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Based on arXiv:1303.6591 with *A. Djouadi*  
& Work in progress with *S. Fichtel*

## Summer Institute 2013

10th International Summer Institute on Phenomenology of Elementary Particles and Cosmology

July 22-28, 2013

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 Kiyomasa Choshiro (IITP, Tokyo, Japan)  
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## Invited Lecturers

- Nima Arkani-Hamed
- Ki-Young Choi
- Ian Low
- Tatsuya Nakada
- Riccardo Rattazzi



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## I) Introduction

Today : The LHC has **discovered** a resonance of  $\sim 125.5$  GeV

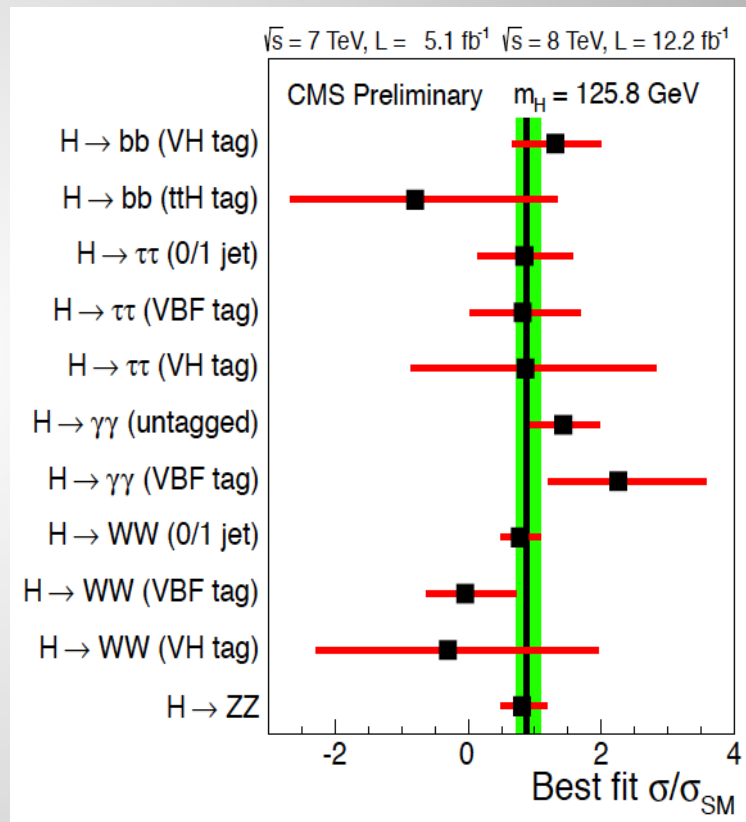
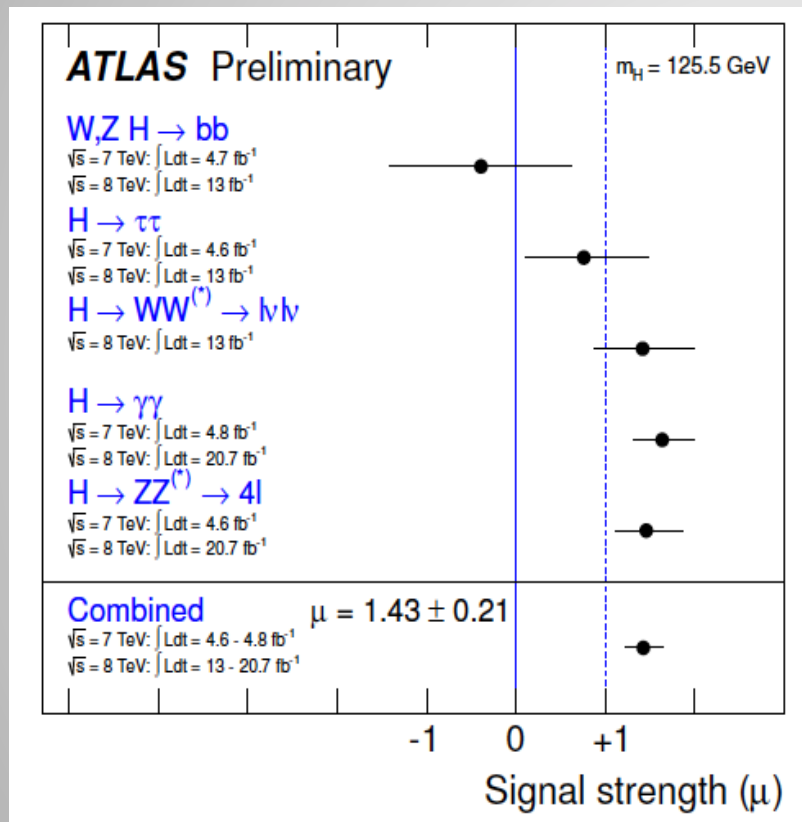
➡ *it is probably the B.E.Higgs boson => **EWSB** mechanism*

+ Tevatron and LHC provide **60** measurements of the Higgs rates

= new precious source of indirect information on BSM physics

➡ *nature of the EWSB : within the **SM** or a **BSM** context !?*

# The latest experimental results...



The first test to do is to fit,

$$\mu_{XX}|_{\text{exp}} = \frac{N^{\text{evts.}}(pp \rightarrow H \rightarrow XX)}{\sum_i \epsilon_i^X \sigma_i(H) \text{BR}(H \rightarrow XX)|_{\text{SM}} \times \mathcal{L}}$$

with,

$$\mu_{XX}|_{\text{th}} = \frac{\sum_i \epsilon_i^X \sigma_i(H) \text{BR}(H \rightarrow XX)}{\sum_i \epsilon_i^X \sigma_i(H) \text{BR}(H \rightarrow XX)|_{\text{SM}}}$$

$c_V$

$$\begin{aligned} \mathcal{L}_h = & c_W g_{HWW} H W_\mu^+ W^{-\mu} + c_Z g_{HZZ} H Z_\mu^0 Z^{0\mu} \\ & - c_t y_t H \bar{t}_L t_R - c_c y_c H \bar{c}_L c_R - c_b y_b H \bar{b}_L b_R - c_\tau y_\tau H \bar{\tau}_L \tau_R + \text{h.c.} \end{aligned}$$

$c_f$

All  $c=1$  in the SM.

## II) Why is the THEORETICAL error crucial in fits ?

\* The SM is in good agreement with the present data on Higgs signal strengths, **but it's not the end of the story...**

*These tests of the SM will become more and more powerful as the EXPERIMENTAL errors on the Higgs rates ( $\mu_{\text{exp}}$ ) will decrease.*

*Then the THEORETICAL errors on the Higgs rates can become dominant.*

\* The QCD uncertainty (P.D.F.,  $\alpha_s^2$ , scale dependence) on the inclusive Higgs production cross section reaches  **$\sim 10\%$**  [LHCHWG]

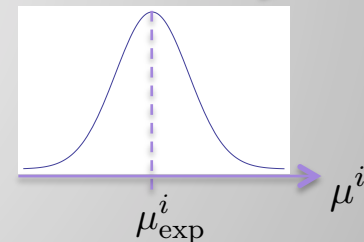
*The typical deviations expected in SUSY or composite Higgs models are about  **$\sim 1 - 20\%$***  [R.S.Gupta, H.Rzehak, J.D.Wells, 2006]

### III) The *present TREATMENT* of th. error in fits

*In most experimental and theoretical papers on Higgs rate fits...*

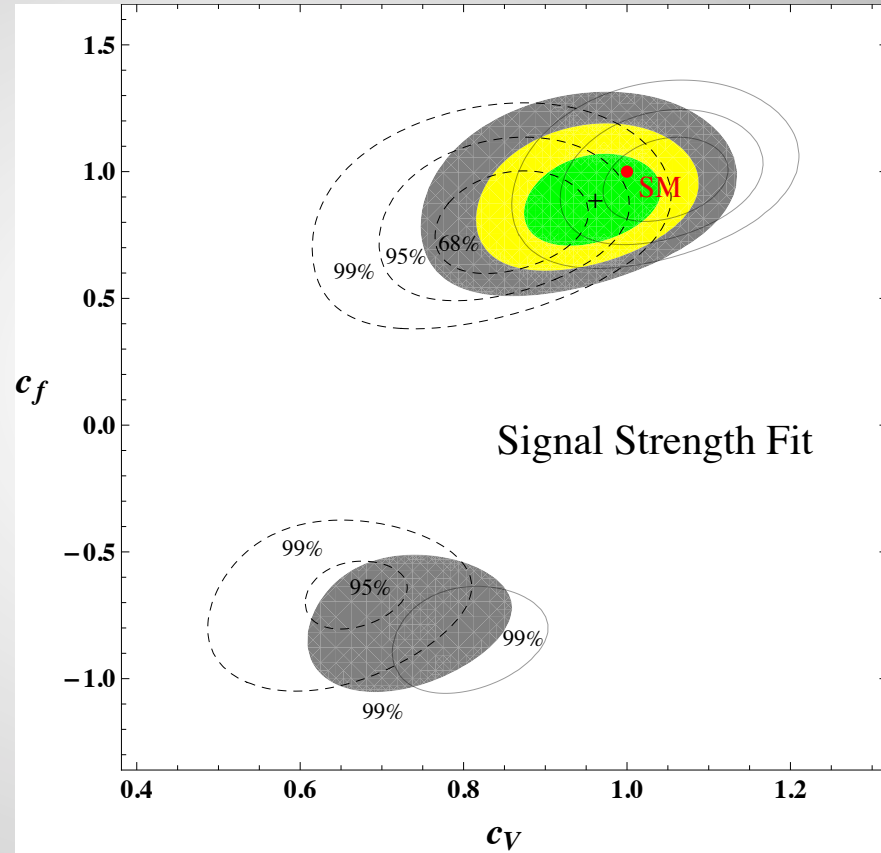
TH uncertainty added in quadrature with EXP one in the *Likelihood* as,

$$\mathcal{L} = pdf\left(\mu_{\text{exp}}^i, \sqrt{(\Delta_{\text{exp}}^i)^2 + (\Delta_{\text{th}}^i)^2} \mid \mu^i(c_f, c_V)\right) = \prod_i pdf_i$$



- ➡ this reflects a decorrelation : correct
- ➡ it means that the TH **pdf** is the same as the EXP one :  
a FLAT **probability distribution** can be better motivated by QCD

## Best-fit regions :

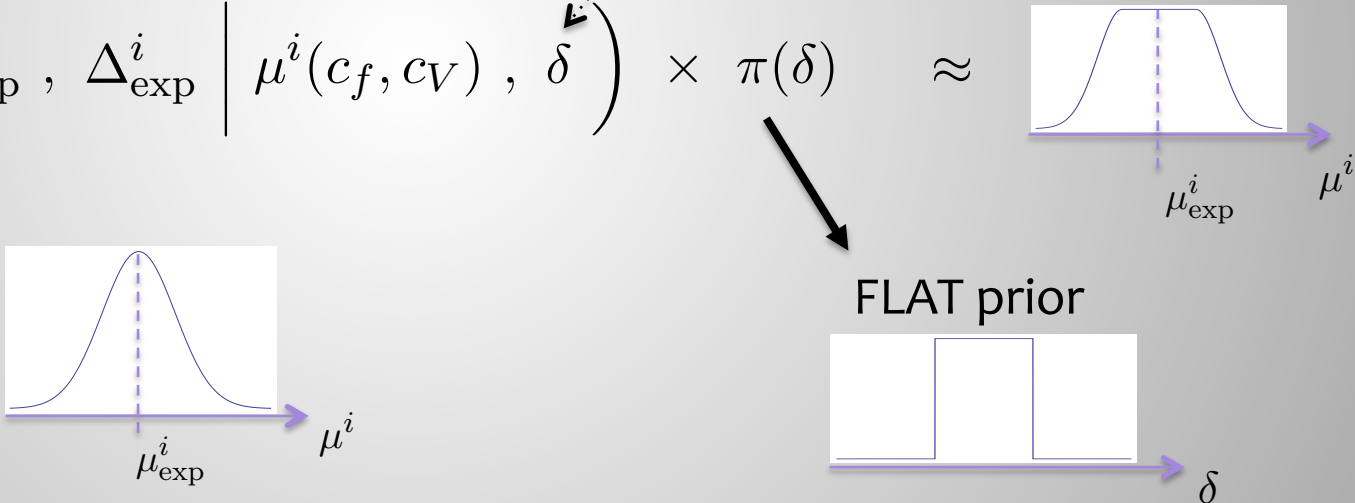


## IV) MARGINALISATION of the th. uncertainty

Use the rigorous Bayesian approach...

$\delta$  is a nuisance parameter :

$\mu_{\text{exp}}^i ( 1 + \delta \times \Delta_{\text{th}}^i )$  with  $\delta \in [-1, 1]$

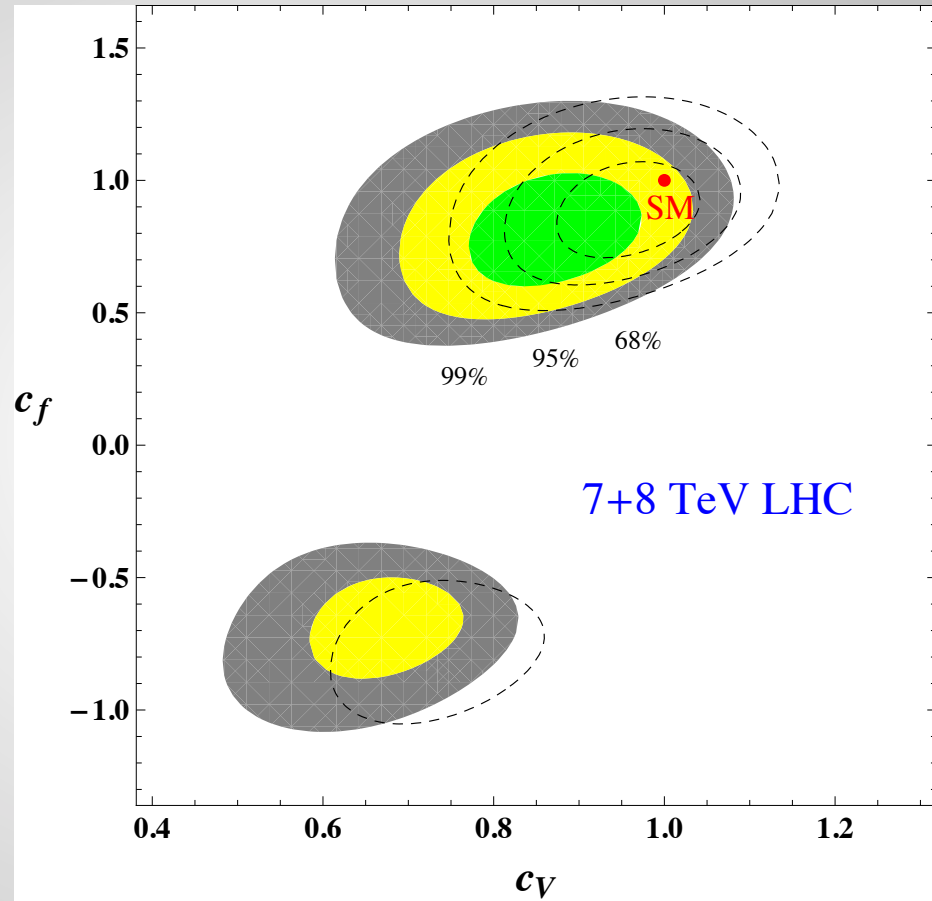
$$\mathcal{L} = \int d\delta \text{ pdf} \left( \mu_{\text{exp}}^i, \Delta_{\text{exp}}^i \mid \mu^i(c_f, c_V), \delta \right) \times \pi(\delta) \approx$$


The diagram illustrates the Bayesian approach to marginalizing theoretical uncertainty. The likelihood function is shown as a Gaussian distribution for  $\mu^i$ , centered at  $\mu_{\text{exp}}^i$ . The prior for the nuisance parameter  $\delta$  is shown as a flat distribution (FLAT prior) over the range  $[-1, 1]$ . The equation is split into two parts: the left part shows the likelihood function, and the right part shows the prior distribution. Arrows point from the equation to these two plots. A dotted arrow points from the text " $\delta$  is a nuisance parameter" to the  $\delta$  term in the equation.

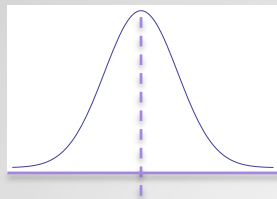
(**first** assuming TH errors purely correlated via a unique  $\delta$ , for simplicity)



Bayesian regions :  
(integration over  $c$ 's)



The « corresponding » Frequentist approach = Profile Likelihood :



still FLAT distribution

$$\mathcal{L}(\delta) = pdf\left( \mu_{\text{exp}}^i, \Delta_{\text{exp}}^i \mid \mu^i(c_f, c_V), \delta \right) \times \pi(\delta)$$

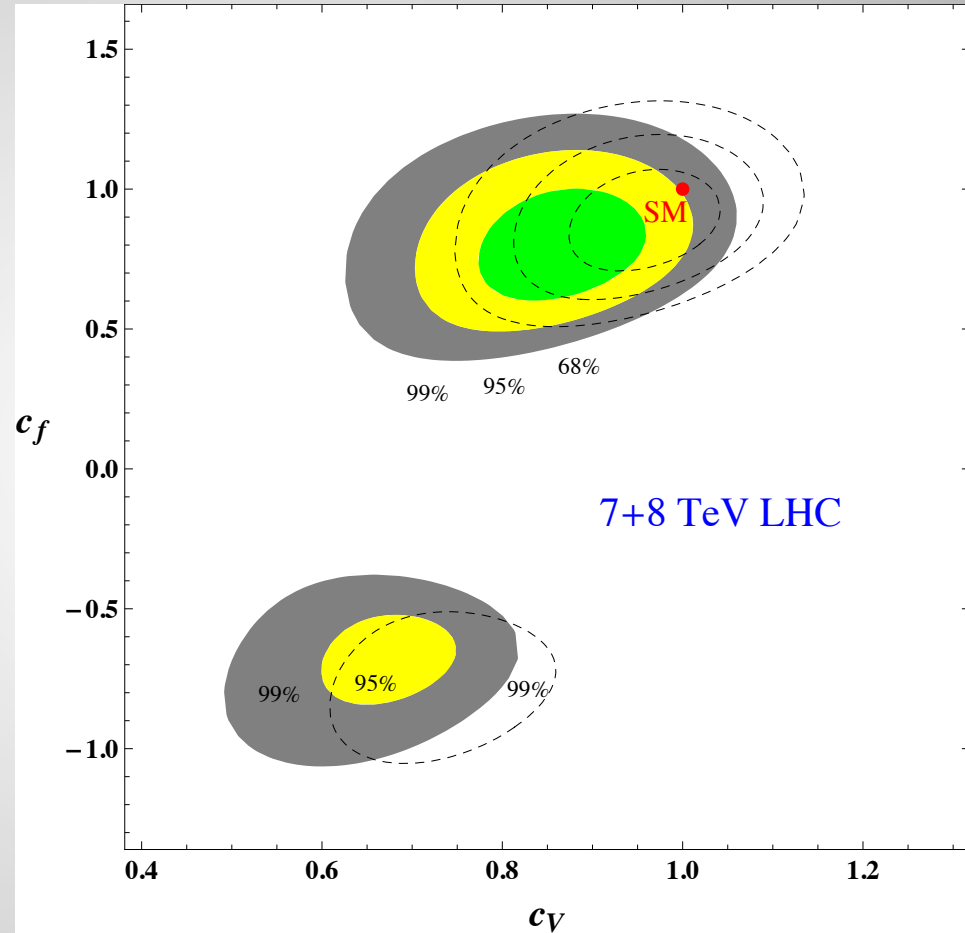
$$\tilde{\chi}^2 = -2 \text{Log}[\mathcal{L}(\delta)] = \underbrace{\sum_i \frac{[ \mu_{\text{exp}}^i (1 + \delta \Delta_{\text{th}}^i) - \mu^i(c_f, c_V) ]^2}{(\Delta_{\text{exp}}^i)^2}}_{\chi^2} - 2 \text{Log}[\pi(\delta)]$$

$$\Delta \tilde{\chi}^2 = \tilde{\chi}^2 - \tilde{\chi}_{\text{min}}^2(\delta, c_f, c_V|_{\text{opt}}) \rightarrow$$

« Preferred error » :  $\delta|_{\text{opt}} = -1$   
i.e. Higgs fit used to determine  
the QCD uncertainty !

Frequentist regions :

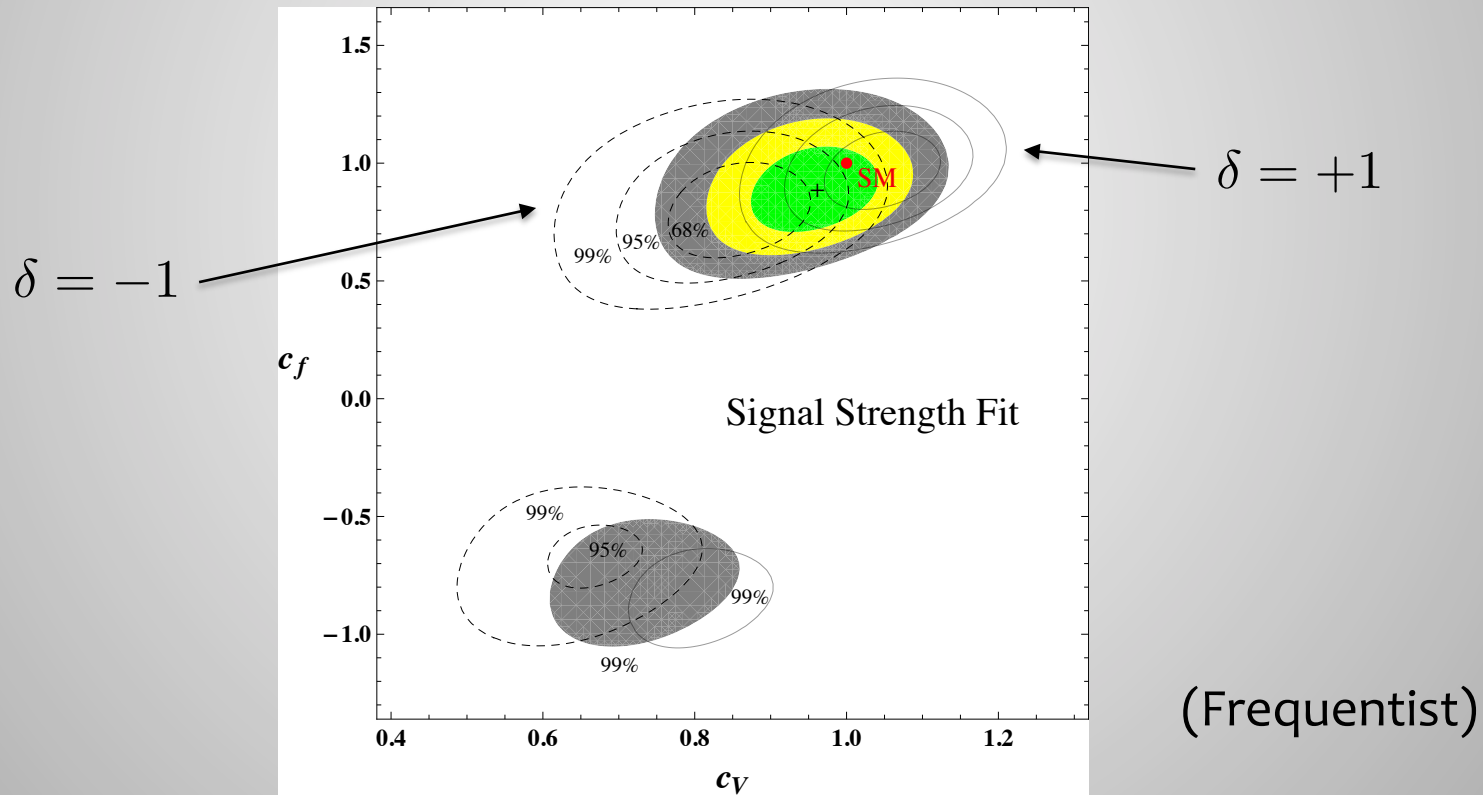
(w.r.t. *best-fit point*)



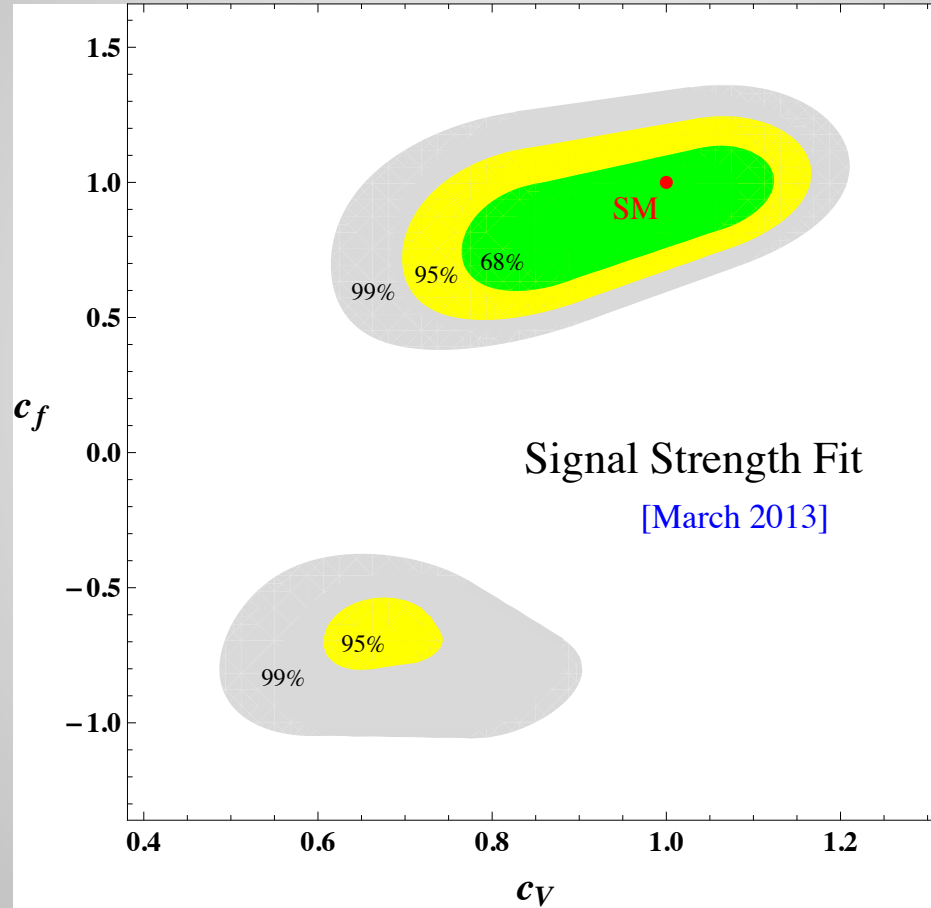
## V) The th. uncertainty as a BIAS

Consider the two extreme values of  $\delta$  to illustrate the QCD error effect on fits :

*(no preferred  $\delta$  value from the Higgs fit)*



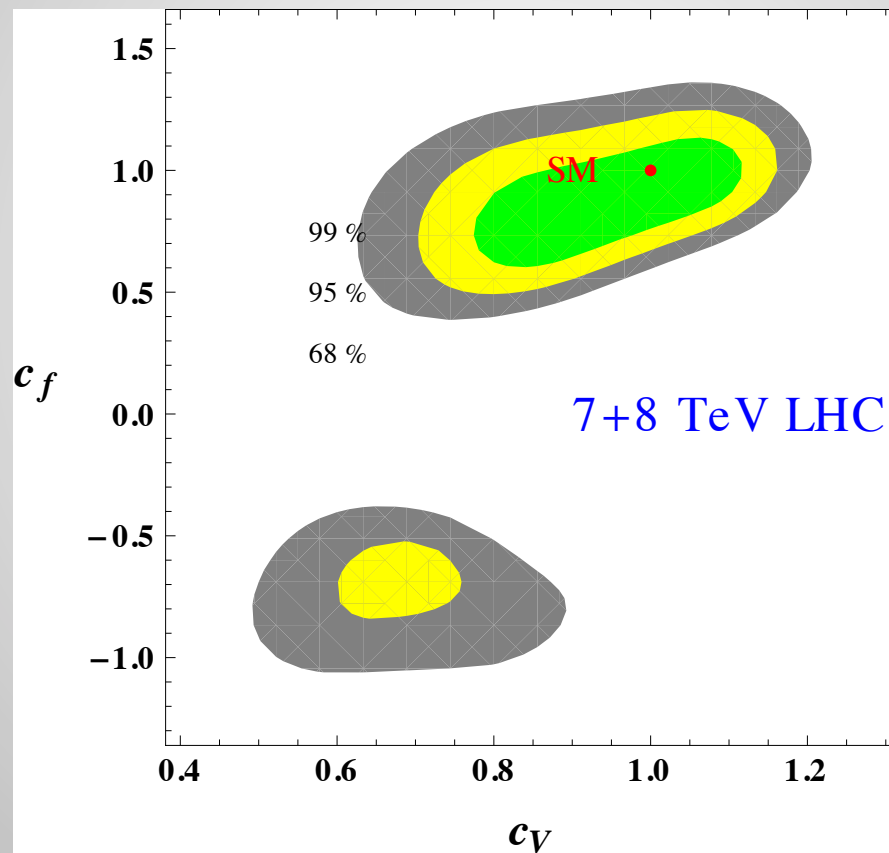
*Varying  $\delta$  continuously ...*



(Frequentist)

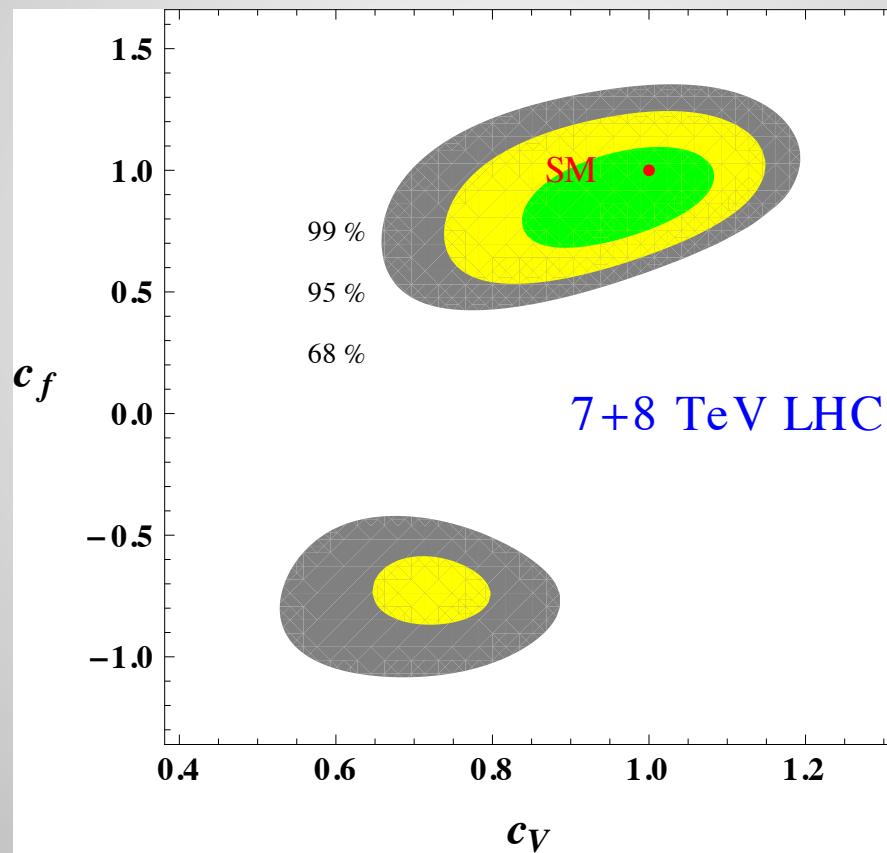
Obtaining this envelop directly through :

$$\Delta\bar{\chi}^2(c_f, c_V) = \text{Min}_\delta \left\{ \chi^2(c_f, c_V, \delta) - \chi^2_{\min}(c_f, c_V |_{\text{opt}}, \delta) \right\}$$



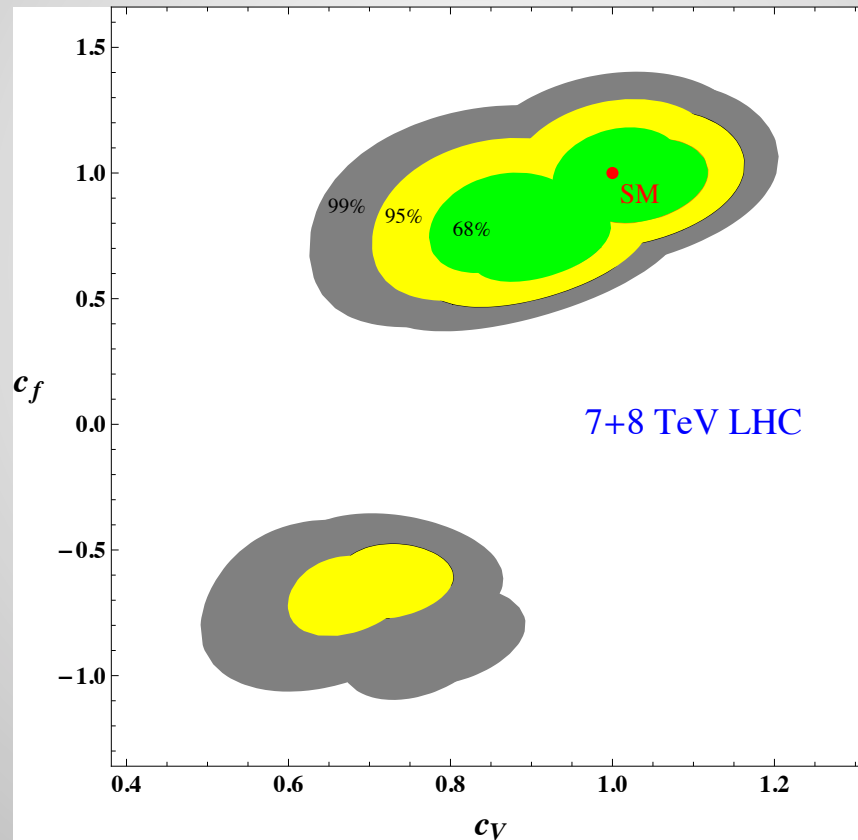
(Frequentist)

The « corresponding » Bayesian approach :



## Beyond the 100% correlated case ...

Dominant QCD error is from  $\text{PDF} + \alpha_s^2 \Rightarrow \delta_{\text{ggF,tth}} \neq \delta_{\text{VBF,Vh}}$



(Frequentist)



# Conclusion

The **determination of the Higgs couplings** - *through the signal strength fit* - **depends** significantly on the **statistical** treatment adopted for the **theoretical uncertainties** (QCD errors on  $\sigma_h$ 's &  $B_h$ 's).