Title: The coupling of the Higgs to charm quarks: how much can the LHC probe?

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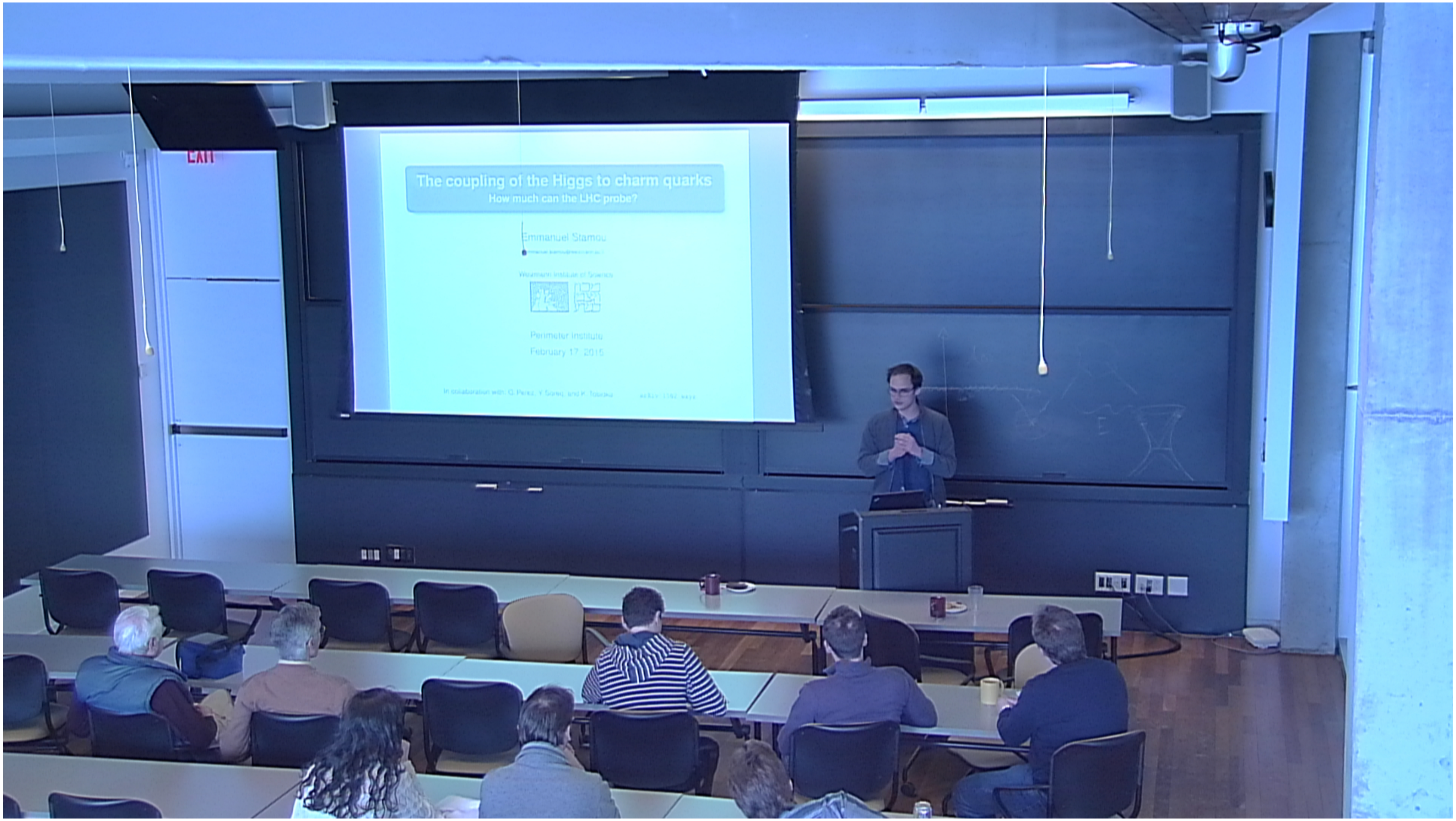
Abstract: <p>The Higgs couplings to fermions are known parameters within the Standard Model. Deviations from these
 expectations would be clear signals of new physics and are thus important target measurements for the LHC program.
 In this talk I shall discuss ways to extra information about the coupling of the Higgs boson to the charm quark with
 emphasis on methods applicable with the available LHC data set. A novel method based on the current ATLAS and CMS
 Hbb measurement will be presented and compared to our knowledge so far. Future projections and the even more
 challenging case of light-quark Yukawa couplings will be discussed.</p>


The coupling of the Higgs to charm quarks
How much can the LHC probe?
Emmanuel Stamou
Perimeter Institute
February 17, 2015

The coupling of the Higgs to charm quarks

How much can the LHC probe?

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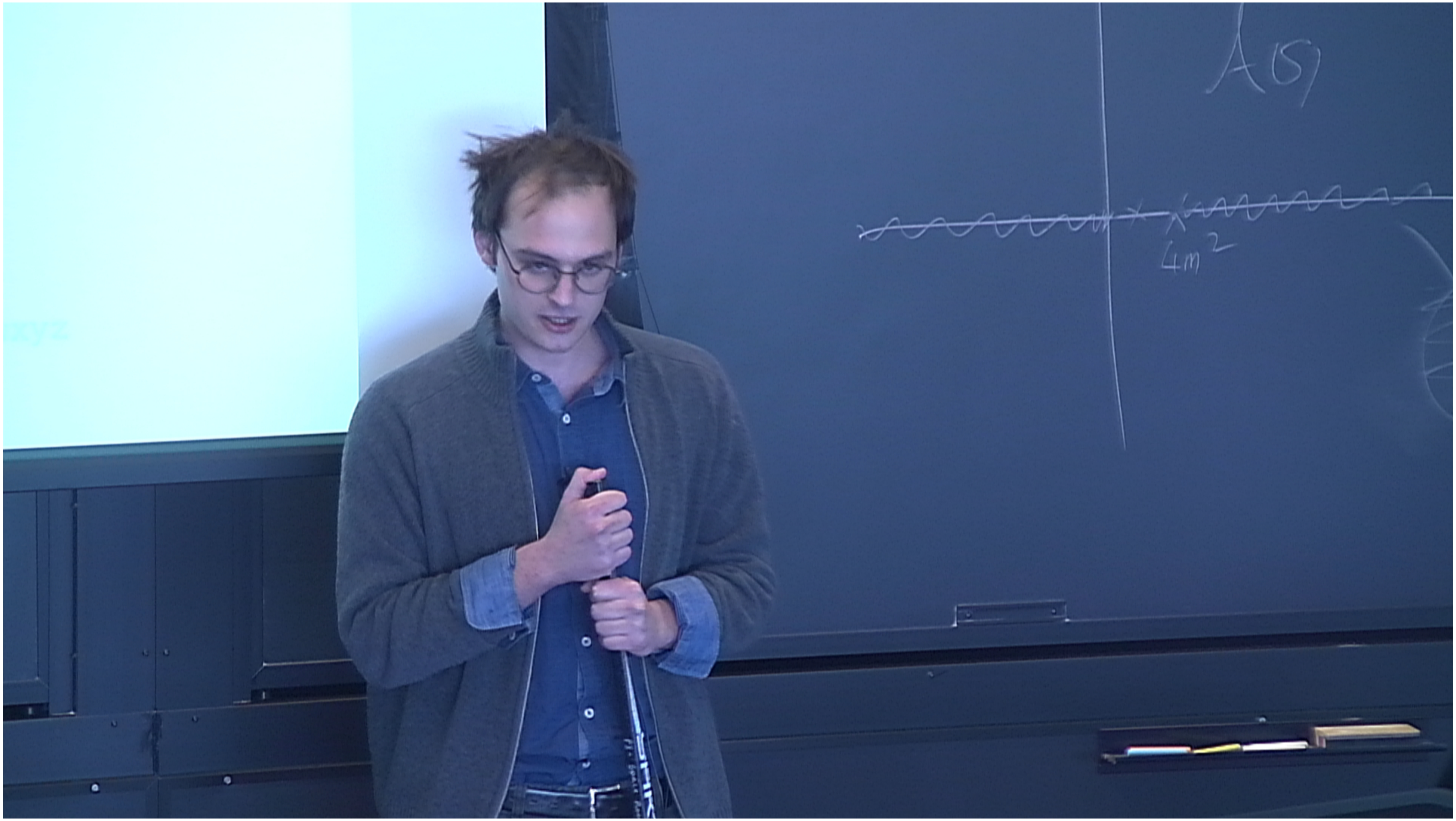
In collaboration with: G. Perez, Y. Soreq, and K. Tobioka   arXiv:1502.wxyz


A(s)
4m²

The Higgs boson within the Standard Model

Theory

Role (I)

- unitarises VV scattering in a minimal way
- its vev induces the W and Z masses
- a 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
- vev induces fermion masses and coupling the CKM

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

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The Higgs particle

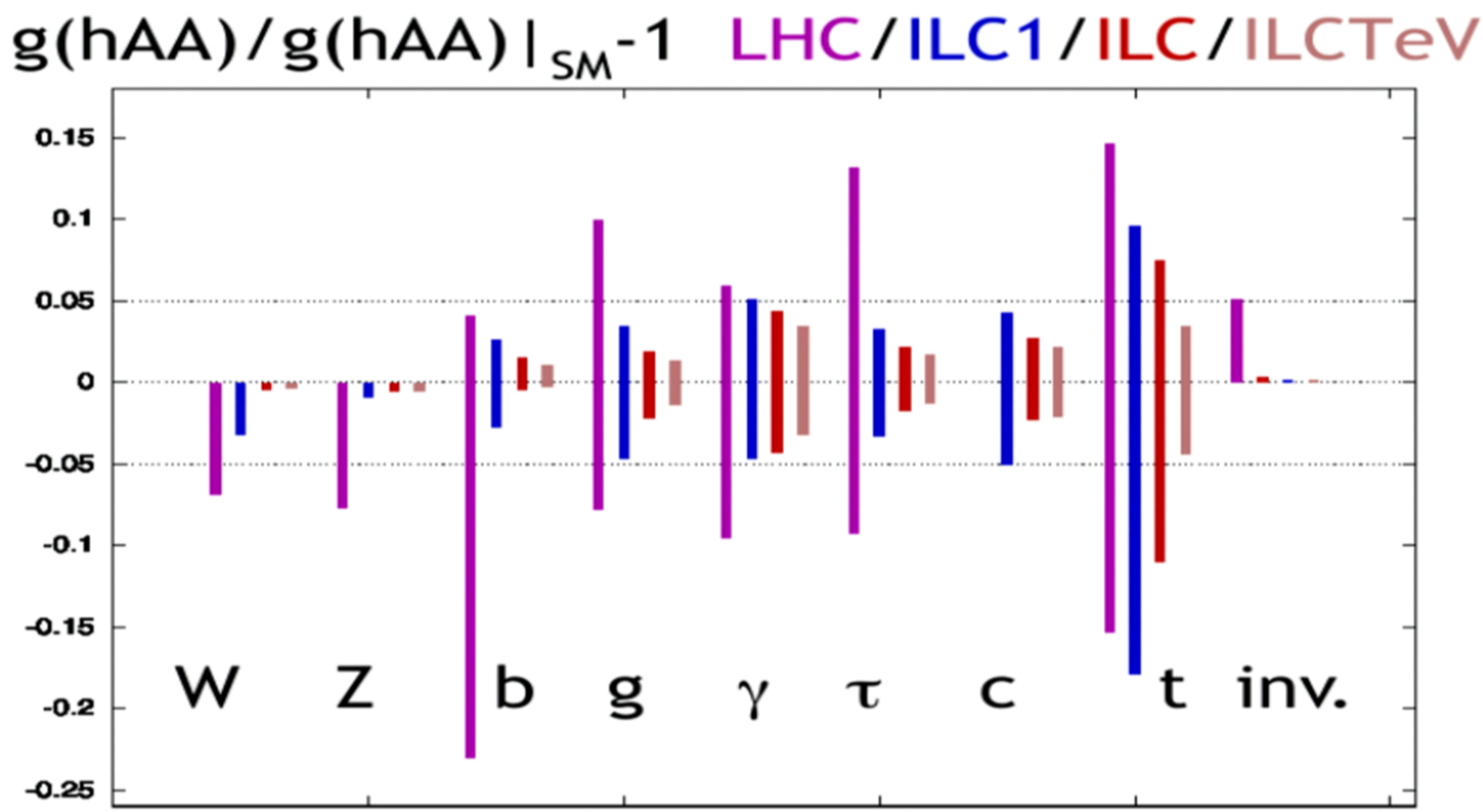
Experiment

A particle like any other. Defined by observing:

Mass	Charge	Spin	Couplings

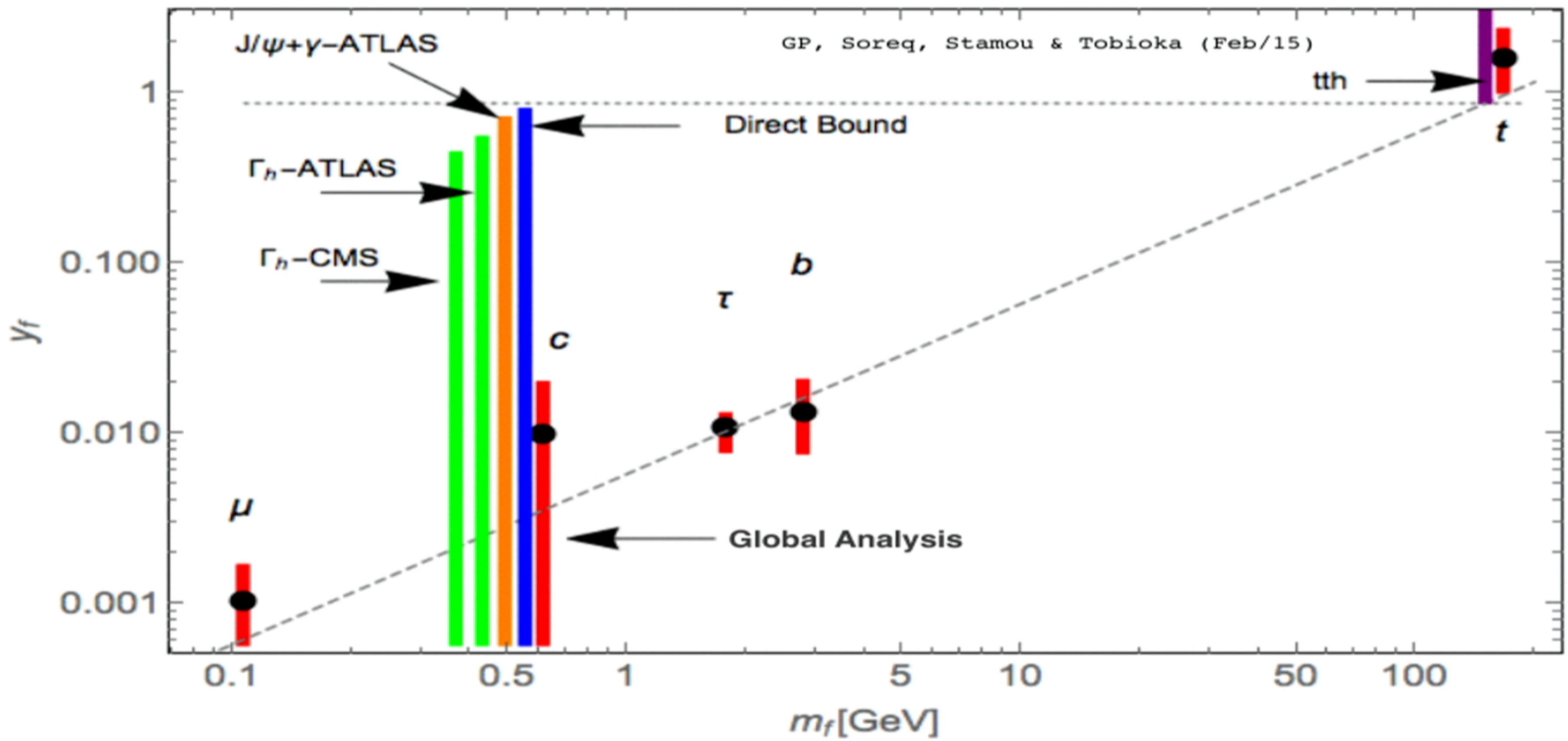
- $m_h = 125.4 \pm 0.37(\text{stat}) \pm 0.18(\text{sys})$ GeV [ATLAS]
  $m_h = 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{sys})$ GeV [CMS] **a new SM parameter** ✓
- neutral ✓
- spin-0 ✓
- couplings predicted $g_X \propto \frac{m_X}{v}$ so far ✓
  - overconstrained in SM, test of the SM
  - Yukawa couplings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

Exercise: find the missing purple line



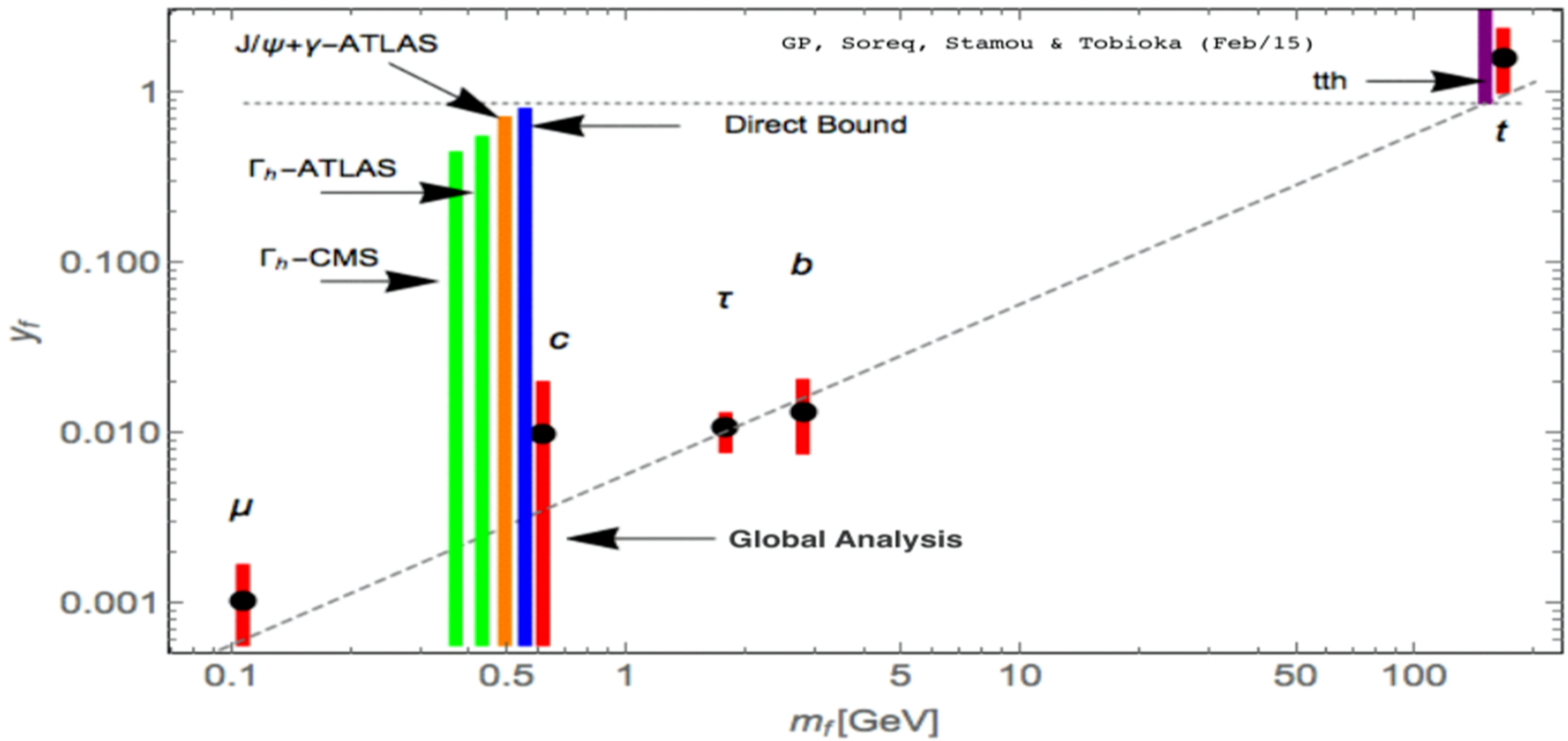
- focus on charm at the LHC using available data [Peskin 12 @ ILC-TDR]

The goal



GP, Soreq, Stamou & Tobioka (Feb/15)
J/ψ+γ–ATLAS
Direct Bound
Γh–ATLAS
Γh–CMS
Global Analysis
tth
μ
c
τ
b
t
1
0.100
0.010
0.001
yf
0.1
0.5
1
5
10
50
100
mf[GeV]

The goal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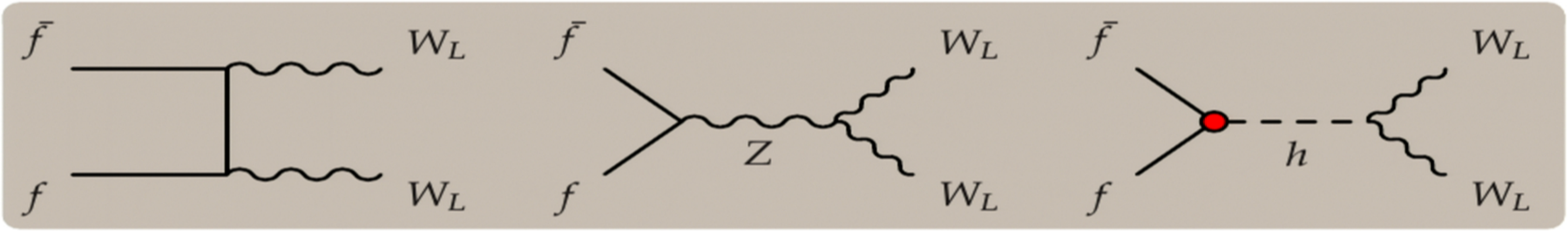
1
5
10
50
100
y_f
m_f[GeV]

Outline

- Introduction
- Probing y_c at LHC8
  - the width of the higgs
  - recasting the ATLAS and CMS $H \to b\bar{b}$ analysis
  - y_c from exclusive Higgs decays
  - global analysis
- Future prospects

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]

- enhancement of Yukawa couplings more promising

Effective theory

- small deviations captured by dim-6 operators

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

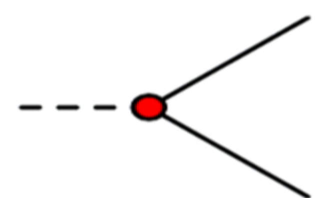
Charm-quark case

- SM case very challenging to observe $y_c^{\rm SM} \simeq 0.4\%$ 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]

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

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



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

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

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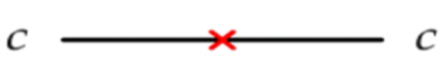

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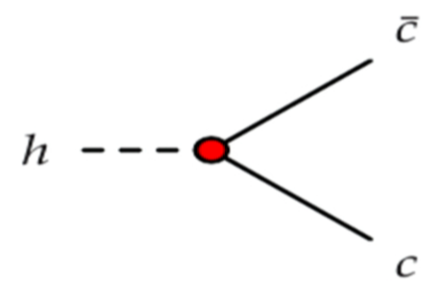

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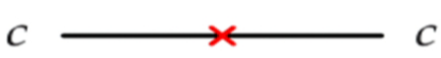

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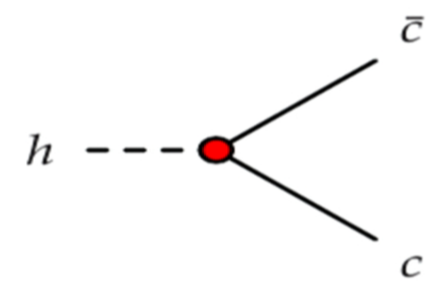

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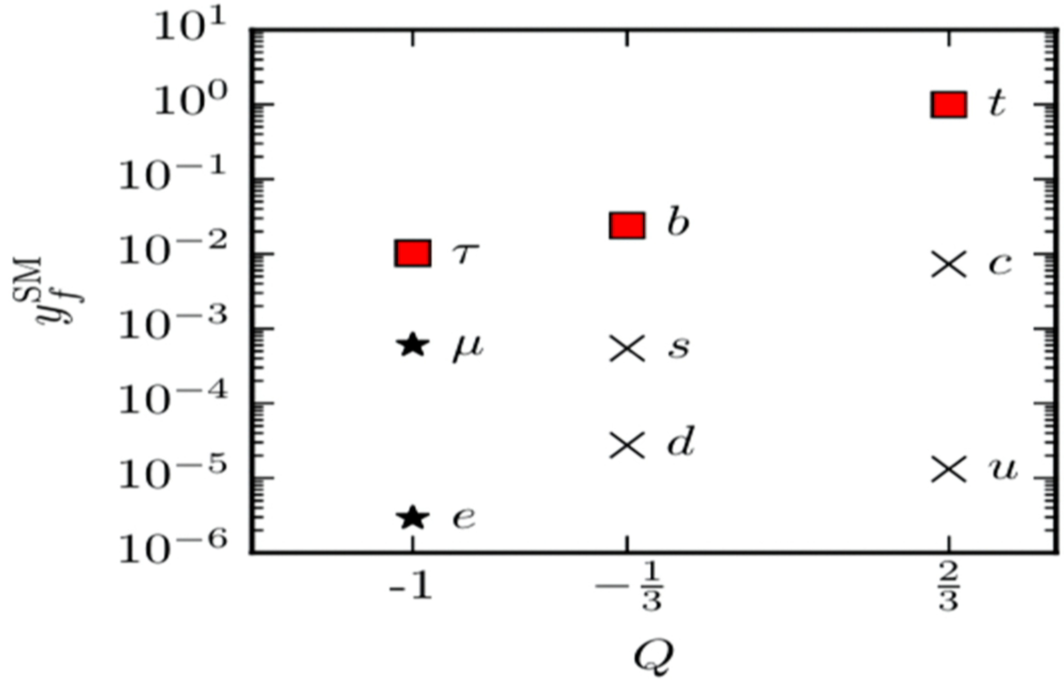
Direct observations for fermionic higgs couplings

- higgs couples to t, b, and τ ✓



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

Signal strenth

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

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

[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]

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

➜ higgs couples non-universally to leptons
What about quarks?

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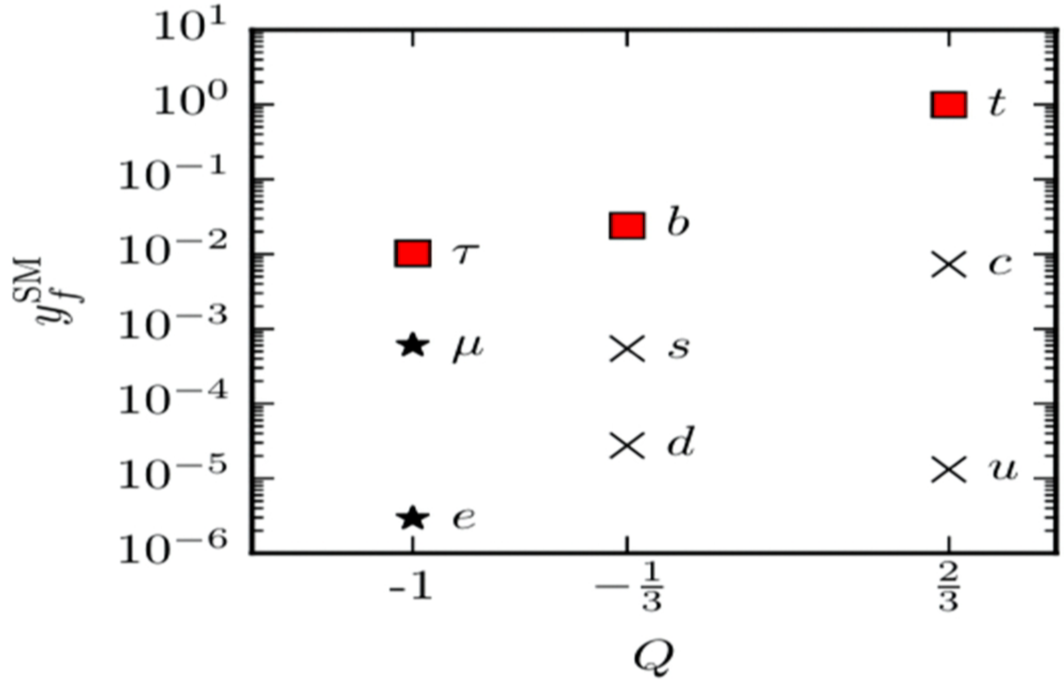

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What about quarks?

$h \to$ 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

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

  [Delaunay, Golling, Perez, Soreq 13; **ATLAS arXiv:1501.01325, ATLAS-CONF-2013-063**; this work]

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

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

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 $\tilde{c} \to c\tilde{\chi}_1$

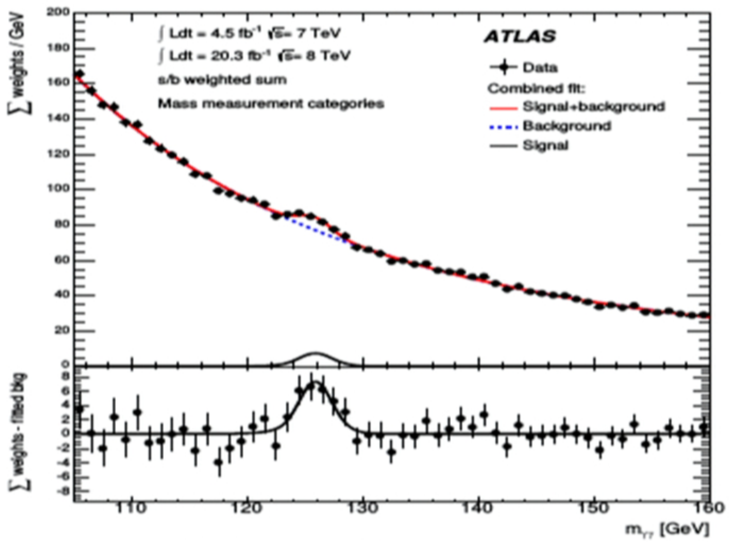
Search for Scalar-Charm Pair Production in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

[ATLAS-CONF-2013-063]

Higgs width

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

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



[ATLAS arXiv:1406.3827]

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

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

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

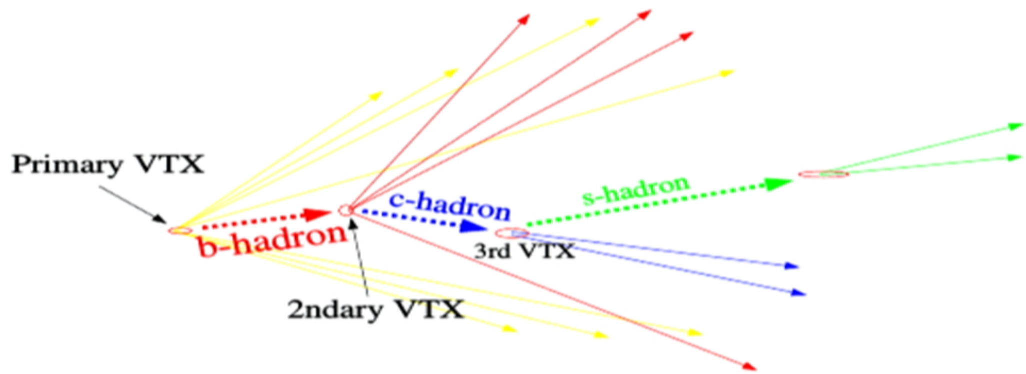
@ 95% CL

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

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

b-jets at LHC are NOT b-quarks

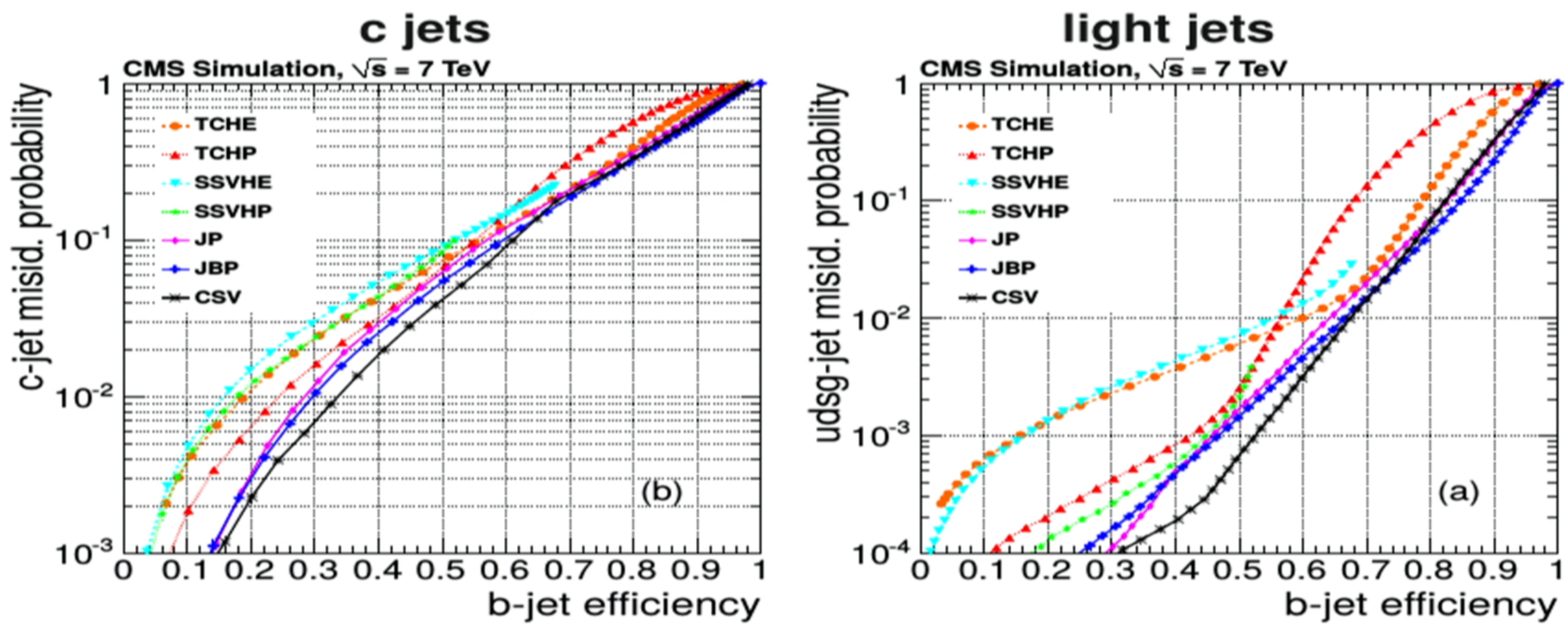
- b-quarks hadronize to B-mesons
- B-mesons are long lived $\sim 440\mu m/c$
- the fly in detector before decaying
- b-tagging is based on looking for such displased vertices



But

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

b-jet efficiencies depend on theshold



[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, ...

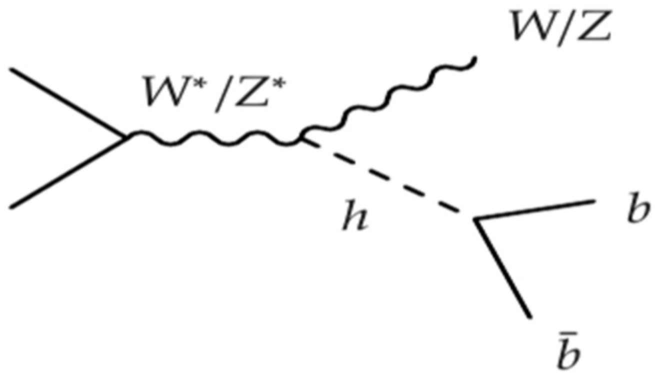
Recasting $H \to b\bar{b}$: Idea

What is the bound on y_c from misstagging?

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

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

- h produced in association with W/Z



- h produced in association with W/Z
- different channels for W/Z decays
  $Z \longrightarrow \nu\bar{\nu}$ [0lepton] $Z \longrightarrow \ell\bar{\ell}$ [2lepton] $W^- \longrightarrow \ell^-\bar{\nu}$ [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)

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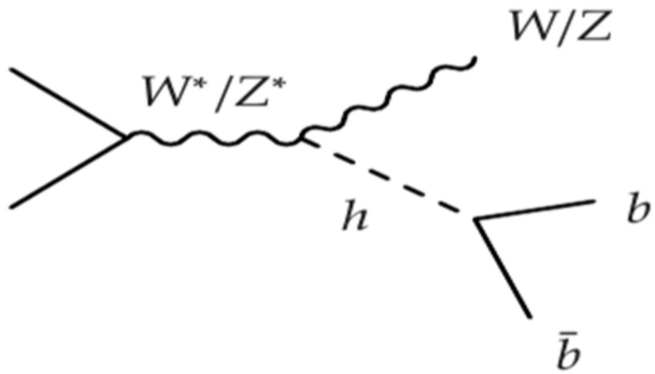

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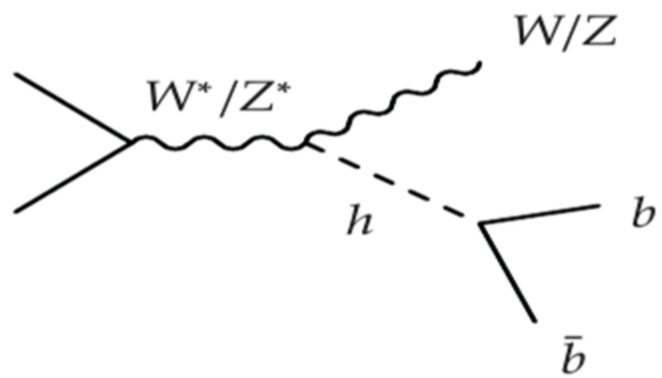

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Recasting $H \to b\bar{b}$: signal strength

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

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

Signal strength including c-misstag

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

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

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

- 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

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

Signal strength including c-misstag

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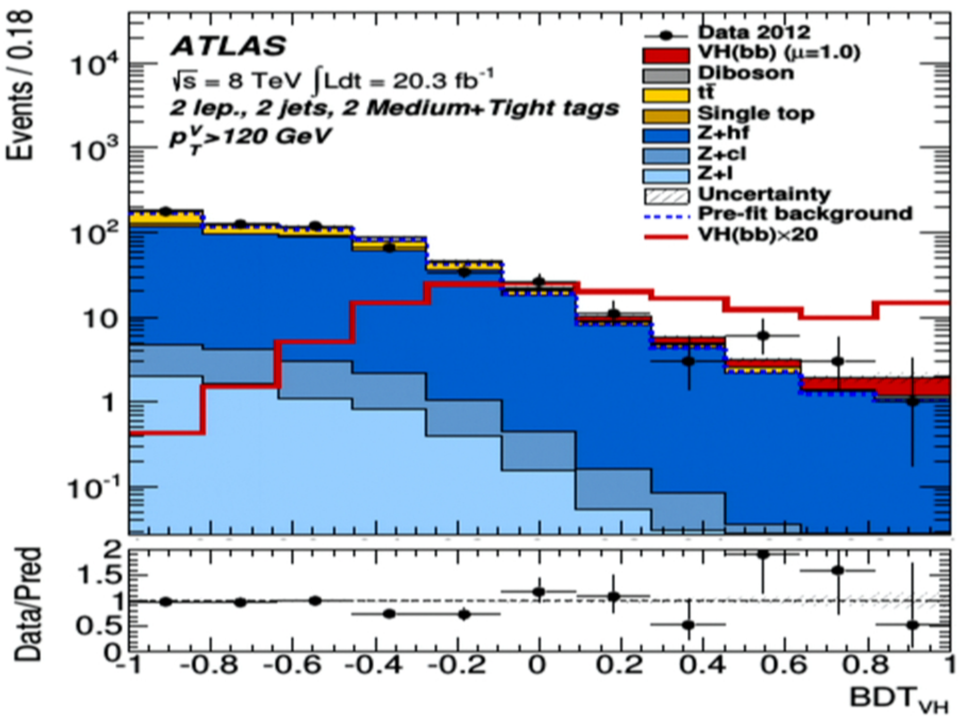
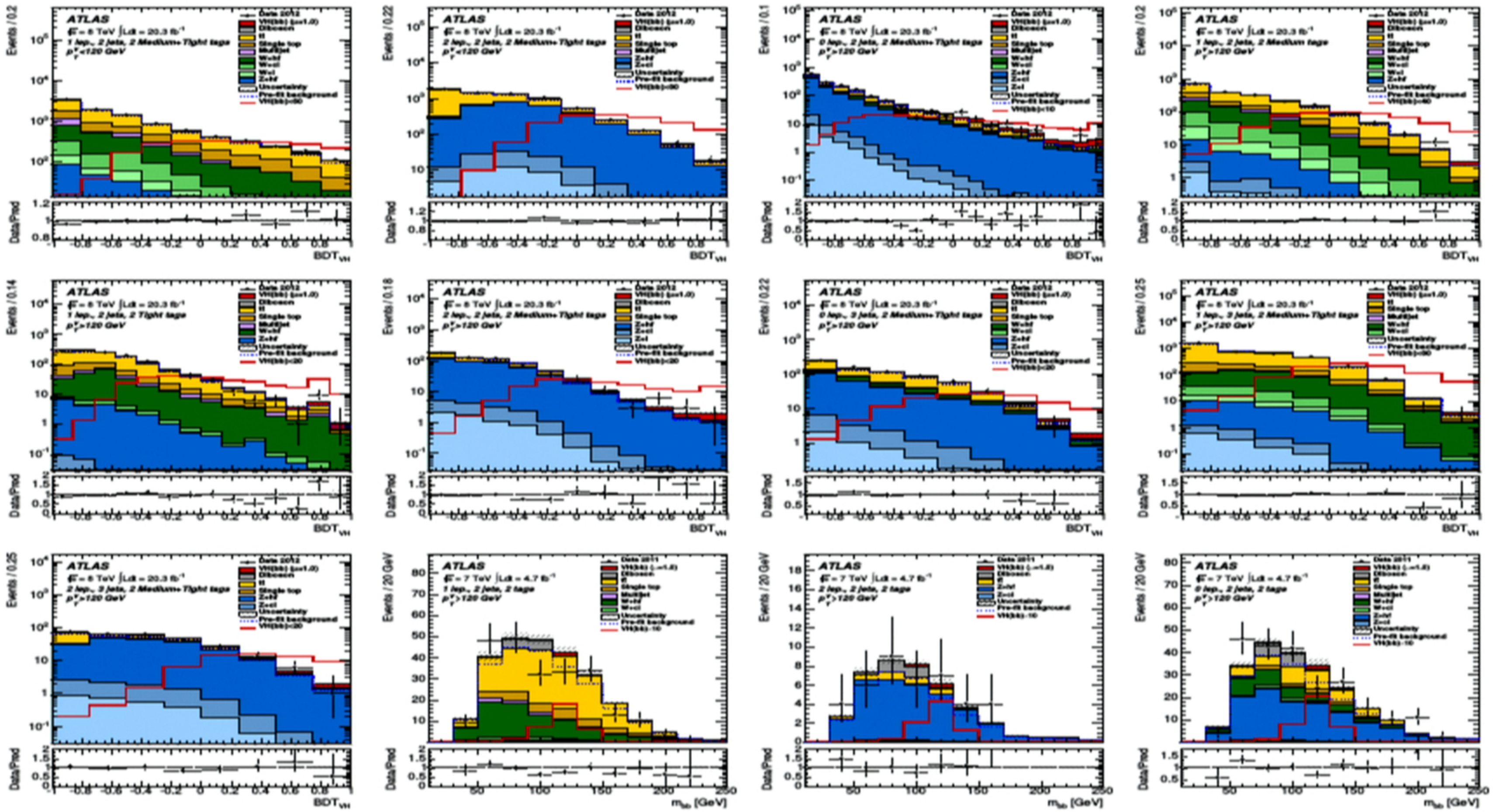
Recasting $H \to b\bar{b}$: an example

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



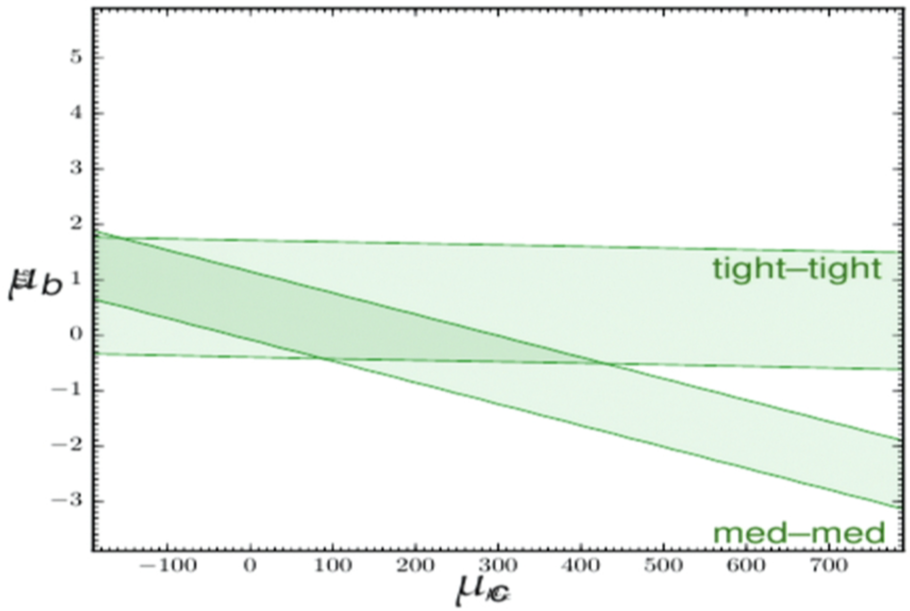
- Signal, Background, Data binned in BTD output
- Each bin is one independent measurement entering the χ^2
- **Bitter reality:**
they don't give tables
digitize plots

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



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

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**

$$\mu_c = 90^{+80(150)}_{-100(190)} \quad @ \quad 68.3\,(95)\%\ \text{CL}$$

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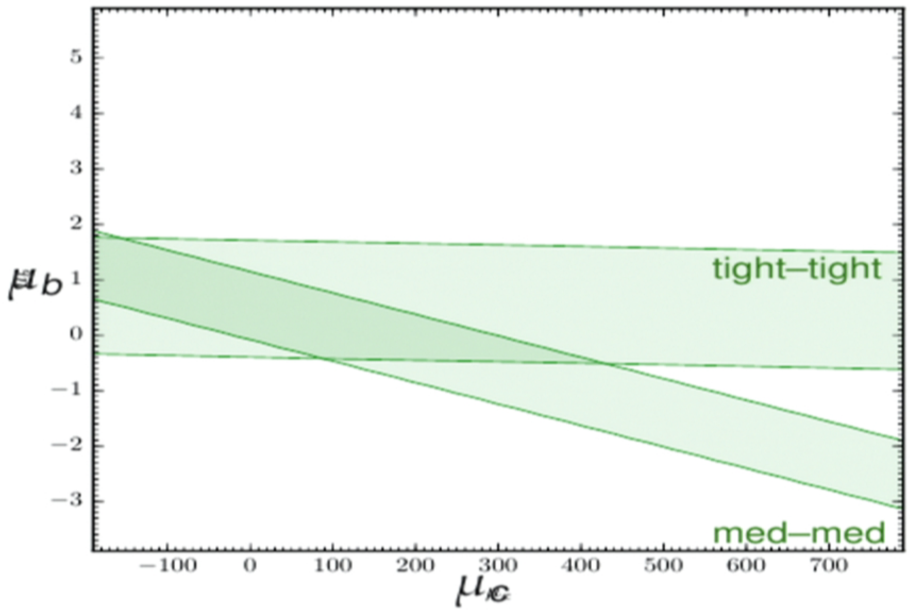

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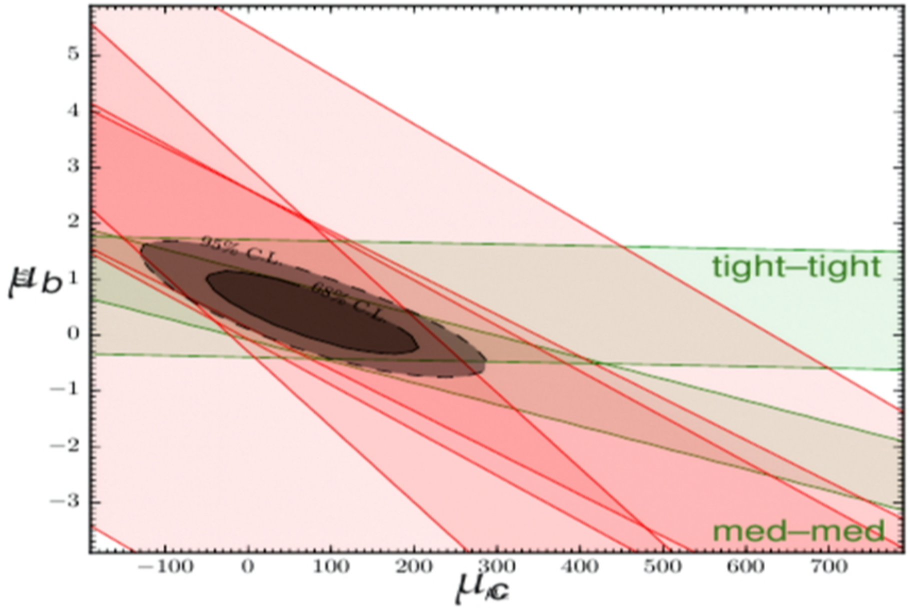

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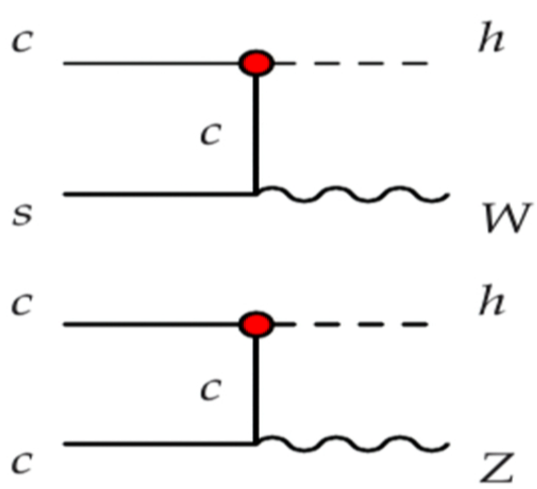
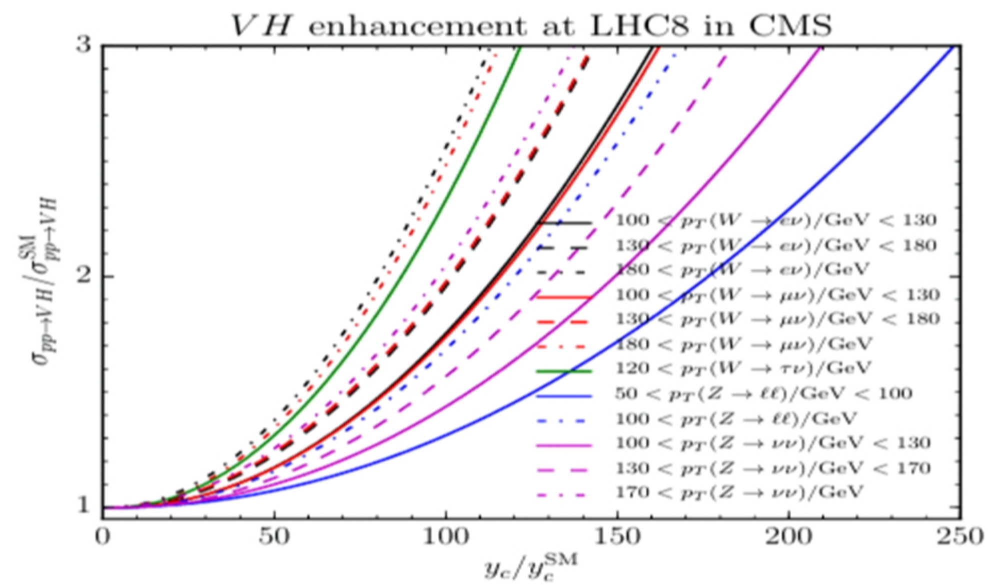
Recasting $H \to b\bar{b}$: production enhancement

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

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

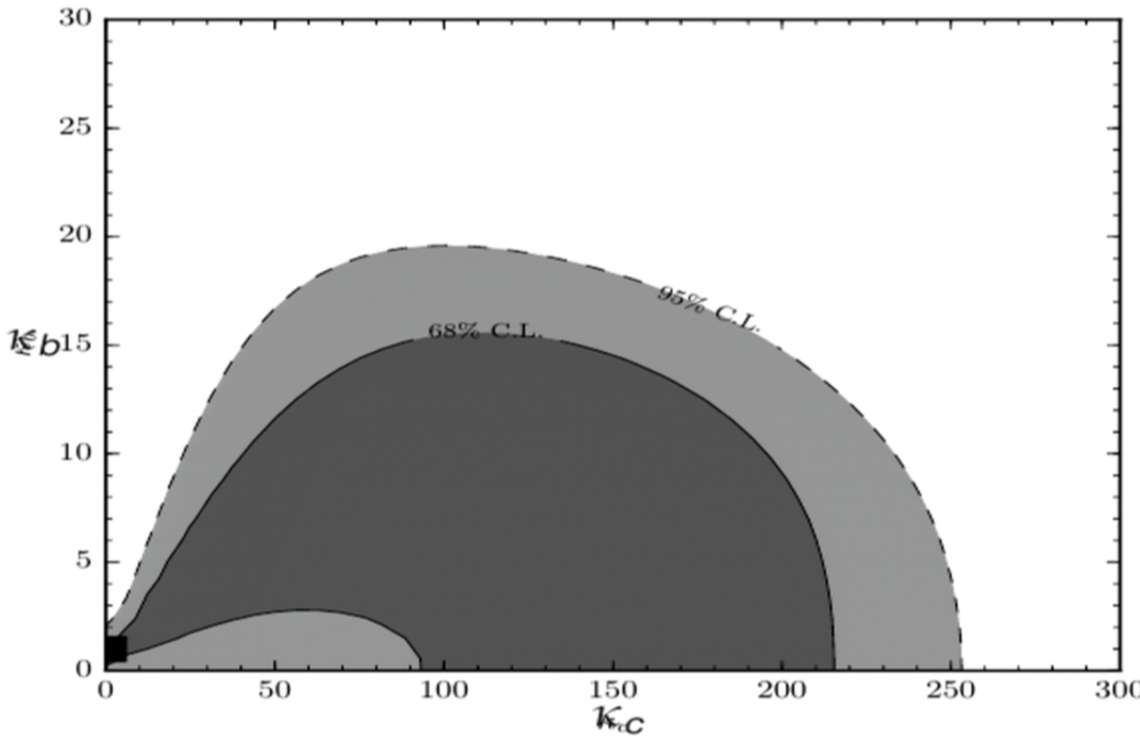
However, a new production mechanism kicks in around $y_c/y_c^{\rm SM} \sim 100$





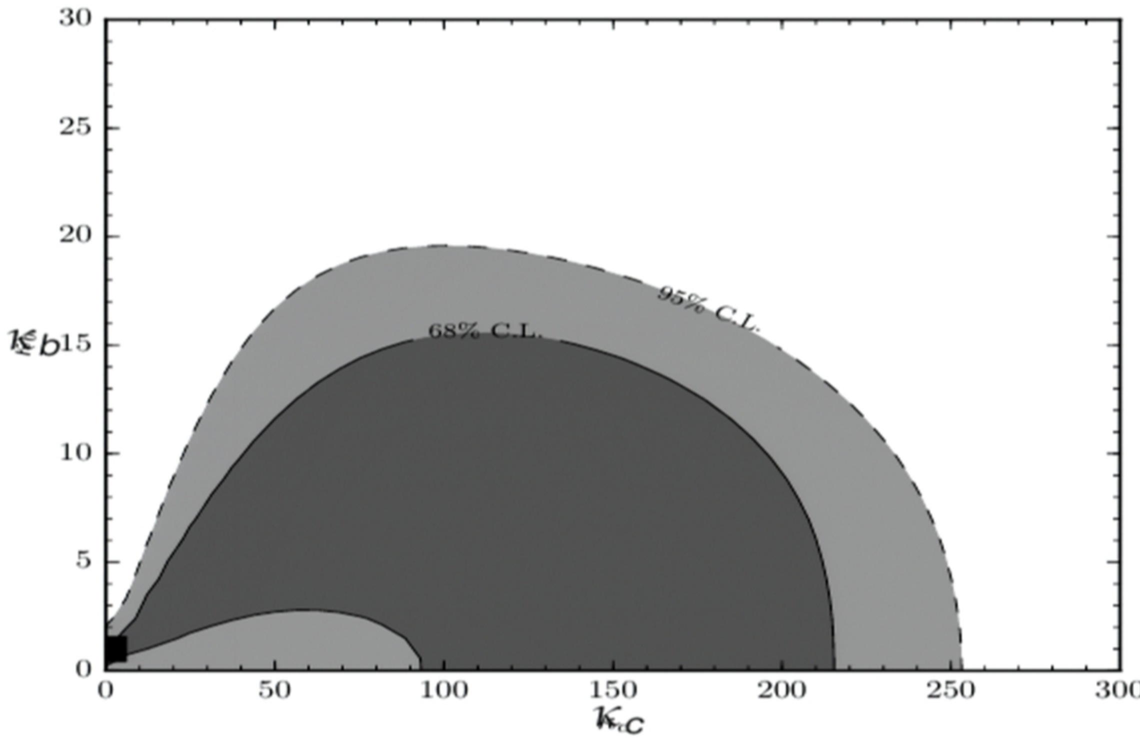
- depends on channel, category and experiment because of cuts

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



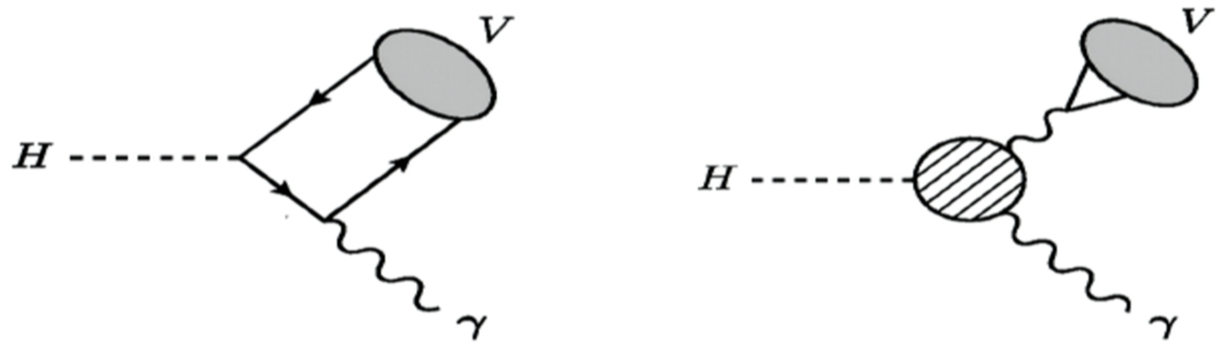
After profiling ➜ $\kappa_c = y_c^{\mathrm{SM}}/y_c \lesssim 245$

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



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

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

Recent ATLAS study:

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

[ATLAS 1501.03276]

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

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

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

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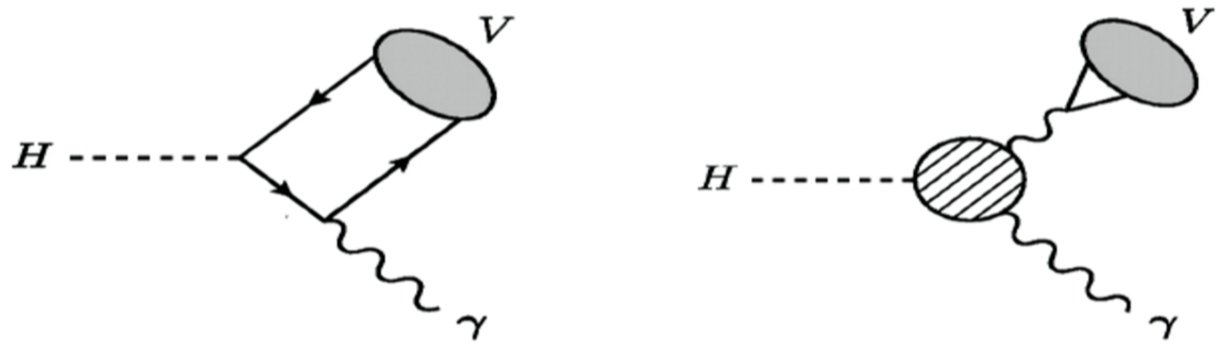

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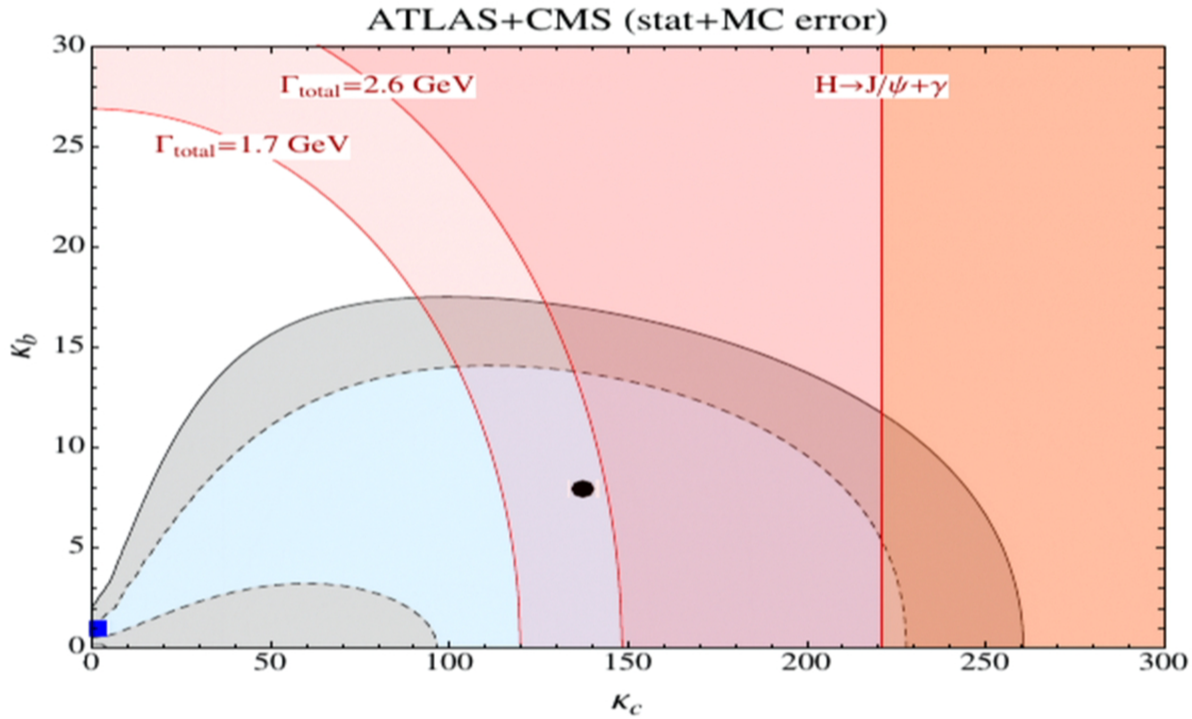
Combination: what we know about y_c from LHC8



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)

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]

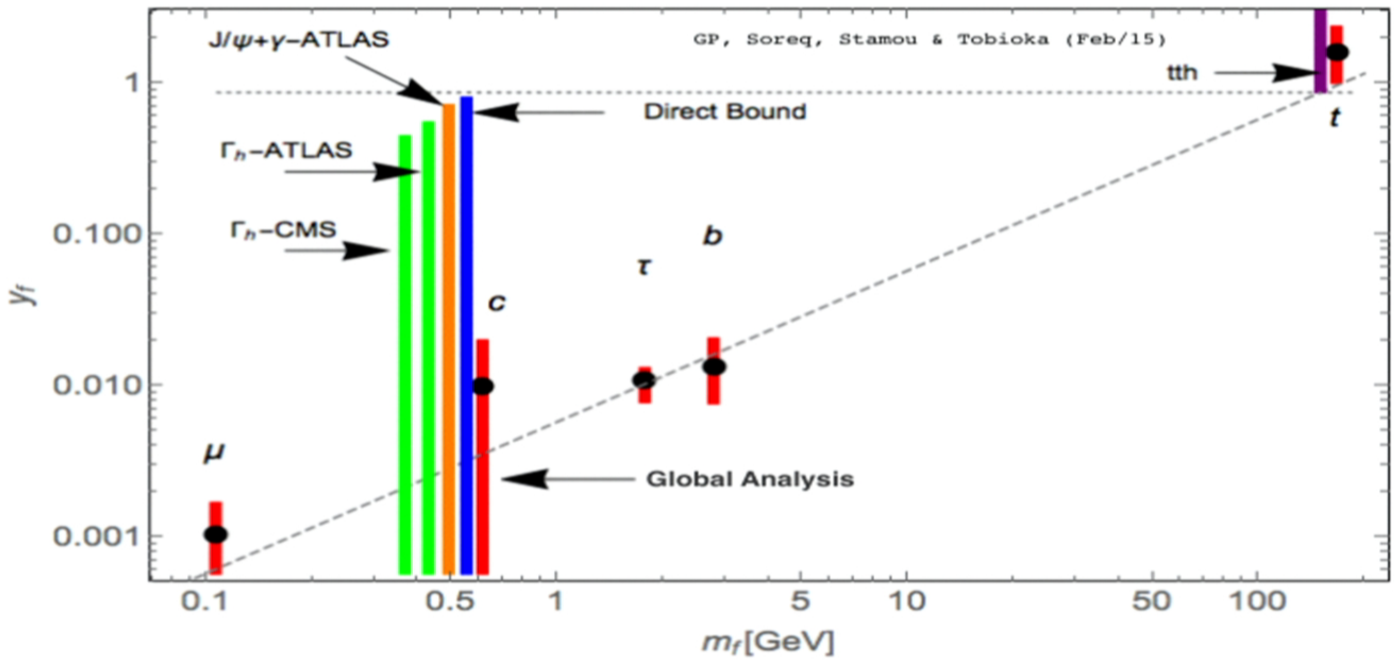
- this translates to a lower bound on the top Yukawa

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

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

$$\boldsymbol{y_c < y_t}$$

Global fit



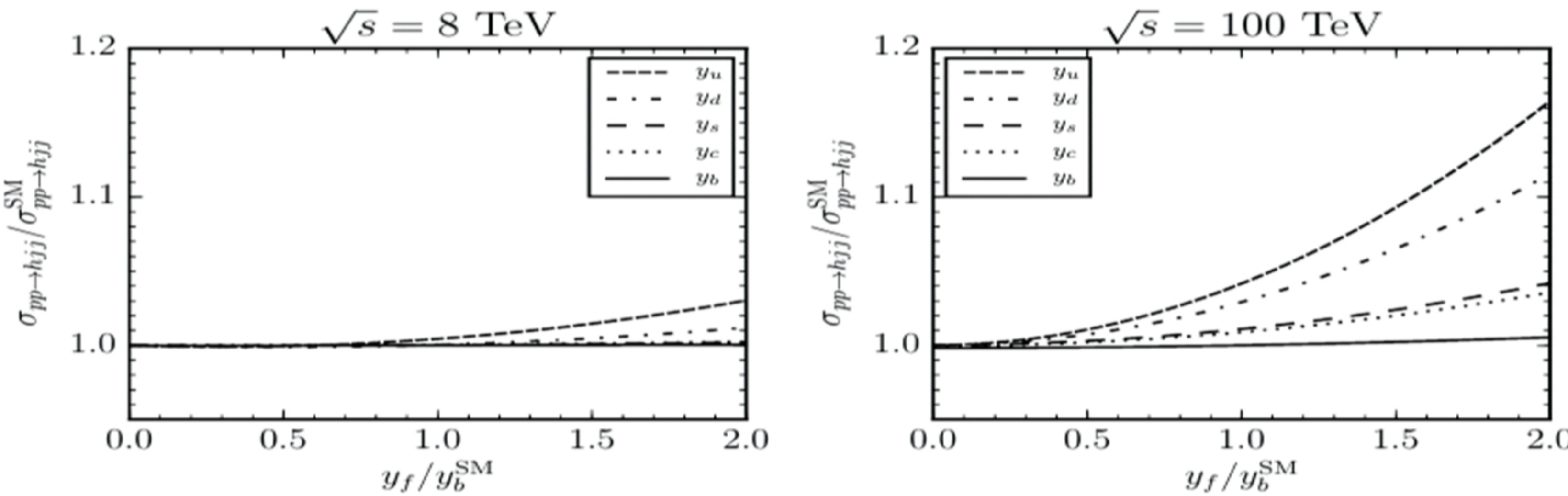
Fit dominated by untagged Higgs decay driven by VBF production.

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

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

New (insufficient) VBF production channel

Enhanced light-quark Yukawas

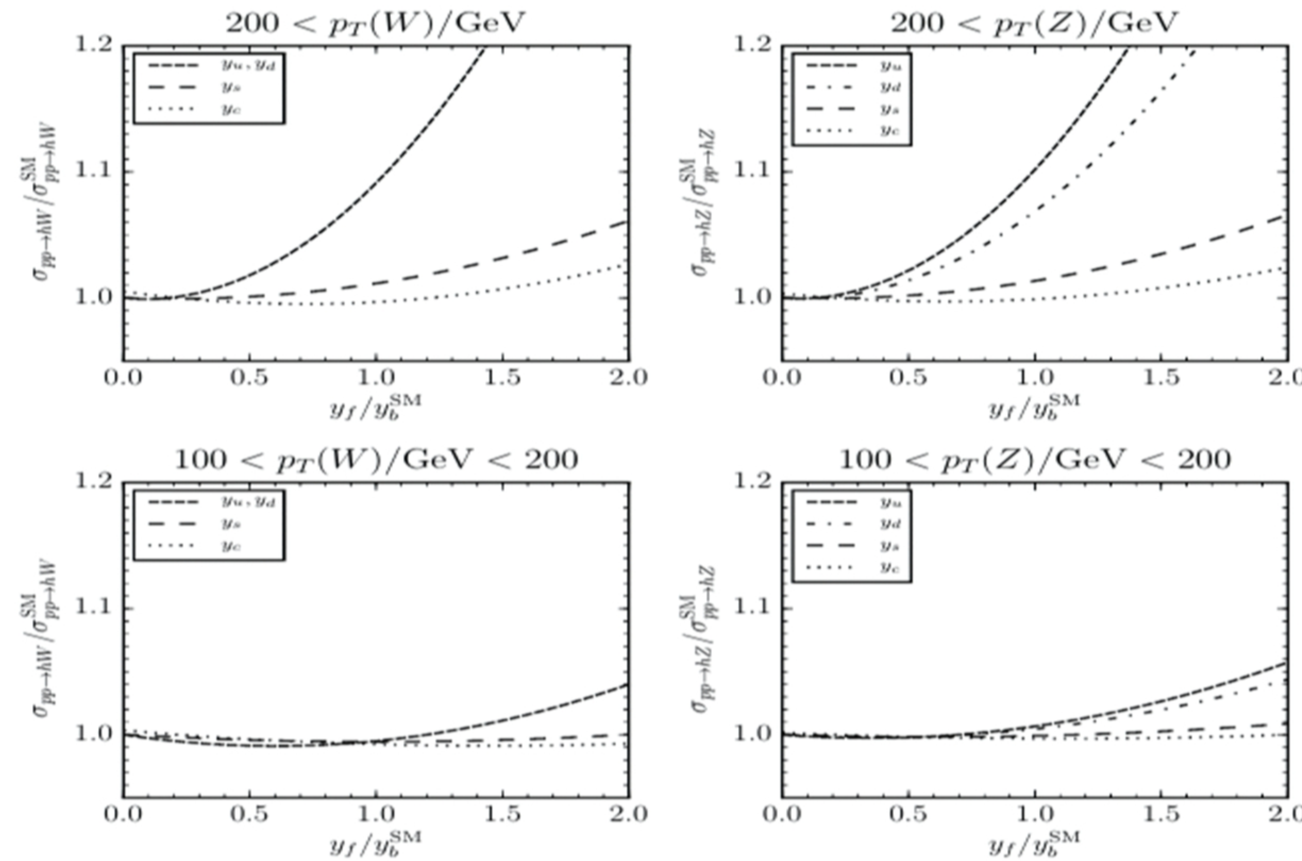


- at LHC8 irrelevant
- at a 100 TeV hadron collider 10% enhancements possible and phenomenologically viable
- if there is ever both a lepton and a hadron collider could be used to cancel *h* decays

  ➜ **y_f sensitivity from production**

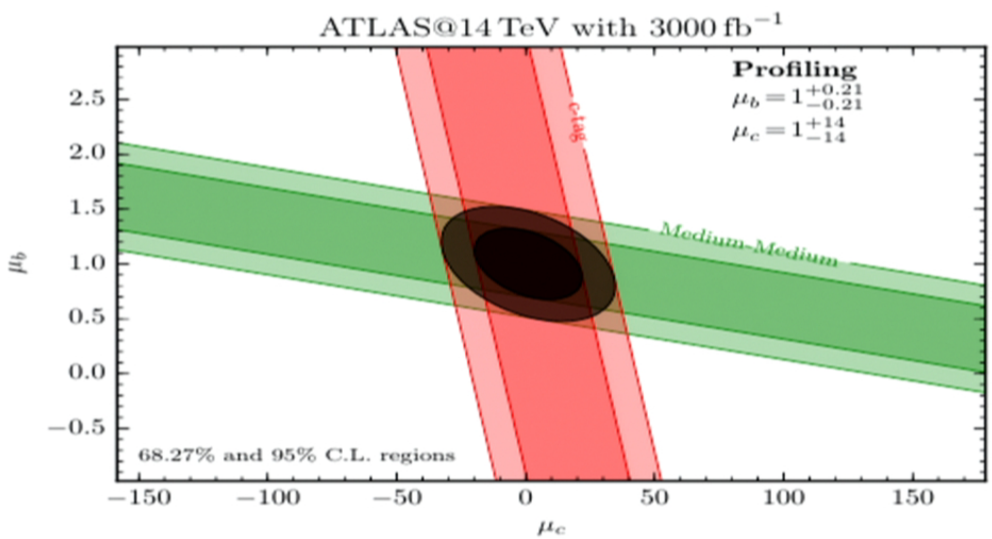
Enhancement of VH production at $\sqrt{s} = 100$ TeV

Enhanced light-quark Yukawas at 100 TeV



μ_c at high-luminocity LHC14 (preliminary)

- focus on ATLAS study at $\sqrt{s} = 14$ TeV with 3000 fb^{-1} [ATL-PHYS-PUB-2014-011]
- study based on med–med working point
- μ_c sensitivity only if two working points
  - ➜ choose c-tag working point
  - ➜ rescale background and signal appropriately



Profiling:

$$\mu_b = 1^{+0.21}_{-0.21} \quad \mu_c = 1^{+14}_{-14}$$

To be compared with previous $\mu_c = 90^{+80}_{-100}$ from recast

\+ could not apply S/B cut
➜ this is conservative

The exclusive window to light-quark Yukawas

Indirect constraints at 95% CL: (varying one(all))

$|\bar{\kappa}_u| = |y_u/y_b^{\rm SM}| < 1.0(1.3)$ $\quad$ $|\bar{\kappa}_d| = |y_d/y_b^{\rm SM}| < 0.9(1.4)$

$|\bar{\kappa}_s| = |y_s/y_b^{\rm SM}| < 0.7(1.4)$ $\quad$ $|\bar{\kappa}_{qq'}| = |y_{qq'}/y_b^{\rm SM}| < 0.6(1.0)$

for $q, q' = u, d, s, c, b$ and $q \neq q'$ [Kagan, Perez, Petriello, Soreq, Stoynev, Zupan 14]

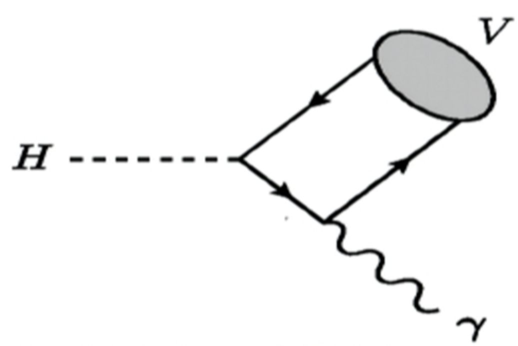
FCNC bound $|\bar{\kappa}_{bs}| = |y_{bs}/y_b^{\rm SM}| < 8 \cdot 10^{-2}$

[Harnik, Kopp, Zupan 12; Blankenburg, Ellis, Isidori 12]

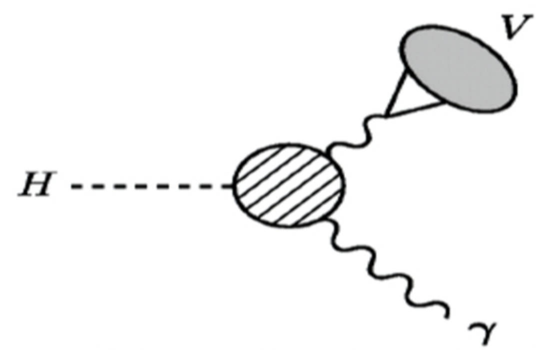
➔large enhancements phenomenologically viable!

- the $h \to J/\psi\gamma$ idea can be generalised to light-quarks/mesons

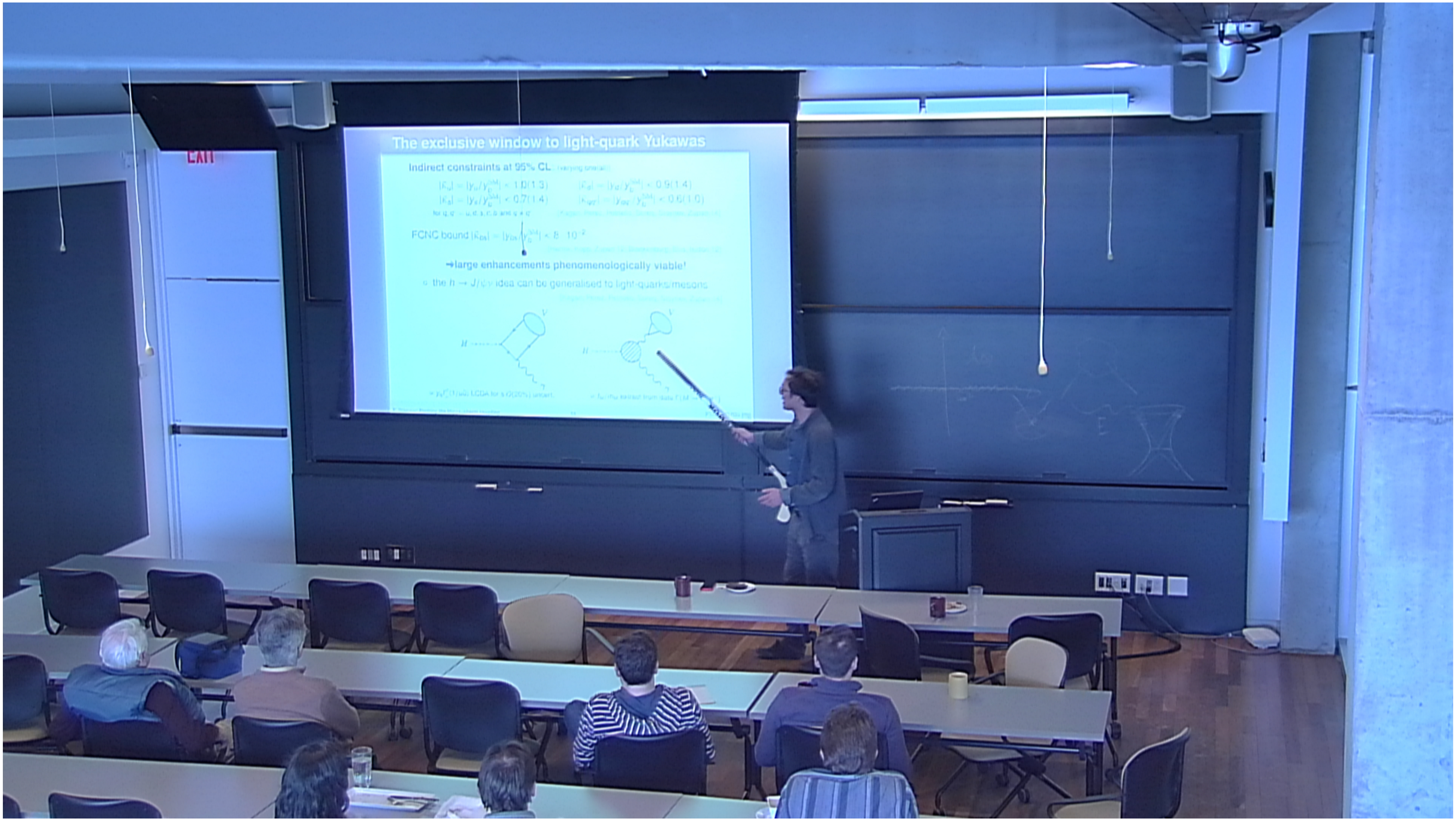
[Kagan, Perez, Petriello, Soreq, Stoynev, Zupan 14]



$\propto y_q f_\perp^\phi \langle 1/u\bar{u} \rangle$ LCDA for s $\mathcal{O}(20\%)$ uncert.



$\propto f_M/m_M$ extract from data $\Gamma(M \to e^+e^-)$



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→large enhancements phenomenologically viable!
the $h \to J/\psi\gamma$ idea can be generalised to light-quarks/mesons

The exclusive window to light-quark Yukawas

Search for:

$h \to \phi\gamma$ ➜ y_s
$h \to \rho\gamma$ ➜ $y_u,\ y_d$
$h \to \omega\gamma$ ➜ $y_u,\ y_d$

- the level of interference between direct and indirect amplitudes depends on M
- $h \to \phi\gamma$ most promising
- QCD backgrounds negligible

$\sqrt{s}$ TeV	# events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\rm stat} > (<)$
14	770	0.56(-1.2)	0.27(-0.81)
33	1380	0.54(-1.2)	0.22(-0.75)
100	5920	0.54(-1.2)	0.13(-0.63)

➜ $6 \times y_s^{\rm SM}$

3σ sensitivity for 3000 fb^{-1}

[Kagan, Perez, Petriello, Soreq, Stoynev, Zupan '14]

Summary & Conclusions

Summary:

- a lot of progress made in extracting y_c both in theo. and exp.
- there are complementary approaches (inclusive, exclusive)
- theoreticians recast of $h \to b\bar{b}$ ➜ $\kappa_c \lesssim 245$
- expect $\Delta\mu_c \simeq 14$ at LHC14 with 3000 fb^{-1}
- sensitivity of the LHC higher than anticipated
- light-quark Yukawas probed in exlusive decays (y_s most promising)

Conclusions:

- **a lot of information hidden in current data**
- **still room for NP in higgs decays**
- **is the Higgs responsible for light-quark masses?**