Resolving the gluon fusion loop for the Higgs production at LHC

Aleksandr Azatov

CERN

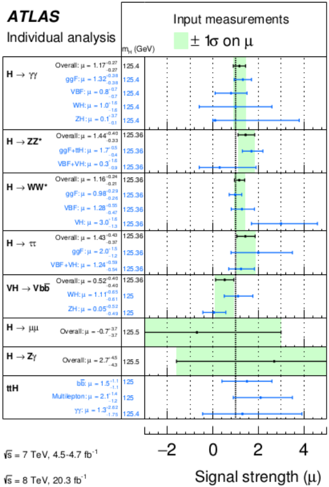
Gearing up for the LHC 13
GGI, Florence

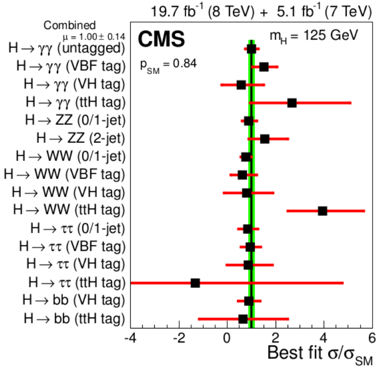
with R.Contino, C.Grojean, G.Panico, A.Paul, E.Salvioni, M.Son arXiv:1309.5273, 1406.6338, 1502.00539 and in progress

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





What is next ?

All the Higgs interaction look so far very similar to the SM ones.
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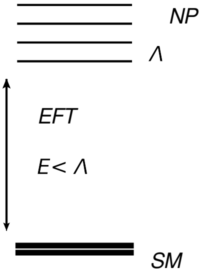
- If new physics states are heavier than the SM states as well as the typical mass scale of the process $\Lambda > E$.
- We can integrate these states out and parametrize their effects in terms of the higher dimensional operators.
- The effects of new physics will appear as a corrections in the $\left(\frac{E}{\Lambda}\right)$ series.



Non-linear EFT lagrangian

Assuming the Higgs scalar is a singlet under $U(1)_{em}$ the most generic lagrangian at dimension 5 level is given by

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\, \partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)} \left(1 + c_\psi \frac{h}{v} + \dots\right)$$
$$+ m_W^2\, W_\mu^+ W^{-\mu}\left(1 + 2c_W\,\frac{h}{v} + \dots\right) + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z\,\frac{h}{v} + \dots\right) + \dots$$
$$+ \left(c_{WW}\, W_{\mu\nu}^+ W^{-\mu\nu} + \frac{c_{ZZ}}{2}\, Z_{\mu\nu}Z^{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{\gamma\gamma}}{2}\,\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{gg}}{2}\, G_{\mu\nu}^a G^{a\mu\nu}\right)\frac{h}{v}$$
$$+ \left(c_{W\partial W}\left(W_\nu^- D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\, Z_\nu \partial_\mu \gamma^{\mu\nu}\right)\frac{h}{v} + \dots$$

Contino et al 1303.3876

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\end{aligned}
$$

c_t

Contino et al 1303.3876

Linear EFT

- Electroweak precision measurements and 7+8 TeV LHC measurements strongly indicate that the Higgs boson is a doublet of the SM. Then the modifications of the Higgs couplings to the SM fields we can parametrize in terms of the dimension 6 lagrangian

$$\begin{aligned} \Delta\mathcal{L} &= \frac{c_u}{v^2} y_t \left(H H^\dagger \bar{q}_L H^c t_R + h.c. \right) \\ &+ c_g \frac{g_s^2}{48\pi^2 v^2} H^\dagger H G^a_{\mu\nu} G^{a,\mu\nu} + c_\gamma \frac{g'^2}{18\pi^2 v^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} \end{aligned}$$

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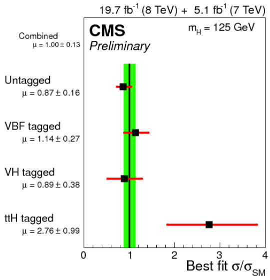
H+jet production in gluon fusion, Off-shell Higgs production in gluon fusion, Higgs pair production

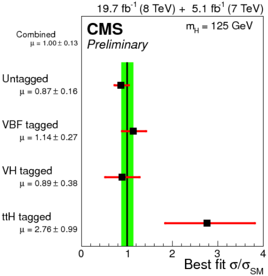
$\boxed{c_u, c_\gamma, c_g}$

Top quark Yukawa coupling

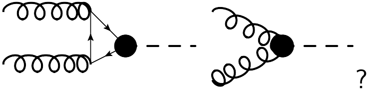


- Direct top Yukava coupling measurements are still weak compared to the other searches
- The dominant constraints on the top Yukawa coupling come from the measurements of the Higgs production in the gluon fusion

Top quark Yukawa coupling



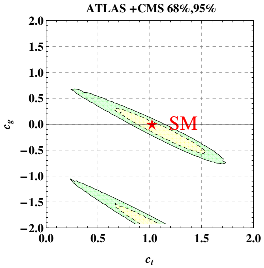
- Direct top Yukava coupling measurements are still weak compared to the other searches
- The dominant constraints on the top Yukawa coupling come from the measurements of the Higgs production in the gluon fusion
- What if the new physics provides simultaneous modifications of the both Higgs top Yukawa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



$(c_t,\ c_g)$ degeneracy

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

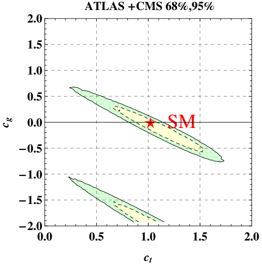
$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$



- 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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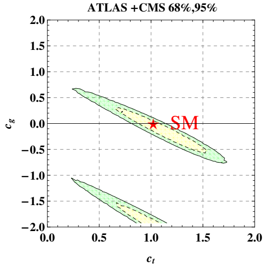

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However the parametrization

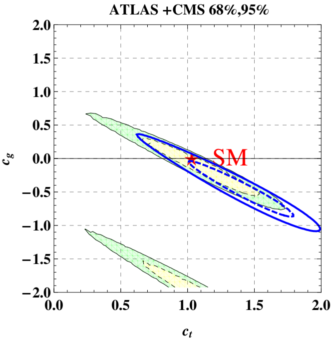
$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

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

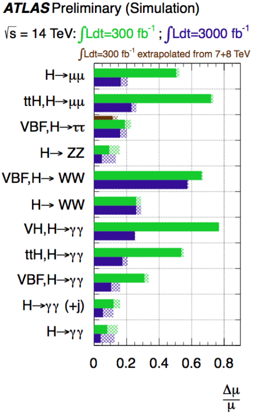
ATLAS-CONF-2015-044,

CMS-PAS-HIG-15-002

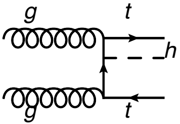
ATLAS $\mu = 1.9^{+0.8}_{-0.7}$

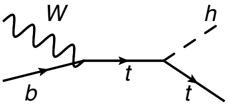
CMS $\mu = 2.9^{+1.0}_{-0.9}$

Prospects for high luminosity LHC



- $\sim 15 - 20\%$ unceraintty on the signal rate $\Rightarrow$ $\sim 7 - 10\%$ 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...





Is there another way to resolve (c_t, c_g) degeneracy?

- c_t, c_g degeneracy originates from the fact that single Higgs production in gluon fusion occurs at the energies $E < m_t$, where all the effects of the top quark in the loop can be parametrized by the effective operator

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

- However if we look at the Higgs production at high p_T we cannot integrate out the top quark any more and infinitely heavy top approximation becomes wrong.

$$\left(\frac{d\sigma^{SM}(m_t)}{dp_T}\right) / \left(\frac{d\sigma^{SM}(m_t \to \infty)}{dp_T}\right)\Big|_{p_t = 300\text{GeV}} \approx 0.7$$

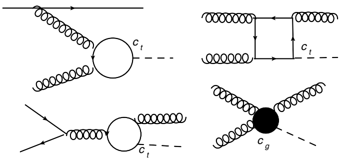
(Grazzini,Sargsyan)

- Similar proposals

Banfi,Martin, Sanz; Grojean,Salvioni,Schlaffer,Weiler;Harlander,Neumann

High p_T Higgs production in (c_t, c_g) plane

$h + X$ is generated by the $gg \to gh, qg \to qh, \bar{q}g \to \bar{q}h, \bar{q}q \to gh$



Momenta incoming into loop can be higher than the top mass

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

Analytical expressions for $f_i(p_T)$ were first calculated in R. K. Ellis, I. Hinchliffe, M. Soldate and J. J. van der Bij, Nucl. Phys. B 297, 221 (1988);U. Baur and E. W. N. Glover, Nucl. Phys. B 339, 38 (1990)

High p_T Higgs production in (c_t, c_g) plane

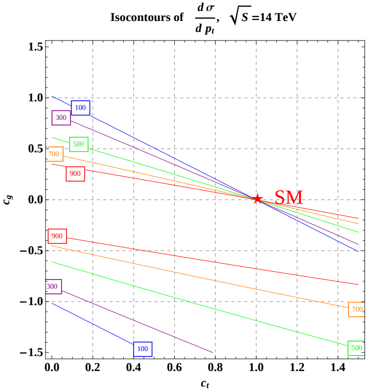
- We have convoluted pdfs from MSTW2008 set with partonic cross sections at LO, setting

$$\mu_R = \mu_F = \sqrt{p_T^2 + m_H^2}$$

- There is no NLO $h + X$ in the SM keeping the full top mass dependence at two loops. To estimate NLO effects we have used K factor

$$K(p_T) = \frac{d\sigma^{NLO}(m_t \to \infty)/dp_T}{d\sigma^{LO}(m_t \to \infty)/dp_T}$$

computed using the HqT code by Grazzini et al

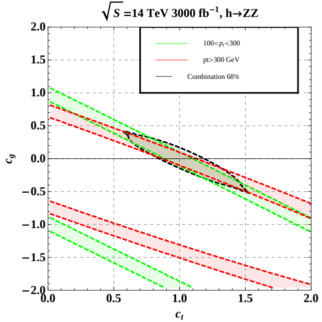


Estimating the LHC potential

- To estimate the LHC potential we have looked at the $h \to ZZ^* \to l^+ l^- l^+ l^-$ decay
- We have separated all the events into two bins with high and low p_T

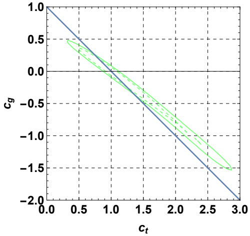
$$\sigma^+(p_T < P_T) = \int_{p_t < P_T} \frac{d\sigma}{dp_T} dp_T$$

$$\sigma^+(p_T > P_T) = \int_{p_T > P_T} \frac{d\sigma}{dp_T} dp_T$$



Recent progress

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



$c_t \in [0.71, 1.24]$ at 95% 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 $h \to \tau\tau, WW^*$

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

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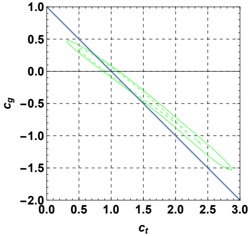

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- constraints on $f^{abc} G^{a\mu}_{\nu} G^{b\nu}_{\rho} G^{c\rho}_{\mu}$ 1411.2029 *Ghosh, Wiebusch*

- **Are there any other processes useful in disentangling the c_t, c_g degeneracy?**
- **We need to be in the regime where the Higgs LET(Shifman et al; Ellis et al) cannot be applied for the Higgs production in gluon fusion**

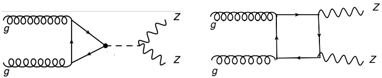
Off-shell Higgs production tests the Higgs production in the energy range much higher than the Higgs mass, thus we can use this information to put constraints on the Higgs couplings

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

Constraints on the Higgs width

- (*Caola,Melnikov 1307.4935*) proposed to use the measurements of the off-shell Higgs production in order to constrain the Higgs width .
- CMS and ATLAS collaborations presented the constraints on the Higgs width by studying the off-shell Higgs production in $gg \to h \to ZZ \to 4l, 2l2\nu$ processes (CMS-PAS-HIG-14-000, CMS-HIG-14-002, ATLAS-CONF-2014-042)

Constraints on the Higgs width



on-shell cross section

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

$\Rightarrow$ flat direction along $g_i = g_i^{SM}\mu, \Gamma = \Gamma^{SM}\mu^4$

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

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

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

$gg \to ZZ$ in SM

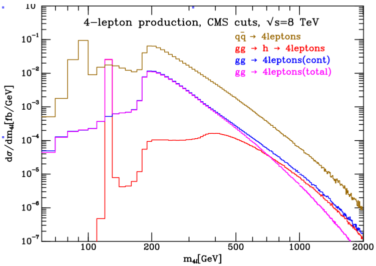
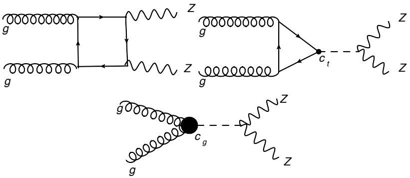


Figure: $gg \to 4l$ in SM from 1311.3589 by Campbell, Ellis and Williams

Why non resonant production effects are important?

- Z bosons are on shell and the process at high energies is dominated by the final state with longitudinal Z bosons.
- Loop function increases near the two top threshold .

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



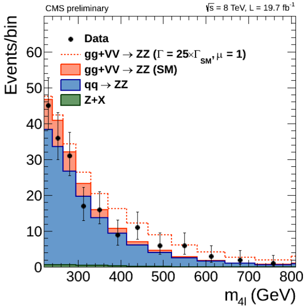
- on shell $\sigma \sim |c_t + c_g|^2$
- off shell

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

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

- 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.

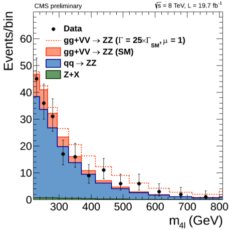
Off-shell production constraints on the Higgs couplings

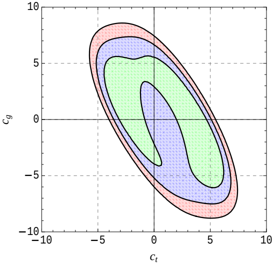


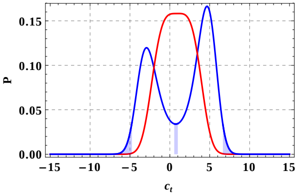
CMS-PAS-HIG-14-002

- In our analysis we focus only on the $gg \to h \to ZZ \to 4l$ channel and simple counting analysis ($\Gamma \lesssim 25\Gamma_{SM}$)
- Signal and interfering background was simulated with the modified version of the MCFM 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.

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

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

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

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

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

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

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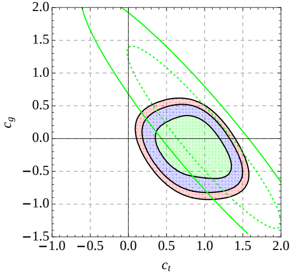
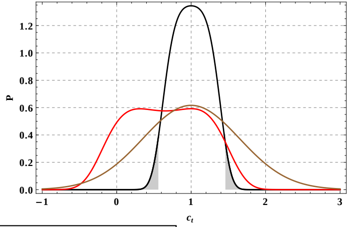
Square of the dimension 6 operators act effectively as the dimension-8 operators. So we can keep $O(c_g^2)$ in the analysis if only

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

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

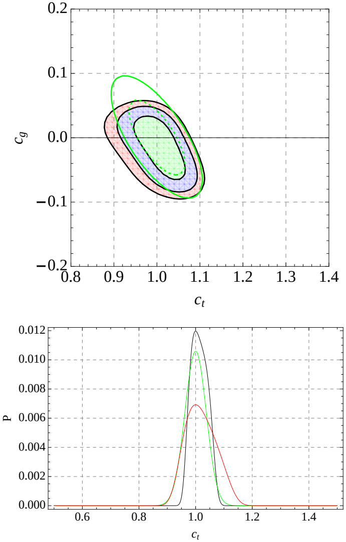
- We simulate the signal and the background with the MCFM 6.8 code, and bin the events in six categories $\sqrt{\hat{s}} = (250, 400, 600, 800, 1100, 1500)$ GeV
- K- factors: we assume the same K-factor for the signal and the interfering background and calculate them using the ggHiggs code.
-
  - nonlinear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





Buschmann et al 1410.5806 $c_t = 0.7, @95\% CL \;\; 1.7 ab^{-1}$

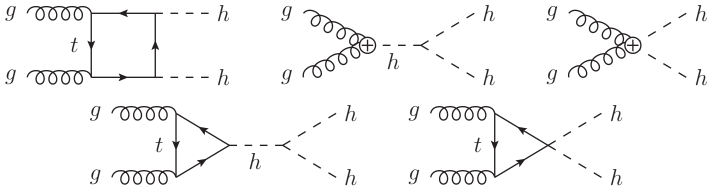
Linear vs nonlinear analysis @ 100 TeV FCC



- nonlinear analysis
  95% $c_t \in [0.96, 1.07]$
- linear analysis 95% $c_t \in [0.93, 1.07]$
- keeping $\sqrt{s} < 1.5$ TeV
  95% $c_t \in [0.92, 1.13]$

Linear and nonlinear analysis lead to very similar results ⇒ we are probing the Wilson coefficients which can be described by perturbation theory, and the effects of dimension-8 operators can be subleading.

Double Higgs production in gluon fusion as a measurement of the top Yukawa coupling



- Constraints on the Higgs trilinear coupling c_3 are weak
- We can measure *tthh* and *gghh* interactions
  Low et al;Goertz et al 1205.5444 ,1405.7040,1410.3471,**1502.00539**

talks by G. Panico and D.Stolarski

Comparison to other channels: 14 TeV $3ab^{-1}$ projections

- Other channels that can be useful in resolving the $c_u - c_g$ degeneracy are *tth* and boosted Higgs (h+j) productions
- No results yet for the 14 TeV projections
- However for the 14 TeV HL-LHC we get:

  - h+j contours are obtained from *1405.4295 Schlaffer, Spannowsky , Takeuchi , Weiler, Wymant*
  - inclusive and tth from ATL-PHYS-PUB-2013-014
  - Higgs pair production from 1502.00539

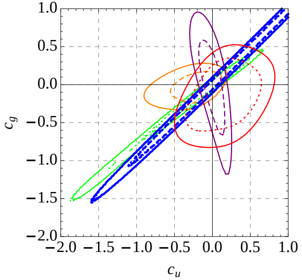


Figure: orange- Higgs pair production (bb $\gamma\gamma$ final state), red off-shell Higgs pair production, green - h+j, blue- inclusive, purple- tth

$$c_u = 1 - c_t, \quad O_u \sim \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R$$

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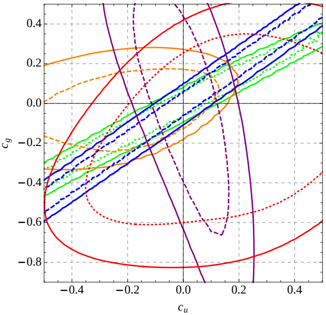


Figure: orange- Higgs pair production (bb $\gamma\gamma$ final state), red off-shell Higgs pair production, green - h+j, blue- inclusive, purple- tth

$$c_u = 1 - c_t$$

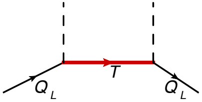
Models with (c_t, c_g) degeneracy

- Simple addition of one vector like fermion

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

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

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



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

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

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

Models with (c_t, c_g) degeneracy

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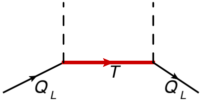

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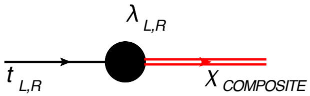
$$c_t = 1 - \frac{Y_*^2 v^2}{2M_*^2} \quad c_g = \frac{Y_*^2 v^2}{2M_*^2}$$

- Composite Higgs models with partial compositeness behave very similarly

(c_g, c_t) in Composite Higgs: Explicit Model MCHM5



- $c_g^{Naive} \sim \frac{\lambda^2}{M_*^2}\frac{v^2}{f^2}$
- In MCHM5

$$V_{CW} = \alpha \sin^2 \frac{h}{f} + \beta \sin^4 \frac{h}{f}$$

$\frac{v^2}{f^2} \ll 1$ requires
$\alpha \sim \beta \Rightarrow \; 2\lambda_R^2 - \lambda_L^2 \sim 0$

- However $c_g \propto 2\lambda_R^2 - \lambda_L^2$

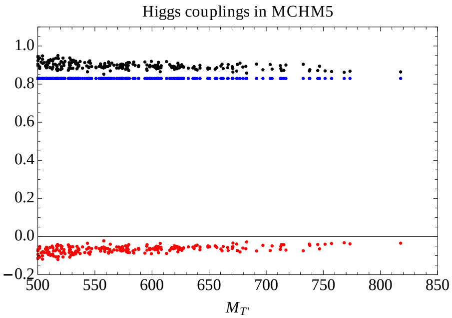


Figure: Blue- $c_g(m_h) = \frac{1-2\xi}{\sqrt{1-\xi}}$, Red- c_g generted by top partners, black c_t, f=700GeV, $\xi = 0.12$

Bounds on top partners

-

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

$$c_{g,u} = \frac{Y_*^2 v^2}{2M_*^2}, \quad c_8 \sim \frac{Y_*^2 v^4}{M_*^4}$$

- we generate also the operators

$$O^3_{Hq} = i\left(H^\dagger \tau^I \overleftrightarrow{D_\mu} H\right)(\bar{q}_L \gamma_\mu \tau^I q_L)$$

$$O^1_{Hq} = i\left(H^\dagger \overleftrightarrow{D_\mu} H\right)(\bar{q}_L \gamma_\mu q_L)$$

$$c^1_{Hq} = -c^3_{Hq} = \frac{Y_*^2 v^2}{M_*^2}$$

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

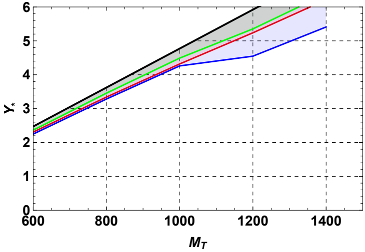


Figure: 95% exclusion in Y_*/top partner mass plane.Red- full calculation, blue linear EFT, green non-linear EFT

Results look weaker than the projections of the direct searches of the top partners *(Matsedonskyi et al 1409.0100)*

Correlations with the sign of c^1_{Hq}

singlet vector-like T predicts

$$-\frac{1}{2}c^3_{Hq} = \frac{1}{2}c^1_{Hq} = c_{g,u} = \frac{Y_*^2 v^2}{2M_*^2}$$

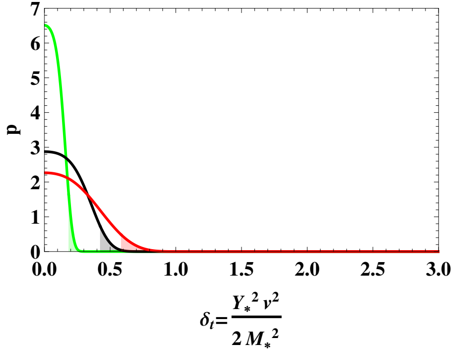


Figure: Red- $c^1_{Hq} = \frac{Y_*^2 v^2}{M_*^2}$, black- $c^1_{Hq} = 0$, green- $c^1_{Hq} = -\frac{Y_*^2 v^2}{M_*^2}$

100 TeV prospects

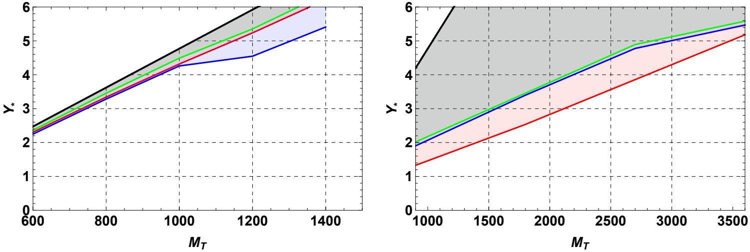


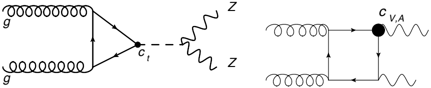
Figure: 95% exclusion curves in Y_*/top partner mass plane. Left 14 TeV $3ab^{-1}$, right- 100 TeV $3ab^{-1}$ analysis. Red- full calculation, blue linear EFT, green non-linear EFT.

Effects of the $\bar{t}tZ$ coupling

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

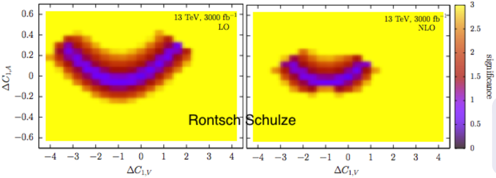
$$F_V = \frac{3 - 8\sin^2\theta_W}{12\sin\theta_W\cos\theta_W}, \quad F_A = -\frac{1}{4\sin\theta_W\cos\theta_W}$$

where in the Standard Model (SM) $c_v = c_A = 1$



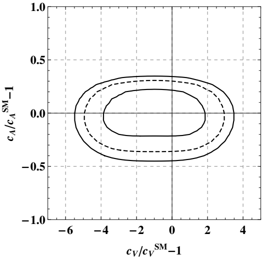
No more cancellations between the triangle and the box diagrams even if $c_t = 1$, and $c_g = 0$

Constraints on $\bar{t}tZ$ couplings from the off-shell Higgs production at 14 TeV



We can measure the ttZ coupling in the top pair and Z production in QCD Rontsch,Shulze 1404.1005

Looks worse than ttZ production but we are in the same range



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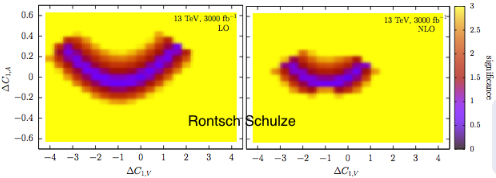
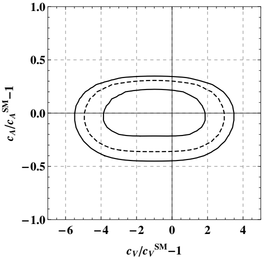




We can measure the *ttZ* coupling in the top pair and Z production in QCD Rontsch,Shulze 1404.1005

Looks worse than ttZ production but we are in the same range

At one loop modifications of the ttZ coupling will feed to the EWPT and flavor physics constraints *hep-ph/9903394; 0806.3247; 1408.0792* leading to much stronger constraints

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.
- The studies of the boosted and off-shell Higgs production can be used as an additional measurement of the top Yukawa coupling
- Double Higgs production provides us with another handle on the SM top Yukawa coupling can be competitive to the tth production.

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 (*arXiv:1403.4951 Gainer, Lykken,Matchev,Mrenna,Park*)

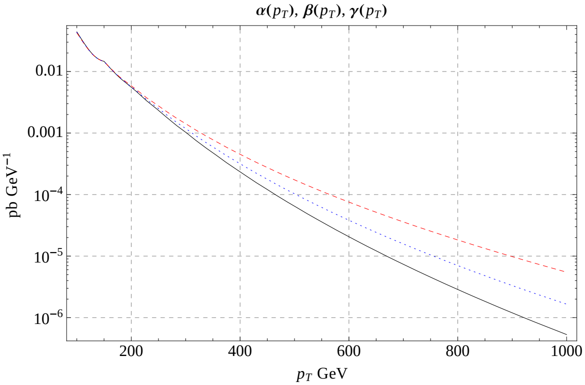
$$O_{\Box} = \frac{c_{\Box}}{v} \Box h Z_{\mu} Z^{\mu}$$
$$68\% : \quad c_{\Box} \in [-0.7, -0.17] \cup [0.42, 0.84] \, ,$$

- 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.

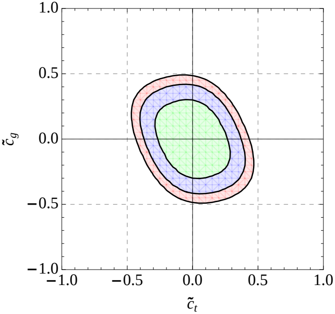
Differential Cross section



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

CP Violating Couplings

- In the presence of the CP odd interactions there is a similar flat direction in $(\tilde{c}_t, \tilde{c}_g)$ plane
  $i\tilde{c}_t \frac{m_t}{v} \bar{t}\gamma_5 t h + \tilde{c}_g \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$
- Off shell higgs production can be used to constrain it.



Flat direction in the Higgs couplings space

What kind of flat direction in the Higgs coupling space are we exploring ?

- to keep the on-shell rate the same

$$\frac{g^2_{gg\to h} g^2_{h\to ZZ}}{\Gamma} = \left(\frac{g^2_{gg\to h} g^2_{h\to ZZ}}{\Gamma}\right)_{SM}$$

- To keep SM like yields in the other channels we need as well

$$\frac{g_i}{g_j} = \left(\frac{g_i}{g_j}\right)_{SM}$$

- 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.

EFT analysis comparison to EWPT

- Assuming the Higgs boson is a doublet then the modifications of the ttZ coupling should come from the dimension six oeprators

$$O^3_{Hq} = i\left(H^\dagger \tau^I \overleftrightarrow{D_\mu} H\right)(\bar{q}_L \gamma_\mu \tau^I q_L), \quad O^1_{Hq} = i\left(H^\dagger \overleftrightarrow{D_\mu} H\right)(\bar{q}_L \gamma_\mu q_L)$$

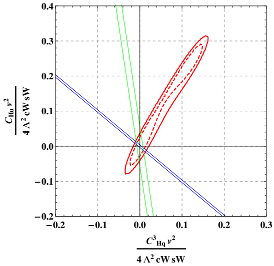
$$O_{Hu} = i\left(H^\dagger \overleftrightarrow{D_\mu} H\right)(\bar{u}_R \gamma_\mu u_R)$$

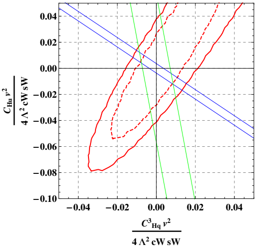
- $Z\bar{b}b$ constraints fixes effectively $C^1_{HQ} = -C^3_{HQ}$
- Then the vector and axial couplings will be modified in the following way:

$$C_V = C_V^{SM} + \frac{v^2}{4\Lambda^2 s_w c_w}\left(2C^3_{Hq} - C_{Hu}\right)$$

$$C_A = C_A^{SM} + \frac{v^2}{4\Lambda^2 s_w c_w}\left(-2C^3_{Hq} - C_{Hu}\right)$$

EFT analysis @ 100 TeV





blue(green) 2σ constraints from $\epsilon_{1(b)}$

- At one loop the modifications of the top interactions will contribute to the electroweak precision tests.
- $$\Delta\epsilon_1 = -\frac{3m_t^2 G_F}{2\sqrt{2}\pi^2}\frac{v^2}{\Lambda^2}\left(C_{Hu} + C_{Hq}^3\right)\log\frac{\Lambda^2}{m_t^2}$$
  $$\Delta\epsilon_b = \frac{m_t^2 G_F}{2\sqrt{2}\pi^2}\frac{v^2}{\Lambda^2}\left(2C_{Hq}^3 + \frac{1}{4}C_{Hu}\right)\log\frac{\Lambda^2}{m_t^2}$$

  Larios et al hep-ph/9903394;Pomarol,Serra 0806.3247;Brod et al 1408.0792

Recently there was a proposal by Brod et al 1408.0792 to use the flavour observables to constrain ttZ couplings, the bounds are similar/stronger than the constraints from EWPT

Higgs couplings fits with and without off-shell measurements, 1505.05516