Probing the Higgs couplings with high p_T Higgs production

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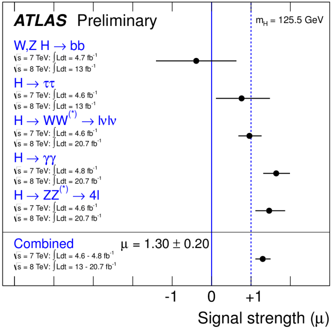
A.A A.Paul arXiv:1309.5273

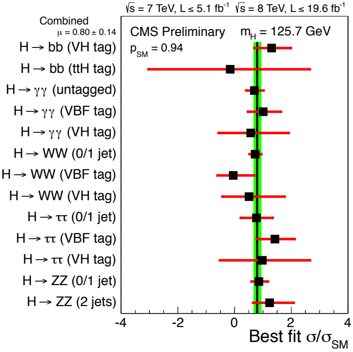
Outline

Searching for new physics through the Higgs couplings

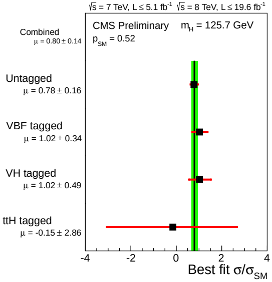
- LHC has discovered Higgs boson, which looks so far vey much like the Standard Model Higgs boson
- Most of the BSM models predict a spin 0 field with couplings to the SM fields which are generically different from the Standard Model predictions: SUSY, Composite Higgs...
- Scalar particle with couplings 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





Top quark Yukawa coupling *(see talk by A. Juste)*



- 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

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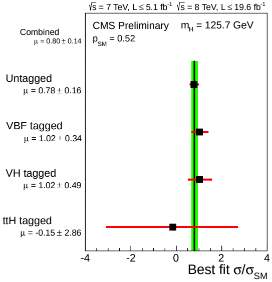
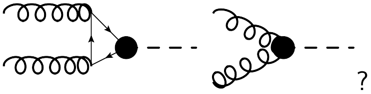


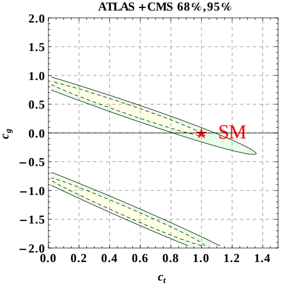
- Direct top Yukava coupling measurements are still weak compared to the other searches
- The dominant constraints on the top Yukawa coupling come from the measurements of the Higgs production in the gluon fusion
- What if the new physics provides simultaneous modifications of the both Higgs top Yukawa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

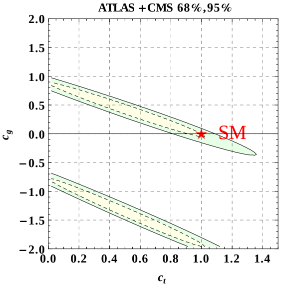
$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$



- 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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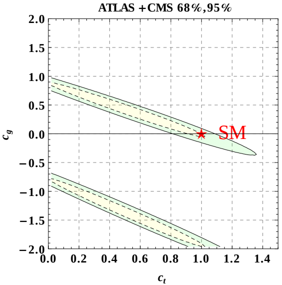

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However the parametrization

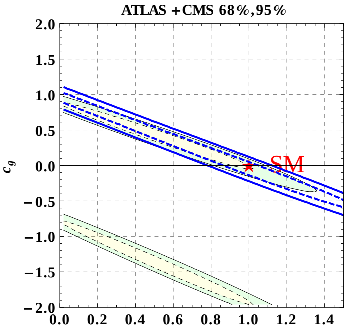
$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

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:

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

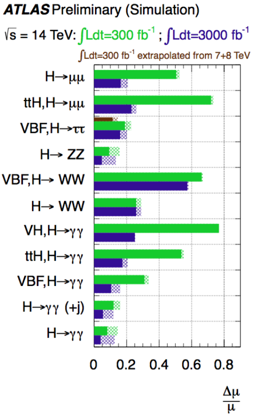


Only the channels with tth production mechanism can break this degeneracy *CMS HIG-13-09, HIG-13-015, ATLAS-CONF-2014-011*

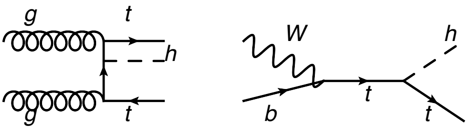
ATLAS $\mu_{bb} = 1.7 \pm 1.4$

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

Prospects for high luminosity LHC



- $\sim 20\%$ uncerainty 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 talk by A. Popov)**



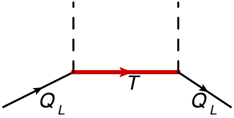
Models with (c_t, c_g) degeneracy

- 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



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

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

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

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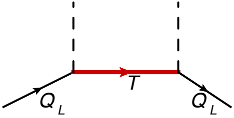

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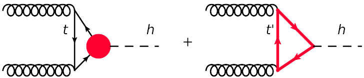
- Are there any motivated models with similar degeneracy?

Composite Higgs models(Georgi,Kaplan;...Agashe,Contino,Pomarol)

- The lightest composite state is usually the fermionic partner of the top quark, which regulates the quadratic sensitivity of the Higgs potential
- The structure of the Higgs couplings to the fermions is fixed by the Goldstone symmetry.
- The overall modification of the gluon fusion becomes proportional to some trigonometric function $F(v/f)$



$\propto F(v/f)$

Falkowski;Low,Vichi;A.A,Galloway; Montull,Riva,Salvioni,Torre...

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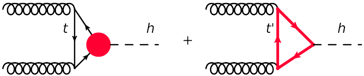

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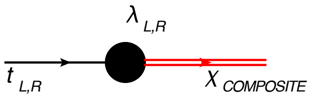
- Not valid for the models, where light fermions are composite

Delaunay,Grojean,Perez

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

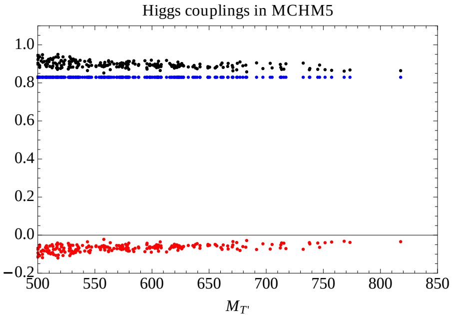


Figure: Blue- $c_g(m_h) = \frac{1-2\xi}{\sqrt{1-\xi}}$, Red- c_g generted by top partners, black c_t, f=700GeV, $\xi = 0.12$

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.

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

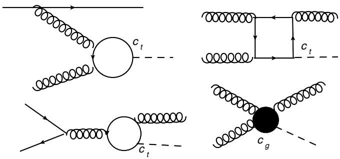
(Grazzini,Sargsyan)

- 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 $gg \to gh, qg \to qh, \bar{q}g \to \bar{q}h, \bar{q}q \to gh$

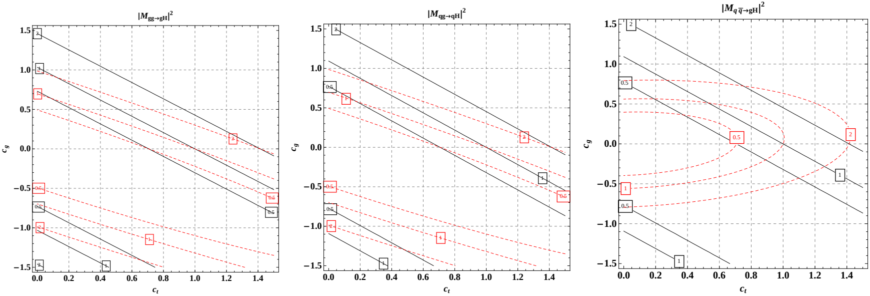


Momenta incoming into loop can be higher than the top mass

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

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)

Isocontours of the partonic cross sections



Black $\sqrt{s} = 130$ GeV, red -$\sqrt{s} = 1000$ GeV

High p_T Higgs production in (c_t, c_g) plane

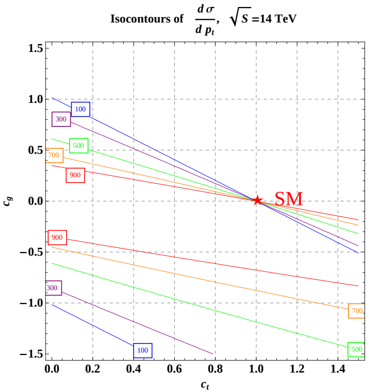
- We have convoluted pdfs from MSTW2008 set with partonic cross sections at LO, setting

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

- 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

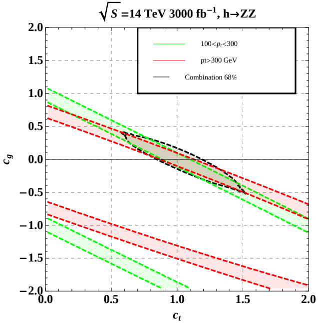


Estimating the LHC potential

- 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

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

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

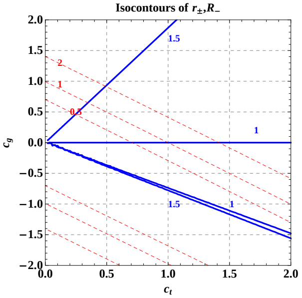


Reducing scale uncertainties

At LO the cross-section is very sensitive to the scale variation and changing the factorization and renormalization scale between $[0.5, 2] \times \sqrt{p_T^2 + m_H^2}$ we get ($\sim 50\%$) modifications. However the ratios of the observed quantities are much less sensitive to the scale variation

$$r_\pm = \frac{N^+/N^-}{\sigma^+_{SM}/\sigma^-_{SM}}$$

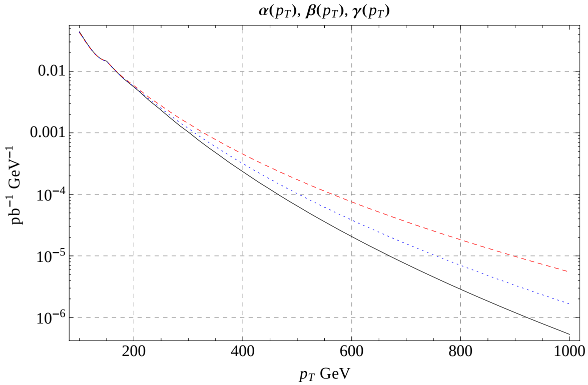
$N^{+,-}$ are the number of observed events in the high and low p_T bins respectively. At LO the scale dependence of the $\sigma^+_{SM}/\sigma^-_{SM}$ reduces to $\sim 10\%$



Conclusion

- Current experimental measurements constrain very weakly the top Yukawa coupling, because only the processes with associated production of the top quark are directly probing this coupling
- This flat direction in the coupling space seems to be especially important for the Composite Higgs models, where the overall Higgs coupling to gluons is less sensitive to the spectrum of resonances
  - Similar analysis can be also important in SUSY for resolving stops mass spectrum *(Grojean, Salvioni,Schlaffer,Weiler*)
- Higgs production at high p_T can help to resolve this degeneracy, so far $h \to ZZ^* \to l^+l^-l^+l^-$seems to be inferior compared to the tth exploring other channels will become useful

Differential Cross section



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