Taming the Off-shell Higgs boson

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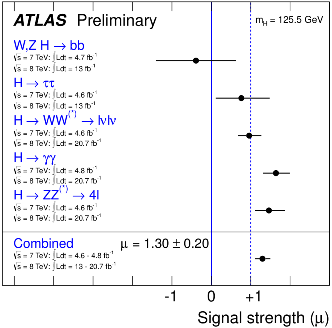
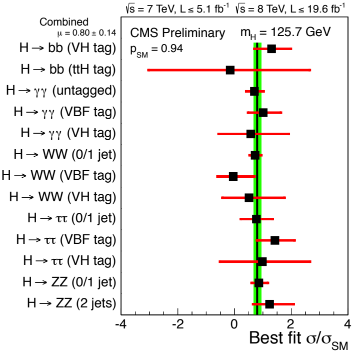
work with C.Grojean,A.Paul, E.Salvioni arXiv:1406.6338

Searching for new physics through the Higgs couplings

- LHC has discovered Higgs boson, which looks so far vey much like the Standard Model Higgs boson
- Most of the BSM models predict a spin 0 field with couplings to the SM fields which are generically different from the Standard Model predictions: SUSY, Composite Higgs...
- Scalar particle with couplings different from the SM ones might be the first indication of the new physics
- New physics states are too heavy for the direct production at the collider but their indirect effects like coupling modification can be tested.

Current constraints on the Higgs interactions





Recent Constraints on the Higgs width

- Recently both CMS and ATLAS collaborations presented the studies of the off-shell Higgs production by studying $gg \to h \to ZZ \to 4l, 2l2\nu$ processes (CMS-PAS-HIG-14-000, CMS-HIG-14-002, ATLAS-CONF-2014-042)
- One can interpret these measurements to constrain the total width of the Higgs boson (*Caola,Melnikov*)
  Talk by K.Melnikov on monday

Off-Shell Higgs production

on-shell cross secyion

$$\sigma \sim \frac{g^2_{\text{prod.}} g^2_{\text{decay}}}{\Gamma}$$

off-shell cross section:

$$\sigma \sim g^2_{\text{prod.}} g^2_{\text{decay}} S + g_{\text{prod.}} g_{\text{decay}} I + B$$

- Assuming the on-shell cross section is exactly as in the SM

$$\sigma_{Off-shell} \sim \frac{\Gamma}{\Gamma_{SM}} S + \sqrt{\frac{\Gamma}{\Gamma_{SM}}} I + B$$

$$\Gamma < 5.4 \times \Gamma_{SM}$$

Flat direction in the Higgs couplings space

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- to keep the on-shell rate the same

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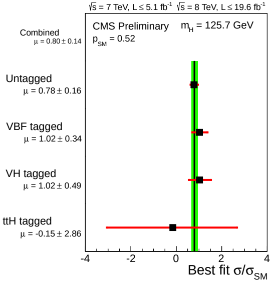
- The flat direction is along $\boxed{g_i = g_i^{SM}\mu, \Gamma = \Gamma^{SM}\mu^4}$
- However $\Gamma_{\text{visible}} \propto g_i^2 \propto \mu^2$ thus we need an invisible decay width

$$\boxed{\Gamma_{\text{invisible}} = \Gamma_{SM}(\mu^4 - \mu^2)}$$

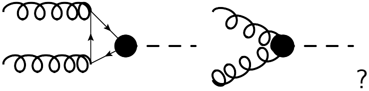
This flat direction is constrained also by the invisible Higgs decay searches.

Are there any other flat directions which can be studied by the off-shell Higgs production measurements?

Contraints on the top Yukawa coupling



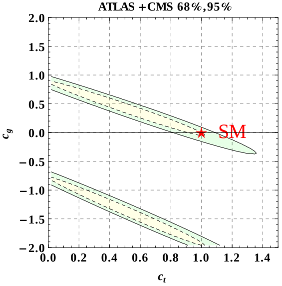
- Direct top Yukava coupling measurements are still weak compared to the other searches
- The dominant constraints on the top Yukawa coupling come from the measurements of the Higgs production in the gluon fusion
- What if the new physics provides simultaneous modifications of the both Higgs top Yukawa couplings and the Higgs couplings to gluons?



$(c_t,\ c_g)$ degeneracy

We can parametrize the modification of the Higgs interactions in the following way

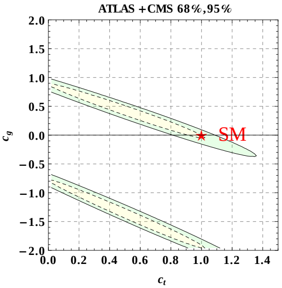
$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$



- Single Higgs production occurs at the scale $O(m_H)$, so that we can integrate out top quark and parametrize the Higgs interaction with gluons by the operator

$$O_g(m_H) \approx \frac{g_s^2}{48\pi^2}(c_g + c_t)\frac{h}{v} G^{\mu\nu} G_{\mu\nu}$$

Channels breaking (c_t, c_g) degeneracy



- All the channels with $\bar{t}th$ production mechanism violate this degeneracy
- All the channels with $\gamma\gamma$ final state $\Gamma(h \to \gamma\gamma) \propto |1.26 - 0.26c_t|^2$

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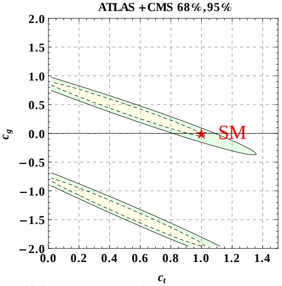

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- All the channels with $\gamma\gamma$ final state $\Gamma(h \to \gamma\gamma) \propto |1.26 - 0.26c_t|^2$

However the parametrization

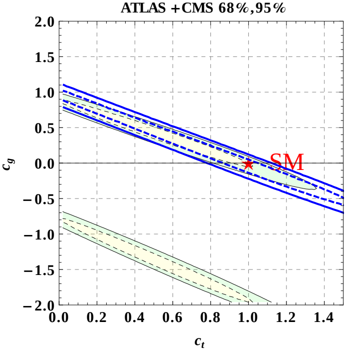
$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

is valid only if the O_g operator is generated by the fields with zero electric charge, most BSM scenarios (SUSY, Composite Higgs) predict that O_g is generated by the "top like" fields.

Channels breaking (c_t, c_g) degeneracy

Assuming that the new Higgs interaction with gluons is generated by the "top-like" fields i.e. fundamentals of $SU(3)$ and with the electric charge 2/3, the new physics lagrangian can be parametrized as:

$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu} + \frac{e^2}{18\pi^2} c_g \frac{h}{v} \gamma_{\mu\nu} \gamma^{\mu\nu}$$

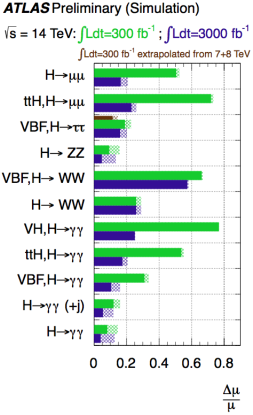


Only the channels with *tth* production mechanism can break this degeneracy *CMS HIG-13-09, HIG-13-015, ATLAS-CONF-2014-011*

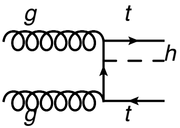
ATLAS $\mu_{bb} = 1.7 \pm 1.4$

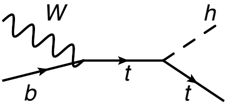
CMS $\mu_{comb} = 2.5^{+1.1}_{-1.0}$

Prospects for high luminosity LHC



- $\sim 20\%$ unceraintiy on the signal rate $\Rightarrow \sim 10\%$ uncertainty on the top Yukawa coupling
- Maltoni, Rainwater, Willenbrock; S. Biswas, E. Gabrielli and B. Mele; S. Biswas, E. Gabrielli, F. Margaroli and B. Mele ; Curtin, Galloway, Wacker; Farina, Grojean, Maltoni, Salvioni, Thamm; Craig, Park, Shelton; Onyisi, Kehoe, Rodriguez , Ilchenko; Agrawal, Bandyopadhyay, Das...(CMS PAS HIG-14-001)





- (c_t, c_g) **degeneracy appears due to the Higgs LET theorems** *Shifman,Vainshtein,Zakharov;Ellis,Gaillard,Nanopoulos*
- **any process which is not within the LET validity region can be used to resolve this flat direction**

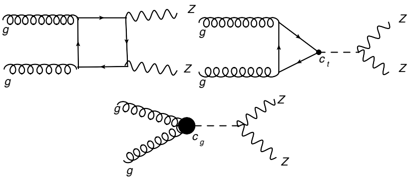
Off-shell Higgs production tests the Higgs production in the energy range much higher than the Higgs mass, thus we can use this information to put constraints on the Higgs couplings

see also by *arXiv:1405.0285 Englert,Spannowsky; arXiv:1406.1757 Cacciapaglia, Deandrea,La Rochelle,Flament.*

- Similar idea was suggested to probe the boosted Higgs production in gluon fusion *Banfi,Martin, Sanz; AA,Paul; Grojean,Salvioni,Schlaffer,Weiler; Harlander,Neumann*

  Talk by S.Dawson on monday

$gg \to h \to ZZ$ matrix element behavior



- on shell $\sigma \sim |c_t + c_g|^2$
- off shell

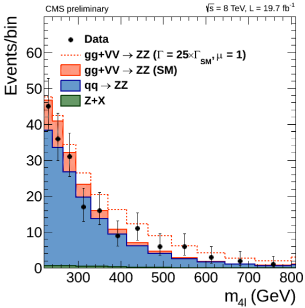
$$\mathcal{M}_{gg\to ZZ} = \mathcal{M}_{bcg} + c_t \mathcal{M}_{c_t} + c_g \mathcal{M}_{c_g}$$

$$\mathcal{M}_{bcg}^{++00} \sim \mathcal{M}_{c_t}^{++00} \sim \log^2 \frac{\hat{s}}{m_t^2}, \quad \mathcal{M}_{c_g}^{++00} \sim \hat{s}$$

- In the SM there in order to preserve unitarity there is a cancellation between the triangle diagram which is logarithmically divergent and the box diagrams.
- New physics contribution grows with $\hat{s}$ - high energy bins become very important.

Off-shell Higgs constraints on the Higgs couplings

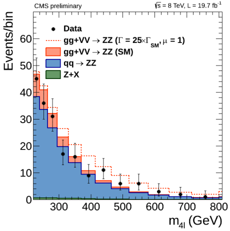
- All the variations of the Higgs couplings can be parametrized by c_t, c_g so that along $c_t + c_g = 1$ line all the branching fractions are SM like.

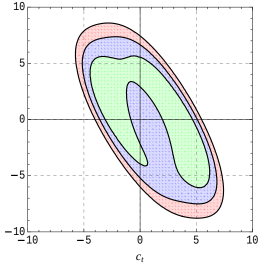


CMS-PAS-HIG-14-002

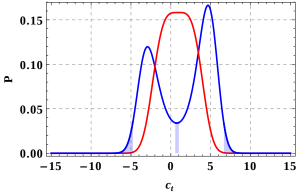
- In our analysis we will focus on the $gg \to h \to ZZ \to 4l$ channel and simple counting analysis
- Signal and interfering background was simulated with the modified version of the MCFM (*Ellis,Campbell,Williams)* code.

First bounds from CMS-PAS-HIG-14-002





imposing the condition $c_t + c_g = 1$ we find



$$68\% : c_t \in [-4, -1.5] \cup [2.9, 6.1]$$

$$95\% : c_t \in [-4.7, 0.5] \cup [1, 6.7]$$

Validity of the EFT analysis

- Effective couplings c_t, c_g can appear as a result of the dimension six operator.

$$\mathcal{L}^{\text{dim-6}} = c_y \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R + \text{h.c.} + \frac{c_g g_s^2}{48\pi^2 v^2} |H|^2 G_{\mu\nu} G^{\mu\nu}$$

$$c_t = 1 - Re(c_y)$$

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$$c_t = 1 - Re(c_y)$$

Our analysis is valid only in the range where the effects of the dimension-8 operators can be ignored

$$O_8 = \frac{c_8 g_s^2}{16\pi^2 v^4} G_{\mu\nu} G^{\mu\nu} \left(D_\lambda H\right)^\dagger D^\lambda H$$

$$\boxed{\sqrt{\hat{s}} \lesssim \sqrt{\frac{c_g, c_y}{c_8}} v}$$

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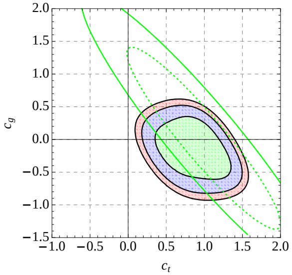
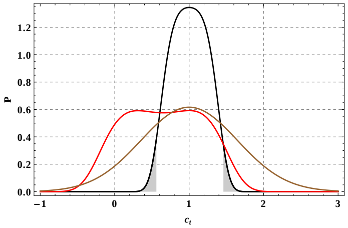
Square of the dimension 6 operators act effectively as the dimension-8 operators. So we can keep $O(c_g^2)$ in the analysis only if

$$\boxed{c_8 \ll c_{g,y}^2}$$

High Luminosity 3 ab^{-1} 14 TeV LHC prospects

- We simulate the signal and the background with the MCFM 6.8 code, and bin the events in six categories $\sqrt{\hat{s}} = (250, 400, 600, 800, 1100, 1500)$ GeV
- K- factors: we assume the same K-factor for the signal and the interfering background and calculate them using the ggHiggs code.
-
    - nonlinear analysis 68% $c_t \in [0.74, 1.28]$
    - linear analysis 68% $c_t \in [0.36, 1.66]$
    - keeping $\sqrt{s} < 600$GeV 68% $c_t \in [0.1, 1.25]$





Models with (c_t, c_g) degeneracy

- Simple addition of one vector-like fermion

$$\mathcal{L} = -y\bar{Q}_L t_R H - M_* \bar{T} T - Y_* \bar{Q}_L T_R H$$

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$$m = \begin{pmatrix} yv & Y_* v \\ 0 & M_* \end{pmatrix} \Rightarrow \quad c_g(m_H) \approx \frac{\partial \log Detm}{\partial \log v} = 1$$

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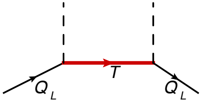
Higgs coupling to the gluons is exactly the same as in the SM, however Higgs couplings to the top quarks is modified



$$y_t \sim y_t^{SM} \left(1 - \frac{Y_*^2 v^2}{M_*^2}\right)$$

$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

$$c_t = 1 - \frac{Y_*^2 v^2}{M_*^2} \quad c_g = \frac{Y_*^2 v^2}{M_*^2}$$

- Similar effect occurs in the composite Higgs models

Bounds on top partners

-

$$\mathcal{L} = -y\bar{Q}_L t_R H - M_* \bar{T}T - Y_* \bar{Q}_L T_R H$$

-

$$c_g = c_y \sim \frac{Y_*^2 v^2}{M_*^2}\,,$$
$$c_8 \sim \frac{Y_*^2 v^4}{M_*^4}$$

- analysis ignoring the dimension eight operator is valid up to the energies $\sqrt{\hat{s}} \lesssim M_*$

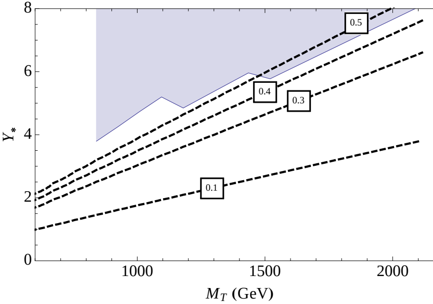


Figure: 95% exclusion in Y_*/top partner mass plane.

Bounding other operators

- We looked only at the operators modifying the production of the Higgs boson however there can be operators modifying its decay as well (*Gainer, Lykken,Matchev,Mrenna,Park*)

$$O_\Box = \frac{c_\Box}{v} \Box h Z_\mu Z^\mu$$
$$68\% : \;\; c_\Box \in [-0.7, -0.17] \cup [0.42, 0.84] \,,$$

- however $O_\Box$ can appear only at the dimension -eight operator level $\frac{(D_\mu H)^2 \Box (H^\dagger H)}{\Lambda^4}$, which leads to the irrelevant bounds on the scale Λ.
- None of the dimension six operators can effect the longitudinal polarizations of the Z

$$(D_\mu H)^\dagger \sigma^a D_\nu H W^{\mu\nu,a}, \quad (D_\mu H)^\dagger D_\nu H B^{\mu\nu}, \quad H^\dagger H B_{\mu\nu} B^{\mu\nu} \,,$$
$$\left(H^\dagger \sigma^a \overleftrightarrow{D}_\nu H\right) (D^\mu W_{\mu\nu})^a, \quad \left(H^\dagger \overleftrightarrow{D}_\nu H\right) (D^\mu B_{\mu\nu})$$

so the overall grows with the energies is SM like.

Summary

- On-shell Higg couplings measurements so far did not observe any significant deviations from the SM.
- Off-shell Higgs production is very sensitive to the higher dimensional operators in production/decay.
- Studies of the off-shell Higgs production can be used as an additional independent constraint on the top Yukawa coupling.

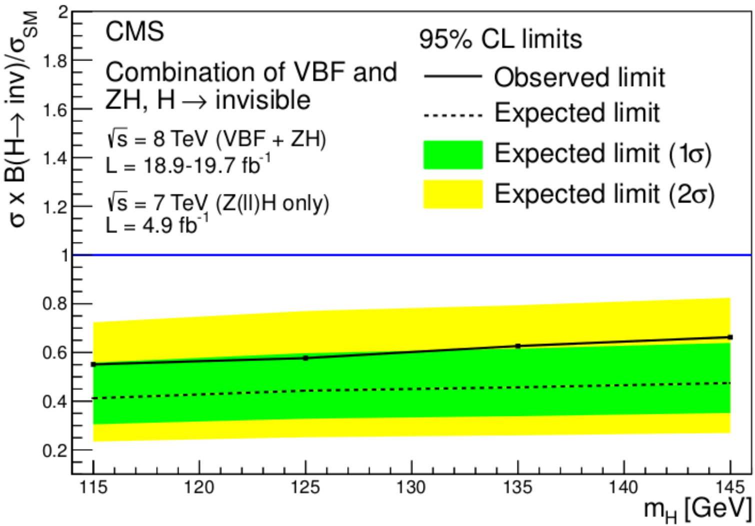
Recent progress

- Higgs plus jet: *Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant* arxiv: 1405.4295, $h \to \tau\tau, WW^*$

$$c_t \in [0.71, 1.24] \text{ at } 95\%$$

- Higgs plus two jets: *Buschmann, Englert , Goncalves ,Plehn Spannowsky* arXiv:1405.7651 $h \to \tau\tau, WW^*$

$$c_t \in [0.7, 1.3] \text{ at } 95\%$$



CMS
Combination of VBF and
ZH, H → invisible
√s = 8 TeV (VBF + ZH)
L = 18.9-19.7 fb-1
√s = 7 TeV (Z(ll)H only)
L = 4.9 fb-1
95% CL limits
Observed limit
Expected limit
Expected limit (1σ)
Expected limit (2σ)
σ x B(H→ inv)/σSM
mH [GeV]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
115
120
125
130
135
140
145