Anomalous Higgs couplings and collider data : some model-independent studies

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JHEP 1210, 062 (2012) and **Phys. Rev. D 89, 053010 (2014)** (with S. Mukhopadhyay and B.Mukhopadhyaya) and
arXiv : 1505.00226 (to appear in JHEP) (with T. Mandal, B. Mellado and B. Mukhopadhyaya)

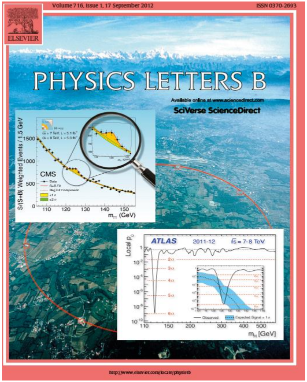
Plan of my talk

- Introductory remarks
- Higgs couplings with no new Lorentz structures
  - Coupling parametrizations
  - χ^2 minimisation technique
  - Allowed parameter space
- Higgs couplings with new Lorentz structures
  - Modified cut-efficiencies @ 8 TeV *LHC*
    - Gauge invariant dimension-6 operators
    - Modified efficiencies
    - Global analysis
  - Observables to disentangle new physics @ 14 TeV $HL-LHC$
- Summary and conclusions

Higgs discovery in 2012 !!!

- Existence of a scalar boson proposed by Higgs, Brout, Englert, Guralnik, Hagen and Kibble around 1964
- Discovery of the celebrated Higgs boson at a mass $\approx$ 125 GeV [a] announced on 4^{th} July, 2012
- Dedicated search methods devised by both the *CMS* and *ATLAS* collaborations at the *LHC* made this discovery possible

[a] CMS + ATLAS (combined) : $M_H = 125.09 \pm 0.21$ (stat.) ± 0.11 (syst.) GeV in the $H \to \gamma\gamma$ and the $H \to ZZ^* \to 4\ell$ channels.



Many studies in similar spirit ...

F. Bonnet, M. B. Gavela, T. Ota and W. Winter (2012)
J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott (2012)
T. Li, X. Wan, Y. k. Wang and S. h. Zhu (2012)
M. Rauch (2012)
J. R. Espinosa, M. Muhlleitner, C. Grojean and M. Trott (2012)
J. Ellis and T. You (2012)
D. Carmi, A. Falkowski, E. Kuflik and T. Volansky (2012)
M. Duhrssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein and D. Zeppenfeld (2004)
R. Lafaye, T. Plehn, M. Rauch, D. Zerwas and M. Duhrssen (2009)
N. Desai, D. K. Ghosh and B. Mukhopadhyaya (2011)
M. Klute, R. Lafaye, T. Plehn, M. Rauch and D. Zerwas (2012)
A. Azatov, R. Contino, D. Del Re, J. Galloway, M. Grassi and S. Rahatlou (2012)

I. Low, J. Lykken and G. Shaughnessy (2012)
T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile and M. C. Gonzalez-Garcia (2012)
P. P. Giardino, K. Kannike, M. Raidal and A. Strumia (2012)
J. Baglio, A. Djouadi and R. M. Godbole (2012)
J. Ellis and T. You (2012)
M. Montull and F. Riva (2012)
J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott (2012)
D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan (2012)
S. Banerjee, S. Mukhopadhyay and B. Mukhopadhyaya (2012)
F. Bonnet, T. Ota, M. Rauch and W. Winter (2012)
T. Plehn and M. Rauch (2012)
A. Djouadi (2013)
B. Batell, S. Gori and L. T. Wang (2013)
G. Moreau (2013)

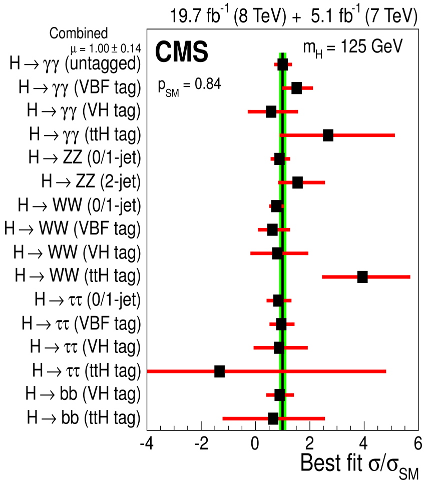
G. Bhattacharyya, D. Das and P. B. Pal (2013)
D. Choudhury, R. Islam and A. Kundu (2013)
G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml (2013)
M. Klute, R. Lafaye, T. Plehn, M. Rauch and D. Zerwas (2013)
K. Cheung, J. S. Lee and P. Y. Tseng (2013)
J. Ellis, V. Sanz and T. You (2013)
P. P. Giardino, K. Kannike, I. Masina, M. Raidal and A. Strumia (2014)
J. Ellis and T. You (2013)
A. Djouadi and G. Moreau (2013)
W. F. Chang, W. P. Pan and F. Xu (2013)
B. Dumont, S. Fichet and G. von Gersdorff (2013)
M. B. Einhorn and J. Wudka (2013)
A. Pomarol and F. Riva (2014)
... many more ...

The 125 GeV boson and its properties

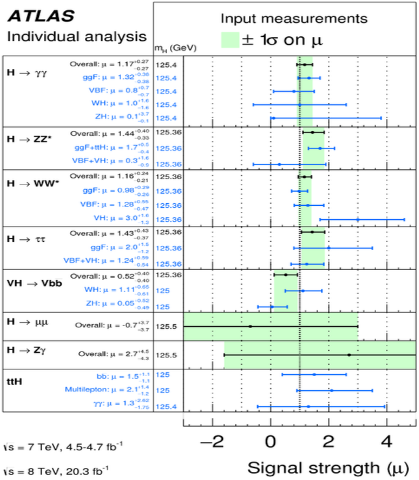
- The nature of the discovered boson is more or less consistent with the *SM* Higgs
- Its combined (CMS + ATLAS) mass is measured to be $M_H = 125.09 \pm 0.21$ (stat.) ± 0.11 (syst.) GeV in the $H \to \gamma\gamma$ and the $H \to ZZ^* \to 4\ell$ channels
- A *CP*-even spin zero hypothesis is favoured
- No more excess seen in the $\gamma\gamma$ channel
- If it is "the Higgs", then its mass has fixed the *SM*
- Crucial check : Independent measurement of self couplings
- Till a reliable measurement of self-coupling is available it is best to consider the available final states that reflect the Higgs couplings

Signal strengths (7 + 8 TeV @ 25 fb^{-1}) !!!

CMS



ATLAS



Case 1 : No new Lorentz structures in Higgs couplings

Higgs amplitudes are modified by multiplicative factors not changing its Lorentz structure

SB, S.Mukhopadhyay, B.Mukhopadhyaya

Updated with the most recent results from the LHC (as shown in the previous slide) !!!

Modified Higgs couplings ...

To fermions

- Higgs couplings to $T_3 = +1/2$ and $-1/2$ fermions can have separate deviations from SM values

$$\mathcal{A}^{eff}_{H\bar{t}t} = e^{i\delta}\alpha_u \mathcal{A}^{SM}_{H\bar{t}t}$$
$$\mathcal{A}^{eff}_{H\bar{b}b} = \alpha_d \mathcal{A}^{SM}_{H\bar{b}b}$$

- *Yukawa* couplings modifications
- *Absorptive phase in top effective loop amplitude (shows up in top and W* loop interference in $H \to \gamma\gamma$) more

To weak bosons

- Higgs couplings to W and Z bosons can be parametrized as

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

- $\beta_W \neq \beta_Z$ can arise from more
  - Gauge-invariant operators of higher dimensions
  - Extended higgs sectors (Higgs triplets etc.)
- Completely model-independent study

Modified Higgs couplings to pairs of gluons and photons

- Such couplings are parametrized as

$$\mathcal{L}_{gg}^{eff} = -x_g f(\alpha_u) \frac{\alpha_s}{12\pi v} H G^a_{\mu\nu} G^{a\mu\nu}$$

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

- f and g : Functions of modified Higgs couplings to fermions and weak bosons
- x_g and x_γ : Effects of new coloured (uncoloured) states in the loops

Possible Higgs invisible width

- Higgs can decay invisibly in a number of models.
- We do not adhere to any specific model.
- Higgs may decay invisibly to a pair of "dark matter" candidates.
- We define a Higgs invisible branching ratio, ϵ as

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

  where Γ_{vis} is the Higgs visible decay width
- All modifications in the Higgs couplings affect ϵ

Channel : ZH, Bound : 75 % at 95% CL, VBF, Bound : 29 % at 95% CL
Assumption : SM production cross section [ATLAS Collaboration] (2014, 2015)
Channels : VBF + ZH, Bound : 58 % at 95% CL, Assumption : SM production cross sections [CMS Collaboration] (2014)

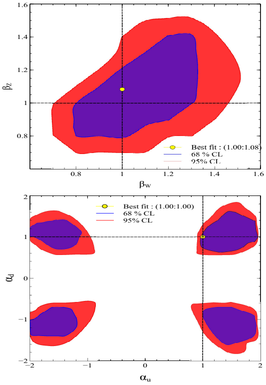
Finding allowed values of parameters

- **Task** : To find the allowed values of the parameters, α_u, α_d, β_W, β_Z, x_g, x_γ, δ and ϵ
- **Method** :
  - Construct a χ^2 function defined as
    $$\chi^2 = \sum_i \frac{(\mu_i - \hat{\mu}_i)^2}{\sigma_i^2}$$
    $$\mu_i = R_i^{prod} \times R_i^{decay} / R^{width}$$ more
    R and μs are functions of the parameters
  - Minimise the χ^2 function w.r.t the parameters
  - Find 95.45% CL reach for each of the parameters about χ^2_{min}

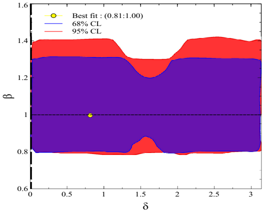
- Best-fit values of $\hat{\mu} = \sigma_{obs}/\sigma_{SM}$ along with their 1σ uncertainties ($7 + 8$ TeV), σ for each of the channels $H \to WW^*, ZZ^*, \gamma\gamma, \tau\bar{\tau}, b\bar{b}$ for various production modes of the Higgs from *CMS* and *ATLAS*.
- Signal-strengths in $WW^*, \gamma\gamma, b\bar{b}, \tau\bar{\tau}$ from Tevatron.
- Two cases : Case-A has $\beta_W \neq \beta_Z$ and $\delta = 0$ and Case-B has $\beta_W = \beta_Z$ and $\delta \neq 0$

Allowed regions in parameter space ...

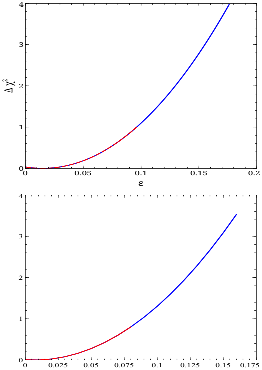
95% CL marginalised contours in Case-A (top : β_W vs β_Z, bottom : α_u vs α_d)



95% CL marginalised contours in Case-B β vs δ



Higgs invisible BR, ϵ, Case-A (top) and Case-B (bottom) at 95.45 % CL



Conclusions from this section ...

- Best-fit values of parameters

Case	α_u	α_d	δ	β_W	β_Z	x_g	x_γ	ϵ
A ($\beta_W \neq \beta_Z$ and $\delta = 0$)	1.00	1.00	0.0	1.00	1.08	1.00	0.99	0.00
B ($\beta_W = \beta_Z$ and $\delta \neq 0$)	1.00	1.00	0.81	1.00	1.00	1.00	1.06	0.00

- A fermiophobic higgs is more or less disfavoured (at least in this simple framework).
- The 8 TeV run puts stronger constraints on the Higgs invisible BR.
- Negative yukawa couplings though disfavoured (compared to the data which came out in 2012) has still not been ruled out completely. Precise measurement of Higgs production cross-section with a single top quark (and another quark) will hopefully shed more light on the sign of the $Ht\bar{t}$ coupling. [CMS-PAS-HIG-14-001]

Case 2 : New Lorentz structures in Higgs couplings

Beyond multiplicative modifications in the HVV couplings

Many studies in this direction ...

T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile and M. C. Gonzalez-Garcia (2013)
E. Masso and V. Sanz (2013)
A. Djouadi, R. M. Godbole, B. Mellado, K. Mohan (2013)
A. Falkowski, F. Riva and A. Urbano (2013)
S. Banerjee, S. Mukhopadhyay and B. Mukhopadhyaya (2013)
J. Elias-Miro, J. R. Espinosa, E. Masso and A. Pomarol (2013)
C. Grojean, E. E. Jenkins, A. V. Manohar and M. Trott (2013)
R. Contino, M. Ghezzi, C. Grojean, M. Muhlleitner and M. Spira (2013)
John Ellis, Veronica Sanz and Tevong You (2014)
Adam Alloul, Benjamin Fuks and Veronica Sanz (2013)
James S. Gainer, Joseph Lykken, Konstantin T. Matchev, Stephen Mrenna, Myeonghun Park (2013 and 2014)

... many more ...

Case 2.1 : Higher dimensional operators @ LHC

Here we study the HVV couplings with new Lorentz structures, in the context of the LHC.

SB, S.Mukhopadhyay, B.Mukhopadhyaya (2013)

New : Modified cut-efficiencies due to anomalous couplings !!!

Gauge invariant operators

- Obtained by integrating out new physics above a scale Λ
- $SU(2) \times U(1)$ invariant
- Production vertices mostly affected by such operators
- Another common formulation
  - Example : $H(k)W^+_\mu(p)W^-_\nu(q)$ vertex parametrized as $i\Gamma^{\mu\nu}(p,q)\epsilon_\mu(p)\epsilon^*_\nu(q)$, with $\Gamma^{\mu\nu}_{SM}(p,q) = -gM_W g^{\mu\nu}$ and $\Gamma^{BSM}_{\mu\nu}(p,q) = \frac{g}{M_W}[\lambda[(p.q)g_{\mu\nu} - p_\nu q_\mu] + \lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma]$, λ (λ') is the effective strength for the anomalous CP-conserving (CP-violating) operators
  - Easier formalism, more experiment friendly
  - Does not take into account the correlations between various HVV couplings explicitly
  - The $D = 6$ operators have the inherent attribute of relating all the Higgs couplings

Gauge-invariant dimension 6 operators : Higgs-Gauge sector

- The operators containing the Higgs doublet Φ and its derivatives [W. Buchmuller and D. Wyler], [B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek] :

$$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\Phi\Phi^\dagger(D^\mu\Phi); \quad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi); \quad \mathcal{O}_{\Phi,3} = \frac{1}{3}(\Phi^\dagger\Phi)^3$$

- The operators containing the Higgs doublet Φ (or its derivatives) and bosonic field strengths :

$$\mathcal{O}_{GG} = \Phi^\dagger\Phi G^a_{\mu\nu}G^{a\,\mu\nu}; \quad \mathcal{O}_{BW} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi; \quad \mathcal{O}_{WW} = \Phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$$

$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi); \quad \mathcal{O}_{BB} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi; \quad \mathcal{O}_{B} = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi),$$

$\hat{W}^{\mu\nu} = i\,\frac{g}{2}\sigma_a W^{a\,\mu\nu}$, $\hat{B}^{\mu\nu} = i\,\frac{g}{2}'B^{\mu\nu}$; $\quad g,\ g'$: $SU(2)_L$, $U(1)_Y$ gauge couplings

$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g\epsilon^{abc}W^b_\mu W^c_\nu$; $\quad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$

$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_s f^{abc}G^b_\mu G^c_\nu$

Φ : Higgs doublet, $D_\mu\Phi = (\partial_\mu + \frac{i}{2}g'B_\mu + ig\frac{\sigma_a}{2}W^a_\mu)\Phi$: Covariant derivative

Effective Lagrangian

The Higgs sector Lagrangian can be written as [a]

$$\mathcal{L} = \kappa \left(\frac{2m_W^2}{v} H W_\mu^+ W^{\mu -} + \frac{m_Z^2}{v} H Z_\mu Z^\mu \right) + \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$$

The effective Lagrangian due to the $D = 6$ operators which affects the Higgs sector is

$$\begin{aligned}\mathcal{L}_{eff} =& g^{(1)}_{HWW} \; (W^+_{\mu\nu} W^{-\mu} \partial^\nu H + h.c.) + g^{(2)}_{HWW} \; H W^+_{\mu\nu} W^{-\mu\nu} \\ & + g^{(1)}_{HZZ} \; Z_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_{HZZ} \; H Z_{\mu\nu} Z^{\mu\nu} \\ & + g^{(1)}_{HZ\gamma} \; A_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_{HZ\gamma} \; H A_{\mu\nu} Z^{\mu\nu} + g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu}\end{aligned}$$

which have different Lorentz structures than the SM one.

[a] κ and β are used interchangeably. They are the same.

$$g^{(1)}_{HWW} = \left(\frac{gM_W}{\Lambda^2}\right) \frac{f_W}{2}$$

$$g^{(2)}_{HWW} = -\left(\frac{gM_W}{\Lambda^2}\right) f_{WW}$$

$$g^{(1)}_{HZZ} = \left(\frac{gM_W}{\Lambda^2}\right) \frac{c^2 f_W + s^2 f_B}{2c^2}$$

$$g^{(2)}_{HZZ} = -\left(\frac{gM_W}{\Lambda^2}\right) \frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2}$$

$$g^{(1)}_{HZ\gamma} = \left(\frac{gM_W}{\Lambda^2}\right) \frac{s(f_W - f_B)}{2c}$$

$$g^{(2)}_{HZ\gamma} = \left(\frac{gM_W}{\Lambda^2}\right) \frac{s(s^2 f_{BB} - c^2 f_{WW})}{c}$$

$$g_{H\gamma\gamma} = -\left(\frac{gM_W}{\Lambda^2}\right) \frac{s^2(f_{BB} + f_{WW})}{2}$$

with $s\,(c)$ being the sine (cosine) of the Weinberg angle.

Modified efficiencies

- We do not assume the efficiencies of experimental cuts for various final states to be same as the corresponding SM ones.
- Global fits performed by comparing experimentally obtained signal strength ($\hat{\mu}_{X\bar{X}}$) in a particular channel $X\bar{X}$ with the signal strength predicted by a particular framework beyond the SM, defined as

$$\mu_{X\bar{X}} = \frac{\left[\sigma(pp \to H) \times \mathrm{BR}(H \to X\bar{X}) \times \epsilon_{X\bar{X}}\right]_{\mathrm{BSM}}}{\left[\sigma(pp \to H) \times \mathrm{BR}(H \to X\bar{X}) \times \epsilon_{X\bar{X}}\right]_{\mathrm{SM}}},$$

- $\epsilon_{X\bar{X}}$: efficiency of experimental cuts applied to select a particular final state.
- $(\epsilon_{X\bar{X}})_{BSM} = (\epsilon_{X\bar{X}})_{SM}$: if Higgs couplings only receive multiplicative modifications to the SM one → not clear if this holds after including different Lorentz structures to the couplings. Kinematic distributions will get modified.

Simulation and its validation

- We consider the $H \to WW^* + 2j, WW^* \to \ell^+ \nu \ell^- \bar{\nu}$ ($\ell = \{e, \mu\}$) channel which includes contributions from both *VBF* and *VH* production modes.
- Cut-flow table by *ATLAS* used for validating our Monte Carlo. ▸ more
- *FeynRules*, *MadGraph*, *Pythia* − 6 used for analysing hadron level events.
- Our MC cut efficiencies match within $\sim 5\%$ of the *ATLAS* results for most of the cuts.

Cut	ATLAS efficiency	Our MC efficiency
$N_{b-jet} = 0$	0.68-0.76 (0.72)	0.74
$p_T^{tot} < 45$	0.81-0.93 (0.87)	0.88
$Z \to \tau\tau$ veto	0.86-1.00 (0.92)	0.95
$\|\Delta y_{jj}\| > 2.8$	0.45-0.51 (0.48)	0.50
$m_{jj} > 500$	0.61-0.64 (0.62)	0.53
No jets in y gap	0.82-0.86 (0.84)	0.81
Both l in y gap	0.94-1.00 (0.97)	0.95
$m_{ll} < 60$	0.87-0.93 (0.90)	0.95
$\|\Delta\phi_{ll}\| < 1.8$	0.89-0.96 (0.93)	0.92

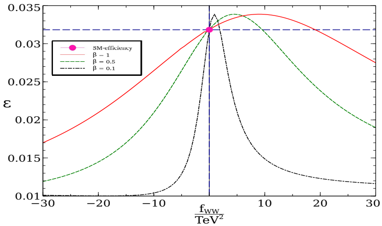
Cut-efficiencies of the signal (*VBF* + *VH*) cross section in the $H \to WW^* \to \ell^+ \nu \ell^- \bar{\nu}$ channel, for the $N_{jet} \geq 2$ category (*ATLAS* @ 8 TeV), demanding different flavour leptons ($e^+\mu^- + \mu^+ e^-$) in the final state.

Modified efficiencies and signal strengths

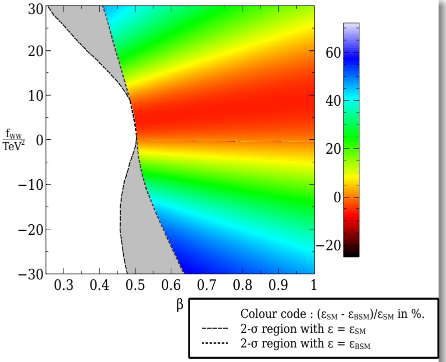
Considering $\mathcal{O}_{WW}$ only, the efficiency as a function of f_{WW} and κ is given by

$$\epsilon_{WW^*+\geq 2-\text{jets}}(\kappa, f_{WW}) = \frac{\left[\sigma(pp \to H)_{\text{VBF+VH}} \times \text{BR}(H \to WW^*)\right]_{\text{After Cuts}}}{\left[\sigma(pp \to H)_{\text{VBF+VH}} \times \text{BR}(H \to WW^*)\right]_{\text{Before Cuts}}} =$$

$$\frac{50.98\kappa^4 + 121.76\kappa^3 f_{WW} + 22.85\kappa^2 f_{WW}^2 + 0.15\kappa f_{WW}^3 + 0.01 f_{WW}^4}{1601.43\kappa^4 + 3796.63\kappa^3 f_{WW} + 666.79\kappa^2 f_{WW}^2 - 1.98\kappa f_{WW}^3 + 0.73 f_{WW}^4}$$



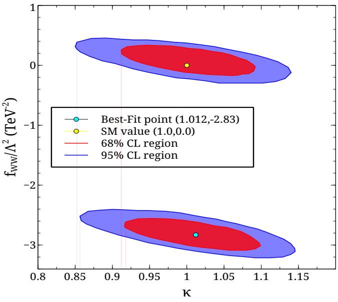
Combined efficiency of all *ATLAS* cuts (ϵ) as a function of f_{WW}



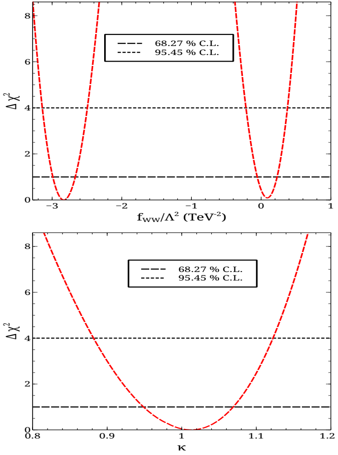
% modification of combined efficiency of all cuts compared to SM case. 95.45% CL region after imposing the *ATLAS* (8 TeV) signal-strength constraint in $H \to WW^* \to 2l2\nu$ in ≥ 2 jets category. Grey region : $\epsilon_{BSM} = \epsilon_{SM}$

Global analysis with LHC data

68.27% and 95.45% CL allowed regions in the $\kappa - f_{WW}$ parameter space, after performing a global fit using the data in all bosonic channels given in table. The best-fit and SM points are also shown.



Marginalised plots



Case 2.2 : Observables to disentangle new physics @ 14 TeV $HL - LHC$

Here we propose observables to measure the anomalous HVV couplings in the context of 14 TeV $HL - LHC$

SB, T. Mandal, B. Mellado, B. Mukhopadhyaya

The premise

- The HD operator coefficients are constrained to values of $\mathcal{O}(1)/\text{TeV}^2$
- Kinematic variables can show very little variations w.r.t. the *SM* for such small coefficients
- One can do a multi-variate analysis (future plan) to probe such small couplings
- One can construct observables sensitive to even small values of the operator coefficients
- Cross-sections and decay widths are sensitive observables
- If we construct ratios, many correlated uncertainties get cancelled

The ratio $\mathcal{R}_1$

$$\mathcal{R}_1(f_i) = \frac{\sigma_{\rm ggF} \times {\rm BR}_{H\to\gamma\gamma}(f_i)}{\sigma_{\rm ggF} \times {\rm BR}_{H\to WW^*\to 2\ell 2\nu}(f_i)}$$

where $\ell = e, \mu$ and f_i's are the operator coefficients.

- Puts very strong bounds on $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$; insensitive to the other two operators $\mathcal{O}_W$ and $\mathcal{O}_B$
- $f_{WW} \approx f_{BB}$ allowed region $\approx [-2.76, -2.65] \cup [-0.06, 0.04]$ TeV^{-2}

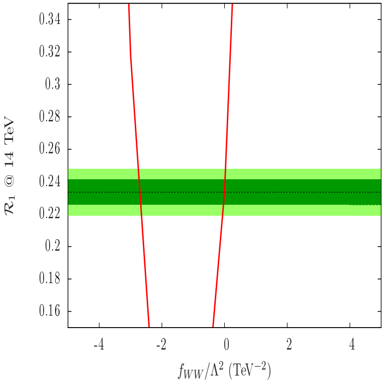


Figure : $\mathcal{R}_1$ versus f_{WW}/Λ^2 (TeV^{-2}). Red line → theoretical expectation in presence of HDOs; Dark green band → uncorrelated theoretical uncertainty; Light green band → total uncorrelated uncertainty at 14 TeV with 3000 fb^{-1} integrated luminosity; Black dotted line → central value.

The ratio $\mathcal{R}_2$

$$\mathcal{R}_2(f_i) = \frac{\sigma_{\rm VBF}(f_i) \times {\rm BR}_{H\to\gamma\gamma}(f_i)}{\sigma_{\rm WH}(f_i) \times {\rm BR}_{H\to\gamma\gamma}(f_i) \times {\rm BR}_{W}}$$

- We consider the bounds from $\mathcal{R}_1$ for $\mathcal{O}_{WW}$ and see that even such small values can be probed at 14 TeV $HL-LHC$
- f_{WW}/Λ^2 excluded region : $[-1.96, +1.62]$ TeV^{-2}, f_W/Λ^2 excluded region : $[-2.10, +2.50]$ TeV^{-2}

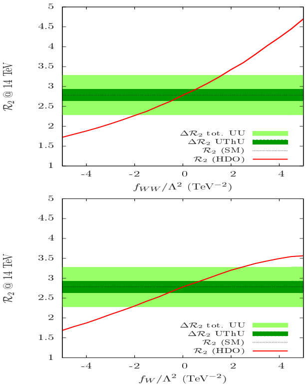


Figure : $\mathcal{R}_2$ versus (a) f_{WW}/Λ^2 (TeV^{-2}), (b) f_W/Λ^2 (TeV^{-2}). Red line $\to$ theoretical expectation in presence of HDOs; Dark green band $\to$ uncorrelated theoretical uncertainty; Light green band $\to$ total uncorrelated uncertainty at 14 TeV with 3000 fb^{-1} integrated luminosity; Black dotted line $\to$ central value.

The ratio $\mathcal{R}_3$

$$\mathcal{R}_3(f_i) = \frac{\sigma_{\rm ggF} \times {\rm BR}_{H\to Z\gamma\to 2\ell\gamma}(f_i)}{\sigma_{\rm ggF} \times {\rm BR}_{H\to WW^*\to 2\ell 2\nu}(f_i)}$$

- $\mathcal{O}_B$ sensitive only to the ZZ^* and $Z\gamma$ channels.
- Sensitivity to ZZ^* is negligible. Sensitivity to $Z\gamma$ is strong, but $H\to Z\gamma$ is not yet measured.
- Projected bounds f_B/Λ^2 is $[-8.44,-7.17]\cup[-0.72,+0.56]$ TeV^{-2}.

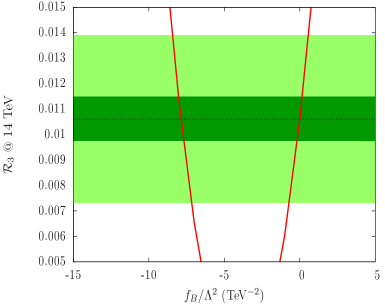


Figure : $\mathcal{R}_3$ versus f_B/Λ^2 (TeV^{-2}). Red line $\to$ theoretical expectation in presence of HDOs; Dark green band $\to$ uncorrelated theoretical uncertainty; Light green band $\to$ total uncorrelated uncertainty at 14 TeV with 3000 fb^{-1} integrated luminosity; Black dotted line $\to$ central value.

Ranges of $\mathcal{R}_1, \mathcal{R}_2$ and $\mathcal{R}_3$

Observable	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_W$	$\mathcal{O}_B$
$\mathcal{R}_1$ @ 7+8 TeV	$[-3.32, -2.91] \cup [+0.12, +0.57]$	$[-3.32, -2.91] \cup [+0.12, +0.57]$	Not bounded	Not bounded
$\mathcal{R}_1$ @ 14 TeV	$[-2.76, -2.65] \cup [-0.06, +0.04]$	$[-2.76, -2.65] \cup [-0.06, +0.04]$	Not bounded	Not bounded
$\mathcal{R}_2$ @ 14 TeV	$[-1.96, +1.62]$	Not bounded	$[-2.10, +2.50]$	Not bounded
$\mathcal{R}_3$ @ 14 TeV	Not used	Not used	Not used	$[-8.44, -7.17] \cup [-0.72, +0.56]$

Table : We summarize our obtained allowed region of the coefficients of HDOs using the three observables. $\mathcal{R}_3$ is not used to constrain the operators $\mathcal{O}_{WW}, \mathcal{O}_{BB}$ and $\mathcal{O}_W$.

Summary and conclusions

- Higgs anomalous couplings can have multiplicative corrections or can have new Lorentz structures
- Present data bounds the multiplicative parameters to near-*SM* values
- Small but finite invisible decay width still allowed by data
- The efficiencies for various acceptance cuts are altered for varying values of f and κ.
- The change can be as large as 50% for certain channels.
- On imposing a global fit to the data, we find that a modest range of (f, κ) is allowed.

Summary and conclusions

- The *VBF* channel is more sensitive to the HD operators when compared to the gluon fusion channel.
- Assumption of specific *UV*-completion is avoided. In a specific *UV*-completion scheme, more than one operators can be generated. It might affect some of our conclusions.
- Studying one operator at a time gives us insight into how it typically affects various observables in the Higgs sector.
- Various ratios can be used to see the effect of small values of operator coefficients.
- Multivariate analyses can be helpful in magnifying the otherwise small differences in kinematic distribution $\rightarrow$ future study

Backup slides

Forms of R

Production

- $R_{GF} = x_g^2 \alpha_u^2$
- $R_{ZH} = \beta_Z^2$
- $R_{WH} = \beta_W^2$
- $R_{t\bar{t}H} = \alpha_u^2$
- $R_{VBF} \simeq \frac{3\beta_W^2 + \beta_Z^2}{4}$

Decay

- $R_{ZZ*} = \beta_Z^2$
- $R_{WW*} = \beta_W^2$
- $R_{\tau\bar{\tau}} = \alpha_d^2$
- $R_{b\bar{b}} = \alpha_d^2$
- $R_{c\bar{c}} = \alpha_u^2$
- $R_{gg} = x_g^2 \alpha_u^2$
- $R_{\gamma\gamma} = x_\gamma^2 \frac{|\frac{4}{3}\alpha_u e^{i\delta} A^H_{1/2}(\tau_t) + \frac{1}{3}\alpha_d A^H_{1/2}(\tau_b) + \alpha_d A^H_{1/2}(\tau_\tau) + \beta_W A^H_1(\tau_W)|^2}{|\frac{4}{3} A^H_{1/2}(\tau_t) + \frac{1}{3} A^H_{1/2}(\tau_b) + A^H_{1/2}(\tau_\tau) + A^H_1(\tau_W)|^2}$

back

Loop functions

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

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

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

In the above equations τ_i denotes the ratio $m_H^2/4m_i^2$.

$\beta_W \neq \beta_Z$ allowance

- $\beta_W \neq \beta_Z \rightarrow$ breakdown of custodial $SU(2) \rightarrow$ restricted by T-parameter
- Such anomalous couplings can arise, for example, from gauge invariant effective operators, an example being $\mathcal{O}_{\Phi_1}$
- This operator in itself gives rise to unequal β_W and β_Z
- Taking this operator alone, precision constraints yield the limits :

$$0.991 \lesssim \beta_W \lesssim 1.001$$
$$0.997 \lesssim \beta_Z \lesssim 1.028$$

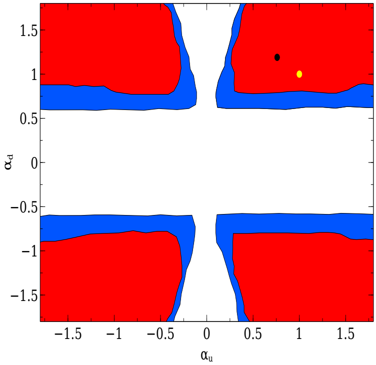
back

The absorptive phase

- 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. [L.Covi (1997)]
- For 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.

back

Case B : α_u vs α_d (marginalised) ... old data



Global analysis with LHC data

- We use the results of the bosonic decay channels of *ATLAS* and *CMS*.

Channel	ATLAS	CMS
$H \to \gamma\gamma$	$1.17^{+0.27}_{-0.27}$	$1.14^{+0.26}_{-0.23}$
$H \to WW^*$	$1.09^{+0.23}_{-0.21}$	$0.83^{+0.21}_{-0.21}$
$H \to ZZ^*$	$1.44^{+0.40}_{-0.33}$	$1.00^{+0.29}_{-0.29}$
$H \to WW^* + 2-\text{jets}$	$1.27^{+0.53}_{-0.45}$	$0.62^{+0.58}_{-0.47}$

Table : *Signal strengths measured by the ATLAS and CMS collaborations, for the bosonic final states.*

back

Decay width parametrizations

- The partial widths (in GeV) in the relevant decay channels are parametrized as :

$$
\begin{aligned}
\Gamma_{H\to WW^*} &= 8.61\times10^{-4}\kappa^2 + 8.51\times10^{-6}\kappa f_{WW} + 2.95\times10^{-8} f_{WW}^2 \\
\Gamma_{H\to ZZ^*} &= 9.28\times10^{-5}\kappa^2 + 4.77\times10^{-7}\kappa f_{WW} + 1.00\times10^{-9} f_{WW}^2 \\
\Gamma_{H\to\gamma\gamma} &= 8.59\times10^{-7} - 8.04\times10^{-6}\kappa - 4.36\times10^{-6} f_{WW} \\
&\quad +1.77\times10^{-5}\kappa^2 + 1.98\times10^{-5}\kappa f_{WW} + 5.68\times10^{-6} f_{WW}^2 \\
\Gamma_{H\to Z\gamma} &= 3.75\times10^{-8} - 7.91\times10^{-7}\kappa - 5.65\times10^{-7} f_{WW} \\
&\quad +7.12\times10^{-6}\kappa^2 + 1.06\times10^{-5}\kappa f_{WW} + 3.82\times10^{-6} f_{WW}^2
\end{aligned}
$$

back

Total decay width and production cross section parametrizations

- The total Higgs boson width can be parametrized as

$$\Gamma_{\rm tot} = [3.07 - 7.82 \times 10^{-3}\kappa - 4.37 \times 10^{-3} f_{WW} + 0.97\kappa^2 + 3.67 \times 10^{-2}\kappa f_{WW} + 8.76 \times 10^{-3} f_{WW}^2] \times 10^{-3}\,{\rm GeV}$$

- The tree-level total cross section for the *VBF* and *VH* processes at 8 TeV *LHC*, before the application of selection cuts, can be expressed as follows

$$\sigma_{pp \to H+2-{\rm jets}}({\rm VBF} + {\rm VH}) = \left(1.473\kappa^2 - 0.022\kappa f_{WW} + 0.002 f_{WW}^2\right)\,{\rm pb}$$

back

Global analysis with LHC data

- Measurement of the inclusive cross section at 8 TeV *LHC* in the WW^* channel has been reported by *ATLAS*, after unfolding all detector effects, and it is found to be (for $m_H = 125$ GeV)

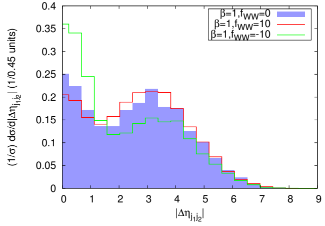
$$\sigma(pp \to H) \times \mathrm{BR}(H \to WW^*)_{ggF} = 4.6 \pm 1.1 \text{ pb}$$
$$\sigma(pp \to H) \times \mathrm{BR}(H \to WW^*)_{VBF} = 0.51^{+0.22}_{-0.17} \text{ pb}$$

  which are slightly more than the expected *SM* cross sections (4.2 ± 0.5 pb) (ggF) and (0.35 ± 0.02 pb) (VBF), but consistent with them within the uncertainties.

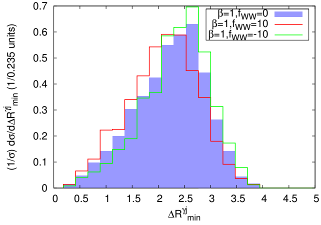
Modification to kinematic distributions : examples

- Here we consider $H \to \gamma\gamma$ in the VBF channel.
- All the distributions (@ 8 TeV LHC) are shown after applying the standard trigger and isolation cuts for the photons and the jets.

$|\Delta\eta_{j_1 j_2}|$



$\Delta R^{\gamma j}_{\rm min}$



N.B. : β and κ have been used interchangeably.

Anomalous VVV interactions

We also consider the anomalous VVV interactions by

$$\mathcal{L}_{WWV} = -ig_{WWV}\{g_1^V \left(W^+_{\mu\nu}W^{-\mu}V^{\nu} - W^+_{\mu}V_{\nu}W^{-\mu\nu}\right) + \kappa_V W^+_{\mu}W^-_{\nu}V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^+_{\mu\nu}W^{-\nu\rho}V_{\rho}^{\mu}\}$$

where $g_{WW\gamma} = g\,s$, $g_{WWZ} = g\,c$, $\kappa_V = 1 + \Delta\kappa_V$ and $g_1^Z = 1 + \Delta g_1^Z$ with

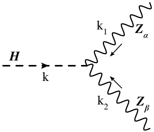
$$\Delta\kappa_\gamma = \frac{M_W^2}{2\Lambda^2}\left(f_W + f_B\right); \quad \lambda_\gamma = \lambda_Z = \frac{3g^2M_W^2}{2\Lambda^2}f_{WWW}$$

$$\Delta g_1^Z = \frac{M_W^2}{2c^2\Lambda^2}f_W; \quad \Delta\kappa_Z = \frac{M_W^2}{2c^2\Lambda^2}\left(c^2f_W - s^2f_B\right)$$

Operator properties

- $\mathcal{O}_{\Phi,1}$: Does not preserve custodial symmetry and is severely constrained by the T-parameter
- $\mathcal{O}_{\Phi,2}$: Preserves custodial symmetry and modifies the SM HVV couplings by multiplicative factors (same Lorentz structure)
- $\mathcal{O}_{\Phi,3}$: Modifies only the Higgs self-interaction and gives an additional contribution to the Higgs potential
- $\mathcal{O}_{GG}$: Introduces HGG coupling with same Lorentz structure as in the SM (effective HGG coupling)
- $\mathcal{O}_{BW}$: Drives tree-level $Z \leftrightarrow \gamma$ mixing and is therefore highly constrained by *EWPD* constraints
- $\mathcal{O}_{WW}$, $\mathcal{O}_{W}$, $\mathcal{O}_{BB}$, $\mathcal{O}_{B}$: Modifies the HVV couplings by introducing new Lorentz structure in the Lagrangian. They are not severely constrained by the *EWPD*

The amplitudes : An example



$$M = i\left(\frac{gM_W}{c}\right)[\kappa g^{\alpha\beta} + T^{\alpha\beta}]$$

$$T^{\alpha\beta} = \frac{1}{2\Lambda^2 c}\{4(s^4 f_{BB} + c^4 f_{WW})[g^{\alpha\beta}(k_1 \cdot k_2) - k_2^\alpha k_1^\beta] + (c^2 f_W + s^2 f_B)$$
$$\times[-g^{\alpha\beta}(k_1^2 + k_2^2 + 2k_1 \cdot k_2) + (k_1^\alpha k_1^\beta + 2k_2^\alpha k_1^\beta + k_2^\alpha k_2^\beta)]\}$$

Non-Higgs process

One f is varied keeping others fixed to zero and $\kappa = 1$

Non-Higgs operator at play : $\mathcal{O}_{WWW} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_{\rho}^{\mu}]$

- We also analyse $e^+e^- \to W^+W^-$ process to see the concomitant behaviour with Higgs processes
- Such a concomitant behaviour possible through such $D = 6$ operators

- σ variations small; strong ν_e mediated t-channel contribution; significant interference with the s-channel
- Strategy to tame down the t-channel effect $\to$ use right-polarised es in linear colliders