Measuring the Higgs coupling to light quarks

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arXiv: 1502.00290 & 1505.06689

Which is the only flavour-dependent interaction in the SM?

➜ Higgs-field interaction ➜

- Goldstone bosons / *W* bosons ➜ flavour violation
  Precision Flavour observables, FCNCs, indirect searches for NP

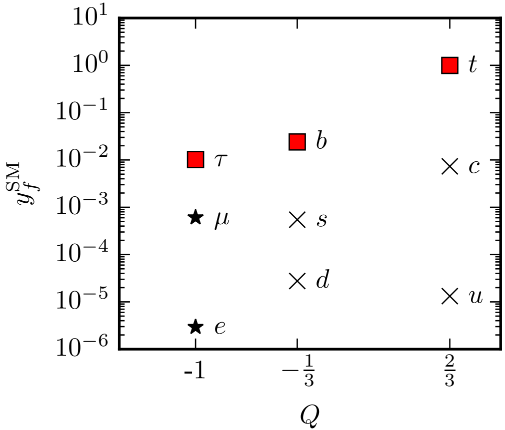
- Higgs particle ➜ interaction strength $\propto$ mass
  New source of flavour data at LHC/future colliders, more room for NP

- More motivations ➜ possible large NP effects
  EWSB $\equiv$ fermion masses only for SM, small deviations $\rightarrow$ large effects
  unitarisation of $ff \rightarrow V^n$ scattering
  $b\bar{b}$: 23 TeV $c\bar{c}$:31 TeV $s\bar{s}$:52 TeV $d\bar{d}$:77 TeV $u\bar{u}$:64 TeV

[Dicus, He 04]

Direct observations for fermionic higgs couplings

- higgs couples to t, b, and τ ✓



- upper bound on higgs to e, μ
- nothing for light quarks

Signal strenth

$$\mu \simeq \frac{\sigma}{\sigma^{\mathrm{SM}}} \frac{\mathcal{BR}}{\mathcal{BR}^{\mathrm{SM}}}$$

- $\mu_\tau = 0.98 \pm 0.22$
- $\mu_b = 0.71 \pm 0.31$
- $\mu_{tth} = 2.41 \pm 0.81$

  [naive ATLAS, CMS averages]
- $\mu_\mu < 7$ @95 CL
- $\mu_e < 3.7 \cdot 10^5$ @95 CL

  [ATLAS, arXiv:1406.7663]

  [CMS, arXiv:1410.6679]

$\frac{\mu_\mu}{\mu_\tau} \sim 280$ for $y_\mu = y_\tau$ but observation $\frac{\mu_\mu}{\mu_\tau} < 15$

➜ higgs couples non-universally to leptons

What about quarks?

$h \to$ light-quark light-quark

Challenges

- SM-higgs decay rates tiny
- huge QCD background
- need some sort of flavour tagging

(*c*-tagging feasible at the LHC)

Directions

- **Be exclusive**
  - $h \to M\,\gamma$ as a flavour proxy (M vector meson)
  - possible for u, d, s, c

  [Bodwin, Peteriello, Stoynev, Velasco 13; Kagan, Perez, Petriello, Soreq, Stoynev, Zupan 14; Bodwin, Chung, Ee, Lee, Petriello 14; König, Neubert 15; **ATLAS: 1501.03276**]
- **Be inclusive**
  - limited by *b*- and *c*-tagging
  - higher statistics

  [Delaunay, Golling, Perez, Soreq 13; Perez, Soreq, ES, Tobioka 15; **ATLAS arXiv:1501.01325, ATLAS-CONF-2013-063**]

Outline

goal

compare methods for **LHC, LHC run 2, HL-LHC, 100 TeV *pp* collider**

steps

inclusive: how is measuring $h \to b\bar{b}$ measuring y_c?

– recasting LHC8 data

– reinterpreting ATLAS's 14 TeV $h \to b\bar{b}$ projection

– "unboosted" Higgs at 100 TeV

exclusive: sensitivity of exclusive Higgs decays

– new data from ATLAS's search for $h \to J/\Psi\gamma$

– extrapolating QCD background

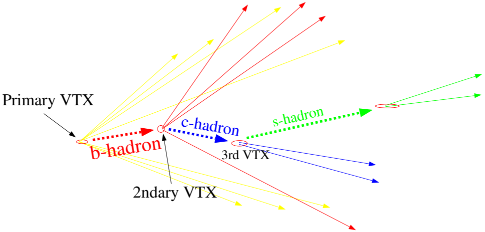
– y_c/y_s sensitivity at diff. colliders

conclusions

Recasting $H \to b\bar{b}$: Idea

b jets at the LHC are NOT b quarks

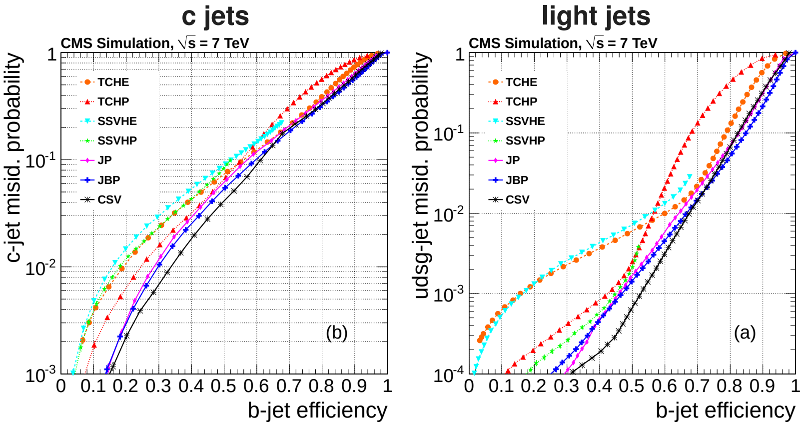
- b quarks hadronize to B mesons
- B mesons are long lived $\sim 440\mu m/c$
- they fly in detector before decaying
- b-tagging is based on looking for such displased vertices



But

- D mesons are also long lived $\sim 120-310\mu m/c$
  ➜ some c quarks are **mistagged** to be b jets
- mistag depends on working point, e.g. $4-40\%$ for c

Efficiencies depend on theshold



[CMS arXiv:1211.4462]

- experiments can and do use different working points
- ϵ_b correlated with mistag propabilities

  in reality: complicated function of p_T, rapidity, channel, . . .

Recasting $H \to b\bar{b}$: signal strength

Signal strength

$$\mu_b^{Vh} = \frac{N^{Vh}_{\text{observed}}}{N^{Vh}_{\text{expected}}} = \frac{\mathcal{L} \cdot \sigma \cdot \mathcal{BR}_b \cdot \epsilon_{b_1} \cdot \epsilon_{b_2} \cdot \epsilon}{\mathcal{L} \cdot \sigma^{\text{SM}} \cdot \mathcal{BR}_b^{\text{SM}} \cdot \epsilon_{b_1} \cdot \epsilon_{b_2} \cdot \epsilon} = \frac{\sigma \cdot \mathcal{BR}_b}{\sigma^{\text{SM}} \cdot \mathcal{BR}_b^{\text{SM}}}$$

- use multi-variate techniques to find best S/B discriminators
- minimize χ^2 over all this BDT output based on poisson statistics

$$\mu_b^{Vh} = 0.52 \pm 0.32 \pm 0.24 \qquad \text{[ATLAS]}$$
$$\mu_b^{Vh} = 1.0 \pm 0.5 \qquad \text{[CMS]}$$

➜Information on y_b
What if y_c was modified by a lot?
➜χ^2 of two signal strenghts

Recasting $H \to b\bar{b}$: signal strength

Signal strength including c-mistag

$$\frac{N^{Vh}_{\text{observed}}}{N^{Vh}_{\text{expected}}} = \frac{\sigma \cdot \mathcal{BR}_b \cdot \epsilon_{b_1} \cdot \epsilon_{b_2} + \sigma \cdot \mathcal{BR}_c \cdot \epsilon_{c_1} \cdot \epsilon_{c_2}}{\sigma^{\text{SM}} \cdot \mathcal{BR}_b^{\text{SM}} \cdot \epsilon_{b_2} \cdot \epsilon_{b_2} \cdot \epsilon}$$

$$= \mu_b + \frac{\mathcal{BR}_c^{\text{SM}}}{\mathcal{BR}_b^{\text{SM}}} \frac{\epsilon_{c_1} \cdot \epsilon_{c_2}}{\epsilon_{b_1} \cdot \epsilon_{b_2}} \mu_c$$

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

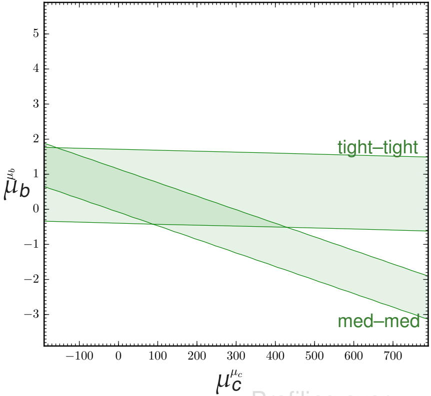
- the larger $\epsilon_{c/b}$ (the mistag) the more sensitivity
- can only constrain the combination (degeneracy)

➜ need different $\epsilon_{c/b}$ working points

- the more different the better

Recasting $H \to b\bar{b}$: breaking the degeneracy

Fit assuming two signal strenths in ATLAS and CMS $\sqrt{s} = 8$ TeV



$$\mathcal{L}(\mu_b, \mu_c) = \prod_i P_{\text{poisson}}(k_i, N^{\text{bkg}}_{\text{SM},i} + \mu_{\text{tot}} N^{\text{signal}}_{\text{SM},i})$$

	1^{st} tag	2^{nd} tag	$\epsilon_{c/b}$
ATLAS	Med	Med	8.2×10^{-2}
ATLAS	Tight	Tight	5.9×10^{-3}
CMS	Med1	Med1	0.18
CMS	Med2	Loose	0.19
CMS	Med1	Loose	0.23
CMS	Med3	Loose	0.16

$$\chi^2 = -2\log\mathcal{L}(\mu_b, \mu_c)$$

Profiling over μ_b ➜ **first bound on μ_c**

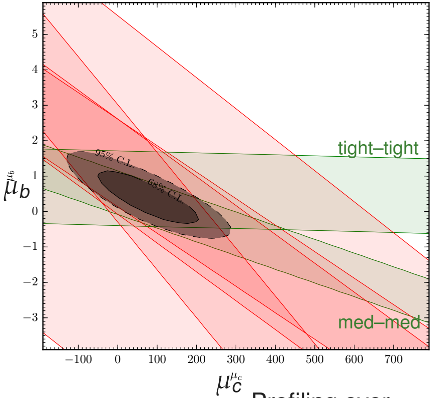
$$\mu_c = 95^{+90(175)}_{-95(180)} \quad @ \quad 68.3\,(95)\%\ \text{CL}$$

assume c-tagging would be employed
➜ $\Delta\mu_c = 50(107)$

[arXiv:1502.00290]

Recasting $H \to b\bar{b}$: breaking the degeneracy

Fit assuming two signal strenths in ATLAS and CMS $\sqrt{s} = 8$ TeV



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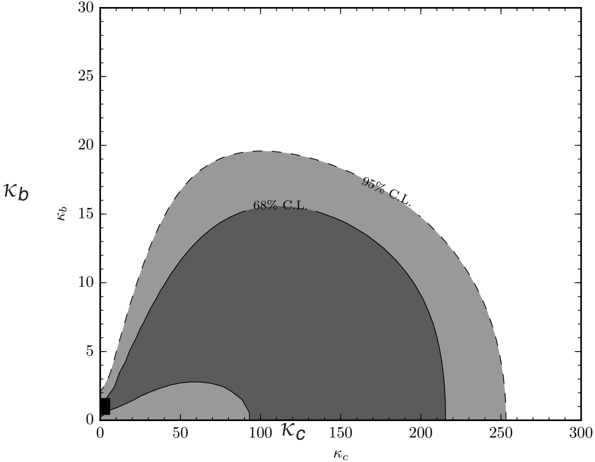
[arXiv:1502.00290]

Recasting $H \to b\bar{b}$: constraining κ_c

Need to include enhancement in prodution otherwise no bound on



kappa$_c$.

After profiling ➜ $\kappa_c = y_c / y_c^{\rm SM} \lesssim 245$

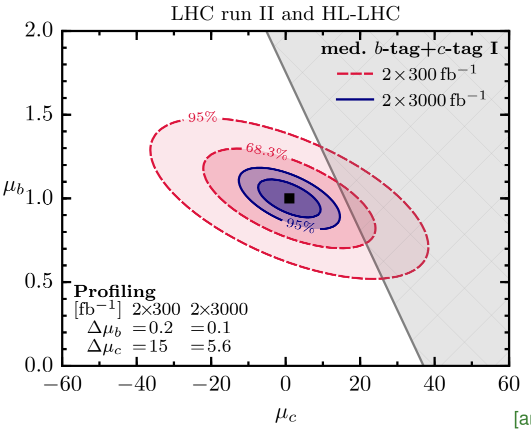
No data, but ATLAS $h \to b\bar{b}$ 14 TeV study [ATL-PHYS-PUB-2014-011]

- MC simulation of all backgrounds ($t\bar{t}$, $Wb\bar{b}$, ...)
- binned analysis (1-lepton, 2-lepton, $p_T(V)$, $m_{b\bar{b}}$, ...)
- based on **med–med** working point
- need at least two working points
  - ➜ choose *c*-tagging working points (I,II,III)

	ϵ_b	ϵ_c	ϵ_l
***b*-tagging**	70%	20%	1.25%
***c*-tagging I** *	13%	19%	0.5%
***c*-tagging II**	20%	30%	0.5%
***c*-tagging III**	20%	50%	0.5%

  - ➜ rescale B's and S appropriately
  - ➜ each event categorised according to tagging info
- small dependence on correlation between *b*- and *c*-tagged jets

c-tagging I



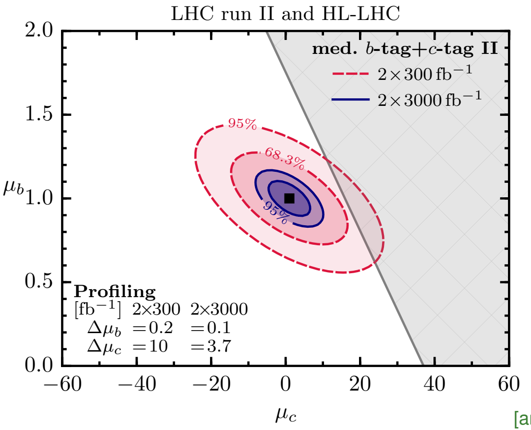
[arXiv:1505.06689]

Grey region unphysical unless Higgs production modified w.r.t. SM

$$\mu_c \mathcal{BR}^{\mathrm{SM}}_{c\bar{c}} + \mu_b \mathcal{BR}^{\mathrm{SM}}_{b\bar{b}} < 1$$

Expect $\mathbf{\Delta\mu_c = \pm 15,\ \pm 5.6}$ at Run 2, HL-LHC

c-tagging II



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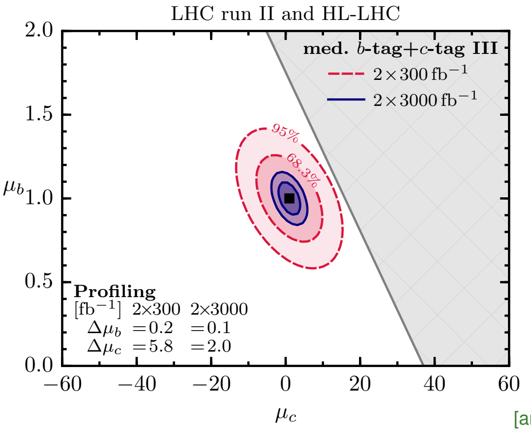
Grey region unphysical unless Higgs production modified w.r.t. SM

$$\mu_c \mathcal{BR}^{\text{SM}}_{c\bar{c}} + \mu_b \mathcal{BR}^{\text{SM}}_{b\bar{b}} < 1$$

Expect **$\Delta\mu_c = \pm 10, \ \pm 3.7$** at Run 2, HL-LHC

c-tagging III



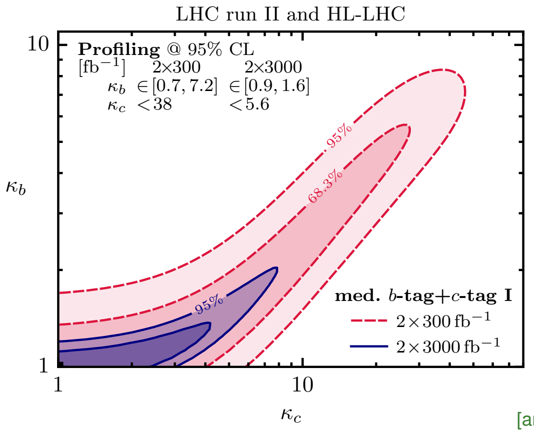
[arXiv:1505.06689]

Grey region unphysical unless Higgs production modified w.r.t. SM

$$\mu_c \mathcal{BR}^{\rm SM}_{c\bar{c}} + \mu_b \mathcal{BR}^{\rm SM}_{b\bar{b}} < 1$$

Expect **$\Delta\mu_c = \pm 5.8, \ \pm 2.0$** at Run 2, HL-LHC

c-tagging I



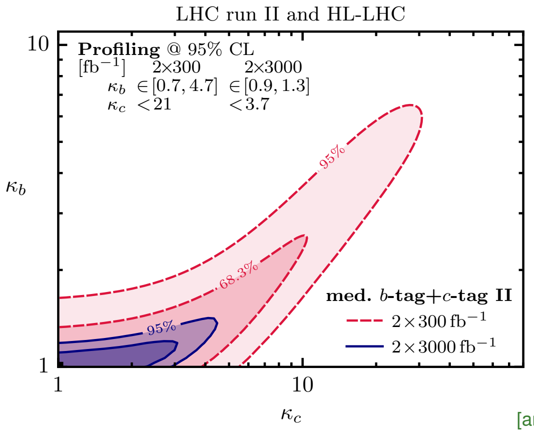
[arXiv:1505.06689]

Production modification only important for 300 fb^{-1}

@95% CL $|\kappa_c| < \pm 38$, ± 5.6 at Run 2, HL-LHC

κ_c prospects at LHC14 $2\times300\,\mathrm{fb}^{-1}$ $2\times3000\,\mathrm{fb}^{-1}$

c-tagging II

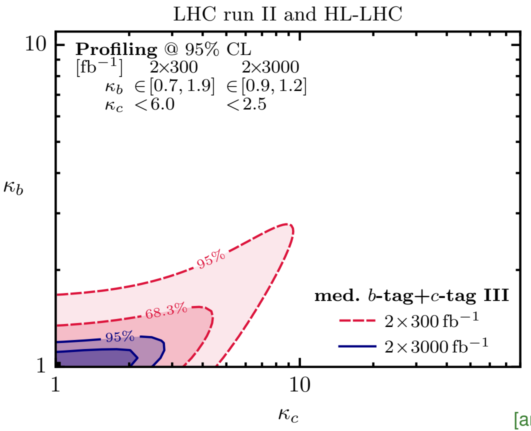


[arXiv:1505.06689]

Production modification only important for 300 fb^{-1}

@95% CL $|\kappa_c| < \pm 21$, $\pm$ **3.7** at Run 2, HL-LHC

c-tagging III



[arXiv:1505.06689]

Production modification only important for 300 fb^{-1}

@95% CL $|\kappa_c| < \pm 6.0$, ± 2.5 at Run 2, HL-LHC

“Unboosting” the Higgs at 100 TeV

- Jet-substructure cuts for boosted Higgs reduce bkg, but cut too much $h \to c\bar{c}$ [arXiv:1505.06689]

Challenge: keep most Higgses (“unboosted” regime) cut away $t\bar{t}$

One way: $t\bar{t}$ heavier system ➜ peaks at larger H_T

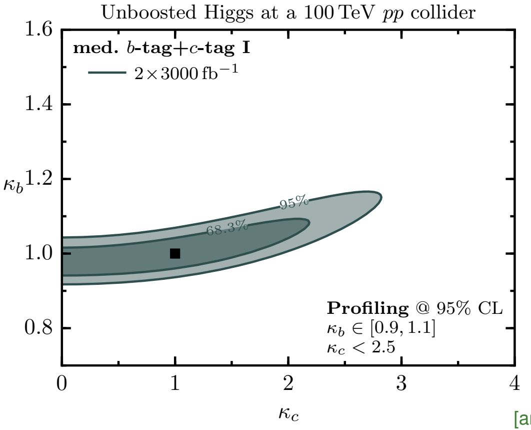
➜ low H_T bins have an increased S/B

- $H_T < 340\,\mathrm{GeV}, \quad 340\,\mathrm{GeV} < H_T < 500\,\mathrm{GeV}, \quad 500\,\mathrm{GeV} < H_T$
- + usual $h \to b\bar{b}$ cuts ($m_{b\bar{b}}, \ldots$)
- the rest similar to boosted analysis

Accessing $|\kappa_c| \approx 2$ seems possible and conservative*

κ_c at 100 TeV with "unboosted" Higgses

c-tagging I



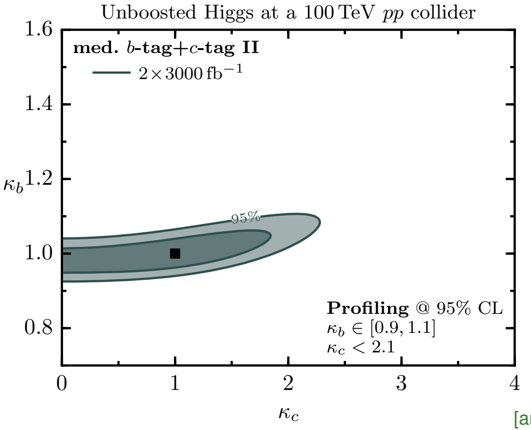
[arXiv:1505.06689]

@95% CL **$|\kappa_c| < 2.5$** assuming $2\times3000\,\text{fb}^{-1}$

Comment: These **direct** bounds are comparable to **indirect** bounds from $\mathcal{BR}_{\text{untagged}} < 10\%$ expected at HL-LHC [ATL-PHYS-PUB-2014-016]

κ_c at 100 TeV with “unboosted” Higgses

c-tagging II



[arXiv:1505.06689]

@95% CL **$|\kappa_c| < 2.1$** assuming $2\times3000\,\mathrm{fb}^{-1}$

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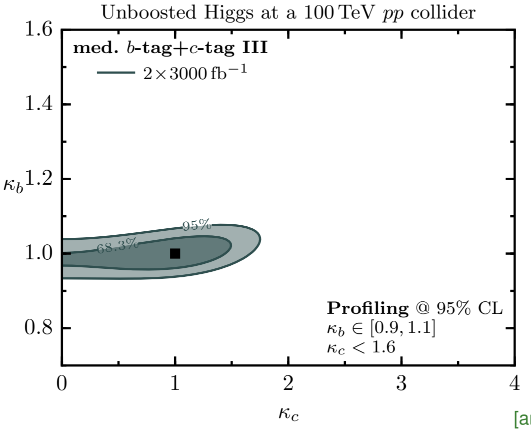
κ_c at 100 TeV with “unboosted” Higgses

c-tagging III



[arXiv:1505.06689]

@95% CL $|\kappa_c| < 1.6$ assuming $2\times3000\,\mathrm{fb}^{-1}$

Comment: These **direct** bounds are comparable to **indirect** bounds from $\mathcal{BR}_{\mathrm{untagged}} < 10\%$ expected at HL-LHC [ATL-PHYS-PUB-2014-016]

Enclusive approach

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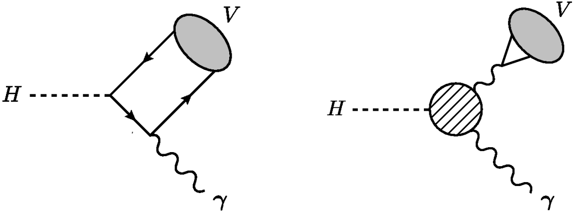
Exclusive approach: $h \to J/\psi\, \gamma$



$$\Gamma_{h \to J/\psi\, \gamma} = |(11.9 \pm 0.2)\kappa_\gamma - (1.04 \pm 0.14)\kappa_c|^2 \cdot 10^{-10}\ \text{GeV}$$

[Bodwin, Petriello, Stoynev, Velasco 13; Bodwin, Chung, Ee, Lee, Petriello 14]

[NEW results: König, Neubert 15]

Highlights

- tagging via the flavour of the meson
- two contributions direct (κ_c) and indirect (κ_γ)
- main effect from interference
- **generalisable to** s, u, d **quarks!** [Kagan et al, 14]

➜only known direct way to access s, u, d Yukawas

Exclusive approach: $h \to J/\psi\, \gamma$ new results

ATLAS $\sigma \cdot \mathcal{BR}(h \to J/\psi\, \gamma) < 33\text{fb}$ at 95% CL

[ATLAS 1501.03276]

Important for 2 reasons:

- translates to a weak $|\kappa_c| < 220$ bound
  (after normalising to $h \to ZZ^*$, and assuming κ_V, κ_γ like in SM) [arXiv:1502.00290]
- **first measurement of a tough QCD background**

➜ QCD+real photon and QCD with jet mistagged as a γ

$$P(j \to \gamma) \simeq 2.9 \cdot 10^{-2}$$

[ATL-COM-PHYS-2010-1051]

➜ expect similar background for other modes

➜ use new data to project sensitivy in ϕ mode [arXiv:1505.06689]

Exclusive projection for y_c

- normalizing to $h \to ZZ^* \to 4\ell$
- find upper bound on μ for $E = 8, 13, 100$ TeV

Assumptions:

- $S_E^{95}/\sqrt{B_E^{95}} \approx S_8^{95}/\sqrt{B_8^{95}}$ plus signal efficiencies unchanged
- $\sigma^{\mathrm{SM}}_{h,(8,14,100)} = 22.3,\ 57.2,\ 897$ pb [Heinemeyer et al, 13] and $\mu^{95}_{J/\Psi\gamma,8} = 515$

Results:

$|\kappa_c| < 91,\ 56,\ 33$

at LHC run 2, HL LHC, and 100 TeV with $2{\times}3000\,\mathrm{fb}^{-1}$

Exclusive projection for y_s

Assumptions for extrapolation:

- $S_E^{95} / \sqrt{B_E^{95}}$ equal for J/Ψ and ϕ mode

  ➜ ratio of backgrounds gives the expected sensitivity
- simulate in PYTHIA $pp \to$ “γ”$J/\Psi(\to \mu^+\mu^-)$ and $pp \to$ “γ”$\Phi(\to K^+K^-)$
- use ratio to rescale measured background

$$\left.\frac{\sigma_8(pp \to \phi \text{“}\gamma\text{”})}{\sigma_8(pp \to J/\Psi \text{ “}\gamma\text{”})}\right|_{\text{PYTHIA}} \sim 9$$

[arXiv:1502.00290]

Results:

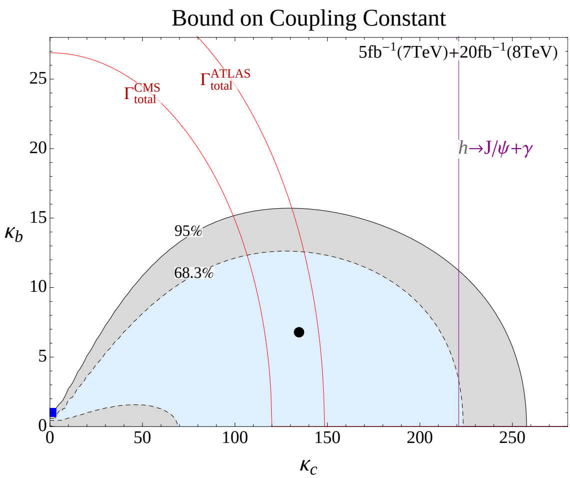
$|\kappa_s| < 3300, \; 2000, \; 1200$

at LHC run 2, HL LHC, and 100 TeV with $2{\times}3000\,\text{fb}^{-1}$

➜exclusive approach struggles with QCD background

possible to reduce in other production modes? $Vh, VBF, t\bar{t}h$**?**

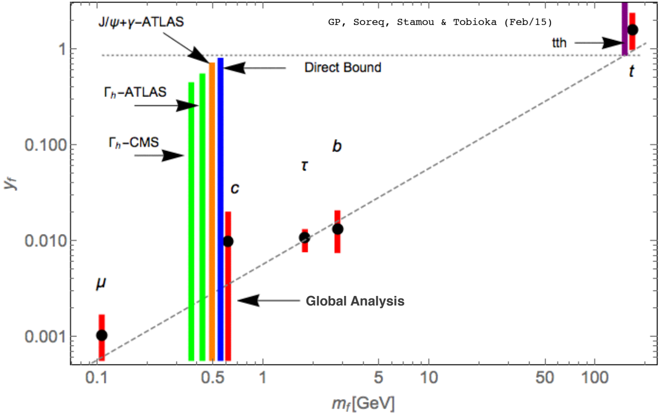
Combination: what we know about y_c from LHC8



Comments:

- width bound will not improve much in the future
- recast bound competes with $J/\psi\gamma$ bound
- experiments can improve our analysis (they don't even need to digitise plots)

Global fit



Fit dominated by untagged Higgs decay driven by VBF production.

$$\mu_{\mathrm{VBF}\to h\to WW^*} = \kappa_V^2 \times \frac{\kappa_V^2}{\Gamma_{\mathrm{tot}}/\Gamma_{\mathrm{tot}}^{\mathrm{SM}}} \;\; \rightarrow \;\; \Gamma_{\mathrm{tot}} < 4\Gamma_{\mathrm{tot}}^{\mathrm{SM}}$$

Robust as long as there is no new VBF production channel.

LHC8 excluded up-quark universality

Summary & Conclusions

Summary:

- a lot of progress made in extracting info on light Yukawas (theo. and exp.)
- there are complementary approaches (inclusive, exclusive)
- sensitivity of the LHC on y_c higher than anticipated
- light-quark Yukawas probed in exlusive decays

3 short messages:

- Positive: **excellent prospects for the inclusive approach at 13, 100 TeV**
- Negative: **exclusive modes suffer from QCD background**
- However, **this must not hold in other production modes** (there is hope and necessary work)

➜ high p_T experiments are measuring flavour parameters ←

Backup

- small deviations captured by dim-6 operators

$$\mathcal{L} \supset \lambda^u_{ij} \overline{Q}_i \, \tilde{H} \, U_j + \frac{g^u_{ij}}{\Lambda^2} H^\dagger H \, \overline{Q}_i \, \tilde{H} \, U_j$$

Charm-quark case

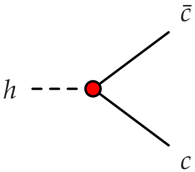
- SM case very challenging to observe $y_c^{\mathrm{SM}} \simeq 0.4\%$ and $\mathcal{BR}(h \to c\bar{c}) \simeq 4\%$
- Dominant mode $\mathcal{BR}(h \to b\bar{b}) \simeq 60\%$ also small Yukawa $y_b \simeq 2\%$
  ➜ deviations of a few significantly modify higgs phenomenology

[Delaunay, Golling, Perez, Soreq 13]

$$\sim \frac{v}{\sqrt{2}} \left(\lambda^u_{ij} + g^u_{ij} \frac{v^2}{2\Lambda^2} \right)$$

$$\Lambda \simeq \frac{25\mathrm{TeV}}{\sqrt{|y_c / y_c^{\mathrm{SM}}| - 1}}$$

a) here $g^u = 16\pi^2$
b) assummed $c_V = 1$
c) main constraint $\mathcal{BR}_{\mathrm{inv}}$



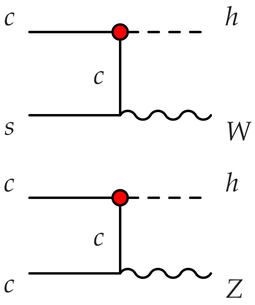
$$\sim \frac{1}{\sqrt{2}} \left(\lambda^u_{ij} + \mathbf{3} \, g^u_{ij} \frac{v^2}{2\Lambda^2} \right)$$

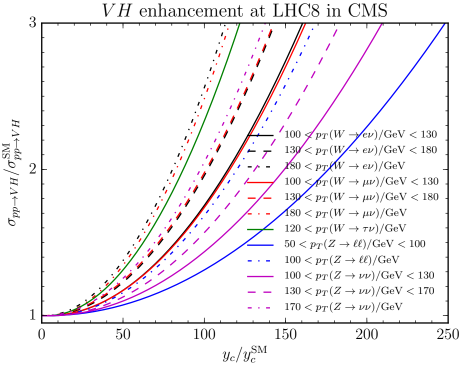
Recasting $H \to b\bar{b}$: production enhancement

- assume no modification of production
- assume $\mathcal{BR}(h \to c\bar{c}) = 100\%$

➜ $\mu_c \sim 33$, our bound is trivially satisfied

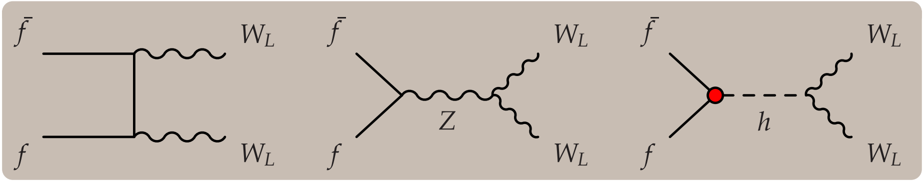
However, a new production mechanism kicks in around $y_c/y_c^{\rm SM} \sim 100$





Unitarity bounds

- any deviation from the SM prediction signals breakdown of theory



A stretched, but phenomenologically viable, scenario:

- higgs does not couple at all to light fermions

  i.e. they obtain masses from a different (TC) sector

  [Giudice, Lebedev 08; Kagan, Perez, Volansky, Zupan 09; Delaunay, Grojean, Perez 13]
- new d.o.f. at the unitarity breaking scales
- scales inaccesible to LHC or realistic future colliders

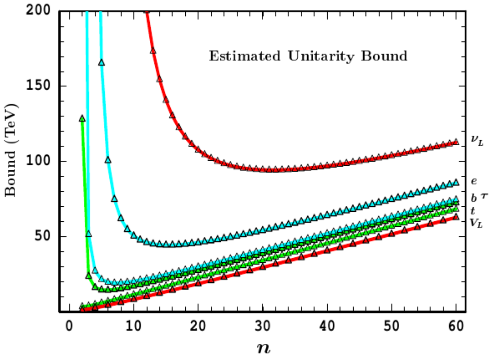
$$\sqrt{s} < \frac{8\pi v^2}{m_{b,c,s,d,u}\sqrt{6}} \simeq 2\cdot 10^2, 1\cdot 10^3, 1\cdot 10^4, 2\cdot 10^5, 5\cdot 10^5 \text{ TeV}$$

[Appelquist, Chanowitz 87]

- bounds are better but enhancement of Yukawa couplings more promising

Improved unitarity bounds

- improve unitarity bounds by looking at $f\bar{f} \to V_L^n$
- phase-space competes with energy enhancements



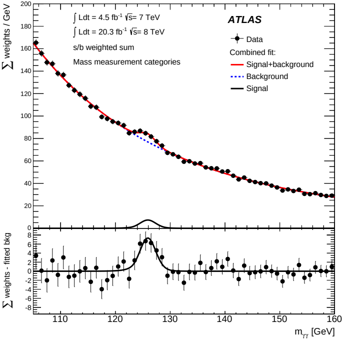
$b\bar{b}$: 23 TeV $c\bar{c}$:31 TeV $s\bar{s}$:52 TeV $d\bar{d}$:77 TeV $u\bar{u}$:64 TeV

[Dicus, He 04]

Higgs width

- ATLAS and CMS constrain the higgs total width with shape analyses of the $\gamma\gamma$ and *ZZ* signal

$$\Gamma_{\text{tot}} < 2.6\text{GeV}[\text{ATLAS}] \qquad \Gamma_{\text{tot}} < 1.7\text{GeV}[\text{CMS}]$$



[ATLAS arXiv:1406.3827]

- to be compared with $\Gamma_{\text{tot}}^{\text{SM}} = 4.15\text{MeV}$

Saturate width with $h \to c\bar{c}$

$$\rightarrow \frac{y_c}{y_c^{\text{SM}}} < 150[\text{ATLAS}] \quad 120[\text{CMS}]$$

@ 95% CL

- not much hope for future improvement due to resolution of experiments

ATLAS's c-tagger, a break through

ATLAS's c-tag working point

$\epsilon_c = 19\%$ $\epsilon_b = 12\%$

– calibrated from data containing D^* mesons employing multivariate techniques with information on *"impact parameter on displaced tracks and topological properties of secondary and tertiary decay vertices"*.

– **factor of 5 rejection of** b**'s** w.r.t. standard medium point by calibrating on simulated $t\bar{t}$ events

ATLAS search for $\tilde{t} \rightarrow c\chi_0$

Search for pair-produced top squarks decaying into charm quarks and the lightest neutralinos using 20.3 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector at the LHC

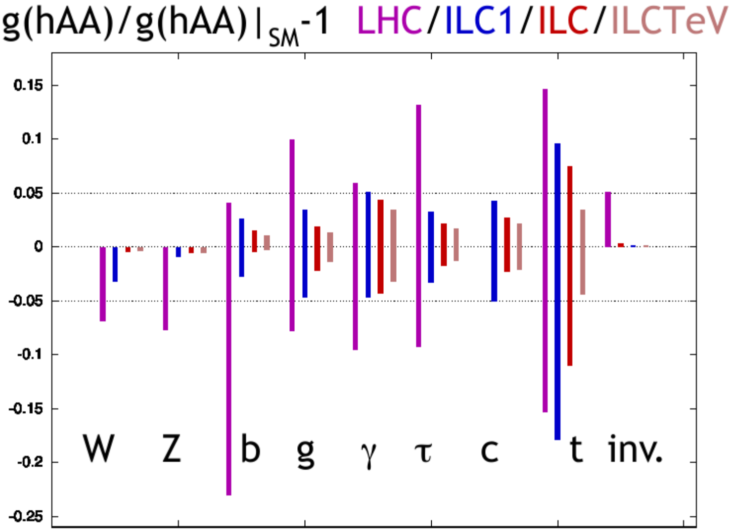
[ATLAS arXiv:1501.01325]

ATLAS search for $\tilde{c}\tilde{c}^*$ with $\tilde{c} \rightarrow c\tilde{\chi}_1$

Search for Scalar-Charm Pair Production in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

[ATLAS-CONF-2013-063]

Exercise: find the missing purple line

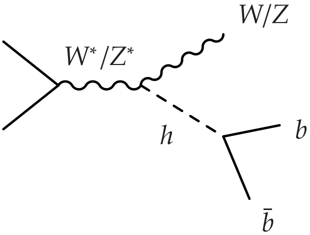


- focus on charm at the LHC using available data

[Peskin 12 @ ILC-TDR]

ATLAS [arXiv:1409.6212] and **CMS** [arXiv:1310.3687] $h \to b\bar{b}$ **analyses**

- h produced in association with W/Z



- h produced in association with W/Z
- different channels for W/Z decays
  $Z \to \nu\bar{\nu}$ [0lepton] $Z \to \ell\bar{\ell}$ [2lepton] $W^- \to \ell^-\bar{\nu}$ [1lepton]
- different categories for $p_T(W/Z)$
- two b-jets required

b-tag working point depends on category (2 in ATLAS, 4 in CMS)

Boosted Higgses at 100 TeV

What improvement can we expect at 100 TeV?

- specifications of a possible 100 TeV *pp* collider are vague
- no dedicated binned study of all backgrounds
- to compete with HL-LHC need regions of large S/B

boosted Higgses + jet-substructure to reduce B's

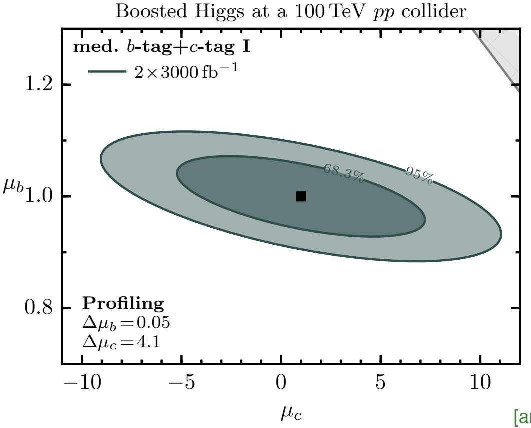
look for a fat jet ($p_T > 350\,\mathrm{GeV}$) with 2 b-tagged subjets

- use jet-substructure results from 13 TeV analysis for $h \to b\bar{b}$ [Backovic, Juknevich, Perez 12]
- assume same rejection power at 100 TeV as at 13 TeV

  ➜ main background $t\bar{t}$ rejected 20 more than signal
- include $W/Z\ h$ and the B's $t\bar{t}$, $W/Z\ b\bar{b}$, $W/Z\ c\bar{c}$

μ_c at 100 TeV with boosted Higgses

c-tagging I

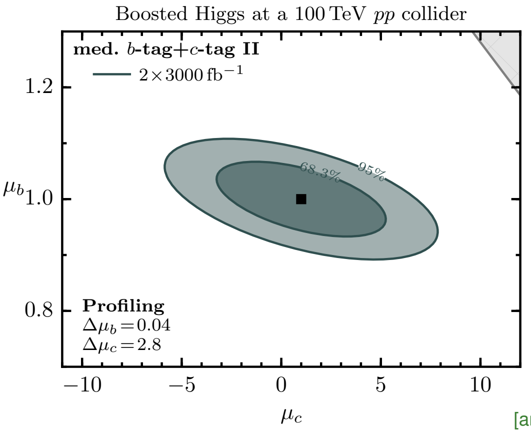


[arXiv:1505.06689]

Expect **$\Delta\mu_c = \pm 4.1$** assuming $2\times3000\,\mathrm{fb}^{-1}$

μ_c at 100 TeV with boosted Higgses

c-tagging II

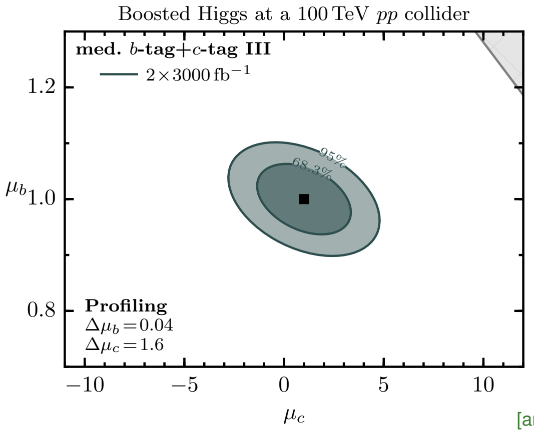


[arXiv:1505.06689]

Expect **$\Delta\mu_c = \pm 2.8$** assuming $2\times3000\,\text{fb}^{-1}$

μ_c at 100 TeV with boosted Higgses

c-tagging III

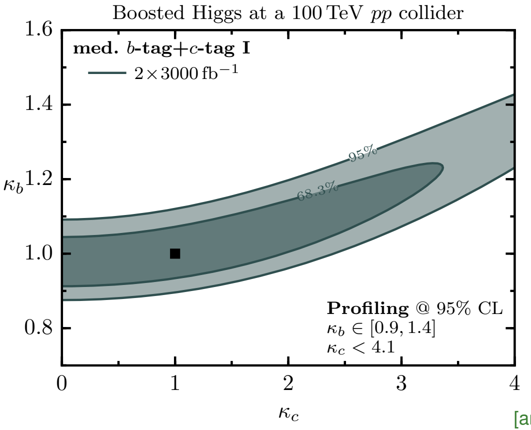


[arXiv:1505.06689]

Expect **$\Delta\mu_c = \pm1.6$** assuming $2\times3000\,\mathrm{fb}^{-1}$

κ_c at 100 TeV with boosted Higgses

c-tagging I



[arXiv:1505.06689]

@95% CL **$|\kappa_c| < 4.1$** assuming 2×3000 fb^{-1}

Substantial improvent for $\Delta\mu_b$! (main background $t\bar{t}$ + mistagged c-quark)

Poor improvent in $\Delta\mu_c$ (too much $h \to c\bar{c}$ signal lost) ➜ **unboost**

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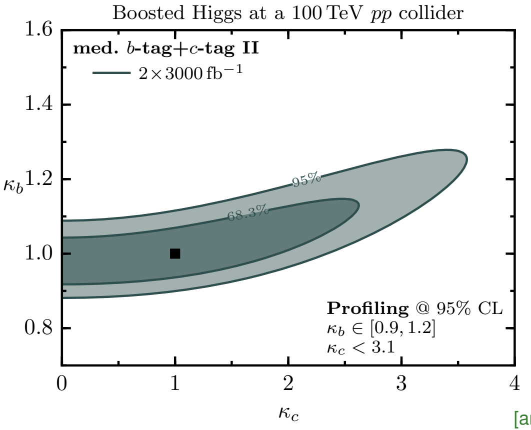
κ_c at 100 TeV with boosted Higgses

c-tagging II



[arXiv:1505.06689]

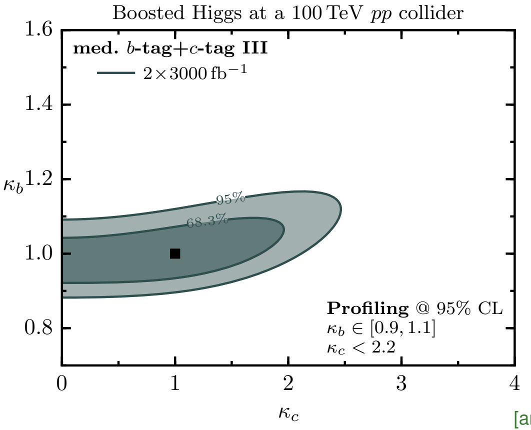
@95% CL **$|\kappa_c| < 3.1$** assuming $2\times3000\,\text{fb}^{-1}$

Substantial improvent for $\Delta\mu_b$! (main background $t\bar{t}$ + mistagged c-quark)

Poor improvent in $\Delta\mu_c$ (too much $h \to c\bar{c}$ signal lost) ➜ **unboost**

κ_c at 100 TeV with boosted Higgses

c-tagging III



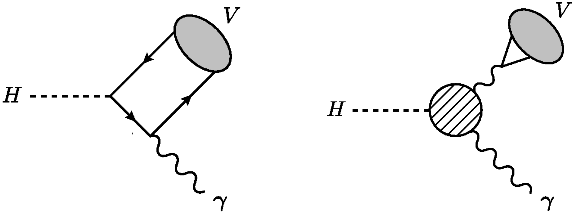
[arXiv:1505.06689]

@95% CL $|\kappa_c| < 2.2$ assuming $2\times3000\,\text{fb}^{-1}$

Substantial improvent for $\Delta\mu_b$! (main background $t\bar{t}$ + mistagged c-quark)

Poor improvent in $\Delta\mu_c$ (too much $h \to c\bar{c}$ signal lost) ➜ **unboost**

Exclusive way: $h \to J/\psi\ \gamma$



$$\Gamma_{h\to J/\psi\ \gamma} = |(11.9 \pm 0.2)\kappa_\gamma - (1.04 \pm 0.14)\kappa_c|^2 \cdot 10^{-10}\ \text{GeV}$$

[Bodwin, Petriello, Stoynev, Velasco 13; Bodwin, Chung, Ee, Lee, Petriello 14]

Recent ATLAS study:

$$\sigma \cdot \mathcal{BR}(h \to J/\psi\ \gamma) < 33\text{fb} \qquad \text{at 95\% CL}$$

[ATLAS 1501.03276]

Cancel production: $\frac{\sigma_{pp\to h}\cdot\mathcal{BR}(h\to J/\psi\ \gamma)}{\sigma_{pp\to h}\cdot\mathcal{BR}(h\to ZZ^*(\ell\ell))} < 2.79\frac{(\kappa_\gamma - 0.087\kappa_c)^2}{\kappa_V^2}\cdot 10^{-2} <$ **9.32**

$$\kappa_c < 210\kappa_V + 11\kappa_\gamma$$

Use robust LEP bound $\kappa_V = 1.08 \pm 0.07$ [Falkowski, Riva 13]

y_t from *tth* and up-quark universality

Can we make any statements about up-quark universality?

$\mu_{tth}^{\text{avg}} = 2.41 \pm 0.81$

[ATLAS and CMS average]

- this translates to a lower bound on the top Yukawa

$$|\kappa_t| > 0.9 \sqrt{\frac{\mathcal{BR}^{\text{SM}}_{h\to\text{relevant modes}}}{\mathcal{BR}_{h\to\text{relevant modes}}}} > 0.9$$

- Since $\frac{y_c}{y_t} \simeq \frac{1}{280}\frac{\kappa_c}{\kappa_t}$ the combination of κ_c/κ_t bounds means

$$\boldsymbol{y_c < y_t}$$