Higgs precision (Higgcision) : A Cornerstone for New Physics

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♠ *Higgs : Arrival*

- **Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC**
  ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Jul 2012. 24 pp.
  Published in **Phys.Lett. B716 (2012) 1-29**
  CERN-PH-EP-2012-218
  DOI: 10.1016/j.physletb.2012.08.020
  e-Print: **arXiv:1207.7214 [hep-ex]** | PDF

  References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
  ADS Abstract Service; Link to all figures including auxiliary figures;
  Interactions.org article

  Detailed record - Cited by 1893 records 1000+

♠ *Higgs : Arrival*

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Jul 2012. 42 pp.
Published in **Phys.Lett. B716 (2012) 30-61**
CMS-HIG-12-028, CERN-PH-EP-2012-220
DOI: 10.1016/j.physletb.2012.08.021
e-Print: **arXiv:1207.7235 [hep-ex]** | PDF

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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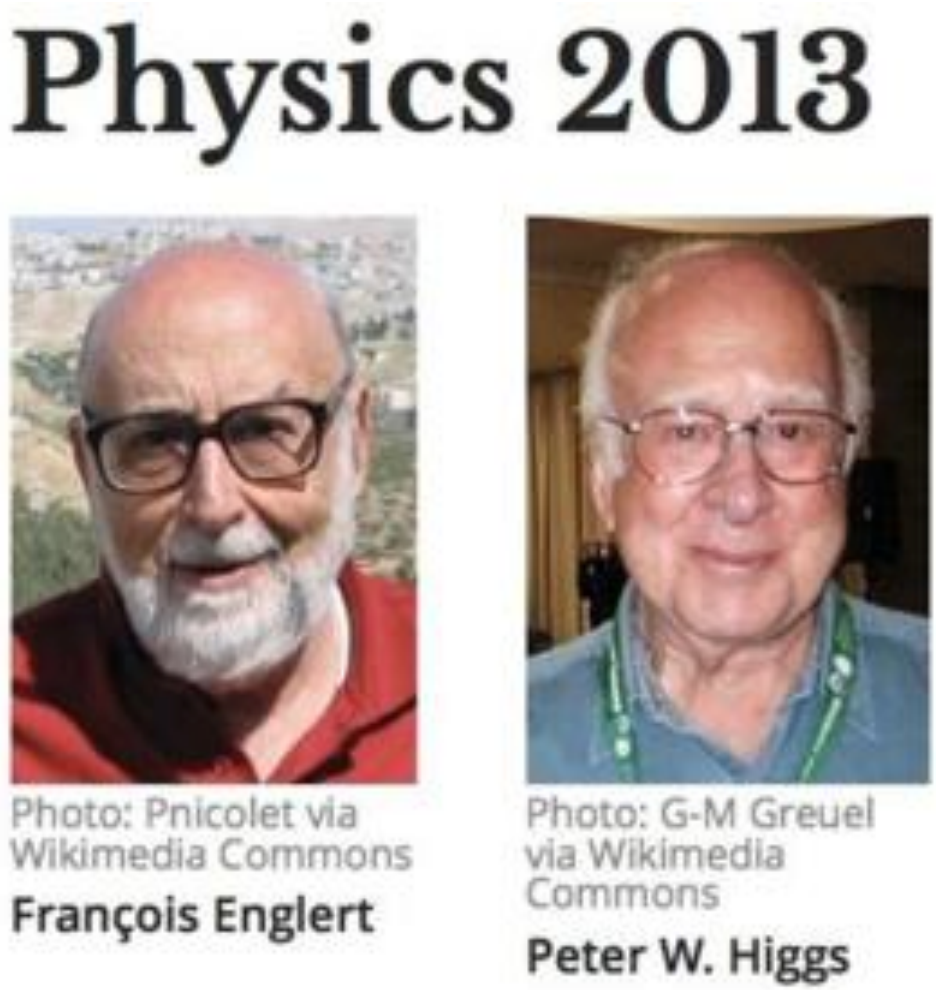
♠ *Higgs : Appraisal*



♠ *Higgs : Alone?*

- For last several decades, we have been supporting the idea ... :

Higgs is not coming alone !

But we have found nothing else ... yet

♠ *Higgs : Alone?*

- At the current stage, before despairing for the absence of NP signals...:

We'd better take a closer look at the Higgs boson
for the time being, at least

who knows ... ?

♠ *Contents*

♠ *Higgs : Spin*

- Landau-Yang Theorem: A spin 1 Higgs can not decay into two photons C. N. Yang, Phys. Rev. 77 (1950) 242; L. D. Landau, Dokl. Akad. Nawk. 60 (1948) 207

It does not have spin 1

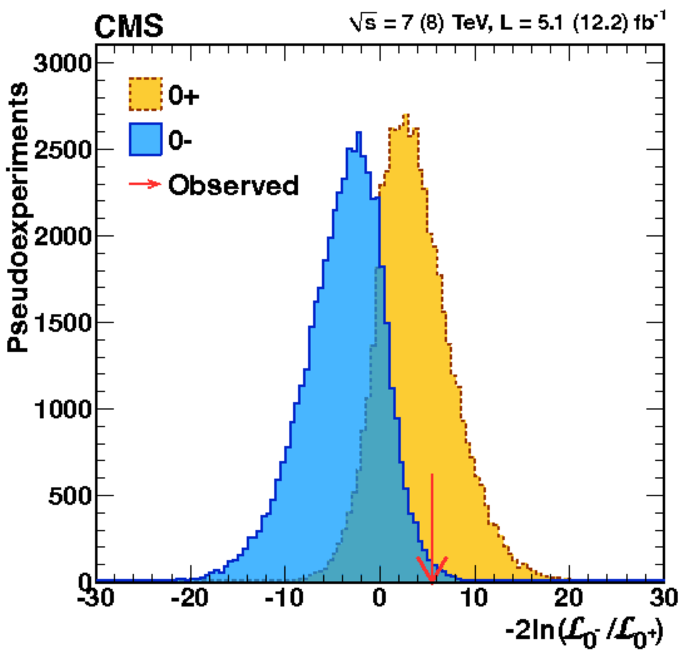
♠ *Higgs : Spin*

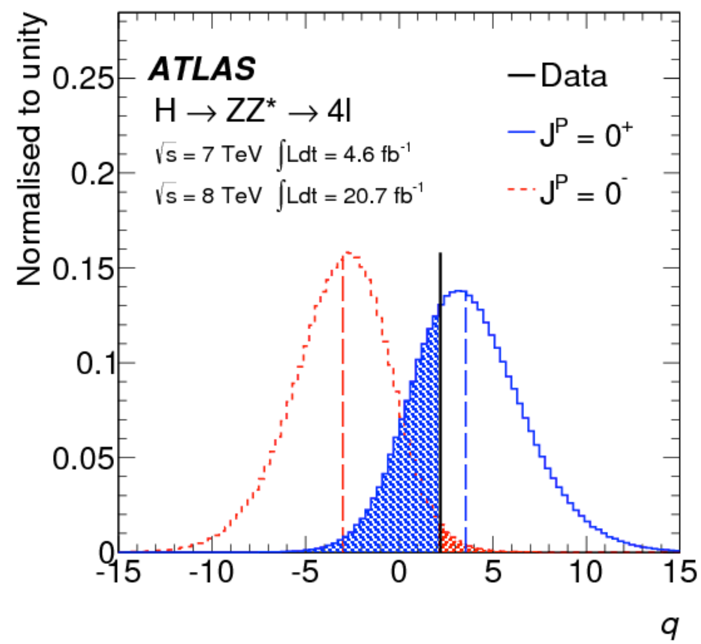
- Then, how about spin 2 ?: *We have shown that the available data on X production and decay already disfavour the possibility that it is a spin-two impostor.* Ellis, Sanz, You, arXiv:1211.3068

Probably nobody, least of all the authors, seriously expects that the X particle has spin two.

♠ *Higgs : CP parity*

- The observed data disfavors the pure pseudoscalar hypothesis. (CMS) arXiv:1212.6639 The $J^P = 0^-$ hypothesis is excluded at 97.8 % CL. (ATLAS) arXiv:1307.1432



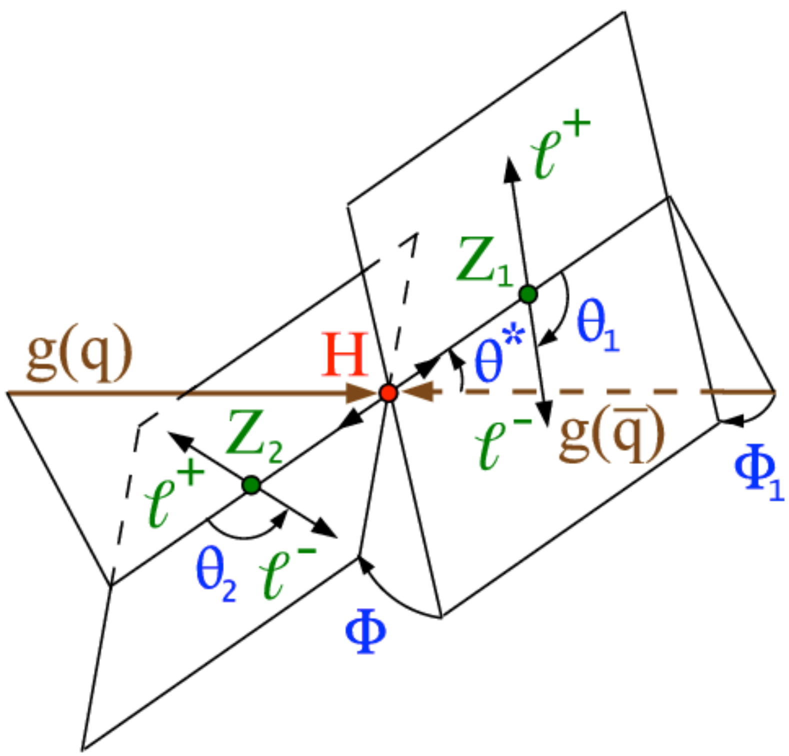


N.B. This doesn't exclude a hypothesis of CP-mixed state

♠ *Higgs : Spin/Parity Analyzer*

- The best (maybe) Higgs spin/parity analyzer: Choi, Miller, Mühlleitner, Zerwas, arXiv:hep-ph/0210077 (PLB); Bolognesi, Gao, Gritsan, Melnikov, Schulze, Tran, Whitbeck, arXiv:1208.4018 (PRD);Chen, Tran, Vega-Morales, arXiv:1211.1959 (JHEP)

$$H \to V_1^{(*)} V_2^{(\prime,*)} \to 4\,f \text{ with } V, V' = \gamma, Z, W$$



$$d\Gamma = d\Gamma(k_1^2, k_2^2, \theta^*; \theta_1, \theta_2, \Phi_1, \Phi)$$

Need ILC and/or PLC ?

♠ *Higgs : Basic Assumption*

- Basic assumption:

Higgs boson is a spin-zero CP-mixed state

♠ *Higgs Couplings*

- Higgs couplings:
  - Higgs couplings to fermions:

$$\mathcal{L}_{H\bar{f}f} = - \sum_{f=u,d,l} \frac{g m_f}{2M_W} \sum_{i=1}^{3} H \, \bar{f} \left(g^S_{H\bar{f}f} + i g^P_{H\bar{f}f} \gamma_5 \right) f$$

For the SM couplings, $g^S_{H\bar{f}f} = 1$ and $g^P_{H\bar{f}f} = 0$

  - Higgs couplings to the 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 the SM couplings, we have $g_{HWW} = g_{HZZ} \equiv g_{HVV} = 1$, respecting the custodial symmetry

♠ *Higgs Couplings*

- Higgs couplings:

  - Higgs couplings to two photons: $k_{1,2}$ are the momenta of the two photons; $\epsilon_{1,2}$ the wave vectors of the corresponding photons with $\epsilon^{\mu}_{1\perp} = \epsilon^{\mu}_{1} - 2k^{\mu}_{1}(k_2 \cdot \epsilon_1)/M_H^2$ and $\epsilon^{\mu}_{2\perp} = \epsilon^{\mu}_{2} - 2k^{\mu}_{2}(k_1 \cdot \epsilon_2)/M_H^2$; $\langle \epsilon_1 \epsilon_2 k_1 k_2 \rangle \equiv \epsilon_{\mu\nu\rho\sigma}\, \epsilon_1^{\mu} \epsilon_2^{\nu} k_1^{\rho} k_2^{\sigma}$

$$\mathcal{M}_{\gamma\gamma H} = -\frac{\alpha M_H^2}{4\pi\, v}\left\{ S^{\gamma}(M_H)\ (\epsilon^*_{1\perp} \cdot \epsilon^*_{2\perp}) - P^{\gamma}(M_H) \frac{2}{M_H^2} \langle \epsilon^*_1 \epsilon^*_2 k_1 k_2 \rangle \right\}$$

Taking $M_H = 125.5$ GeV: ($S^{\gamma}_{\rm SM} = -6.64 + 0.043\, i$ and $P^{\gamma}_{\rm SM} = 0$)

$$\begin{aligned} S^{\gamma} &\simeq -8.35\, g_{HWW} + 1.76\, g^S_{H\bar{t}t} + (-0.015 + 0.017\, i)\, g^S_{H\bar{b}b} \\ &\quad + (-0.024 + 0.021\, i)\, g^S_{H\bar{\tau}\tau} + (-0.007 + 0.005\, i)\, g^S_{H\bar{c}c} \\ P^{\gamma} &\simeq 2.78\, g^P_{H\bar{t}t} + (-0.018 + 0.018\, i)\, g^P_{H\bar{b}b} \\ &\quad + (-0.025 + 0.022\, i)\, g^P_{H\bar{\tau}\tau} + (-0.007 + 0.005\, i)\, g^P_{H\bar{c}c} \end{aligned}$$

♠ *Higgs Couplings*

- Higgs couplings:
  - Higgs couplings to two gluons:

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

Taking $M_H = 125.5$ GeV:

$$\begin{aligned} S^g &\simeq 0.688\, g^S_{H\bar{t}t} + (-0.037 + 0.050\, i)\, g^S_{H\bar{b}b} \\ P^g &\simeq 1.047\, g^P_{H\bar{t}t} + (-0.042 + 0.050\, i)\, g^P_{H\bar{b}b} \end{aligned}$$

$S^g_{\rm SM} = 0.651 + 0.050\, i$ and $P^g_{\rm SM} = 0$

♠ *Higgs Couplings: Short notations*

- Short notations for the Higgs couplings:

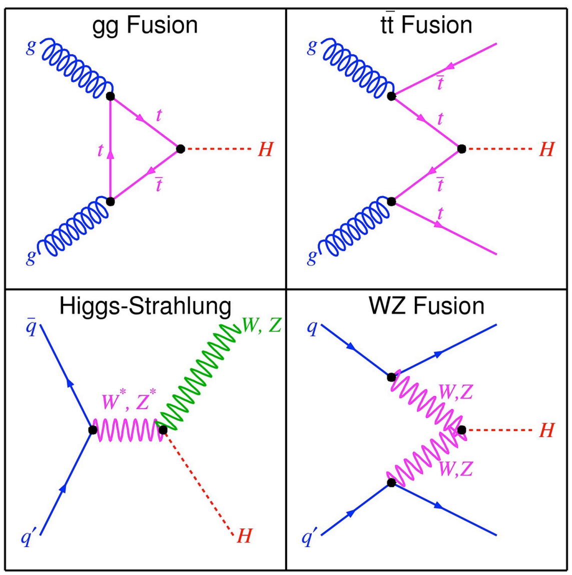
$$C_u^S = g^S_{H\bar{u}u}\,, \quad C_d^S = g^S_{H\bar{d}d}\,, \quad C_\ell^S = g^S_{H\bar{l}l}\,; \quad C_v = g_{HVV}\,;$$

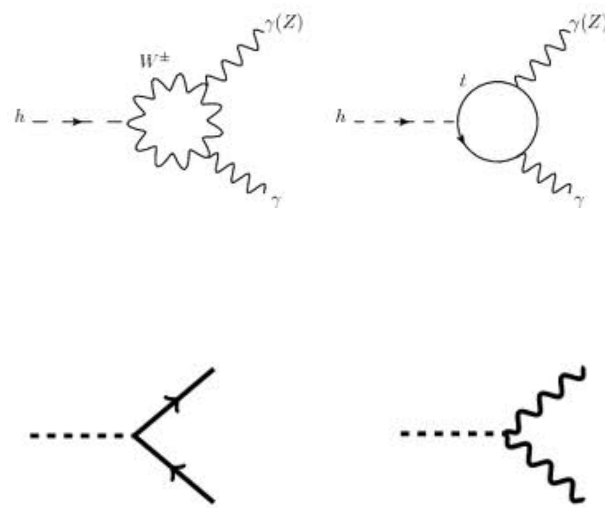
$$C_u^P = g^P_{H\bar{u}u}\,, \quad C_d^P = g^P_{H\bar{d}d}\,, \quad C_\ell^P = g^P_{H\bar{l}l}\,;$$

Here we assume generation independence and also custodial symmetry between W and Z bosons

♠ *Higgs : Production and Decay at the LHC*

- We are not measuring each of the couplings, instead...





$$\left(C_u^{S,P}, C_d^{S,P}, C_v\right) \qquad \times \qquad \left(C_v, C_u^{S,P}, C_d^{S,P}, C_\ell^{S,P}\right)$$

♠ *Higgs : Strategy*

Strategy :

Assuming general Higgs couplings, find out a set of coupling values which fits all the measured quantities most well

♠ *Higgs : Model-independent (MI) approach*

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Sorry for an incomplete list ...

♠ *Higgs* : χ^2

- $\underline{\chi^2}$: The χ^2 associated with an uncorrelated observable is

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

where $\sigma^{\rm EXP}(\mathcal{Q},\mathcal{D})$ denotes the experimental error. For two correlated observables, we use

$$\begin{aligned}\chi^2(\mathcal{Q}_1,\mathcal{D};\mathcal{Q}_2,\mathcal{D}) \quad = \quad & \left\{\frac{\left[\mu(\mathcal{Q}_1,\mathcal{D}) - \mu^{\rm EXP}(\mathcal{Q}_1,\mathcal{D})\right]^2}{\left[\sigma^{\rm EXP}(\mathcal{Q}_1,\mathcal{D})\right]^2} + \frac{\left[\mu(\mathcal{Q}_2,\mathcal{D}) - \mu^{\rm EXP}(\mathcal{Q}_2,\mathcal{D})\right]^2}{\left[\sigma^{\rm EXP}(\mathcal{Q}_2,\mathcal{D})\right]^2}\right. \\ & \left. -2\rho\,\frac{\left[\mu(\mathcal{Q}_1,\mathcal{D}) - \mu^{\rm EXP}(\mathcal{Q}_1,\mathcal{D})\right]\left[\mu(\mathcal{Q}_2,\mathcal{D}) - \mu^{\rm EXP}(\mathcal{Q}_2,\mathcal{D})\right]}{\left[\sigma^{\rm EXP}(\mathcal{Q}_1,\mathcal{D})\right]\left[\sigma^{\rm EXP}(\mathcal{Q}_2,\mathcal{D})\right]}\right\} \Big/ (1-\rho^2)\end{aligned}$$

where ρ is the correlation coefficient

♠ *Higgs : Signal Strength*

- Signal strength: $\mathcal{Q}$ = experimentally defined channel involved with the decay $\mathcal{D}$; $C_{\mathcal{Q}\mathcal{P}}$ = decomposition coefficients depending on the relative Higgs production cross sections for a given Higgs-boson mass, experimental cuts, etc

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

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

$$\begin{aligned}
\widehat{\mu}(\mathrm{ggF}) &= \left[\left|S^g(M_H)\right|^2 + \left|P^g(M_H)\right|^2\right] / \left|S^g_{\mathrm{SM}}(M_H)\right|^2 ; \widehat{\mu}(\mathrm{VBF}) = g^2_{HWW,HZZ} ; \\
\widehat{\mu}(\mathrm{VH}) &= g^2_{HWW,HZZ} ; \widehat{\mu}(\mathrm{ttH}) = \left(g^S_{H\bar{t}t}\right)^2 + \left(g^P_{H\bar{t}t}\right)^2
\end{aligned}$$

$$\widehat{\mu}(\mathcal{D}) = B(H\to\mathcal{D})/B(H_{\mathrm{SM}}\to\mathcal{D})$$

♠ *Higgs : Data used for presentation in this talk*

- The ATLAS Collaboration, ATLAS-CONF-2013-012, "Measurements of the properties of the Higgs-like boson in the two photon decay channel with the ATLAS detector using 25 fb^{-1} of proton-proton collision data" (Mar. 2013).
- The ATLAS Collaboration, ATLAS-CONF-2013-034, "Combined coupling measurements of the Higgs-like boson with the ATLAS detector using up to 25 fb^{-1} of proton-proton collision data" (Mar. 2013).
- The CMS Collaboration, CMS PAS HIG-13-001, "Updated measurements of the Higgs boson at 125 GeV in the two photon decay channel" (Mar. 2013).
- The CMS Collaboration, CMS PAS HIG-13-002, "Properties of the Higgs-like boson in the decay $H \to ZZ \to 4l$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV" (Mar. 2013).
- The CMS Collaboration, CMS PAS HIG-13-003, "Update on the search for the standard model Higgs boson in pp collisions at the LHC decaying to W^+W^- in the fully leptonic final state" (Mar. 2013).
- The CMS Collaboration, CMS PAS HIG-13-004, "Search for the Standard-Model Higgs boson decaying to tau pairs in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV" (Mar. 2013).
- Aurelio Juste, "Standard Modek Higgs boson searches at the Tevatron", talk at HCP2012, 15 Nov 2012, Kyoto, Japan, http://kds.kek.jp/conferenceDisplay.py?confId=9237.
- Yuji Enari, "$H \to b\bar{b}$ from Tevatron", talk at HCP2012, 14 Nov 2012, Kyoto, Japan, http://kds.kek.jp/conferenceDisplay.py?confId=10808.

♠ χ^2 [SM]

- We have used 22 data points and obtained the chi-square relative to the SM:
  K.Cheung, JSL, P.-Y. Tseng, arXiv:1302.3794 (JHEP)

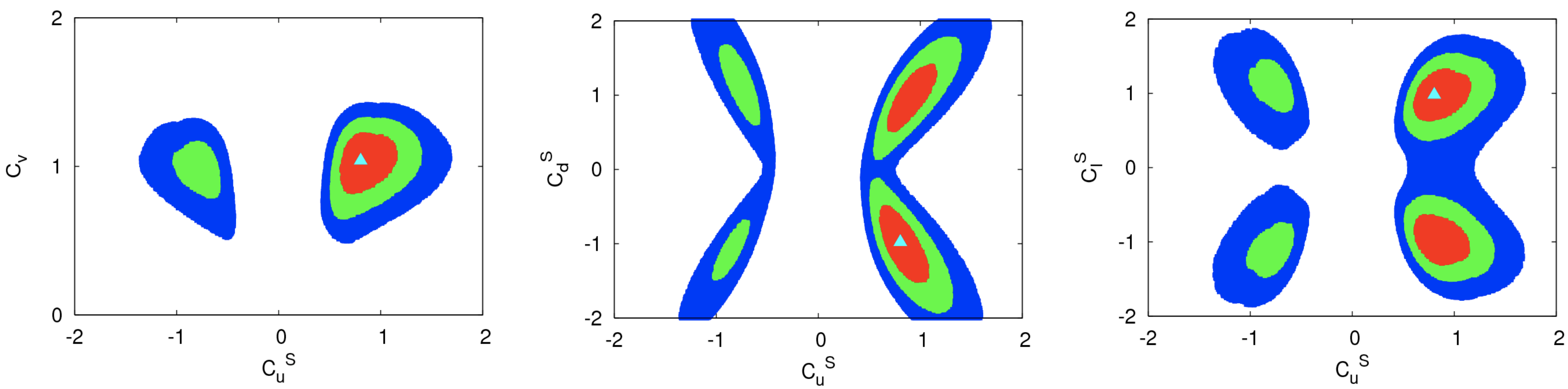
$$18.94 = 7.89(\gamma\gamma : 6) + 1.65(ZZ^* : 2) + 3.70(WW^* : 5) + 3.55(b\bar{b} : 4) + 2.15(\tau^+\tau^- : 5)$$

  where the numbers in parentheses denote the number of data points adopted in each decay mode

- **SM**: $\chi^2/\mathrm{dof} = 0.86$ and p-value$=0.65$

♠ Fits : CPC(4:MI)

- **CPC(4:MI)**: Varying $C^S_{u,d,\ell}$ and C_v K.Cheung, JSL, P.-Y. Tseng, arXiv:1302.3794 (JHEP)



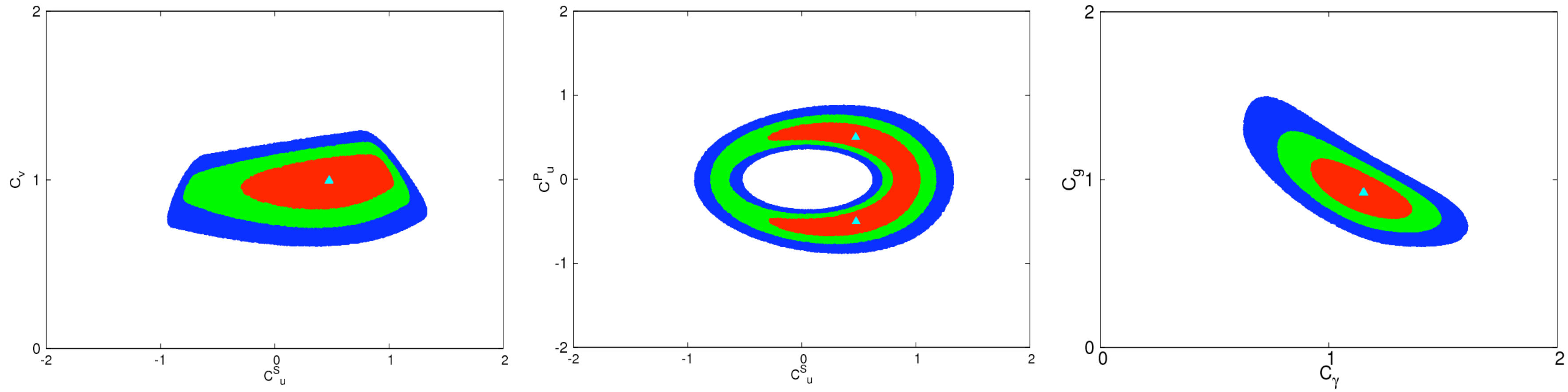
Colors: $\Delta\chi^2 \leq 2.3\,(68.3\%\,CL)$, $5.99\,(95\%\,CL)$, and $11.83\,(99.7\%\,CL)$

$C^S_u = 0.80^{+0.16}_{-0.13}$, $C^S_d = -0.98^{+0.31}_{-0.34}$, $C^S_\ell = 0.98^{+0.21}_{-0.21}$, $C_v = 1.04^{+0.12}_{-0.14}$

$\chi^2/\text{dof} = 17.82/18$, p-value$= 0.48$

♠ *Fits : CPV(3:MI)*

- **CPV(3:MI)**: Varying $C_u^{S,P}$ and C_v The other couplings are assumed to take the SM values



Two ellipses: $C_\gamma : 1.1 \approx \sqrt{\frac{(-8.4+1.76C_u^S)^2+(2.78C_u^P)^2}{(-6.64)^2}}$, $C_g : 0.9 \approx \sqrt{\frac{(0.688C_u^S)^2+(1.047C_u^P)^2}{(0.65)^2}}$

with $C_g \equiv \sqrt{(|S^g|^2 + |P^g|^2)/(\left|S^g_{\rm SM}\right|^2)}$ and $C_\gamma \equiv \sqrt{(|S^\gamma|^2 + |P^\gamma|^2)/(\left|S^\gamma_{\rm SM}\right|^2)}$

$$C_u^S = 0.48^{+0.44}_{-0.48},\ C_u^P = 0.50^{+0.11}_{-0.40}\ (C_u^P = -0.50^{+0.44}_{-0.11}),\ C_v = 0.995^{+0.097}_{-0.104}$$

$\chi^2/\mathrm{dof} = 17.17/19$, p-value$= 0.58$ *Maximal CPV in the top-quark sector?*

♠ *2HDMs*

- Taking some specific models, there are correlations among the couplings and also constraints on them

- 2HDMs:

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– S. Choi, S. Jung and P. Ko, arXiv:1307.3948 [hep-ph].
– S. Chang, S. K. Kang, J. -P. Lee, K. Y. Lee, S. C. Park and J. Song, arXiv:1310.3374 [hep-ph].

Sorry for an incomplete list, again ...

♠ 2HDMs

- Potential and parameters

$$
\begin{aligned}
\mathrm{V} \;=\; & -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2) - m_{12}^{*2}(\Phi_2^\dagger\Phi_1) \\
& +\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
& +\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \frac{\lambda_5^*}{2}(\Phi_2^\dagger\Phi_1)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_6^*(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1) \\
& +\lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \lambda_7^*(\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)
\end{aligned}
$$

with the parameterization

$$
\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\,(v_1 + \phi_1^0 + i a_1) \end{pmatrix} \;; \quad \Phi_2 = \mathrm{e}^{i\xi} \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}\,(v_2 + \phi_2^0 + i a_2) \end{pmatrix}
$$

One may remove μ_1^2, μ_2^2, and $\Im\mathrm{m}(m_{12}^2 \mathrm{e}^{i\xi})$ from the 2HDM potential using three tadpole conditions.

To fully specify the general 2HDM potential, setting aside the vacuum expectation value v, one may need the following 12 parameters plus one sign:

$$t_\beta = v_2/v_1\,,|m_{12}|\,;$$
$$\lambda_1\,,\lambda_2\,,\lambda_3\,,\lambda_4\,,|\lambda_5|\,,|\lambda_6|\,,|\lambda_7|\,;$$
$$\phi_5+2\xi\,,\phi_6+\xi\,,\phi_7+\xi\,,\mathrm{sign}[\cos(\phi_{12}+\xi)]$$

- $m_{12} = |m_{12}|e^{i\phi_{12}}$ and $\lambda_{5,6,7} = |\lambda_{5,6,7}|e^{i\phi_{5,6,7}}$
- $\sin(\phi_{12}+\xi)$ is fixed by the CP-odd tadpole condition and $\cos(\phi_{12}+\xi)$ is determined up to the two-fold ambiguity
- One may take the convention with $\xi = 0$ without loss of generality

.... too many parameters

♠ 2HDMs

- Mixing:

$$(\phi_1^0, \phi_2^0, a)^T_\alpha \quad = \quad O_{\alpha i}(H_1, H_2, H_3)^T_i$$

such that $O^T \mathcal{M}_0^2 O = \mathrm{diag}(M_{H_1}^2, M_{H_2}^2, M_{H_3}^2)$ with the ordering of $M_{H_1} \leq M_{H_2} \leq M_{H_3}$

- Mass matrix:

$$\mathcal{M}_0^2 = M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta & 0 \\ -s_\beta c_\beta & c_\beta^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{M}_\lambda^2 \equiv M_A^2\, \mathcal{X}(\beta) \; + \; v^2\, \mathcal{Y}(\lambda)$$

with

$$M_A^2 \quad = \quad M_{H^\pm}^2 + \frac{1}{2}\lambda_4 v^2 - \frac{1}{2}\Re\mathrm{e}(\lambda_5 \mathrm{e}^{2i\xi})v^2\,,$$

$$M_{H^\pm}^2 \quad = \quad \frac{\Re\mathrm{e}(m_{12}^2 \mathrm{e}^{i\xi})}{c_\beta s_\beta} - \frac{v^2}{2c_\beta s_\beta}\left[\lambda_4 c_\beta s_\beta + c_\beta s_\beta \Re\mathrm{e}(\lambda_5 \mathrm{e}^{2i\xi}) + c_\beta^2 \Re\mathrm{e}(\lambda_6 \mathrm{e}^{i\xi}) + s_\beta^2 \Re\mathrm{e}(\lambda_7 \mathrm{e}^{i\xi})\right]\,,$$

and

$$\mathcal{Y}(\lambda) = \begin{pmatrix} \lambda)2\lambda_1 c_\beta^2 + \Re\mathrm{e}(\lambda_5 \mathrm{e}^{2i\xi}) s_\beta^2 & \lambda_{34} c_\beta s_\beta + \Re\mathrm{e}(\lambda_6 \mathrm{e}^{i\xi}) c_\beta^2 & -\frac{1}{2}\Im\mathrm{m}(\lambda_5 \mathrm{e}^{2i\xi}) s_\beta \\ +2\Re\mathrm{e}(\lambda_6 \mathrm{e}^{i\xi}) s_\beta c_\beta & +\Re\mathrm{e}(\lambda_7 \mathrm{e}^{i\xi}) s_\beta^2 & -\Im\mathrm{m}(\lambda_6 \mathrm{e}^{i\xi}) c_\beta \\ & & \\ \lambda_{34} c_\beta s_\beta + \Re\mathrm{e}(\lambda_6 \mathrm{e}^{i\xi}) c_\beta^2 & 2\lambda_2 s_\beta^2 + \Re\mathrm{e}(\lambda_5 \mathrm{e}^{2i\xi}) c_\beta^2 & -\frac{1}{2}\Im\mathrm{m}(\lambda_5 \mathrm{e}^{2i\xi}) c_\beta \\ +\Re\mathrm{e}(\lambda_7 \mathrm{e}^{i\xi}) s_\beta^2 & +2\Re\mathrm{e}(\lambda_7 \mathrm{e}^{i\xi}) s_\beta c_\beta & -\Im\mathrm{m}(\lambda_7 \mathrm{e}^{i\xi}) s_\beta \\ -\frac{1}{2}\Im\mathrm{m}(\lambda_5 \mathrm{e}^{2i\xi}) s_\beta & -\frac{1}{2}\Im\mathrm{m}(\lambda_5 \mathrm{e}^{2i\xi}) c_\beta & 0 \\ -\Im\mathrm{m}(\lambda_6 \mathrm{e}^{i\xi}) c_\beta & -\Im\mathrm{m}(\lambda_6 \mathrm{e}^{i\xi}) s_\beta & \end{pmatrix}$$

where $\lambda_{34} = \lambda_3 + \lambda_4$.

- $v = gM_W/2$
- $a = -s_\beta a_1 + c_\beta a_2$ and $H^+ = -s_\beta \phi_1^+ + c_\beta \phi_2^+$

♠ 2HDMs

- Yukawa couplings (Neutral Higgses)

$$
\begin{aligned}
-\mathcal{L}_{H_i \bar{f} f} &= \frac{m_u}{v}\left[\bar{u}\left(\frac{O_{\phi_2 i}}{s_\beta} - i\,\frac{c_\beta}{s_\beta} O_{ai}\,\gamma_5\right) u\right] H_i \\
&+ \frac{m_d}{v}\left[\bar{d}\left(\frac{\eta_1^d O_{\phi_1 i} + \eta_2^d O_{\phi_2 i}}{\eta_1^d c_\beta + \eta_2^d s_\beta} - i\,\frac{\eta_1^d s_\beta - \eta_2^d c_\beta}{\eta_1^d c_\beta + \eta_2^d s_\beta} O_{ai}\,\gamma_5\right) d\right] H_i \\
&+ \frac{m_l}{v}\left[\bar{l}\left(\frac{\eta_1^l O_{\phi_1 i} + \eta_2^l O_{\phi_2 i}}{\eta_1^l c_\beta + \eta_2^l s_\beta} - i\,\frac{\eta_1^l s_\beta - \eta_2^l c_\beta}{\eta_1^l c_\beta + \eta_2^l s_\beta} O_{ai}\,\gamma_5\right) l\right] H_i
\end{aligned}
$$

	2HDM I	2HDM II	2HDM III	2HDM IV
η_1^d	0	1	0	1
η_2^d	1	0	1	0
η_1^l	0	1	1	0
η_2^l	1	0	0	1

♠ *2HDMs*

- All the couplings including $C_v = c_\beta O_{\phi_1 i} + s_\beta O_{\phi_2 i}$ can be specified once the mixing angles $O_{\phi_1 i}$, $O_{\phi_2 i}$, O_{ai} and $\tan\beta$ are known (assuming the i-th neutral Higgs for the 125-GeV Higgs candidate):

2HDM I	$C_d^S = O_{\phi_2 i}/s_\beta$	$C_l^S = O_{\phi_2 i}/s_\beta$	$C_d^P = O_{ai}/t_\beta$	$C_l^P = O_{ai}/t_\beta$
2HDM II	$C_d^S = O_{\phi_1 i}/c_\beta$	$C_l^S = O_{\phi_1 i}/c_\beta$	$C_d^P = -t_\beta O_{ai}$	$C_l^P = -t_\beta O_{ai}$
2HDM III	$C_d^S = O_{\phi_2 i}/s_\beta$	$C_l^S = O_{\phi_1 i}/c_\beta$	$C_d^P = O_{ai}/t_\beta$	$C_l^P = -t_\beta O_{ai}$
2HDM IV	$C_d^S = O_{\phi_1 i}/c_\beta$	$C_l^S = O_{\phi_2 i}/s_\beta^S$	$C_d^P = -t_\beta O_{ai}$	$C_l^P = O_{ai}/t_\beta$

And the mixing angles can be fixed once $C_u^{S,P}$ and $\tan\beta$ are given:

$$O_{\phi_2 i} = s_\beta\, C_u^S\,, \quad O_{ai} = -t_\beta\, C_u^P\,; \quad O_{\phi_1 i} = \pm\left[1 - s_\beta^2 (C_u^S)^2 - t_\beta^2 (C_u^P)^2\right]^{1/2}$$

♠ 2HDMs

- *Effectual Higgcision*: Instead of specifying the 2HDMs fully, concentrate on the couplings of the 125-GeV Higgs candidate. Then all the relevant signal strengths can be calculated when C_u^S, C_u^P, and $\tan\beta$ are given. One can use C_v as an input parameter replacing $\tan\beta$ by exploiting the relation

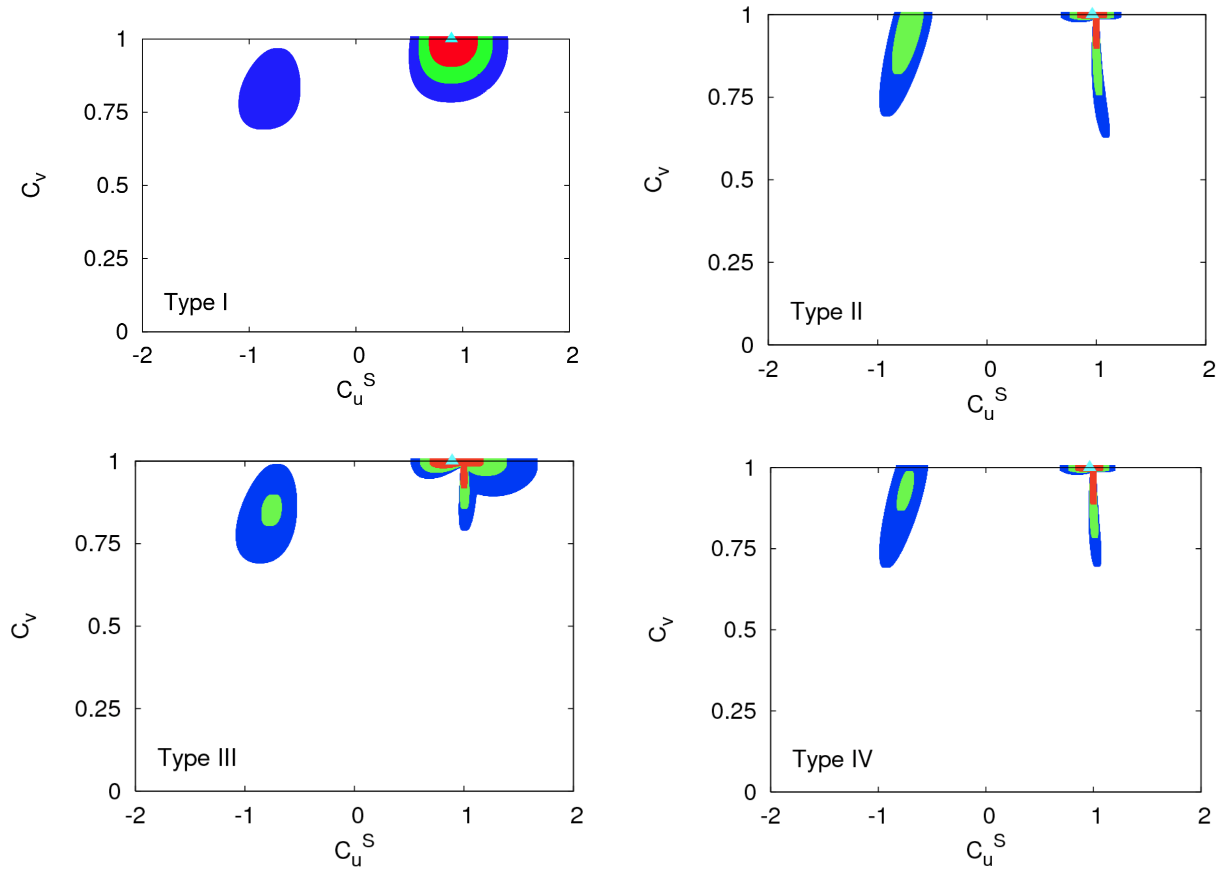
$$s_\beta^2 = \frac{1 - C_v^2}{(1 - C_v^2) + (C_u^S - C_v)^2 + (C_u^P)^2}$$

In 2HDMs, therefore, Higgcision can be implemented only with the following 3 (instead of 12) input parameters: C_u^S, C_u^P, and C_v

K.Cheung, JSL, P.-Y. Tseng, arXiv:1310.3937

♠ *Fits: CPC(2:2HDMs)*

- **CPC(2:2HDM)**: Varying C_u^S and C_v K.Cheung, JSL, P.-Y. Tseng, arXiv:1310.3937



  – Best-fit values (C_u^S,C_v):

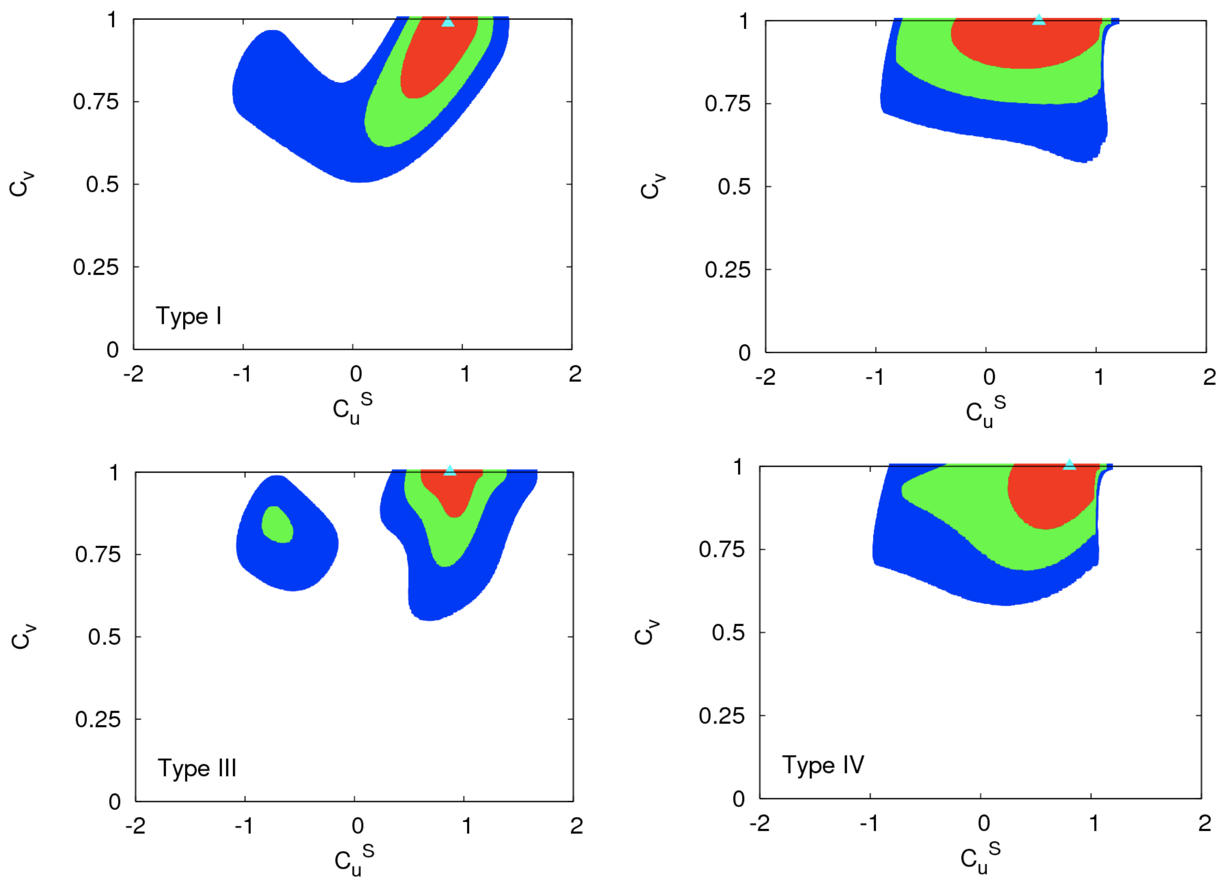
    $(0.895, 1.000)$ (I)
    $(0.963, 1.000)$ (II)
    $(0.892, 1.000)$ (III)
    $(0.965, 1.000)$ (IV)

  – (χ^2,p-value):

    $(18.39, 0.562)$ (I)
    $(18.68, 0.543)$ (II)
    $(18.44, 0.558)$ (III)
    $(18.66, 0.544)$ (IV)

♠ *Fits: CPV(3:2HDMs)*

- **CPV(3:2HDM)**: Varying C_u^S,C_u^P and C_v



– Best-fit values (C_u^S,C_u^P,C_v):

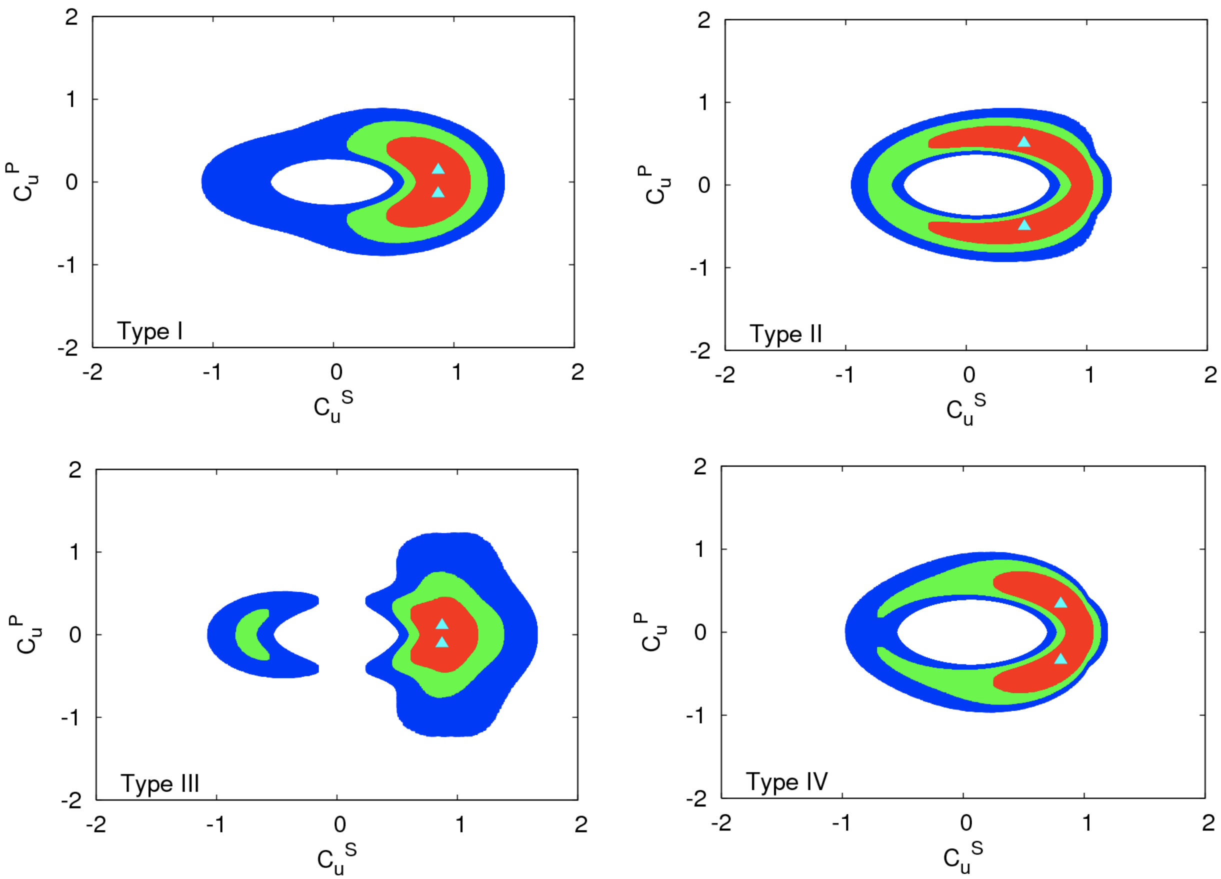
$(0.867, \pm 0.142, 0.988)$ (I)
$(0.476, \pm 0.505, 0.998)$ (II)
$(0.873, \pm 0.110, 1.000)$ (III)
$(0.806, \pm 0.339, 1.000)$ (IV)

– (χ^2,p-value):

$(18.37, 0.498)$ (I)
$(17.17, 0.578)$ (II)
$(18.41, 0.495)$ (III)
$(18.16, 0.512)$ (IV)

♠ Fits: CPV(3:2HDMs)

- **CPV(3:2HDM)**: Varying C_u^S,C_u^P and C_v



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♠ *Fits: CPV(3:2HDMs)*

- **CPV(3:2HDM)**: Note that maximal CP violation with $C_u^S \sim |C_u^P|$ is possible even when $C_v \simeq 1$: When $C_v \simeq 1$, $\sin\beta$ is very small and

$$C_v = 1 - \frac{1}{2}\beta^2 \left[\left(C_u^S - 1\right)^2 + \left(C_u^P\right)^2\right] + \mathcal{O}(\beta^3)$$

Taking an example of $C_u^S = C_u^P = 1/2$, one may have

$$O_{\phi_2 i} = \beta/2\,, \quad O_{ai} = -\beta/2\,, \quad O_{\phi_1 i} = 1 - \beta^2/4\,, \quad C_v = 1 - \beta^2/4$$

up to $\mathcal{O}(\beta^3)$. Hence, although the 125-GeV observed state is mostly CP-even dominated by the ϕ_1 component, it can have maximally CP-violating couplings to the up-type quarks with $C_u^S = |C_u^P| = 1/2$.

♠ *New Particles*

- In the presence of New Particles not contained in the SM, the Higgs couplings to two gluons and two photons receive additional contributions

$$
\begin{aligned}
S^\gamma(C_v, C^S_{u,d,\ell}) &\rightarrow S^\gamma(C_v, C^S_{u,d,\ell}) + \Delta S^\gamma \\
P^\gamma(C^P_{u,d,\ell}) &\rightarrow S^\gamma(C^P_{u,d,\ell}) + \Delta P^\gamma \\
S^g(C^S_{u,d}) &\rightarrow S^g(C^S_{u,d}) + \Delta S^g \\
P^g(C^P_{u,d}) &\rightarrow P^g(C^P_{u,d}) + \Delta P^g
\end{aligned}
$$

♠ New Particles

- For example, (Following the CPsuperH conventions and notations JSL et al., hep-ph/0307377, arXiv:0712.2360 [hep-ph], arXiv:1208.2212 [hep-ph])

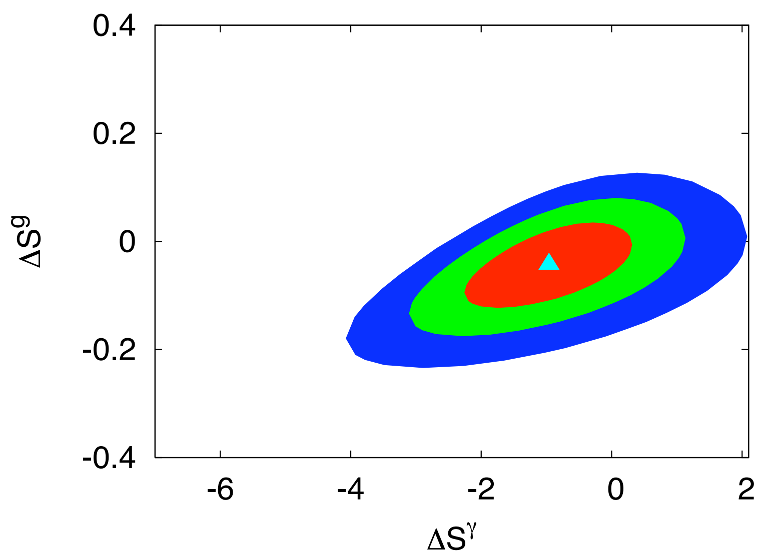
$$
\begin{aligned}
(\Delta S^\gamma)^{\rm MSSM} &= (\Delta S^\gamma)^{H^\pm} + \sqrt{2}g \sum_{f=\tilde\chi_1^\pm,\tilde\chi_2^\pm} g^S_{H_i\bar f f}\,\frac{v}{m_f}F_{sf}(\tau_{if}) \\
&\quad - \sum_{\tilde f_j=\tilde t_1,\tilde t_2,\tilde b_1,\tilde b_2,\tilde\tau_1,\tilde\tau_2} N_C\,Q_f^2 g_{H_i\tilde f_j^*\tilde f_j}\frac{v^2}{2m^2_{\tilde f_j}}F_0(\tau_{i\tilde f_j}) \\
(\Delta P^\gamma)^{\rm MSSM} &= \sqrt{2}g \sum_{f=\tilde\chi_1^\pm,\tilde\chi_2^\pm} g^P_{H_i\bar f f}\,\frac{v}{m_f}F_{pf}(\tau_{if}) \\
(\Delta S^g)^{\rm MSSM} &= -\sum_{\tilde f_j=\tilde t_1,\tilde t_2,\tilde b_1,\tilde b_2} g_{H_i\tilde f_j^*\tilde f_j}\frac{v^2}{4m^2_{\tilde f_j}}F_0(\tau_{i\tilde f_j}) \\
(\Delta P^g)^{\rm MSSM} &= 0
\end{aligned}
$$

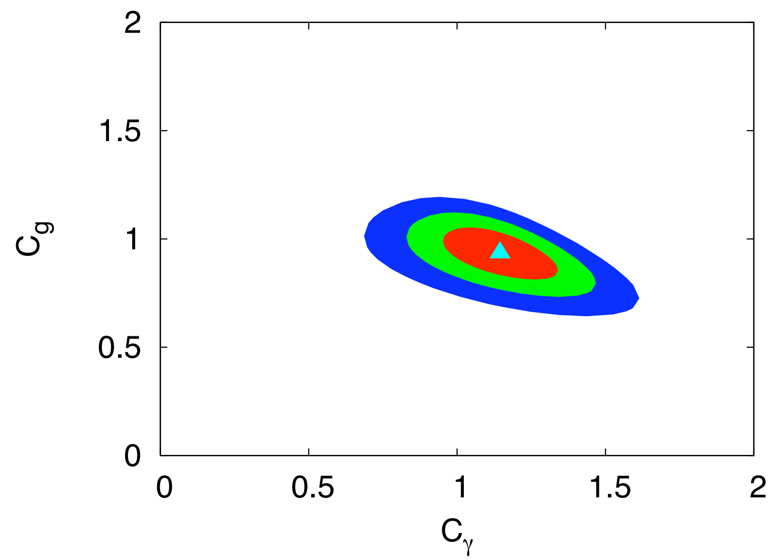
with $(\Delta S^\gamma)^{H^\pm} = -g_{H_iH^+H^-}\frac{v^2}{2M^2_{H^\pm}}F_0(\tau_{iH^\pm})$.

♠ *Fits : CPC(2:MI)*

- **CPC(2:MI)**: Varying ΔS^γ and ΔS^g The other couplings are assumed to take the SM values

K.Cheung, JSL, P.-Y. Tseng, arXiv:1302.3794 (JHEP)





$$\Delta S^\gamma = -0.96^{+0.84}_{-0.85},\ \Delta S^g = -0.043 \pm 0.052$$

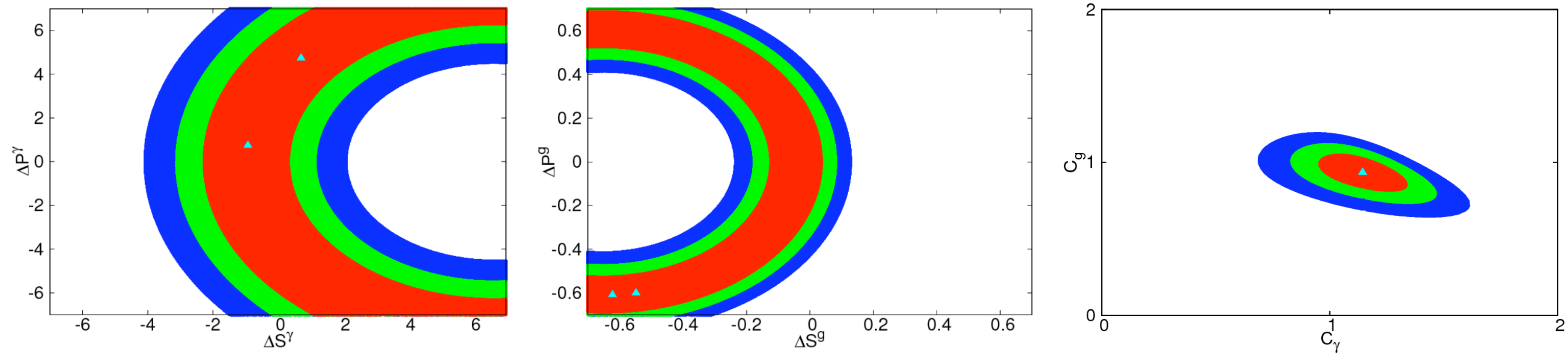
$\chi^2/\mathrm{dof} = 17.55/20$, p-value$= 0.62$ [p-value(SM)$= 0.65$]

$C_\gamma \simeq 1.14,\ C_g \simeq 0.93$

$$C_V = \sqrt{\left[\left|S^V\right|^2 + \left|P^V\right|^2\right] / \left|S^V_{\rm SM}\right|^2}$$

♠ *Fits : CPV(4:MI)*

- **CPV(4:MI)**: Varying $\Delta S^{\gamma,g}$ and $\Delta P^{\gamma,g}$ The other couplings are assumed to take the SM values



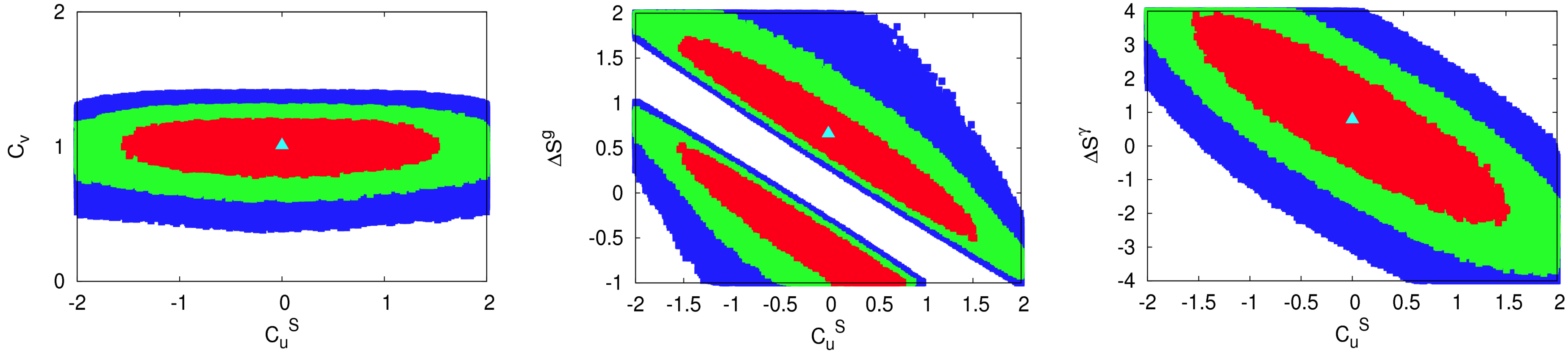
$$\Delta S^{\gamma} = -0.92^{+16.00}_{-0.89},\ \Delta S^{g} = -0.55^{+0.56}_{-0.76};\ \ \Delta P^{\gamma} = 0.77^{+7.67}_{-9.21},\ \Delta P^{g} = -0.60^{+1.26}_{-0.06}$$

$\chi^2/\mathrm{dof} = 17.55/18$, p-value$= 0.49$

Two ellipses: $C_\gamma : 1.1 \approx \sqrt{\frac{(-6.64+\Delta S^\gamma)^2+(\Delta P^\gamma)^2}{(-6.64)^2}}$ and $C_g : 0.9 \approx \sqrt{\frac{(0.65+\Delta S^g)^2+(\Delta P^g)^2}{(0.65)^2}}$

♠ Fits : CPC(6:MI)

- **CPC(6:MI)**: Varying $C^S_{u,d,\ell}$, C_v, $\Delta S^{\gamma,g}$



$C^S_u = 0.00 \pm 1.18$, $C_v = 1.01^{+0.13}_{-0.14}$, $C^S_d = 1.06^{+0.41}_{-0.35}$ (*not shown*), $C^S_l = 1.01 \pm 0.23$ (*not shown*);

$\Delta S^g = 0.66^{+0.42}_{-0.83}$, $\Delta S^\gamma = 0.78^{+2.34}_{-2.28}$, $\chi^2/\mathrm{dof} = 16.89/16$, p-value$= 0.39$

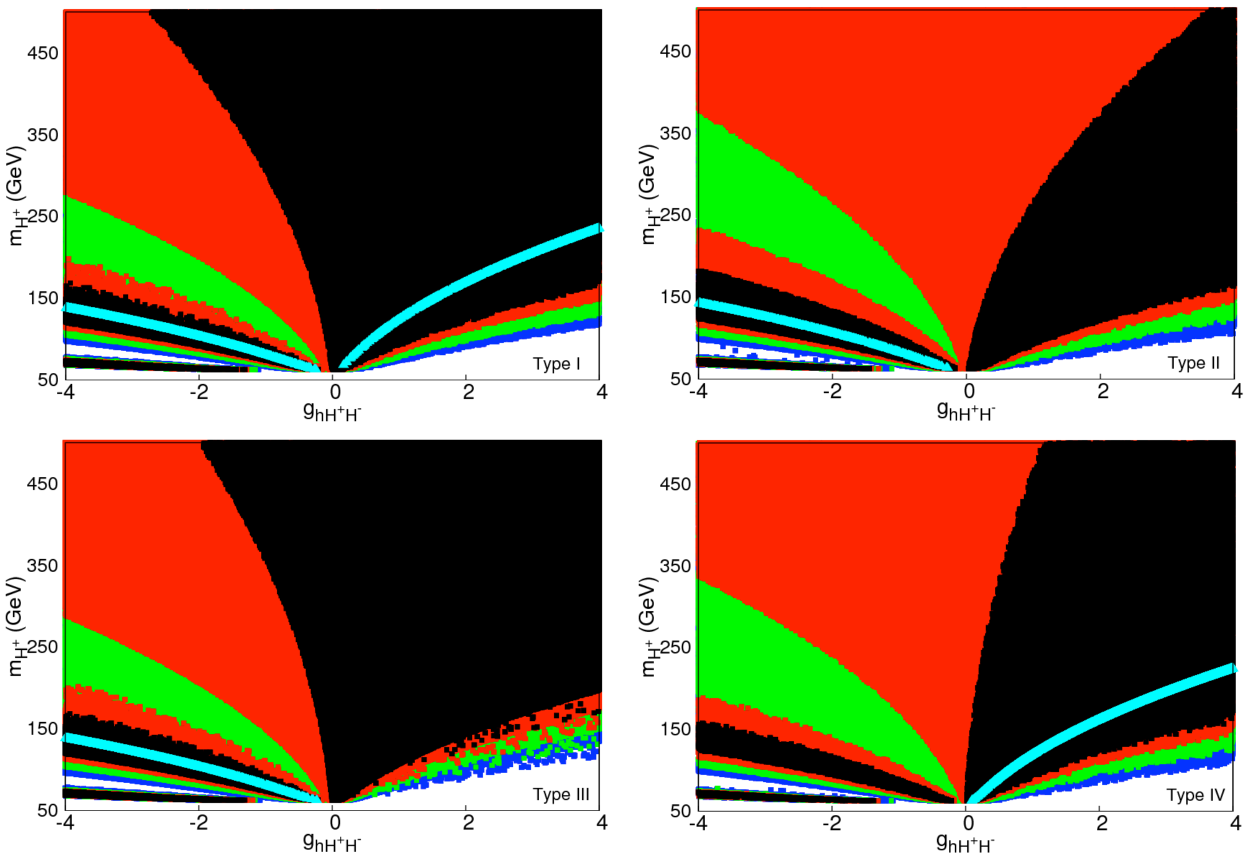
Have we really observed the top-quark Yukawa coupling? ... direct contribution enters into the current Higgs data only through the ttH production

We may need to measure the top-quark Yukawa couplings directly

... possible at the LHC ? or need ILC/PLC?

♠ *Fits : CPC(3:2HDM)*

- **CPC(3:2HDM)**: Varying C_u^S, C_v, and $(\Delta S^\gamma)^{H^\pm}$ K.Cheung, JSL, P.-Y. Tseng, arXiv:1310.3937



– Black region: $\delta\chi^2 < 1$ (39.3% CL) 68.3% 95% 99.7%

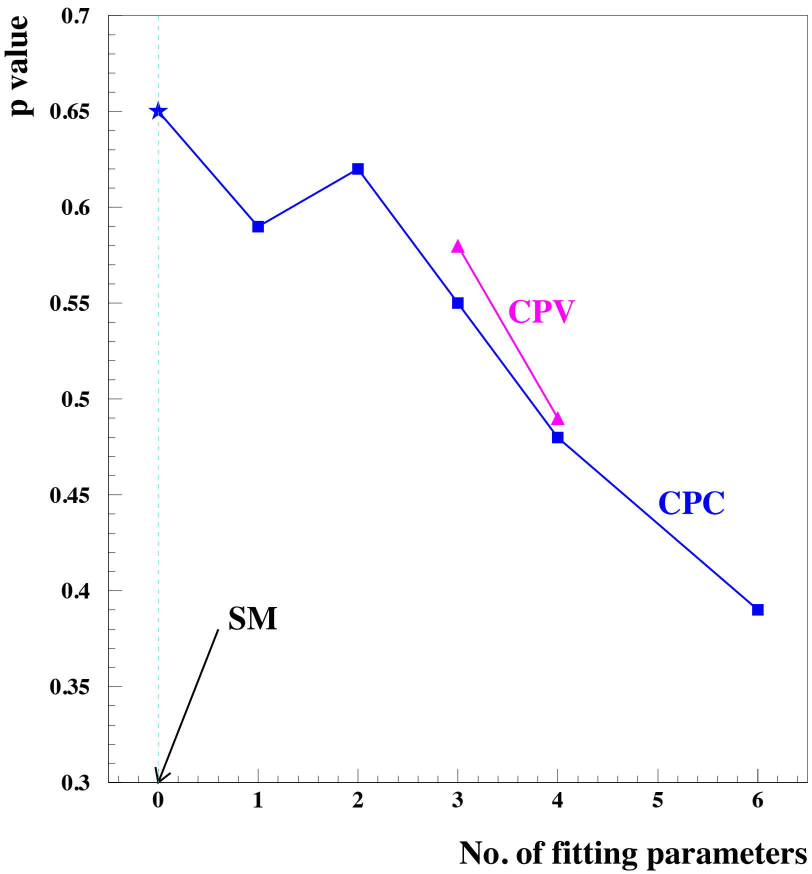
– Best-fit values $(C_u^S, C_v, (\Delta S^\gamma)^{H^\pm})$:
$(0.924, 0.965, -0.756)$ (I)
$(-0.921, 0.965, 2.377)$ (I)
$(-0.822, 1.000, 2.218)$ (II)
$(-0.912, 0.967, 2.365)$ (III)
$(0.955, 1.000, -0.835)$ (IV)

– $(\chi^2, p$-value):
$(17.64, 0.547)$ (I)
$(17.30, 0.570)$ (II)
$(17.63, 0.547)$ (III)
$(17.54, 0.553)$ (IV)

– (Recall) $(\Delta S^\gamma)^{H^\pm} = -g_{H_i H^+ H^-} \frac{v^2}{2M_{H^\pm}^2} F_0(\tau_{iH^\pm})$

♠ Fits : Summary (MI)

- The SM provides the best to all the current data

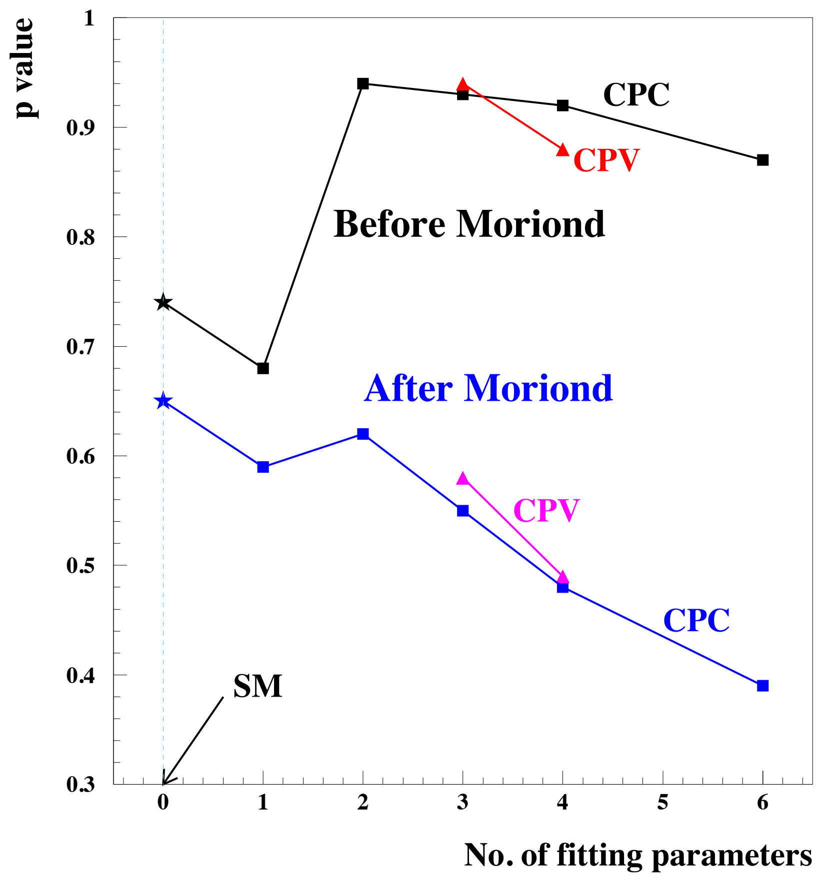


Varying parameters:

- **CPC(1:MI)**:$\Delta\Gamma_{\rm tot}$
- **CPC(2:MI)**:$\Delta S^{\gamma,g}$
- **CPC(3:MI)**:$\Delta S^{\gamma,g}$, $\Delta\Gamma_{\rm tot}$
- **CPC(4:MI)**:$C^S_{u,d,\ell}$, C_v
- **CPC(6:MI)**:$C^S_{u,d,\ell}$, C_v, $\Delta S^{\gamma,g}$
- **CPV(3:MI)**:C^S_u, C^P_u, C_v
- **CPV(4:MI)**:$\Delta S^{\gamma,g}$, $\Delta P^{\gamma,g}$

♠ Fits : Summary (MI)

- But...



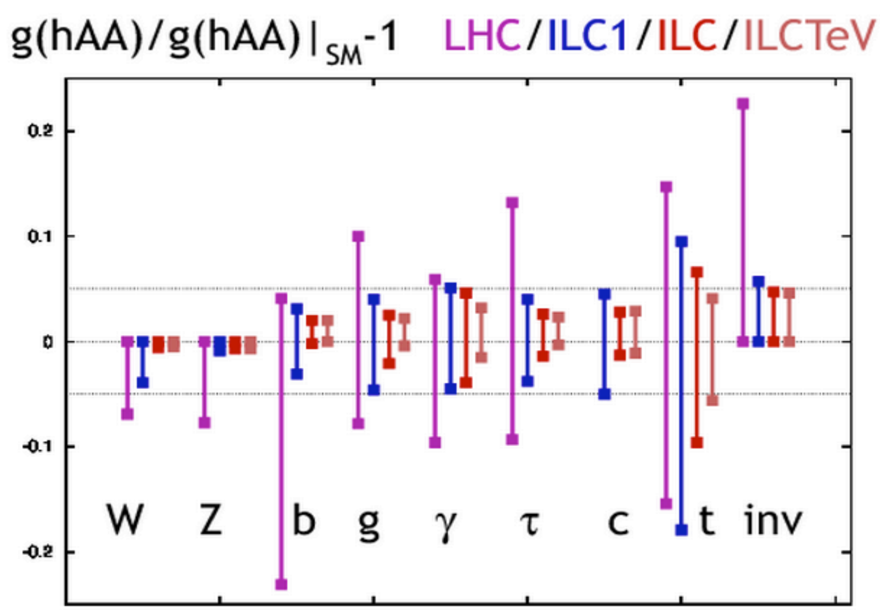
– Before Moriond 2013:

$$\mu^{H\to\gamma\gamma}_{ggH+ttH}(\text{ATLAS}) = 1.8 \pm 0.49$$
$$\mu^{H\to\gamma\gamma}_{\text{untagged}}(\text{CMS}) = 1.42^{+0.55}_{-0.49}$$

– After Moriond 2013:

$$\mu^{H\to\gamma\gamma}_{ggH+ttH}(\text{ATLAS}) = 1.6 \pm 0.4$$
$$\mu^{H\to\gamma\gamma}_{\text{untagged}}(\text{CMS}) = 0.78^{+0.28}_{-0.26}$$

Definitely, we need more precise Higgs data



Peskin, arXiv:1208.5152

♠ *Others Higgses*

- Decoupling, alignment, and fine-tuning Carena, Low, Shah, Wangner, arXiv:1310.2248

To be specific, in 2HDMs, the 3×3 mass matrix of the neutral Higgses:

$$\mathcal{M}_0^2 = M_A^2\,\mathcal{X}(\beta) \;+\; v^2\,\mathcal{Y}(\lambda)$$

For the eigen-vector state λ_X with mass M_X, from the relation $\mathcal{M}_0^2\,\lambda_X = M_X^2\,\lambda_X$, one may have

$$\mathcal{X}(\beta)\,\lambda_X = \left[-\frac{v^2}{M_A^2}\,\mathcal{Y}(\lambda) + \frac{M_X^2}{M_A^2}\,\mathbf{1}_{3\times 3}\right]\,\lambda_X$$

- Decoupling: $\lambda_X \to \lambda_{\rm SM} = (c_\beta, s_\beta, 0)^T$ (or $C_v = 1$) when $M_A \gg v, M_X$
- Alignment: $\lambda_X \to \lambda_{\rm SM}$ is also possible if the R.H.S. vanishes (fine-tuning)
- Alignment without fine-tuning seems possible ...

No need for the other Higgses to be heavy necessarily

♠ *Summary*

- The total χ^2 is currently dominated by $H \to \gamma\gamma$ signal strength: the CMS and ATLAS diphoton data are on the $opposite$ side of the SM value and the dynamics of the fit cannot effectively reduce the χ^2 from the diphoton data

- Therefore, the SM provides the best to all the current data

- Meanwhile, the CPV fits are as good as CPC ones

- The Higgcision (Higgs Precision) era has just begun! The future precision data enable us to, for example,
  - find out hint for NP beyond the SM, complementing direct searches or beyond
  - discriminate NP models
  - find new features never revealed before (e.g. new CPV for BAU)