Effective couplings of the Higgs boson in the light of recent LHC and Tevatron data

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The 125 GeV boson and its properties

- The ATLAS and CMS collaborations have discovered a new boson with mass $\sim 125 - 126\ \mathrm{GeV}$ (more than 5σ excess in each experiment).
- Since it decays to 2 photons, it cannot be a spin-1 resonance (Landau-Yang Theorem)
- This leaves us with two possibilities: either spin-0 or spin-2 $\longrightarrow$ spin and CP quantum number determination will take some time.
- Apart from its couplings to fermions and gauge bosons, the self-coupling will also need to be measured as a consistency check of the SM.
- The mass of 125 GeV is very interesting: many decay modes observable with sufficient branching ratios.
- There are some deviations in the data from the predictions for an SM Higgs boson (for e.g., in the $\gamma\gamma$ channel)
- However, it is too early to say anything definitive based on the data $\rightarrow$ set up the framework of analysis.

Effective couplings of the Higgs

- One can look into the Higgs data in the context of a specific model, like SUSY. Or one can also parametrize the deviations from the SM in the framework of a chiral Lagrangian.
- But in these approaches the couplings of the Higgs to up and down type fermions or to the different gauge bosons can get related in a specific way.
- Here, we want to study the effective couplings of the Higgs to SM and non-SM states in a general and model-independent way.
- The number of parameters involved increases $\rightarrow$ the global fit becomes somewhat difficult because of computational limitations.

Fermion couplings

- Classifying all $T_3 = +1/2$ fermions as u, and all $T_3 = -1/2$ fermions as d, we assume (for cases A and C)

$$\mathcal{L}^{eff}_{H\bar{u}u} = -\alpha_u \frac{m_u}{v} H\bar{u}u$$
$$\mathcal{L}^{eff}_{H\bar{d}d} = -\alpha_d \frac{m_d}{v} H\bar{d}d$$

  where H denotes the scalar with a Higgs-like appearance.
- This parametrization implicitly assumes the couplings of H to all fermions to be proportional to their masses.
- $\alpha_u \neq \alpha_d$ includes the possibility of H being part of a scenario containing more than one doublets, including the supersymmetric case.
- In the SM, $\alpha_u = \alpha_d = 1$

α_u, α_d : Range of variation

- There are essentially no limits on $|\alpha_u|$ and $|\alpha_d|$ from earlier data, except those from perturbativity of the Yukawa couplings.
- We take the maximum value of $|\alpha_u|$ to be 2 (keeping the top quark Yukawa coupling in mind)
- $|\alpha_d|$, to start with, is allowed to lie all the way upto 40.
- However, very large $|\alpha_d|$ $\Rightarrow$ the $b\bar{b}$ mode then dominates $\Rightarrow$ too much suppression for the $H \longrightarrow \gamma\gamma$ rate $\Rightarrow$ not admissible by current data.
- $\rightarrow$ We also limit the maximum value of $|\alpha_d|$ to 2 in our final analysis.
- There is some arbitrariness in this choice $\rightarrow$ limitations from computational time on the size of scanning grid

Gauge boson pair couplings

- We parametrize the interactions of the observed scalar to a pair of weak gauge bosons as

$$\mathcal{L}^{eff}_{HWW} = \beta_W \frac{2m_W^2}{v} H W^+_\mu W^{\mu -}$$

$$\mathcal{L}^{eff}_{HZZ} = \beta_Z \frac{m_Z^2}{v} H Z_\mu Z^\mu$$

- Such anomalous couplings can arise, for example, from gauge invariant effective operators, an example being

$$\mathcal{O}_\phi = \frac{f_\phi}{\Lambda^2} (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D_\mu \Phi)$$

- The Lorentz structure of the interaction has been tentatively taken to be the same as in the standard model.
- Allowing $\beta_W \neq \beta_Z$, allows one to address the apparent suppression of the WW channel as opposed to the ZZ channel, as indicated in the 2011 data.
- Higher-dimensional operators can change Lorentz structure $\rightarrow$ work in progress!

Electroweak precision data and β_W, β_Z

- Strong precision electroweak constraints, in particular, for $\beta_W \neq \beta_Z$ (breakdown of custodial SU(2), restricted by the T-parameter).
- For $\beta_W = \beta_Z \equiv \beta$, taking into account the contributions to the S and T parameters, for a Higgs mass of 125 GeV, electroweak precision constraints restrict β in the range

$$0.84 \leq \beta^2 \leq 1.4$$

  Azatov, Contino and Galloway, 2012
- However, $\beta_W \neq \beta_Z$ possible with new higher dimensional operators. The constraints from S,T,U-parameters vary from operator to operator. New states might be necessary to cancel contribution to T-parameter (Farina, Grojean and Salvioni, 2012)
- We consider both $\beta_W = \beta_Z$ (cases B and C), and $\beta_W \neq \beta_Z$ (case-A).
- For case-A, we vary β_W and β_Z between 0 and 2.

Effective couplings to gluons and photons

- Gluon fusion is the dominant production mode for a Higgs of mass around 125 GeV $\rightarrow$ overwhelmingly driven by the top quark loop.
- Departure of α_u from unity will be reflected in the production cross-section
- The decay amplitude to two-photons $\rightarrow$ contributions from both fermion-and W-induced loops.
- Thus the parameter β_W also dictates the rate for the two-photon final state.
- But there is more to the story, if additional states contribute in the loops.
- For e.g., the contribution of Kaluza-Klein towers in theories with extra compact dimensions, where fermions and/or gauge bosons propagate in the bulk.
- It is necessary in a general study to include an additional parameter to properly quantify new physics effects in the gluon fusion channel.
- For the two-photon amplitude, this parameter can well be different, since new physics can be quite different in the coloured and non-coloured sectors.

Effective gluon-gluon and photon-photon couplings...

- Parametrization:

$$\mathcal{L}^{eff}_{gg} = -x_g f(\alpha_u) \frac{\alpha_s}{12\pi v} H G^a_{\mu\nu} G^{a\mu\nu}$$
$$\mathcal{L}^{eff}_{\gamma\gamma} = -x_\gamma g(\alpha_u, \alpha_d, \beta_W, \delta) \frac{\alpha_{em}}{8\pi v} H F_{\mu\nu} F^{\mu\nu}$$

- Here x_g and x_γ encapsulate the overall modification due to new intermediate states in the two cases
- The functions $f(\alpha_u)$ and $g(\alpha_u, \alpha_d, \beta_W, \delta)$ encapsulate the modifications of these couplings due to fermion and W-boson loops.
- Since there is no restriction till now on x_g and x_γ , we let each of them vary from 0.2 to 3.0.
- Not too much room for variation being consistent with data : still, some arbitrariness again (also, vacuum stability not taken into account).

Invisible width

- An invisible width can occur if, for example, the Higgs serves as a portal to a 'dark matter' sector.
- The exact expression of the width in terms of the coupling to the dark sector will require one to know the nature of the invisible particle(s), for example, whether they are scalars or spin-1/2 objects.
- In order to be model-independent, we take as a free parameter the *invisible width* Γ_{inv}, which is independent of the nature of the invisible state.
- Very little guideline on the range over which Γ_{inv} should be varied $\longrightarrow$ start from ϵ, the invisible branching ratio, and let it vary between 0 and 1.
- The invisible width is then expressed as

$$\Gamma_{inv} = \frac{\epsilon}{1-\epsilon} \sum \Gamma_{vis}$$

where $\sum \Gamma_{vis}$ is the total decay width into all visible channels.

LHC and Tevatron data

- CMS: Combination of 7 TeV ($5.1\,\mathrm{fb}^{-1}$ data) and 8 TeV ($5.3\,\mathrm{fb}^{-1}$ data) results from CMS in all channels $\to \gamma\gamma$(inclusive), $ZZ^* \to 4\ell, WW^* \to \ell\ell\nu\nu, \gamma\gamma jj, \tau^+\tau^-$ and $b\bar{b}$.
- ATLAS: $\gamma\gamma$ and ZZ^* channels: $7+8$ TeV combinations, 2011 results for the remaining channels ($4.9\,\mathrm{fb}^{-1}$ for 7 TeV and $5.9\,\mathrm{fb}^{-1}$ for 8 TeV).
- The $\gamma\gamma jj$ results from ATLAS were not available at the time of analysis.
- Tevatron (combined CDF and D0) results for $WW^*, \gamma\gamma$ and $b\bar{b}$, integrated luminosity: $10\,\mathrm{fb}^{-1}$.
- Total of 14 input data points for our global analysis.
- All SM production cross-sections and decay widths for the Higgs: taken from the LHC Higgs Cross Section Working Group results, `S. Dittmaier et al., 2011 and 2012, twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections`

Input data set: $\hat{\mu}_i$ and their 1σ uncertainties

Experiment	Channel	$\hat{\mu}$	M_H (GeV)	Energy (TeV)
Tevatron	$H \to W^+W^-$	$0.32^{+1.13}_{-0.32}$	125	1.96
	$H \to b\bar{b}$	$1.97^{+0.74}_{-0.68}$		
	$H \to \gamma\gamma$	$3.62^{+2.96}_{-2.54}$		
ATLAS	$H \to \gamma\gamma$	$1.9^{+0.50}_{-0.50}$	126.5	$7+8$
	$H \to ZZ^* \to 4l$	$1.3^{+0.60}_{-0.60}$	126.5	$7+8$
	$H \to WW^* \to l^+l^-\nu\bar{\nu}$	$0.52^{+0.57}_{-0.60}$	126	7
	$H \to \tau\bar{\tau}$	$0.16^{+1.72}_{-1.84}$	126	7
	$H \to b\bar{b}$	$0.48^{+2.17}_{-2.12}$	126	7
CMS	$H \to \gamma\gamma$	$1.56^{+0.43}_{-0.43}$	125.3	$7+8$
	$H \to ZZ^* \to 4l$	$0.7^{+0.40}_{-0.40}$		
	$H \to WW^* \to l^+l^-\nu\bar{\nu}$	$0.62^{+0.43}_{-0.45}$		
	$H \to \tau\bar{\tau}$	$-0.14^{+0.76}_{-0.73}$		
	$H \to b\bar{b}$	$0.15^{+0.73}_{-0.66}$		
	$H \to \gamma\gamma jj$	$1.58^{+1.06}_{-1.06}$		

Value of Higgs mass

- CMS best fit value for the Higgs mass (m_H): 125.3 ± 0.6 GeV
- ATLAS best-fit m_H : 126.5 GeV .
- We use the average of these two values: 125.9 GeV to calculate the SM rates at the LHC.
- For the Tevatron analysis, $m_H = 125$ GeV has been used, following combined CDF and D0 analysis.

Methodology

- Experimental inputs: observed signal strengths in the i^{th} channel

$$\hat{\mu}_i = \sigma_i^{obs} / \sigma_i^{SM}$$

σ_i^{obs}: observed signal cross-section for a particular Higgs mass

σ_i^{SM}: signal cross-section for an SM Higgs with the same mass.

- Uncertainty in each channel included, some data are given with asymmetric error bars.
- We calculate the corresponding values of μ_i for various points in the parameter space $(\alpha_u, \alpha_d, \beta_W ...)$.
- One can express μ_i as

$$\mu_i = R_i^{prod} \times R_i^{decay} / R^{width}$$

R_i^{prod}: factor modifying the SM production cross-sections
R_i^{decay}: factor modifying decay width in a particular channel
R^{width}: factor modifying the total decay width of the Higgs

Production mechanisms

- For $\gamma\gamma$(inclusive), $ZZ^* \to 4\ell$, $WW^* \to \ell\ell\nu\nu$ and $\tau^+\tau^- \to$ include all the production processes, namely, gluon fusion, vector boson fusion, associated WH, ZH and $t\bar{t}H$ production.
- Only the associated WH and ZH production channels can lead to $b\bar{b}$ final states that can be separated from backgrounds.
- VBF and GF are the dominant production modes for the $\gamma\gamma jj$ channel reported by CMS.
- $\gamma\gamma jj$: The contribution of VBF dominates once the appropriate cuts to identify forward tagged jets are imposed.
- $\gamma\gamma jj$: This is reflected in the corresponding efficiencies: 15% for VBF, and 0.5% for GF.

Modification factors: production

- Gluon Fusion: $x_g^2 \alpha_u^2$ (R_{GF})
- Associated production with a Z (ZH): β_Z^2 (R_{ZH})
- Associated production with $W^\pm$ (WH): β_W^2 (R_{WH})
- Associated production with $t\bar{t}$ ($t\bar{t}H$):α_u^2 ($R_{t\bar{t}H}$)
- In the vector boson fusion (VBF) channel, the corresponding factor is given by

$$R_{VBF} \simeq \frac{3\beta_W^2 + \beta_Z^2}{4}$$

$\rightarrow$ The interference of the WW-fusion and the ZZ-fusion diagrams is of the order of 1% $\rightarrow$ ignored in our calculation.
$\rightarrow$ The WW-fusion contribution to the total cross-section is roughly 3 times that of the ZZ-fusion contribution.
$\rightarrow$ For details see: A. Djouadi, Phys. Rept. 457 (2008) 1.
$\rightarrow$ Cross-checked these facts for the LHC energies using the VBF@NNLO code, Bolzoni, Maltoni, Moch and Zaro, 2010.

Effect of Cut Efficiencies

- Simplification: for inclusive channels, all production modes assumed to have same cut efficiencies
- Mainly because the experimental groups do not report the efficiencies yet.
- But, the p_T distribution for the Higgs itself can be different in different production modes, leading to different kinematics for decay products.
- One exception: CMS result on $\gamma\gamma jj$
- As reported by CMS, the overall acceptance times selection efficiency of the dijet tag for Higgs boson events is 15% for VBF (ξ_{VBF}) and 0.5% for GF (ξ_{GF}).
- $\rightarrow$ For the VBF channel, the factor modifying the SM production cross-section is given by

$$R_{Hjj} = \frac{\xi_{VBF} R_{VBF} \sigma^{SM}_{VBF} + \xi_{GF} R_{GF} \sigma^{SM}_{GF}}{\xi_{VBF} \sigma^{SM}_{VBF} + \xi_{GF} \sigma^{SM}_{GF}}$$

Decay width modification: $H \to \gamma\gamma$

Mainly due to the top quark and W-boson loops (and a small contribution due to the bottom and tau loops):

$$R_{\gamma\gamma} = x_\gamma^2 \frac{|\frac{4}{3}\alpha_u e^{i\delta} A^H_{1/2}(\tau_t) + \frac{1}{3}\alpha_d A^H_{1/2}(\tau_b) + \alpha_d A^H_{1/2}(\tau_\tau) + \beta_W A^H_1(\tau_W)|^2}{|\frac{4}{3} A^H_{1/2}(\tau_t) + \frac{1}{3} A^H_{1/2}(\tau_b) + A^H_{1/2}(\tau_\tau) + A^H_1(\tau_W)|^2}$$

where the relevant loop functions are given by

$$A^H_{1/2}(\tau_i) = 2[\tau_i + (\tau_i - 1)f(\tau_i)]\tau_i^{-2}$$
$$A^H_1(\tau_i) = -[2\tau_i^2 + 3\tau_i + 3(2\tau_i - 1)f(\tau_i)]\tau_i^{-2}$$

Here, $f(\tau_i)$, for $\tau_i \leq 1$ is expressed as, $f(\tau_i) = (\sin^{-1}\sqrt{\tau_i})^2$
while, for $\tau_i > 1$, it is given by

$$-\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau_i^{-1}}}{1-\sqrt{1-\tau_i^{-1}}} - i\pi\right]^2$$

$\tau_i = m_H^2/4m_i^2$.

Decay widths in other channels

The modification factors are simple in other channels:

- WW^*: β_W^2
- ZZ^*: β_Z^2
- $\tau\bar{\tau}$: α_d^2
- $b\bar{b}$: α_d^2
- $c\bar{c}$: α_u^2
- gg: $x_g^2\alpha_u^2$

Global Fits

- To obtain the best fit values of the parameters (upto 7 at a time) calculate the global minimum of the χ^2 function:

$$\chi^2 = \sum_i \frac{(\mu_i - \hat{\mu}_i)^2}{\sigma_i^2}$$

- Prescription for Asymmetric error bars on the data:
- If $(\mu_i - \hat{\mu}_i) > 0$, use the positive error bar σ_i^+
- If $(\mu_i - \hat{\mu}_i) < 0$, use the negative error bar σ_i^-

`Fred James, private communication`.

Global Fits: continued...

- Combining more than one experimental data points to obtain a single input data: average signal strength $\bar{\hat{\mu}}$ and the uncertainty $\bar{\sigma}$ using

$$\frac{1}{\bar{\sigma}^2} = \sum_i \frac{1}{\sigma_i^2}$$

$$\frac{\bar{\hat{\mu}}}{\bar{\sigma}^2} = \sum_i \frac{\hat{\mu}_i}{\sigma_i^2}$$

- This method used for CMS data on inclusive $\gamma\gamma$ and $\gamma\gamma jj$ channels, where the results were presented as different kinematic categories.
- Same method in combining different contributions to the theoretically calculated μ values.
- Example: while combining the contributions of $WH \to l\nu b\bar{b}$, $ZH \to l^+l^- b\bar{b}$ and $ZH \to \nu\bar{\nu}b\bar{b}$ to associated Higgs production with gauge bosons and the subsequent decay of the Higgs to a bottom pair.
- Such combinations are necessary because the experimental collaborations have reported a single signal strength value in the $b\bar{b}$ channel.

Two-dimensional contours for confidence intervals

- After obtaining the best-fit values for the parameters: consider two-dimensional contours for various pairs of them about the global minimum, fixing the remaining ones at their best-fit values.
- The contours are drawn for 68.3% and 95.4% confidence intervals.
- One important point in which our study differs from most earlier ones is that, in the cases where these two-dimensional contours are drawn, *the remaining parameters are fixed not at their SM values but at values corresponding to the global minimum of the* χ^2 *fit.*
- Also obtained some two-dimensional contours by marginalizing over the other parameters $\rightarrow$ computationally difficult with 7 parameters.

Results: Best Fit Values

Case	β_W	β_Z	α_u	α_d	x_g	x_γ	ϵ
A	1.2	1.6	-0.6	-1.2	1.8	1.3	0.6
C	1.07	1.07	-1.3	-0.96	0.65	0.95	0.2

Table: Best-fit values of the various parameters. In case C, the relation $\beta_W = \beta_Z$ has been imposed, and their values have been restricted within precision constraints.

Note that:

- In case-A, larger values of x_g, x_γ and β_Z can keep the $\gamma\gamma$ and ZZ^* rates up and at the same-time allow for a larger BR into the invisible channel.
- α_u best-fit value negative $\rightarrow$ noticed by many groups.
- The sign of α_u enters into the $\gamma\gamma$ decay rate.
- Negative α_u leads to a constructive interference term between the top loop and the W loop $\rightarrow$ increase in $\gamma\gamma$ rate.
- A negative sign is like a phase ($= e^{i\pi}$) in the effective top quark Yukawa coupling to the Higgs $\rightarrow$ can a phase in general appear (case-B)?

A phase in the $t\bar{t}H$ effective coupling

- Introduce a phase in the effective coupling:

$$\mathcal{L}^{eff}_{H\bar{t}t} = -e^{i\delta}\alpha_u \frac{m_t}{v} H\bar{t}t$$

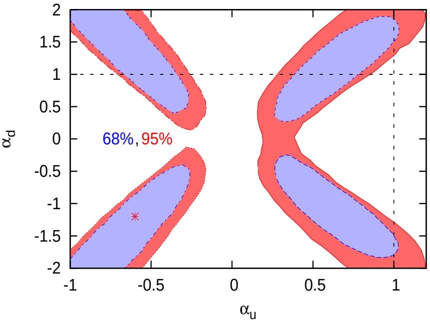
- Note that this is not a phase in the Lagrangian as such, which is required to be Hermitian.
- A phase in the $Ht\bar{t}$ effective coupling can arise due to imaginary (absorptive) parts coming from loop diagrams for the transition where some of the intermediate SM states in the loop graphs, being lighter than the Higgs boson, can go on-shell.
- Example: a heavy W' like gauge boson having $W'tb$ type couplings can give rise to additional contributions to the $Ht\bar{t}$ effective coupling, via a triangle loop involving two b-quarks, where the b-quarks can go on-shell inside the loop.
- This would then give rise to an imaginary part in the effective interaction.
- The phase enters only in interference terms between the fermion and W-boson loops, for example, in the decay $H \longrightarrow \gamma\gamma$.
- Since the bottom quark Yukawa's are themselves small, an additional phase there is dropped.

Best-fit values with non-zero δ

Case	β_W	β_Z	α_u	α_d	x_g	x_γ	ϵ	δ
B	1.06	1.06	-1.05	0.95	0.8	1.0	0.2	0.55

Table: Best-fit values of the various parameters with δ varied in the range $[0, \pi]$. $\beta_W = \beta_Z$ has been imposed, and their values have been restricted within precision constraints.

Confidence intervals: case-A



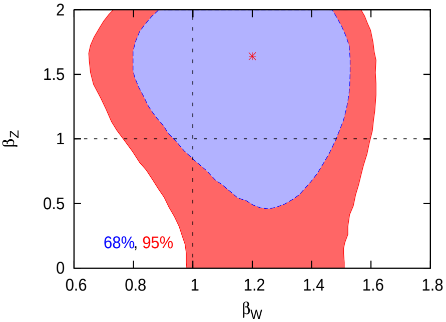


Figure: Two-dimensional contour plots for 68% and 95% confidence intervals, for case A, with rest of the parameters fixed at their best-fit values. Best-fit point: marked by a '∗'.

Confidence intervals: case-A

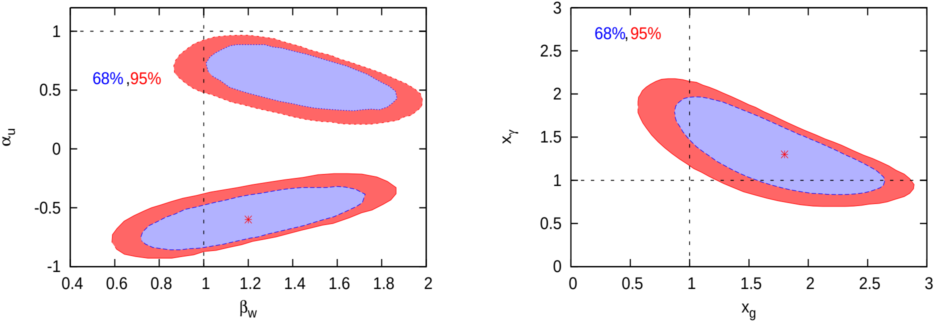


Figure: Two-dimensional contour plots for 68% and 95% confidence intervals, for case A, with rest of the parameters fixed at their best-fit values. Best-fit point: marked by a '$*$'.

Confidence intervals: Case-B

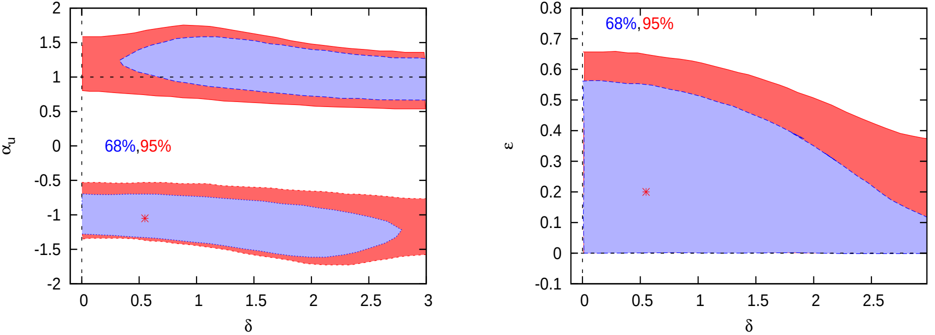


Figure: Two-dimensional contour plots for 68% and 95% confidence intervals, for case B, with rest of the parameters fixed at their best-fit values. Best-fit point: marked by a '$*$'.

Confidence intervals: Case-B

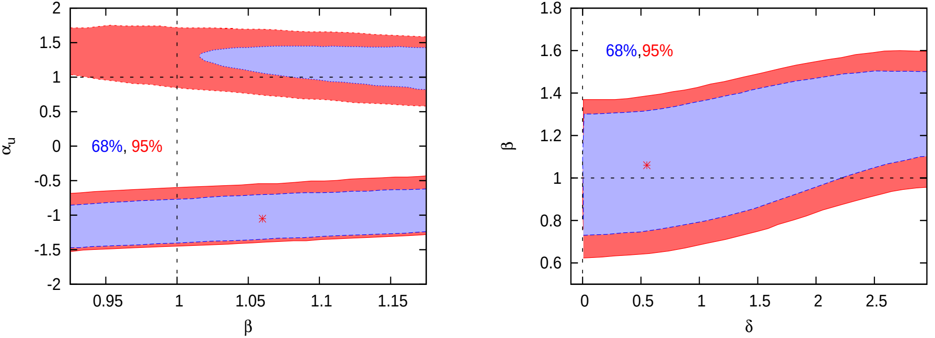


Figure: Two-dimensional contour plots for 68% and 95% confidence intervals, for case B, with rest of the parameters fixed at their best-fit values. Best-fit point: marked by a '$*$'.

ϵ vs χ^2

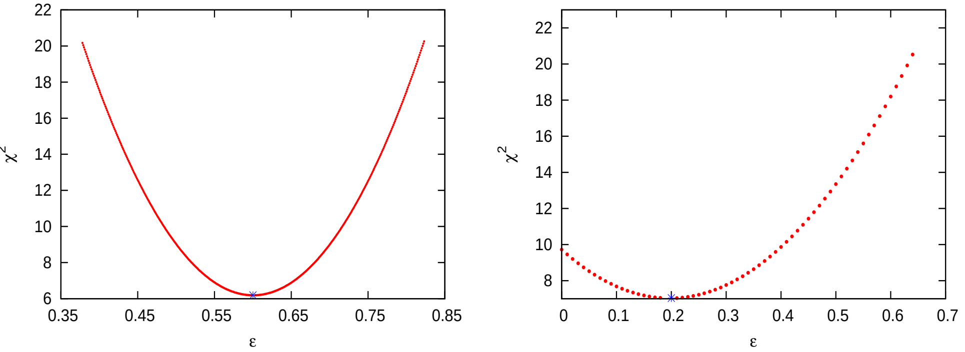


Figure: Variation of the χ^2 function with the invisible branching fraction of H (ϵ) in cases A (left panel) and B (right panel). In case A, $\delta = 0$ and $\beta_W \neq \beta_Z$, whereas in case B, δ has been varied in the range $\{0, \pi\}$ and $0.92 \leq \beta \leq 1.18$, with $\beta \equiv \beta_W = \beta_Z$.

Less room for ϵ when $\beta_W = \beta_Z$.

δ vs χ^2

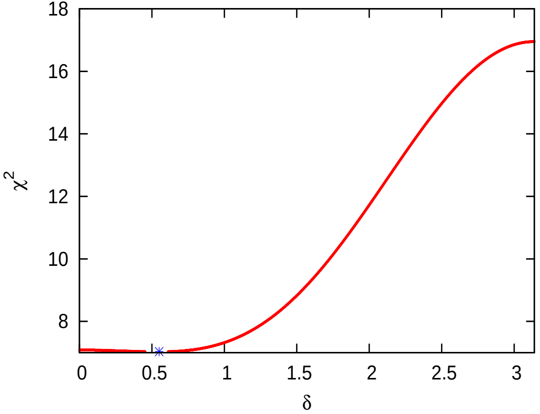


Figure: Variation of the χ^2 function with the phase in the up-type quark Yukawa coupling, δ, in case B. In this case δ has been varied in the range $\{0, \pi\}$, whereas $0.92 \leq \beta \leq 1.18$, with $\beta \equiv \beta_W = \beta_Z$.

The χ^2 function is very slowly varying in the entire range between 0 and 0.6.

Effect of marginalization

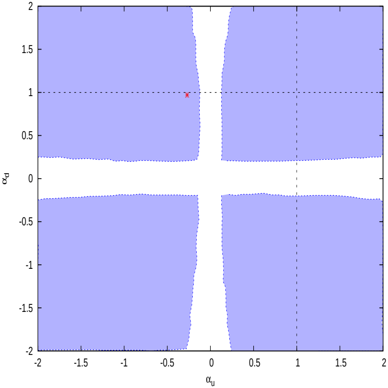


Figure: A marginalized contour for 68% confidence interval, case-C.

- Marginalization increases the size of the allowed region.
- Computationally difficult.

Summary

- We try to see how much scope exists for new physics in the Higgs data in a general setting.
- The 2σ contours do allow departures from SM values at the moment.
- A fermiophobic Higgs is by and large disfavoured.
- There is a hint in the best-fit values of a relative sign between the couplings to the up-type fermion and the gauge boson pairs.
- An invisible decay width of the Higgs is still allowed $\rightarrow$ upto 20% or more is possible when custodial symmetry is respected.
- This is just seeting up the framework of global analysis $\rightarrow$ new data will be available soon, and we can get more accurate results.

Open Ends

- Cut efficiencies of various production modes in inclusive channels $\rightarrow$ wait for the experimental collaborations to report them.
- Different Lorentz structure for gauge boson couplings coming from higher-dimensional operators $\rightarrow$ work in progress.
- Compatibility of invisible width with dark matter relic abundance and direct detection experiments.
- A better algorithm to marginalize over the other parameters in finding two dimensional confidence intervals $\rightarrow$ may be use a Monte-Carlo technique to sample the parameter space and find the minima?
- How can the phase in the effective $Ht\bar{t}$ coupling arise? Possible physics explanations other than loop-effects.
- Is there a way to decide proper upper and lower limits on the parameters, and then perform the scan? Note that parametrization in terms of BR's will mix up all new physics effects in a complicated way.