Light Yukawa couplings in HH production

Berlin BSM workshop

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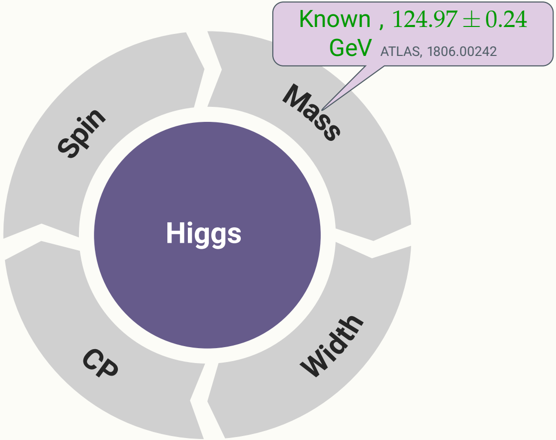
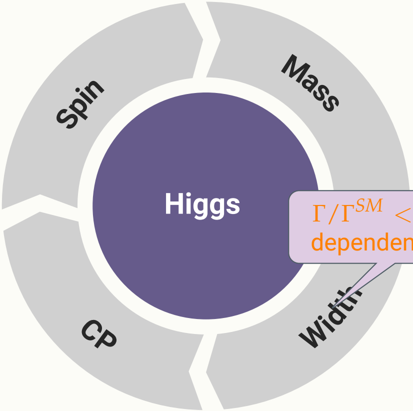
What can be known about the Higgs ?

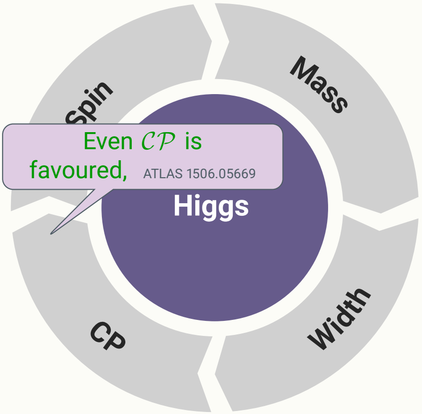


What can be known about the Higgs ?



$\Gamma/\Gamma^{SM} < 3.5$, model-dependent ATLAS 1808.001191

What can be known about the Higgs ?



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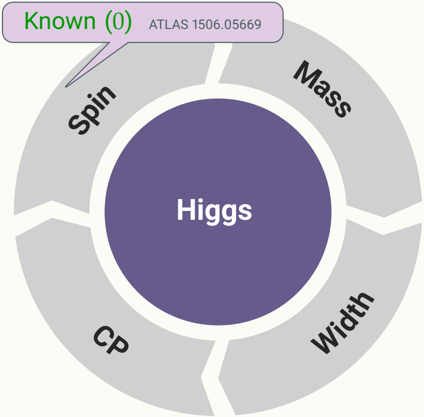

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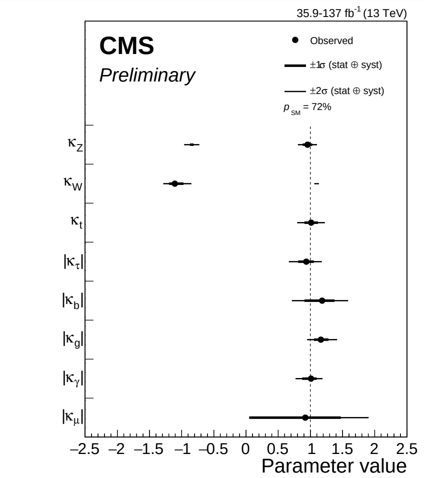


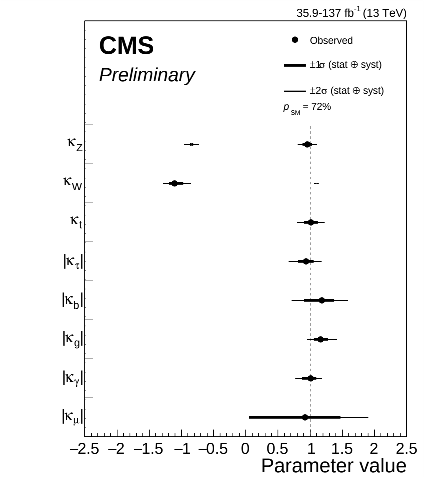
CMS-PAS-HIG-19-005

Higgs couplings :

We define the scaling factor a coupling κ as $\kappa = \frac{g_h}{g_h^{SM}}$

- To electroweak bosons Known,$\kappa_{W/Z/\gamma} \sim 0.6 - 1.2$
- To 3rd family quarks Known, most recent CMS-TOP-17-004 $\kappa_t < 1.67$, @ 95% CL)
- To τ Known, CMS-HUG-16-043
- The coupling $g_{h\mu\mu}$ has a recent bound ATLAS-CONF-2019-028.
- To 1st and 2nd generation quarks.
- self couplings

What can be known about the Higgs ?



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Current bounds are not very constraining

Currents bound on light Yukawa couplings

- The current bounds on the light Yukawa couplings (2nd and 1st generation quarks),are (model-dependent, global fit):

$$|\kappa_d| < 1270, \quad |\kappa_u| < 1150;$$

$$|\kappa_s| < 53, \quad |\kappa_c| < 5.$$

  Obtained by allowing the couplings to be scaled one at a time F. Yu,'16
- The current bounds are very weak :(

New Higgs fermion coupling from linear SMEFT

We have the Lagrangian :

$$\mathcal{L} \supset -Y_u \bar{Q}_L \Phi u_R - Y_d \bar{Q}_L \tilde{\Phi} d_R + h.c. + \frac{\Phi^\dagger \Phi}{\Lambda^2} \left(c_u \bar{Q}_L \Phi u_R + c_d \bar{Q}_L \tilde{\Phi} d_R + h.c \right)$$

SMEFT Yukawa

$$g_{hf\bar{f}} = g^{SM}_{hf\bar{f}} - \frac{\xi}{\sqrt{2}} c_f = \kappa_f \, g^{SM}_{hf\bar{f}} .$$

Linear $hhf\bar{f}$ coupling

$$g_{hhf\bar{f}} = -3 \, g^{SM}_{hf\bar{f}} \frac{(1-\kappa_f)}{v}$$

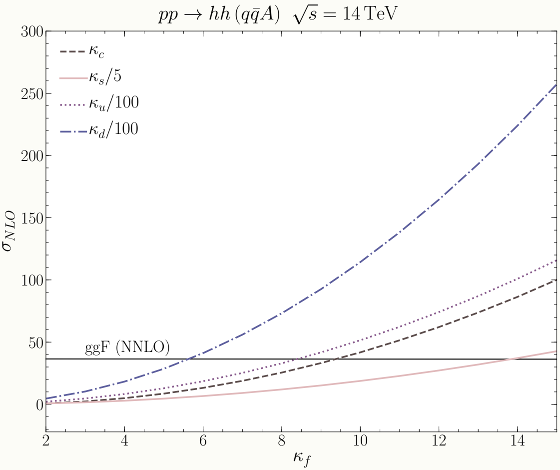
We identify :

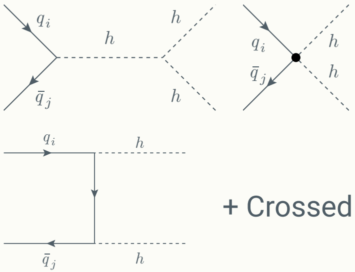
$$g^{SM}_{hf\bar{f}} = \frac{m_f}{v}, \;\; \xi = \frac{v^2}{\Lambda^2},$$

and the scaling:

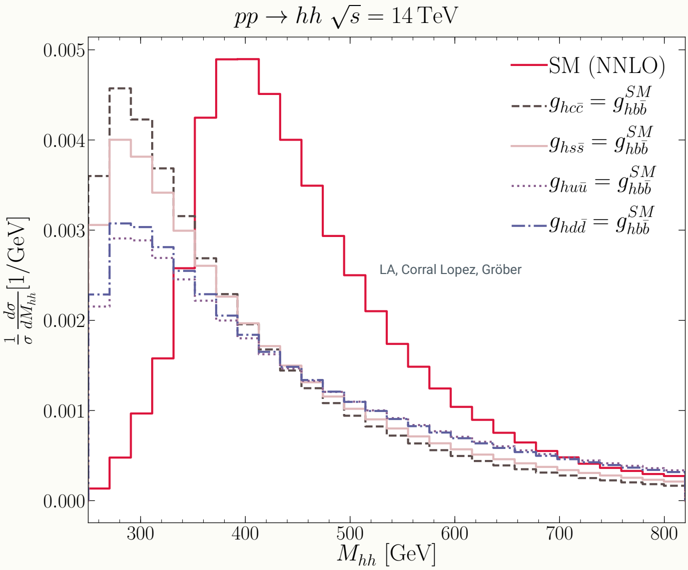
$$\kappa_f = \left(1 - \frac{c_f}{\sqrt{2}} \, \xi \, \frac{v}{m_f} \right) .$$

The channel $q\bar{q} \to hh$ (inclusive cross section)





The channel $q\bar{q} \to hh$ (differential cross section)



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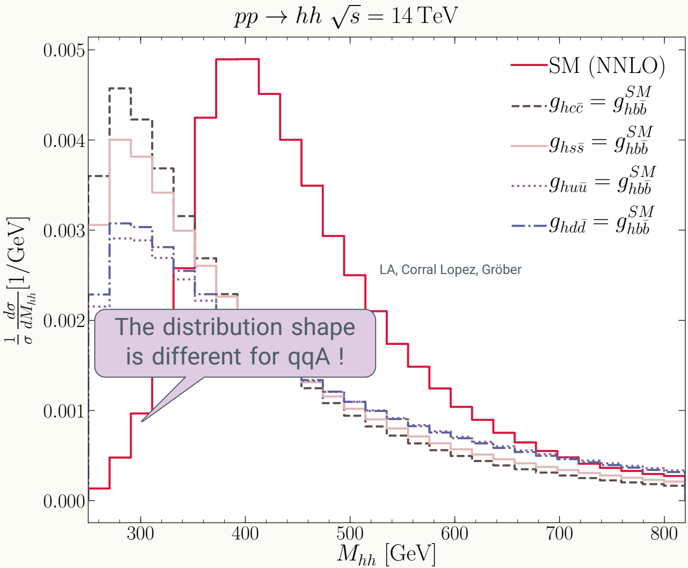
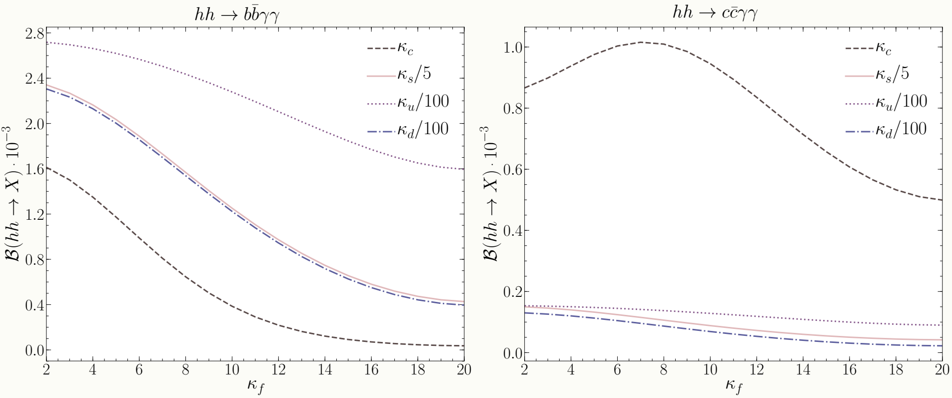


The channel $q\bar{q} \to hh$ (partial widths)

The branching ratios (BR) are changed significantly with κ_f scaling. The BR's were calculated via a modified version of `HDECAY` A. Djouadi *et al.* '98



Analysis strategy

The expected number of Higgs pairs that are produced at the LHC and decaying into $b\bar{b}(c\bar{c})\gamma\gamma$ with particular $b(c)$-tagging working point is given by

- 3 pb^{-1}(High Luminosity-LHC), end of run II.

$$\mathcal{N} = \int \mathscr{L} dt \; \sigma_{pp \to hh} \cdot 2\mathcal{B}_{h \to \gamma\gamma} \mathcal{B}_{h \to \bar{b}b} \; \varepsilon_{Sel}$$

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- $= \varepsilon_{\text{Acc}} \cdot \varepsilon_{\text{Rec}} \cdot \varepsilon_{\text{Meth}} \cdot \varepsilon_{\text{Trig}} \cdot \varepsilon_{\text{Strip}} \cdot \approx 0.052 - 0.045$

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Use combination of $b-$ and $c-$ tagging to probe $hh \to \bar{c}c\gamma\gamma$, as we shall see later on.

Analysis strategy

We define the signal strength

$$\mu = \frac{\mathcal{N}_s}{\mathcal{N}_s^{SM} + \mathcal{N}_b^{SM}}$$

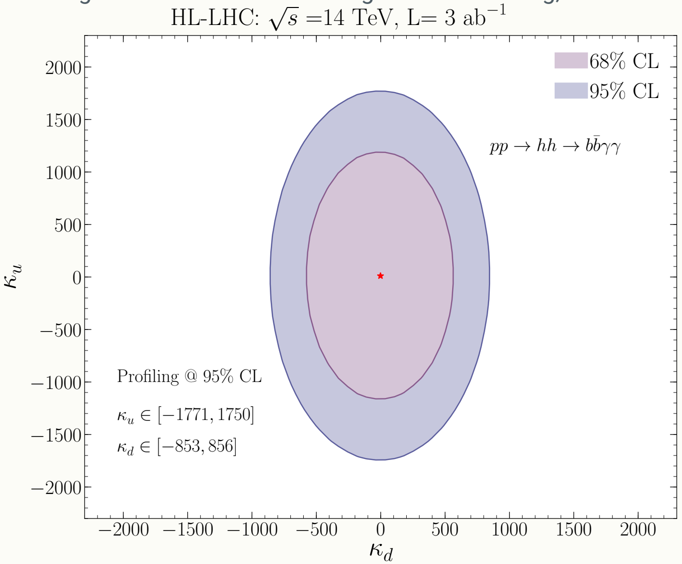
We use toy experiments to generate Asimov data, for the HL-LHC sensitivity estimation, we find that

$$\hat{\mu} = 1.2 \pm 0.9 (@95\%CL)$$

Here, we have assumed that the null hypothesis is the SM HH with SM background.
The backgrounds are taken from A. Azatov et al. ‘15.

Results 1st gen.

Preforming a Liklihood fit on the 1nd generation scaling, we obtain the bounds



Results for non-linear EFT

We could consider scenarios where HH production is particularly sensitive to, mainly speaking the non-linear EFT emerging from the chiral Lagrangian (0 th mode)

$$-\mathcal{L} = \bar{q}_L \frac{m_q}{v} \left(v + c_q h + \frac{c_{qq}}{v} h^2 + \dots \right) q_R + h.c.$$

Resulting in the couplings:

Yukawa coupling

$$g_{h\bar{q}_i q_i} = c_q g^{\text{SM}}_{h\bar{q}_i q_i},$$

$hhq\bar{q}$ coupling

$$g_{hh\bar{q}_i q_i} = c_{qq} g^{\text{SM}}_{h\bar{q}_i q_i} v^{-1}.$$

Here, the Yukawa couplings are independent / uncorrelated from the $hh\bar{q}q$ coupling.

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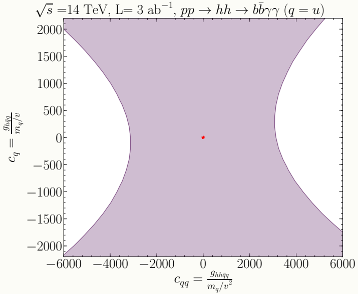
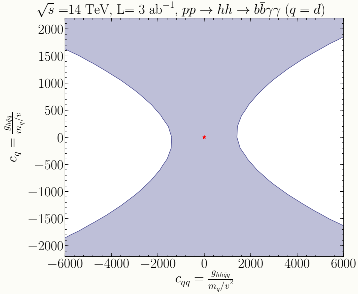
Yukawa coupling	$hq\bar{q}$ coupling
$g_{h\bar{q}_i q_i} = c_q g^{\text{SM}}_{h\bar{q}_i q_i}$,	$g_{hh\bar{q}_i q_i} = c_{qq} g^{\text{SM}}_{h\bar{q}_i q_i} v^{-1}$.

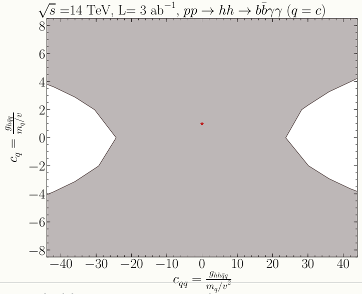
Here, the Yukawa couplings are independent / uncorrelated from the $hh\bar{q}q$ coupling.

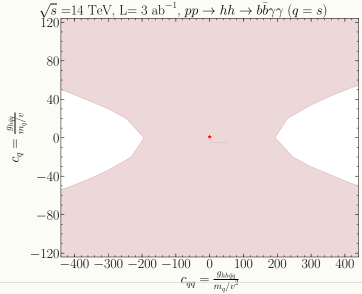
No other accessible processes are sensitive to c_{qq} other than HH !

Results for non-linear EFT









Probing $hh \to \bar{c}c\gamma\gamma$

Applying the technique developed by D. Kim et al. 16 & G. Perez et al.('15 '16),
it is possible to probe the final state $hh \to \bar{c}c\gamma\gamma$ without full $c-$ tagging

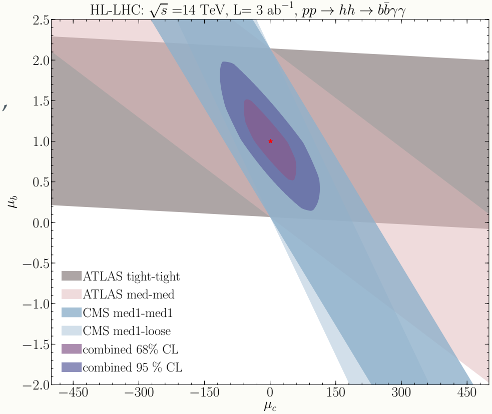
The signal strength is given by

$$\hat{\mu} = \mu_b \, \epsilon_f + 0.05 \cdot \left(\epsilon_{c/b}^{b\text{-tag}}\right)^2 \epsilon_f \cdot \mu_c \,,$$

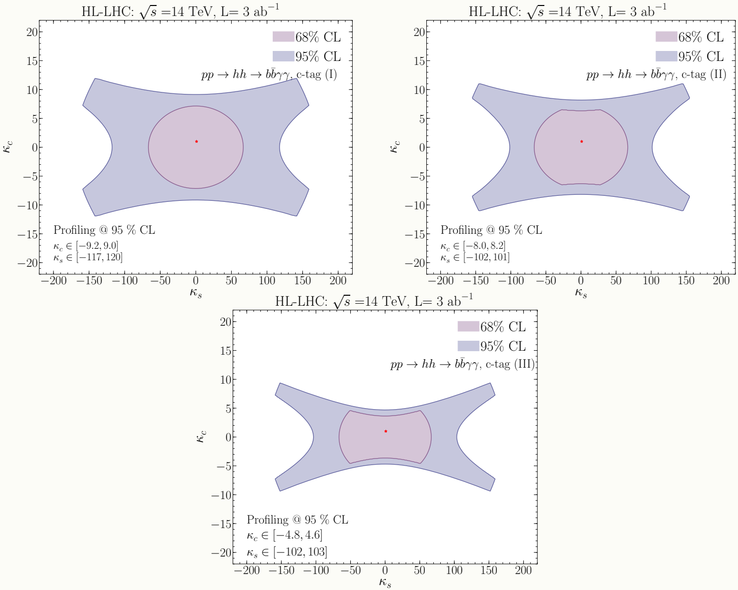
The ratio of a flavour f-tagging efficiencies is defined as

$$\left(\epsilon_{c/b}^{f_1\text{-tag}}\right)^2 = \frac{\epsilon_{f_1 \to f_2,1} \epsilon_{f_1 \to f_2,2}}{\epsilon_{f_1 1} \epsilon_{f_1 2}} \,.$$

c-tagging	ϵ_c	$\epsilon_{c \to b}$	$\mu_c\,(up)$ 95% CL
c-tag I	19%	13%	10.1
c-tag II	30%	20%	8.2
c-tag III	50%	20%	3.8



Results from $hh \to \bar{c}c\gamma\gamma$



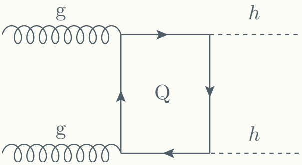
Conclusion and Outlook

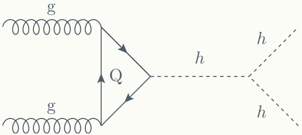
- HH production offer promising sensitivity bounds on light-quark Yukawa couplings„ comparable to other processes e.g. exotic Higgs decays $h \to M\gamma$ etc ... G. T. Bodwin *et al.* '13.
- Combining $c-$ and $b-$ tagging working points for the process $hh \to jj\gamma\gamma$ would offer a better probe for the 2nd gen. (mainly c) Yukawa couplings.
- The HH production (also HHj) is the only accessible process at the LHC that could probe the coupling $g_{hh\bar{q}q}$, particularly the non-linearity between this coupling and Yukawa.
- This work could be extended by analysis of final states $hh \to \bar{b}b\bar{b}b$, $hh \to \bar{b}b\bar{c}c$, $hh \to \bar{c}c\bar{c}c$, and so on.. applying $c-$tagging working points.

Backup Slides

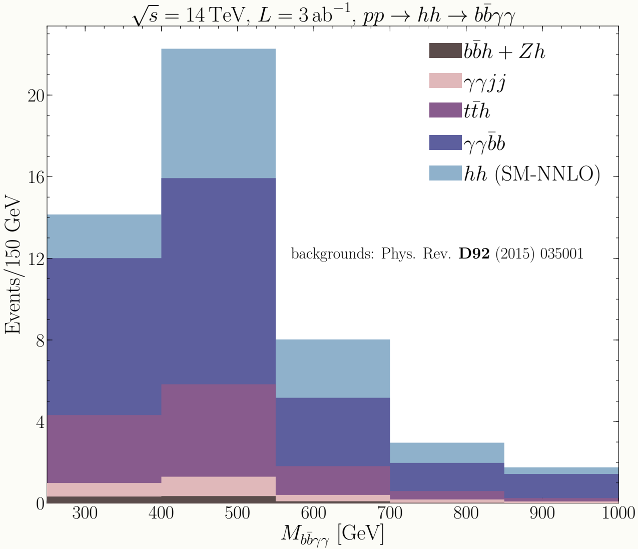
The SM double Higgs production

Gluon gluon fusion (ggF), is the dominant channel for the SM double Higgs production at the LHC.



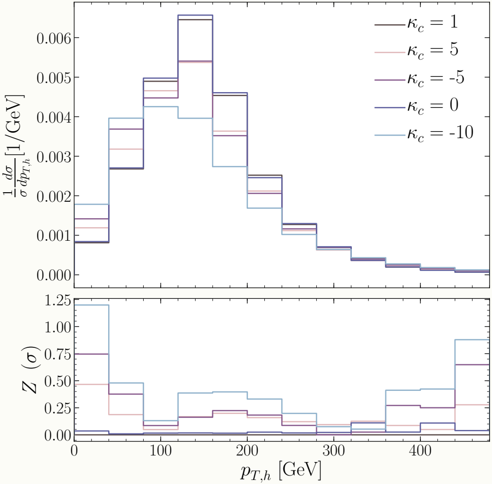


The SM backgrounds



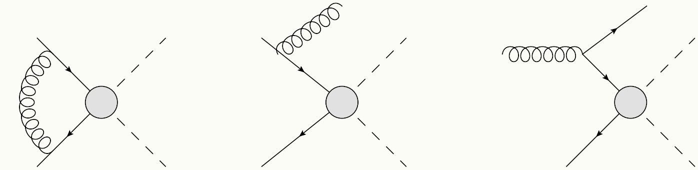
The ggF hh production with modified Yukawa

The p_T distributions are not very sensitive to small changes in κ_c, unlike the hj F. Bishara *et al.* ‘16



NLO corrections to $q\bar{q} \to hh$

Next-to-leading order (NLO) QCD corrections to the s-channel $q\bar{q} \to hh$ have been calculated using the same corrections for $b\bar{b} \to h$ D. Dicus *et al.*, C. Balazs *et al.* , M. Spira and T. Plehn *et al.*.



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$$\begin{aligned} \sigma(q\bar{q} \to h) &= \sigma_{LO} + \Delta\sigma_{q\bar{q}} + \Delta\sigma_{qg} \\ \Delta\sigma_{q\bar{q}} &= \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_H}^{1} d\tau \sum_{q} \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \sigma_0 \int_{\tau}^{1} dz\, \omega_{q\bar{q}}(z) \\ \Delta\sigma_{qg} &= \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_H}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{bg}}{d\tau} \sigma_0 \int_{\tau}^{1} dz\, \omega_{qg}(z) \end{aligned}$$

with $z = \tau_H/\tau$, $\tau_H = (2\, m_h)^2/s$.

Analysis of $pp \to hh \to b\bar{b}\gamma\gamma$

ROOT was used to carry out the analysis of generated events, along with FASTJET, the Mass-drop tagger M. Dasgupta *et al.* 13' for identifying b-jets was applied, and cuts as in A. Azatov *et al.* 15'.

- Select within LHC reconstruction requirements:

$$p_T(\gamma/j) > 25\,\text{GeV}, \quad |\eta(\gamma/j)| < 2.5;$$

- Veto events with hard leptons :

$$p_T(\ell) > 20\,\text{GeV}, \quad |\eta(\ell)| < 2.5;$$

- Select only *hardest* b-tagged jets, and photons

$$p_{T>}(b/\gamma) > 50\,\text{GeV}, \quad p_{T<}(b/\gamma) > 30\,\text{GeV};$$

Analysis of $pp \to hh \to b\bar{b}\gamma\gamma$

- Ensure well- separated b jets and photons:

$$\Delta R(b,b) < 2, \quad \Delta R(\gamma,\gamma) < 2, \quad \Delta R(b,\gamma) > 1.5$$

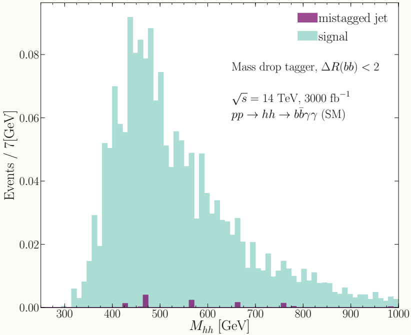
  Where ΔR is the jet-radius, and it is given by :

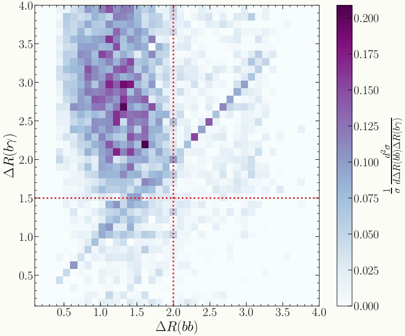
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

- Higgs mass window :

$$105 < m_{b\bar{b}} < 145\,\text{GeV}, \quad 123 < m_{\gamma\gamma} < 130\,\text{GeV}$$

Analysis of $pp \to hh \to b\bar{b}\gamma\gamma$





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