loop of Hgg . There are no new particles that the Higgs boson h can decay into.

$$\Delta S^\gamma \neq 0, \quad \Delta S^g = 0, \quad \Delta \Gamma_{\text{tot}} = 0$$



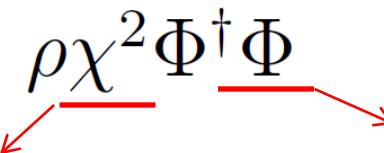
charged Higgs H^+

Formalism: Singlet Higgs Bosons

- Simple extensions of the SM Higgs sector with one Higgs singlet fields. It could provide a dark matter candidate.
- Renormalizable interaction:

$$\rho \chi^2 \Phi^\dagger \Phi$$

real singlet Higgs field SM Higgs doublet



- Impose a discrete Z_2 symmetry $\chi \leftrightarrow -\chi$, χ become dark matter candidate and couples to the Higgs via interaction $\chi^2 H$ and $\chi^2 H^2$.

$$H \xrightarrow{\text{Decay}} \chi\chi \quad \text{accommodated by} \quad \Delta\Gamma_{\text{tot}} \neq 0$$

Formalism: Supersymmetry Model

- At least two Higgs doublets in SUSY models.
- In the minimal supersymmetry model (MSSM), there are 3 neutral Higgs state ($i=1,2,3$), any of them could be the observed Higgs:

$$C_u^S = \frac{O_{\phi_2 i}}{\sin \beta}, \quad C_d^S = C_\ell^S = \frac{O_{\phi_1 i}}{\cos \beta}, \quad C_v = O_{\phi_1 i} \cos \beta + O_{\phi_2 i} \sin \beta;$$

$$C_u^P = -\frac{\cos \beta}{\sin \beta} O_{ai}, \quad C_d^P = C_\ell^P = -\frac{\sin \beta}{\cos \beta} O_{ai},$$

where $O_{\phi_1 i, \phi_2 i}$ and O_{ai} denote the CP-even and CP-odd components of the i -th Higgs state.

Formalism: Supersymmetry Model

- SUSY particles will contribute to the loop of $H\gamma\gamma$ and Hgg . Higgs can decay into non-SM particle.

$$\Delta S^\gamma \neq 0, \quad \Delta S^g \neq 0, \quad \Delta \Gamma_{\text{tot}} \neq 0$$

$$\Delta P^\gamma \neq 0, \quad \Delta P^g \neq 0$$

Formalism: 4th Generation Model

- The 4th generation model is an extension of the SM by adding an analogous generation of fermions.
- The new charged leptons and quarks can run in the loop of $H\gamma\gamma$, and colored quarks in loop of Hgg .

$$\left\{ \begin{array}{l} C_u^S = C_d^S = C_l^S = C_\nu^S = 1 \\ C_u^P = C_d^P = C_l^P = 0 \\ \Delta S^\gamma \neq 0, \quad \Delta S^g \neq 0, \quad \Delta \Gamma_{\text{tot}} = 0 \end{array} \right.$$

Higgs Data

- Data on signal strength of $H \rightarrow \gamma\gamma$.

Channel	Signal strength μ	M_H (GeV)	Production mode				χ^2_{sm} (each)
			ggF	VBF	VH	ttH	
ATLAS ($4.8 fb^{-1}$ at 7TeV + $13.0 fb^{-1}$ at 8TeV): Table 3 of [9] (Dec. 2012)							
$\mu_{\text{ggF+ttH}}$	1.8 ± 0.49	126.6	100%	-	-	-	2.67
μ_{VBF}	2.0 ± 1.4	126.6	-	100%	-	-	0.53
μ_{VH}	1.9 ± 2.6	126.6	-	-	100%	-	0.12
CMS ($5.1 fb^{-1}$ at 7TeV + $5.3 fb^{-1}$ at 8TeV): Fig. 10 of [13] (Nov. 2012)							
untagged	$1.42^{+0.55}_{-0.49}$	125.8	87.5%	7.1%	4.9%	0.5%	0.73
VBF tagged	$2.25^{+1.34}_{-1.04}$	125.8	17%	83%	-	-	1.44
Tevatron ($10.0 fb^{-1}$ at 1.96TeV): Page 32 of [7] (Nov. 2012)							
Combined	$6.14^{+3.25}_{-3.19}$	125	78%	5%	17%	-	2.60
						subtotal: 8.09	

Higgs Data

- Data on signal strength of $H \rightarrow \gamma\gamma$.

Channel	Signal strength μ	M_H (GeV)	Production mode				χ^2_{sm} (each)
	c.v \pm error		ggF	VBF	VH	ttH	
ATLAS ($4.8 fb^{-1}$ at 7TeV + $13.0 fb^{-1}$ at 8TeV): Table 3 of [9] (Dec. 2012)							
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Higgs Data

- Data on signal strength of $H \rightarrow \gamma\gamma$.

Channel	Signal strength μ		$M_H(\text{GeV})$	Production mode				$\chi^2_{\text{SM}}(\text{each})$	
	Before	After		ggF	VBF	VH	ttH	Before	After
ATLAS (4.8 fb^{-1} at 7TeV + 13.0 (20.7) fb^{-1} at 8TeV): [9, 25]									
$\mu_{ggH+ttH}$	1.8 ± 0.49	1.6 ± 0.4	126.8	100%	-	-	-	2.67	2.25
μ_{VBF}	2.0 ± 1.4	1.7 ± 0.9	126.8	-	100%	-	-	0.53	0.60
μ_{VH}	1.9 ± 2.6	$1.8^{+1.5}_{-1.3}$	126.8	-	-	100%	-	0.12	0.38
CMS (5.1 fb^{-1} at 7TeV + 5.3 (19.6) fb^{-1} at 8TeV) [13, 27]									
untagged	$1.42^{+0.55}_{-0.49}$	$0.78^{+0.28}_{-0.26}$	125	87.5%	7.1%	4.9%	0.5%	0.73	0.62
VBF tagged	$2.25^{+1.34}_{-1.04}$	$2.25^{+1.34}_{-1.04}$	125.8	17%	83%	-	-	1.44	1.44
Tevatron (10.0 fb^{-1} at 1.96TeV): [7]									
Combined	$6.14^{+3.25}_{-3.19}$	$6.14^{+3.25}_{-3.19}$	125	78%	5%	17%	-	2.60	2.60
							subtot:	8.09	7.89

$$\mu(\mathcal{Q}, \mathcal{D}) = \sum_{\mathcal{P}=\text{ggF, VBF, VH, ttH}} C_{\mathcal{Q}\mathcal{P}} \hat{\mu}(\mathcal{P}, \mathcal{D})$$

Higgs Data

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Combined	$6.14^{+3.25}_{-3.19}$	125	78%	5%	17%	-	2.60
							subtotal: 8.09

$$\mu(\mathcal{Q}, \mathcal{D}) = \sum_{\mathcal{P}=\text{ggF,VBF,VH,ttH}} C_{\mathcal{Q}\mathcal{P}} \hat{\mu}(\mathcal{P}, \mathcal{D})$$

Higgs Data

- Data on signal strength of $H \rightarrow \gamma\gamma$.

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	Before	After		ggF	VBF	VH	ttH	Before	After
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$\mu_{ggH+ttH}$	1.8 ± 0.49	1.6 ± 0.4	126.8	100%	-	-	-	2.67	2.25
μ_{VBF}	2.0 ± 1.4	1.7 ± 0.9	126.8	-	100%	-	-	0.53	0.60
μ_{VH}	1.9 ± 2.6	$1.8^{+1.5}_{-1.3}$	126.8	-	-	100%	-	0.12	0.38
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VBF tagged	$2.25^{+1.34}_{-1.04}$	$2.25^{+1.34}_{-1.04}$	125.8	17%	83%	-	-	1.44	1.44
Tevatron (10.0fb^{-1} at 1.96TeV): [7]									
Combined	$6.14^{+3.25}_{-3.19}$	$6.14^{+3.25}_{-3.19}$	125	78%	5%	17%	-	2.60	2.60
							subtot:	8.09	7.89

Higgs Data

- Data on signal strength of $H \rightarrow \gamma\gamma$.

Channel	Signal strength μ		M_H (GeV)	Production mode				χ^2_{SM} (each)	
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μ_{VBF}	2.0 ± 1.4	1.7 ± 0.9	126.8	-	100%	-	-	0.53	0.60
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Tevatron (10.0fb^{-1} at 1.96TeV): [7]									
Combined	$6.14^{+3.25}_{-3.19}$	$6.14^{+3.25}_{-3.19}$	125	78%	5%	17%	-	2.60	2.60
subtot:								8.09	7.89

Higgs Data

- Total we used 22 data points in our analysis, including 5 decay channels of the Higgs boson:

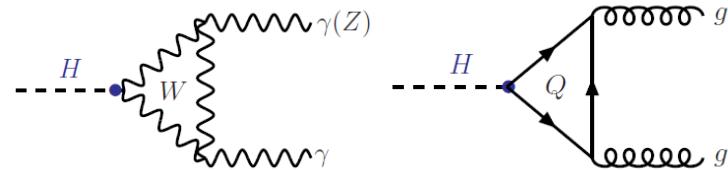
$$H \rightarrow \gamma\gamma, \quad ZZ^*, \quad WW^*, \quad b\bar{b}, \quad \tau^+\tau^-$$

- The chi-square of these 22 data to the SM is *before*:17.5, *after*:18.94.
- The chi-square per degree of freedom (dof) is *before*: $17.5/22=0.80$, *after*: $18.94/22=0.86$.
- **SM is good fit to the Higgs data.**
- The $H \rightarrow \gamma\gamma$ data give the largest contribution to the chi-square.

CP Conserving Fits: 2-parameter

- **2-parameter fit:**

$$\left\{ \begin{array}{ll} \text{varying:} & \Delta S^\gamma, \Delta S^g \\ \text{fixed:} & C_u^S = C_d^S = C_l^S = C_\nu = 1, \Delta \Gamma_{\text{tot}} = 0 \end{array} \right.$$

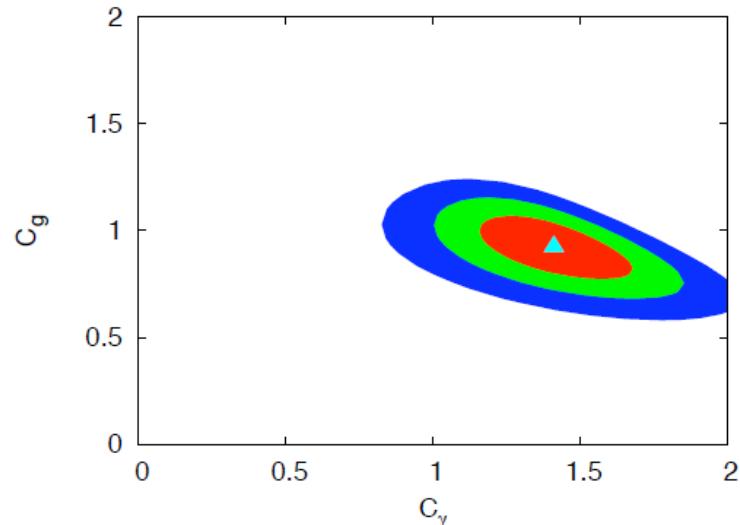
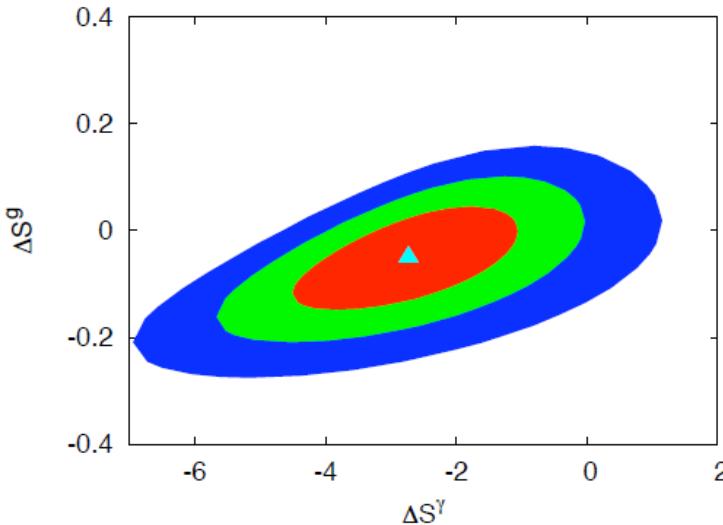


- *before* : The best fit values are: $\chi^2 / dof = 11.27 / 20 = 0.56$
Turn out, this is the most efficient way to fit the data statistically.
- *after* : The best fit values are: $\chi^2 / dof = 17.55 / 20 = 0.88$

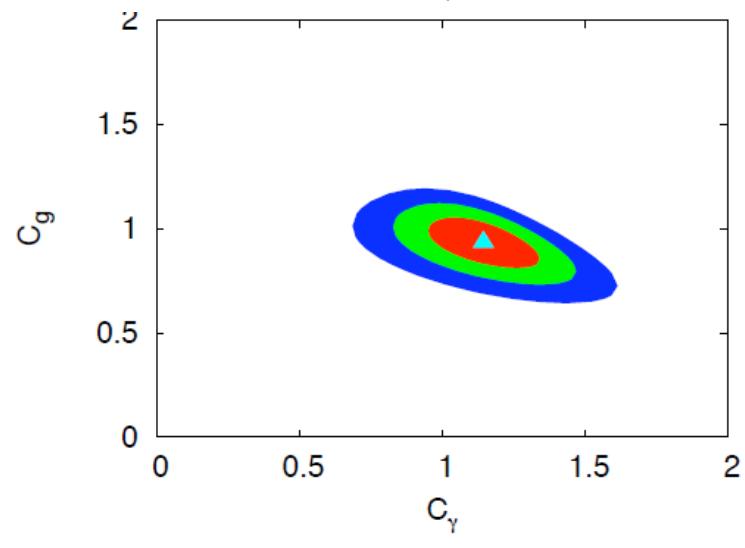
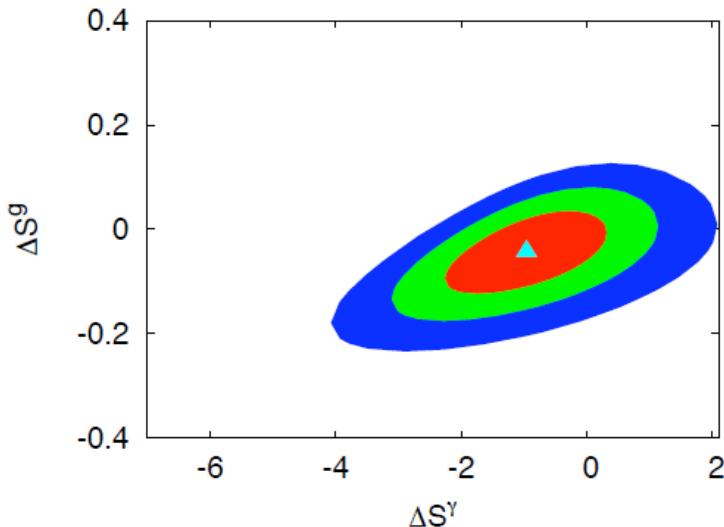
CP Conserving Fits: 2-parameter

- **2-parameter fit** $\Delta S^\gamma, \Delta S^g$.

before:



after:



CP Conserving Fits: 2/3-parameter

- **3-parameter fit:**

$$\left\{ \begin{array}{ll} \text{varying:} & \Delta S^\gamma, \Delta S^g, \boxed{\Delta \Gamma_{\text{tot}}} \\ \text{fixed:} & C_u^S = C_d^S = C_l^S = C_v = 1 \end{array} \right.$$

- *after* : The best fit values are:

$$\Delta S^\gamma = -0.96^{+0.84}_{-0.87}, \quad \Delta S^g = -0.040^{+0.12}_{-0.086}, \quad \Delta \Gamma_{\text{tot}} = \underline{0.027}^{+1.33}_{-0.80} \text{ MeV}, \quad \chi^2/dof = 17.55/19 = 0.92.$$

- Including $\Delta \Gamma_{\text{tot}}$ does not improve the χ^2 / dof .
- Since $\Delta \Gamma_{\text{tot}}$ is still consistent with zero in this case, we will fixed $\Delta \Gamma_{\text{tot}} = 0$ in the later fit.

CP Conserving Fits: 4-parameter fit

- The best fit values are:

Parameters	Vary $\Delta\Gamma_{\text{tot}}$	Vary ΔS^γ , ΔS^g	Vary ΔS^γ , ΔS^g , $\Delta\Gamma_{\text{tot}}$	Vary C_u^S , C_d^S , C_ℓ^S , C_v	Vary C_u^S , C_d^S , C_ℓ^S , C_v ΔS^γ , ΔS^g
C_u^S	1	1	1	$-0.88^{+0.16}_{-0.21}$	0.00 ± 1.13
C_d^S	1	1	1	$1.12^{+0.45}_{-0.38}$	$1.19^{+0.57}_{-0.41}$
C_ℓ^S	1	1	1	$-0.97^{+0.30}_{-0.29}$	0.98 ± 0.30
C_v	1	1	1	$0.97^{+0.13}_{-0.15}$	$0.96^{+0.13}_{-0.15}$
ΔS^γ	0	$-2.73^{+1.11}_{-1.15}$	$-2.93^{+1.19}_{-1.31}$	0	$-1.23^{+2.44}_{-2.49}$
ΔS^g	0	$-0.050^{+0.064}_{-0.065}$	$0.0063^{+0.15}_{-0.11}$	0	$0.73^{+0.81}_{-0.80}$
$\Delta\Gamma_{\text{tot}}$ (MeV)	$-0.022^{+0.63}_{-0.48}$	0	$0.79^{+2.01}_{-1.11}$	0	0
χ^2/dof	17.48/21	11.27/20	10.83/19	10.46/18	9.89/16

- The ratio of $H\gamma\gamma$ and Hgg couplings relative to SM from the best fit points are :

$$C_\gamma = 1.44, C_g = 0.99 \quad C_{Z\gamma} = 1.06$$

CP Conserving Fits: 4-parameter fit

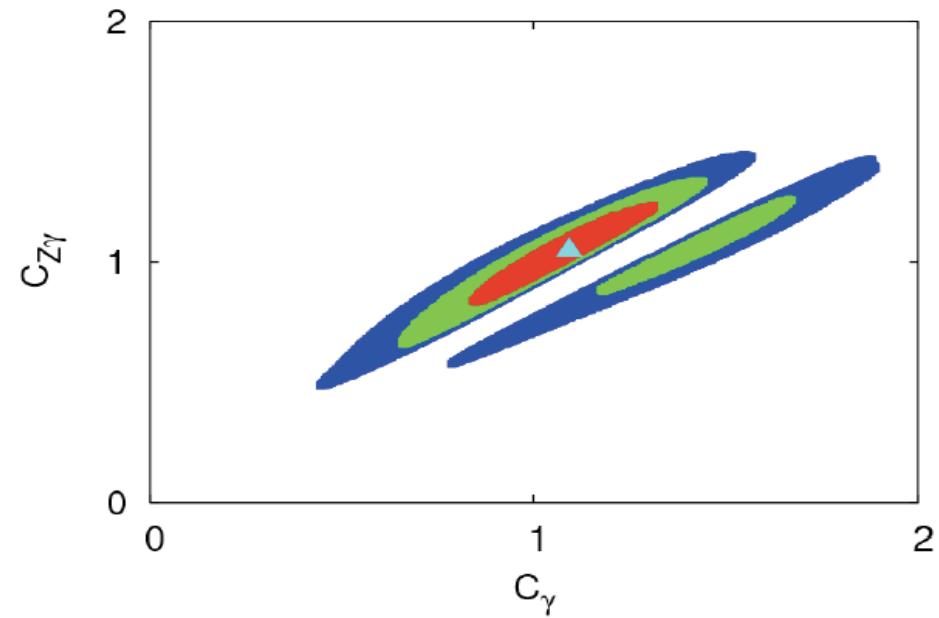
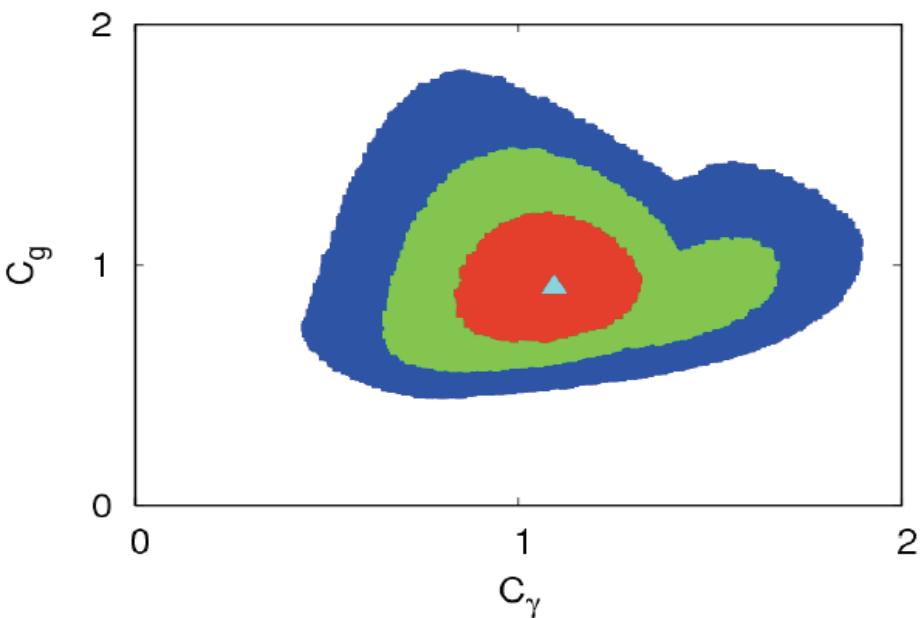
- *after:* The best fit values are: $\chi^2 / dof = 17.82 / 18 = 0.99$

Parameters	Vary $\Delta\Gamma_{\text{tot}}$	Vary ΔS^γ ,	Vary ΔS^g ,	Vary $C_u^S, C_d^S, C_\ell^S, C_v$	Vary $C_u^S, C_d^S, C_\ell^S, C_v$
		ΔS^g	$\Delta S^g, \Delta\Gamma_{\text{tot}}$	C_ℓ^S, C_v	$\Delta S^\gamma, \Delta S^g$
After Moriond					
C_u^S	1	1	1	$0.80^{+0.16}_{-0.13}$	0.00 ± 1.18
C_d^S	1	1	1	$-0.98^{+0.31}_{-0.34}$	$1.06^{+0.41}_{-0.35}$
C_ℓ^S	1	1	1	$0.98^{+0.21}_{-0.21}$	1.01 ± 0.23
C_v	1	1	1	$1.04^{+0.12}_{-0.14}$	$1.01^{+0.13}_{-0.14}$
ΔS^γ	0	$-0.96^{+0.84}_{-0.85}$	$-0.96^{+0.84}_{-0.87}$	0	$0.78^{+2.34}_{-2.28}$
ΔS^g	0	-0.043 ± 0.052	$-0.040^{+0.12}_{-0.086}$	0	$0.66^{+0.42}_{-0.83}$
$\Delta\Gamma_{\text{tot}}$ (MeV)	$0.10^{+0.51}_{-0.41}$	0	$0.027^{+1.33}_{-0.80}$	0	0
χ^2/dof	18.89/21	17.55/20	17.55/19	17.82/18	16.89/16
p -value	0.59	0.62	0.55	0.48	0.39

CP Conserving Fits: 4-parameter fit

- The ratio of $H\gamma\gamma$ and Hgg couplings relative to SM from the best fit points are : *after*

$$C_\gamma = \boxed{1.09}, C_g = \boxed{0.91} \quad C_{Z\gamma} = \boxed{1.05}$$



- The $C_{Z\gamma}$ increase or decrease in the same direction as C_γ , but is always smaller than C_γ .

$$\Delta\chi^2 = 2.3(\text{red}), 5.99(\text{green}), 11.83(\text{blue}) \Rightarrow \text{CL}=68.3\%, 95\%, 99.7\%$$

CP Conserving Fits: 6-parameter fit

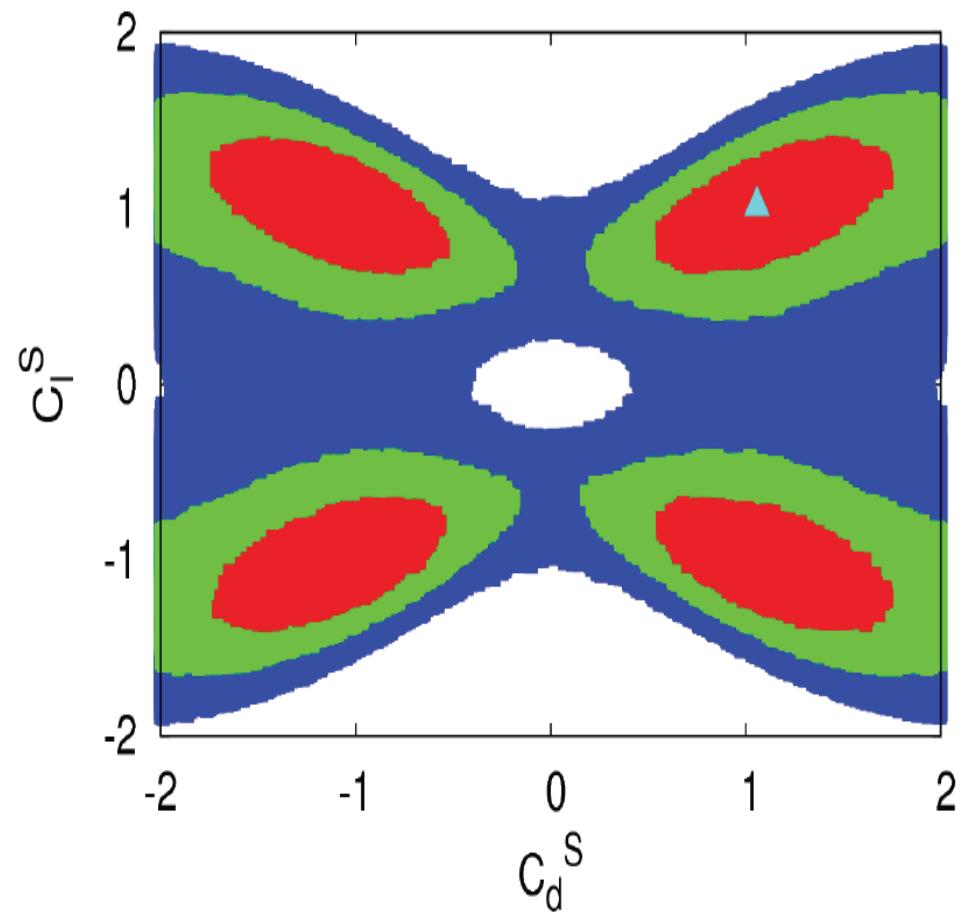
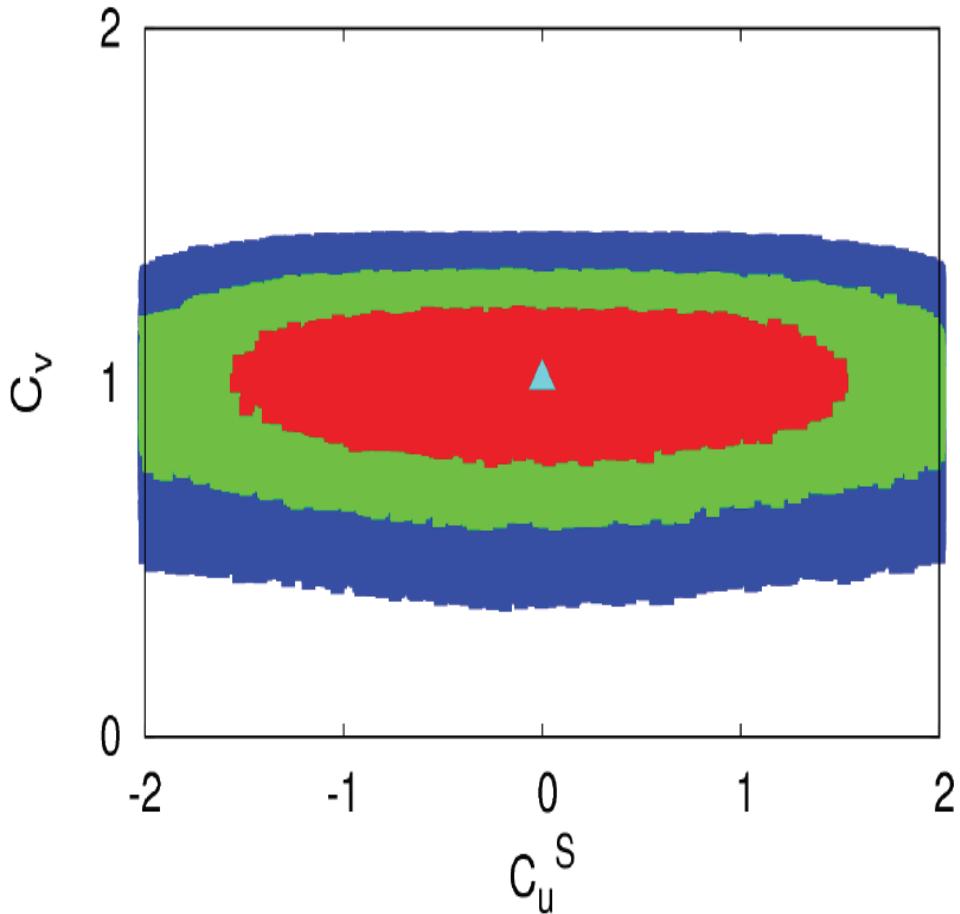
- **6-parameter fits:**

$$\left\{ \begin{array}{ll} \text{varying: } & C_u^S, C_d^S, C_l^S, C_v, \Delta S^\gamma, \Delta S^g \\ \text{fixed: } & \Delta\Gamma_{\text{tot}} = 0 \end{array} \right.$$

- Due to the new dof in $\Delta S^\gamma, \Delta S^g$, the confident-level region enlarged.
- The best fit value of C_u^S shift from $0.8 \rightarrow 0$.

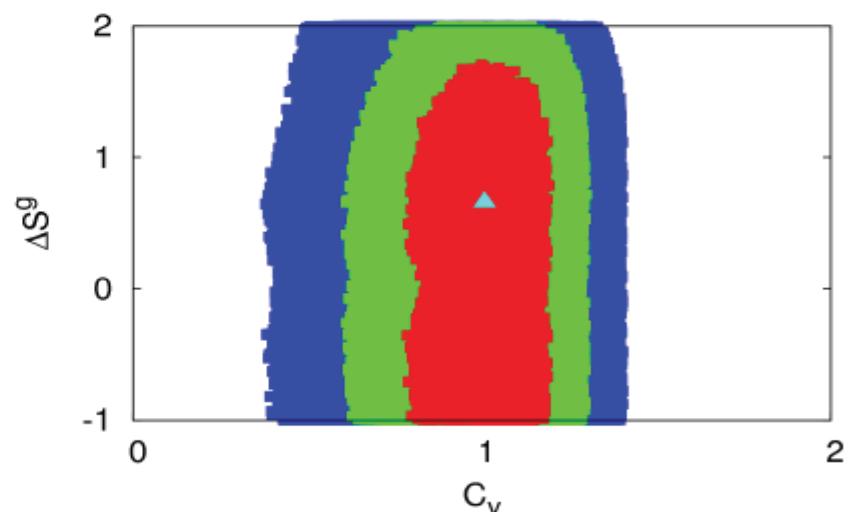
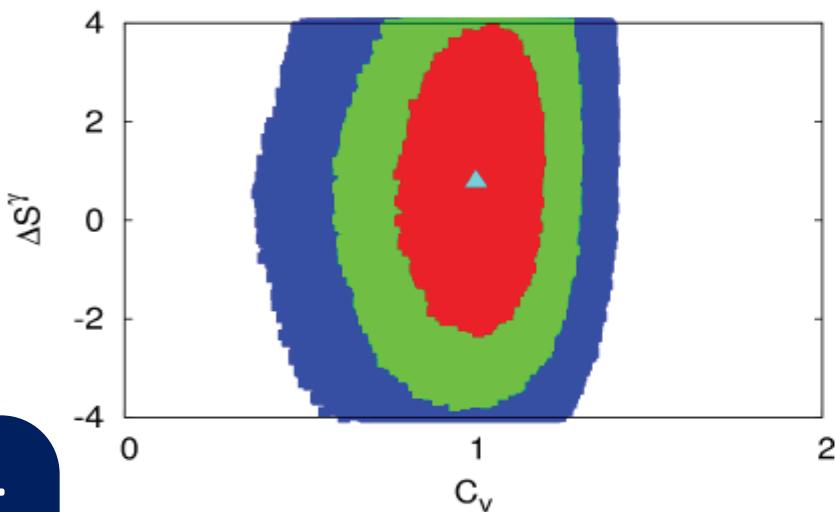
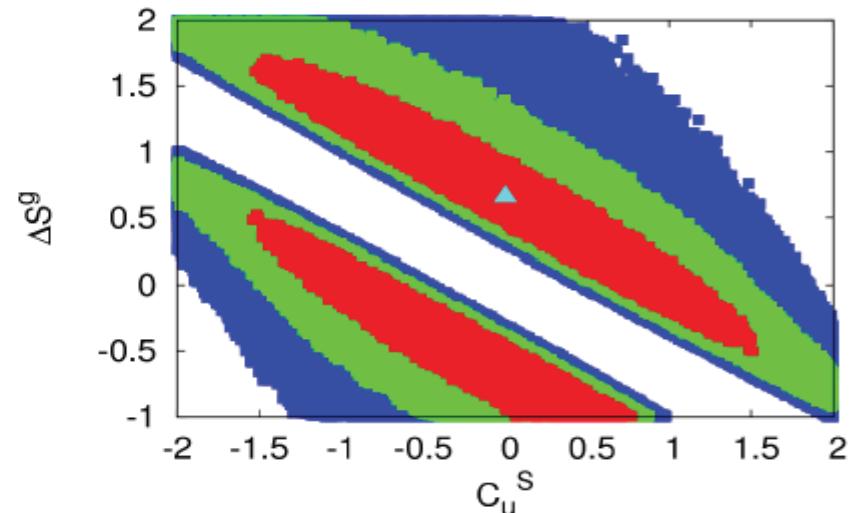
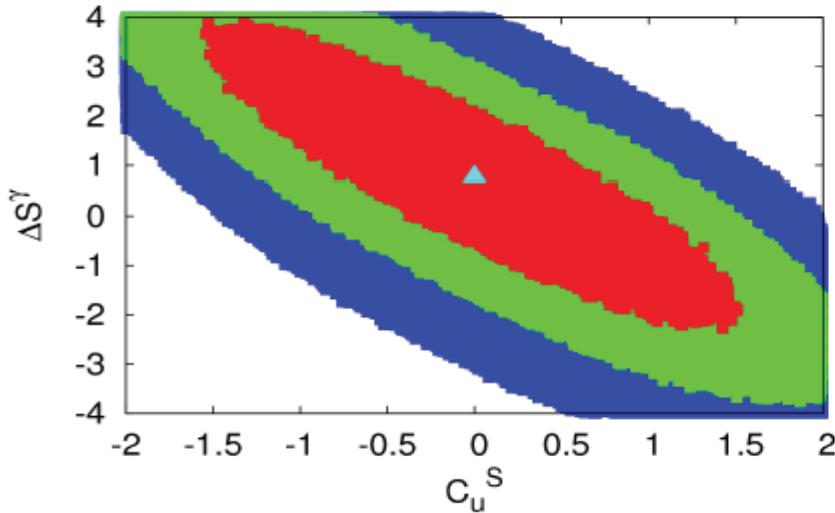
CP Conserving Fits: 6-parameter fit

- The 2-dim contours for the correlations of any 2 parameters of $C_u^S, C_d^S, C_l^S, C_\nu, \Delta S^\gamma, \Delta S^g$. *after:*



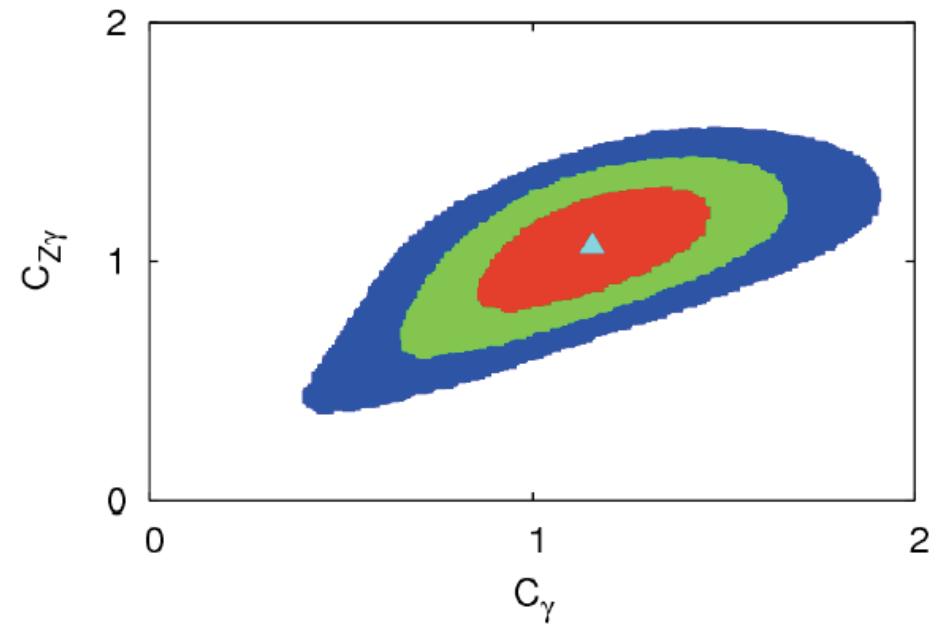
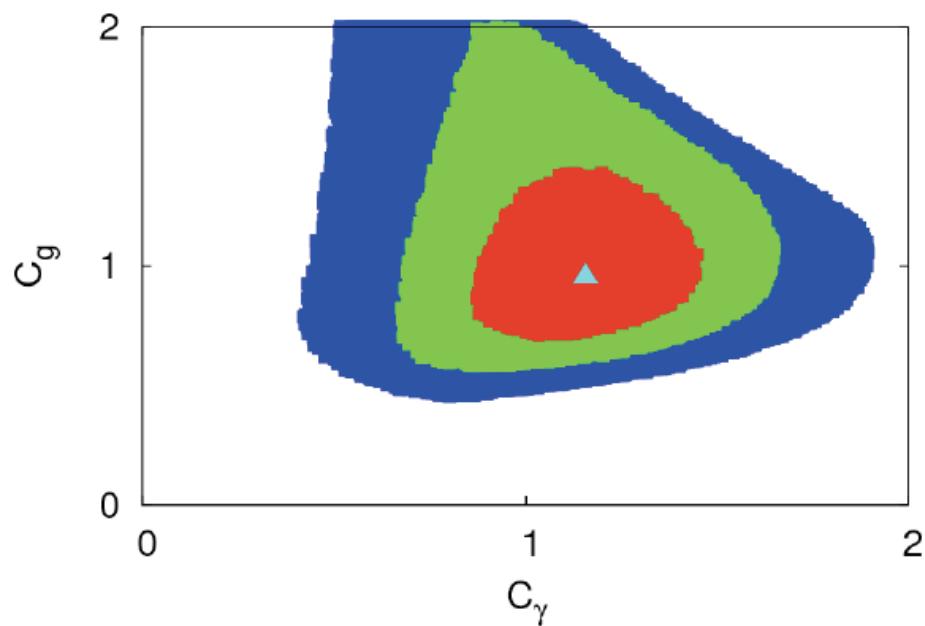
CP Conserving Fits: 6-parameter fit

- The 2-dim contours for the correlations of any 2 parameters of $C_u^S, C_d^S, C_l^S, C_v, \Delta S^\gamma, \Delta S^g$. *after:*



CP Conserving Fits: 6-parameter fit

- The ratio of $H\gamma\gamma$ and Hgg couplings relative to SM from the best fit points are : *after*



- The $C_{Z\gamma}$ increase or decrease in the same direction as C_γ , but is always smaller than C_γ .

30. $\Delta\chi^2 = 2.3(\text{red}), 5.99(\text{green}), 11.83(\text{blue}) \Rightarrow \text{CL}=68.3\%, 95\%, 99.7\%$

CP Conserving Fits: 6-parameter fit

- The C_u^S shift from $0.8 \rightarrow 0$ can be understood from the numerical expression of S^γ (the scalar part of the amplitude for the decay $H \rightarrow \gamma\gamma$).

$$S^\gamma(M_H) = 2 \sum_{f=b,t,\tau} N_C Q_f^2 g_{H\bar{f}f}^S F_{sf}(\tau_f) - g_{HWW} F_1(\tau_W) + \Delta S^\gamma$$

$$\text{numerical} \Rightarrow S^\gamma \approx -8.35C_\nu + 1.76C_u^S + \Delta S^\gamma$$

- In 4-parameter fit $\Delta S^\gamma = 0$ fixed, in order to let $C_\gamma \approx 1$, C_u^S is made positive to cancel the W loop contribution ; whereas in 6-parameter fit, the C_u^S goes to zero and ΔS^γ do the job for C_u^S . This also explain the anti-correlation between C_u^S and ΔS^γ .

CP Conserving Fits: 6-parameter fit

- The best fit values are: *after*

Parameters	Vary $\Delta\Gamma_{\text{tot}}$	Vary ΔS^γ , ΔS^g	Vary ΔS^γ , ΔS^g , $\Delta\Gamma_{\text{tot}}$	Vary C_u^S, C_d^S , C_ℓ^S, C_v	Vary $C_u^S, C_d^S, C_\ell^S, C_v$ $\Delta S^\gamma, \Delta S^g$
	After Moriond				
C_u^S	1	1	1	$0.80^{+0.16}_{-0.13}$	0.00 ± 1.18
C_d^S	1	1	1	$-0.98^{+0.31}_{-0.34}$	$1.06^{+0.41}_{-0.35}$
C_ℓ^S	1	1	1	$0.98^{+0.21}_{-0.21}$	1.01 ± 0.23
C_v	1	1	1	$1.04^{+0.12}_{-0.14}$	$1.01^{+0.13}_{-0.14}$
ΔS^γ	0	$-0.96^{+0.84}_{-0.85}$	$-0.96^{+0.84}_{-0.87}$	0	$0.78^{+2.34}_{-2.28}$
ΔS^g	0	-0.043 ± 0.052	$-0.040^{+0.12}_{-0.086}$	0	$0.66^{+0.42}_{-0.83}$
$\Delta\Gamma_{\text{tot}}$ (MeV)	$0.10^{+0.51}_{-0.41}$	0	$0.027^{+1.33}_{-0.80}$	0	0
χ^2/dof	18.89/21	17.55/20	17.55/19	17.82/18	16.89/16
p-value	0.59	0.62	0.55	0.48	0.39

CP Conserving Fits: 6-parameter fit

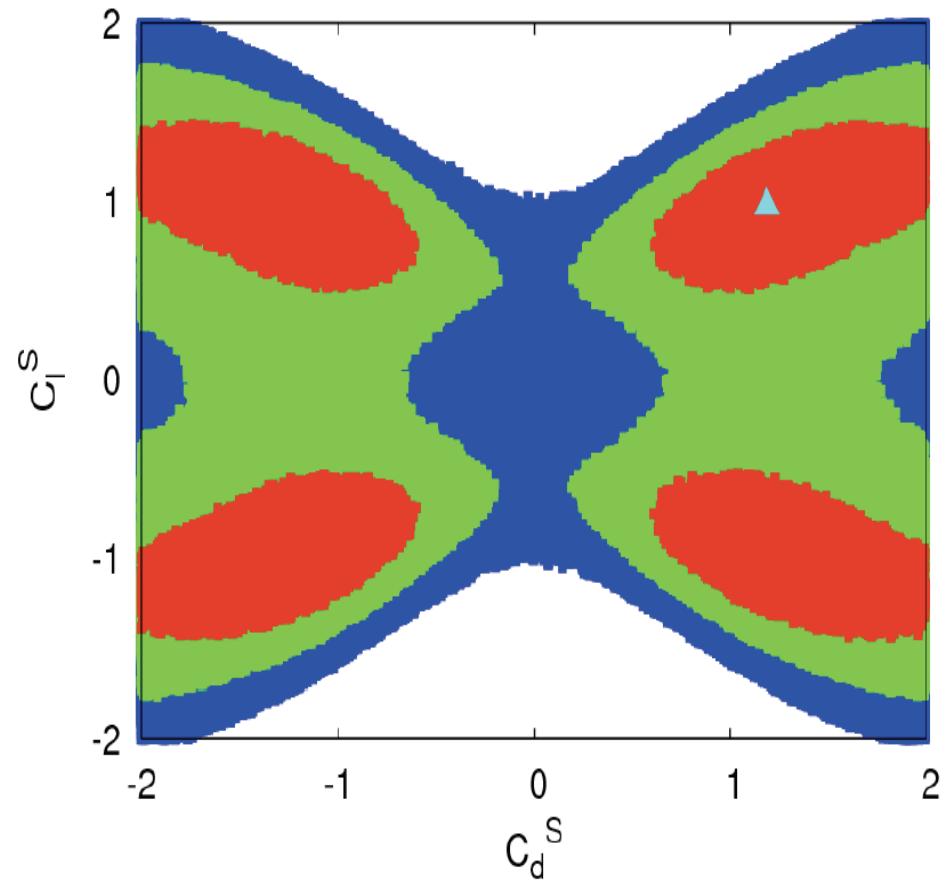
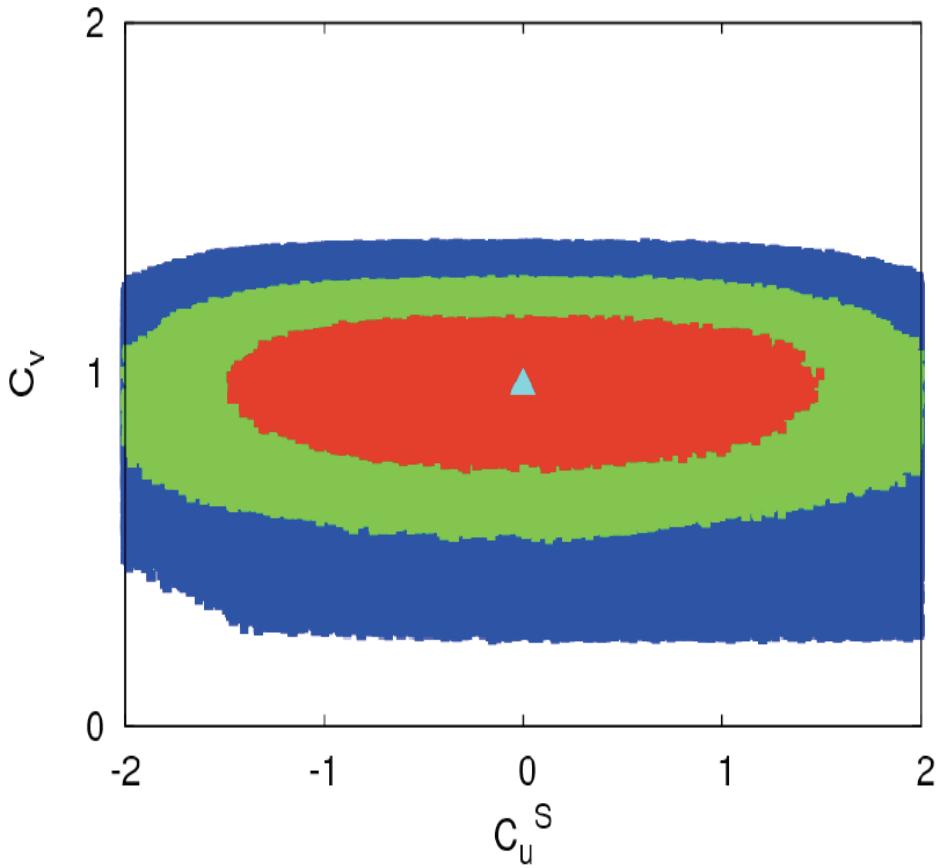
- 6-parameter fits:

$$\left\{ \begin{array}{ll} \text{varying: } & C_u^S, C_d^S, C_l^S, C_v, \Delta S^\gamma, \Delta S^g \\ \text{fixed: } & \Delta\Gamma_{\text{tot}} = 0 \end{array} \right.$$

- Due to the new dof in $\Delta S^\gamma, \Delta S^g$, the confident-level region enlarged.
- The best fit value of C_u^S shift from $-0.88 \rightarrow 0$.

CP Conserving Fits: 6-parameter fit

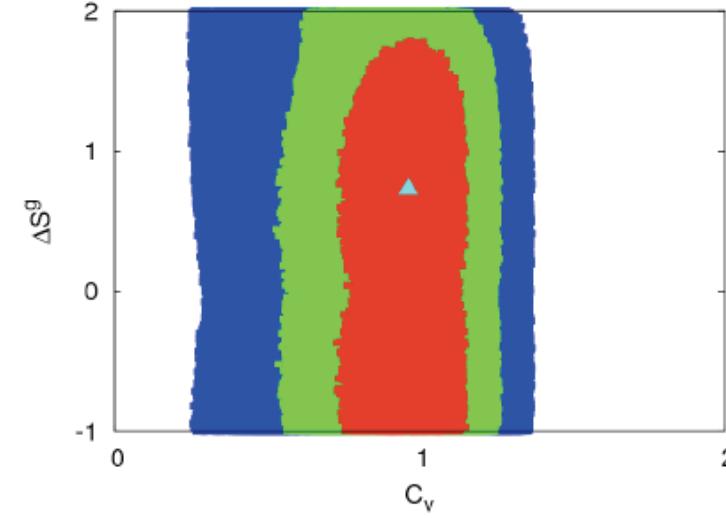
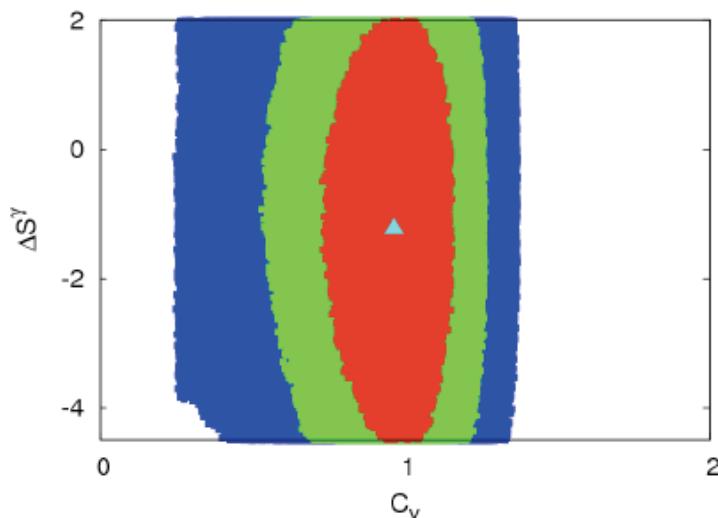
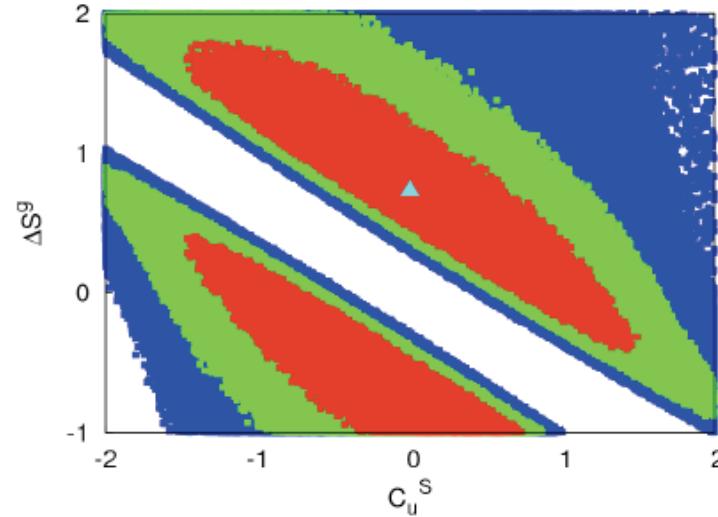
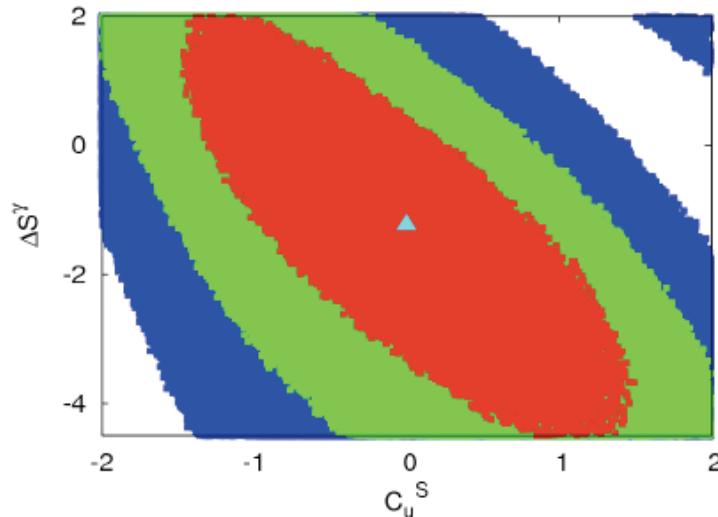
- The 2-dim contours for the correlations of any 2 parameters of $C_u^S, C_d^S, C_l^S, C_\nu, \Delta S^\gamma, \Delta S^g$.



$$\Delta\chi^2 = 2.3(\text{red}), 5.99(\text{green}), 11.83(\text{blue}) \Rightarrow \text{CL}=68.3\%, 95\%, 99.7\%$$

CP Conserving Fits: 6-parameter fit

- The 2-dim contours for the correlations of any 2 parameters of $C_u^S, C_d^S, C_l^S, C_v, \Delta S^\gamma, \Delta S^g$.



CP Conserving Fits: 6-parameter fit

- The C_u^S shift from $-0.88 \rightarrow 0$ can be understood from the numerical expression of S^γ (the scalar part of the amplitude for the decay $H \rightarrow \gamma\gamma$).

$$S^\gamma(M_H) = 2 \sum_{f=b,t,\tau} N_C Q_f^2 g_{H\bar{f}f}^S F_{sf}(\tau_f) - g_{HWW} F_1(\tau_W) + \Delta S^\gamma$$

$$\text{numerical} \Rightarrow S^\gamma \approx -8.35C_\nu + 1.76C_u^S + \Delta S^\gamma$$

- In 4-parameter fit $\Delta S^\gamma = 0$ fixed, C_u^S is made negative to increase the S^γ ; whereas in 6-parameter fit the C_u^S goes to zero and ΔS^γ goes to negative to enhance S^γ . This also explain the anti-correlation between C_u^S and ΔS^γ .

CP Conserving Fits: 6-parameter fit

- The best fit values are:

Parameters	Vary $\Delta\Gamma_{\text{tot}}$	Vary ΔS^γ ,	Vary ΔS^γ ,	Vary C_u^S, C_d^S ,	$\Delta S^\gamma, \Delta S^g$
		ΔS^g	$\Delta S^g, \Delta\Gamma_{\text{tot}}$	C_ℓ^S, C_v	
C_u^S	1	1	1	$-0.88^{+0.16}_{-0.21}$	0.00 ± 1.13
C_d^S	1	1	1	$1.12^{+0.45}_{-0.38}$	$1.19^{+0.57}_{-0.41}$
C_ℓ^S	1	1	1	$-0.97^{+0.30}_{-0.29}$	0.98 ± 0.30
C_v	1	1	1	$0.97^{+0.13}_{-0.15}$	$0.96^{+0.13}_{-0.15}$
ΔS^γ	0	$-2.73^{+1.11}_{-1.15}$	$-2.93^{+1.19}_{-1.31}$	0	$-1.23^{+2.44}_{-2.49}$
ΔS^g	0	$-0.050^{+0.064}_{-0.065}$	$0.0063^{+0.15}_{-0.11}$	0	$0.73^{+0.81}_{-0.80}$
$\Delta\Gamma_{\text{tot}}$ (MeV)	$-0.022^{+0.63}_{-0.48}$	0	$0.79^{+2.01}_{-1.11}$	0	0
χ^2/dof	17.48/21	11.27/20	10.83/19	10.46/18	9.89/16

CP Conserving Fits: Concluding Remarks

- The diphoton signal strength $pp \rightarrow H \rightarrow \gamma\gamma$ dominates the chi-square in the current data. This signal strength depends on S^γ and S^g , which in turns depends mostly on C_u^S and ΔS^γ .

$$\begin{cases} \text{varying:} & C_u^S, \Delta S^\gamma \\ \text{fixed:} & C_d^S = C_l^S = C_v = 1, \Delta S^g = \Delta \Gamma_{\text{tot}} = 0 \end{cases}$$

- The best fit values are:

$$C_u^S = 0.92^{+0.094}_{-0.095}, \quad \Delta S^\gamma = -2.62^{+1.02}_{-1.04}, \quad \chi^2/dof = 11.17/20$$

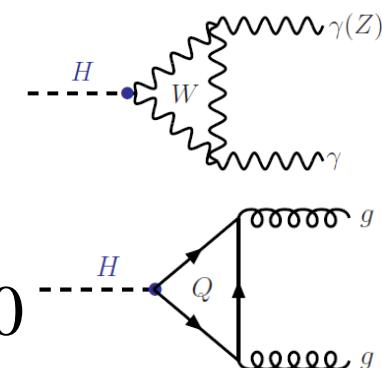
- The χ^2 is only 0.1 better than the 2-parameter fit ($\Delta S^\gamma, \Delta S^g$).

CP Conserving Fits: Concluding Remarks

- *Before:* The diphoton signal strength $pp \rightarrow H \rightarrow \gamma\gamma$ dominates the chi-square in the data. This signal strength depends on S^γ and S^g , which in turns depends mostly on $C_u^S, \Delta S^\gamma$.

$\left\{ \begin{array}{l} \text{varying:} \\ \text{fixed: } C_d^S = C_l^S = C_v = 1, \Delta S^g = \Delta \Gamma_{\text{tot}} = 0 \end{array} \right.$

$$C_u^S, \Delta S^\gamma$$



- The best fit values are:

$$C_u^S = 0.92^{+0.094}_{-0.095}, \quad \Delta S^\gamma = -2.62^{+1.02}_{-1.04}, \quad \chi^2/dof = 11.17/20$$

- The χ^2 is only 0.1 better than the **2-parameter fit** ($\Delta S^\gamma, \Delta S^g$).

CP Conserving Fits: Concluding Remarks

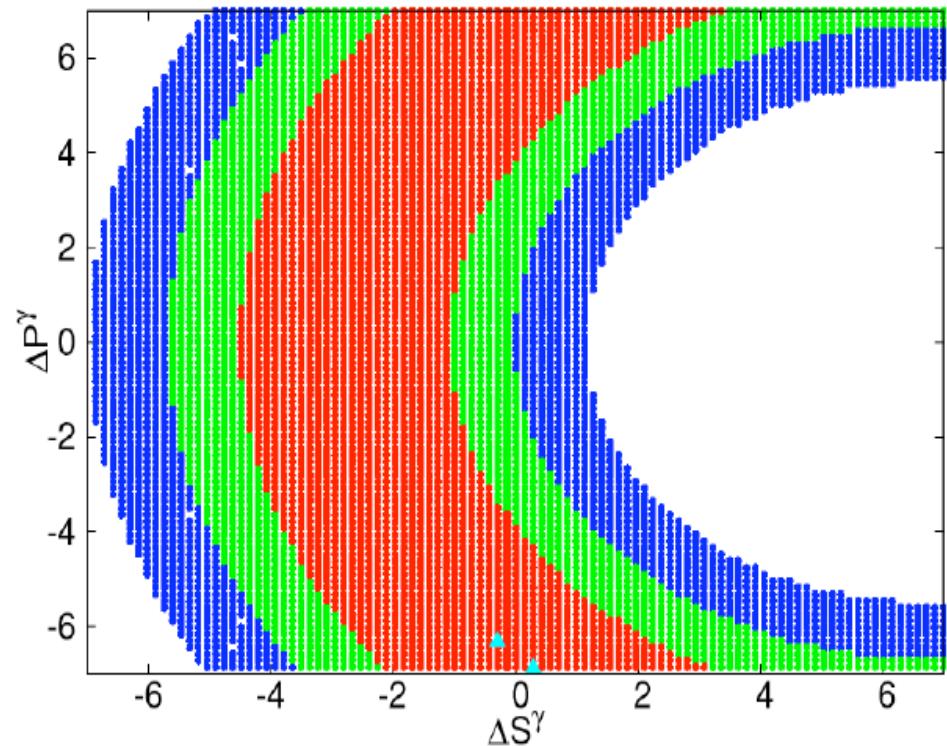
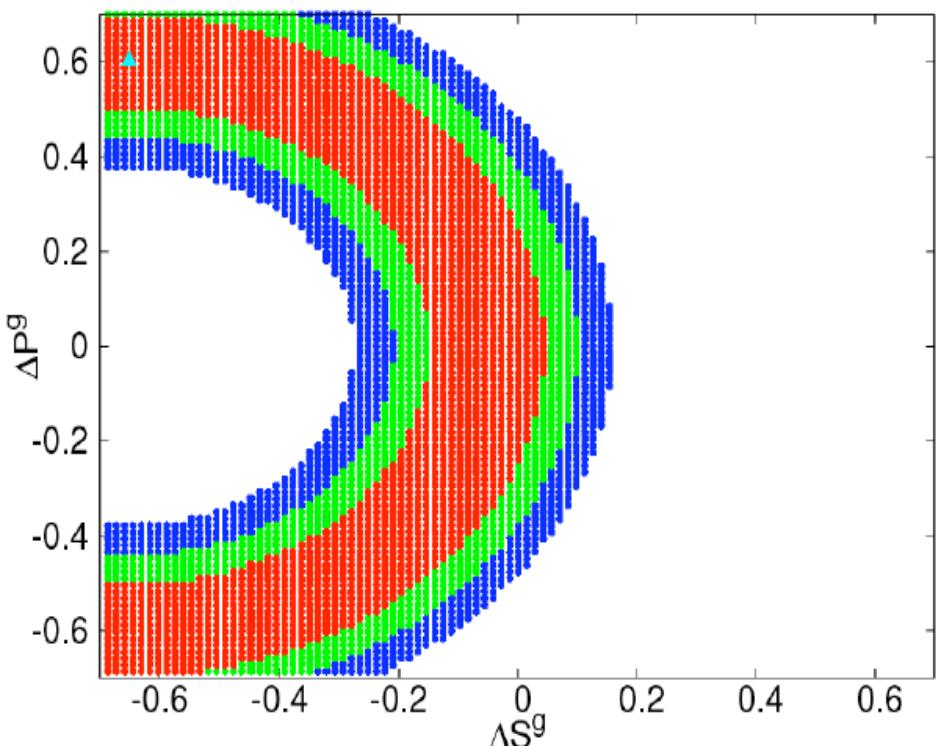
- *after*: The diphoton signal strength $pp \rightarrow H \rightarrow \gamma\gamma$ still dominates the chi-square in the current data. However, **CMS** diphoton rate changed from **1.42** to **0.78**. Now **ATLAS** and **CMS**'s diphoton rate are on the **opposite** side of SM value.
- The dynamics of fit cannot do anything to effectively reduce the chi-square from diphoton data.
- *After Moriond*, all the fits give χ^2/dof or *p-value* worse than SM.

CP Violating Fits

- This section include the pseudoscalar Yukawa couplings C_u^P and the pseudoscalar contributions ΔP^γ and ΔP^g .

CP Violating Fits: A.

- The confidence-level regions of the fit: *after*



CP Violating Fits: A.

- Using the best fit point for:

$$C_\gamma \approx 1.1, \quad C_g \approx 0.9$$

- These can explain the two ellipses in the previous slide.

SM

$$C_\gamma \approx 1.1 = \sqrt{\frac{(-6.64 + \Delta S^\gamma)^2 + (\Delta P^\gamma)^2}{(-6.64)^2}},$$
$$C_g \approx 0.9 = \sqrt{\frac{(0.65 + \Delta S^g)^2 + (\Delta P^g)^2}{(0.65)^2}}.$$

- Recall:

$$C_g \equiv \sqrt{\frac{|S^g|^2 + |P^g|^2}{|S_{\text{SM}}^g|^2}}; \quad C_\gamma \equiv \sqrt{\frac{|S^\gamma|^2 + |P^\gamma|^2}{|S_{\text{SM}}^\gamma|^2}}$$

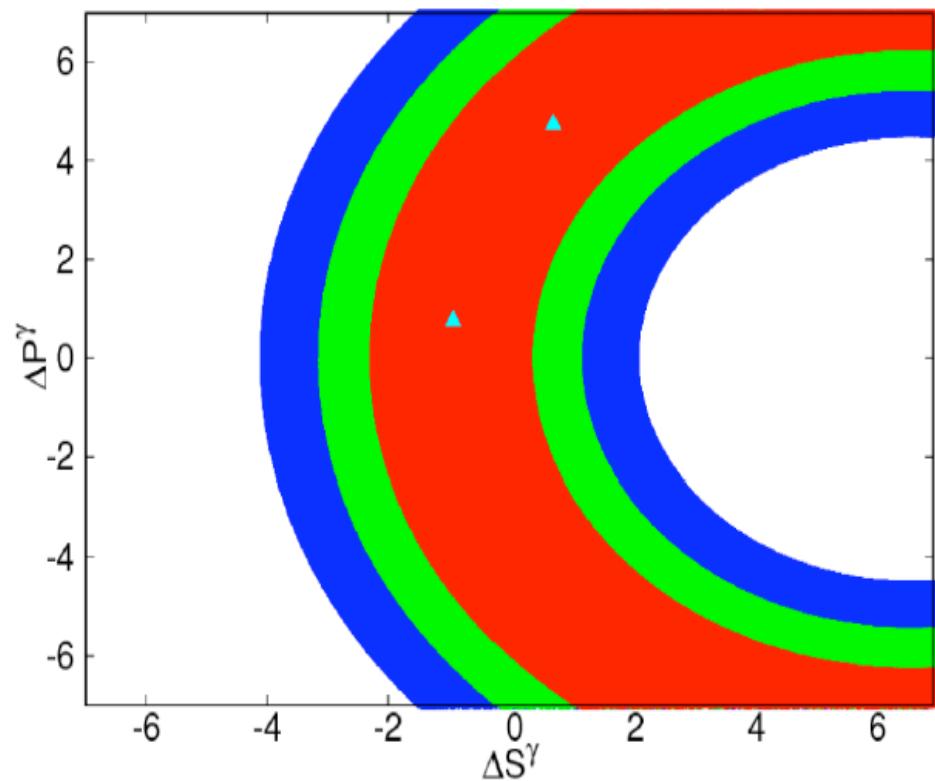
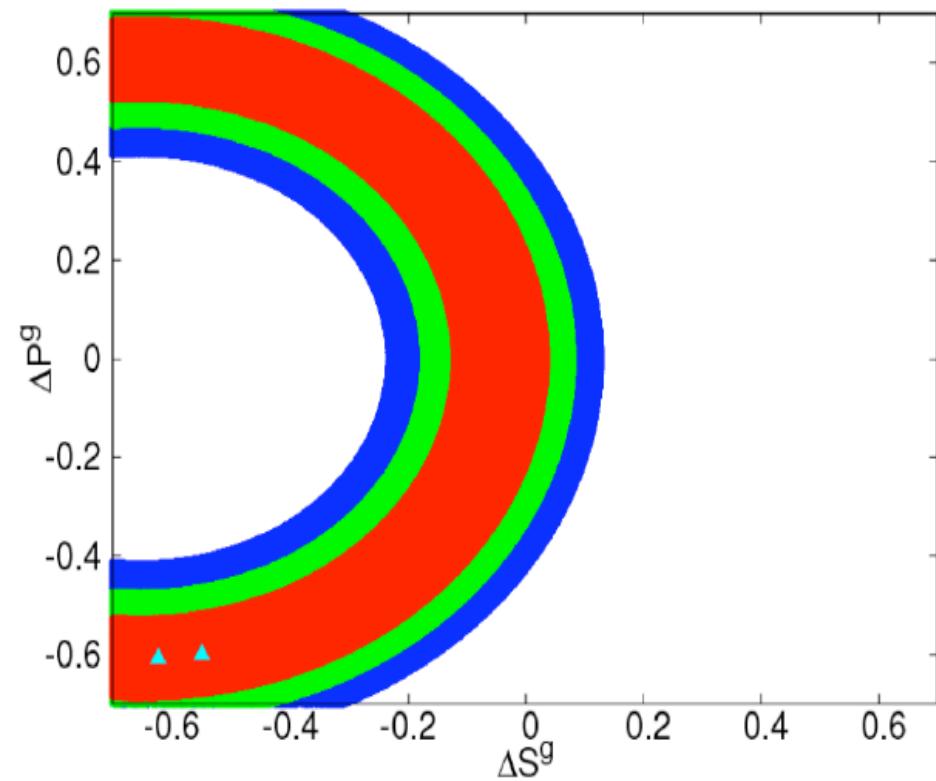
CP Violating Fits: A.

- We learned from CP-conserving fits that varying $\Delta S^\gamma, \Delta S^g$ is the efficient way to fit the data *before Moriond*.
- In order to understand the effects of pseudoscalar nature of the Higgs boson, we vary the scalar contribution $\Delta S^\gamma, \Delta S^g$, as well as the pseudoscalar contribution $\Delta P^\gamma, \Delta P^g$ to the $H\gamma\gamma, Hgg$ vertices.

$$\left\{ \begin{array}{l} \text{varying: } \boxed{\Delta S^\gamma, \Delta S^g, \Delta P^\gamma, \Delta P^g} \\ \text{fixed: } C_u^S = C_d^S = C_l^S = C_v = 1, C_u^P = C_d^P = C_l^P = 0, \Delta \Gamma_{\text{tot}} = 0 \end{array} \right.$$

CP Violating Fits: A.

- The confidence-level regions of the fit: *after*



CP Violating Fits: A.

- The total $\chi^2 = 17.55$, almost the same as the total $\chi^2 = 17.55$ of the case varying $\Delta S^\gamma, \Delta S^g$.
- Including the **pseudoscalar contribution** does **NOT** improve the fit. In fact, the χ^2 / dof is worsened.

CP Violating Fits: A.

- Using the best fit point for:

$$C_\gamma \approx 1.4, \quad C_g \approx 0.9$$

- These can explain the two ellipses in the previous slide.

SM

$$C_\gamma \approx 1.4 = \sqrt{\frac{(-6.64 + \Delta S^\gamma)^2 + (\Delta P^\gamma)^2}{(-6.64)^2}},$$
$$C_g \approx 0.9 = \sqrt{\frac{(0.65 + \Delta S^g)^2 + (\Delta P^g)^2}{(0.65)^2}}.$$

- Recall:

$$C_g \equiv \sqrt{\frac{|S^g|^2 + |P^g|^2}{|S_{\text{SM}}^g|^2}}; \quad C_\gamma \equiv \sqrt{\frac{|S^\gamma|^2 + |P^\gamma|^2}{|S_{\text{SM}}^\gamma|^2}}$$

CP Violating Fits: A.

- The total $\chi^2 = 11.26$, almost the same as the total $\chi^2 = 11.27$ of the case varying $\Delta S^\gamma, \Delta S^g$.
- Including the pseudoscalar contribution does not improve the fit. In fact, the χ^2 / dof is worsened

CP Violating Fits: B.

- In the $C_u^S - C_v$ plot, the 2 islands in CP-conserving 4-parameter fit C_u^S, C_d^S, C_l^S, C_v are now linked together, because of the additional parameter C_u^P .
- The sickle-shaped region in the $C_u^S - C_u^P$ plot indicate that C_u^S and C_u^P satisfy some equations of ellipses.

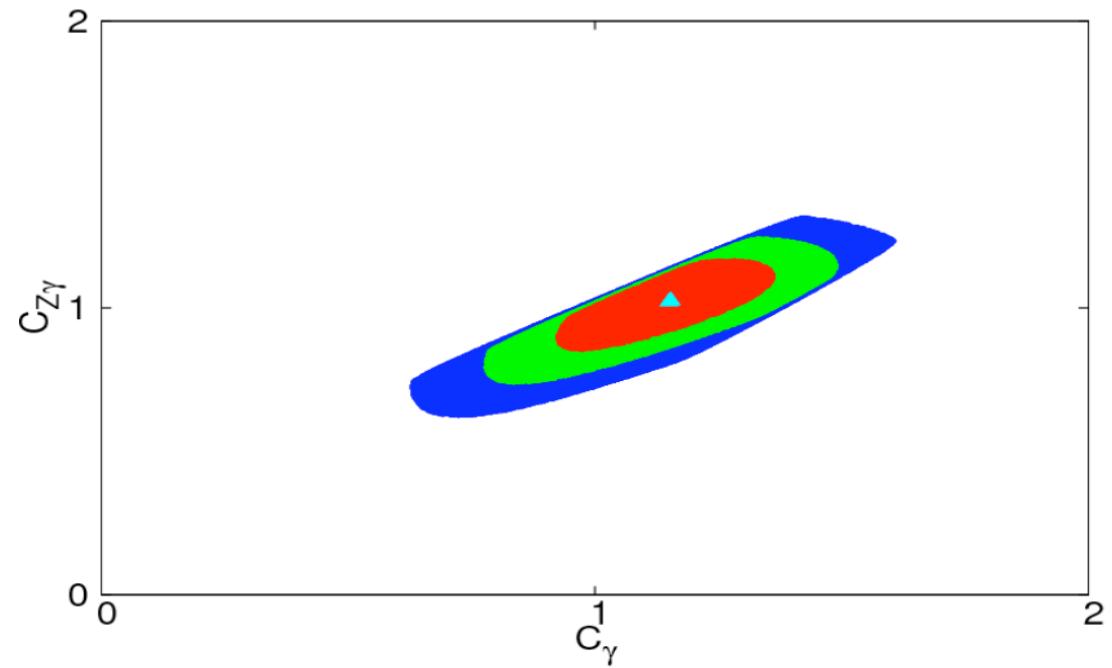
$$\left\{ \begin{array}{l} C_\gamma \approx 1.1 = \sqrt{\frac{(-8.4C_v + 1.76C_u^S)^2 + (2.78C_u^P)^2}{(-6.64)^2}} \\ C_g \approx 0.9 = \sqrt{\frac{(0.688C_u^S)^2 + (1.047C_u^P)^2}{(0.65)^2}} \end{array} \right. \approx 1$$

⇒ two ellipese overlap

CP Violating Fits: B.

- The total chi-square is $\chi^2 = 17.17$, slightly better than the total chi-square $\chi^2 = 17.82$ of the 4-parameter fit $C_u^S, C_d^S, C_l^S, C_\nu$.
- Again at the best fit points: $C_\gamma \approx 1.1, C_g \approx 0.9$

$$C_{Z\gamma} \approx 1.05$$



45. $\Delta\chi^2 = 2.3(\text{red}), 5.99(\text{green}), 11.83(\text{blue}) \Rightarrow \text{CL}=68.3\%, 95\%, 99.7\%$

CP Violating Fits: B.

- The confidence-level regions of the fit: *after*

