Higgcisison (Higgs precision) in the two-Higgs Doublet models

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JHEP 01(2014)085, arXiv:[hep-ph] 1310.3937

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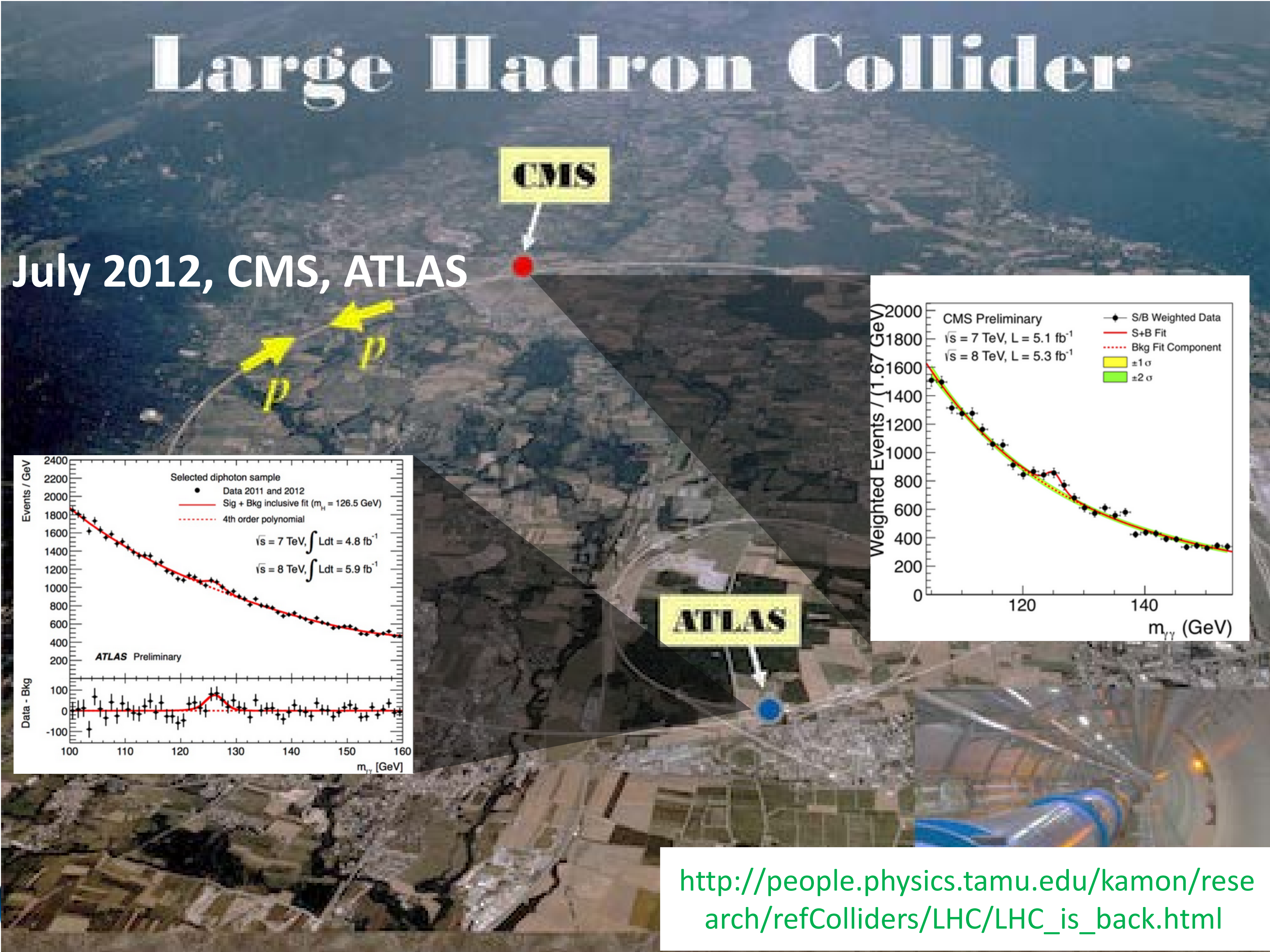
Introduction

1.

Large Hadron Collider

July 2012, CMS, ATLAS



http://people.physics.tamu.edu/kamon/research/refColliders/LHC/LHC_is_back.html

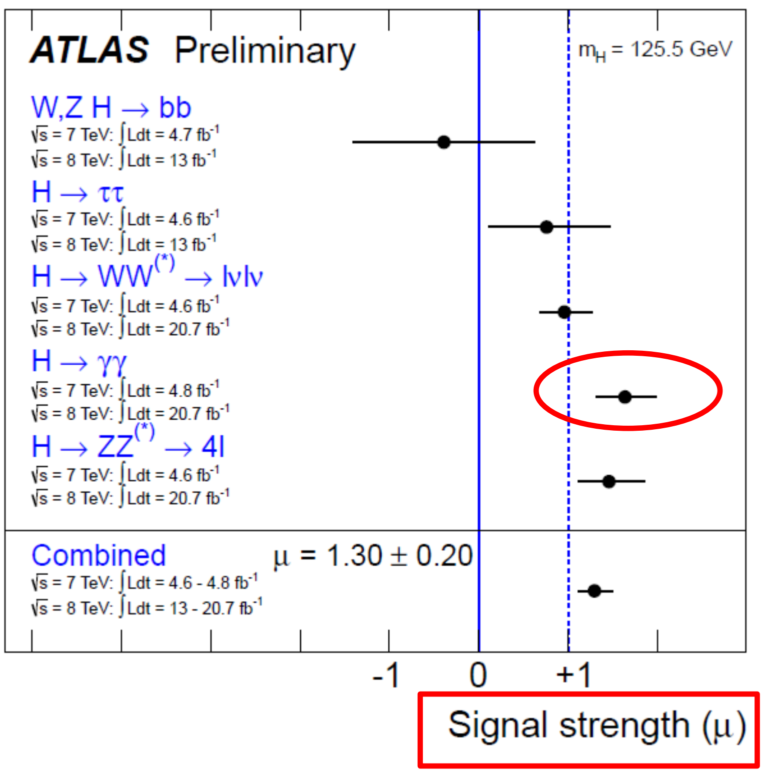
Introduction

- The diphoton production rate *after* **Moriond 2013**:

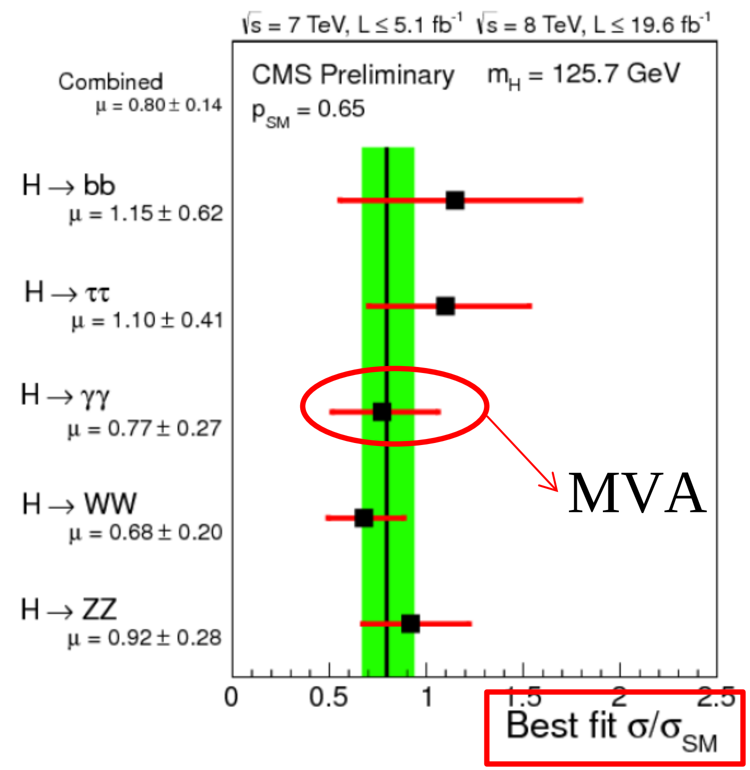
  ATLAS is higher than SM by a factor of 1.6.

  CMS is smaller than SM by a factor of 0.8.

ATLAS-CONF-2013-034



CMS PAS HIG-13-005



Introduction

- By preforming a model independent global fitting to the data of ATLAS, CMS, and Tevatron, the **observed 126GeV Higgs couplings** to SM particles can be extracted out.

- Here, we focus on the **2HDMs** with a discrete symmetry implemented (Type I to IV). See if the current data prefers one of 2HDMs or SM.

- We consider a general case for 2HDM, which the **observed 126GeV Higgs boson** could be a hybrid of **CP-even** and **CP-odd** state.

2HDM

2HDM

- The general 2HDM (two-Higgs doublet models) potential:

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

,with the parameterization

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1^0 + ia_1) \end{pmatrix}; \qquad \Phi_2 = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2^0 + ia_2) \end{pmatrix}$$

, $v_1 = v\cos\beta = vc_\beta,\ \ v_2 = v\sin\beta = vs_\beta$ are the vacuums of each Higgs doublet.

2HDM

- Without charged Higgs $H^{\pm}$ contribution to $H-\gamma-\gamma$. The Higgcision studies of 2HDM can be performed with 3-parameters:

C_u^S: top scalar Yukawa

C_u^P: top pseudoscalar Yukawa

$\tan\beta$: v_2 / v_1 ratio of two VEV

- The mixing between the mass eigenstates $h_{1,2,3}$ and the EW eigenstates ϕ_1, ϕ_2, a is described by an orthogonal matrix $O_{\alpha j}$:

$$\left(\phi_1, \phi_2, a\right)_\alpha^T = O_{\alpha j} \left(h_1, h_2, h_3\right)_j^T$$

CP even (ϕ_1, ϕ_2)　CP odd (a)

2HDM

- We identify one of the $h_{1,2,3}$ as the 125.5GeV observed Higgs boson $H = h_i$. But we did not specify whether H is the lightest or heavies one.

- The mixing matrix can be expressed by $C_u^S, C_u^P, \tan\beta$:

$$O_{\phi_2 i} = s_\beta C_u^S, \qquad O_{ai} = -t_\beta C_u^P;$$

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

$$\text{with } s_\beta^2 = \frac{\left(1 - C_V^2\right)}{\left(1 - C_V^2\right) + \left(C_u^S - C_V\right)^2 + \left(C_u^P\right)^2}$$

where $s_\beta = \sin\beta,\ c_\beta = \cos\beta,\ t_\beta = \tan\beta \equiv$ ratio of two VEV.

2HDM

- Imposing the discrete symmetry to avoid the Flavor-Changing-Neutral-Current (FCNC), the Yukawa coupling:

$$-\mathcal{L}_Y = h_u \overline{u_R} Q^T (i\tau_2) \Phi_2 + h_d \overline{d_R} Q^T (i\tau_2) \left(- \eta_1^d \widetilde{\Phi}_1 - \eta_2^d \widetilde{\Phi}_2 \right) + h_l \overline{l_R} L^T (i\tau_2) \left(- \eta_1^l \widetilde{\Phi}_1 - \eta_2^l \widetilde{\Phi}_2 \right) + \text{h.c.}$$

- The Yukawa couplings of down-type quarks and lepton can also been expressed by $C_u^S, C_u^P, \tan\beta$.

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	$C_d^S = \frac{O_{\phi_1 i}}{c_\beta}$	$C_l^S = \frac{O_{\phi_1 i}}{c_\beta}$	$C_d^P = t_\beta^2 C_u^P$	$C_l^P = t_\beta^2 C_u^P$
2HDM III	$C_d^S = C_u^S$	$C_l^S = \frac{O_{\phi_1 i}}{c_\beta}$	$C_d^P = -C_u^P$	$C_l^P = t_\beta^2 C_u^P$
2HDM IV	$C_d^S = \frac{O_{\phi_1 i}}{c_\beta}$	$C_l^S = C_u^S$	$C_d^P = t_\beta^2 C_u^P$	$C_l^P = -C_u^P$

where $C_{d,l}^{S,P} = g_{H\bar{d}d, H\bar{l}l}^{S,P}$

i. Back to SM case:

$$\tan\beta \gg 1$$

$$\Rightarrow \begin{cases} O_{\phi_1 i} \to 0 \\ O_{\phi_2 i} \to 1 \\ O_{ai} \to 0 \end{cases} \Rightarrow \begin{cases} h_i \approx \phi_2 \\ C_V \approx 1 \end{cases}$$

$$\text{Yukawa: } \frac{m_t}{v}\left[\bar{t}\left(\frac{O_{\phi_2 i}}{s_\beta} - i\frac{c_\beta}{s_\beta}O_{ai}\gamma_5\right)t\right]h_i$$

$$\Rightarrow \frac{m_t}{v}\bar{t}th_i$$

ii. HVV coupling is almost SM like, but sizable deviation from SM Yukawa coupling:

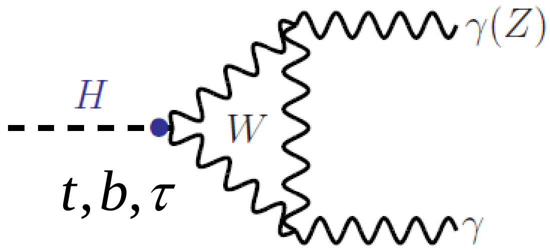
$$\tan\beta \ll 1$$

$$\Rightarrow \begin{cases} O_{\phi_1 i} \to 1 \\ O_{\phi_2 i} \to 0 \\ O_{ai} \to 0 \end{cases} \Rightarrow \begin{cases} h_i \approx \phi_1 \\ C_V \approx 1 \end{cases}$$

$$\text{Yukawa: } \frac{m_t}{v}\left[\bar{t}\left(\frac{O_{\phi_2 i}}{s_\beta} - i\frac{c_\beta}{s_\beta}O_{ai}\gamma_5\right)t\right]h_i$$

2HDM

- The $H^{\pm}$ will contribute to $H-\gamma-\gamma$ coupling:



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

$$\text{CP even}: S^{\gamma} = -8.35C_V + 1.76C_u^S + \Delta S^{\gamma}$$

$$\text{CP odd}: P^{\gamma} = 2.78C_u^P$$

new particles

top Yukawa: scalar

top Yukawa: pseudoscalar

W contribution

$$(\Delta S_i^{\gamma})^{H^{\pm}} = -g_{H_iH^+H^-}\frac{v^2}{2M_{H^{\pm}}^2}F_0(\tau_{iH^{\pm}})$$

$$\tau_{iH^{\pm}} = M_{H_i}^2 / 4M_{H^{\pm}}^2$$

2HDM

- Overall, we use ***4 parameters*** to study 2HDM:

$$C_u^S,\ C_u^P,\ \tan\beta,\ (\Delta S_i^{\gamma})^{H^{\pm}}$$

- We cannot say much about the two neutral Higgs boson in 2HDM, and whether they are lighter or heavier than 126 GeV Higgs.

Fits

Fits

- 2HDM, including CP-conserving and CP-violating case, can be performed by $C_u^S,\ C_u^P,\ \tan\beta,\ (\Delta S_i^{\gamma})^{H^{\pm}}$.

- In the following, we will consider 4 cases:

  - CP-conserving (CPC) cases

$$\begin{cases} \text{CPC2:}\ \ C_u^S, \tan\beta \\ \text{CPC3:}\ \ C_u^S, \tan\beta,\ (\Delta S_i^{\gamma})^{H^{\pm}} \end{cases}$$

  - CP-violating (CPV) cases

$$\begin{cases} \text{CPV3:}\ \ C_u^S, \tan\beta, C_u^P \\ \text{CPV4:}\ \ C_u^S, \tan\beta,\ (\Delta S_i^{\gamma})^{H^{\pm}}, C_u^P \end{cases}$$

Fits: data

- Totally, we using 22 data points.

- The chi-square value of 22 data points fitted by SM:

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

- The chi-square per degree of freedom and p-value:

$$\chi^2 / dof = 18.94 / 22 = 0.86, \quad p_{SM} = 0.65$$

Fits: CP-conserving (CPC2)

- **CPC2:** the varying parameters are $C_u^S,\ \tan\beta$.

Fits	Type	χ^2	χ^2/dof	p-value	Best-fit values				
					C_u^S	C_u^P	C_v	$\tan\beta$	$(\Delta S^\gamma)^{H^\pm}$
	I	18.39	0.920	0.562	0.895	0	1.000	*limit*	0
CPC2	II	18.68	0.934	0.543	0.963	0	1.000	*limit*	0
	III	18.44	0.922	0.558	0.892	0	1.000	*limit*	0
	IV	18.66	0.933	0.544	0.965	0	1.000	*limit*	0

- Chi-square difference among these 4 types 2HDM are very small. ***Statistically, the current Higgs data does NOT prefer any type of 2HDM***.

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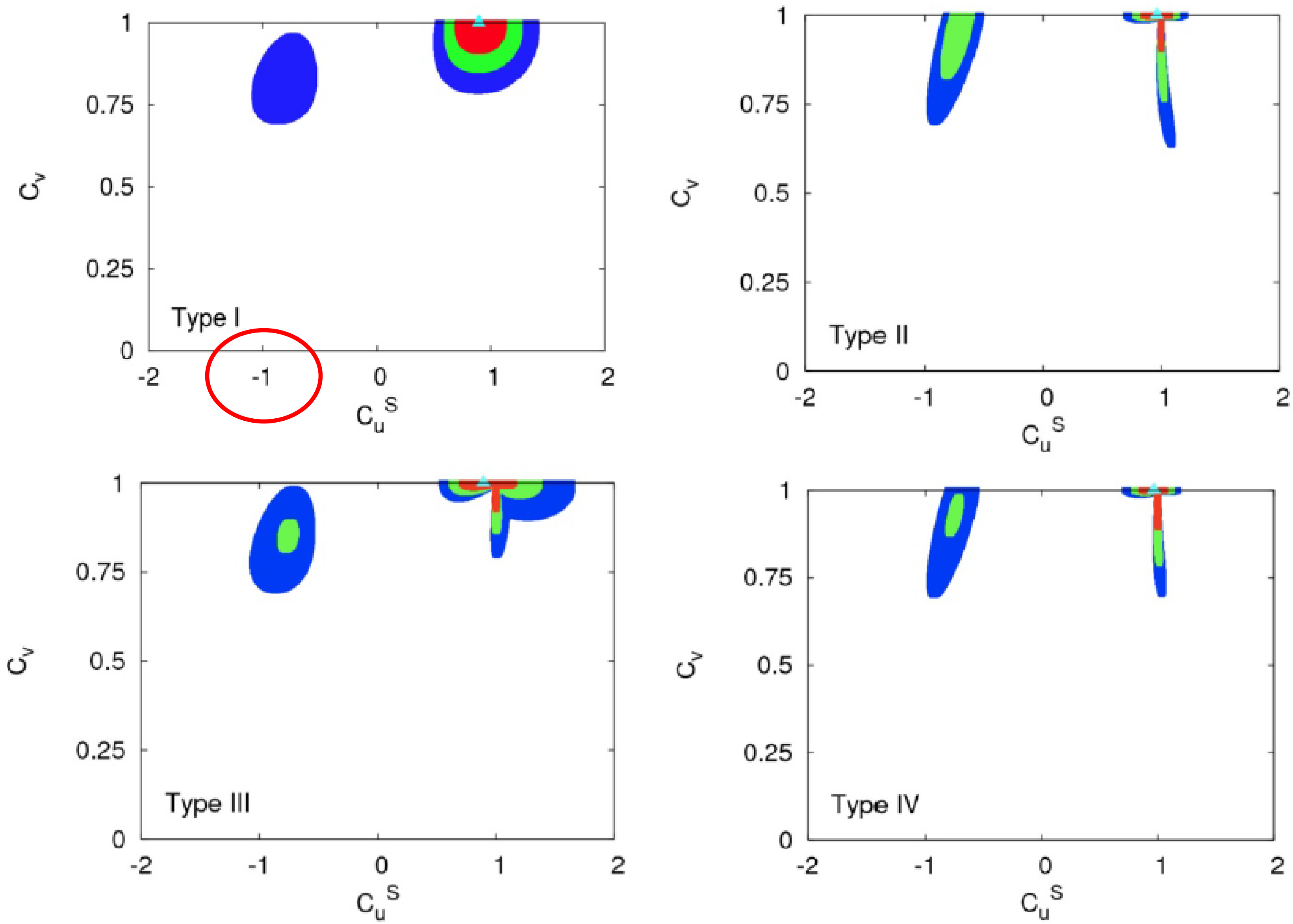
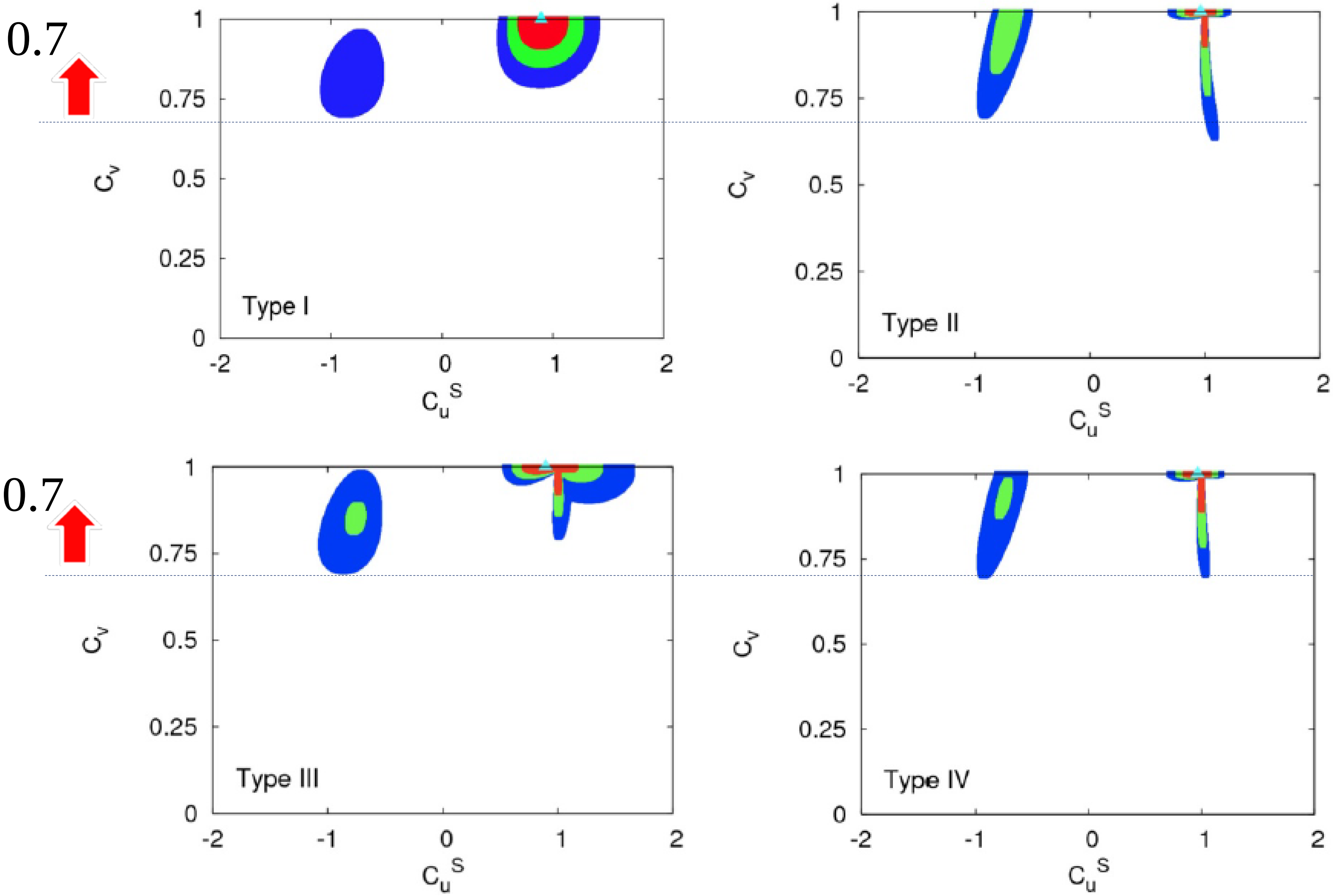


$$\Delta\chi^2 \le 2.3(\text{red } 68.3\%),\ 5.99(\text{green } 95\%),\ 11.83(\text{blue } 99.7\%)$$

Fits: CP-conserving (CPC2)



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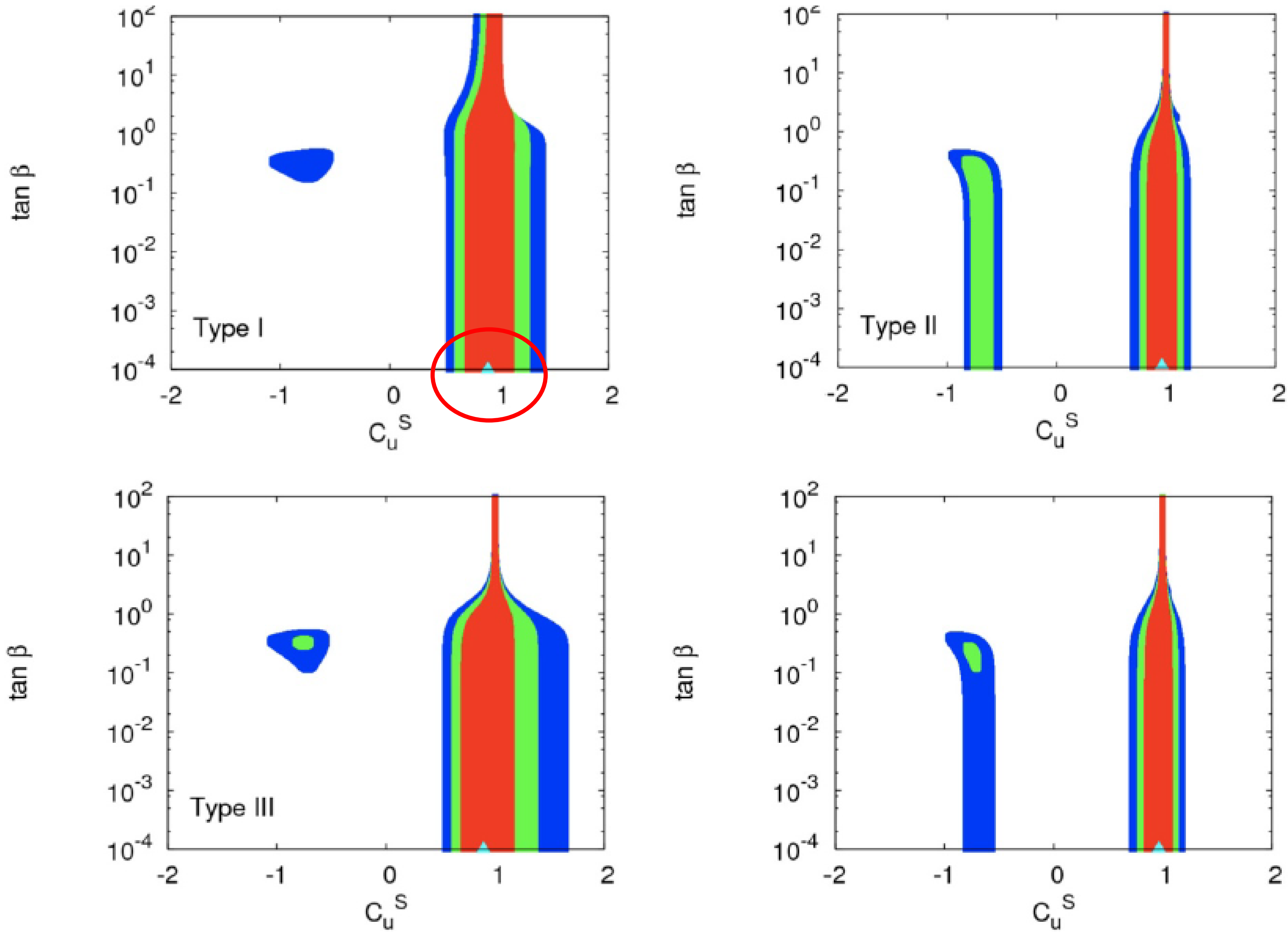

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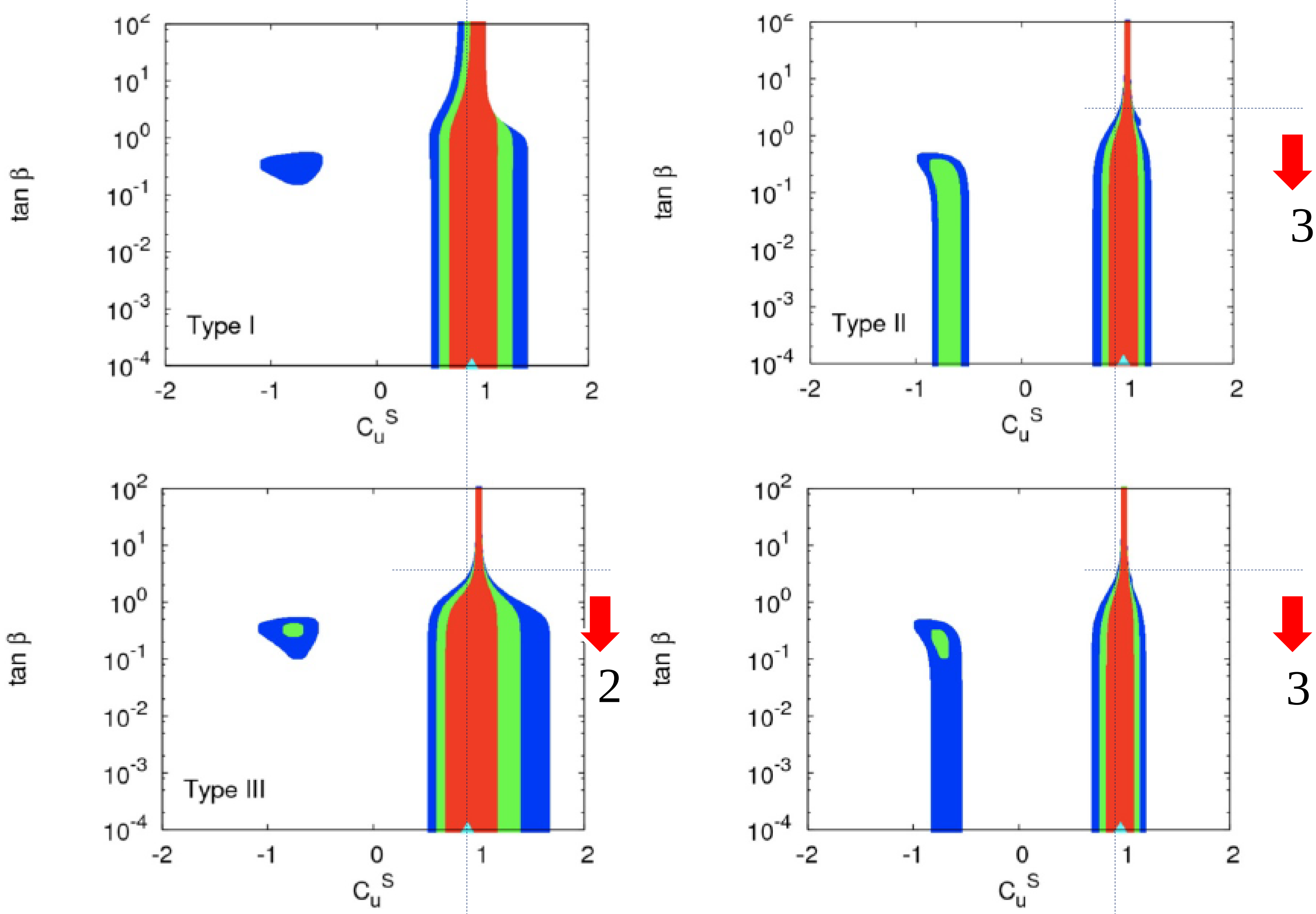

$$\therefore C_u^S < (C_V)_{\min} \Rightarrow \text{upper bound of } \tan\beta$$

Fits: CP-conserving (CPC2)

- If precise and independent measurements of C_u^S and t_β are available in future experiments, one can tell the phenomenological viability of 2HDM.

- For example: $\tan\beta > 10$ and $C_u^S \neq 1$ are measured, then one can rule out type II, III, IV models.

- Next, we consider:

$$\begin{cases} \text{CPV3:} \;\; C_u^S, \tan\beta, C_u^P \\ \text{CPV4:} \;\; C_u^S, \tan\beta, \; (\Delta S_i^\gamma)^{H^\pm}, C_u^P \end{cases}$$

Fits: CP-violating(CPV3)

- **CPV3:** the varying parameters are $C_u^S, \ \tan\beta, \ C_u^P$.

Fits	Type	χ^2	χ^2/dof	p-value	Best-fit values				
					C_u^S	C_u^P	C_v	$\tan\beta$	$(\Delta S^\gamma)^{H^\pm}$
CPV3	I	18.37	0.967	0.498	0.867	0.142	0.988	0.840	0
	I	18.37	0.967	0.498	0.867	-0.142	0.988	0.840	0
	II	17.17	0.904	0.578	0.476	-0.505	0.998	0.082	0
	II	17.17	0.904	0.578	0.475	0.505	0.998	0.095	0
	III	18.41	0.969	0.495	0.873	-0.110	1.000	2×10^{-4}	0
	III	18.41	0.969	0.495	0.873	0.109	1.000	1.2×10^{-4}	0
	IV	18.16	0.956	0.512	0.806	0.339	1.000	*limit*	0
	IV	18.16	0.956	0.512	0.806	-0.339	1.000	1.2×10^{-4}	0

Remind SM: $\chi^2/dof = 18.94/22 = 0.86, \quad p_{SM} = 0.65$

Fits: CP-violating(CPV3)

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					C_u^S	C_u^P	C_v	$\tan\beta$	$(\Delta S^\gamma)^{H^\pm}$
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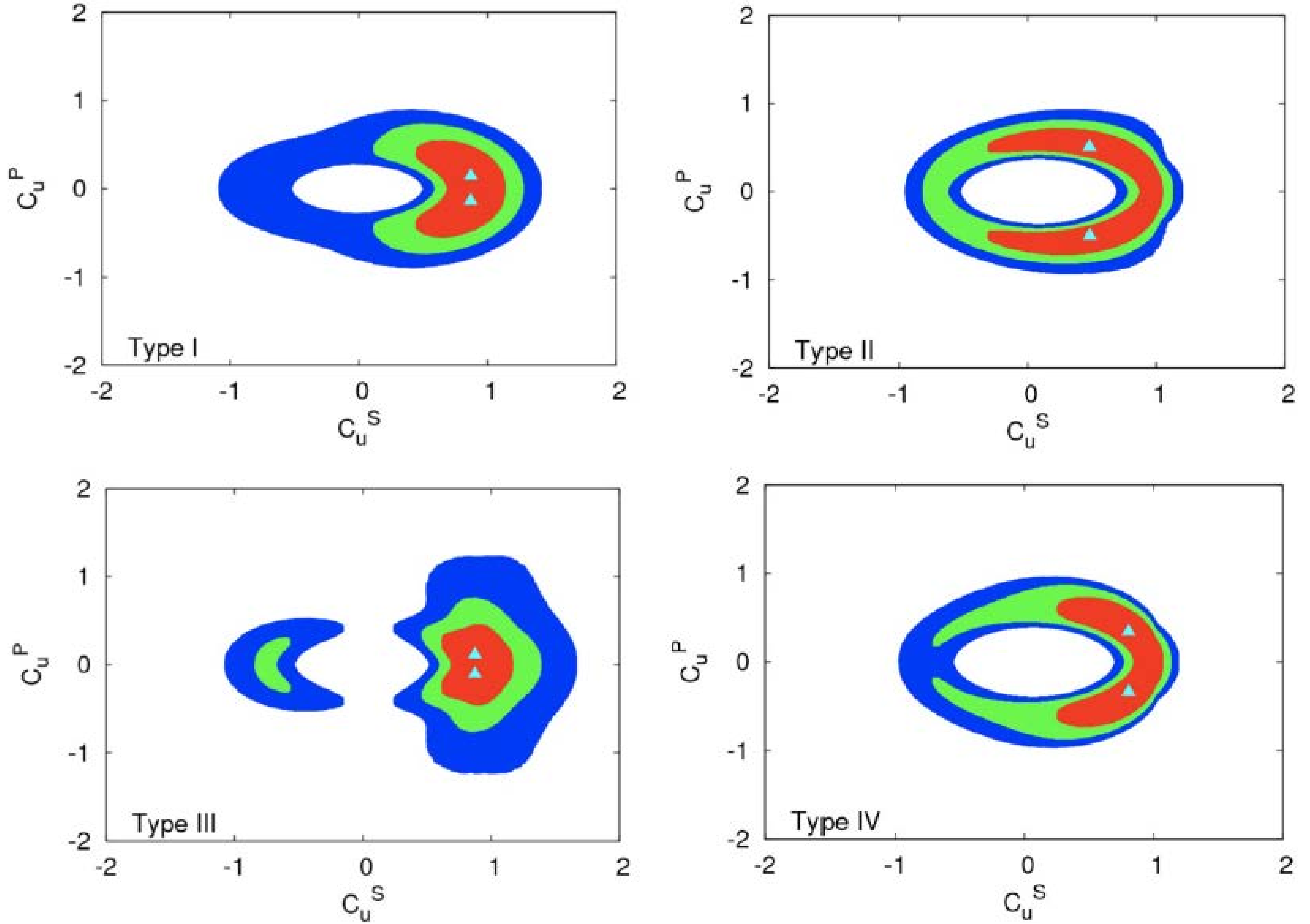
Fits: CP-violating(CPV3)



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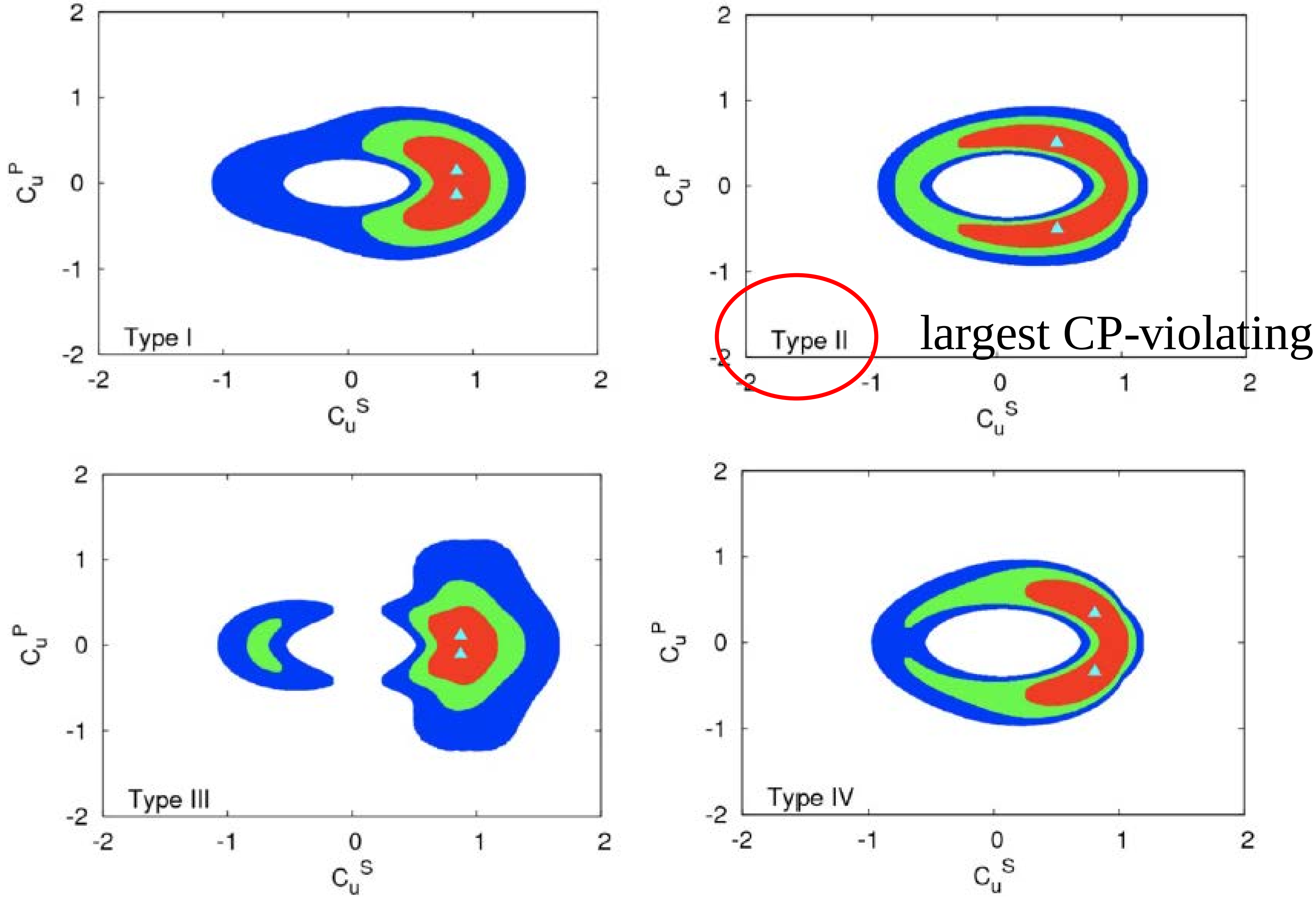

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Summary

Summary

- Only used parameters $C_u^S,\ C_u^P,\ \tan\beta$ to define the Yukawa couplings.

- The χ^2 differences are too small to claim any preference of *various types 2HDMs* statistically.

- The Higgs coupling to gauge boson C_V is constrained to be close to 1. The observed Higgs boson is entirely responsible for **breaking the EW symmetry**.

Summary

- Future precision measurements of $C_u^S, \ \tan\beta$ can provide the discriminating power among types of 2HDMs especially when C_u^S deviates from its SM value 1.

- Parameters $C_u^S, \ C_u^P$ are constrained in the shape of some ellipses. The current Higgs observables are **not** sensitive to CP-violating effects.

Thank you !