Higgs Flavour

inclusive meansurements and distributions

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arXiv:1503.00290 & 1505.06689

Outline

- **Introduction**
- ***h* → quark quark**
  methods and prospects to measure light quark Yukawas at LHC
  - ➜**inclusively**
  - ➜**exclusively** [see talk by König]
  - ➜**via distributions NEW**
- **Conclusions**

The Higgs boson within the Standard Model

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:

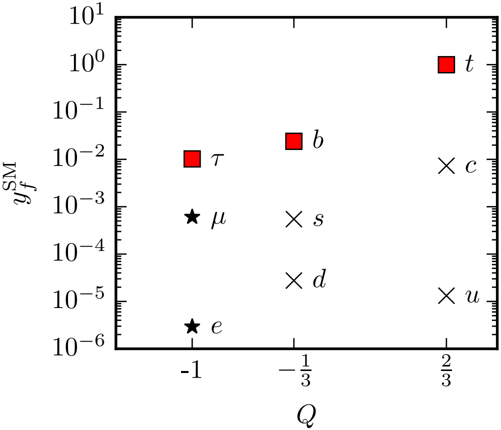
Mass   Charge   Spin
Couplings

- $m_h = 125.4 \pm 0.37(\mathrm{stat}) \pm 0.18(\mathrm{sys})$ 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?

Effective theory

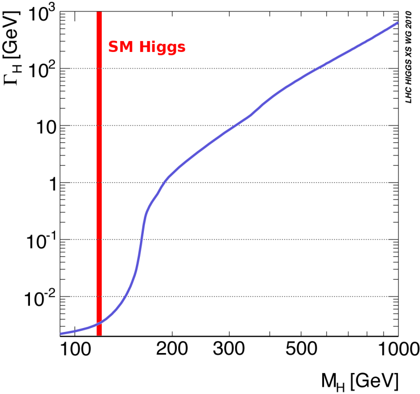
If **deviations** from SM **small** and **no new d.o.f.**:

- 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,...]



$h \to$ 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

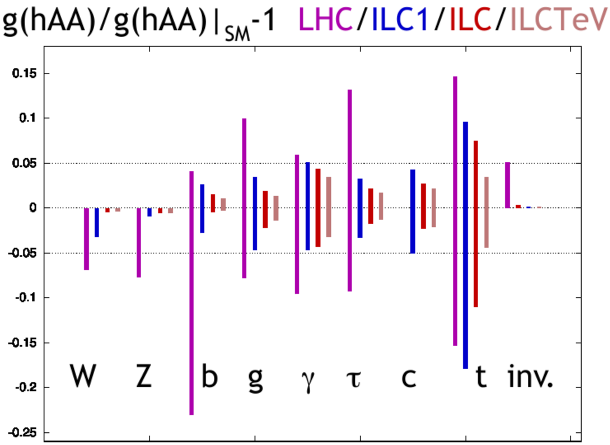
- **Be exclusive** [talk by König]
  - $h \to M\,\gamma$ as a flavour proxy (M vector meson)
  - possible for u, d, s, c ($h \to J/\Psi\gamma$, $h \to \phi\gamma$, $h \to \rho\gamma$)

  [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



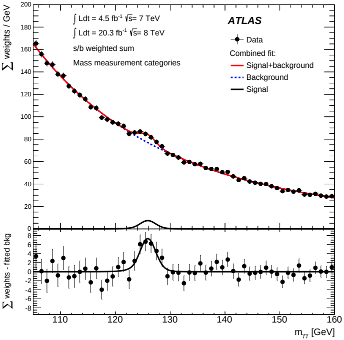
[Peskin 12 @ ILC-TDR]

- focus on **charm**
  LHC8 does constrain y_c, but mildly $|\kappa_c| < 245$
  LHC14 we can expect substantial improvements $|\kappa_c| < \mathcal{O}(10)$

Higgs width

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

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



[ATLAS arXiv:1406.3827]

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

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

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

@ 95% CL

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

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 $\tilde{t} \to c\chi_0$

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]

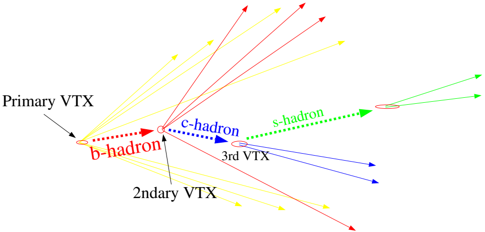
ATLAS search for $\tilde{c}\tilde{c}^*$ with $\tilde{c} \to c\tilde{\chi}_1$

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

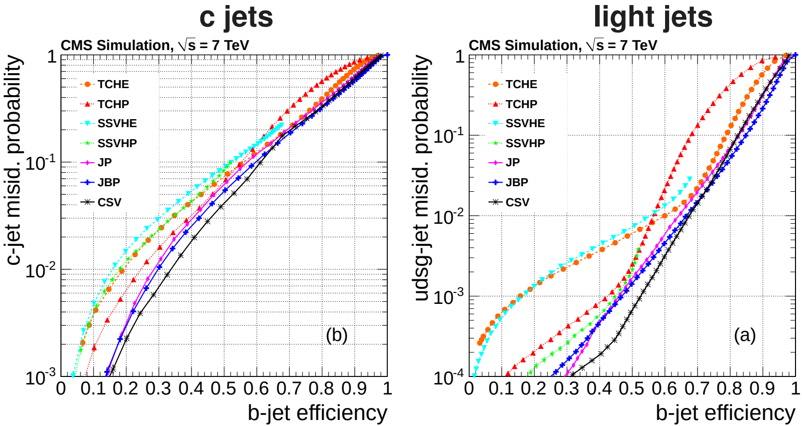
- b quarks hadronize to B mesons
- B-mesons are long lived $\sim 440\mu m/c$
- they fly in detector before decaying
- b-tagging is based on looking for such displased vertices



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, . . .

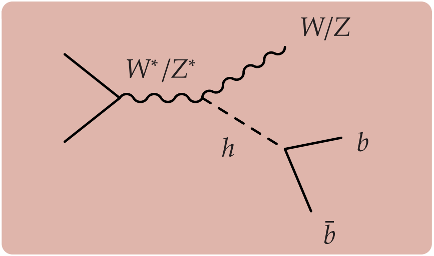
Recasting $H \to b\bar{b}$: Idea

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] $h \to b\bar{b}$ **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)

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

Signal strength including c-mistag

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

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

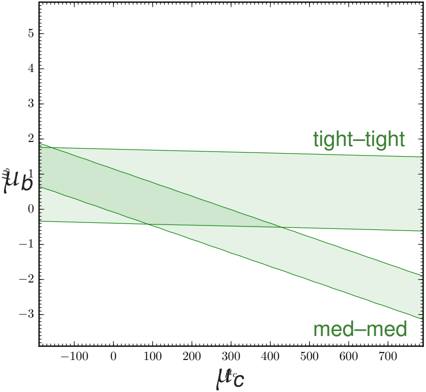
$$= \mu_b + 0.05 \cdot \epsilon_{c/b} \cdot \mu_c$$

- 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

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

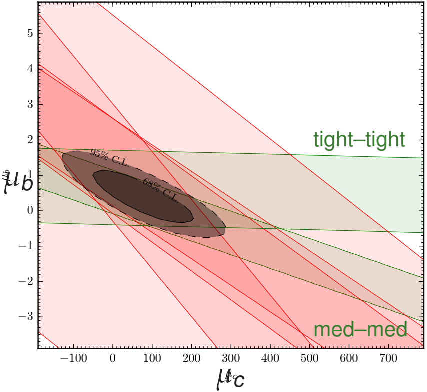
$$\chi^2 = -2 \log \mathcal{L}(\mu_b, \mu_c)$$

Profiling over μ_b ➜ first bound on μ_c

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

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

Fit assuming two signal strenths in ATLAS and CMS



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

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

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

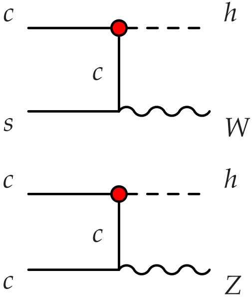
Recasting $H \to b\bar{b}$: production enhancement

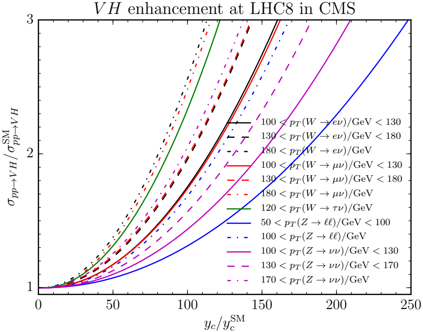
- assume no modification of production
- assume $\mathcal{BR}(h \to c\bar{c}) = 100\%$

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

However, a new production mechanism kicks in around

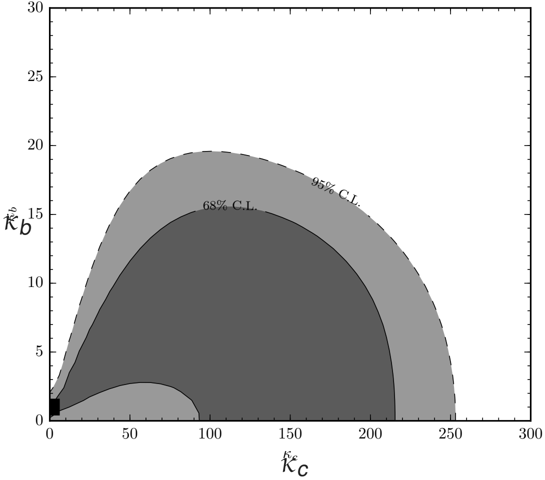
$y_c / y_c^{\mathrm{SM}} \sim 100$





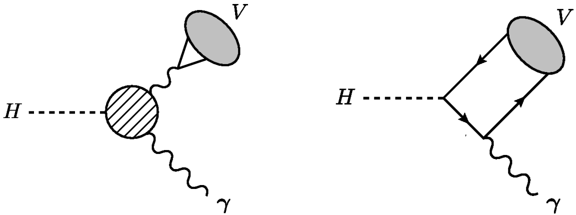
- depends on channel, category, due to cuts

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]

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

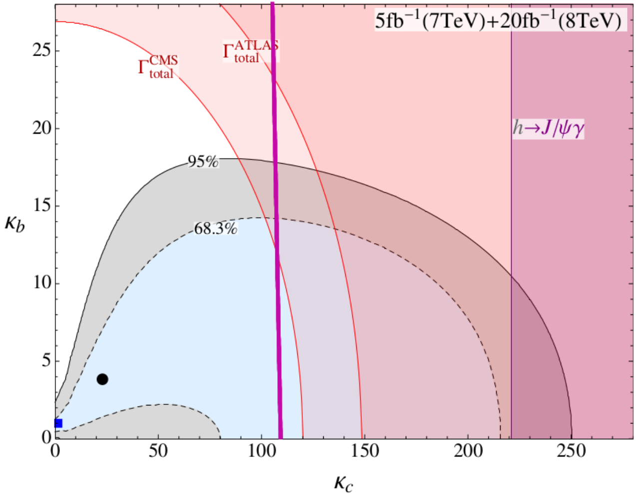
Cancel production: [ATLAS 1501.03276 / CMS 1507.03031]

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

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

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

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

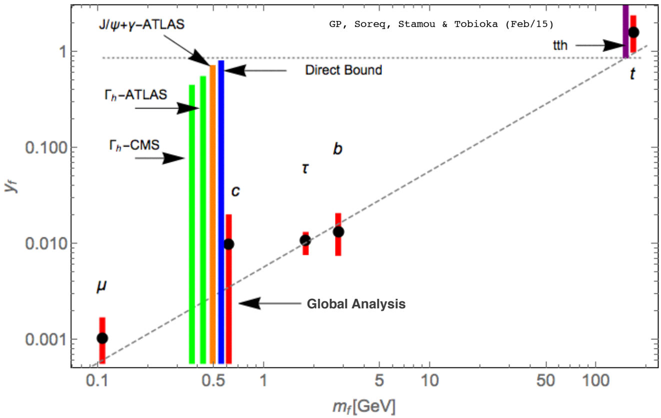
- Since $\frac{y_c}{y_t} \simeq \frac{1}{280}\frac{\kappa_c}{\kappa_t}$ the combination of κ_c/κ_t bounds means

$$\boldsymbol{y_c < y_t}$$

- LHC8 data excluded up-quark universality

Down-quark universality? Possibly in the future via distributions. [see below, i.e., Soreq et al 16]

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

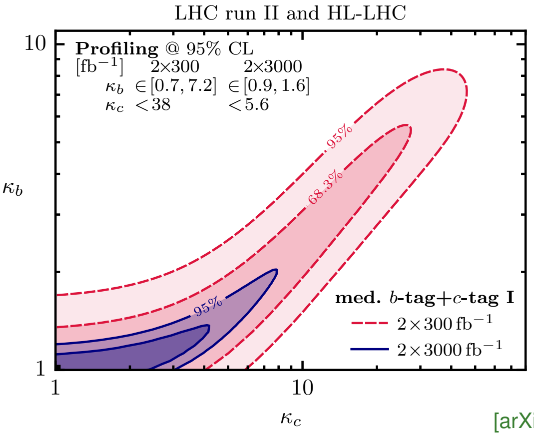
[ATL-PHYS-PUB-2014-011]

- 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

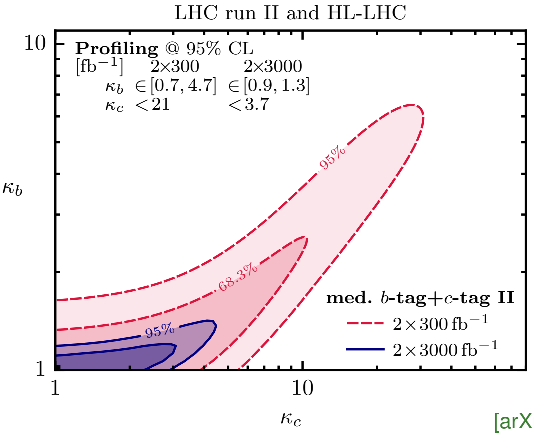


[arXiv:1505.06689]

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

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

c-tagging II



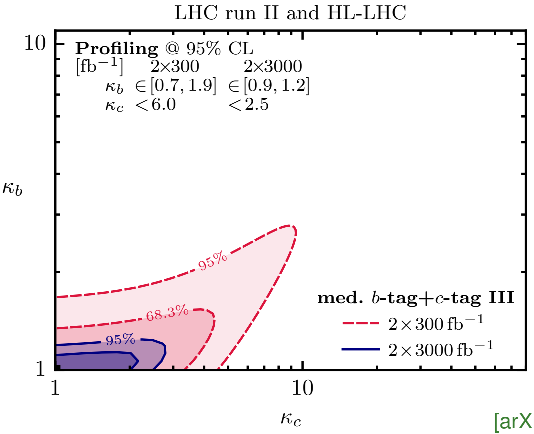
[arXiv:1505.06689]

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

@95% CL **$|\kappa_c| < \pm21$, $\pm\,3.7$** at Run 2, HL-LHC

κ_c prospects at LHC14 2×300 fb^{-1} 2×3000 fb^{-1}

c-tagging III



[arXiv:1505.06689]

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

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

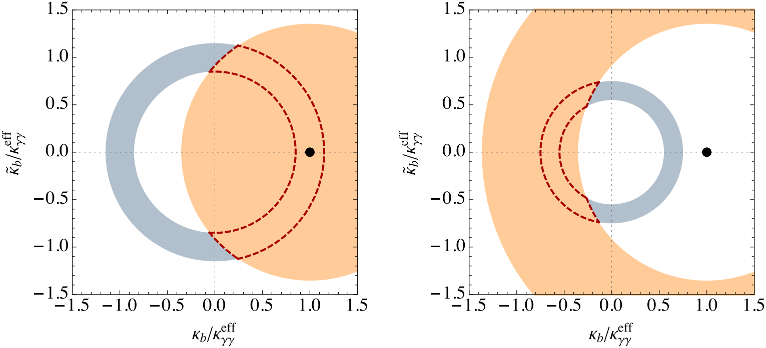
Exclusive possibilities

- only known way to flavour-tag **light-quarks**

[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 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 $2\times3000\,\text{fb}^{-1}$

Results for strange-Yukawa

$|\kappa_s| < 3300,\ 2000,\ 1200$
at LHC run 2, HL LHC, and a 100 TeV with $2\times3000\,\text{fb}^{-1}$

➜ exclusive approach struggles with QCD background 🠸

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

[Perez et al, 15]

New approach: Yukawa couplings via distributions

- be less direct ➜ abandon strict flavour tagging
  (exclusive or inclusive)
- look at p_T/y distributions that are affected by Yukawa modifications

  ➜ bottom, charm, strange [Bishara, Haisch, Monni, Re 16]

  ➜ up, down, strange [Soreq, Zhu, Zupan 16]
- consider normalised distribution, e.g.,

$$\frac{1}{\sigma}\frac{d\sigma}{dp_T}$$

  in which part of theoretical uncertainties cancel [Catani et al 07]

Charm from distributions I [Bishara et al 16]

- p_T distribution of Higgs plus jet events
- @ LO: $gg \to hj$, $gq \to hq$, $q\bar{q} \to hg$

gg fusion

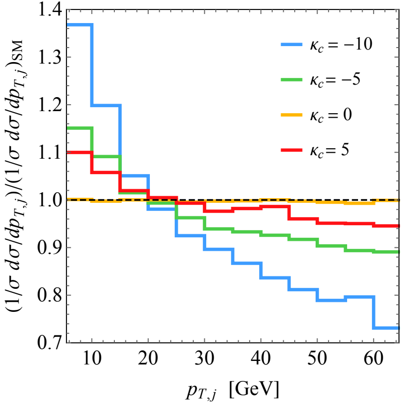
- inteference between q and top loop

  ➜ linear dependence on κ_q, sign sensitivity
- real emission of jets in $m_q < p_T < m_h$

  ➜ large double log

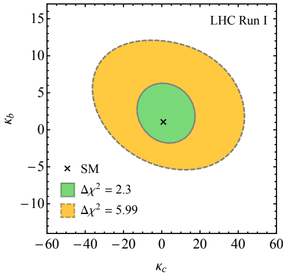
$$\propto \kappa_q \frac{m_q^2}{m_h^2} \log^2\left(\frac{p_T^2}{m_q^2}\right)$$

The $p_{T,j}$ spectrum by varying the charm-quark Yukawa at 8 TeV



similar results for the $p_{T,h}$ spectrum

Racast of ATLAS's and CMS's $p_{T,j}$ and $p_{T,h}$ spectra



@LHC run I $\kappa_c \in [-20, 25]$ at 95% CL

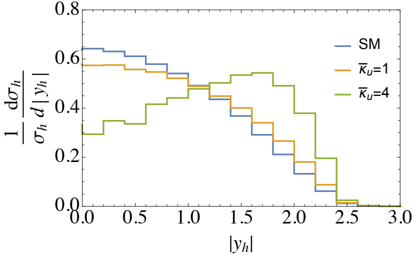
significantly more stringent constraint that from the inclusive or exclusive approach

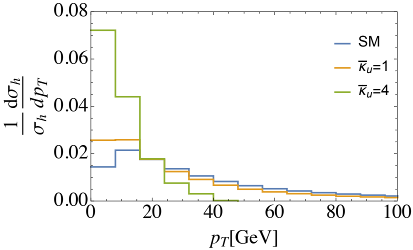
@LHC run II	$\kappa_c \in [-4.7, 5.5]$	at 95% CL, **projection**
@HL-LHC	$\kappa_c \in [-2.9, 4.2]$	at 95% CL, **projection**

- consider y_h and $p_{T,h}$ distributions
- in SM gg fusion dominates, g's equal partonic x

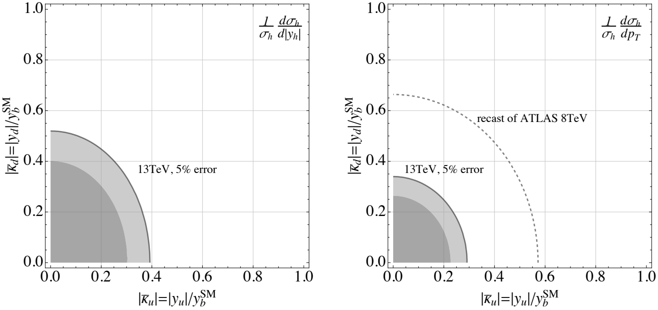
  rapidity distribution peaks at $y_h = 0$
- enhance, e.g, up Yukawa ➜ $u\bar{u}$ fusion

  - asymmetric rapidity distribution (*u* valence and $\bar{u}$ sea quark)
  - p_T spectrum peaks before *gg* fusion (different effective radiation strength)





ATLAS and CMS recast and LHC13 projection



At 95% CL the p_T distributions lead to:

$\bar\kappa_u \equiv y_u/y_b^{SM} < 0.46(0.27)$ at LHC8 (LHC13 with $2ab^{-1}$)

$\bar\kappa_d \equiv y_d/y_b^{SM} < 0.54(0.31)$ at LHC8 (LHC13 with $2ab^{-1}$)

Stronger bounds than from inclusive fit!

Together with $\bar\kappa_b$ projection may

exclude down-quark universality in down sector at LHC13!

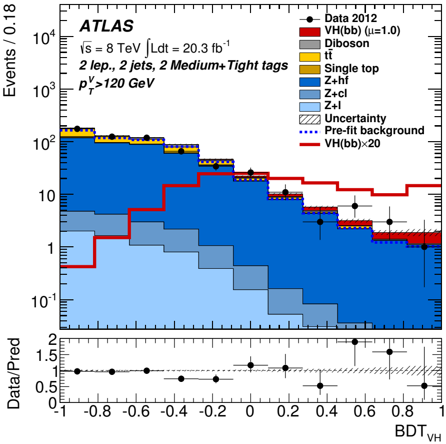
Summary & Conclusions

LHC tests for the first time directly the flavour of the Higgs

- 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)
  - **via distributions** - theory limitations, less direct
- sensitivity of the LHC higher than anticipated, good prospects and valuable information to extract
- collaborations already pursuing some directions

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

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

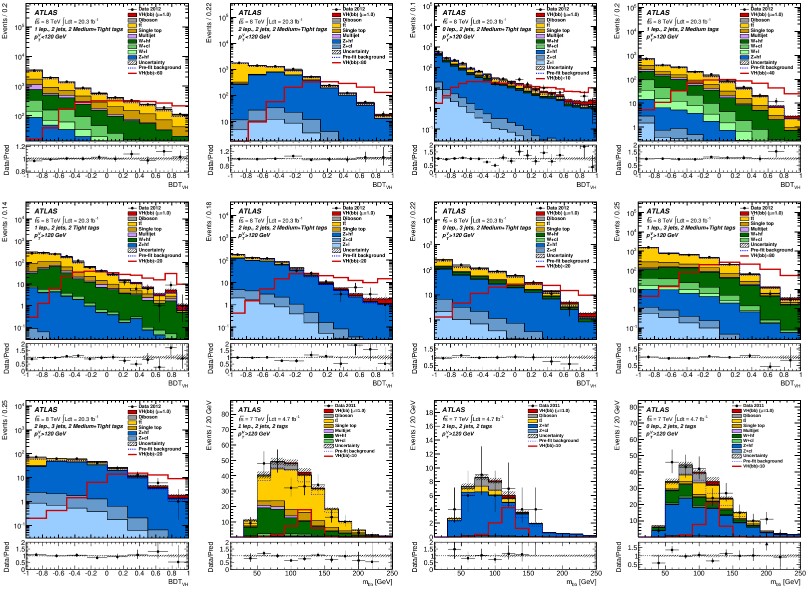


- Signal, Background, Data binned in BTD output

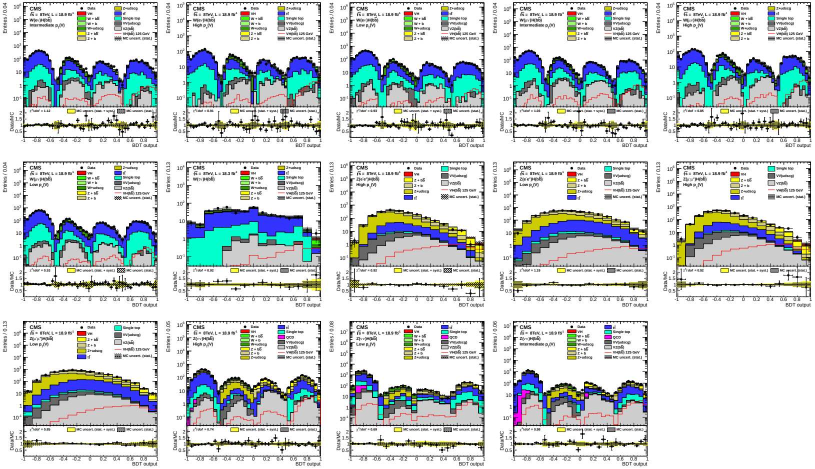
- Each bin is one independent measurement entering the χ^2

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

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

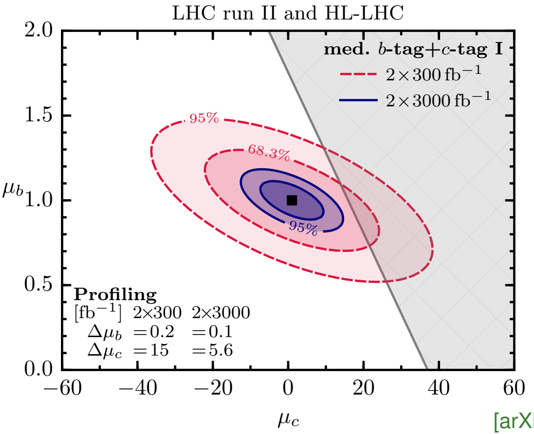


Recasting $H \to b\bar{b}$: CMS



- 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.)

c-tagging I



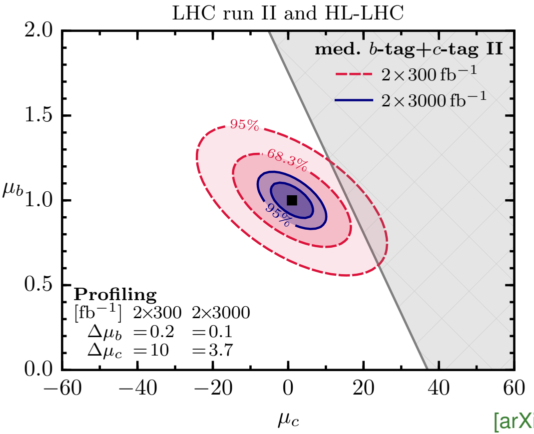
[arXiv:1505.06689]

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

c-tagging II



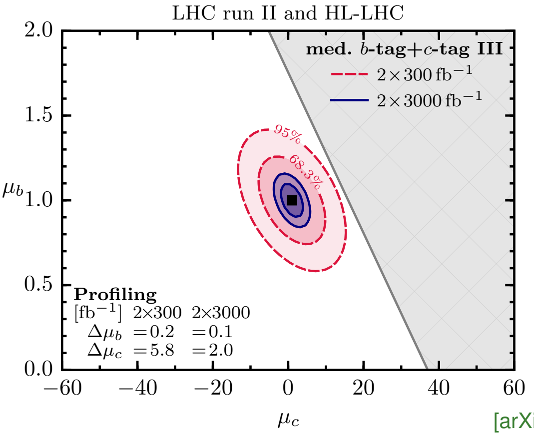
[arXiv:1505.06689]

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 $\boldsymbol{\Delta\mu_c = \pm 10, \ \pm 3.7}$ at Run 2, HL-LHC

c-tagging III



[arXiv:1505.06689]

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

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

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

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]