Top-Higgs interactions and exclusive measurements

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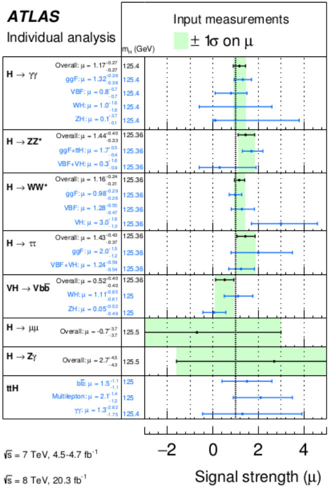
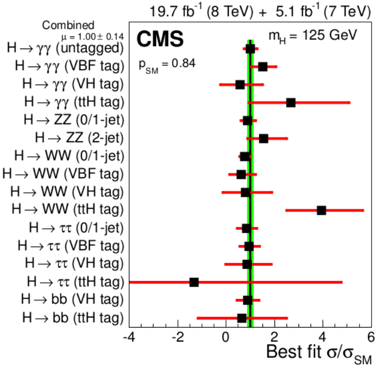
ICTP

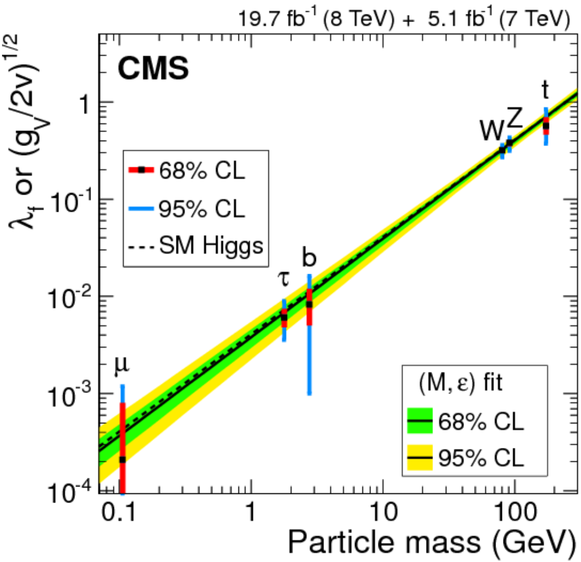
Higgs Hunting 2016

~~Current~~ constraints on the Higgs interactions

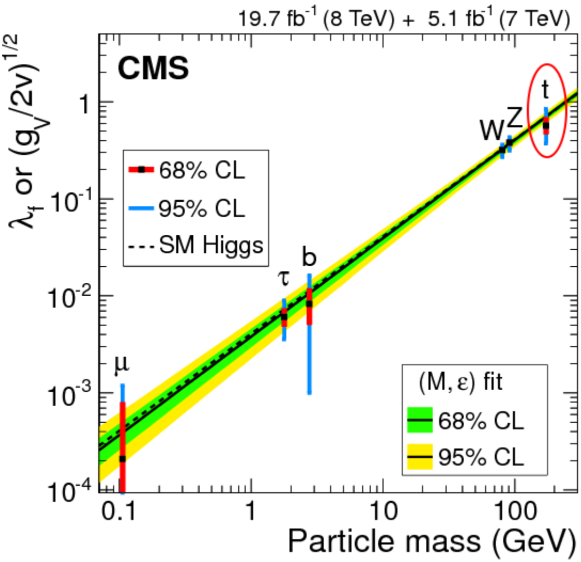
13 TeV constraints are already comparable/stronger in some fo the channels!





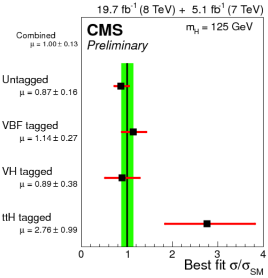


So far good agreement with SM!

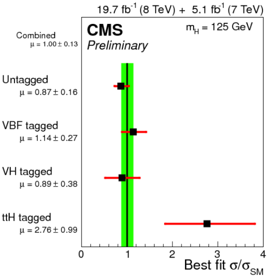


So far good agreement with SM!

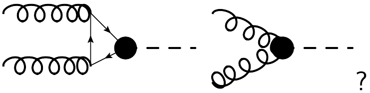
Top quark Yukawa coupling



Top quark Yukawa coupling



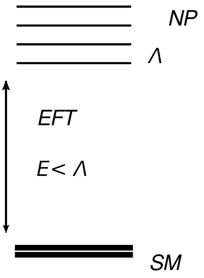
- Direct top Yukava coupling measurements are still weak compared to the other searches
- The dominant constraints on the top Yukawa coupling come from the measurements of the Higgs production in the gluon fusion
- What if the new physics provides simultaneous modifications of the both Higgs top Yukawa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



Parametrizing the new physics effects

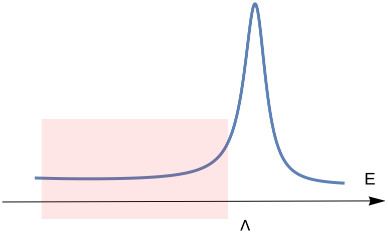
EFT provides a consistent framework for the parametrization of the new physics effects. (talk by Riva)

- If new physics states are heavier than the SM states and the typical mass scale of the process $E < \Lambda$.
- We can integrate these states out and parametrize their effects in terms of the higher dimensional operators.
- The effects of new physics will appear as a corrections in the $\left(\frac{E}{\Lambda}\right)$ series.



Range of validity

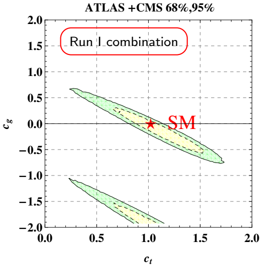
- EFT expansion is valid only below the mass of the new heavy resonance
- We are testing the deviations from the SM in the tails of the Breight -Wigner resonances.
- EFT analysis becomes important if the new resonances are too heavy to be directly produced at the collider.



Higgs coupling degeneracy in the gluon fusion

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

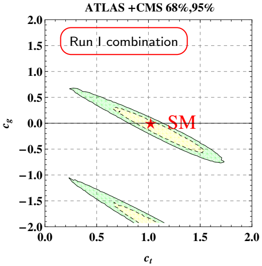
$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$



- 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

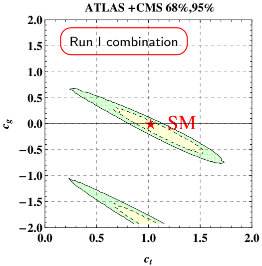
$$O_g(m_H) \approx \frac{g_s^2}{48\pi^2}(c_g + c_t)\frac{h}{v} G^{\mu\nu} G_{\mu\nu}$$

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 $\Gamma(h \to \gamma\gamma) \propto |1.26 - 0.26c_t|^2$

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 $\Gamma(h \to \gamma\gamma) \propto |1.26 - 0.26c_t|^2$

However the parametrization

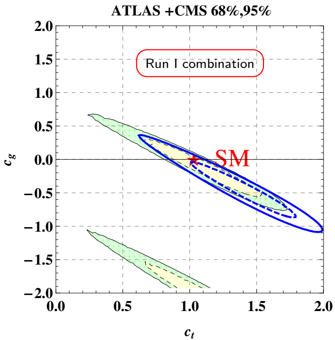
$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

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

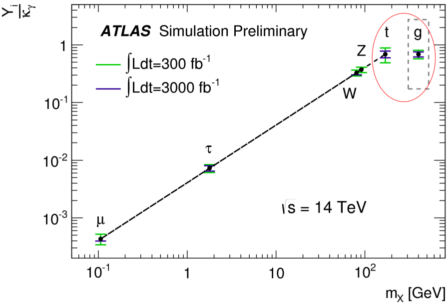
ATLAS-CONF-2015-044,

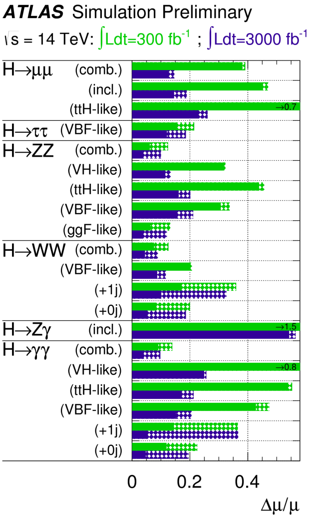
CMS-PAS-HIG-15-002

$$\mu_{ATLAS} = 1.9^{+0.8}_{-0.7}, \ \mu_{CMS} = 2.9^{+1.0}_{-0.9}$$

$$\boxed{\mu^{13}_{ATLAS} = 1.7 \pm 0.8}$$

HL-LHC projections



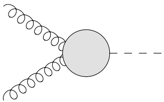


Constraints on the top Yukawa couplings from *tth* production $\sim 10\%$, roughly two times weaker than from the gluon fusion.

Resolving the gluon fusion loop

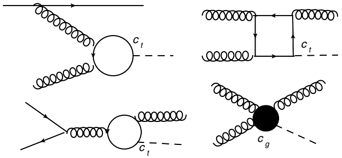
$c_t - c_g$ degeneracy appears because the single Higgs production occurs at the energy scale m_H, where we can integrate safely the top quarks

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



studies of the kinematic distributions can break this degeneracy

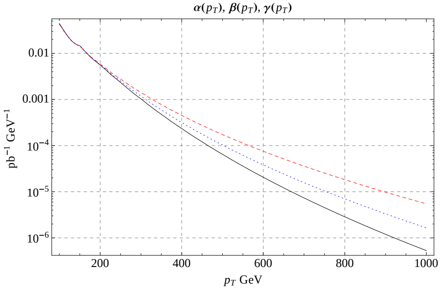
High p_T Higgs production in (c_t, c_g) plane 1309.5273, 1312.3317



The energy scale of the process can be higher than the top mass, we cannot integrate it out any more

$$\frac{d\sigma}{dp_T} = \sum_i \kappa_i |f_i(p_T) c_t + c_g|^2$$

$$\boxed{\frac{d\sigma}{dp_T} = \alpha c_t^2 + \beta c_g^2 + 2\gamma c_t c_g}$$



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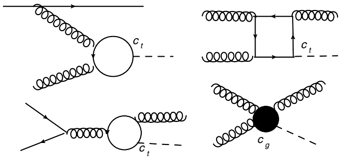

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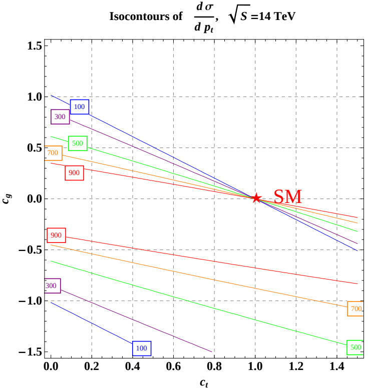
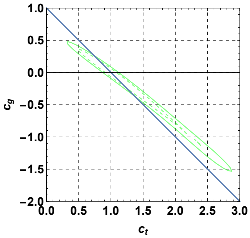


Prospects of the constraints

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



$$\boxed{c_t \in [0.71, 1.24] \text{ at } 95\% \text{ if } c_t + c_g = 1}$$

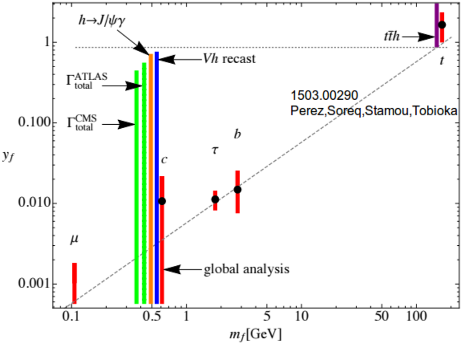
Figure : 68,95 % contours extracted from 1405.4295

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

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

Boosting the Higgs to test light quark Yukawa couplings

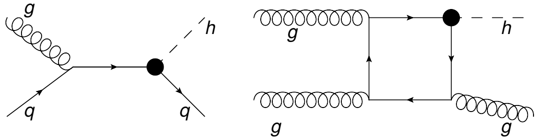
- At LHC it is very hard to measure the Yukawa couplings of the first two generations (talk by E. Stamou)



- p_T distributions of the Higgs production in gluon fusion are sensitive to the modifications of the light quark Yukawa couplings.

Light quark Yukawas from $\frac{d\sigma}{dp_T}$ distribution

1606.09253,1606.09621,1608.04376



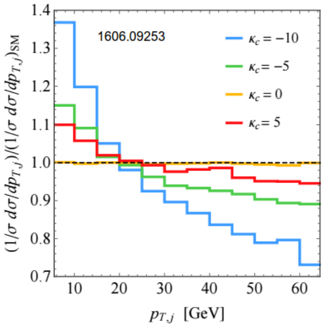
- Two types of contribution:
  - Direct : from the possibly enhanced value of the quark Yukawa coupling, $\sigma \sim y_q^2$
  - New contribution to the gluon fusion loop, we can have large interference with the SM top quark loop.

Bounding light quark Yukawa couplings from differential distributions 1606.09253,1606.09621,1608.04376

- Modifications of the light quark Yukawa couplings modify the differential distributions.
- Sudakov's dilogarithms *1606.09253* enhance the production cross-section

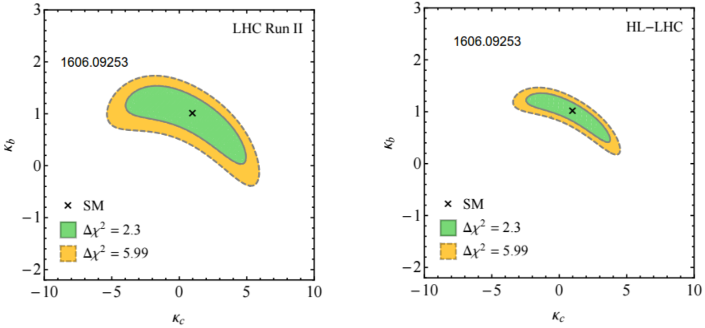
$$\sim k_Q \frac{m_Q^2}{m_h^2} \ln^2 \frac{p_\perp^2}{m_Q^2}$$

  modifications are especially important in the region $m_Q \ll p_\perp \ll m_h$.
- The main contribution appears from the interference with the top quark loop, which scales as y_Q not y_Q^2.

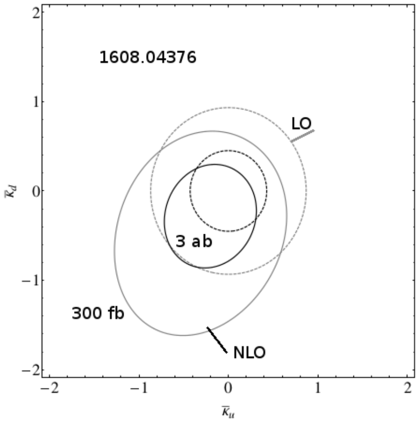


Bounding light quark Yukawa couplings from differential distributions 1606.09253,1606.09621,1608.04376

- from $h \to \gamma\gamma, ZZ, WW$ using $p_T \in [0, 70]$ GeV



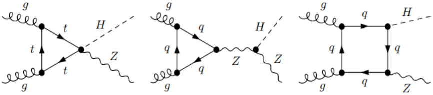
Constraints on the light quark Yukawa couplings

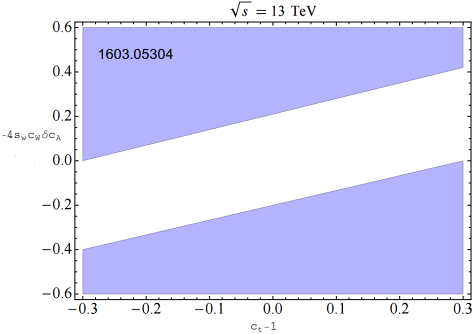


$\boxed{\sim \bar{q}q\dfrac{m_b}{v}\bar{k}_q}$, couplings are normalized to the bottom quark Yukawa .

Other processes that can test the gluon fusion loop

$gg \to HZ$ 1601.08193 ,1603.05304

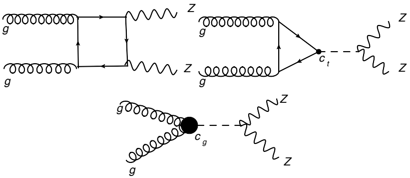




- $(H^\dagger \overleftrightarrow{D}_\mu H)\bar{t}_R \gamma^\mu t_R$ leads to the new $\bar{t}tZ, \bar{t}tHZ$ interactions
- The process is sensitive to the modifications of the top Yukawa couplings, through the box diagram
- No dependence on c_g!

There is a strong correlation in constraints of the ttZ, tth couplings

Off-shell Higgs production $gg \to h \to ZZ$ 1406.6338



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

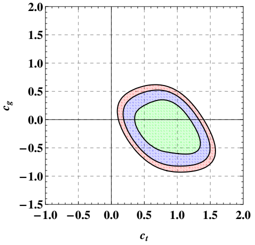
$$\mathcal{M}_{gg\to ZZ} = \mathcal{M}_{bcg} + c_t\mathcal{M}_{c_t} + c_g\mathcal{M}_{c_g}$$

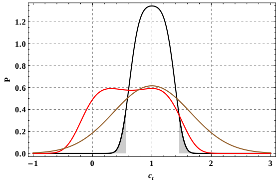
$$\mathcal{M}_{c_t}^{++00} \sim \log^2\frac{\hat{s}}{m_t^2}, \quad \mathcal{M}_{c_g}^{++00} \sim \hat{s}$$

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

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

- Bounds presented are derived using 4-lepton final state with simple counting analysis
- K- factors: we assume the same K-factor for the signal and the interfering background.
-
  - black- nonlinear analysis 68% $c_t \in [0.74, 1.28]$
  - brown- linear analysis 68% $c_t \in [0.36, 1.66]$
  - red- keeping $\sqrt{s} < 600$GeV 68% $c_t \in [0.1, 1.25]$



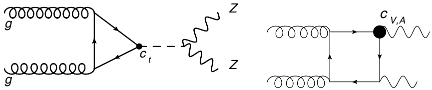


Buschmann et al 1410.5806 (analysis taking into account angular distributions to suppress the background) $\boxed{c_t = 0.7, @95\% CL \quad 1.7 ab^{-1}}$

Sensitivity to the modifications of the other couplings

1608.00977

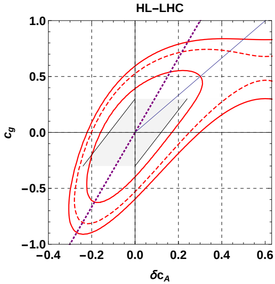
If ttZ interactions are different from the SM ones



No more cancellations between the triangle and the box diagrams even if $c_t = 1$, and $c_g = 0$. The amplitude grows as $\sim \log s$

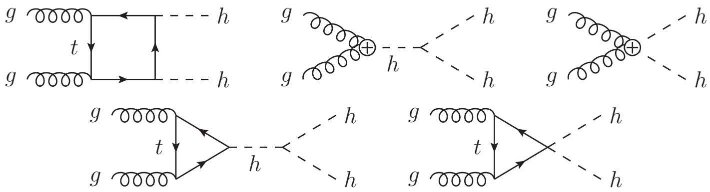
$$e\bar{t}[\gamma_\mu(c_V F_V + \gamma_5 c_A F_A)]t_R Z^\mu$$

- assuming $c_t + c_g = 1$ we get



strong correlation between c_A, c_g, similar to $gg \to hZ$

Double Higgs production (talk by Panico tomorrow)

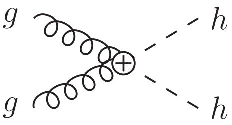


- dimension six operators $|H|^2 \bar{Q}_L \widetilde{H} t_R, |H|^2 G_{\mu\nu} G^{\mu\nu}$ lead to the additional interactions $t\bar{t}hh, gghh$, which can be probed in the double Higgs production

  *1205.5444 ,1405.7040,1410.3471,***1502.00539**

HL-LHC will have sensitivity to the O(1) modifications of the cross-section, which leads to the O(5) sensitivity to the modifications of the triple Higgs coupling.

Double Higgs production



$\boxed{A(c_g) \sim \hat{s}}$

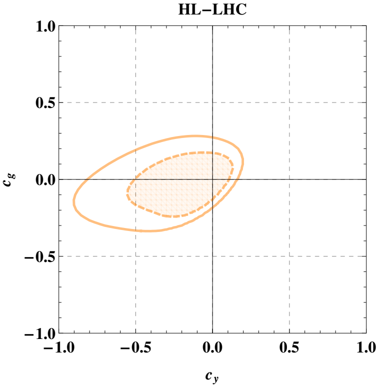


Figure : $\boxed{c_y = 1 - c_t}$

The contact interaction *gghh* constrain very strongly the c_g coefficient

$$\boxed{c_g \in [-0.28, 0.14] \quad @95\%, \quad c_g = c_y}$$

Combination @ 14 TeV $3ab^{-1}$ projections 1608.00977

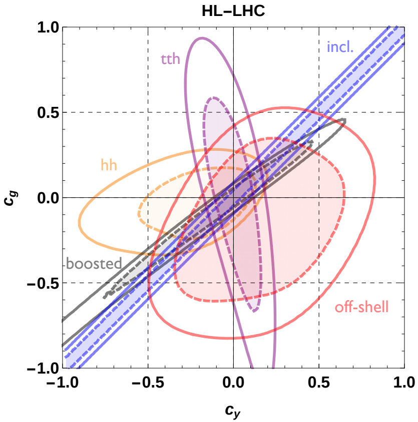


Figure : orange- Higgs pair production (bb $\gamma\gamma$ final state), red off-shell Higgs pair production, grey - h+j, blue- inclusive, purple- tth

$$\boxed{c_u = 1 - c_t}$$

Combination @ 100 TeV $20ab^{-1}$ projections 1608.00977

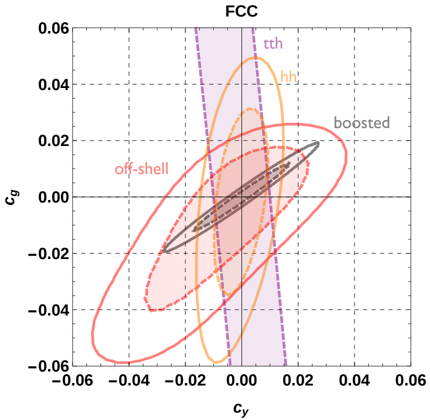


Figure : orange- Higgs pair production (bb $\gamma\gamma$ final state), red off-shell Higgs pair production, grey - h+j, blue- inclusive, purple- tth

$$\boxed{c_u = 1 - c_t}$$

Summary

- So far no significant deviations of the Higgs couplings have been observed.
- However current measurements constrain mostly the inclusive rates, also the direct constraints on the top Yukawa coupling are weak, significant new physics contribution to the gluon fusion is still allowed.
- The studies of the boosted and off-shell Higgs production can be used to test the gluon fusion loop and also provide a new handle on the light quark Yukawa couplings.
- Double Higgs production provides us with another handle on the gluon fusion loop which can be competitive with the tth measurements.