A Higgs or the Higgs ? A detailed look at anomalous Higgs couplings

Shankha Banerjee

Harish-Chandra Research Institute, Allahabad, India

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Based on

JHEP 1210, 062 (2012) and **Phys. Rev. D 89, 053010 (2014)**

(with S. Mukhopadhyay and B.Mukhopadhyaya)

and **arXiv:1405.3957**

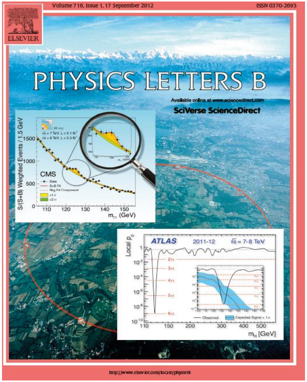
(with G. Amar, S. Buddenbrock, A. Cornell, T.Mandal, B.Mellado and B. Mukhopadhyaya)

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 @ *LHC*
    - Gauge invariant dimension-6 operators
    - Modified efficiencies
    - Global analysis
  - Study at an e^+e^- collider
    - Phenomenology
    - Cross-sections and their ratios
    - Observables
    - Illustrative plots with variation of parameters
- 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 ≈ 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 : $M_H = 125.03^{+0.26}_{-0.27}$ (stat.) $^{+0.13}_{-0.15}$ (syst.) GeV

ATLAS : $M_H = 125.37 \pm 0.36$ (stat.) ± 0.18 (syst.) GeV

The 125 GeV boson and its properties

- The nature of the discovered boson is more or less consistent with the *SM* Higgs
- 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
- Issues concerning Naturalness and vacuum stability are still open
- Time to make final comments on the nature of the boson ?
- It is still a bit early for final conclusions about the nature of the boson

Higgs signal strengths ...

Channel	$\hat{\mu}$	Experiment	Energy in TeV (Luminosity in fb^{-1})
$h \to \gamma\gamma$	$1.17^{+0.27}_{-0.27}$	ATLAS	7 (4.5) + 8 (20.3)
$h \to \gamma\gamma$	$1.14^{+0.26}_{-0.23}$	CMS	7 (5.1) + 8 (19.7)
$h \xrightarrow{ZZ^*} 4l$	$1.44^{+0.40}_{-0.33}$	ATLAS	7 (4.5) + 8 (20.3)
$h \xrightarrow{ZZ^*} 4l$	$1.00^{+0.29}_{-0.29}$	CMS	7 (5.1) + 8 (19.7)
$h \xrightarrow{WW^*} 2l2\nu$	$1.08^{+0.22}_{-0.20}$	ATLAS	7 (4.5) + 8 (20.3)
$h \xrightarrow{WW^*} 2l2\nu$	$0.83^{+0.21}_{-0.21}$	CMS	7 (5.1) + 8 (19.7)
$h \to b\bar{b}$	$0.52^{+0.40}_{-0.40}$	ATLAS (VH)	7 (4.7) + 8 (20.3)
$h \to b\bar{b}$	$0.93^{+0.49}_{-0.49}$	CMS (VH)	7 (5.1) + 8 (19.7)
$h \to \tau\bar{\tau}$	$1.42^{+0.44}_{-0.38}$	ATLAS	7 (4.5) + 8 (20.3)
$h \to \tau\bar{\tau}$	$0.91^{+0.27}_{-0.27}$	CMS	7 (5.1) + 8 (19.7)

Table: Data set used in our analysis, with the values of $\hat{\mu}_i$ (signal strengths) in various channels and their 1σ uncertainties as reported by the *ATLAS* and *CMS* collaborations.

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 ...

Effective couplings of the Higgs

- Global fits on Higgs data used extensively by experimentalists and theorists to derive bounds on possible departures from *SM*
- Deviations can either be parametrized by including a multiplicative factor to the *SM* coupling strengths or by including new Lorentz structures not present in the renormalisable *SM* Lagrangian
- Here we will consider *SM* as an effective field theory valid below a cut-off scale Λ
- Higher dimensional operators involving the *SM* fields and invariant under the *SM* gauge group are used to capture possible new physics effects

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 !!!

Modified Higgs couplings ...

To fermions

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

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

- *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

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

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

- 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, Assumption : SM production cross section [ATLAS Collaboration] (2014)

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

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

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

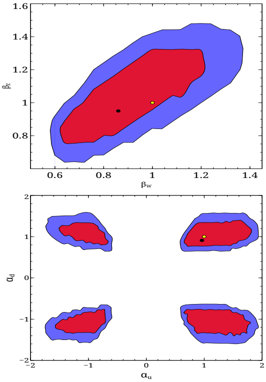
    more

    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}

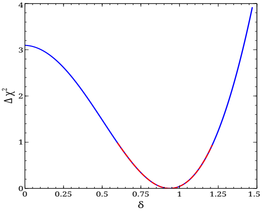
- Best-fit values of $\hat{\mu} = \sigma_{obs}/\sigma_{SM}$ along with their 1σ uncertainties ($7 + 8$ TeV), σ for each of the channels $H \to WW^*, ZZ^*, \gamma\gamma, \tau\bar{\tau}, b\bar{b}$ for various production modes of the Higgs from *CMS* and *ATLAS*.
- Signal-strengths in $WW^*, \gamma\gamma,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



Case B : δ at 95.45 % CL



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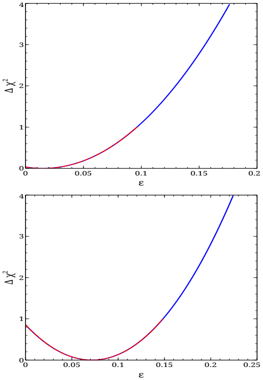
Higgs invisible BR, ϵ, Case-A (top) and Case-B (bottom) at 95.45 % CL



Case 2 : New Lorentz structures in Higgs couplings

Beyond multiplicative modifications in the HVV couplings

Many studies in this direction ...

E. Masso and V. Sanz (2013)

A. Falkowski, F. Riva and A. Urbano (2013)

S. Banerjee, S. Mukhopadhyay and B. Mukhopadhyaya (2013)

A. Pomarol and F. Riva (2014)

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)

T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile and M. C. Gonzalez-Garcia (2013)

... 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 !!!

Effective couplings of the Higgs

- Complete list of dimension-6 operators given in W. Buchmuller and D. Wyler. Minimal basis obtained rather recently in B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek.
- Such an approach valid till there is no light degree of freedom coupled to the SM sector below the scale Λ.
- *EWPD* constrain the overall strengths of these operators. These come from the one-loop contributions of these operators to the self-energy diagrams of the gauge bosons.

K.Hagiwara et. al.

- The Higgs couplings to the W, Z or γ can be affected at the tree level by a class of such operators $\rightarrow$ possible to impose stronger constraints from the *LHC* data.
- Such constraints have been derived in many recent studies using different parametrizations.

A.Falkowski et. al., , E.Masso et. al.

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:

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

- 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]

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

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

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

which have different Lorentz structures than the SM one.

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

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

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

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

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

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

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

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

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 $\to$ not clear if this holds after including different Lorentz structures to the couplings. Kinematic distributions will get modified.
- Such distributions studied with special emphasis on spin-parity determination of the newly discovered particle.

R.M.Godbole et.al., T.Plehn et. al

Modified efficiencies (continued)

- We focus on the $H \to WW^* + 2j$ final state
- Apart from the HD-operators, scaling of the SM-like coupling of the Higgs boson to the weak bosons allowed
- Custodial symmetry ensured
- Illustrative study : two HD-operators; taken one at a time
- More than one HD-operator can be present in the effective low energy theory with different coupling strengths
- Focuses on modified cut-efficiencies on introducing such operators
- Method developed here is general and can be extended to include all possible HD operators.

The operators considered

- We consider $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$ for illustrating our point
- Terms involving derivatives on gauge fields bring in momentum dependent vertices $\rightarrow$ modified kinematics in Higgs production in the *VBF* and *VH* channels.
- Kinematics affected most when the operators affect both the production and decay vertices. more more

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* $- 6$ and our own detector simulation code 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
$\lvert\Delta y_{jj}\rvert > 2.8$	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
$\lvert\Delta\phi_{ll}\rvert < 1.8$	0.89-0.96 (0.93)	0.92

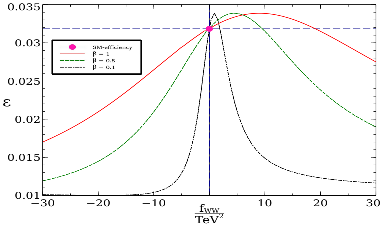
Cut-efficiencies of the signal (*VBF* + *VH*) cross section in the $H \to WW^* \to \ell^+ \nu \ell^- \bar{\nu}$ channel, for the $N_{jet} \geq 2$ category (*ATLAS* @ 8 TeV), demanding different flavour leptons ($e^+\mu^- + \mu^+e^-$) in the final state.

Modified efficiencies and signal strengths

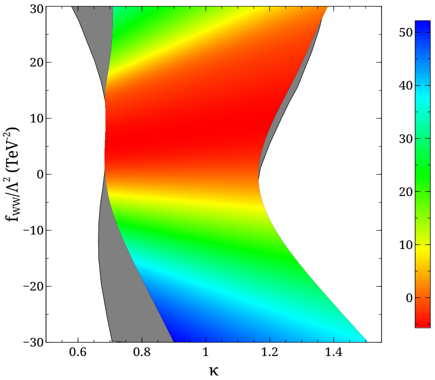
Considering $\mathcal{O}_{WW}$ only, the efficiency as a function of f_{WW} and κ is given by

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

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

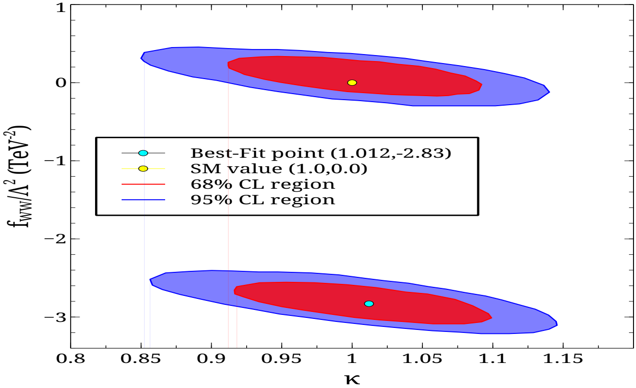


Combined efficiency of all *ATLAS* cuts (ϵ) as a function of f_{WW}



% 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 $\geq$ 2 jets category. Grey region : $\epsilon_{BSM} = \epsilon_{SM}$

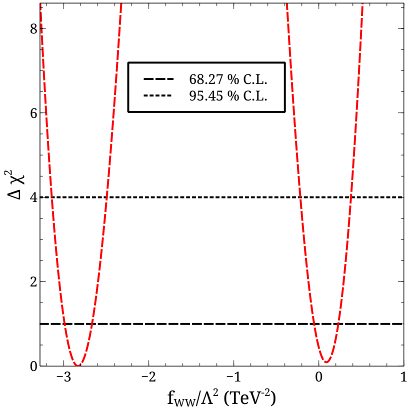
Global analysis with LHC data



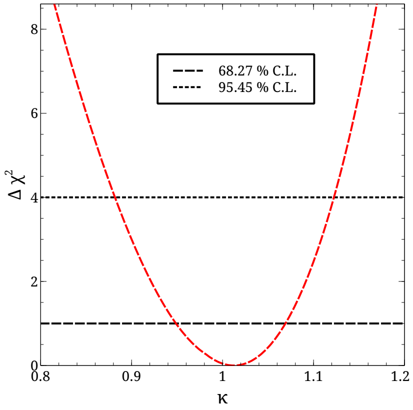
68.27% and 95.45% CL allowed regions in the $\kappa - f_{WW}$ parameter space, after performing a global fit using the data in all bosonic channels given in table. The best-fit and SM points are also shown.

Marginalised plots

$\Delta\chi^2$ vs f_{WW}/Λ^2



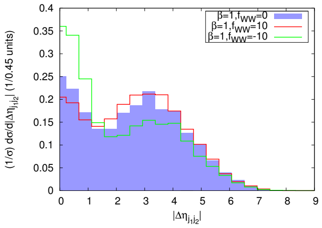
$\Delta\chi^2$ vs κ



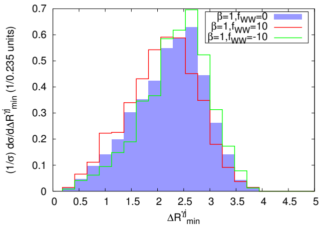
Modification to kinematic distributions : examples

- 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.

Case 2.2 : Higher dimensional operators @ e^+e^- colliders

Here we study the anomalous HVV couplings in the context of e^+e^- colliders (Higgs factories).

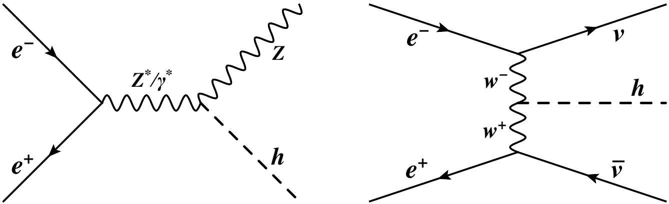
G.Amar, SB, S.Buddenbrock, A.Cornell, T.Mandal, B.Mellado and B.Mukhopadhyaya

14 TeV *LHC* and why e^+e^- colliders

- 14 TeV run at *LHC* will yield better statistics and hence couplings will be measured with less errors
- There will still be large backgrounds and uncertainties
- In an ongoing study in the context of 14 TeV, we are trying to probe anomalous couplings by looking at different kinematic regions for different channels, simultaneously
- e^+e^- colliders are relatively cleaner with lesser backgrounds
- Bremsstrahlung (ISR) and beamstrahlung effects are still there
- Experiments will try to reduce the loss of beam energies due to such effects ▸ more
- Following study is illustrative and does not include these effects
- For precision studies the beam energies nead to be convoluted such that beamstrahlung effects are taken into account
- Following study shows the importance of total rates and their ratios for disentangling anomalous couplings from *SM* ones

Phenomenology at an e^+e^- collider

Two main Higgs production processes are

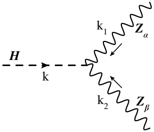


- $e^+e^- \to \nu\bar{\nu}H$ process is an admixture of s and t-channel processes
- Possible to separate s and t-channel from $e^+e^- \to \nu\bar{\nu}H$ events by applying

$$E_H\text{-cut:} \quad \left| E_H - \frac{S + M_H^2 - M_Z^2}{2\sqrt{S}} \right| \leq \Delta (= 5 \text{ GeV})$$

- $\Delta \sim \Delta E_{jet}$ where $\Delta E_{jet}/E_{jet} \lesssim 0.3/\sqrt{E_{jet}}$. For two b-jets each with energy 100 GeV, $\Delta E_{jet} = \sqrt{2 \times (0.3 \times \sqrt{100})^2} \sim 4$ GeV

The amplitudes : An example



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

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

- $\mathcal{M}_{e^+e^- \to ZH}$ is a linear combination of $x_i \in \{\kappa, f_{WW}, f_W, f_{BB}, f_B\}$
- Cross-section can always be expressed as a bilinear combination

$$\sigma_{ZH}(\sqrt{S}, x_i) = \sum_{i,j=1}^{5} x_i C_{ij}(\sqrt{S}) x_j$$

Fitted cross sections

$$\sigma(\sqrt{S}) = \mathcal{X} \cdot \mathcal{M}(\sqrt{S}) \cdot \mathcal{X}^T$$

where $\mathcal{X} = (\kappa, f_{WW}, f_W, f_{BB}, f_B)$ is a row vector on parameter-space

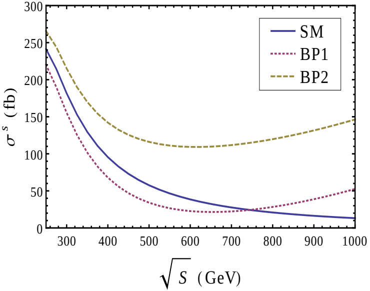
$$\mathcal{M}^s_{ZH}(300\ GeV) = \begin{pmatrix} 181.67 & -6.43 & -2.99 & -0.51 & -0.71 \\ -6.43 & 0.46 & 0.18 & -0.03 & -0.08 \\ -2.99 & 0.18 & 0.14 & -0.02 & -0.06 \\ -0.51 & -0.03 & -0.02 & 0.02 & 0.03 \\ -0.71 & -0.08 & -0.06 & 0.03 & 0.08 \end{pmatrix}$$

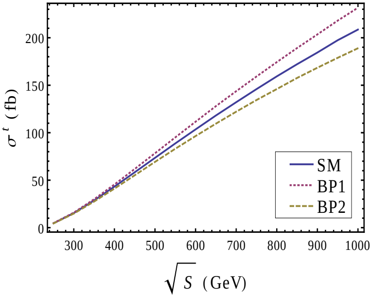
$$\mathcal{M}^t_{\nu\bar{\nu}H}(300\ GeV) = \begin{pmatrix} 15.36 & 0.04 & 0.07 \\ 0.04 & 1.2 \times 10^{-3} & -7.7 \times 10^{-4} \\ 0.07 & -7.7 \times 10^{-4} & 4.6 \times 10^{-4} \end{pmatrix}$$

- σ^s is less sensitive on $\mathcal{O}_{BB}$ and $\mathcal{O}_B$ but σ^t is almost insensitive to HDOs

σ vs. $\sqrt{S}$

Benchmark points: $BP1 = \{1, 0, 5, 0, 0\}$, $BP2 = \{1, 0, -5, 0, 0\}$ (allowed by *EWPD* constraints and *LHC* data)





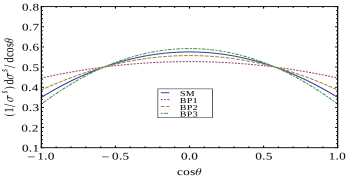
In the SM: $\sigma_{ZH} \sim 1/S$ and $\sigma^t_{\nu\bar{\nu}H} \sim \ln(S/M_H^2)$

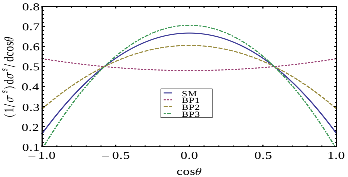
In presence of HDOs, the $\sqrt{S}$-dependency is non-trivial especially for the s-channel

θ_H distributions ...

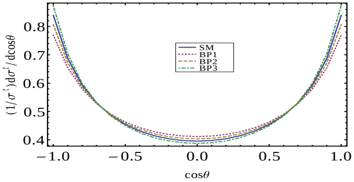
Benchmark points: $BP1 = \{1, 0, 5, 0, 0\}$, $BP2 = \{1, 0, -5, 0, 0\}$ and $BP3 = \{1, -3, 8, -4, 3\}$ (allowed by *EWPD* constraints and *LHC* data) [$\sqrt{s} = 300$ GeV (top row) and $\sqrt{s} = 500$ GeV (bottom row)]

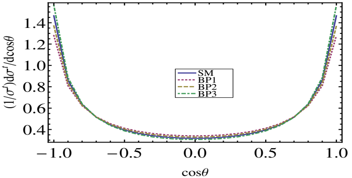
s-channel





t-channel





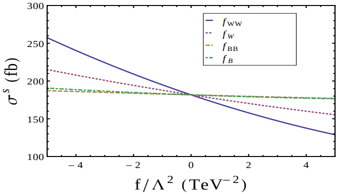
Observables

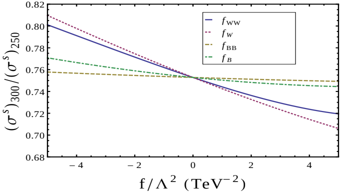
- At smaller *CME* ($\sim$ 250-300 GeV) (Energies at Higgs factories) and for smaller f's the above kinematic distributions are not good observables. There can be some other observables if we consider the full decay and it might give us some observable differences.
- For smaller *CME*, the *HDO*s are effectively adding a constant term to the *SM* vertex to scale up/down the total rate
- No significant change in distributions unless we make f's large and/or $\sqrt{S}$ large to boost up the momentum dependent terms
- Total rates are good observables at smaller *CME*
- s and t-channel have different kinematics and hence affected differently by momentum-dependent interactions
- Good observables: $\sigma^s(\sqrt{S_1})$, $\sigma^t(\sqrt{S_1})$, $\sigma^s(\sqrt{S_2})$, $\sigma^t(\sqrt{S_2})$
- Better observables: $\frac{\sigma^s(\sqrt{S_1})}{\sigma^s(\sqrt{S_2})}$, $\frac{\sigma^t(\sqrt{S_1})}{\sigma^t(\sqrt{S_2})}$, $\frac{\sigma^s(\sqrt{S_1})}{\sigma^t(\sqrt{S_1})}$, $\frac{\sigma^s(\sqrt{S_2})}{\sigma^t(\sqrt{S_2})}$

Varying one parameter at a time ...

$\kappa = 1$ and only one f is varied keeping others fixed at zero.

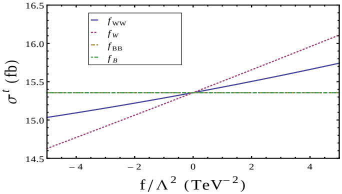
s-channel

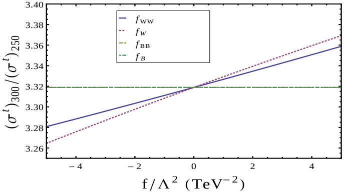




Top: σ^s_{300} (fb); Bottom: $\sigma^s_{300}/\sigma^s_{250}$

t-channel





Top: σ^t_{300} (fb); Bottom: $\sigma^t_{300}/\sigma^t_{250}$

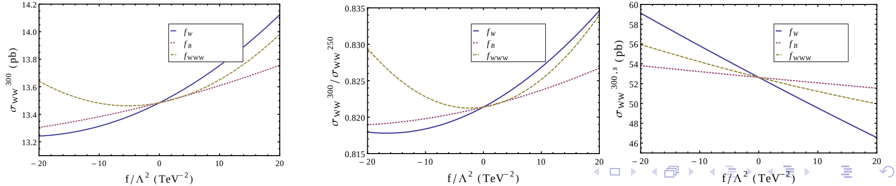
Non-Higgs process

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 → use right-polarised es in linear colliders

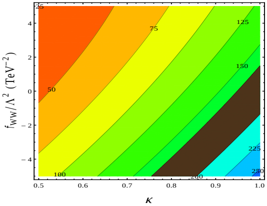


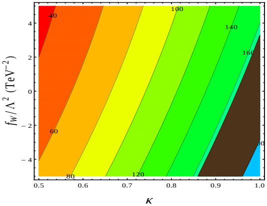
Varying two parameters at the same time ...

Two parameters are varied keeping others fixed ($\sqrt{S} = 300$ GeV).

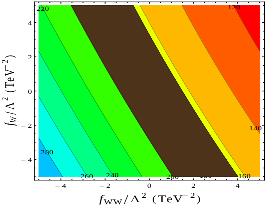
Brown patches signify $\sigma_{SM} \pm \sigma_{SM} \times 10\%$

s-channel





s-channel



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
- In the e^+e^- sector, the total rates can be very important observables
- Different ratios of s and t-channel cross sections at fixed or variable *CME*s can be important probes
- 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

- $R_{ZZ*} = \beta_Z^2$
- $R_{WW*} = \beta_W^2$
- $R_{\tau\bar{\tau}} = \alpha_d^2$
- $R_{b\bar{b}} = \alpha_d^2$
- $R_{c\bar{c}} = \alpha_u^2$
- $R_{gg} = x_g^2 \alpha_u^2$
- $R_{\gamma\gamma} = x_\gamma^2 \frac{|\frac{4}{3}\alpha_u e^{i\delta} A_{1/2}^H(\tau_t) + \frac{1}{3}\alpha_d A_{1/2}^H(\tau_b) + \alpha_d A_{1/2}^H(\tau_\tau) + \beta_W A_1^H(\tau_W)|^2}{|\frac{4}{3}A_{1/2}^H(\tau_t) + \frac{1}{3}A_{1/2}^H(\tau_b) + A_{1/2}^H(\tau_\tau) + A_1^H(\tau_W)|^2}$

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 :

$$0.991 \lesssim \beta_W \lesssim 1.001$$

$$0.997 \lesssim \beta_Z \lesssim 1.028$$

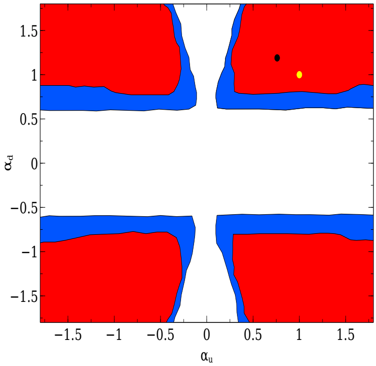
back

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.
- 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



Best-fit values

Case	α_u	α_d	δ	β_W	β_Z	x_g	x_γ	ϵ
A ($\beta_W \neq \beta_Z$ and $\delta = 0$)	0.96	0.91	0.0	0.86	0.95	1.11	1.14	0.015
B ($\beta_W = \beta_Z$ and $\delta \neq 0$)	1.08	0.98	0.94	0.95	0.95	1.02	0.95	0.07

back

Global analysis with LHC data

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

Channel	ATLAS	CMS
$H \to \gamma\gamma$	$1.17^{+0.27}_{-0.27}$	$1.14^{+0.26}_{-0.23}$
$H \to WW^*$	$0.99^{+0.31}_{-0.28}$	$0.83^{+0.21}_{-0.21}$
$H \to ZZ^*$	$1.44^{+0.40}_{-0.33}$	$1.00^{+0.29}_{-0.29}$
$H \to WW^* + 2\text{−jets}$	$1.28^{+0.53}_{-0.45}$	$0.62^{+0.58}_{-0.47}$

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 :

$$\Gamma_{H\to WW^*} = 8.61\times10^{-4}\kappa^2 + 8.51\times10^{-6}\kappa f_{WW} + 2.95\times10^{-8} f_{WW}^2$$

$$\Gamma_{H\to ZZ^*} = 9.28\times10^{-5}\kappa^2 + 4.77\times10^{-7}\kappa f_{WW} + 1.00\times10^{-9} f_{WW}^2$$

$$\Gamma_{H\to\gamma\gamma} = 8.59\times10^{-7} - 8.04\times10^{-6}\kappa - 4.36\times10^{-6} f_{WW} + 1.77\times10^{-5}\kappa^2 + 1.98\times10^{-5}\kappa f_{WW} + 5.68\times10^{-6} f_{WW}^2$$

$$\Gamma_{H\to Z\gamma} = 3.75\times10^{-8} - 7.91\times10^{-7}\kappa - 5.65\times10^{-7} f_{WW} + 7.12\times10^{-6}\kappa^2 + 1.06\times10^{-5}\kappa f_{WW} + 3.82\times10^{-6} f_{WW}^2$$

back

Total decay width and production cross section parametrizations

- The total Higgs boson width can be parametrized as

$$\Gamma_{\rm tot} = [3.07 - 7.82\times10^{-3}\kappa - 4.37\times10^{-3} f_{WW} + 0.97\kappa^2 + 3.67\times10^{-2}\kappa f_{WW} + 8.76\times10^{-3} f_{WW}^2]\times10^{-3}\,{\rm GeV}$$

- 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.

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

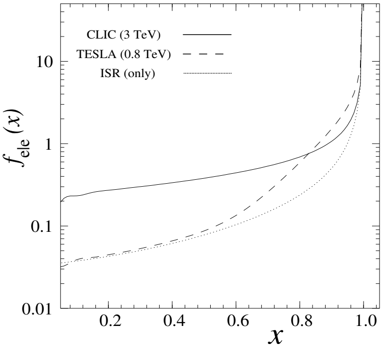
$$\Delta\kappa_\gamma = \frac{M_W^2}{2\Lambda^2}(f_W + f_B); \quad \lambda_\gamma = \lambda_Z = \frac{3g^2 M_W^2}{2\Lambda^2} f_{WWW}$$

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

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*

Bremsstrahlung and beamstrahlung



Illustrating the electron luminosity $f_{e|e}(x)$ as a function of $x = E_e/E_b$, the energy fraction of the electron (positron) after radiation of one or more photons. The (dashed) solid line shows the prediction at the *TESLA* (*CLIC*) machine, where the beamstrahlung parameter is $\Upsilon = 0.09$ (8.1). The dotted line shows the (unconvoluted) ISR prediction at the *TESLA* energy.

$$f_{e/e}^{\rm ISR}(x) = \frac{\beta}{16}\left[(8+3\beta)(1-x)^{\beta/2-1} - 4(1+x)\right]$$

with $\beta = \frac{2\alpha}{\pi}\left(\log\frac{s}{m_e^2} - 1\right)$ and α : running fine-structure constant evaluated at E_b

Beamstrahlung effects depend on E_b, the bunch length σ_z and the beamstrahlung parameter $\Upsilon = \frac{E_b}{m_e}\left(\frac{B}{B_c}\right)$ where B : effective magnetic field in beam, $B_c = m_e^2/e\hbar \simeq 4.4 \times 10^{13}$ Gauss $\longrightarrow$ Schwinger critical field for electrons.

Combining : electron spectrum at collision point well approximated by a simple convolution of the two respective spectral densities

$$f_{e|e}(x) = \int_x^1 \frac{d\xi}{\xi}\, f_{e|e}^{\rm ISR}(\xi)\, f_{e|e}^{\rm beam}\left(\frac{x}{\xi}\right)$$

Rohini M. Godbole, Santosh Kumar Rai and Sreerup Raychaudhuri (2006)

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