Probing light Yukawa couplings in Higgs pair production

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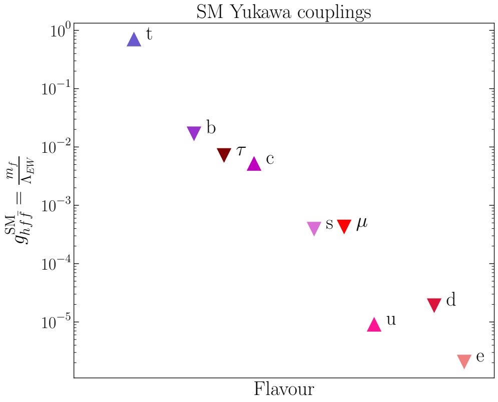
The flavour puzzle of the SM !

- The flavour sector is the least understood of the SM, with $10 = 6 + 3 + 1$ free parameters in the quark sector.
- Looking at the quark masses, we observe an *unnatural hierarchy* between their generations demanding an explanation.



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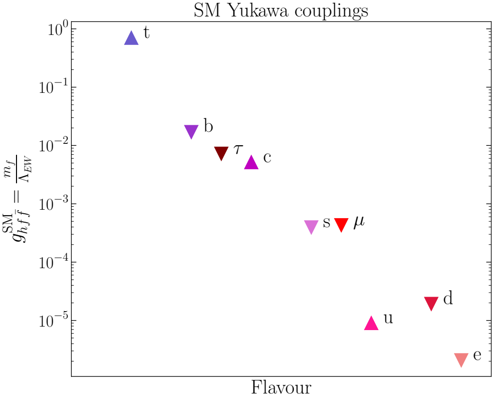


We should measure the light Yukawa couplings !

Currents bound of Yukawa couplings

- We define the scaling factor of a quark flavour f Yukawa coupling κ_f as:

$$\kappa_f = \frac{g_{hf\bar{f}}}{g_{hf\bar{f}}^{\mathrm{SM}}}.$$

- The top and beauty Yukawa couplings are strongly constrained $|\kappa_t| \sim |\kappa_b| \sim 1$ (most recent CMS-TOP-17-004 $\kappa_t < 1.67,$ @ 95% CL) .
- We are concerned with the light Yukawa couplings (2nd and 1st generations), the current bounds are (model-dependent, global fit):

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

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

Obtained by allowing the couplings to be scaled one at a time F. Yu,'16

Formulation of the problem

- Light Yukawa couplings are poorly constrained, as the single Higgs production $gg \to h$ is only sensitive by

  $$\sim \kappa_q \, m_q^2/m_h^2 \ln^2(m_h/m_q),$$

  to light quarks contributions.
- Moreover, we need an extra particle/ jet in order to construct distributions for exclusive bounds.
- Using exotic Higgs decays (e.g. $h \to M\,\gamma$, $M = \rho, \omega, \phi, J/\psi$), as a probe for Light Yukawa couplings has been proposed by G. T. Bodwin *et al.* '13.
- The channel $q\bar{q} \to h \;\; q = c, s, u, d$ remains subdominant $\sim \mathcal{O}(10^1 - 10^2)$ fb compared to the beauty quark channel ~ 2 pb.

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

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

Linear $hhf\bar{f}$ coupling

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

We identify :

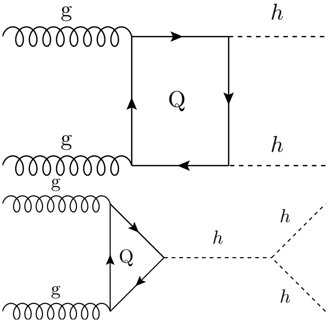
$$g^{\mathrm{SM}}_{hf\bar{f}} = \frac{m_f}{v}, \quad \xi = \frac{v^2}{\Lambda^2},$$

and the scaling:

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

The SM double Higgs production

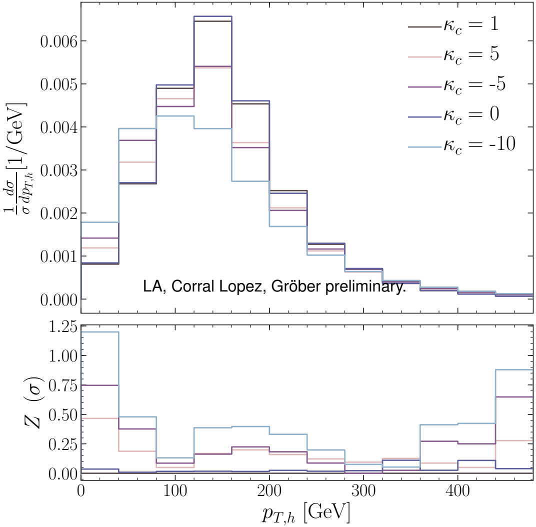
Gluon gluon fusion (ggF), is the dominant channel for the SM double Higgs production at the LHC.



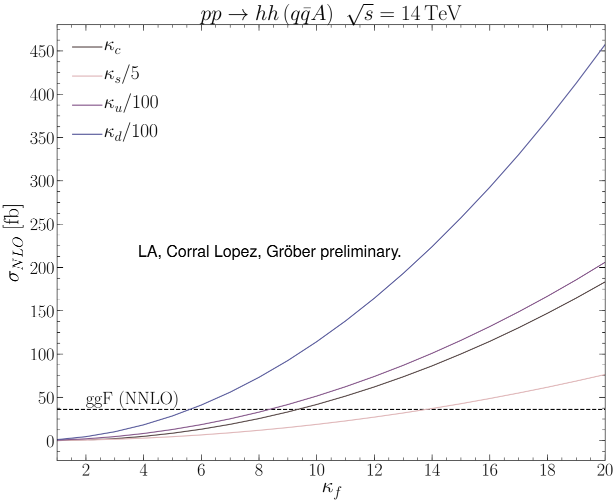
The ggF hh production with modified Yukawa

The p_T distributions are not very sensitive to small changes in κ_c, unlike the hj F.

Bishara *et al.* ‘16

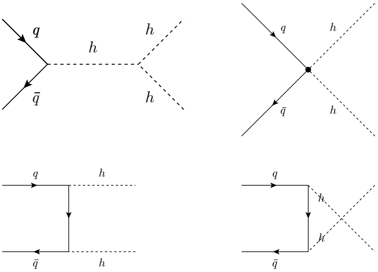


The channel $q\bar{q} \to hh$



$pp \to hh\,(q\bar{q}A)\ \ \sqrt{s} = 14\,\mathrm{TeV}$

LA, Corral Lopez, Gröber preliminary.



Remarks

- We use a benchmark point in the light Yukawa scaling space where :

$$|\kappa_d| = 889.36, \quad |\kappa_u| = 1878.65;$$

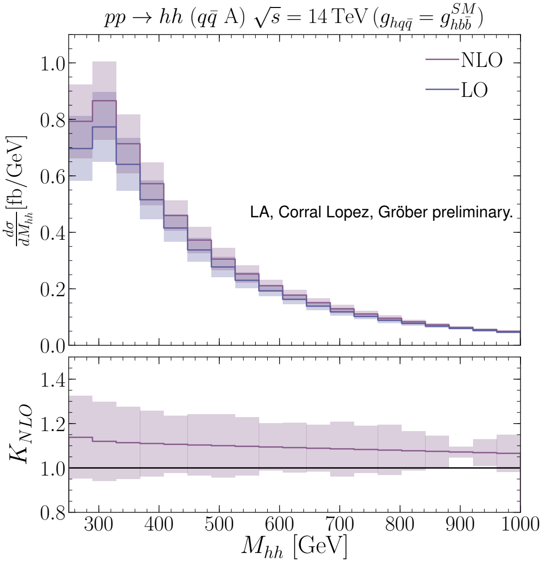
$$|\kappa_s| = 44, \quad |\kappa_c| = 3.28.$$

  This corresponds to setting all the light Yukawa couplings equal to the SM beauty quark Yukawa coupling in the $\bar{M}S$ scheme, i.e.

$$g_{hq\bar{q}} = g^{SM}_{hb\bar{b}}, \quad \forall q = c, s, u, d.$$

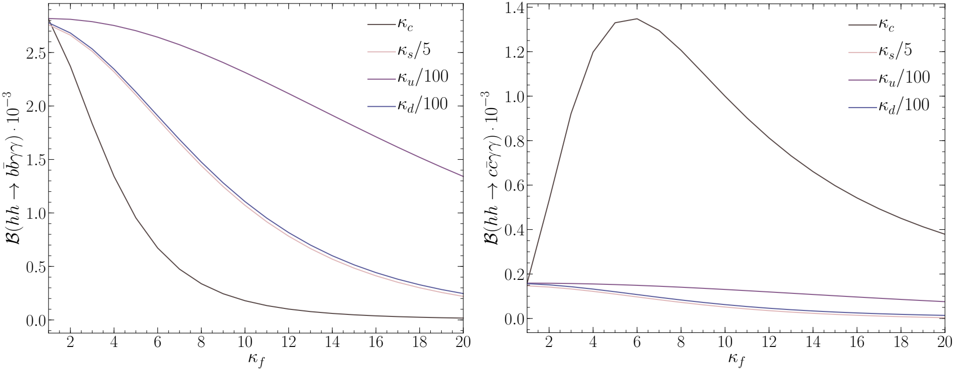
- Since FCNC are strongly constrained, we assumed that the dim 6 operator is flavour diagonal.

Distribution for $q\bar{q} \to hh$



Effects on the decay partial widths

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



LA, Corral Lopez, Gröber preliminary.

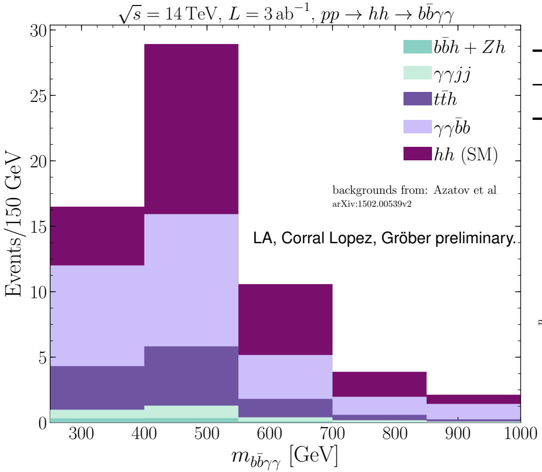
Analysis of $pp \to hh \to b\bar{b}\gamma\gamma$

The following is the 'theoretical' and ' expected' event yields after cuts for the HL-LHC @ 14 TeV, and final state $hh \to b\bar{b}\gamma\gamma$ following the analysis of A. Azatov *et al.* '15 :

	σ_{NLO} [fb]	$\mathcal{B}(hh \to b\bar{b}\gamma\gamma)$	N_{Th}	N_{Expec}
SM	$34.5^{+10.35}_{-8.97}$	2.7×10^{-3}	292	13
$(g_{hq\bar{q}} = g^{SM}_{hb\bar{b}})$	$328.0^{+65.60}_{-49.21}$	1.7×10^{-4}	167	9

Statistical analysis and bounds on μ

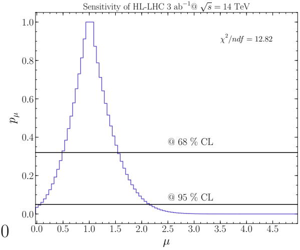
The likelihood profile (ratio) method was use in order to estimate the 68% and 95% CL expected limits on the signal strength μ .



backgrounds from: Azatov et al arXiv:1502.00539v2

LA, Corral Lopez, Gröber preliminary.

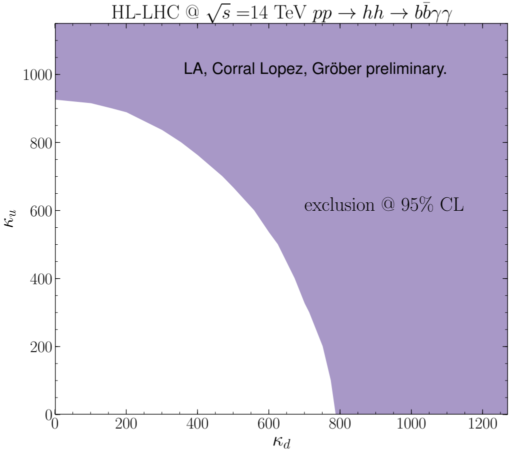
	68% CL	95 % CL
$\hat{\mu} = 0.93$	1.58	2.12



Bounds on the 1st generation Yukawa scaling

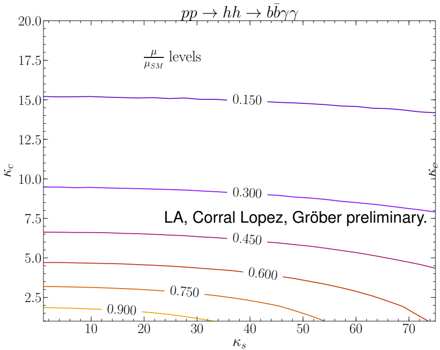
Using the above analysis we get the new bounds of 1st gen. Yukawa scaling:

$$|\kappa_d| < 790, \quad |\kappa_u| < 920;$$



The problem with the 2nd generation

We were unable to construct bounds using μ_b . Possible, even strong bounds could be made via μ_c.



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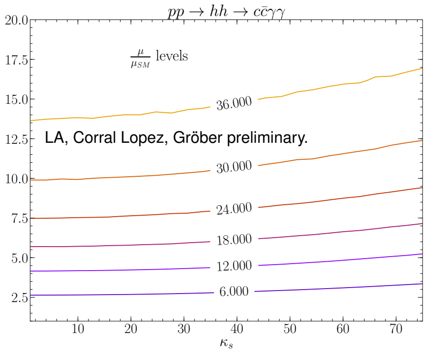

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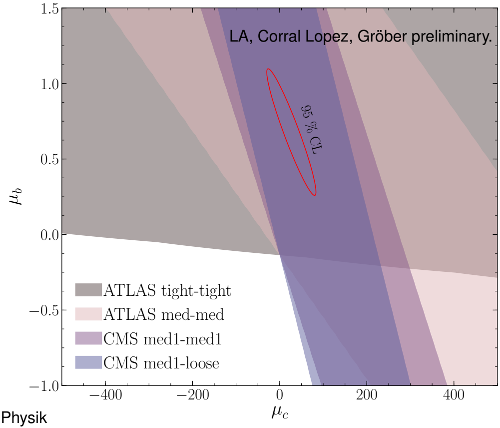
Mistagging of b-jets as a probe for μ_c

$$\hat{\mu} = \frac{\sigma_{hh}\,\mathcal{B}_b\,\epsilon_{Rec}\,\epsilon_{b1}\,\epsilon_{b2} + \sigma_{hh}\,\mathcal{B}_c\,\epsilon_{Rec}\,\epsilon_{c2}\,\epsilon_{c2}}{\sigma_{hh}^{SM}\,\mathcal{B}_b^{SM}\,\epsilon_{Rec}\,\epsilon_{b1}\,\epsilon_{b2}}$$

see : D. Kim *et al.* ‘16 & G. Perez *et al.*(’15 & ‘16)



Profiling over μ_b we obtain the 95 % CL upper bound on μ_c :

$$\mu_c(\text{up}) = 38.32\,^{+7.13}_{-34.92}$$

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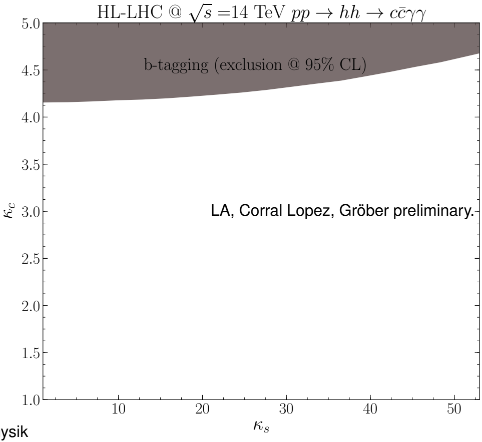

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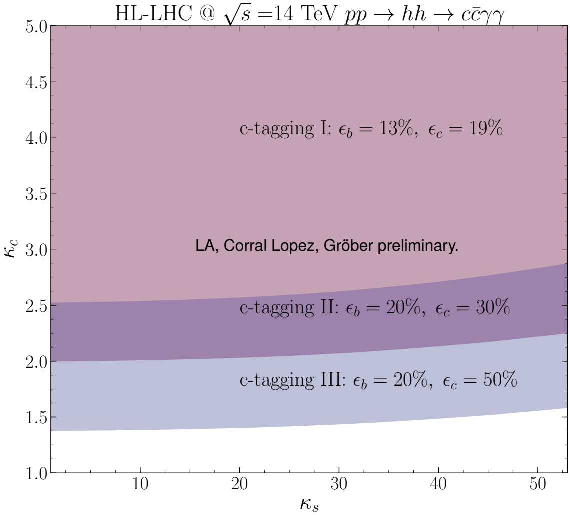
c-tagging working points

See : ATLAS 1501.01325, ATLAS 1407.0608, ATL-PHYS-PUB-2015 and CERN-LHCC-2010-013. ATLAS-TDR-19



Outlook

- The hh production at the HL-LHC has an interesting potential for setting much tighter bounds on the light-Yukawa couplings;

$$|\kappa_d| < 790, \quad |\kappa_u| < 920;$$

$$|\kappa_c| < 1.4, \quad |\kappa_s| < ???;$$

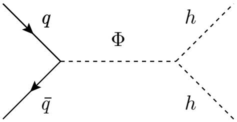
- These bounds are comparable to the expected model-dependent global fit J. De Blas *et al*'19. :

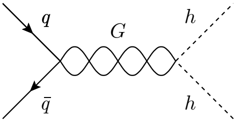
$$|\kappa_u| < 570\,, \qquad |\kappa_d| < 270\,, \qquad |\kappa_s| < 13\,, \qquad |\kappa_c| < 1.2\,.$$

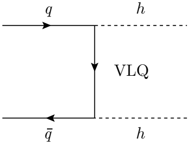
- The next step, is to consider non-linear EFT, FCNC and specific models.

Backup Slides

Examples of UV complete models

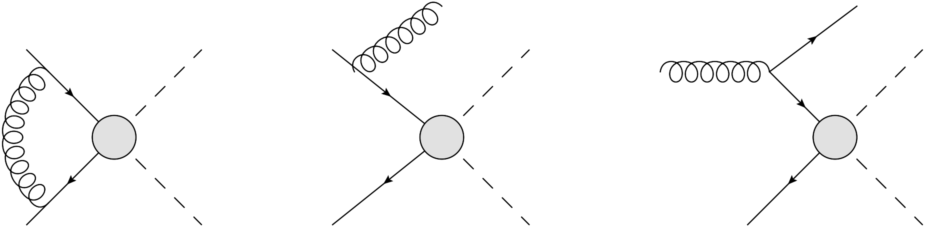






NLO corrections to $q\bar{q} \to hh$

Next-to-leading order (NLO) QCD corrections to the s-channel $q\bar{q} \to hh$ has 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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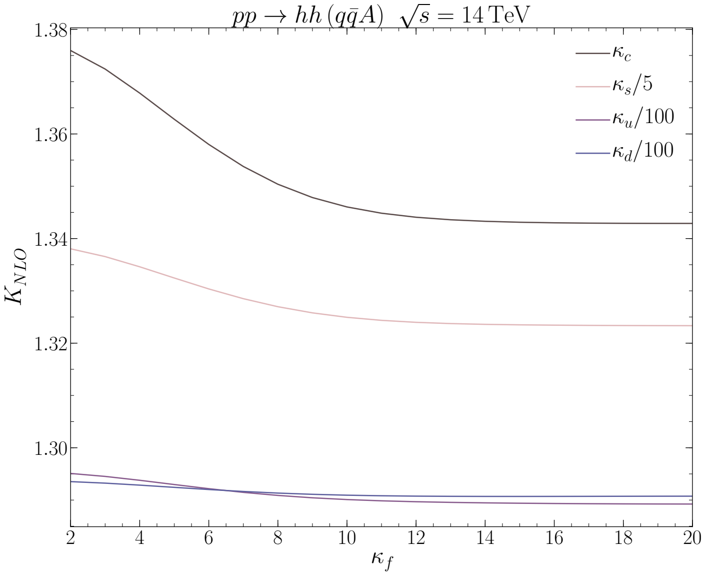
$$\sigma(q\bar{q} \to h) = \sigma_{LO} + \Delta\sigma_{q\bar{q}} + \Delta\sigma_{qg}$$

$$\Delta\sigma_{q\bar{q}} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_H}^{1} d\tau \sum_{q} \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \sigma_0 \int_{\tau}^{1} dz\, \omega_{q\bar{q}}(z)$$

$$\Delta\sigma_{qg} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_H}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{bg}}{d\tau} \sigma_0 \int_{\tau}^{1} dz\, \omega_{qg}(z)$$

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

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



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:

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

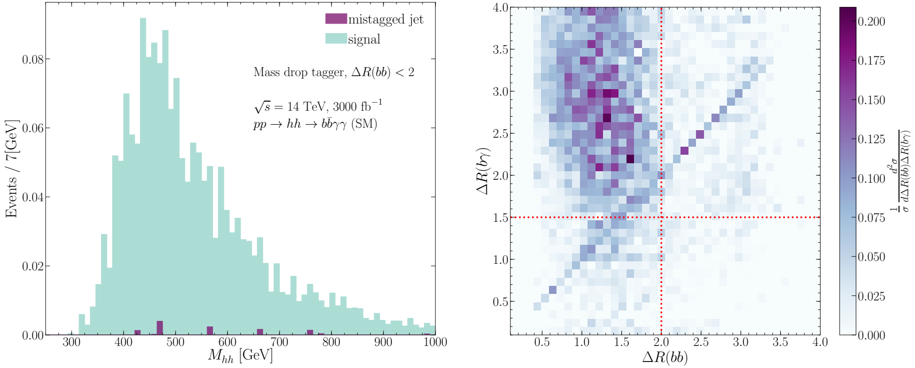
Where ΔR is the jet-radius, and it is given by :

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

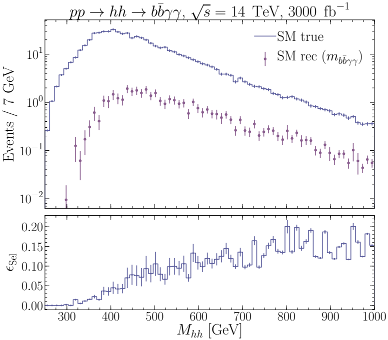
- Higgs mass window :

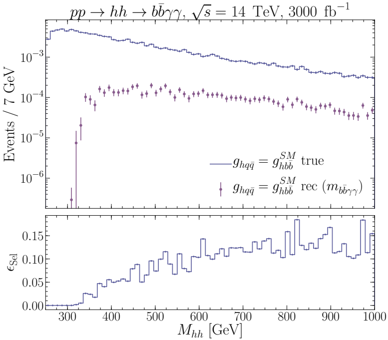
$$105 < m_{b\bar{b}} < 145\,\text{GeV}, \quad 123 < m_{\gamma\gamma} < 130\,\text{GeV}$$

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



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





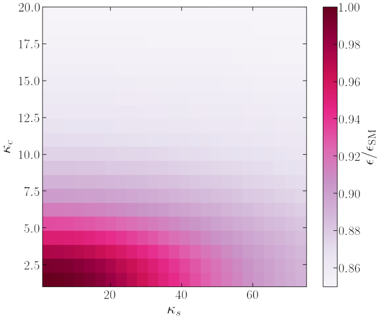
Analysis of $pp \to hh \to b\bar{b}\gamma\gamma$:: efficiency estimation

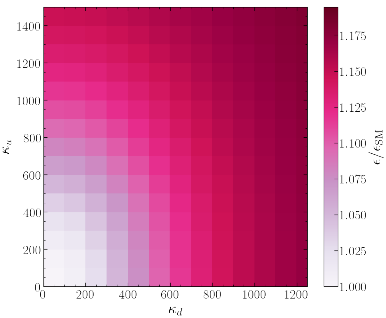
The efficiency can be parametrised by the following relation :

$$\epsilon = \frac{\sigma_{gg}\,\epsilon_{gg} + \sigma_{q\bar{q}}\,\epsilon_{qq}}{\sigma_{gg} + \sigma_{q\bar{q}}}; \quad \epsilon_{gg} = 0.044$$

var	ϵ_{qq}
κ_u	0.050
κ_d	0.049
κ_u & κ_d	0.053
κ_c	0.034
κ_s	0.037
κ_c & κ_s	0.039

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

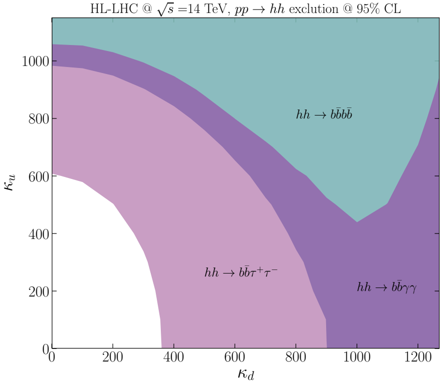




Bounds on the 1st generation Yukawa scaling, More final states

see ATL-PHYS-PUB-2018-05

$$|\kappa_d| < 358, \quad |\kappa_u| < 606;$$



Mistagging of b-jets as a probe for μ_c

We could use the ideas developed by D. Kim *et al.* '16 & G. Perez *et al.*('15 & '16) in order to probe the c-channels via the relation :

$$\hat{\mu} = \frac{\sigma_{hh}\,\mathcal{B}_b\,\epsilon_{Rec}\,\epsilon_{b1}\,\epsilon_{b2} + \sigma_{hh}\,\mathcal{B}_c\,\epsilon_{Rec}\,\epsilon_{c2}\,\epsilon_{c2}}{\sigma_{hh}^{SM}\,\mathcal{B}_b^{SM}\,\epsilon_{Rec}\,\epsilon_{b1}\,\epsilon_{b2}}$$

This simplifies to :

$$\hat{\mu} = \mu_b + 0.05 \cdot \epsilon_{c/b} \cdot \mu_c.$$

for $\mathcal{B}_c^{SM}/\mathcal{B}_b^{SM} \approx 0.05$
And the ratio of tagging efficiency :

$$\epsilon_{c/b} = \frac{\epsilon_{c1}\epsilon_{c2}}{\epsilon_{b1}\epsilon_{b2}}$$

For b-tagging, we have for example $\epsilon_b = 70\%$ and $\epsilon_c \sim 20\%$

c-tagging working points

Reconsider the previous relation, with c-tagging in mind:

$$\hat{\mu} = \frac{\sigma_{hh}\,\mathcal{B}_b\,\epsilon_{Rec}\,\epsilon_{b1}\,\epsilon_{b2} + \sigma_{hh}\,\mathcal{B}_c\,\epsilon_{Rec}\,\epsilon_{c2}\,\epsilon_{c2}}{\sigma_{hh}^{SM}\,\mathcal{B}_b^{SM}\,\epsilon_{Rec}\,\epsilon_{b1}\,\epsilon_{b2} + \sigma_{hh}^{SM}\,\mathcal{B}_c^{SM}\,\epsilon_{Rec}\,\epsilon_{c1}\,\epsilon_{c2}}$$

This simplifies to:

$$\hat{\mu} = \left(\mu_b + 0.05\,\epsilon_{c/b}\mu_c\right) / \left(1 + 0.05\,\epsilon_{c/b}\right)$$

We used the c-tagging efficiency obtained at ATLAS run I (as c-tagging I), and the expected Insertable B-Layer (IBL) subdetector c-tagging efficiency (as c-tagging II and III) .

See : arXiv:1501.01325, arXiv:1407.0608, ATL-PHYS-PUB-2015 and CERN-LHCC-2010-013. ATLAS-TDR-19

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