EFT analysis of the off-shell Higgs production in gluon fusion at FCC

Aleksandr Azatov

CERN

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

Off-shell Higgs production in SM

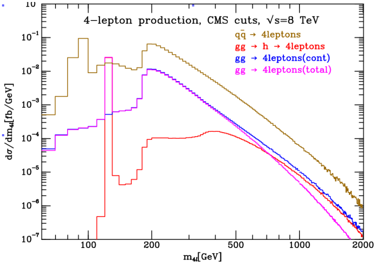
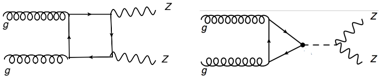


Figure: $gg \to 4l$ in SM from 1311.3589 by Campbell, Ellis and Williams



- 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

- Off-shell ZZ production is important at energies which are higher than m_H, m_t
- How can we use it to constrain new physics?

Off-Shell Higgs production

- One can use off-shell Higgs measurements to constrain the total width of the Higgs boson (*Caola,Melnikov*)

on-shell:

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

off-shell:

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

- There is a flat direction along $\Gamma \propto g^2_{prod} g^2_{decay}$ which can be probed by off-shell Higgs measurements

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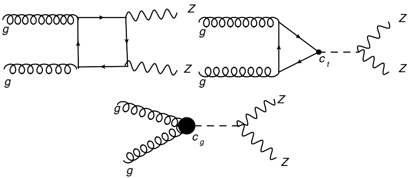
- There is an invisible Higgs decay, so the total width and the couplings are independent parameters.
- Variations of all the Higgs couplings are universal in order to keep the ratios of the on-shell branching ratios SM like.
- There are no higher dimensional operators effecting the Higgs production or decay.

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

Constraining EFT: operators modifying the Higgs decay

- $$\mathcal{L} = \frac{m_Z^2}{v}\kappa_Z h Z_\mu Z^\mu + \kappa_{Z,1}\frac{h}{v}Z_{\mu\nu}Z^{\mu\nu} + \kappa_{Z,2}\frac{h}{v}\partial_\mu Z^{\mu\nu}Z_\nu + \kappa_\Box \Box\frac{h}{v}Z_\mu Z^\mu$$
- $hZ_\mu Z^\mu$ is constrained by the on-shell measurements
- $\frac{h}{v}Z_{\mu\nu}Z^{\mu\nu}$, $\frac{h}{v}\partial_\mu Z^{\mu\nu}Z_\nu$ contribute only to the transverse Z polarizations $\rightarrow$ growth with $\sqrt{s}$ is SM-like, going off-shell does not help
- $\Box h Z_\mu Z^\mu$ grows as $\hat{s}$ in the off-shell production, however if the Higgs is a doublet can appear only as a dimension 8 operator $\frac{(D_\mu H)^2\Box(H^\dagger H)}{\Lambda^4}$ $\Rightarrow$ weak constraints on Λ.

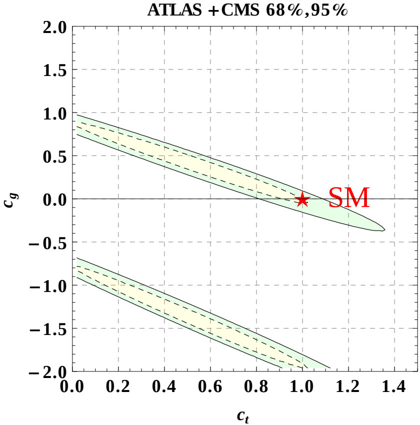
EFT interpretation: operators moidying the Higgs production



- $$\mathcal{L}^{\text{dim-6}} = c_y \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R + \frac{c_g g_s^2}{48\pi^2 v^2} |H|^2 G_{\mu\nu}^2$$
  $$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu}^2$$
  $$c_t = 1 - Re(c_y)$$
- off-shell production :
  $$\mathcal{M}_{gg \to ZZ} = \mathcal{M}_{bcg} + c_t \mathcal{M}_{c_t} + c_g \mathcal{M}_{c_g}$$
  $$\mathcal{M}_{bcg}^{++00} \sim \mathcal{M}_{c_t}^{++00} \sim \log^2 \frac{\hat{s}}{m_t^2}, \quad \mathcal{M}_{c_g}^{++00} \sim \hat{s}$$
- New physics contribution grows with $\hat{s}$ - high energy bins become very important.

Combination with on-shell constraints

- $\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu}^2$
- on-shell production is proportional to $|c_t + c_g|^2$.
- The degenereacy in c_t, c_g is broken only by the tth production $\propto c_t^2$ and and the Higgs decay into two photons $\Gamma(h \to \gamma\gamma) \propto |1.26 - 0.26 c_t|^2$



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- **If the new Higgs interactions are generated by the "top-like" fields i.e. fundamentals of $SU(3)$ and electric charge $2/3$**

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

only tth can break the $c_t - c_g$ degeneracy

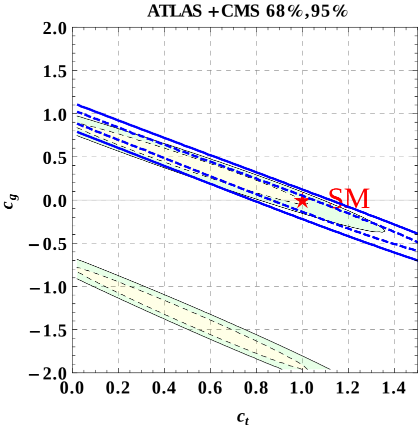
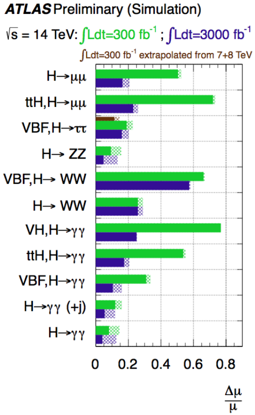
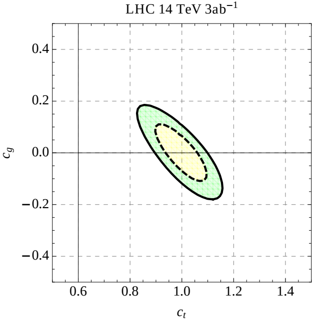


Figure: For top partners $c_t - c_g$ degeneracy becomes much stronger.

Combination with on-shell constraints HL-LHC

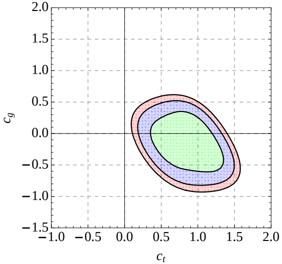




The constraints will be dominated by the *tth* measurement, inclusion/omission of $\frac{e^2}{18\pi^2} c_g \frac{h}{v} \gamma_{\mu\nu}^2$ interaction almost does not change the fit. **The rest of the results are presented in the presence of the photonic operator.**

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

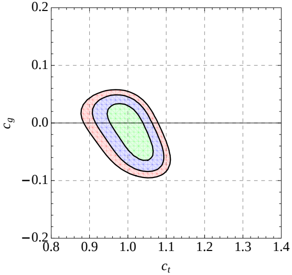
- We simulate the signal and the background with the MCFM 6.8 code, and bin the events in six categories $\sqrt{\hat{s}} = (250, 400, 600, 800, 1100, 1500)$ GeV
- K- factors: we assume the same K-factor for the signal and the interfering background and calculate them using the ggHiggs code.

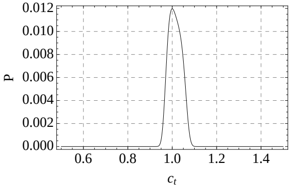


The resulting bound looks weaker then the prospects of the tth measurements: $\sim 25\%$ against $\sim 10\%$ in tth. **However studies of the distributions will definitely improve the bounds. For 8 TeV analysis** $\Gamma \lesssim 20\Gamma_{SM} \Rightarrow \Gamma \lesssim 5\Gamma_{SM}$ **...**

High Luminosity 3 ab^{-1} 100 TeV FCC 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, 1500,2000,3000,4000,5000) GeV
- K- factors: we assume the same K-factor for the signal and the interfering background and calculate them using the ggHiggs code.
- Assuming $|c_t + c_g| = 1$ we find at 95% $c_t \in [0.96, 1.07]$





Validity of the EFT analysis

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

$$\mathcal{L}^{\text{dim-6}} = c_u \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R + \text{h.c.} + \frac{c_g g_s^2}{48\pi^2 v^2} |H|^2 G_{\mu\nu} G^{\mu\nu}$$
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Our analysis is valid only in the range where the effects of the dimension-8 operators can be ignored

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

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

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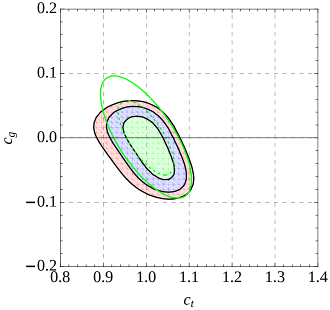
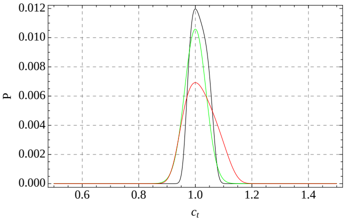
Square of the dimension 6 operators act effectively as the dimension-8 operators. So we can keep $O(c_g^2)$ in the analysis only if

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

Linear vs nonlinear analysis

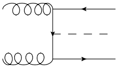


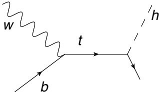


- nonlinear analysis
  95% $c_t \in [0.96, 1.07]$
- linear analysis 95% $c_t \in [0.93, 1.07]$
- keeping $\sqrt{s} < 1.5$ TeV
  95% $c_t \in [0.92, 1.13]$

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

The other channels breaking the c_t, c_g degeneracy

-  top pair production with the Higgs boson

- 

single top production with the Higgs boson

  CMS-PAS-HIG-14-001,1211.0499, 1211.3736 ...

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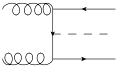
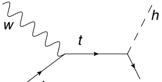
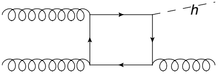
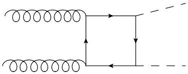
-  top pair production with the Higgs boson
- 

single top production with the Higgs boson *CMS-PAS-HIG-14-001,1211.0499, 1211.3736 ...*
- 

Boosted Higgs production (Higgs + hard QCD jet)*1308.4771 ,1309.5273 , 1312.3317 ,1405.7651*
-  Higgs pair production *1502.00539 ,1507.02245 ,1410.3471 , 1405.4295*

Comparison to other channels

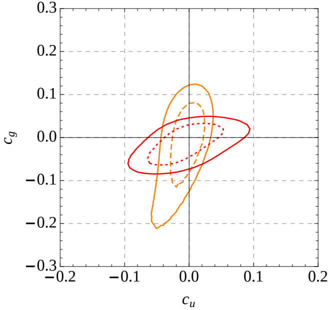


Figure: orange- Higgs pair production (bb $\gamma\gamma$ final state), red- off-shell Higgs pair production

$c_u \equiv 1 - c_t$

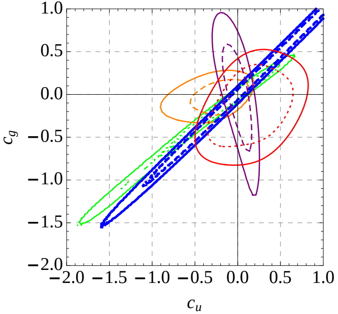
- another channel that can break this degeneracy is the Higgs pair production (talk by Panico)
- The contours are obtained using the 100 TeV 3 ab^{-1} projections from (1502.00539) .

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 100 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

tth and the pair production look to be the most promising ones...



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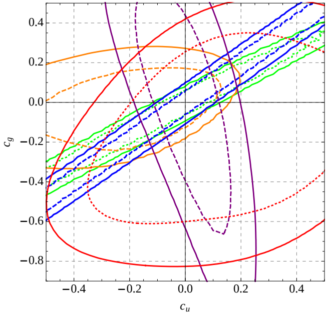

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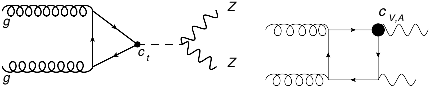
Effects of the $\bar{t}tZ$ coupling

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

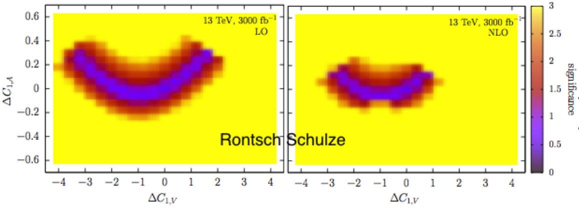
$$F_V = \frac{3 - 8\sin^2\theta_W}{12\sin\theta_W\cos\theta_W}, \quad F_A = -\frac{1}{4\sin\theta_W\cos\theta_W}$$

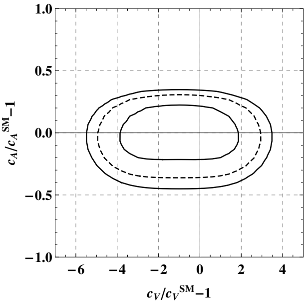
where in the Standard Model (SM) $c_v = c_A = 1$



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

Measuring the ttZ couplings in the off-shell Higgs production 14 TeV

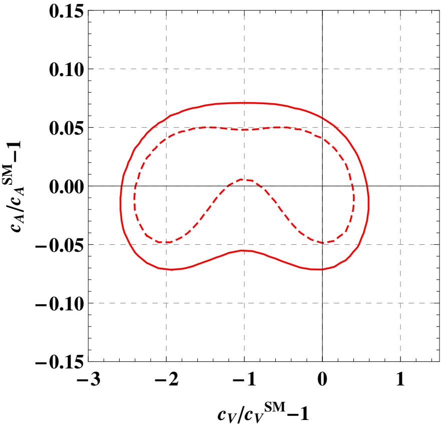




We can measure the $\bar{t}tZ$ coupling in the top pair and Z production in QCD Rontsch,Shulze 1404.1005

Looks worse than ttZ production but we are in the same ball park

Projections for the 100 TeV collider 3 ab^{-1}



- The cross section is second order polynomial in $c^2_{V,A} \Rightarrow$ there four degenerate solutions in the coupling space.
- sensitivity to the c_V is very week we cannot exclude even at 1-σ $c_V = 0$

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

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

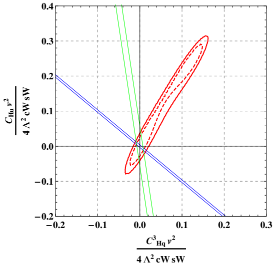
$$O_{Hu} = i\left(H^\dagger \overleftrightarrow{D_\mu} H\right)(\bar{u}_R \gamma_\mu u_R)$$

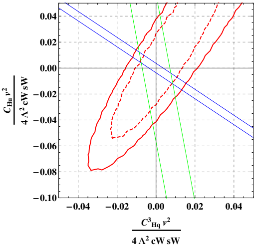
- $Z\bar{b}b$ constraints fixes effectively $C^1_{HQ} = -C^3_{HQ}$
- Then the vector and axial couplings will be modified in the following way:

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

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

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.
-

$$\Delta\epsilon_1 = -\frac{3m_t^2 G_F}{2\sqrt{2}\pi^2}\,\frac{v^2}{\Lambda^2}\left(C_{Hu} + C^3_{Hq}\right)\log\frac{\Lambda^2}{m_t^2}$$

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

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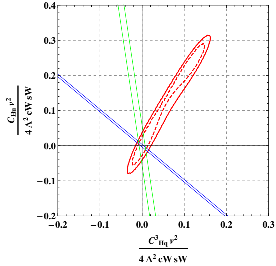

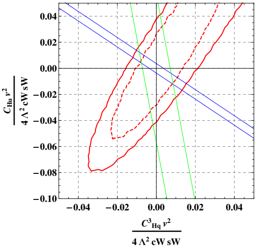

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Recently there was a proposal by Brod et al 1408.0792 to use the flavour observables to constrain ttZ couplings, the bounds are similar/stronger than the constraints from EWPT

Models with (c_t, c_g) degeneracy

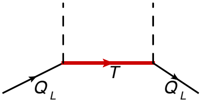
- Simple addition of one vector like fermion

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

$$m = \begin{pmatrix} yv/\sqrt{2} & Y_* v/\sqrt{2} \\ 0 & M_* \end{pmatrix}$$ (Using HLET Shifman et al;Ellis et al)

$$\Rightarrow \quad \kappa_{ggH}(m_H) \approx \frac{\partial \log Detm}{\partial \log v} = 1$$

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



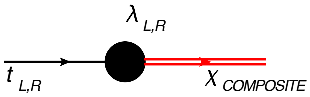
$$y_t \sim y_t^{SM} \left(1 - \frac{Y_*^2 v^2}{2M_*^2}\right)$$

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

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

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

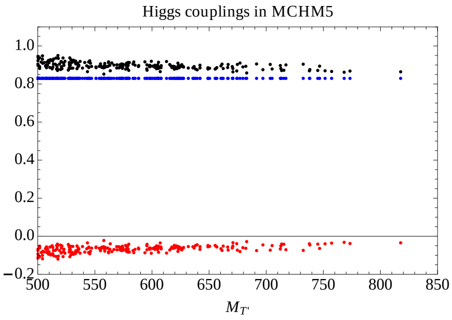


Figure: Blue- $c_g(m_h) = \frac{1-2\xi}{\sqrt{1-\xi}}$, Red- c_g generted by top partners, black c_t, f=700GeV, $\xi = 0.12$

Bounds on top partners

- $$\mathcal{L} = -y\bar{Q}_L t_R H - M_* \bar{T}T - Y_* \bar{Q}_L T_R H$$
- $$\frac{1}{2} c^1_{Hq} = c_{g,y} = \frac{Y_*^2 v^2}{2M_*^2}, \quad c_8 \sim \frac{Y_*^2 v^4}{M_*^4}$$
- analysis ignoring the dimension eight operator is valid up to the energies $\sqrt{\hat{s}} \lesssim M_*$

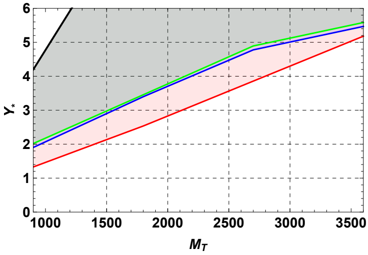


Figure: 95% exclusion in Y_*/top partner mass plane.Red- full calculation, blue linear EFT, green non-linear EFT

Due to the sign of the c^1_{Hq} the bound on the top partners becomes weaker.

Results look weaker than the projections of the direct searches of the top partners *(Matsedonskyi et al 1409.0100)* , however studying the distributions will improve the constraints.

Summary

- Studies of the off-shell Higgs production lead to an additional constraint on the total Higgs decay width.
- They can be also used to constrain the higher dimensional operators contributing to the Higgs production/decay.
- At the dimension-6 level we are especially sensitive to the contact operator between the Higgs boson and gluons.
- Studying the distribution of the $pp \to ZZ$ helps to resolve the information about the particles contributing to the gluon fusion loop.
- The prospects of the indirect constraints look so far weaker than the direct searches, however there is still significant room for the improvement.