Measuring Higgs couplings to quarks
Inclusively and exclusively

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arXiv:1503.00290 & 1505.06689

A little flowchart

Do you believe in the Hierarchy problem?

NO
because I have better things to do

YES
because radiative corrections are physical

Like what?

Where is NP?

understanding new data from LHC

looking for them in hidden corners

Higgs couplings are new data and are sensitive to NP

Outline

- **Introduction**

- ***h*** **$\rightarrow$ quark quark**
  methods and prospects to measure light quark Yukawas at LHC
  - ➜**inclusively**
  - ➜**exclusively**

- **Conclusions**

THEORY

Role (I)

- minimal VV scattering unitarisation
- induces W/Z masses
- single extra d.o.f., h

Quantitatively tested at LHC
– direct: observing $h \to WW, ZZ$
– indirect: electroweak precision

Role (II) [this talk]

- unitarises $f\bar{f} \to VV$ scattering
- induces fermion masses, and CKM

Many (small) parameters
– overconstrained system
– observation of 3rd gen. couplings only
– significant progress can and is being made

EXPERIMENT

Characterisation by observation of:

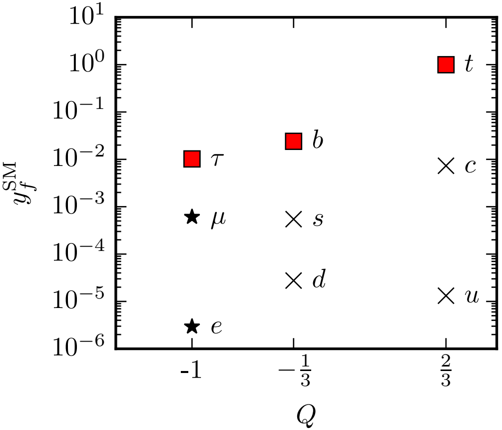
Mass Charge Spin
Couplings

- $m_h = 125.4 \pm 0.37(\mathrm{stat}) \pm 0.18(\mathrm{sys})$ GeV [ATLAS]
  $m_h = 125.7 \pm 0.3(\mathrm{stat}) \pm 0.3(\mathrm{sys})$ GeV [CMS] **a new SM parameter** ✓
- neutral ✓
- $J^P = 0^+$ preferred (at 97.8% over 0^-) ✓
- couplings predicted $g_X \propto \frac{m_X}{v}$ so far ✓
  - **overconstrained in SM, test of the SM**
  - **Yukawa couplings may not be related to EWSB**
  - **window to new physics**

Direct observations of fermionic Higgs couplings

Signal strenth

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



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

  [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]

If $y_\mu = y_\tau$ ➜ $\frac{\mu_\mu}{\mu_\tau} \sim 280$

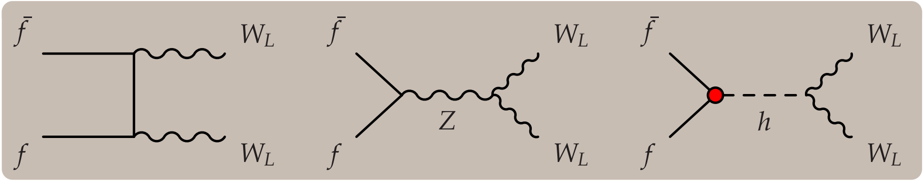
Observation $\frac{\mu_\mu}{\mu_\tau} < 15$

➜ higgs couples non-universally to leptons

What about quarks?

Unitarity bounds

$y \not\propto m/v$ ➜ 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

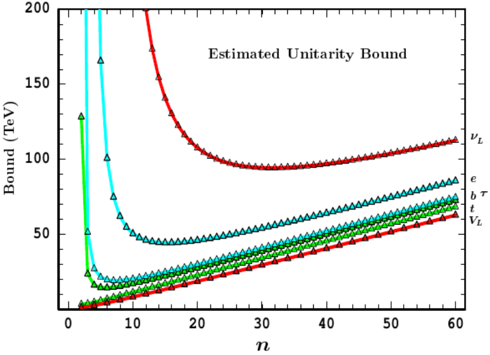
  [Giudice et al 08;Kagan et al 09;Delaunay et al 13; Altmannshofer et al 15; Ghosh et al 15]
- new d.o.f. at the unitarity breaking scales
- scales inaccesible to LHC or realistic future colliders

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

[Appelquist, Chanowitz 87]

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]

Too weak to be tested ➜ look for enhancements in Yukawa couplings

Effective theory

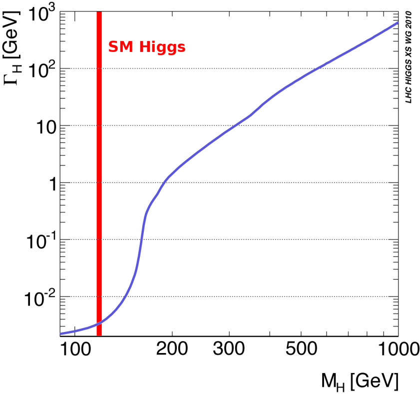
If **deviations** from SM **small** and **no new d.o.f.**:

- EFT applies, effects controlled by dim-6 operators, i.e.

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

- small SM width, $\Gamma_h^{\rm SM} = 4.1$ MeV
- this enhances the sensitivity to:
  ➜ Exotic decays
  [Falkowski et al 10; Curtin et al 13/14, . . .]

  ➜ Modified $\mathcal{BR}$ for SM channels
  [Delaunay et al 13; Bodwin et al 13, Kagan al 14, König et al 15, arXiv:1503.00290 & 1505.06689,. . .]



Example: anomalous charm Yukawa

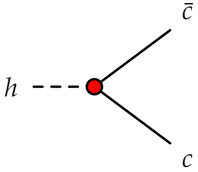
- SM case challenging to observe
  $y_c^{\rm SM} \simeq 0.4\%$ and $\mathcal{BR}(h \to c\bar{c}) \simeq 4\%$
- But dominant mode $\mathcal{BR}(h \to b\bar{b}) \simeq 60\%$ also small Yukawa $y_b \simeq 2\%$
- deviations of a few significantly modify higgs phenomenology

[Delaunay et al 13]

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

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

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



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

- In EFT, couplings correlated to radiative corrections to mass (➜ cancellations/fine-tuning necessary?)

Outline

- Introduction

- ***h* → quark quark**
  methods and prospects to measure light quark Yukawas at LHC
  ➜inclusively
  ➜exclusively

- Conclusions

$h \to$ light-quark light-quark

Challenges

- SM-higgs branching ratios tiny
- huge QCD background
- need some sort of flavour tagging

(c-tag seems possible at the LHC)

Directions

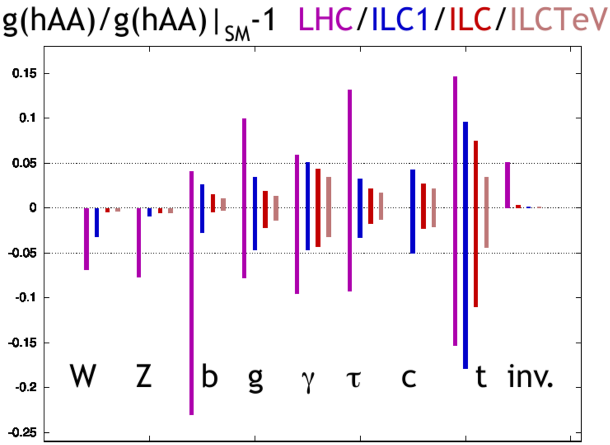
- **Be exclusive**
  - $h \to M\,\gamma$ as a flavour proxy (M vector meson)
  - possible for u, d, s, c ($h \to J/\Psi\gamma$, $h \to \phi\gamma$, $h \to \rho\gamma$)

  [Bodwin et al 13; Kagan et al 14; Bodwin et al 14; König et al 15; ATLAS:1501.03276; CMS:1507.03031]
- **Be inclusive**
  - limited by b- and c-tag
  - higher statistics

  [Delaunay et al 13; ATLAS arXiv:1501.01325; ATLAS-CONF-2013-063; this works]

Impressive progress in c-tag in ATLAS used already in SUSY

Find the missing purple line



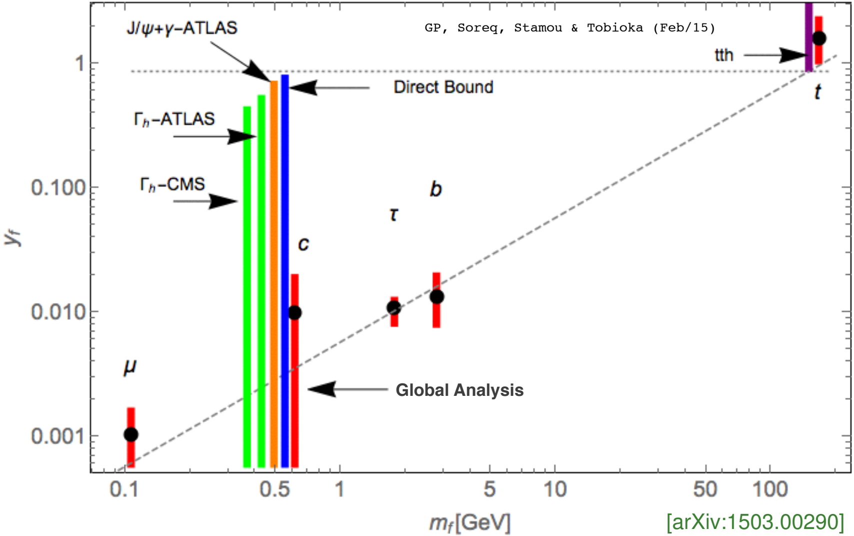
[Peskin 12 @ ILC-TDR]

- focus on **charm**

  LHC8 does constrain y_c, but mildly $|\kappa_c| < 245$

  LHC14 we can expect substantial improvements $|\kappa_c| < \mathcal{O}(10)$

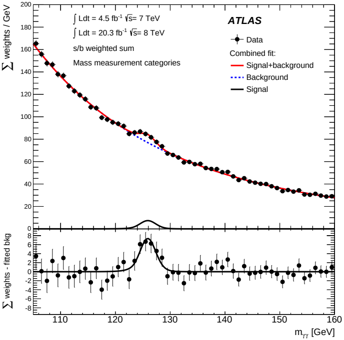
The goal



[arXiv:1503.00290]

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

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



[ATLAS arXiv:1406.3827]

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

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

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

@ 95% CL

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

ATLAS's c-tagger, a breakthrough

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]

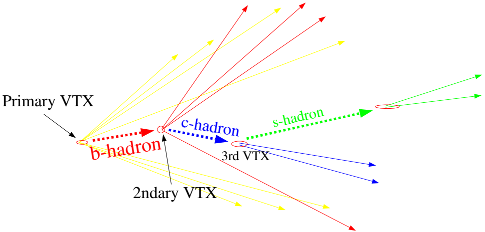
ATLAS search for $\tilde{c}\tilde{c}^*$ with $\tilde{c} \rightarrow c\tilde{\chi}_1$

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

[ATLAS-CONF-2013-063]

b-jets at LHC are NOT b-quarks

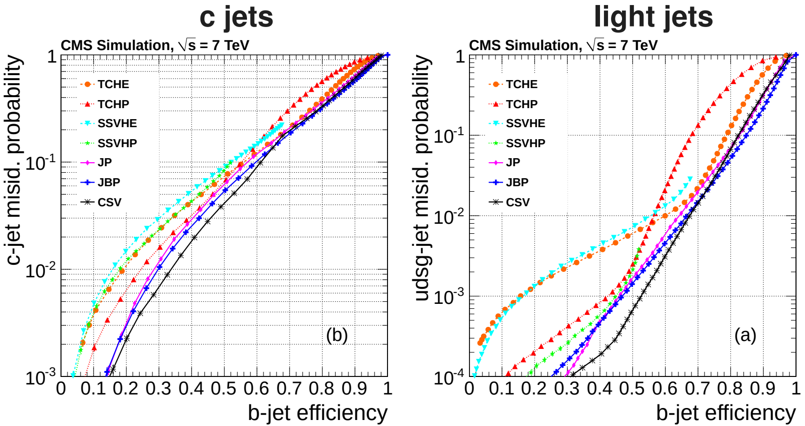
- b quarks hadronize to B mesons
- B-mesons are long lived $\sim 440\mu m/c$
- they fly in detector before decaying
- b-tagging is based on looking for such displased vertices



But

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

Jet-tagging efficiencies are correlated



[CMS arXiv:1211.4462]

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

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

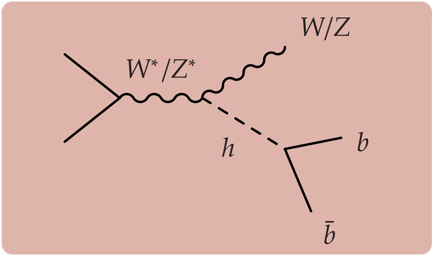
Recasting $H \to b\bar{b}$: Idea

What is the bound on y_c from mistagging?

Recasting $H \to b\bar{b}$: ATLAS and CMS analyses

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

- 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)

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

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

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

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

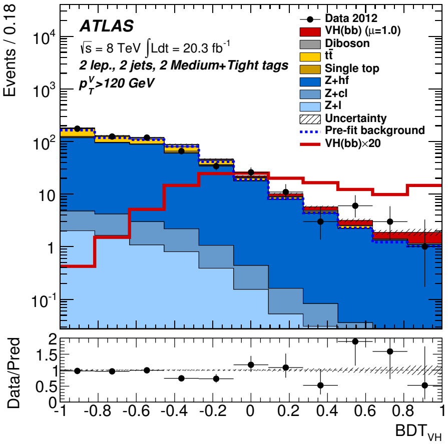
- the larger $\epsilon_{c/b}$ (the misstag) the more sensitivity
- can only constrain the combination (degeneracy)

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

- the more different the better

Recasting $H \to b\bar{b}$: an example

ATLAS: $pp \to Z(\ell\ell)\ \ H(b\bar{b})$ with $p_T(Z) > 120$ GeV

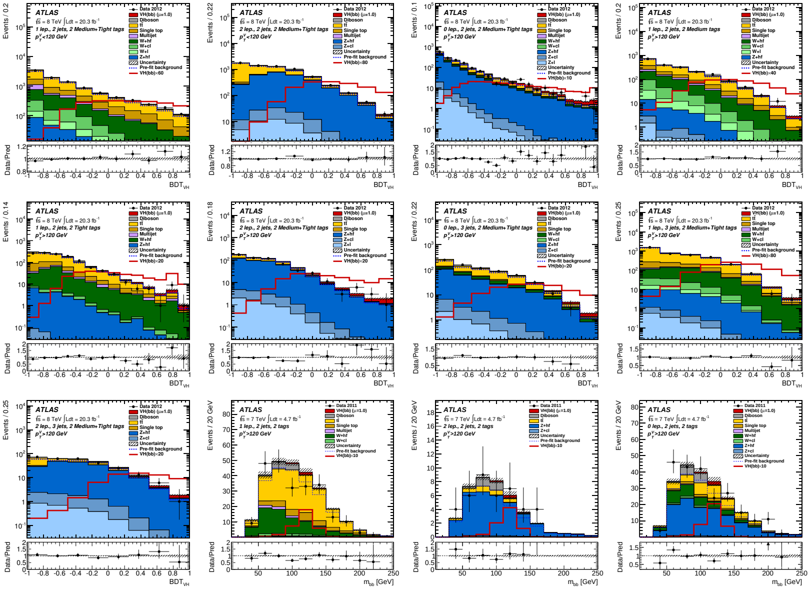


- Signal, Background, Data binned in BTD output

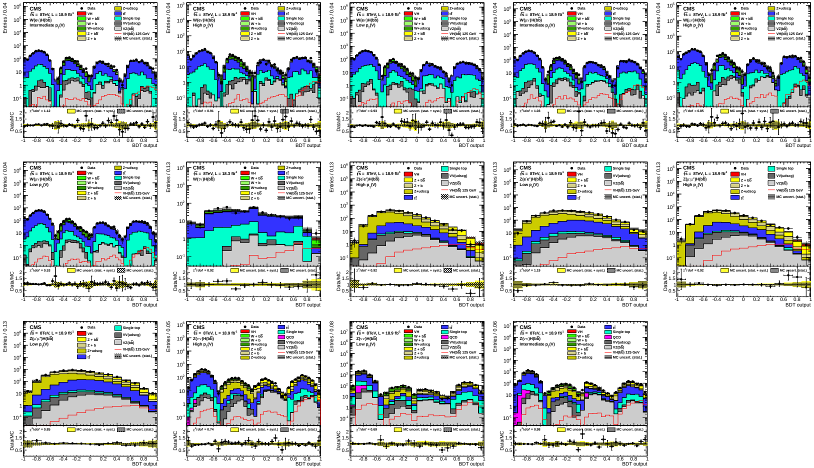
- Each bin is one independent measurement entering the χ^2

- Unfortunately, they don't give tables ➜ digitize plots

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

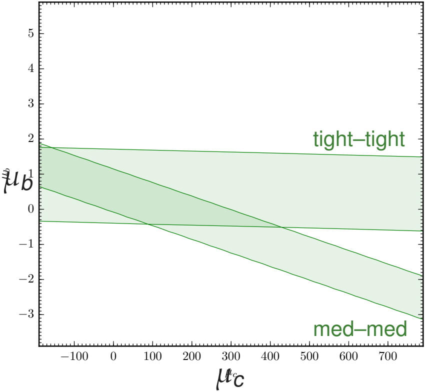


Recasting $H \to b\bar{b}$: CMS



- reproduced ATLAS and CMS μ_b result and error up to 10% ✓
- statistical error dominating (otherwise impossible to reproduce)
- use only S/B$>$ 2.5% (because we cannot control sys. of bkg like the exp.)

Fit assuming two signal strenths in ATLAS and CMS



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

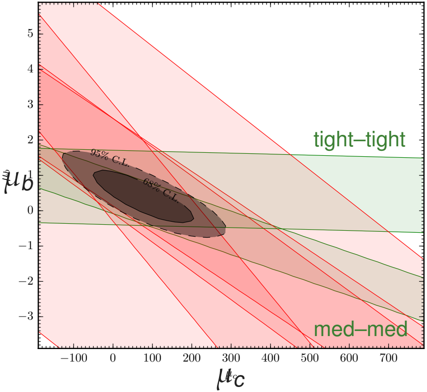
	1st tag	2nd tag	$\epsilon_{c/b}$
ATLAS	Med	Med	8.2×10^{-2}
ATLAS	Tight	Tight	5.9×10^{-3}
CMS	Med1	Med1	0.18
CMS	Med2	Loose	0.19
CMS	Med1	Loose	0.23
CMS	Med3	Loose	0.16

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

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

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

Fit assuming two signal strenths in ATLAS and CMS



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

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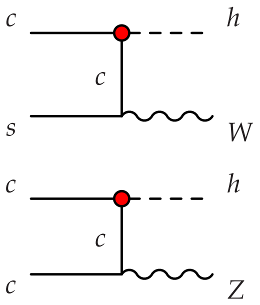
Recasting $H \to b\bar{b}$: production enhancement

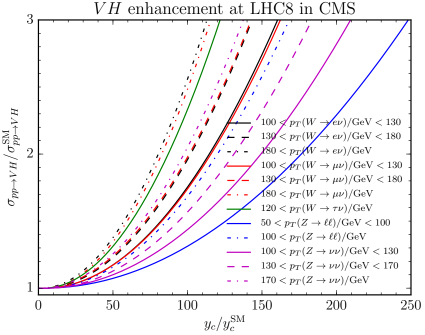
- assume no modification of production
- assume $\mathcal{BR}(h \to c\bar{c}) = 100\%$

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

However, a new production mechanism kicks in around

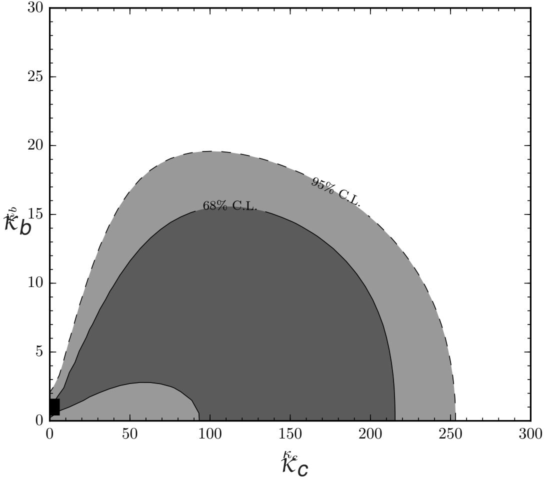
$$y_c/y_c^{\rm SM} \sim 100$$





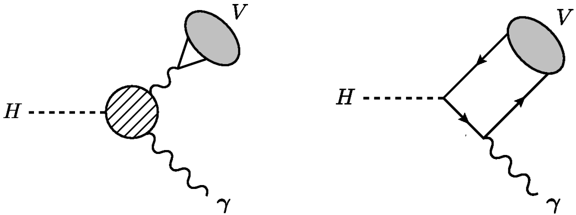
- depends on channel, category, due to cuts

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



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

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 et al 13, 14]

ATLAS/CMS search:

[**Improved predictions** König, Neubert 15]

$$\sigma \cdot \mathcal{BR}(h \to J/\psi\ \gamma) < 33/7.3\text{fb} \qquad \text{at 95\% CL}$$

Cancel production:

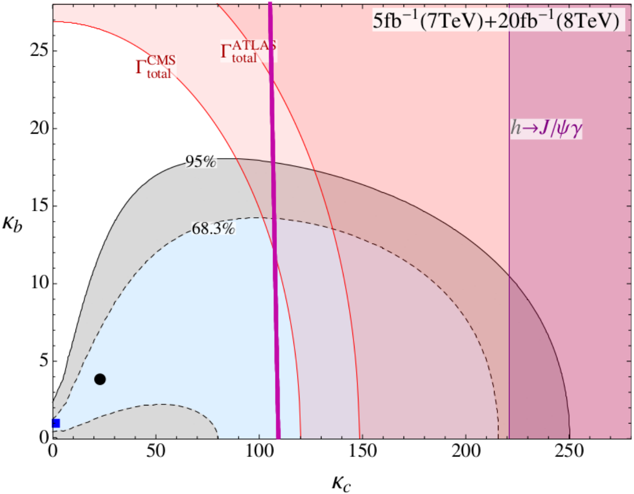
[ATLAS 1501.03276 / CMS 1507.03031]

$$\frac{\sigma_{pp\to h}\cdot\mathcal{BR}(h\to J/\psi\ \gamma)}{\sigma_{pp\to h}\cdot\mathcal{BR}(h\to ZZ^*(\ell\ell))} < 2.79\frac{(\kappa_\gamma - 0.087\kappa_c)^2}{\kappa_V^2}\cdot 10^{-2} < \mathbf{9.3/2.0}$$

$$\kappa_c < 210(97)\kappa_V + 11\kappa_\gamma$$

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

Combination: what we know about y_c from LHC8



- width bound will not improve much in the future
- recast bound competes with $J/\psi\gamma$ bound
- collaborations can improve our analysis

y_t from *tth* and up-quark universality

Can we make any statements about up-quark universality?

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

[ATLAS and CMS average]

- this translates to a lower bound on the top Yukawa

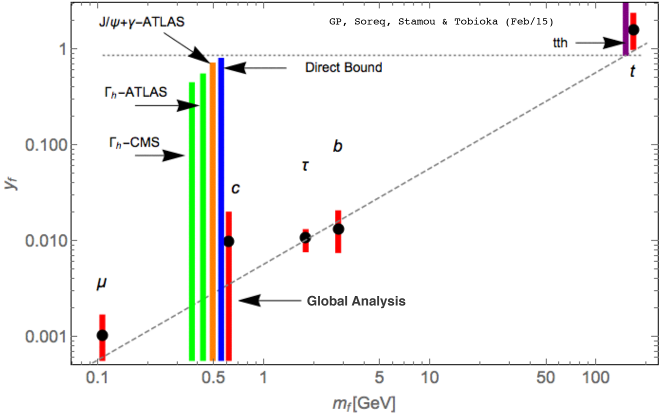
$$|\kappa_t| > 0.9\sqrt{\frac{\mathcal{BR}^{\rm SM}_{h\to \rm relevant\ modes}}{\mathcal{BR}_{h\to \rm relevant\ modes}}} > 0.9$$

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

$$\boldsymbol{y_c < y_t}$$

- LHC8 data excluded up-quark universality

Global fit



Fit dominated by untagged Higgs decay driven by VBF production.

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

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

No data, but ATLAS $h \to b\bar{b}$ 14 TeV study

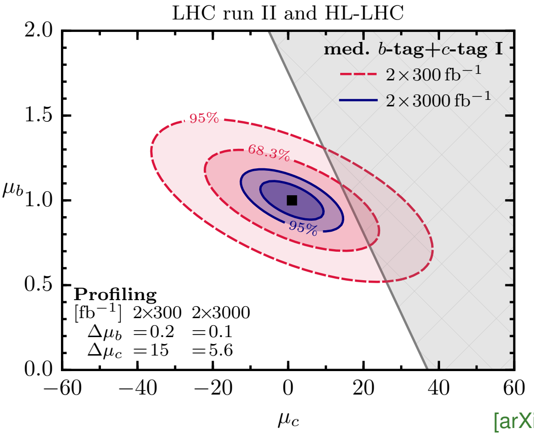
[ATL-PHYS-PUB-2014-011]

- 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



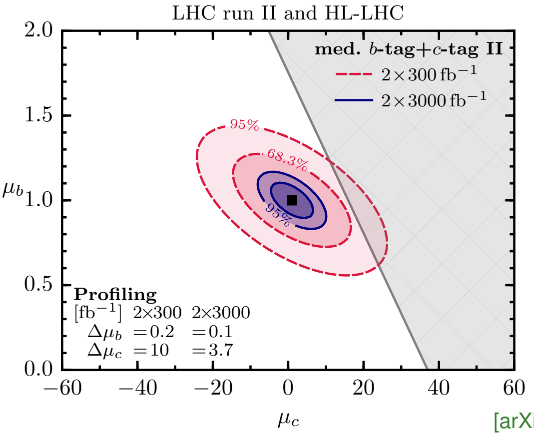
[arXiv:1505.06689]

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

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

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

c-tagging II



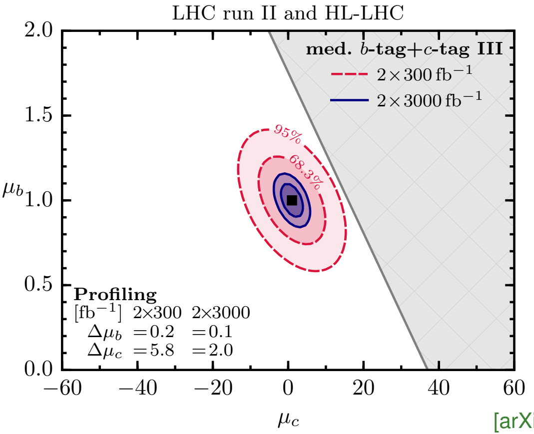
[arXiv:1505.06689]

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

c-tagging III



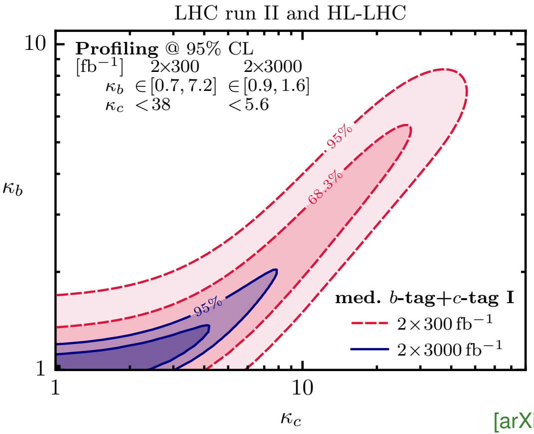
[arXiv:1505.06689]

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

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

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

c-tagging I



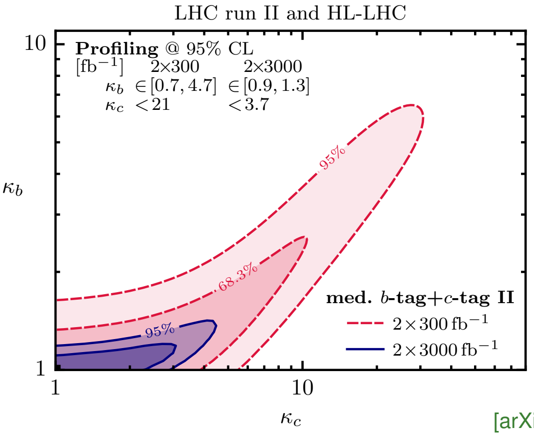
[arXiv:1505.06689]

Production modification only important for $300\,\mathrm{fb}^{-1}$

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

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

c-tagging II

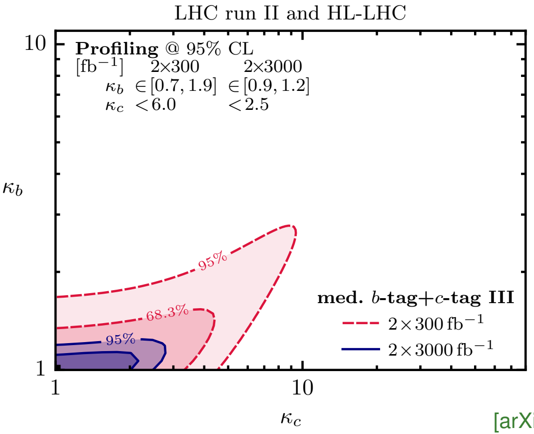


[arXiv:1505.06689]

Production modification only important for $300\,\text{fb}^{-1}$

@95% CL **$|\kappa_c| < \pm21$, $\pm\,3.7$** 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

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 ($p_T > 350$ GeV) with 2 *b*-tagged subjets

- use jet-substructure results from 13 TeV analysis for $h \to b\bar{b}$

  [Backovic, Juknevich, Perez 12]

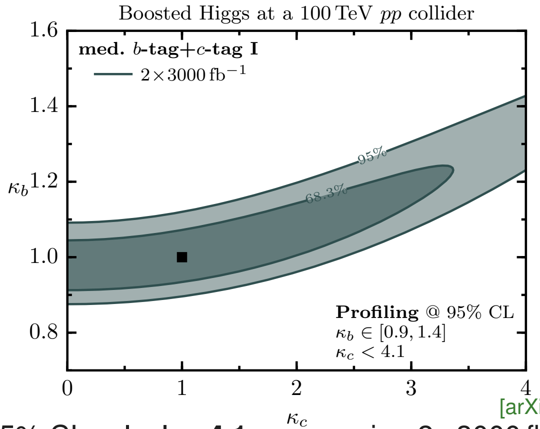
- assume same rejection power at 100 TeV as at 13 TeV

  ➜ main background $t\bar{t}$ rejected 20 more than signal

- include $W/Z\ h$ and the B's $t\bar{t}$, $W/Z\ b\bar{b}$, $W/Z\ c\bar{c}$

κ_c at 100 TeV with boosted Higgses

c-tagging I



[arXiv:1505.06689]

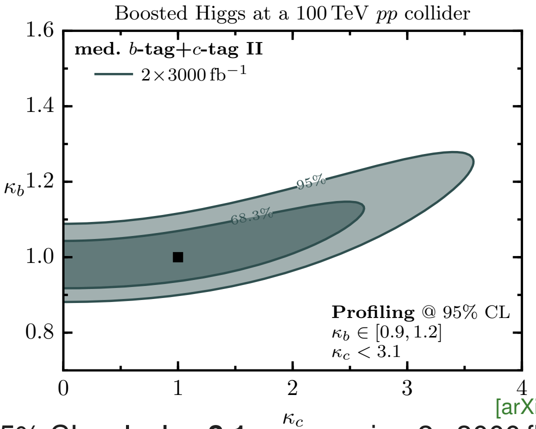
@95% CL **$|\kappa_c| < 4.1$** assuming $2\times3000\,\text{fb}^{-1}$

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

c-tagging II



[arXiv:1505.06689]

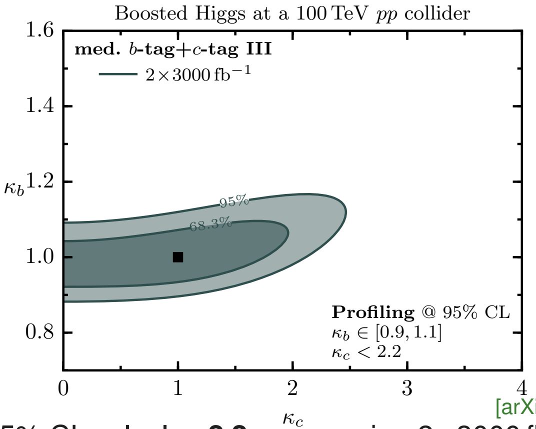
@95% CL **$|\kappa_c| < 3.1$** assuming $2{\times}3000\,\text{fb}^{-1}$

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

c-tagging III



[arXiv:1505.06689]

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

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

“Unboosting” the Higgs at 100 TeV

- Jet-substructure cuts did great, but cut too much $h \to c\bar{c}$

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

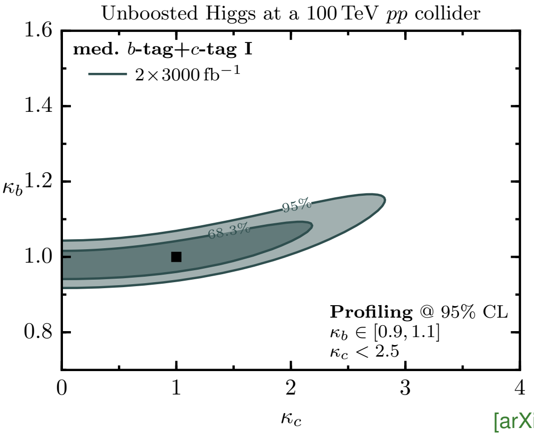
One way: $t\bar{t}$ heavier system ➜ peaks at larger H_T

➜ 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

c-tagging I

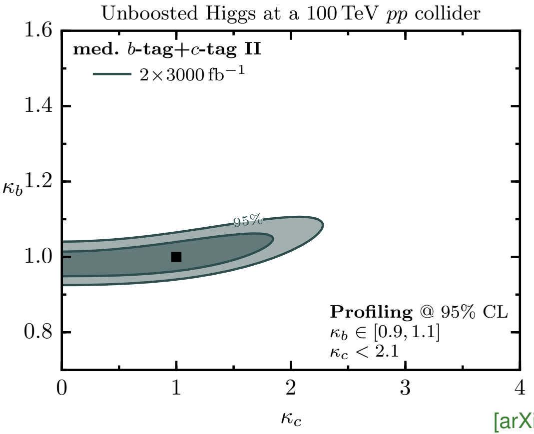


[arXiv:1505.06689]

@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]

c-tagging II

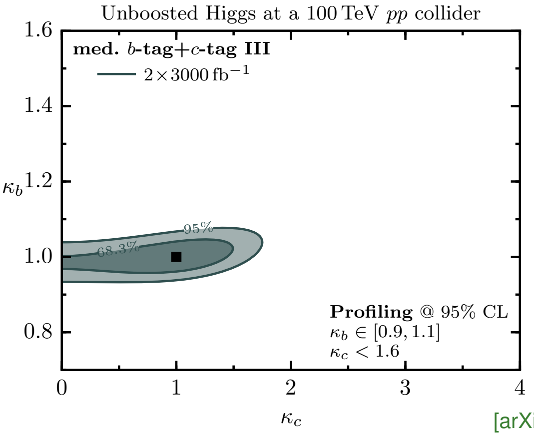


[arXiv:1505.06689]

@95% CL $|\kappa_c| < 2.1$ assuming $2\times 3000\,\text{fb}^{-1}$

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

c-tagging III



[arXiv:1505.06689]

@95% CL $|\kappa_c| < 1.6$ 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]

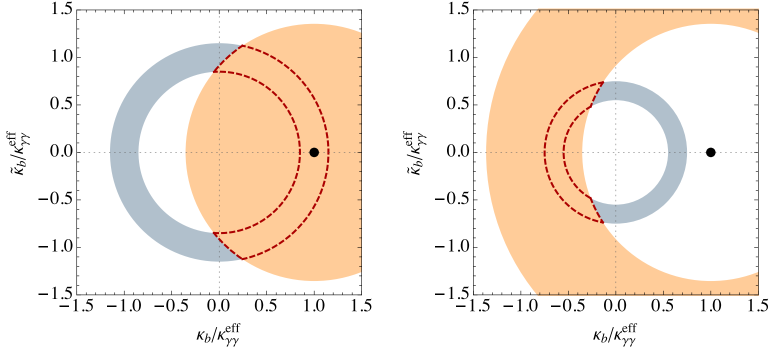
Exclusive possibilities

- only known way to access **light-quark Yukawas**

[Kagan et al 14]

- predictions under control [Bodwin et al 13/14, König et al 15]
- interference effect ➜ amplitude-level info.

i.e. the sign of y_b (assuming 50% precision in $\mathcal{BR}(\Upsilon\gamma)/\mathcal{BR}(\gamma\gamma)$)



[König et al 15]

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

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 and y_s

Assumptions for extrapolation: $S_E/\sqrt{B_E} \sim S_8/\sqrt{B_8}$, unchanged signal efficiencies, $S_E/\sqrt{B_E}$ same in J/ψ and ϕ mode, PYTHIA simulation to rescale B

Results for charm-Yukawa

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

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

Results for strange-Yukawa

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

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

➜ exclusive approach struggles with QCD background 🠔

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

[Perez et al, 15]

Summary & Conclusions

Higgs couplings sensitive to deviations from the SM

- **directly** accessible for the first time at the LHC
- a lot of progress made in extracting fermion Yukawas (both theo. and exp.)
- complementary approaches
  - **inclusive** - limited applicability (b,c)
  - **exclusive** - limited statistics (QCD bkg)
- sensitivity of the LHC higher than anticipated, good prospects and valuable information to extract