Current Fits to Higgs Signal Strength

Hint of New Physics

Kingman Cheung :: LCWS, Sendai 2019

References

1. "Higgs Precision (Higgcision) Era begins", K.C., J. Lee, P. Tseng, 1302.3794

2. "New Emerging Results in Higgs Precision Analysis Updates 2018 after Establishment of Third-Generation Yukawa Couplings, K.C., J. Lee, P. Tseng, 1810.02521

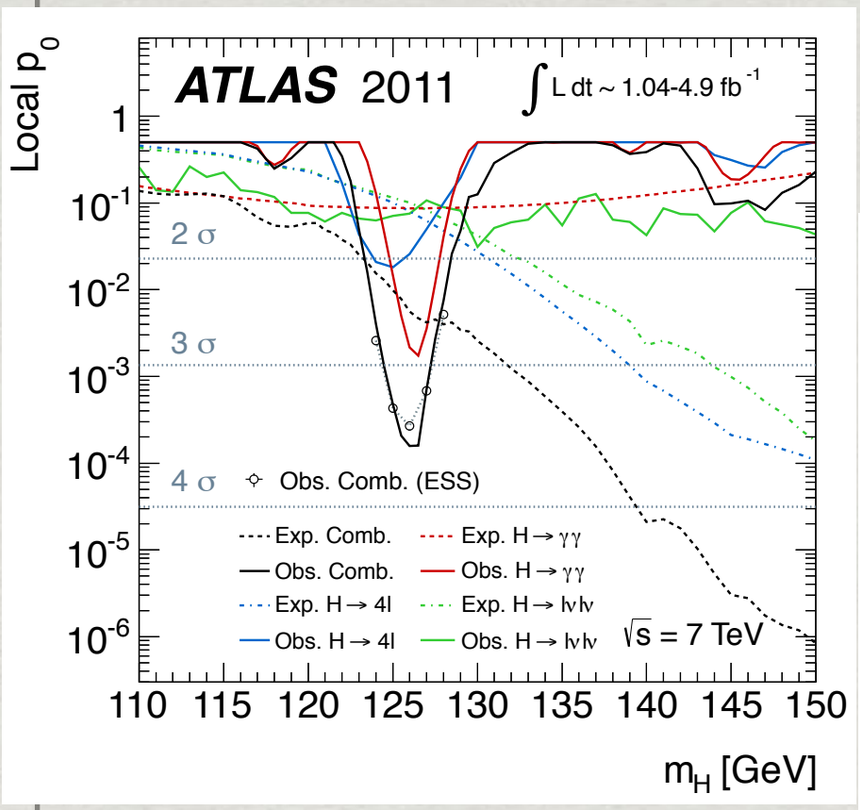
3. "Vector-like Quark Interpretation of Excess in Higgs Signal Strength", KC, W. Keung, J. Lee, P. Tseng, 1901.05626.

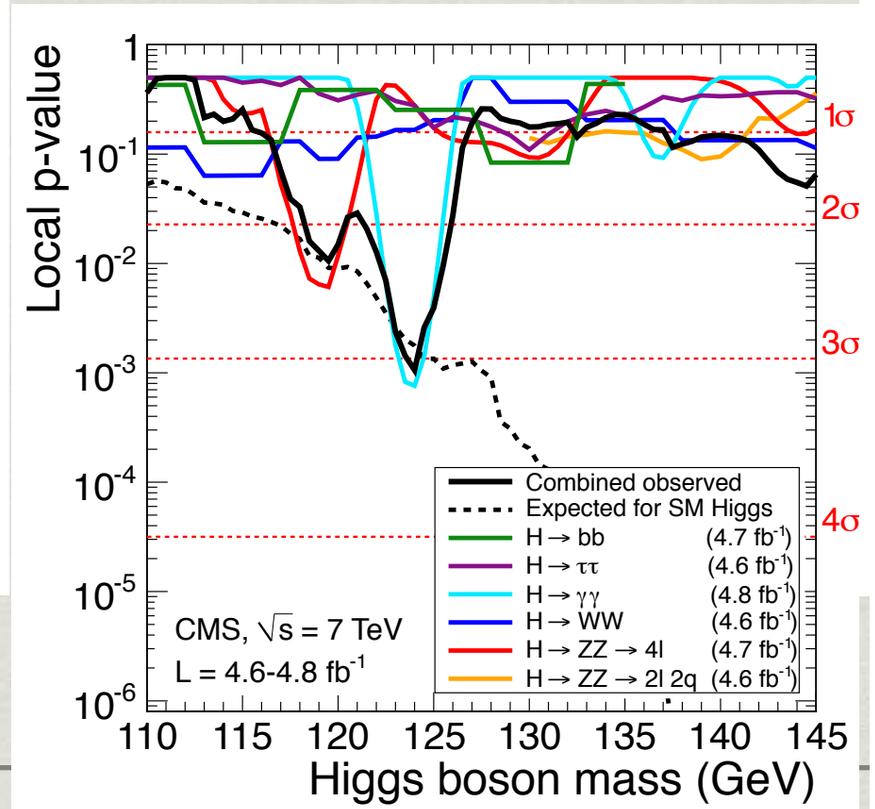
A little Journey before Discovery till now

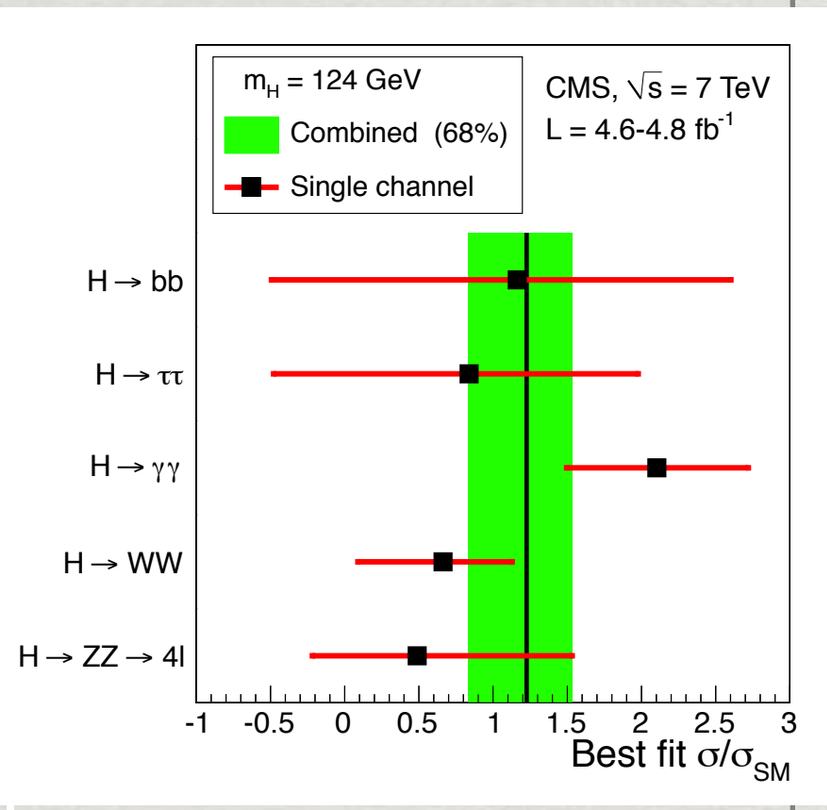
Start of LHC run in 2008 till end of 2010

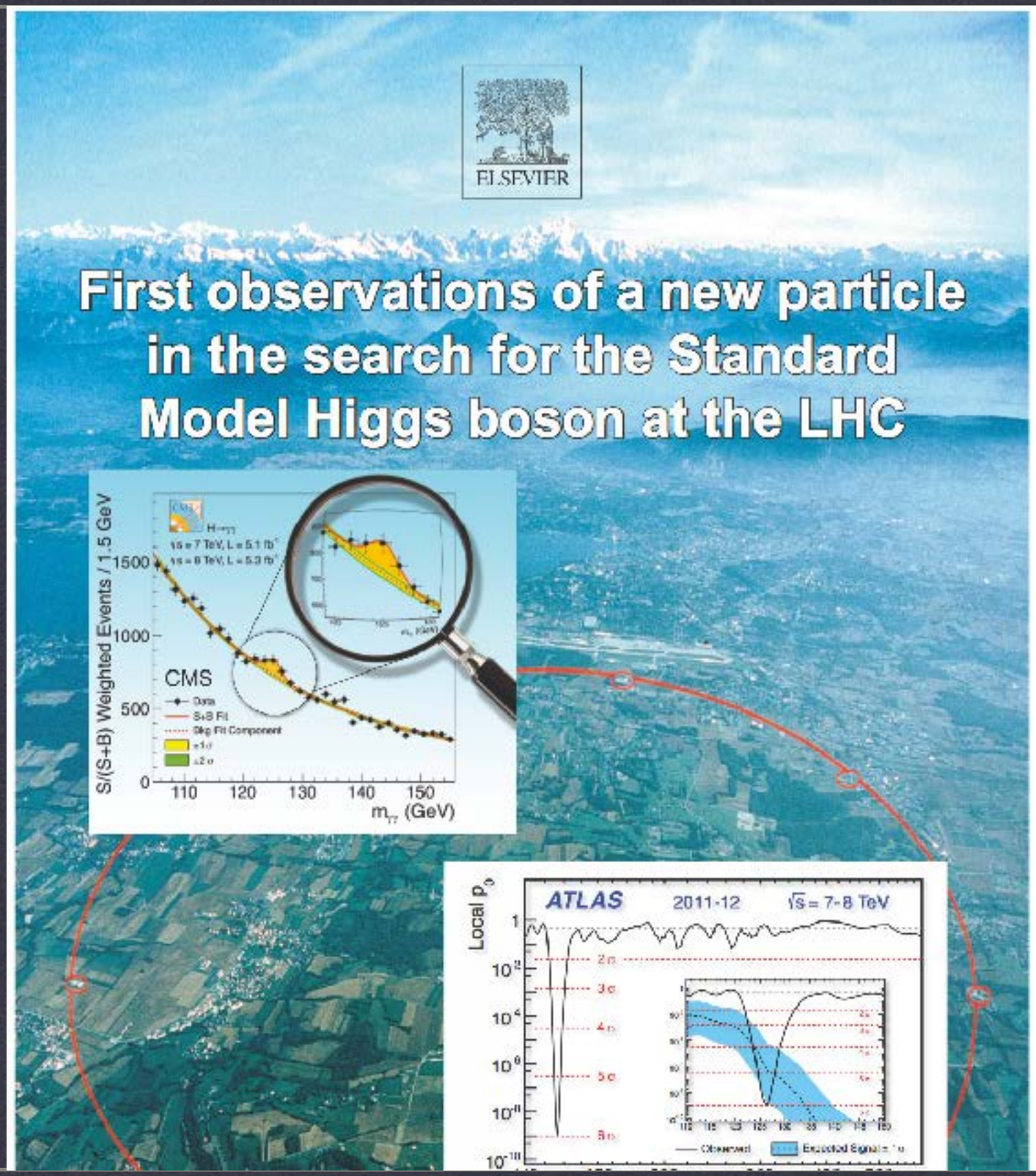
Panic of no sign of Higgs boson

- Around the end of 2011, LHC announced that they saw something.
- Most channels are consistent with the SM, except for diphoton.
- It stimulated a lot of speculations.



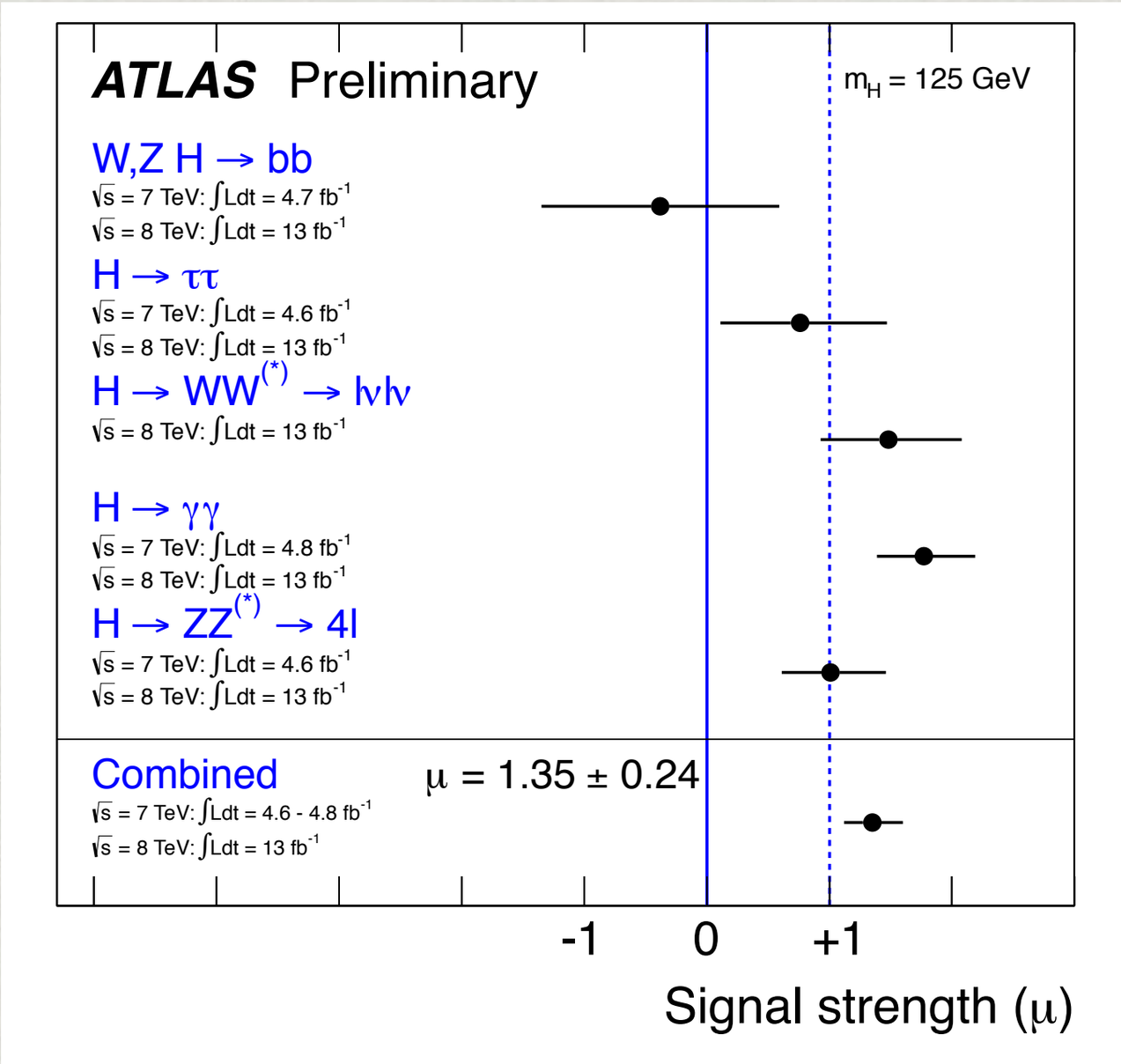


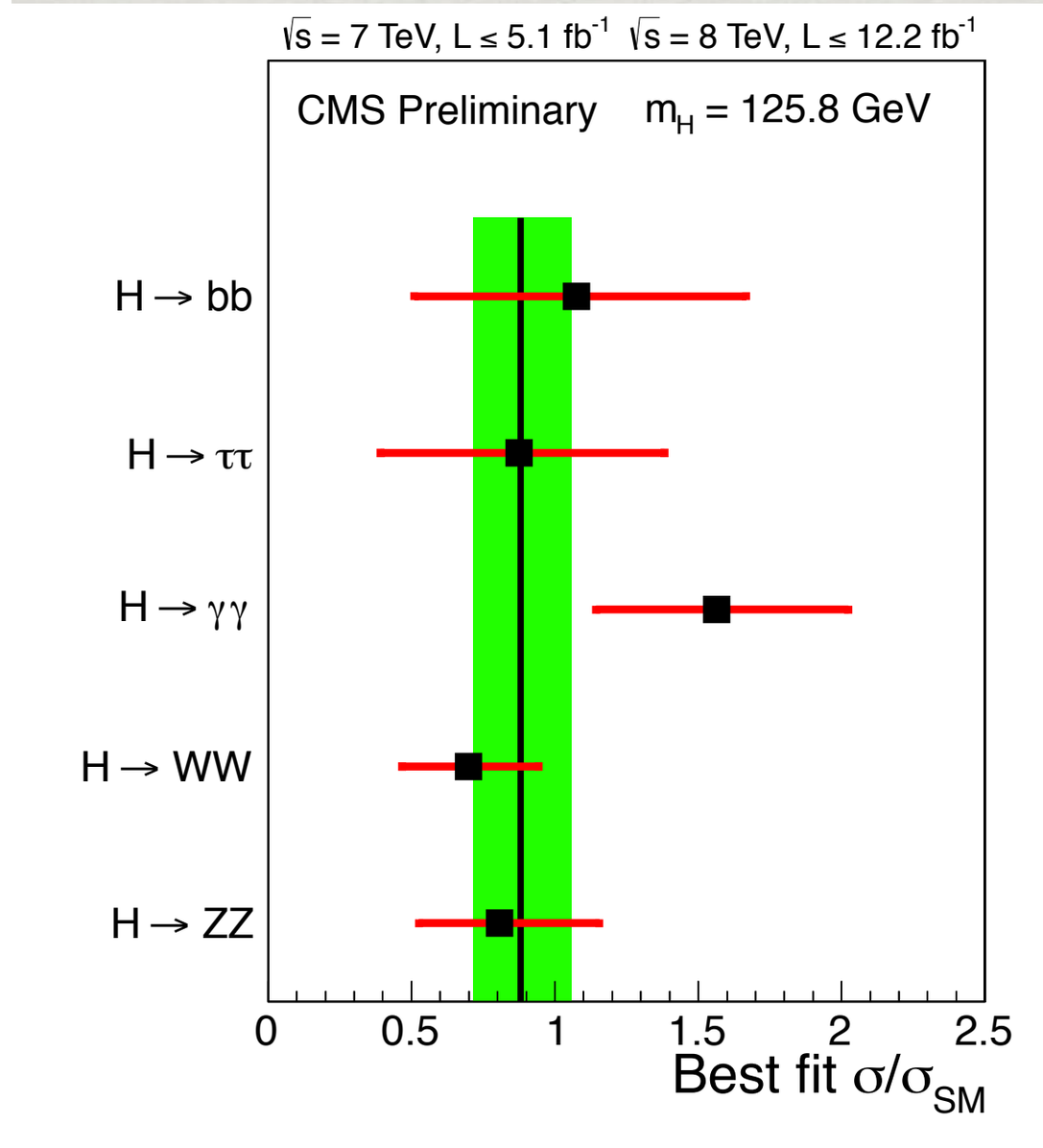




JOURNAL COVER IN PLB 2012

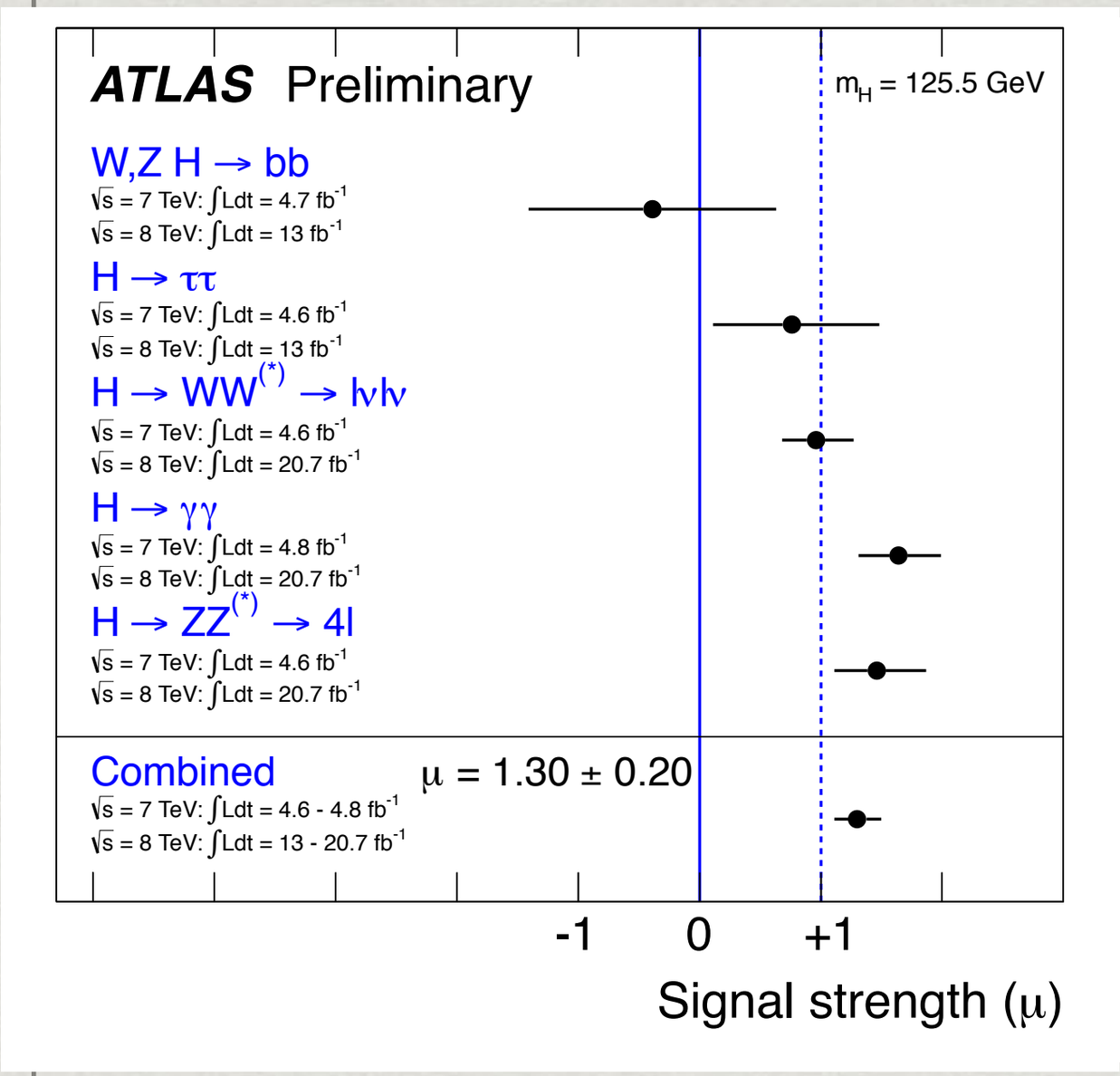
Around the end of 2012

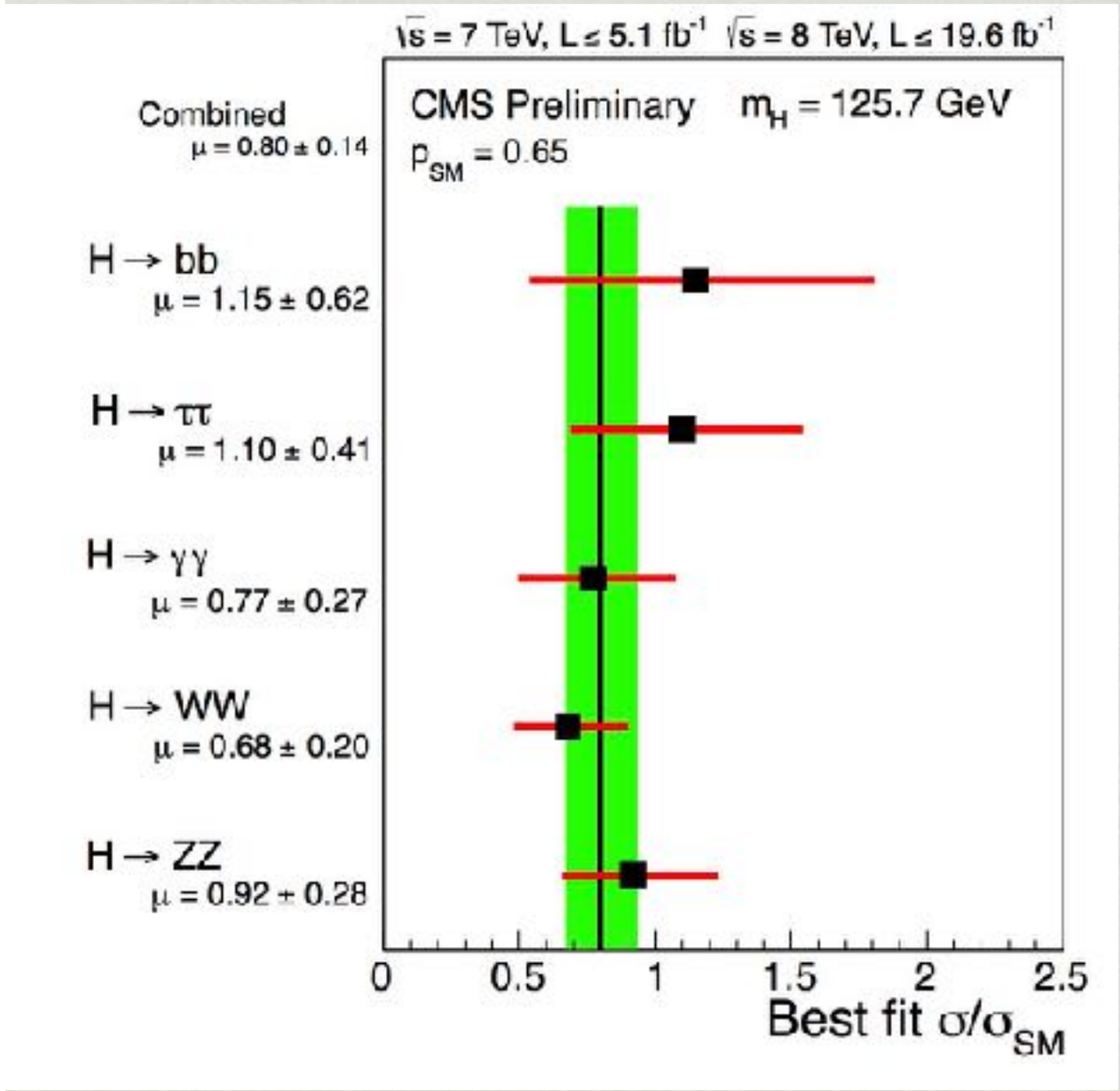




Full datasets for 7 + 8 TeV

The SM Higgs boson provides the best fit to both CMS and ATLAS datasets.





Till Summer 2018 with
part of 13 TeV data

Remarkable achievements

- Establish the gauge couplings of the Higgs boson.
- Establish the loop vertices of $Hgg, H\gamma\gamma$.
- Establishment of third generation fermion Yukawa Couplings

$$pp \to t\bar{t}H\,, \qquad H \to \tau^+\tau^-\,, \qquad H \to b\bar{b}$$

All these motivate the update of the Higgs fits

TABLE II. **(LHC: 7+8 TeV)** Combined ATLAS and CMS data on signal strengths from Table 8 of Ref. [9].

	Decay mode				
Production mode	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to bb$	$H \to \tau^+\tau^-$
ggF	$1.10^{+0.23}_{-0.22}$	$1.13^{+0.34}_{-0.31}$	$0.84^{+0.17}_{-0.17}$	-	$1.0^{+0.6}_{-0.6}$
VBF	$1.3^{+0.5}_{-0.5}$	$0.1^{+1.1}_{-0.6}$	$1.2^{+0.4}_{-0.4}$	-	$1.3^{+0.4}_{-0.4}$
WH	$0.5^{+1.3}_{-1.2}$	-	$1.6^{+1.2}_{-1.0}$	$1.0^{+0.5}_{-0.5}$	$-1.4^{+1.4}_{-1.4}$
ZH	$0.5^{+3.0}_{-2.5}$	-	$5.9^{+2.6}_{-2.2}$	$0.4^{+0.4}_{-0.4}$	$2.2^{+2.2}_{-1.8}$
ttH	$2.2^{+1.6}_{-1.3}$	-	$5.0^{+1.8}_{-1.7}$	$1.1^{+1.0}_{-1.0}$	$-1.9^{+3.7}_{-3.3}$
					$\chi^2_{\rm SM}$(subtot): 19.93

(KC, JS Lee, PY Tseng 1810.02521)

	Decay mode						
Production mode	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to bb$	$H \to \tau^+\tau^-$	$\mu^{\rm prod}_{\rm combined}$	$\chi^2_{\rm SM}(\chi^2_{\rm min})$
ggF	$1.02^{+0.12}_{-0.11}$	$1.09^{+0.11}_{-0.11}$	$1.29^{+0.16}_{-0.16}$	$2.51^{+2.43}_{-2.01}$	$1.06^{+0.40}_{-0.37}$	$1.11^{+0.07}_{-0.07}$	5.42(3.15)
VBF	$1.23^{+0.32}_{-0.31}$	$1.51^{+0.59}_{-0.59}$	$0.54^{+0.32}_{-0.31}$	-	$1.15^{+0.36}_{-0.34}$	$1.02^{+0.18}_{-0.18}$	7.53(7.51)
VH/WH	$1.42^{+0.51}_{-0.51}$	$0.71^{+0.65}_{-0.65}$	$3.27^{+1.88}_{-1.70}$	$1.07^{+0.23}_{-0.22}$	$3.39^{+1.68}_{-1.54}$	$1.15^{+0.20}_{-0.19}$	7.05(6.44)
ZH	-	-	$1.00^{+1.57}_{-1.00}$	$1.20^{+0.33}_{-0.31}$	$1.23^{+1.62}_{-1.35}$	$1.19^{+0.32}_{-0.30}$	0.45(0.02)
ttH	$1.36^{+0.38}_{-0.37}$	$0.00^{+0.53}_{-0.00}$	-	$0.91^{+0.45}_{-0.43}$	-	$0.93^{+0.24}_{-0.24}$	5.96(5.86)
ttH (excl.)	$1.39^{+0.48}_{-0.42}$	-	$1.59^{+0.44}_{-0.43}$	$0.77^{+0.36}_{-0.35}$	$0.87^{+0.73}_{-0.73}$	$1.16^{+0.22}_{-0.22}$	4.17(3.62)
$\mu^{\rm dec}_{\rm combined}$	$1.10^{+0.10}_{-0.10}$	$1.05^{+0.11}_{-0.11}$	$1.20^{+0.14}_{-0.13}$	$1.05^{+0.19}_{-0.19}$	$1.15^{+0.24}_{-0.23}$	$1.10^{+0.06}_{-0.06}$	
$\chi^2_{\rm SM}(\chi^2_{\rm min})$	6.83(5.72)	9.13(8.88)	9.48(7.32)	1.56(1.51)	3.58(3.20)		30.58(27.56)

Combined 13 TeV ATLAS and CMS — 2018

Overall average signal strength

TABLE II. Combined average signal strengths for the Tevatron at 1.96 TeV, and for ATLAS and CMS at $7+8$ TeV and 13 TeV.

Energy	ATLAS	CMS	Combined
1.96 TeV [Table VII]			1.44 ± 0.55
7+8 TeV [15]	$1.20^{+0.15}_{-0.14}$	$0.97^{+0.14}_{-0.13}$	$1.09^{+0.11}_{-0.10}$
13 TeV [Table I]	1.09 ± 0.08	$1.11^{+0.09}_{-0.08}$	1.10 ± 0.06
			1.10 ± 0.05

The SM Higgs boson provides a good description to the data in general, but the overall strength shows a 2σ deviation.

(KC, JS Lee, PY Tseng 1810.02521)

Parameterization

Higgs couplings to fermions:

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

Higgs couplings to the massive vector bosons:

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

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

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

Loop vertices

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

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

The theoretical signal strength may be written as the product

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

$$\widehat{\mu}(\mathrm{ggF}) = \frac{|S^g(M_H)|^2 + |P^g(M_H)|^2}{\left|S^g_{\mathrm{SM}}(M_H)\right|^2}\,,$$

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

$$\widehat{\mu}(\mathrm{VBF}) = g^2_{HWW,HZZ}\,,$$

$$B(H\to\mathcal{D}) = \frac{\Gamma(H\to\mathcal{D})}{\Gamma_{\mathrm{tot}}(H) + \Delta\Gamma_{\mathrm{tot}}}$$

$$\widehat{\mu}(\mathrm{VH}) = g^2_{HWW,HZZ}\,,$$

$$\widehat{\mu}(\mathrm{ttH}) = \left(g^S_{H\bar{t}t}\right)^2 + \left(g^P_{H\bar{t}t}\right)^2\,;$$

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

for Q : an experimental defined channel

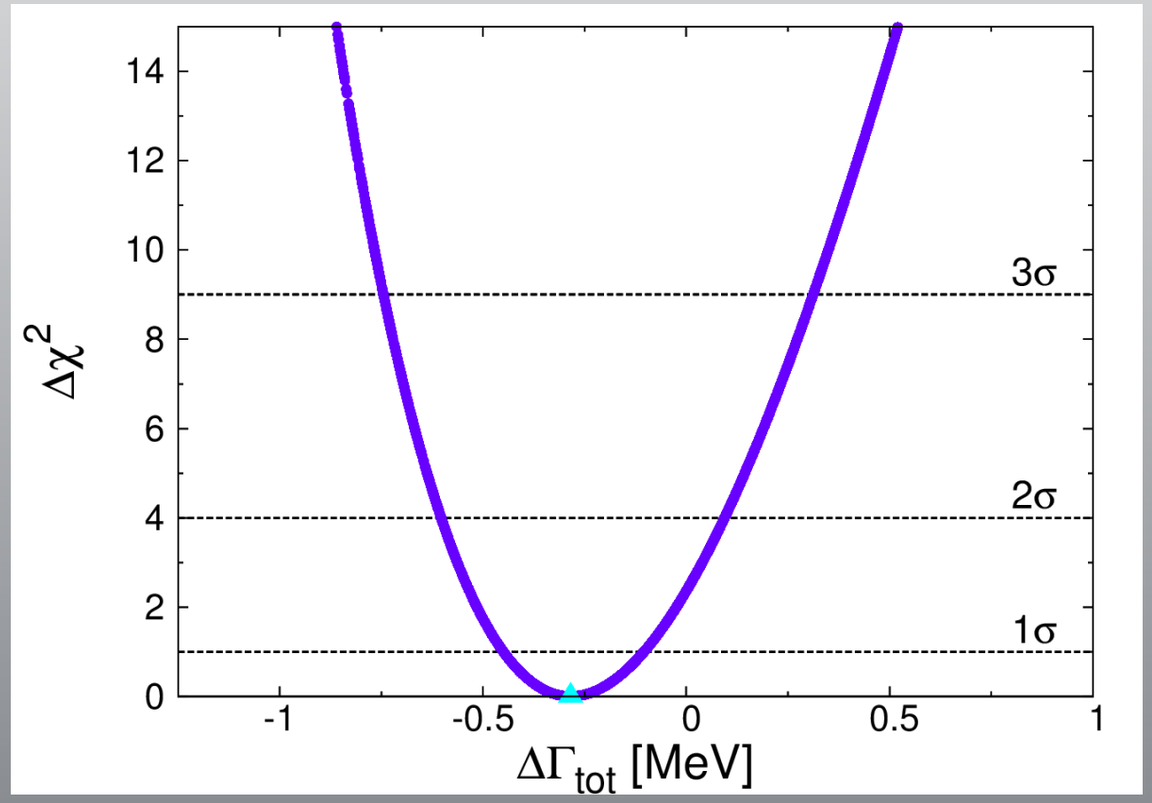
$$C^S_u = g^S_{H\bar{u}u}\,,\qquad C^S_d = g^S_{H\bar{d}d}\,,\qquad C^S_\ell = g^S_{H\bar{l}l}\,;\qquad C_w = g_{HWW}\,,\quad C_z = g_{HZZ}$$

$$C^P_u = g^P_{H\bar{u}u}\,,\qquad C^P_d = g^P_{H\bar{d}d}\,,\qquad C^P_\ell = g^P_{H\bar{l}l}\,.$$

CP Conserving Fits

Cases	**CPC1**	**CPC2**	**CPC3**	**CPC4**	**CPC6**
Parameters	Vary $\Delta\Gamma_{\rm tot}$	Vary ΔS^{γ} ΔS^{g}	Vary ΔS^{γ} ΔS^{g}, $\Delta\Gamma_{\rm tot}$	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}
After ICHEP 2018					
C_u^S	1	1	1	$1.001^{+0.056}_{-0.055}$	$1.033^{+0.079}_{-0.082}$
C_d^S	1	1	1	$0.962^{+0.101}_{-0.101}$	$0.945^{+0.109}_{-0.105}$
C_ℓ^S	1	1	1	$1.024^{+0.093}_{-0.093}$	$1.018^{+0.095}_{-0.094}$
C_v	1	1	1	$1.019^{+0.044}_{-0.045}$	$1.012^{+0.047}_{-0.048}$
ΔS^{γ}	0	$-0.226^{+0.32}_{-0.32}$	$-0.150^{+0.32}_{-0.33}$	0	$-0.128^{+0.368}_{-0.369}$
ΔS^{g}	0	$0.016^{+0.025}_{-0.025}$	$-0.003^{+0.034}_{-0.031}$	0	$-0.032^{+0.061}_{-0.057}$
$\Delta\Gamma_{\rm tot}$ (MeV)	$-0.285^{+0.18}_{-0.17}$	0	$-0.247^{+0.31}_{-0.27}$	0	0
χ^2/dof	51.44/63	51.87/62	51.23/61	50.79/60	50.46/58
goodness of fit	0.851	0.817	0.809	0.796	0.749
p-value	0.124	0.379	0.461	0.554	0.764

The most economical way to improve is to reduce the width (CPC1 fit)



$$\Delta\Gamma_{\rm tot} = -0.285\,^{+0.18}_{-0.17}\ \text{MeV}$$

or 7% decrease of total width

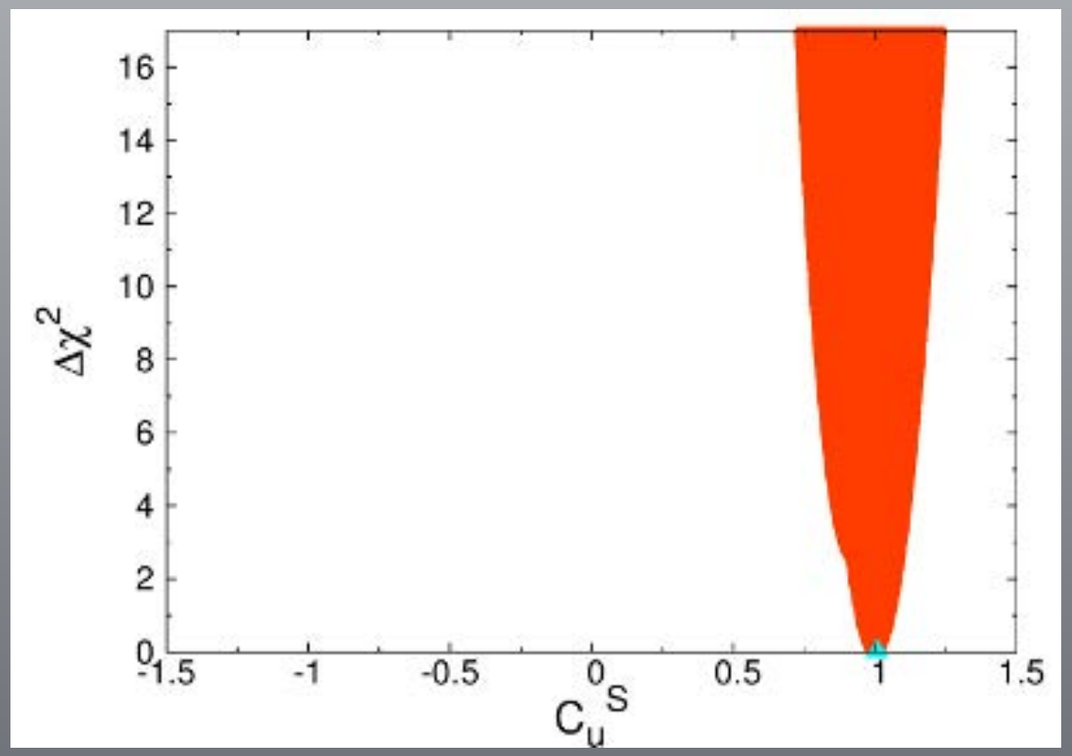
$$B(H \to \text{nonstandard}) < 8.4\%\,,$$

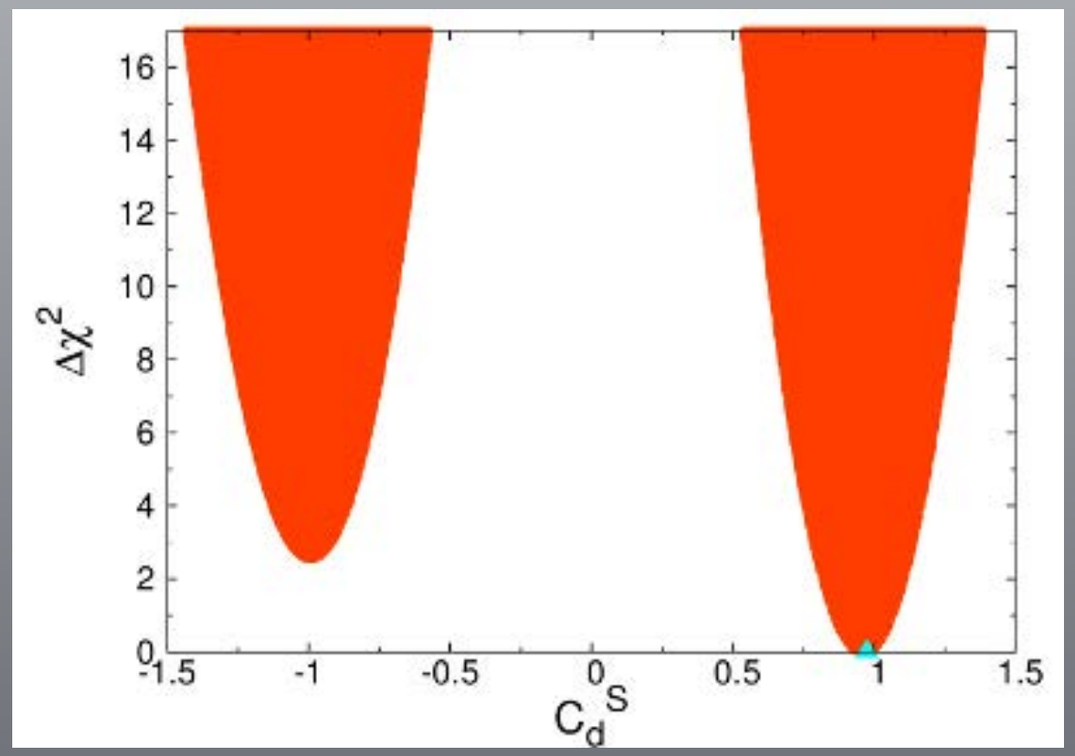
(KC, JS Lee, PY Tseng 1810.02521)

CPC4 fit :: only vary Yukawa's and C_v

Positive sign for bottom Yukawa for the first time thanks to the Hgg vertex

$$S^g \simeq 0.688\, g^S_{H\bar{t}t} + (-0.037 + 0.050\, i)\, g^S_{H\bar{b}b} + \Delta S^g \,,$$

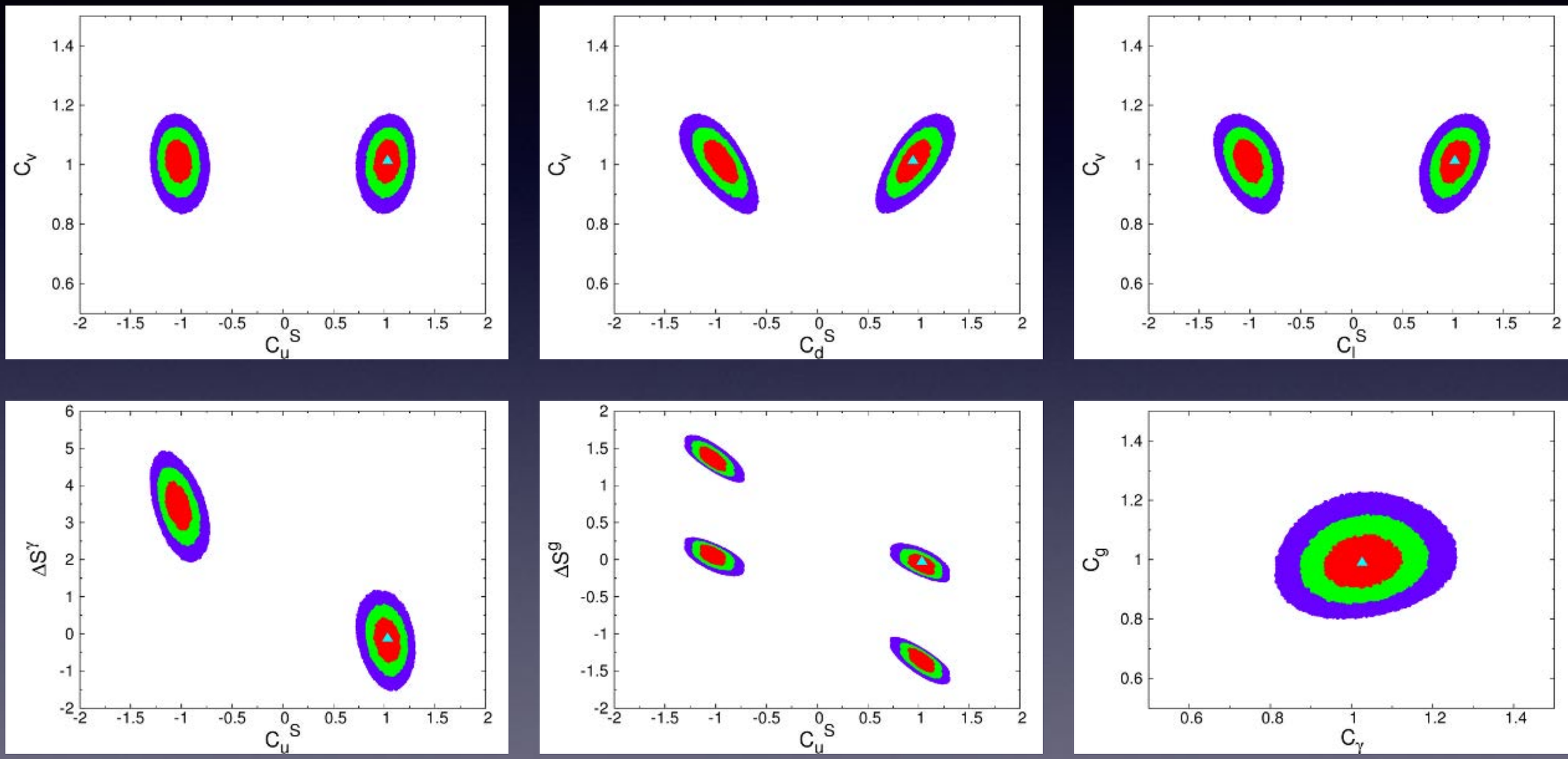




Positive sign of bottom Yukawa is preferred

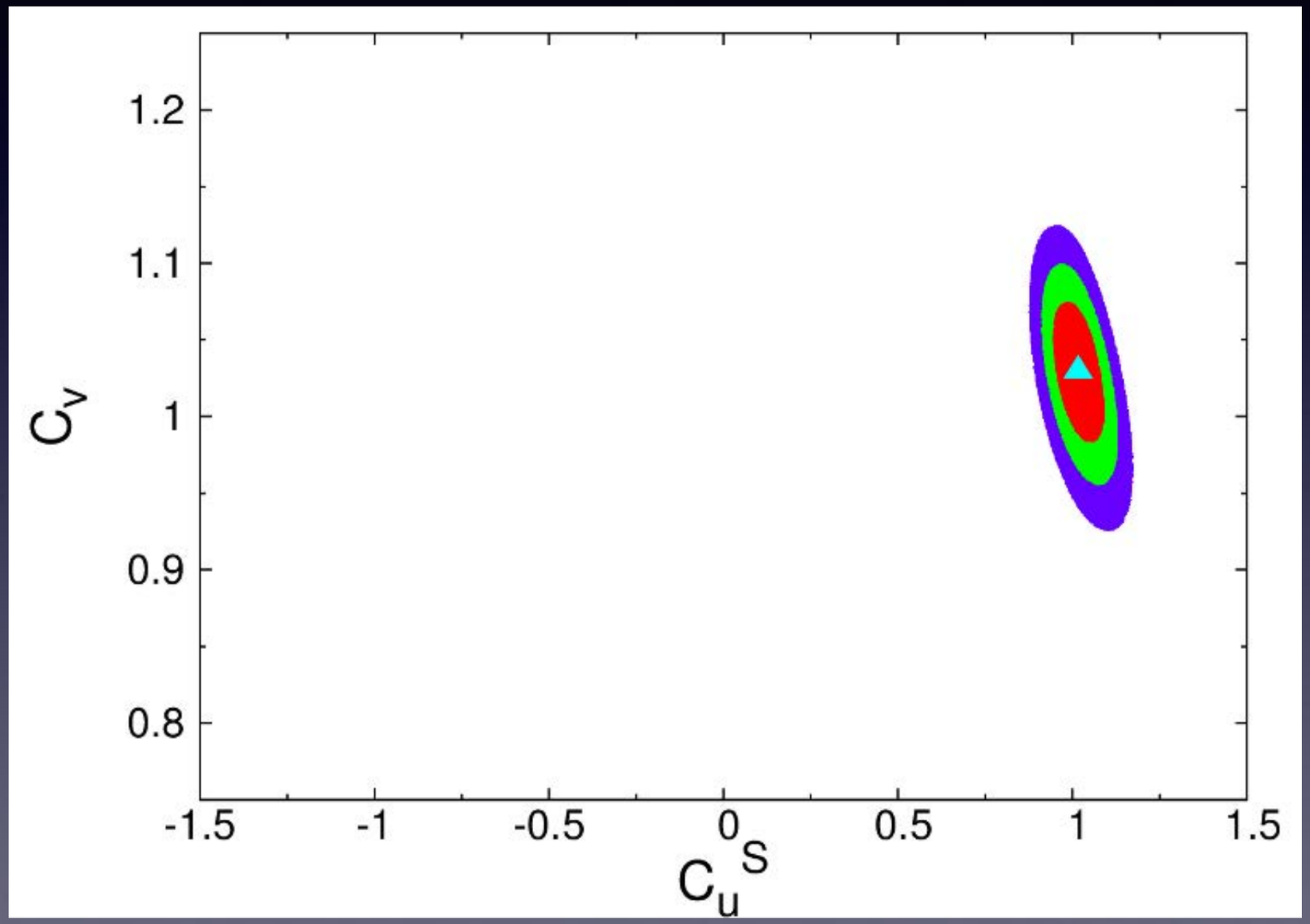
(KC, JS Lee, PY Tseng 1810.02521)

CPC6 : $C_u^S, C_d^S, C_\ell^S, C_v, \Delta S^\gamma, \Delta S^g$

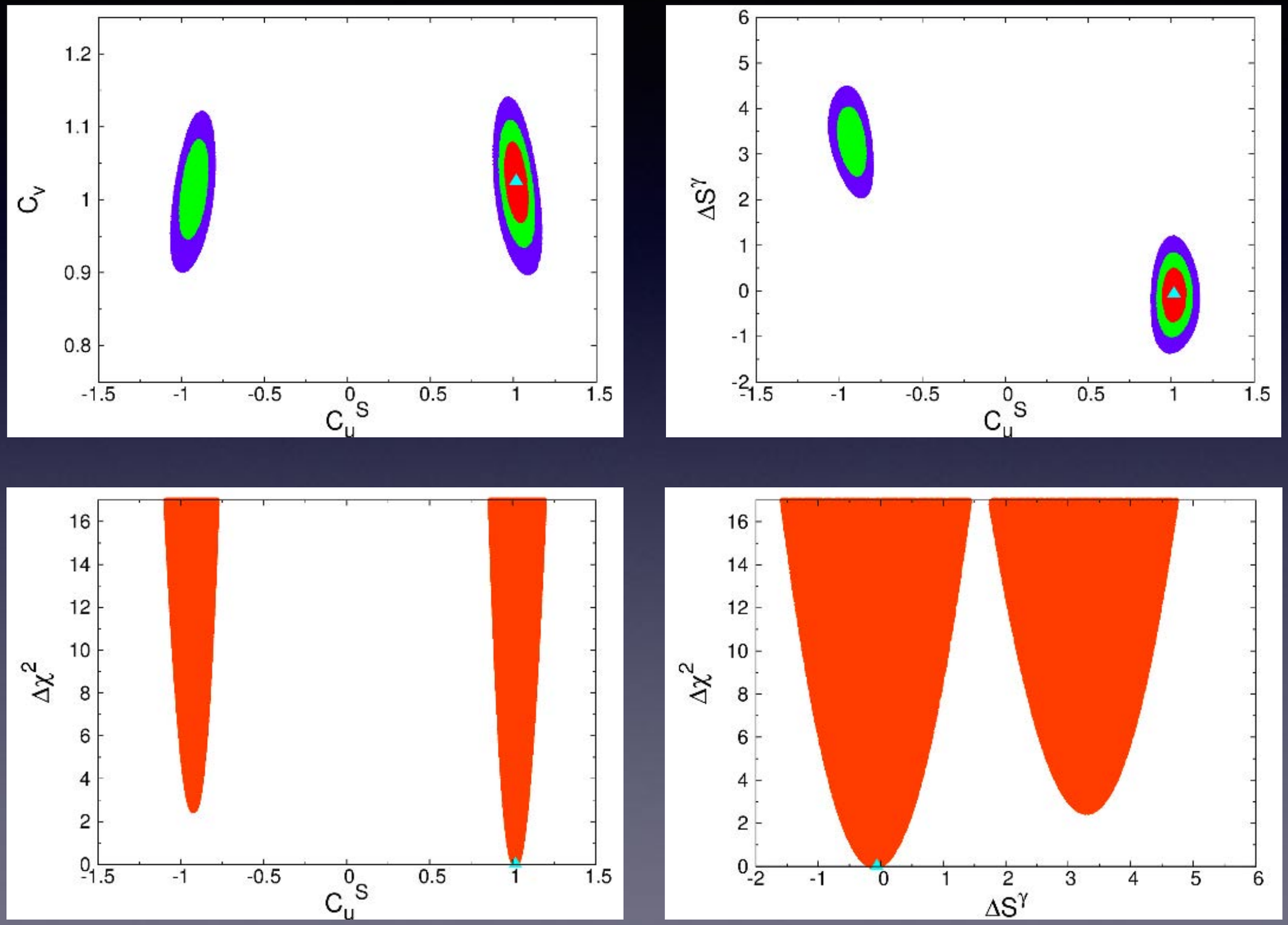


Cases	**CPCN2**	**CPCN3**	**CPCN4**			
Parameters	Vary C_u^S, C_v	Vary C_u^S, C_v ΔS^γ	Vary C_u^S, C_v ΔS^γ, ΔS^g			
After ICHEP 2018						
C_u^S	$1.017^{+0.039}_{-0.037}$	$1.016^{+0.039}_{-0.038}$	$1.042^{+0.077}_{-0.081}$	$1.042^{+0.078}_{-0.081}$	$-1.042^{+0.081}_{-0.078}$	$-1.042^{+0.081}_{-0.078}$
C_d^S	1	1	1	1	1	1
C_ℓ^S	1	1	1	1	1	1
C_v	$1.030^{+0.028}_{-0.028}$	$1.025^{+0.034}_{-0.035}$	$1.027^{+0.034}_{-0.036}$	$1.027^{+0.034}_{-0.036}$	$1.028^{+0.034}_{-0.036}$	$1.028^{+0.034}_{-0.036}$
ΔS^γ	0	$-0.090^{+0.36}_{-0.36}$	$-0.129^{+0.37}_{-0.37}$	$-0.129^{+0.37}_{-0.37}$	$3.524^{+0.41}_{-0.42}$	$3.523^{+0.41}_{-0.42}$
ΔS^g	0	0	$-0.021^{+0.057}_{-0.055}$	$-1.34^{+0.066}_{-0.065}$	$0.095^{+0.055}_{-0.057}$	$1.414^{+0.066}_{-0.066}$
$\Delta\Gamma_{\rm tot}$ (MeV)	0	0	0	0	0	0
χ^2/dof	51.16/62	51.10/61	50.96/60			
goodness of fit	0.835	0.813	0.791			
p-value	0.266	0.439	0.583			

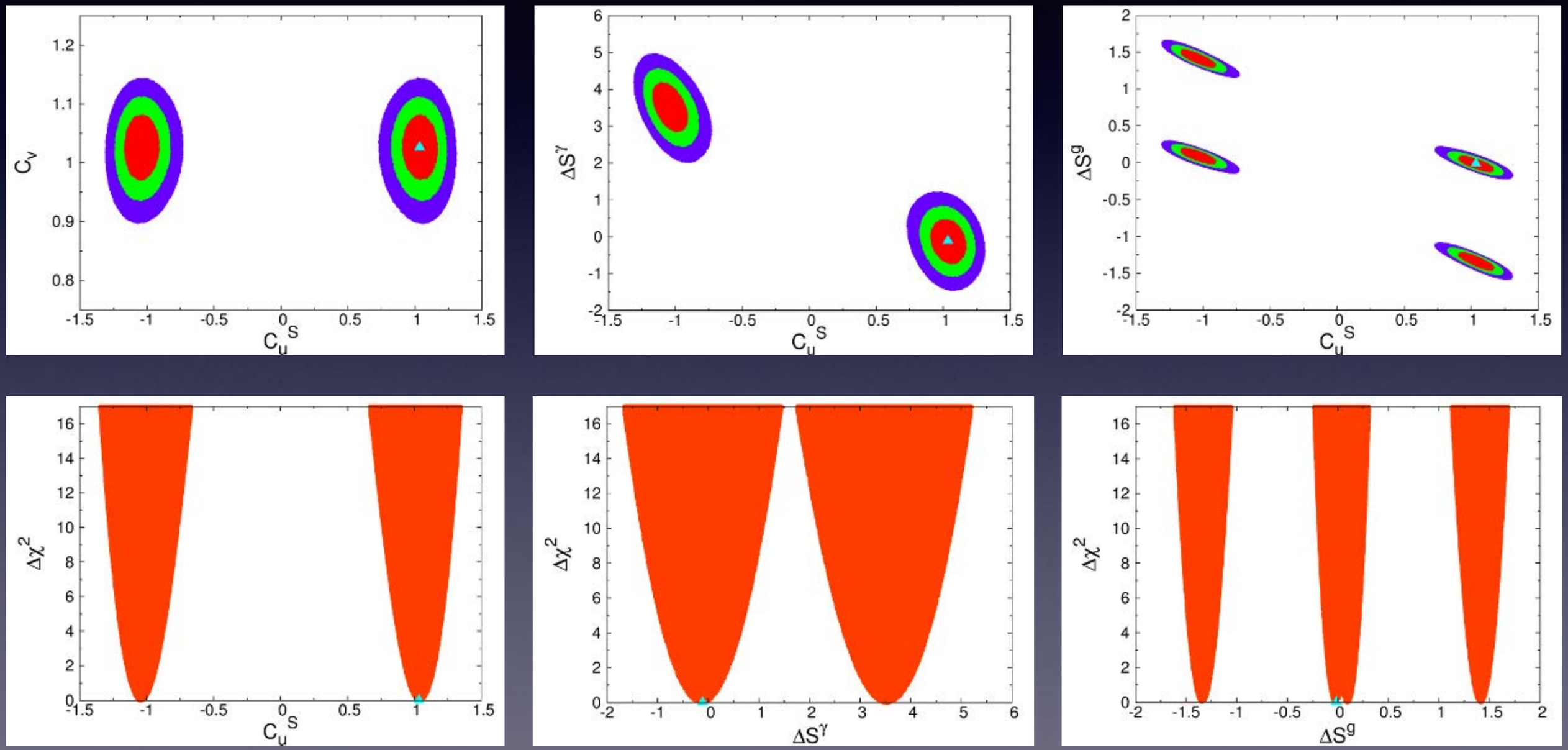
CPN2 - minimal : C_u^S, C_v



CPCN3 : $C_u^S, C_v, \Delta S^\gamma$

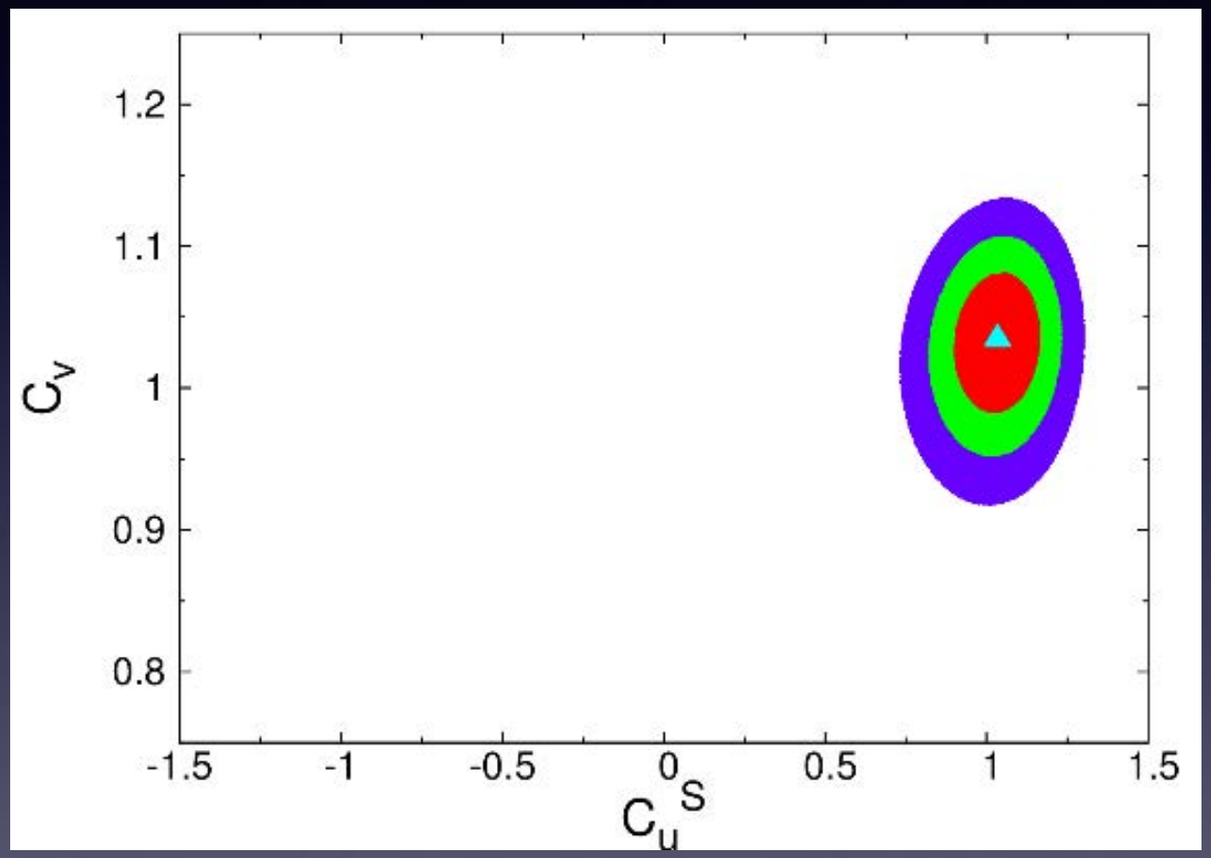


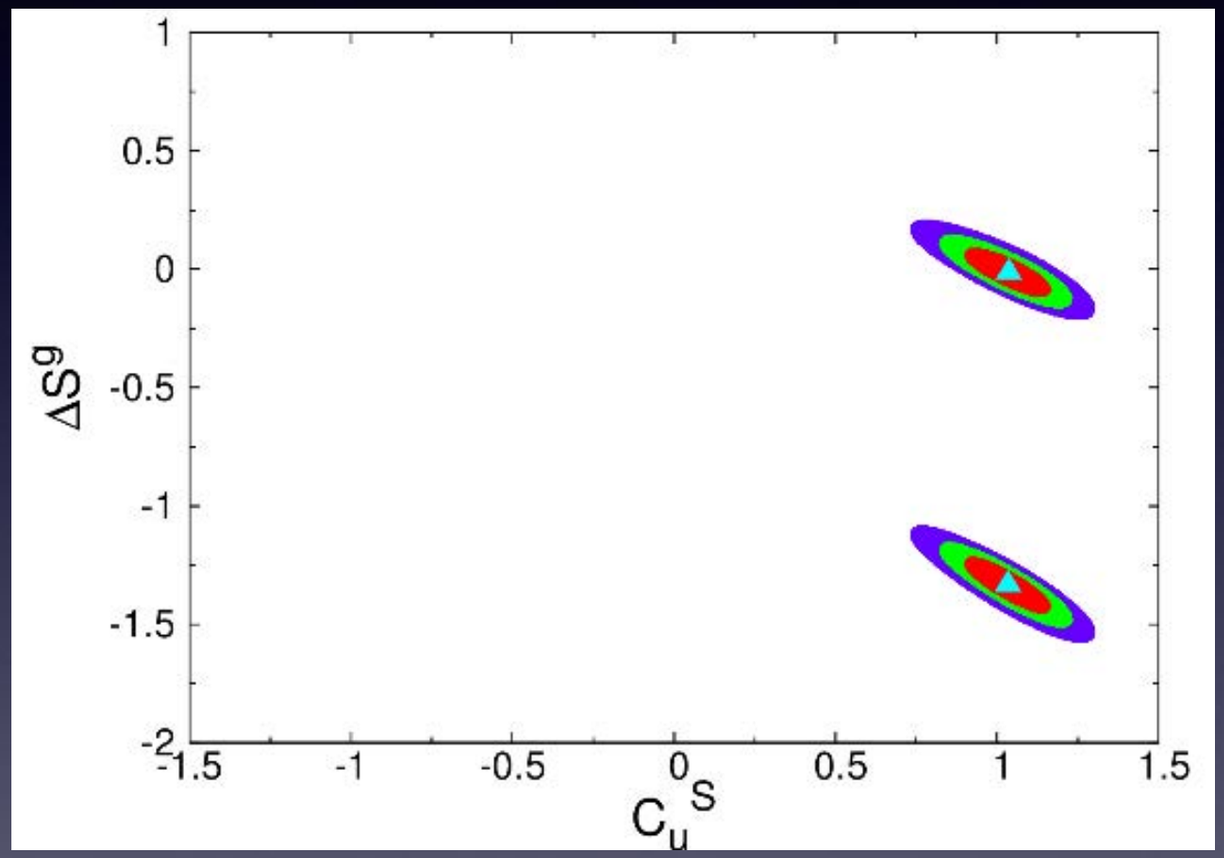
CPCN4 : $C_u^S, C_v, \Delta S^\gamma, \Delta S^g$



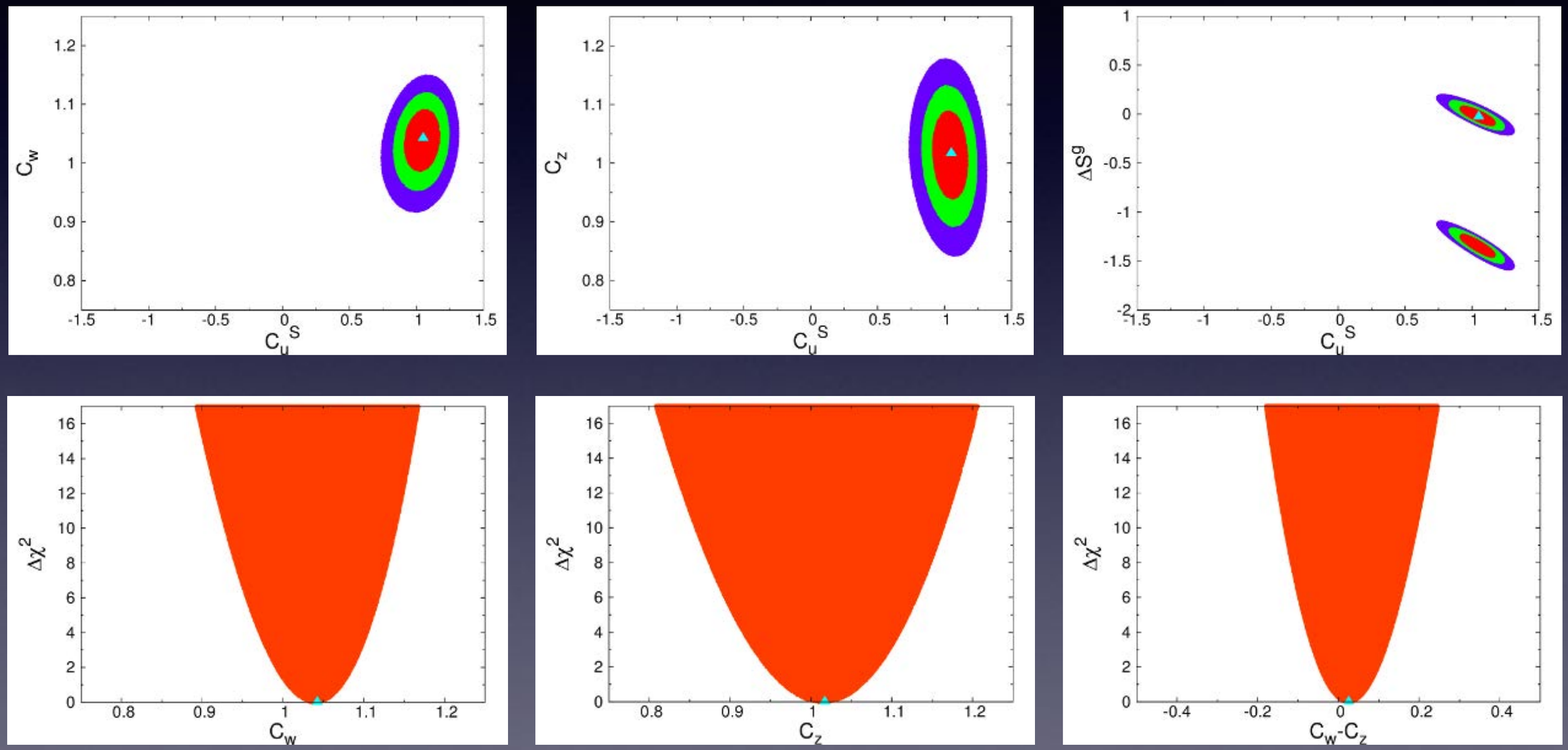
Cases	**CPCX2**	**CPCX3**		Cases	**CPCX4**	
Parameters	Vary $C_v, \Delta\Gamma_{\rm tot}$	Vary C_u^S, C_v ΔS^g		Parameters	Vary C_u^S, C_w C_z, ΔS^g	
After ICHEP 2018						
C_u^S	1	$1.04^{+0.08}_{-0.08}$	$1.04^{+0.08}_{-0.08}$	C_u^S	$1.045^{+0.078}_{-0.081}$	$1.045^{+0.078}_{-0.081}$
C_d^S	1	1	1	C_d^S	1	1
C_ℓ^S	1	1	1	C_ℓ^S	1	1
C_v	$1.020^{+0.051}_{-0.049}$	$1.03^{+0.03}_{-0.03}$	$1.03^{+0.03}_{-0.03}$	C_w	$1.040^{+0.033}_{-0.034}$	$1.040^{+0.032}_{-0.034}$
-				C_z	$1.015^{+0.048}_{-0.049}$	$1.015^{+0.048}_{-0.049}$
ΔS^γ	0	0	0	ΔS^γ	0	0
ΔS^g	0	$-0.02^{+0.06}_{-0.05}$	$-1.34^{+0.07}_{-0.06}$	ΔS^g	$-0.020^{+0.056}_{-0.054}$	$-1.345^{+0.067}_{-0.067}$
$\Delta\Gamma_{\rm tot}$ (MeV)	$-0.134^{+0.43}_{-0.36}$	0	0	$\Delta\Gamma_{\rm tot}$ (MeV)	0	0
χ^2/dof	51.25/62	51.08/61		χ^2/dof	50.84/60	
goodness of fit	0.833	0.813		goodness of fit	0.820	
p-value	0.278	0.435		p-value	0.5631	

CPCX3 : $C_u^S, C_v, \Delta S^g$





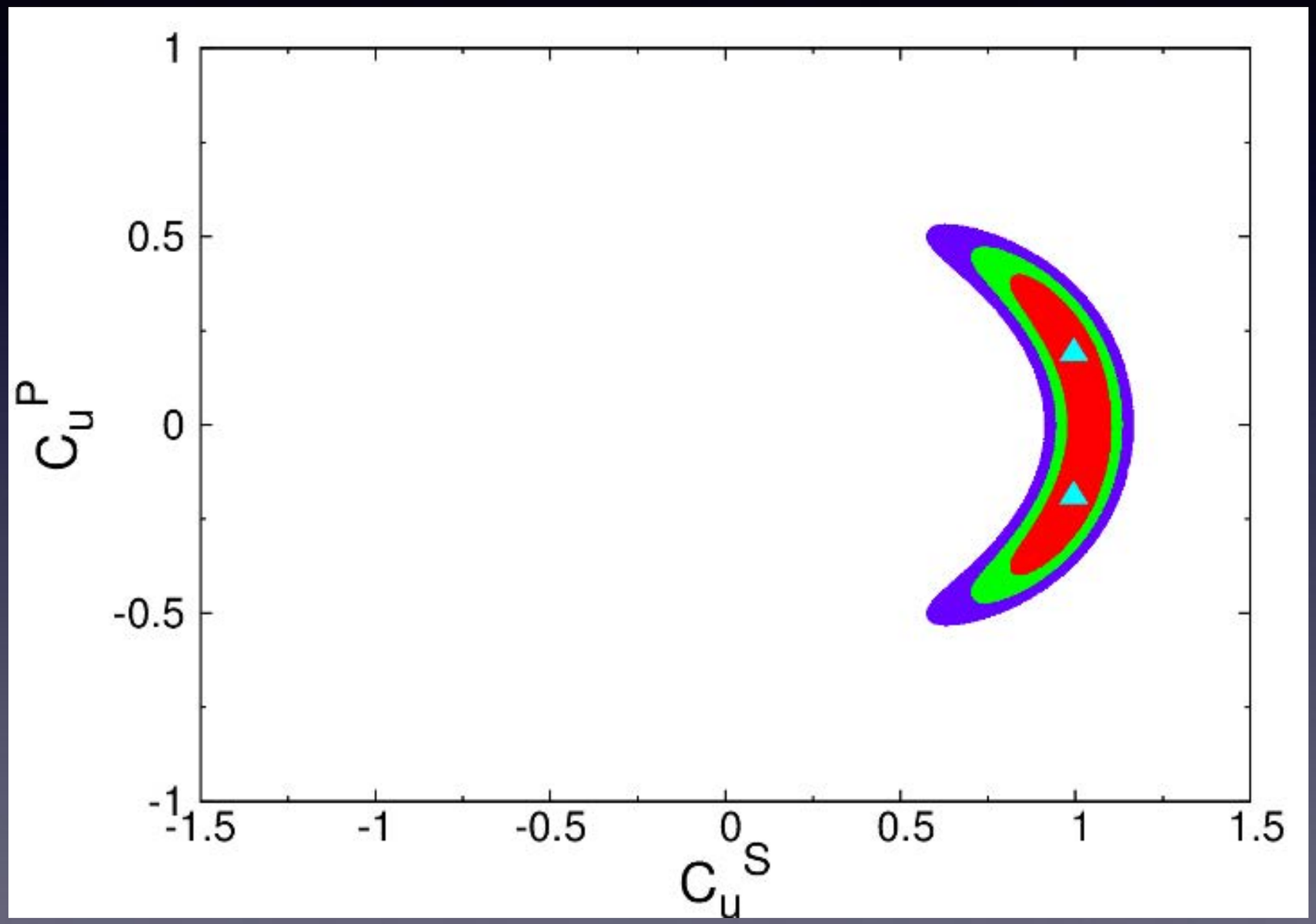
CPCX4 : $C_u^S, C_w, C_z, \Delta S^g$



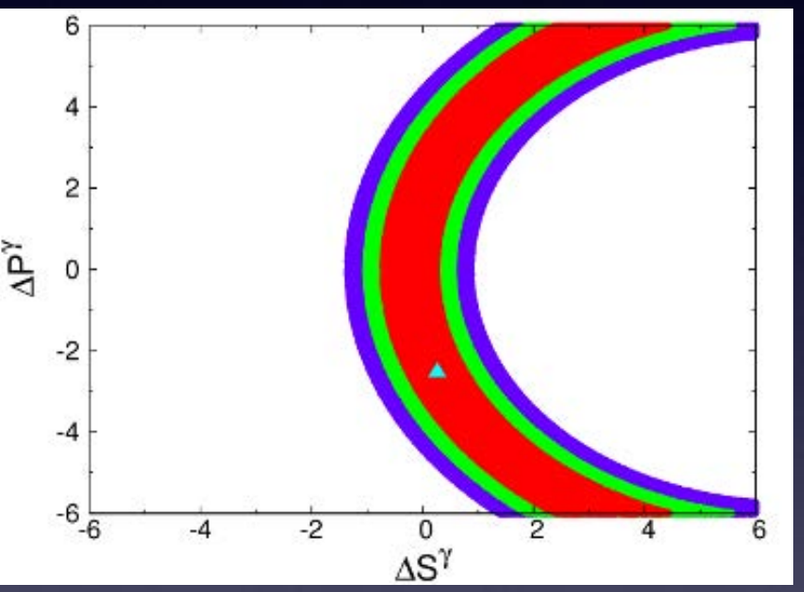
CP Violating Fits

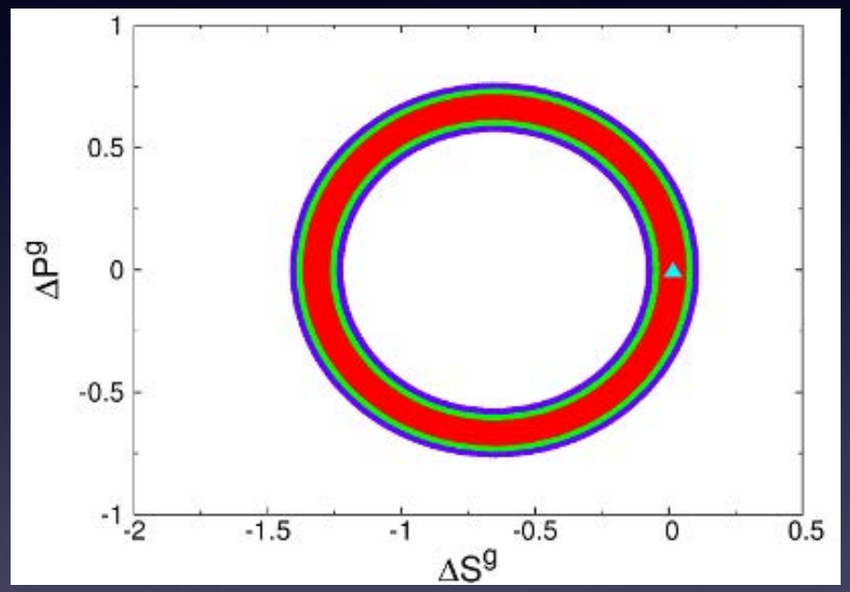
Cases	**CPV2**		**CPV3**	**CPV4**	**CPVN3**	
Parameters	Vary C_u^S, C_u^P		Vary C_u^S, C_u^P C_v	Vary $\Delta S^\gamma, \Delta S^g$ ΔP^γ, ΔP^g	Vary C_u^S, C_u^P $\Delta\Gamma_{\rm tot}$	
After ICHEP 2018						
C_u^S	$1.00^{+0.07}_{-0.11}$	$1.00^{+0.07}_{-0.11}$	$1.02^{+0.04}_{-0.10}$	1	$0.99^{+0.07}_{-0.10}$	$0.99^{+0.07}_{-0.10}$
C_d^S	1	1	1	1	1	1
C_ℓ^S	1	1	1	1	1	1
C_v	1	1	$1.03^{+0.03}_{-0.03}$	1	1	1
ΔS^γ	0	0	0	$0.26^{+13.56}_{-0.81}$	0	0
ΔS^g	0	0	0	$0.016^{+0.025}_{-}$	0	0
$\Delta\Gamma_{\rm tot}$ (MeV)	0	0	0	0	$-0.27^{+0.34}_{-0.28}$	$-0.27^{+0.34}_{-0.28}$
C_u^P	$0.19^{+0.14}_{-0.52}$	$-0.19^{+0.52}_{-0.14}$	$0.00^{+0.28}_{-0.28}$	0	$0.11^{+0.19}_{-0.41}$	$-0.11^{+0.41}_{-0.19}$
ΔP^γ	0	0	0	$-2.54^{+9.72}_{-4.65}$	0	0
ΔP^g	0	0	0	$0.00^{+0.69}_{-0.69}$	0	0
χ^2/dof	52.07/62		51.16/61	51.87/60	51.42/61	
goodness of fit	0.812		0.811	0.763	0.804	
p-value	0.419		0.449	0.747	0.495	

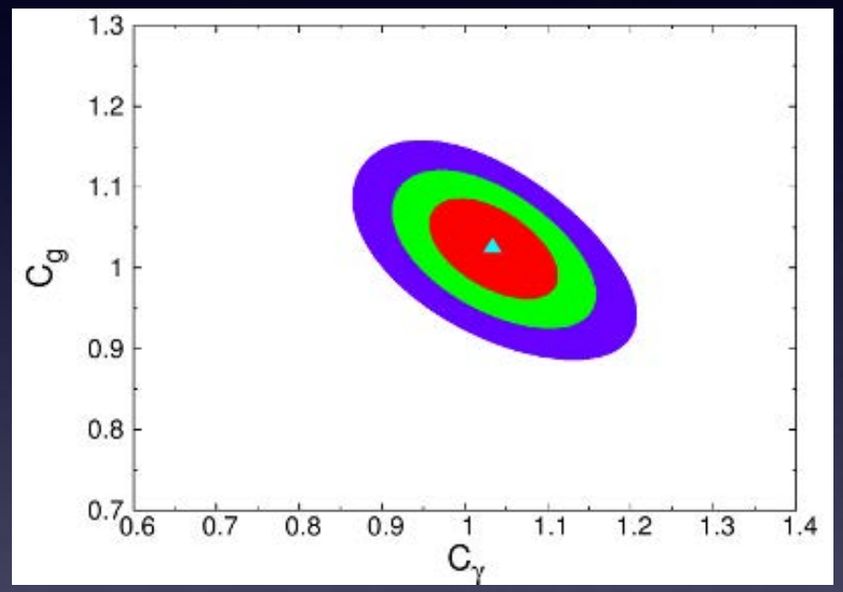
CPV2 : C_u^S, C_u^P



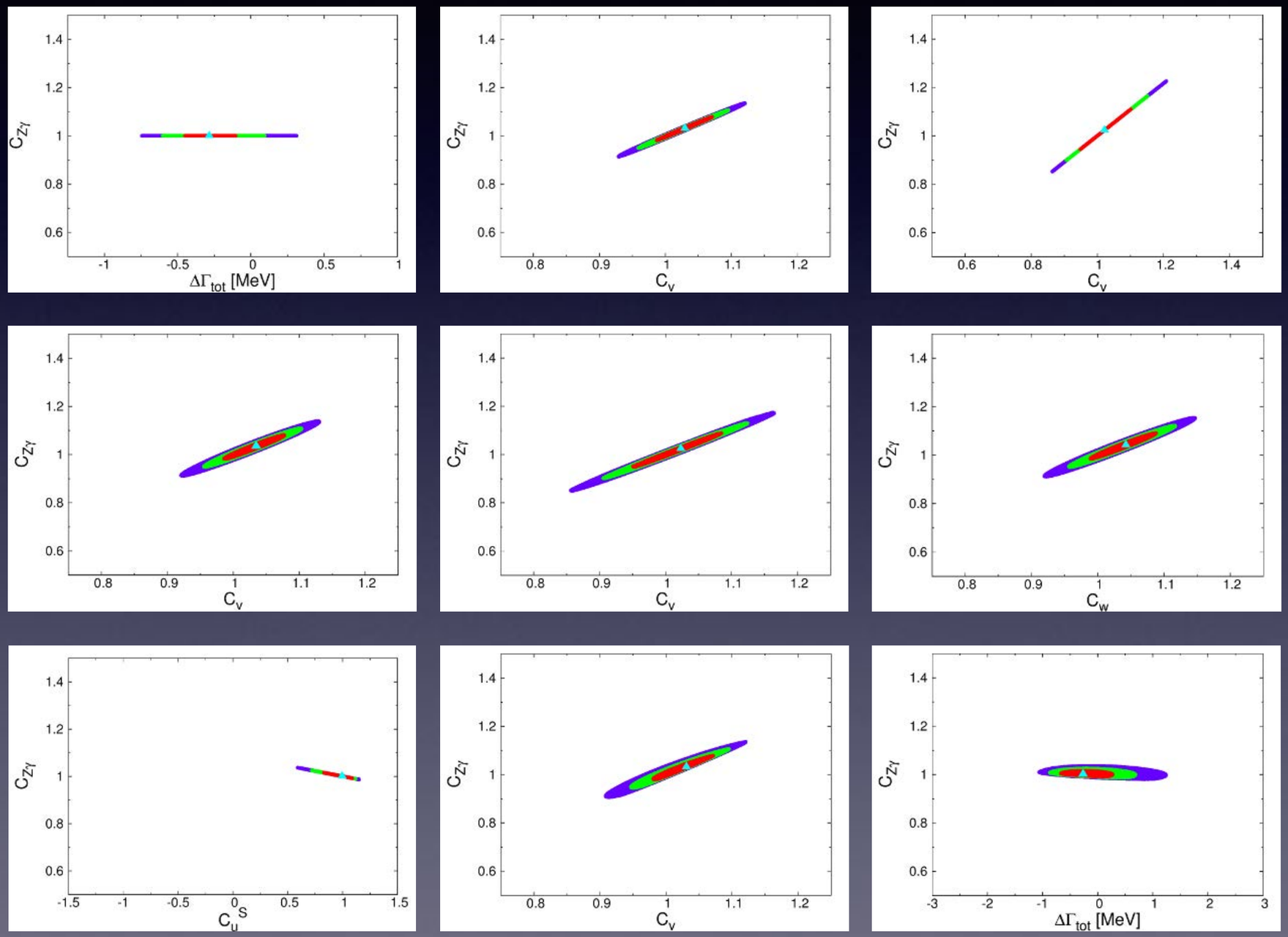
CPV4 : $\Delta S^{\gamma}, \Delta P^{\gamma}, \Delta S^{g}, \Delta P^{g}$







Predictions of Z gamma in CPC's : at most ±20%



- Most scenarios (fits) are consistent with the SM with p-value ≥ 0.3, except for CPC1.
- CPC1 has a p-value of 0.124.
- So the most economical way to improve the fit is by reducing the decay width of the Higgs.

Vector-like Quark Interpretation of Excess in Higgs Signal Strength

Kingman Cheung[1,2,3,4], Wai-Yee Keung[5,1], Jae Sik Lee[6,7], and Po-Yan Tseng[8,1]

* 2σ excess comes from a large collection of data, not so easy to go away overnight.
* One of the most economic way to improve the fit is to reduce the total width.
* The first to consider is H —> b b-bar mode.
* This is done via mixing between b quark with a b′ from a doublet of hypercharge Y/2 = -5/6.

Introduce a vector-like quark doublet with Y/2 = -5/6

$$\mathcal{B}_{L,R} = \begin{pmatrix} b'^{-\frac{1}{3}} \\ p'^{-\frac{4}{3}} \end{pmatrix}_{L,R} , \quad \left(\frac{Y}{2}\right)_{\mathcal{B}} = -\frac{5}{6} .$$

New coupling with the Higgs doublet H

$$\mathcal{L} \supset g_{\mathcal{B}} \overline{\mathcal{B}_L} \widetilde{H} b_R + \text{ h.c. } = g_{\mathcal{B}} (\overline{b'_L} \ , \ \overline{p'_L} \ ) \begin{pmatrix} -\frac{1}{\sqrt{2}}(v+h) \\ H^- \end{pmatrix} b_R + \text{ h.c. } ,$$

Quark mass matrix and interactions with the Higgs

$$\mathcal{L}_Y \supset -(\overline{b_L} \ , \ \overline{b'_L} \ ) \begin{pmatrix} m(1+\frac{h}{v}) & 0 \\ \frac{g_{\mathcal{B}} v}{\sqrt{2}}(1+\frac{h}{v}) & M \end{pmatrix} \begin{pmatrix} b_R \\ b'_R \end{pmatrix} + \text{ h.c.}$$

(KC, WY Keung, JS Lee, PY Tseng 1901.05626)

(KC, WY Keung, JS Lee, PY Tseng 1901.05626)

Rotate into Mass Eigenstates

$$\begin{pmatrix} b \\ b' \end{pmatrix}_{L.R} = \begin{pmatrix} \cos\theta_{L,R} & \sin\theta_{L,R} \\ -\sin\theta_{L,R} & \cos\theta_{L,R} \end{pmatrix} \begin{pmatrix} b \\ b' \end{pmatrix}^{m}_{L.R}$$

M, $\Delta = g_B v/\sqrt{2} \gg m$

$$m_1^2 = \frac{m^2}{1+\frac{\Delta^2}{M^2}}, \qquad m_2^2 = \Delta^2 + M^2 . \qquad \delta \equiv \Delta/M$$

$$\sin\theta_L \equiv s_L \simeq \frac{m\Delta}{M^2+\Delta^2} \qquad \cos\theta_L \equiv c_L \simeq 1 - \frac{1}{2}\left(\frac{m\Delta}{M^2+\Delta^2}\right)^2$$

$$\sin\theta_R \equiv s_R \simeq \frac{\Delta}{\sqrt{M^2+\Delta^2}}, \qquad \cos\theta_R \equiv c_R \simeq \frac{M}{\sqrt{M^2+\Delta^2}} .$$

With the hierarchy $\cos\theta_L = 1$, $\theta_R \gg \theta_L$

(KC, WY Keung, JS Lee, PY Tseng 1901.05626)

Modification to Yukawa couplings

$$\mathcal{L}_Y \supset -\frac{h}{v}\,(\overline{b_L^m}\ ,\ \overline{b_L'^m}\ )\begin{pmatrix} m_b(1+\delta^2)^{-1/2}c_R & m_b(1+\delta^2)^{-1/2}s_R \\ \Delta c_R & \Delta s_R \end{pmatrix}\begin{pmatrix} b_R^m \\ b_R'^m \end{pmatrix} + H.c.$$

Reduction to bottom Yukawa $C_b \equiv c_R/\sqrt{1+\delta^2}$

Modifications to Zbb couplings

$$-\mathcal{L} \supset g_Z(\overline{b_L^m}\ ,\ \overline{b_L'^m}\ )\gamma^\mu Z_\mu \begin{pmatrix} -\frac{1}{2}(c_L^2-s_L^2)+\frac{1}{3}x_w & -c_L s_L \\ -c_L s_L & \frac{1}{2}(c_L^2-s_L^2)+\frac{1}{3}x_w \end{pmatrix}\begin{pmatrix} b_L^m \\ b_L'^m \end{pmatrix}$$

$$+\, g_Z(\overline{b_R^m}\ ,\ \overline{b_R'^m}\ )\gamma^\mu Z_\mu \begin{pmatrix} \frac{1}{2}s_R^2+\frac{1}{3}x_w & -\frac{1}{2}c_R s_R \\ -\frac{1}{2}c_R s_R & \frac{1}{2}c_R^2+\frac{1}{3}x_w \end{pmatrix}\begin{pmatrix} b_R^m \\ b_R'^m \end{pmatrix}.$$

Left-handed modification is small: $s_L^2/2$

Right-handed modification is large: $s_R^2/2$

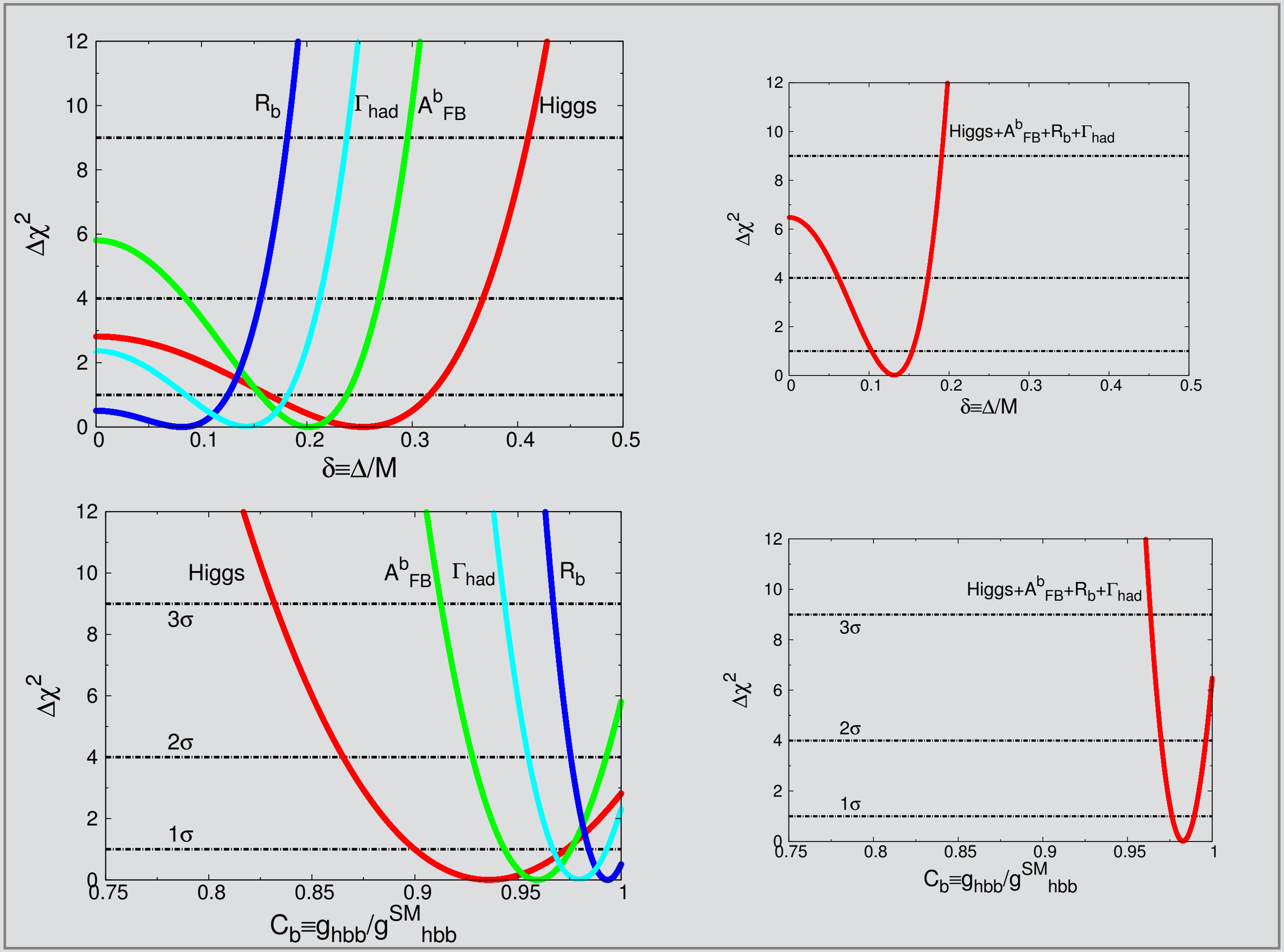
Such a modification brings changes to

- reduction in Higgs total width
- Z boson total hadronic width
- A_{BF}(b quark)
- R_b

$$\mathcal{A}^b_{FB} = \frac{3}{4} \times \frac{(-\frac{1}{2}+x_w)^2 - x_w^2}{(-\frac{1}{2}+x_w)^2 + x_w^2} \times \frac{(-\frac{1}{2}(c_L^2 - s_L^2) + \frac{1}{3}x_w)^2 - (\frac{1}{2}s_R^2 + \frac{1}{3}x_w)^2}{(-\frac{1}{2}(c_L^2 - s_L^2) + \frac{1}{3}x_w)^2 + (\frac{1}{2}s_R^2 + \frac{1}{3}x_w)^2}$$

Experimental Data	SM values	χ^2(SM)
Higgs-signal strengths with the average		
$\mu_{\rm Higgs} = 1.10 \pm 0.05$	$\mu^{\rm SM} = 1.00$	53.81 [11]
$(\mathcal{A}^b_{\rm FB})^{\rm EXP} = 0.0992 \pm 0.0016$	0.1030 ± 0.0002	5.29 [27]
$R_b^{\rm EXP} = 0.21629 \pm 0.00066$	0.21582 ± 0.00002	0.49 [27]
$\Gamma_{\rm had} = 1.7444 \pm 0.0020$ GeV	1.7411 ± 0.0008	2.35 [27]

(KC, WY Keung, JS Lee, PY Tseng 1901.05626)


R_b
Γ_{had}
A^b_{FB}
Higgs
$\Delta\chi^2$
$\delta \equiv \Delta/M$
Higgs+A^b_{FB}+R_b+Γ_{had}
$C_b \equiv g_{hbb}/g^{SM}_{hbb}$
3σ
2σ
1σ

Cases	v	Fit-I	Fit-II
data	Higgs+$\left(\mathcal{A}^b_{\rm FB}\right)^{\rm EXP}$ $+R_b^{\rm EXP}+\Gamma_{\rm had}$	Higgs+$\left(\mathcal{A}^b_{\rm FB}\right)^{\rm EXP}$	Higgs+ $\left(\mathcal{A}^b_{\rm FB}\right)^{\rm EXP}$ $+R_b^{\rm EXP}+\Gamma_{\rm had}$
x_w	0.23154	$0.23109^{+0.00076}_{-0.00082}$	$0.23202^{+0.00031}_{-0.00031}$
$\delta\equiv\Delta/M$	$0.132^{+0.022}_{-0.028}$	$0.253^{+0.063}_{-0.090}$	$0.115^{+0.037}_{-0.027}$
$C_b\equiv g_{hbb}/g^{\rm SM}_{hbb}$	$0.9826^{+0.0066}_{-0.0063}$	$0.936^{+0.037}_{-0.036}$	$0.9868^{+0.0055}_{-0.0099}$
$\chi^2_{\rm Higgs}$	52.53	50.99	52.80
$\mathcal{A}^b_{\rm FB}$	0.10144	0.09922	0.09918
R_b	0.21708	0.22082	0.21677
$\Gamma_{\rm had}$[GeV]	1.7439	1.7523	1.7432
$\chi^2_{\rm total}$	55.88	113.6	53.68

delta =Δ/M = g_Bv/(√2 M)= 0.1 - 0.2, m_2=1-2 TeV

$$\Gamma(b'\to bh)=\left(\frac{\Delta}{v}\right)^2\frac{M_{b'}}{32\pi}\,c_R^2\left(1-\frac{m_h^2}{M_{b'}^2}\right)^2$$

$$\Gamma(b'\to bZ)=\left(\frac{\Delta}{v}\right)^2\frac{M_{b'}}{32\pi}\left(1+\frac{2m_Z^2}{M_{b'}^2}\right)\left(1-\frac{m_Z^2}{M_{b'}^2}\right)^2$$

$$b'\overline{b'}\to(bX)(\bar{b}Z)\to(bX)(\bar{b}\ell^+\ell^-)$$

X = h, Z

Current search in ATLAS

1806.10555

With Z->l+l- and >2 j $\mathcal{L} = 36.1\ \mathrm{fb}^{-1}$ $\epsilon = 0.28\%$

$$b'\overline{b'} \to (bX)(\bar{b}Z) \to (bX)(\bar{b}\ell^+\ell^-)$$

$$N = \sigma(pp \to b'\overline{b'}) \times \mathcal{L} \times \epsilon$$

Requiring N < 2 $\sigma(pp \to b'\overline{b'}) \lesssim 20\ \mathrm{fb}$

$$M_{b'} \gtrsim 1.1\ \mathrm{TeV}$$

Further searches in b'b' -> (bh)(bh), (bZ)(bZ), (bh)(bZ) are possible

Conclusions

- Higgs couplings enter the era of precision measurements
- Third generation fermion couplings are established
- The global signal strength shows a 2-sigma excess.
- The most economical way to improve the fit — reduce the Higgs —> b b-bar width.
- The other scenarios are consistent with the SM with p-values ≥ 0.3.

Back up Slides

Higgs Pair Production
Probing HHH coupling

Higgs Sector Itself

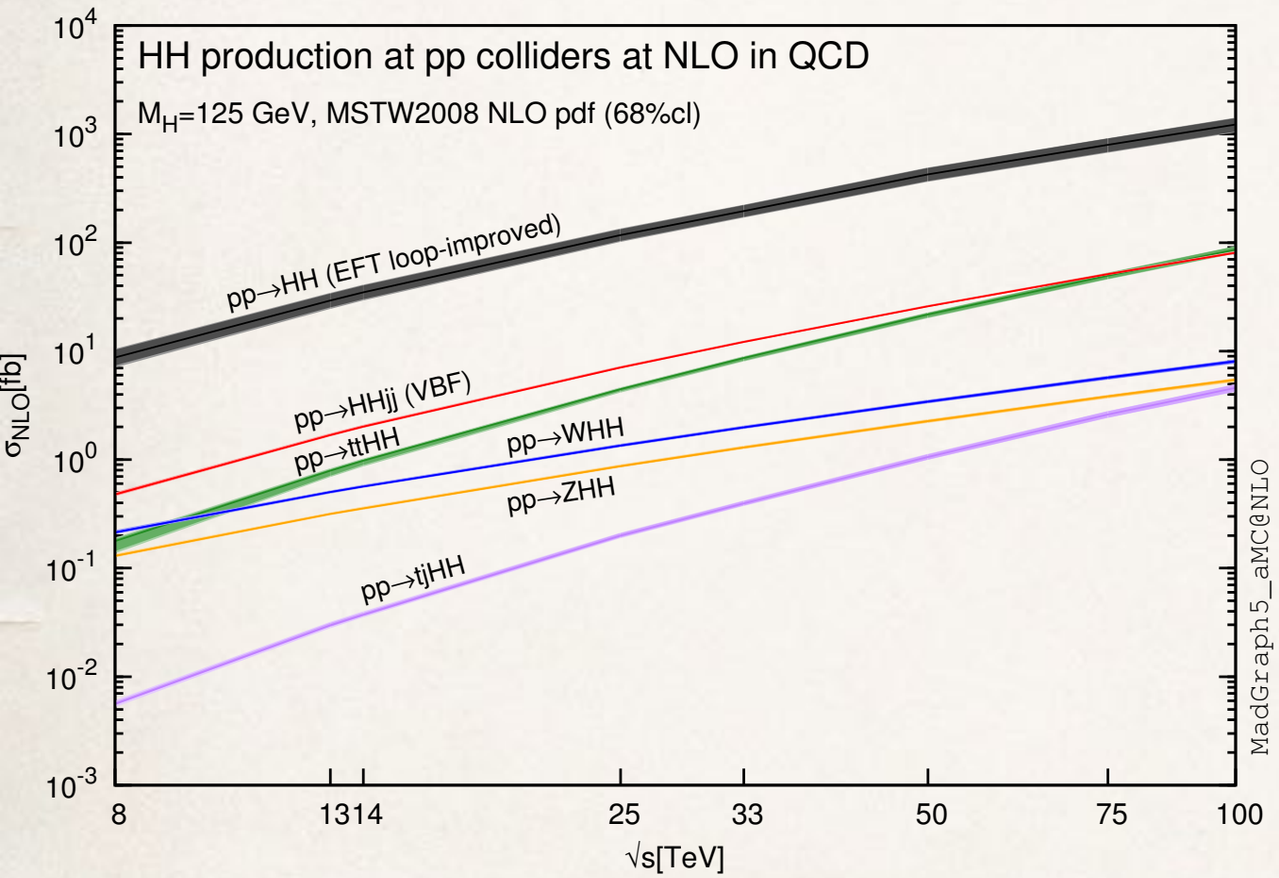
We have no information about $V(\Phi)$ except that it gives a nontrivial VEV. In the SM,

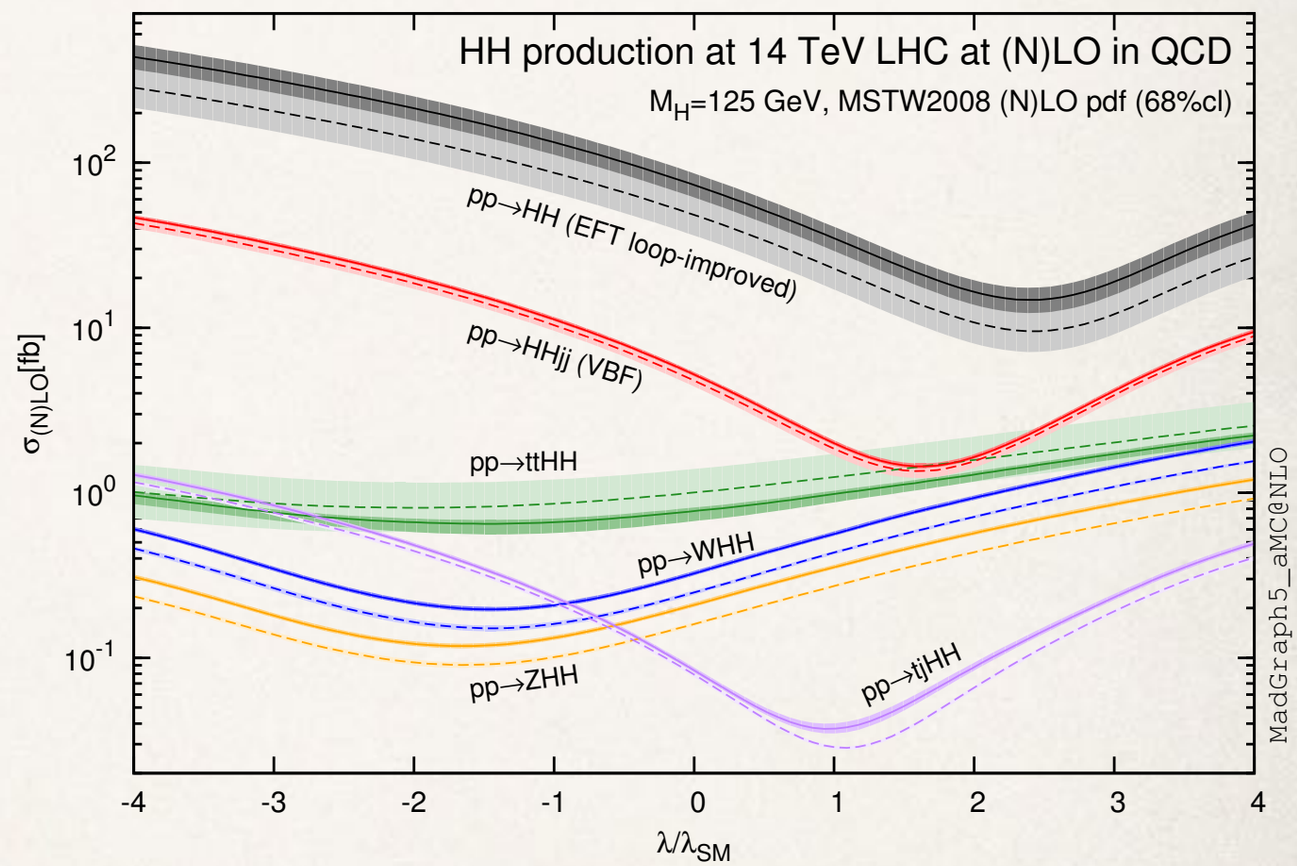
$$V(\phi) = -\frac{\lambda}{4}v^4 + \frac{1}{2}m_H^2 H^2 + \frac{m_H^2}{2v}H^3 + \frac{\lambda}{4}H^4$$

This is the simplest structure. The self couplings are fixed. But for extended Higgs sector it is not the case.

Probing self interactions of the Higgs boson becomes an important avenue to understand the Higgs sector.

Channels for testing HHH coupling

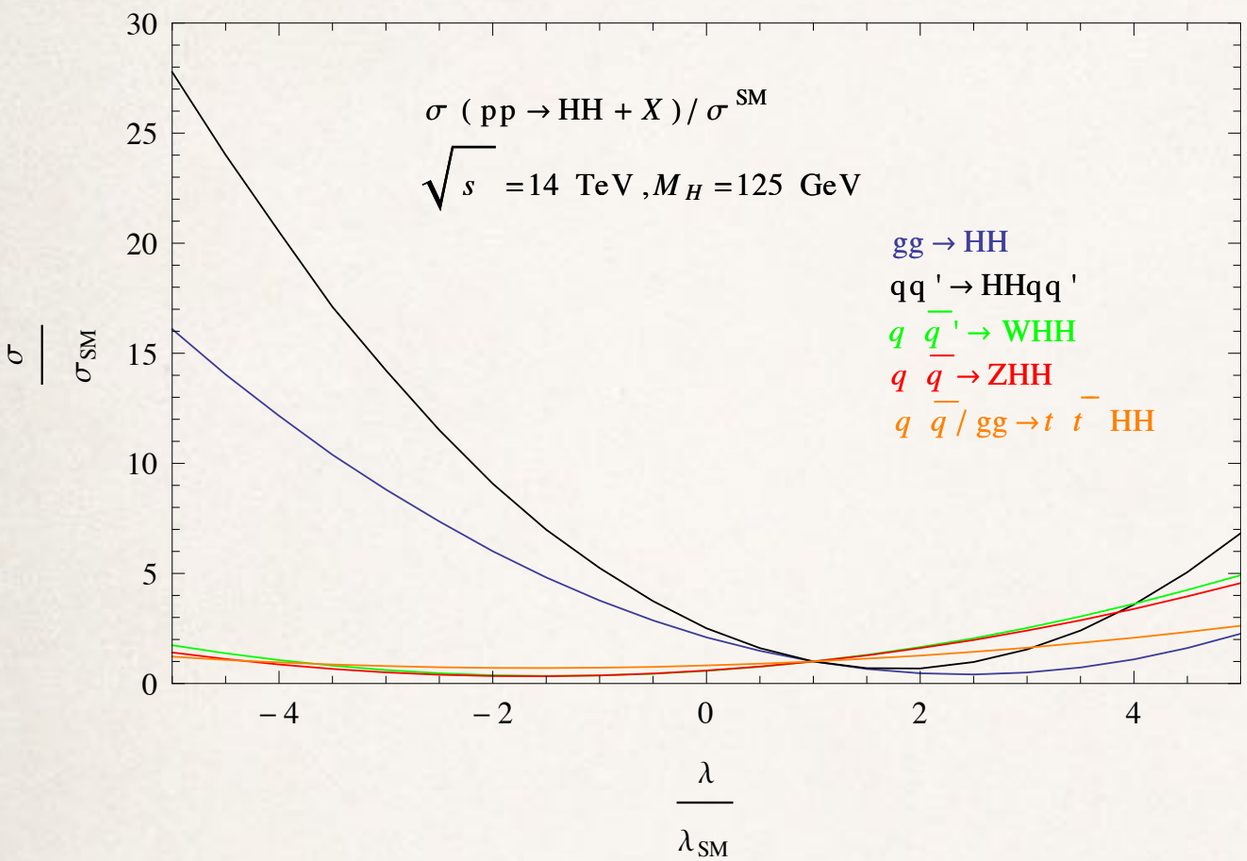


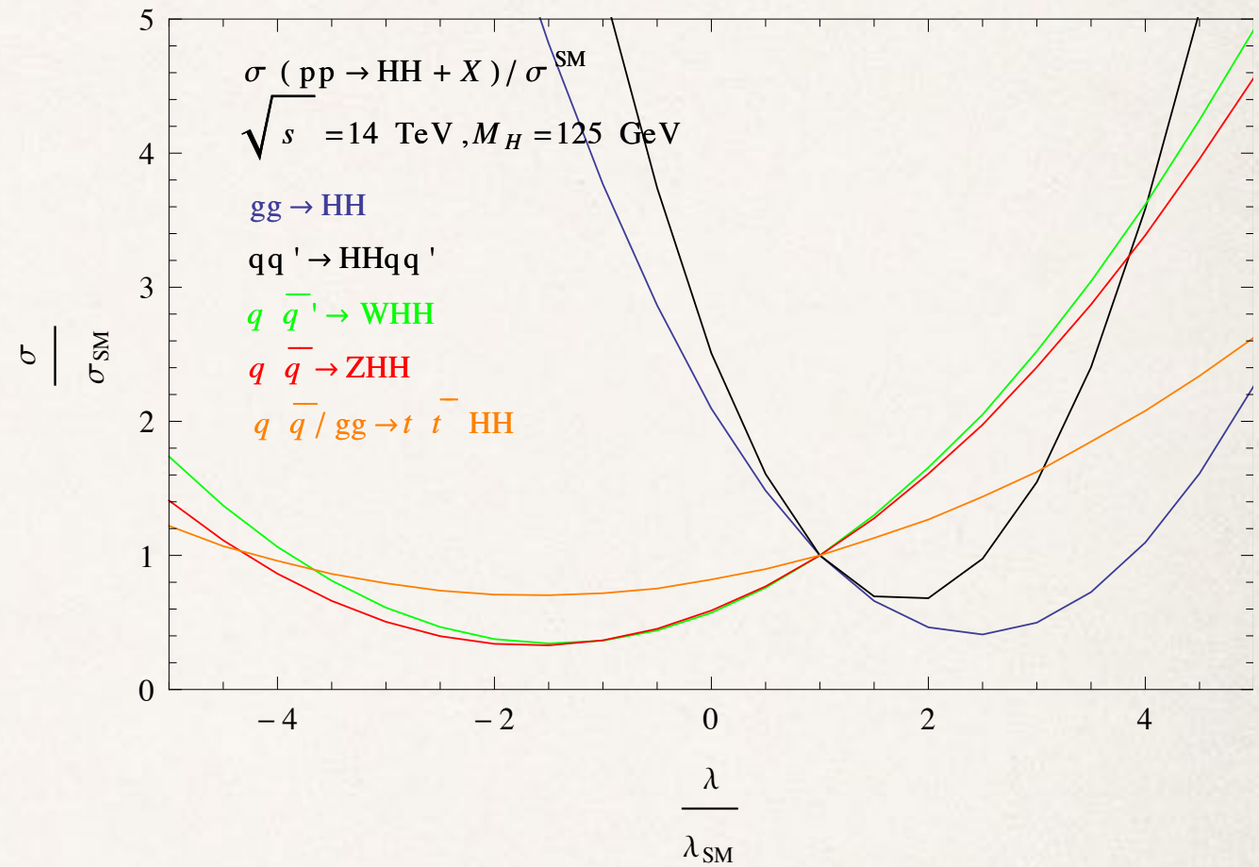


Frederix et al. 1401.7340

SM Cross sections [4]

$\sqrt{s}$ [TeV]	$\sigma^{\mathrm{NLO}}_{gg\to HH}$ [fb]	$\sigma^{\mathrm{NLO}}_{qq'\to HHqq'}$ [fb]	$\sigma^{\mathrm{NNLO}}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\mathrm{NNLO}}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\mathrm{LO}}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82





The ggF has the largest cross section, of order 10 - O(100) fb.

The VBF has the best sensitivity to Lambda_3H, but the cross section is one order smaller.

ggF Higgs pair production

Jung Chang, KC, Jae Sik Lee, Chih-Ting Lu, Jubin Park

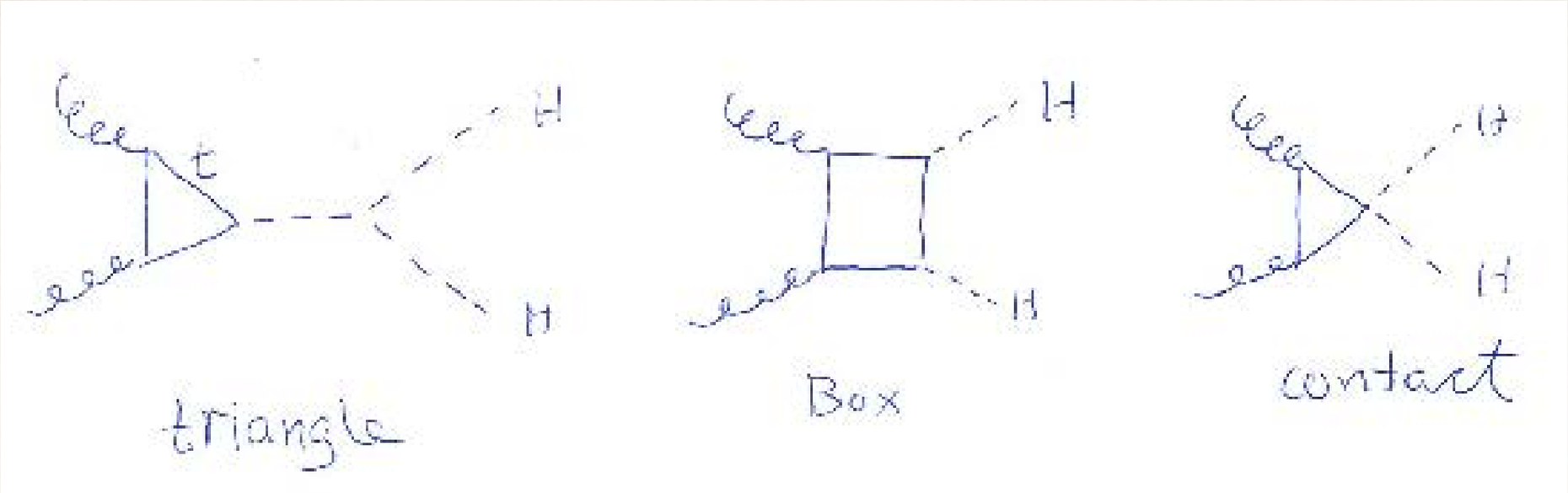
- Interactions:

$$-\mathcal{L} = \frac{1}{3!}\left(\frac{3M_H^2}{v}\right)\lambda_{3H}\,H^3 + \frac{m_t}{v}\,\bar{t}\left(g_t^S + i\gamma_5 g_t^P\right)t\,H + \frac{1}{2}\frac{m_t}{v^2}\bar{t}\left(g_{tt}^S + i\gamma_5 g_{tt}^P\right)t\,H^2$$

- In the SM, $\lambda_{3H} = g_t^S = 1$ and $g_t^P = 0$ and $g_{tt}^{S,P} = 0$.
- The SM result:

$$\frac{d\hat{\sigma}(gg \to HH)}{d\hat{t}} = \frac{G_F^2\alpha_s^2}{512(2\pi)^3}\left[\left|\lambda_{3H}\,g_t^S\,D(\hat{s})F_\triangle^S + (g_t^S)^2 F_\square^{SS}\right|^2 + \left|(g_t^S)^2 G_\square^{SS}\right|^2\right]$$

where $D(\hat{s}) = \frac{3M_H^2}{\hat{s} - M_H^2 + iM_H\Gamma_H}$.



Production cross section normalized to the SM one is

$$
\begin{aligned}
\frac{\sigma(gg \to HH)}{\sigma_{\rm SM}(gg \to HH)} \quad = \quad & \lambda_{3H}^2 \left[c_1(s)(g_t^S)^2 + d_1(s)(g_t^P)^2 \right] + \lambda_{3H} g_t^S \left[c_2(s)(g_t^S)^2 + d_2(s)(g_t^P)^2 \right] \\
& + \left[c_3(s)(g_t^S)^4 + d_3(s)(g_t^S)^2(g_t^P)^2 + d_4(s)(g_t^P)^4 \right] \\
& + \lambda_{3H} \left[e_1(s) g_t^S g_{tt}^S + f_1(s) g_t^P g_{tt}^P \right] + g_{tt}^S \left[e_2(s)(g_t^S)^2 + f_2(s)(g_t^P)^2 \right] \\
& + \left[e_3(s)(g_{tt}^S)^2 + f_3(s) g_t^S g_t^P g_{tt}^P + f_4(s)(g_{tt}^P)^2 \right]
\end{aligned}
$$

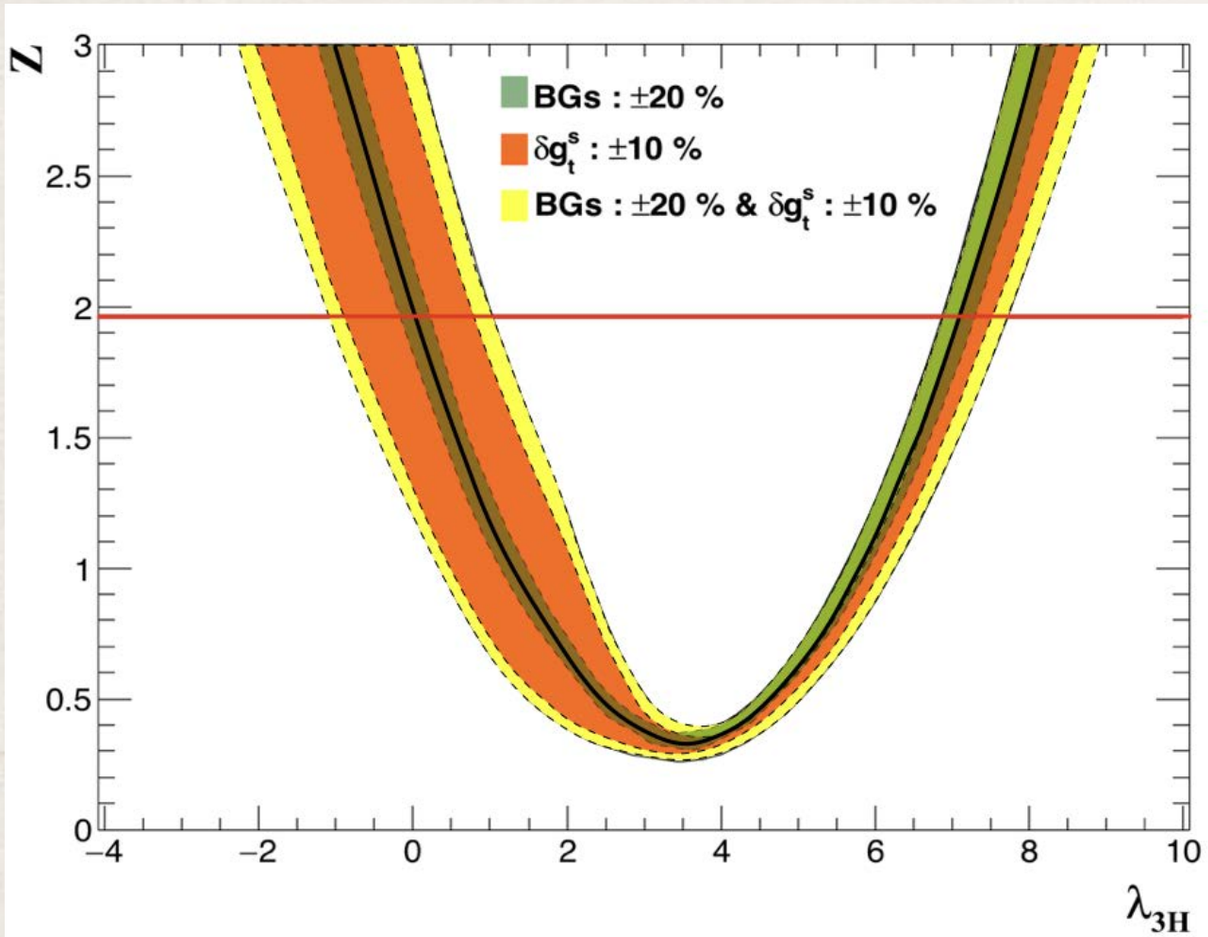
Decay channels:

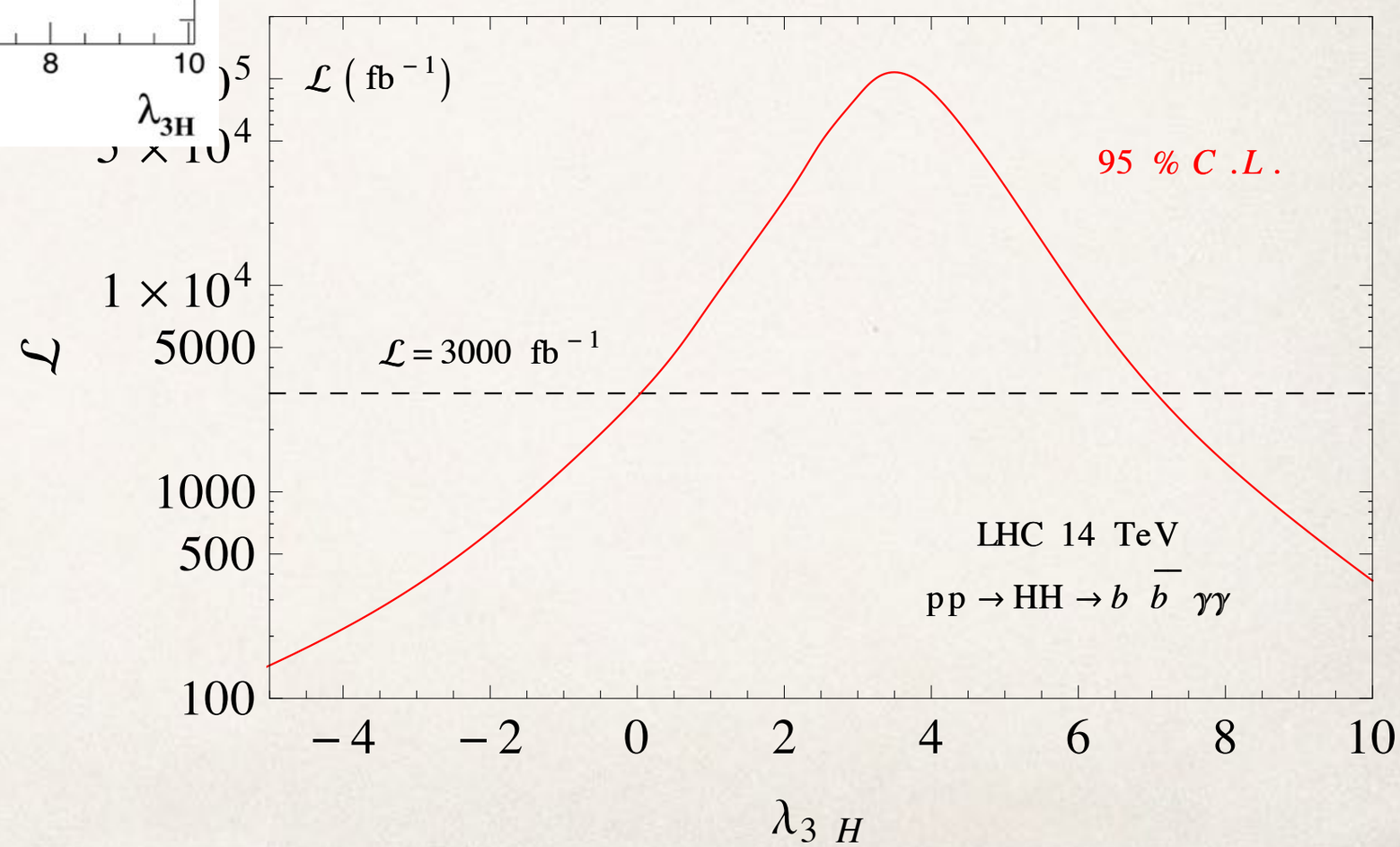
Decay channels	$HH \to bb\gamma\gamma$	$HH \to bb\tau\tau$	$HH \to bbWW$	$HH \to bbbb$	$\cdots$
Branching ratios	0.263%	7.29%	24.8%	33.3%	

Due to background consideration and clean HH reconstruction we focus on $HH \to bb\gamma\gamma$

To some extent other modes should be considered to increase the significance of the already-small signal.

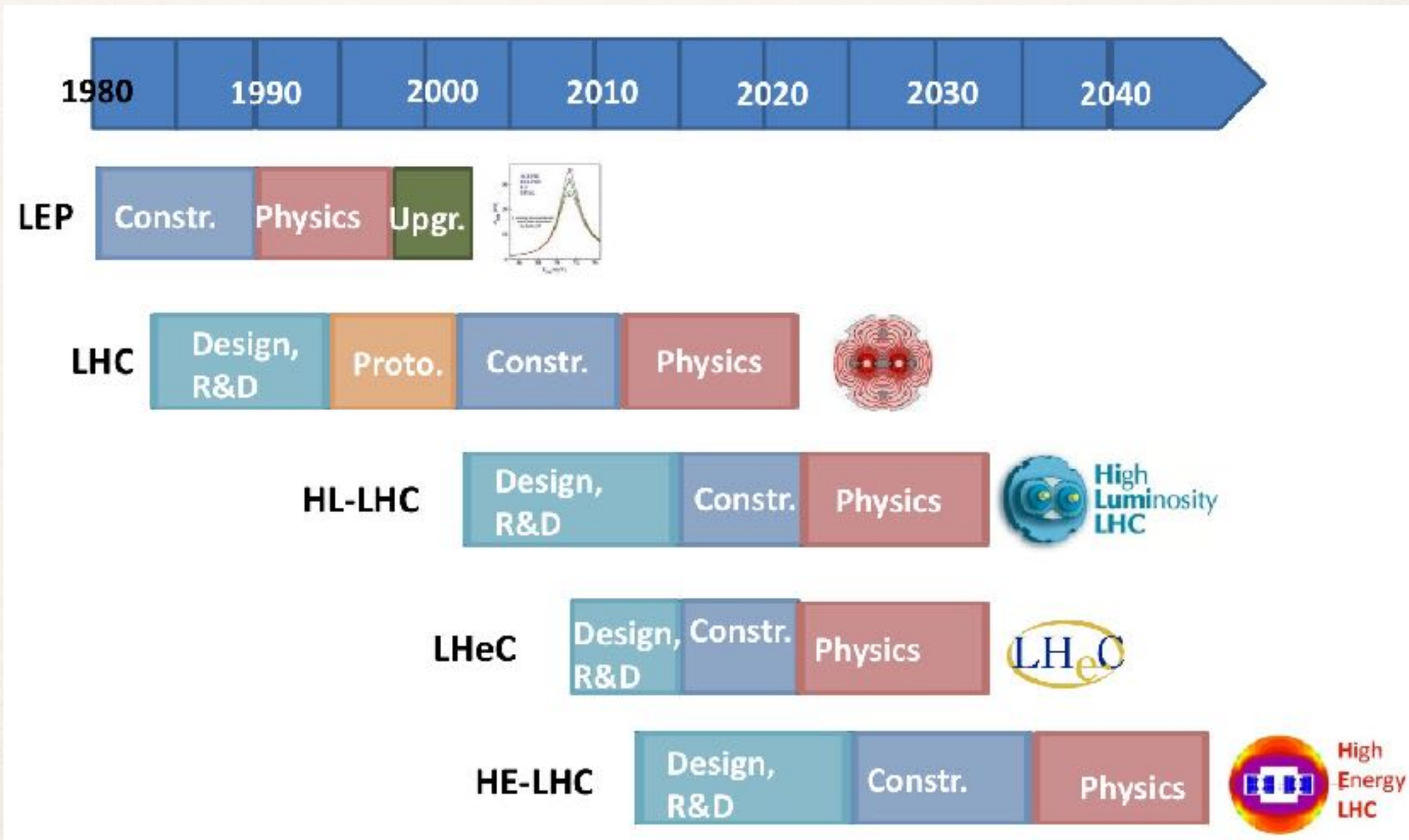
Expected yields (3000 fb^{-1}) Samples	Total	Barrel-barrel	Other (End-cap)	Ratio (O/B)
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = -4$	77.14	57.03	20.11	0.35
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 0$	19.50	14.33	5.17	0.36
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 1$	11.42	8.53	2.89	0.34
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 2$	6.82	5.14	1.68	0.33
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 6$	11.03	7.91	3.12	0.39
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 10$	57.46	41.94	15.52	0.37
$gg\,H(\gamma\gamma)$	6.60	4.50	2.10	0.47
$t\,\bar{t}\,H(\gamma\gamma)$	13.21	9.82	3.39	0.35
$Z\,H(\gamma\gamma)$	3.62	2.44	1.18	0.48
$b\,\bar{b}\,H(\gamma\gamma)$	0.15	0.11	0.04	0.40
$b\,\bar{b}\,\gamma\,\gamma$	18.86	11.15	7.71	0.69
$c\,\bar{c}\,\gamma\,\gamma$	7.53	4.79	2.74	0.57
$j\,j\,\gamma\,\gamma$	3.34	1.59	1.75	1.10
$b\,\bar{b}\,j\,\gamma$	18.77	10.40	8.37	0.80
$c\,\bar{c}\,j\,\gamma$	5.52	3.94	1.58	0.40
$b\,\bar{b}\,j\,j$	5.54	3.81	1.73	0.45
$Z(b\,\bar{b})\,\gamma\gamma$	0.90	0.54	0.36	0.67
$t\,\bar{t}$ ($\geq$ 1 leptons)	4.98	3.04	1.94	0.64
$t\,\bar{t}\,\gamma$ ($\geq$ 1 leptons)	3.61	2.29	1.32	0.58
Total Background	92.63	58.42	34.21	0.59
Significance Z	1.163	1.090	0.487	
Combined significance		1.194		

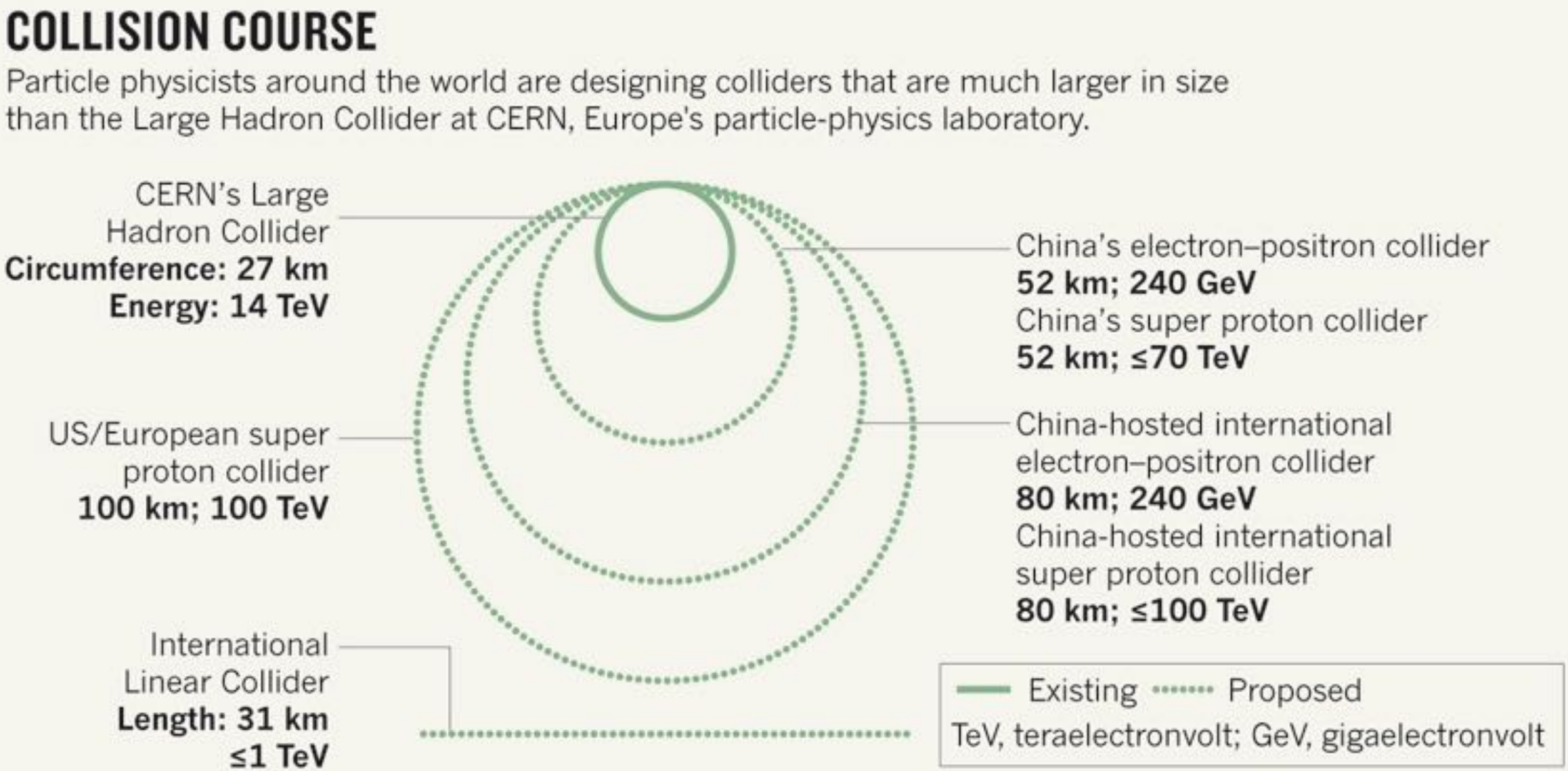

Z
BGs : ±20 %
δg_t^s : ±10 %
BGs : ±20 % & δg_t^s : ±10 %
λ_{3H}


$\mathcal{L}$ (fb^{-1})
95 % C.L.
$\mathcal{L}$ = 3000 fb^{-1}
LHC 14 TeV
pp → HH → $b\,\bar{b}\,\gamma\gamma$
$\mathcal{L}$
λ_{3H}

HL-LHC

$\sqrt{s}$ = 14 TeV, L =3000 fb^{-1} Focus on $H(\to b\bar{b})H(\to \gamma\gamma)$ Analysis





100 TeV pp Collider:

US/Europe vs China

Expected yields (3000 fb^{-1}) Samples	Total	Barrel-barrel	Other (End-cap)	Ratio (O/B)
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = -4$	5604.46	4257.36	1347.10	0.32
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 0$	1513.56	1163.04	350.52	0.30
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 1$	941.37	723.86	217.51	0.30
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 2$	557.36	431.45	125.91	0.29
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 6$	753.18	566.18	187.00	0.33
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 10$	3838.33	2924.25	914.08	0.31
$gg\,H(\gamma\gamma)$	890.47	742.97	147.50	0.20
$t\,\bar{t}\,H(\gamma\gamma)$	868.73	659.33	209.40	0.32
$Z\,H(\gamma\gamma)$	168.86	122.91	45.95	0.37
$b\,\bar{b}\,H(\gamma\gamma)$	9.82	7.00	2.82	0.40
$b\,\bar{b}\,\gamma\gamma$	783.87	443.70	340.17	0.77
$c\,\bar{c}\,\gamma\gamma$	222.88	111.44	111.44	1.00
$j\,j\,\gamma\gamma$	32.28	20.98	11.30	0.54
$b\,\bar{b}\,j\,\gamma$	1982.88	1516.32	466.56	0.31
$c\,\bar{c}\,j\,\gamma$	293.81	216.49	77.32	0.36
$b\,\bar{b}\,j\,j$	3674.16	1924.56	1749.60	0.91
$Z(b\,\bar{b})\,\gamma\gamma$	54.87	35.72	19.15	0.54
$t\,\bar{t}$ ($\geq$ 1 leptons)	59.32	38.32	21.00	0.55
$t\,\bar{t}\,\gamma$ ($\geq$ 1 leptons)	105.68	62.53	43.15	0.69
Total Background	9147.63	5902.27	3245.36	0.55
Significance Z	9.681	9.239	3.777	
Combined significance		9.981		

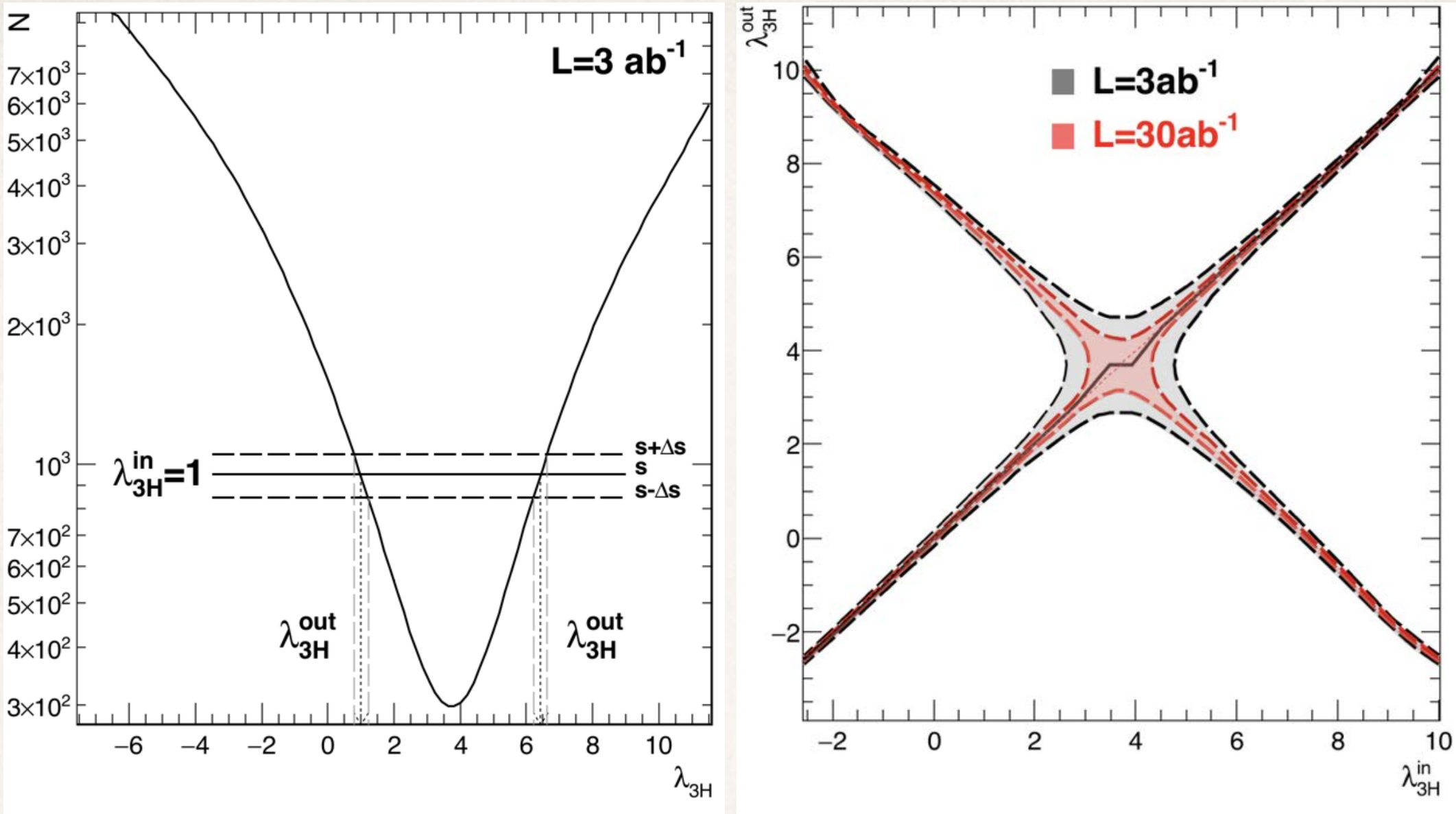


FIG. 9. **HL-100 TeV**: (Left) The number of signal events N versus λ_{3H} with 3 ab^{-1}. The horizontal solid line is for the number of signal events s when $\lambda_{3H}^{\rm in} = 1$ and the dashed lines for $s \pm \Delta s$ with the statistical error of $\Delta s = \sqrt{s+b}$. (Right) The 1-σ error regions versus the input values of $\lambda_{3H}^{\rm in}$ assuming 3 ab^{-1} (black) and 30 ab^{-1} (red).

Outlook for HH

- Probing the self-interactions of the Higgs boson is necessary for understanding the EWSB sector.

- At HL-LHC, constrain only $-1 \leq$ lambda_3H < 7.6. Significance is not high enough to establish the SM value.

- At HL-100, $3ab^{-1}$ can measure lambda_3H well, except for $2.6 <$ lambda_3H < 4.8. The SM value can be measured with 20% accuracy.