Probing Light Quarks Yukawa

Yotam Soreq

C. Delaunay, T. Golling, G. Perez and YS (1310.7029)

A. Kagan, G. Perez, F. Petriello, YS, S. Stoynev and J. Zupan (1406.1722)

G. Perez, YS, E. Stamou and K. Tobioka (1503.00290)

INTRODUCTION

Higgs in the Standard Model (SM)

unitarises $V_L V_L \to V_L V_L$ scattering

VEV induce W and Z masses

was tested in a quantitative way:

(1) direct: measuring $h \to WW, ZZ$

(2) indirect: EW precision

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unitarises $ff \to V_L V_L$ scattering
VEV induce fermion masses

much less known:
mainly on 3rd generation

significant progress can be made

OUTLINE

- Introduction
- Recasting and interpolating the current data and establishment of quark Higgs non-universality
- Exclusive Higgs decays
- Future prospects
- Summary

INTRODUCTION

Higgs and Flavor → Yukawa interaction

$$\mathcal{L}_Y = Y^u_{ij}\bar{u}^i_L u^j_R h + Y^d_{ij}\bar{d}^i_L d^j_R h + Y^\ell_{ij}\bar{\ell}^i_L \ell^j_R h + h.c.$$

flavor **dependent** interaction
unlike gauge interactions which are flavor blind

$$y_f^{\mathrm{SM}} = \frac{m_f}{v}$$

- non-universal and hierarchical
- diagonal

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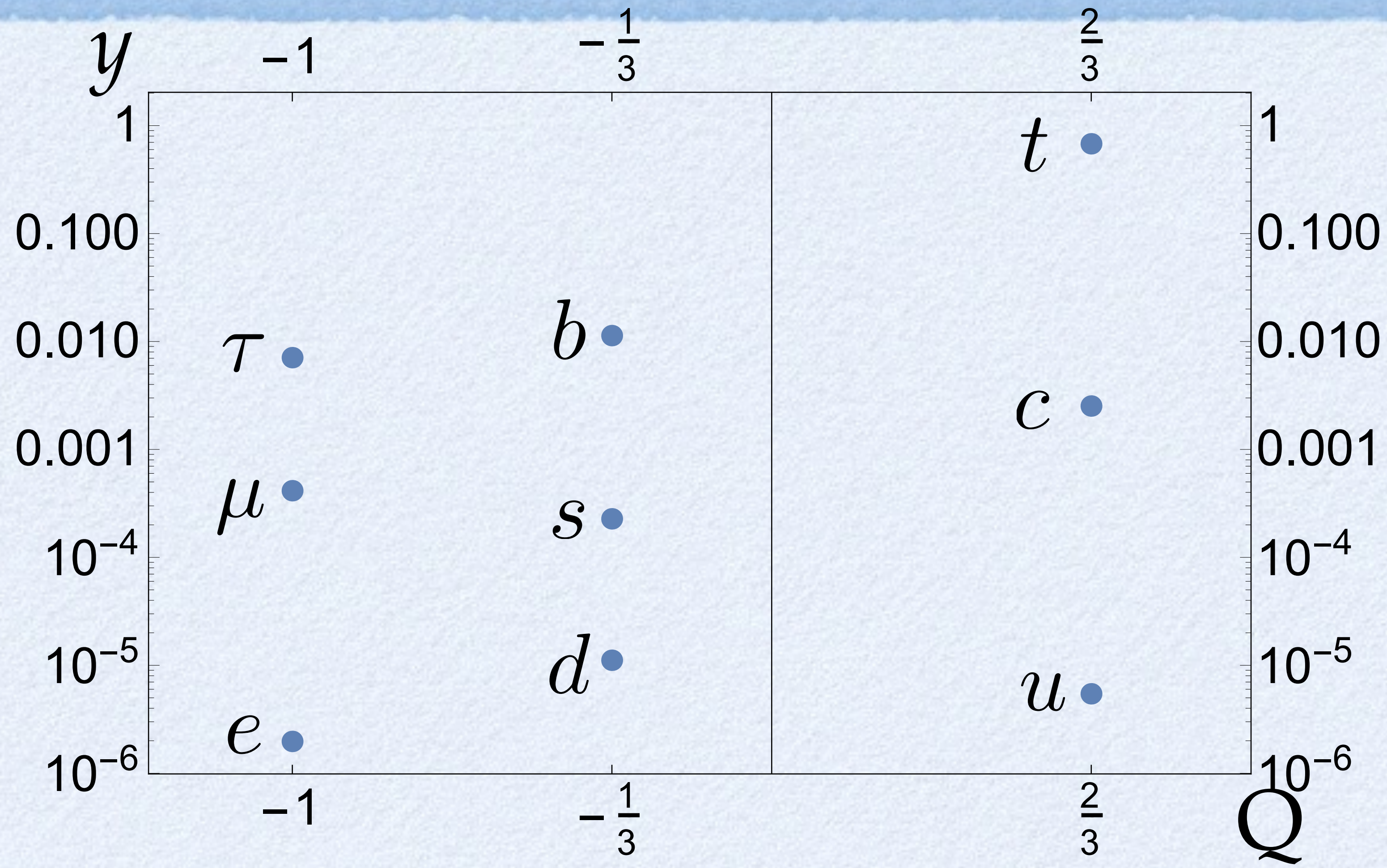
flavor **dependent** interaction
unlike gauge interactions which are flavor blind

$$y_f^{\rm SM} = \frac{m_f}{v}$$

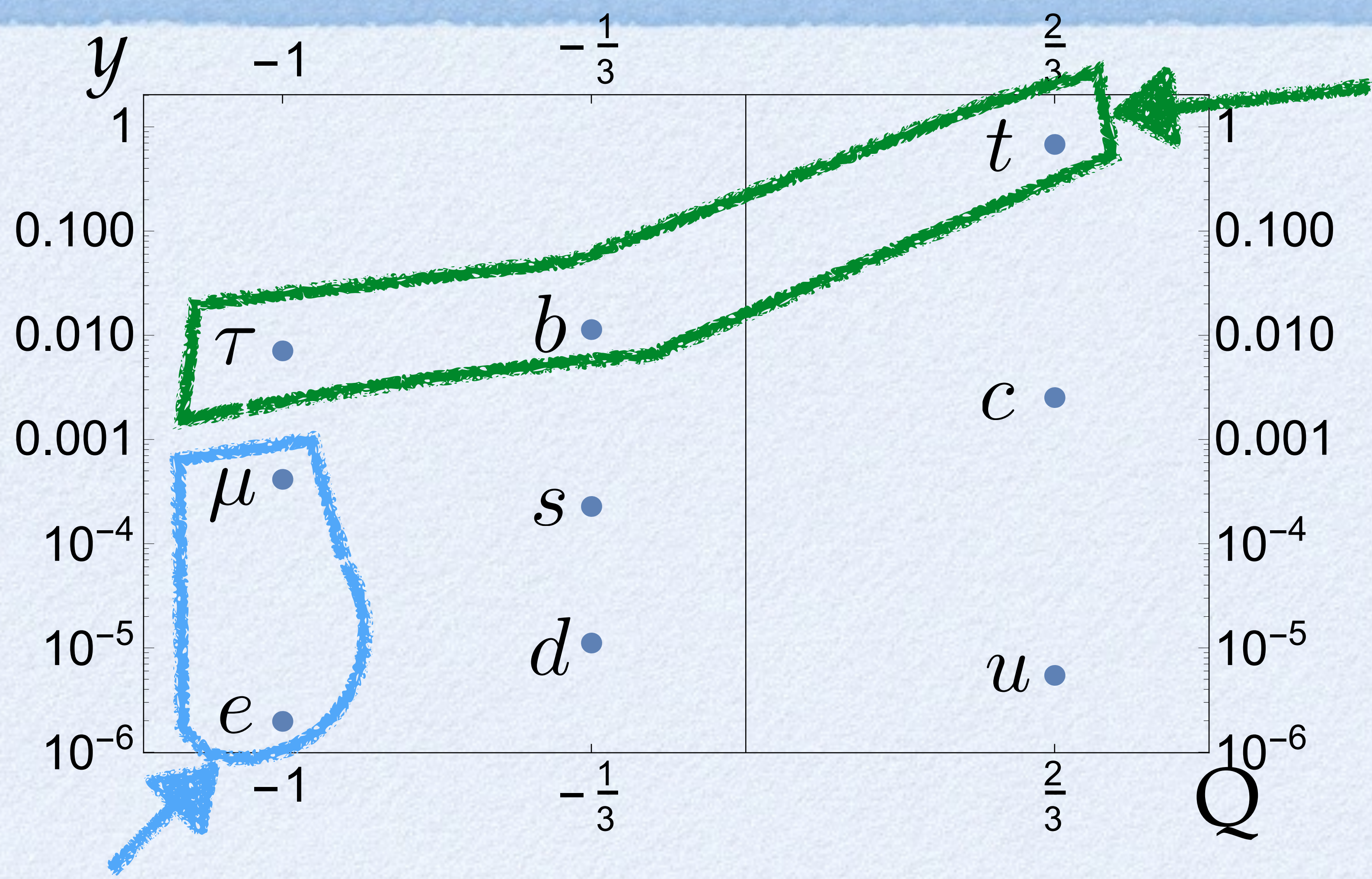
- non-universal and hierarchical
- diagonal

measure: $\mu_{i\,,f} = \frac{\sigma_{i\to h}{\rm BR}_{h\to f}}{\sigma^{\rm SM}_{i\to h}{\rm BR}^{\rm SM}_{h\to f}} = \frac{\kappa_i^2\ \kappa_f^2}{\Gamma_h/\Gamma_h^{\rm SM}}$ $\quad \kappa_X = g_X/g_X^{\rm SM}$

INTRODUCTION



INTRODUCTION



current measurements
(ATLAS+CMS)

$$\mu_\tau = 0.98 \pm 0.22$$

$$\mu_b = 0.71 \pm 0.31$$

$$\mu_{t\bar{t}h} = 2.4 \pm 0.8$$

upper bounds:

CMS
ATLAS $\mu_\mu < 7.4$

$$\mu_e < 4 \times 10^5$$

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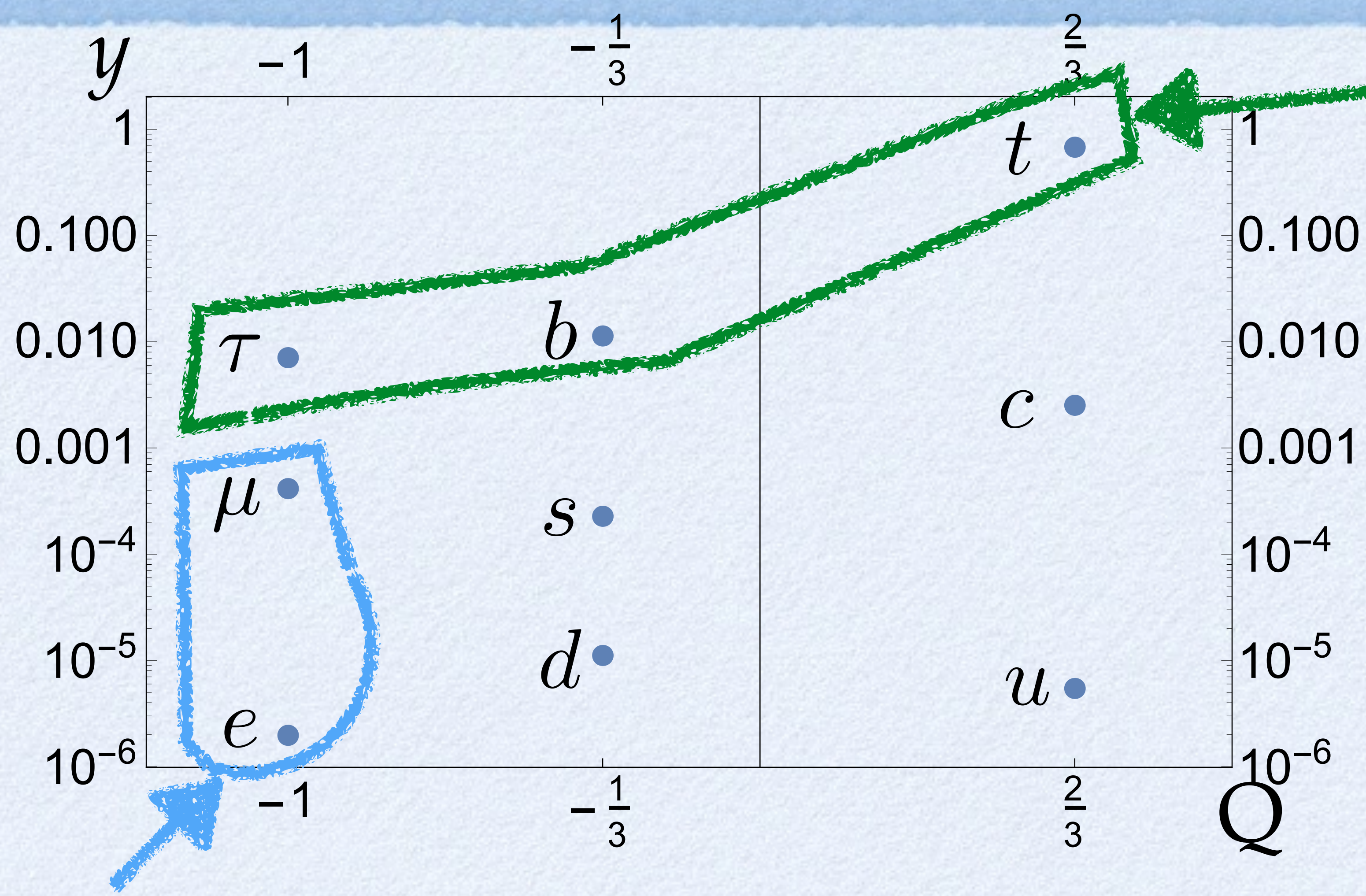

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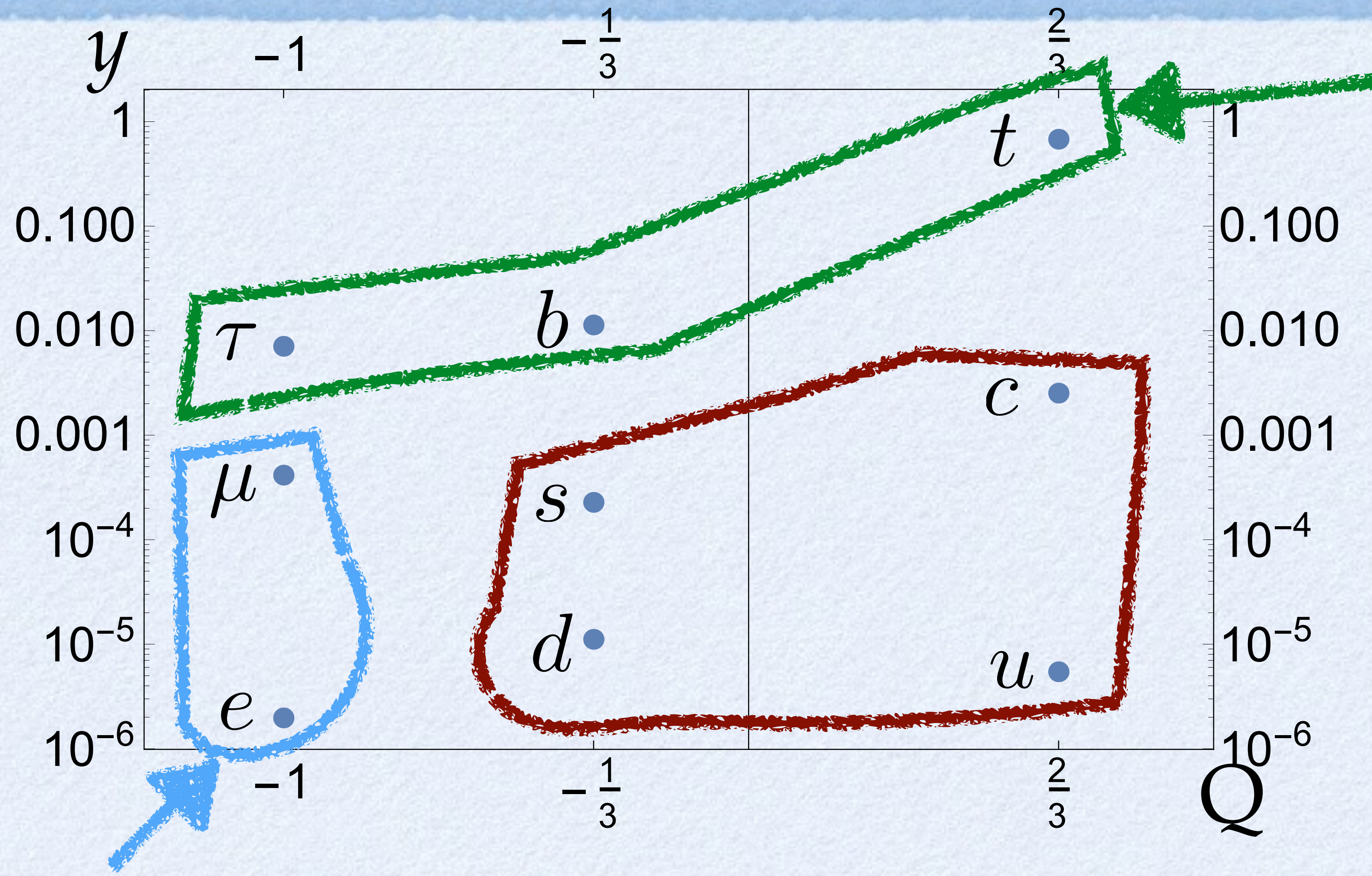
upper bounds:

CMS
ATLAS
$$\mu_\mu < 7.4$$
$$\mu_e < 4 \times 10^5$$

$$\frac{\mu_\mu}{\mu_\tau} < 15 \quad \Rightarrow \quad y_\mu < y_\tau$$

$$\left.\frac{\mu_\mu}{\mu_\tau}\right|_{y_\tau = y_\mu} \approx 280$$

INTRODUCTION



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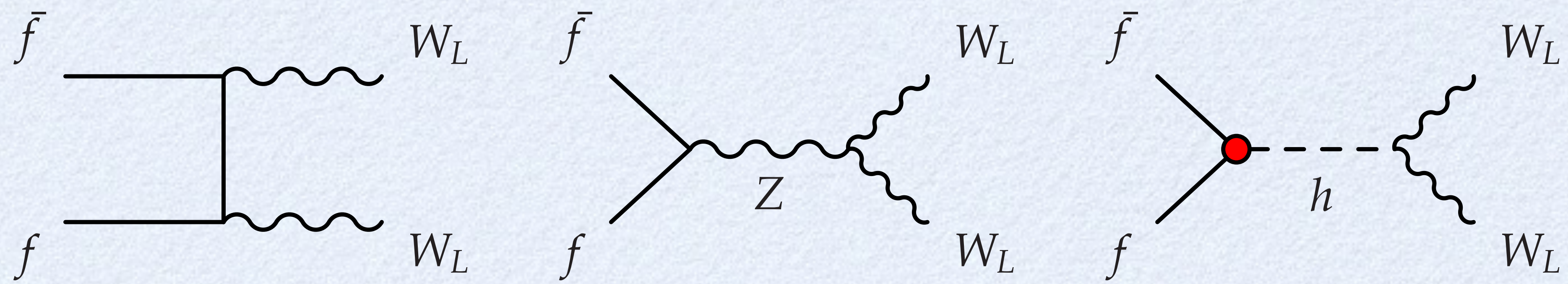
upper bounds:

Does the Higgs couple like the mass to light quarks?

INTRODUCTION

Higgs does not couple at all to light fermions:

(masses from different a different sector)



⇨ unitarity bounds (cut-off)

INTRODUCTION

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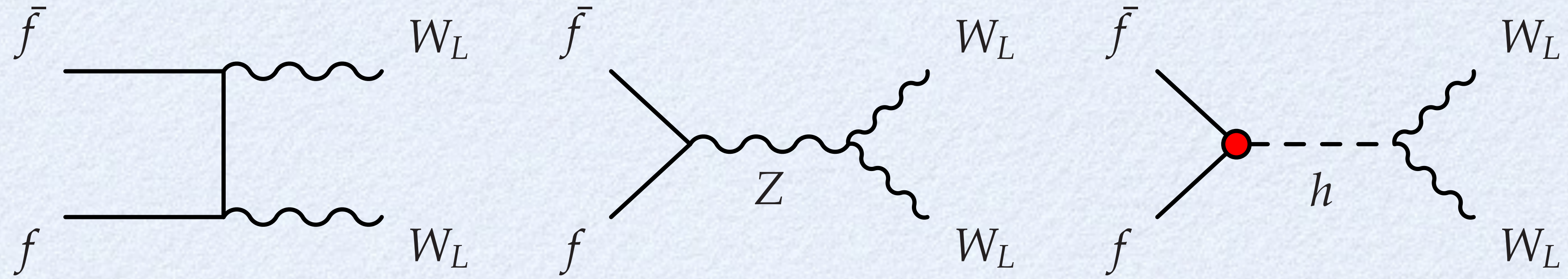

unitarity bounds (cut-off)

$$q\bar{q} \to V_L V_L \;:\; \sqrt{s} \lesssim \frac{8\pi v^2}{\sqrt{6} m_{b,c,s,d,u}} \approx 200,\ 1\times10^3,\ 1\times10^4,\ 2\times10^5,\ 5\times10^5\ \text{TeV}$$

Chivukula, Christensen, Coleppa, Simmons hep-ph/0702281
Marciano, Valencia, Willenbrock 89'
Applequist, Channowitz 87'

INTRODUCTION

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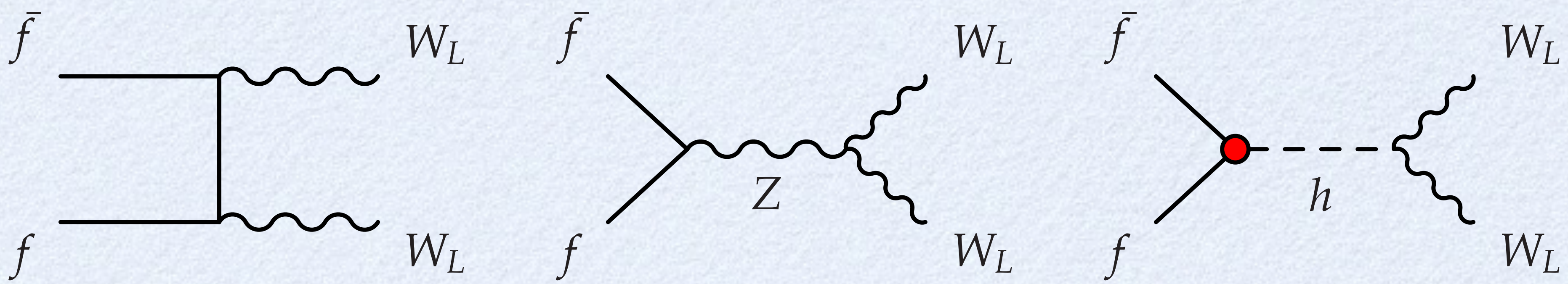

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Chivukula, Christensen, Coleppa, Simmons hep-ph/0702281
Marciano, Valencia, Willenbrock 89'
Applequist, Channowitz 87'

$$q\bar{q} \to n\, V_L \; : \; \sqrt{s} \lesssim 23,\ 31,\ 52,\ 77,\ 84 \ \text{TeV}$$

Maltoni, Niczyporuk, Willenbrock hep-ph/0006358
Dicus, He hep-ph/0409131

Probing light quarks

Challenges for probing light-quarks (u,d,s,c) Yukawa:

- The SM-Higgs branching ratios are tiny.
- Huge QCD background.
- Flavor tagging - only charm is possible at LHC.

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Two paths to probe light quarks Yukawa

inclusive: - b/c-tagging only for c at the LHC

Delaunay, Golling, Perez, YS 1310.7029
Perez, YS, Stamou, Tobioka 1503.00290
ATLAS-CONF-2013-068
ATLAS-CONF-2014-063
ATL-PHYS-PUB-2015-001

exclusive: - $h \to M\gamma$, MW, MZ (M=vector meson) possible for u,d,s,c

Bodwin, Peteriello, Stoynev, Velasco 1306.5770
Kagan, Perez, Petriello, YS, Stoynev, Zupan 1406.1722
Bodwin, Chung, Ee, Lee, Petriello 1407.6695
Perez, YS, Stamou, Tobioka 1503.00290
ATLAS: 1501.03276

What do we know from the current data? Quark non-university establishment

C. Delaunay, T. Golling, G. Perez and YS (1310.7029)

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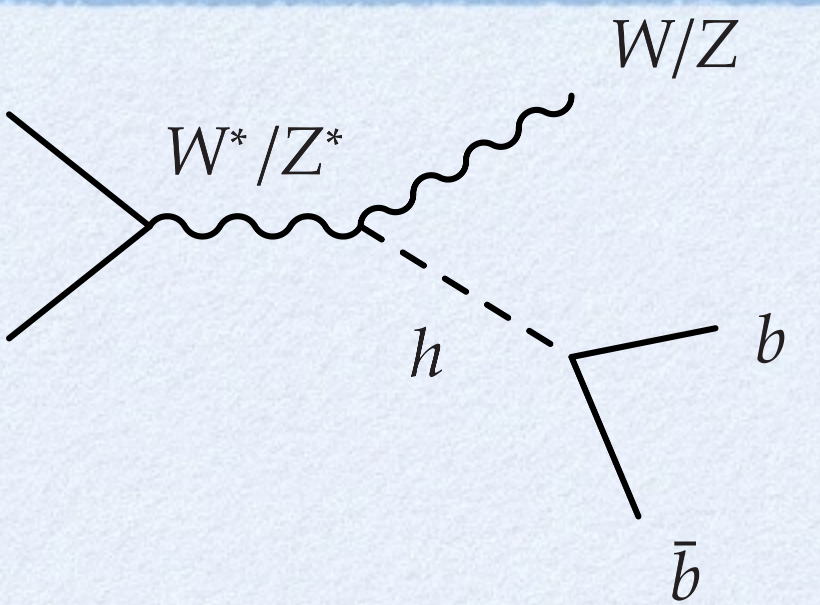
Information on the up sector Yukawa

- On the **charm** Yukawa:
  - Direct constraint: recast *Vh(bb),* (2 working points)
  - Interpreting of the recent ATLAS $h \to J/\psi\gamma$ bound
  - Direct bound on the total Higgs width
- On the **top** Yukawa: direct information from *tth*
- Global Higgs fit - both **top** and **charm**

Recasting of $h \to bb$

Vh(bb) search:



the two *b* are tagged, with some acceptance to charm

Recasting of h→bb

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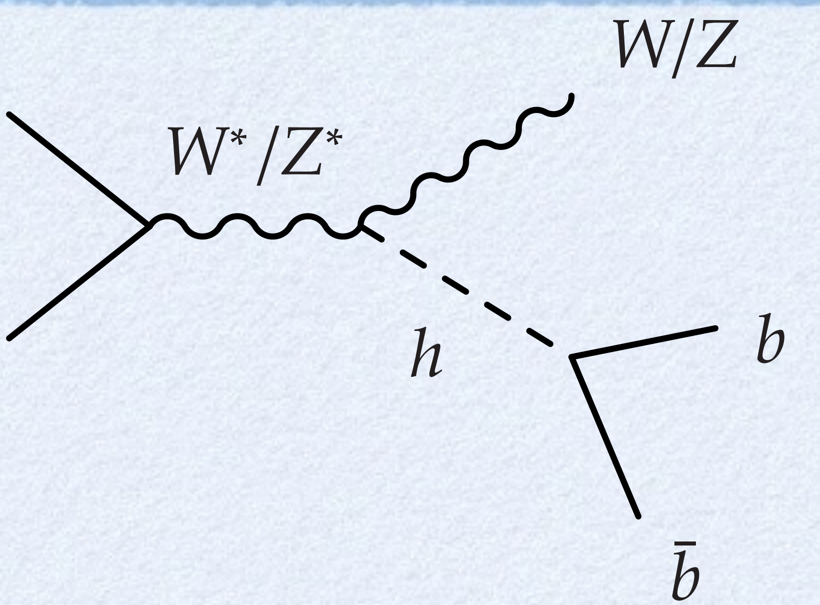


the two *b* are tagged, with some acceptance to charm

$$\frac{N^{Vh}_{\text{observed}}}{N^{Vh}_{\text{expected}}} = \frac{\sigma \text{BR}_{b\bar{b}} \epsilon_{b_1} \epsilon_{b_2} + \sigma \text{BR}_{c\bar{c}} \epsilon_{c_1} \epsilon_{c_2}}{\sigma_{\text{SM}} \text{BR}^{\text{SM}}_{b\bar{b}} \epsilon_{b_1} \epsilon_{b_2}}$$

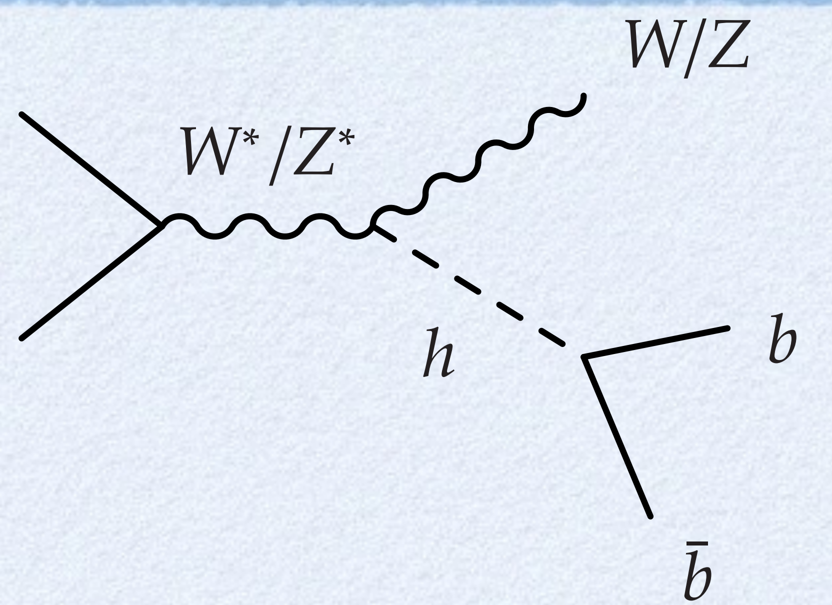
$$= \mu_b + \frac{\sigma\, \text{BR}^{\text{SM}}_{c\bar{c}}\ \epsilon_{c_1} \epsilon_{c_2}}{\sigma\, \text{BR}^{\text{SM}}_{b\bar{b}}\ \epsilon_{b_1} \epsilon_{b_2}} \mu_c$$

$$= \mu_b + 0.05\, \epsilon^2_{c/b}\, \mu_c$$

tagging efficiencies

Recasting of H→bb

Vh(bb) search:



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$$= \mu_b + 0.05\,\epsilon^2_{c/b}\,\mu_c$$

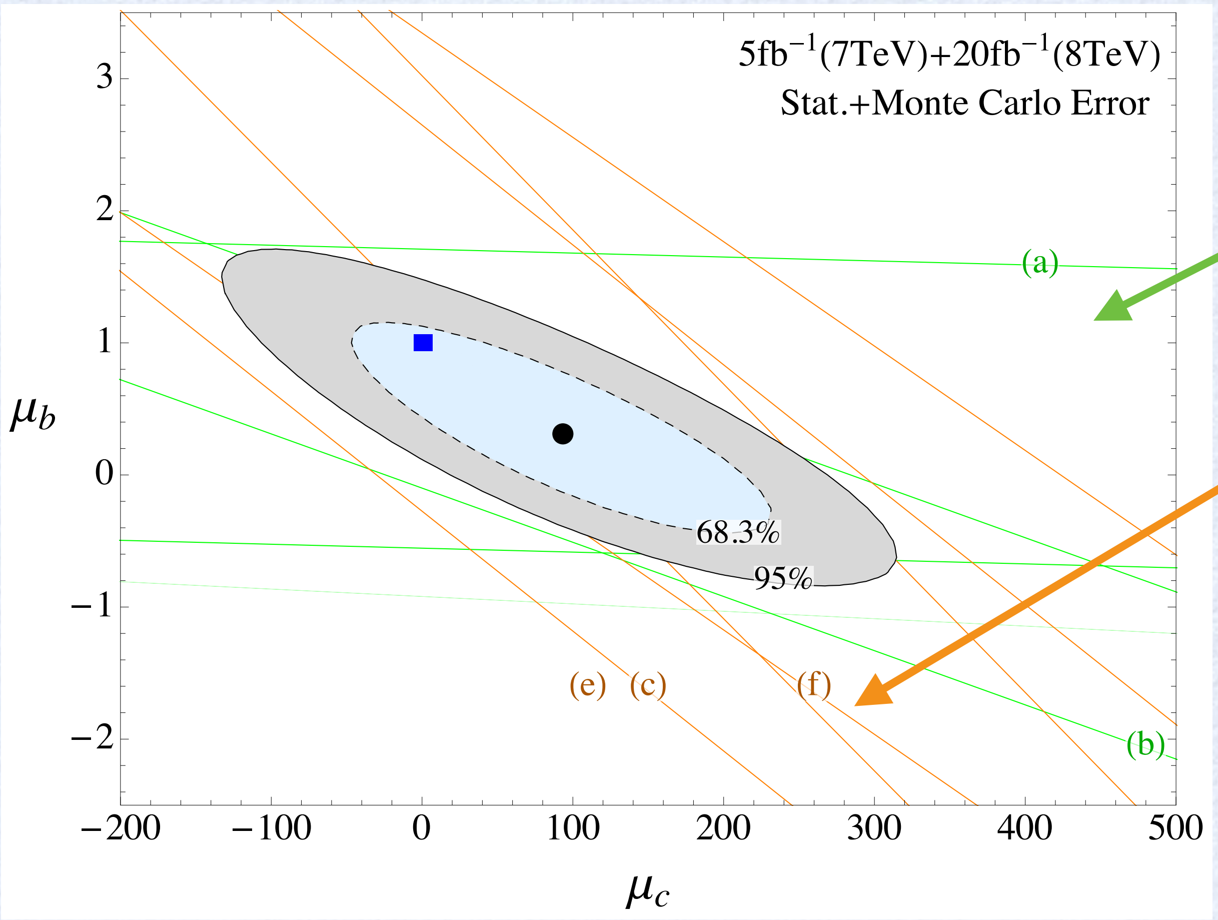
tagging efficiencies

Use several "charm-tagging" working points

Direct constrain the charm signal strength

Recasting of H→bb

$$\mu_b \to \mu_b + 0.05\,\epsilon^2_{c/b}\mu_c$$



	1st tag	2nd tag	$\epsilon^2_{c/b}$
(a) ATLAS	Med	Med	0.082
(b) ATLAS	Tight	Tight	0.059
(c) CMS	Med1	Med1	0.18
(d) CMS	Med2	Loose	0.19
(e) CMS	Med1	Loose	0.23
(f) CMS	Med3	Loose	0.16

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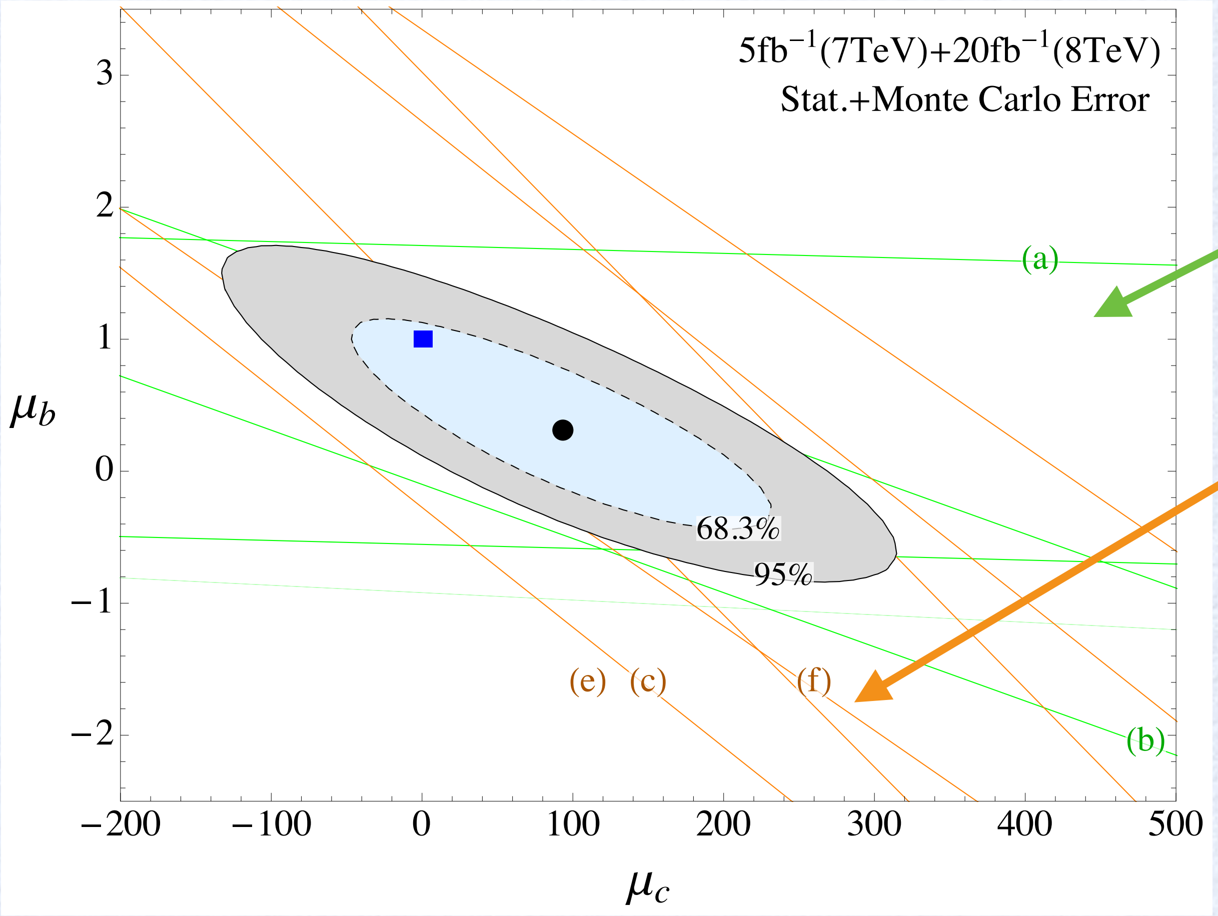

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$$\mu_c = 95^{+90(175)}_{-95(180)}$$

μ_b is profiled @ 68.3(95)% CL

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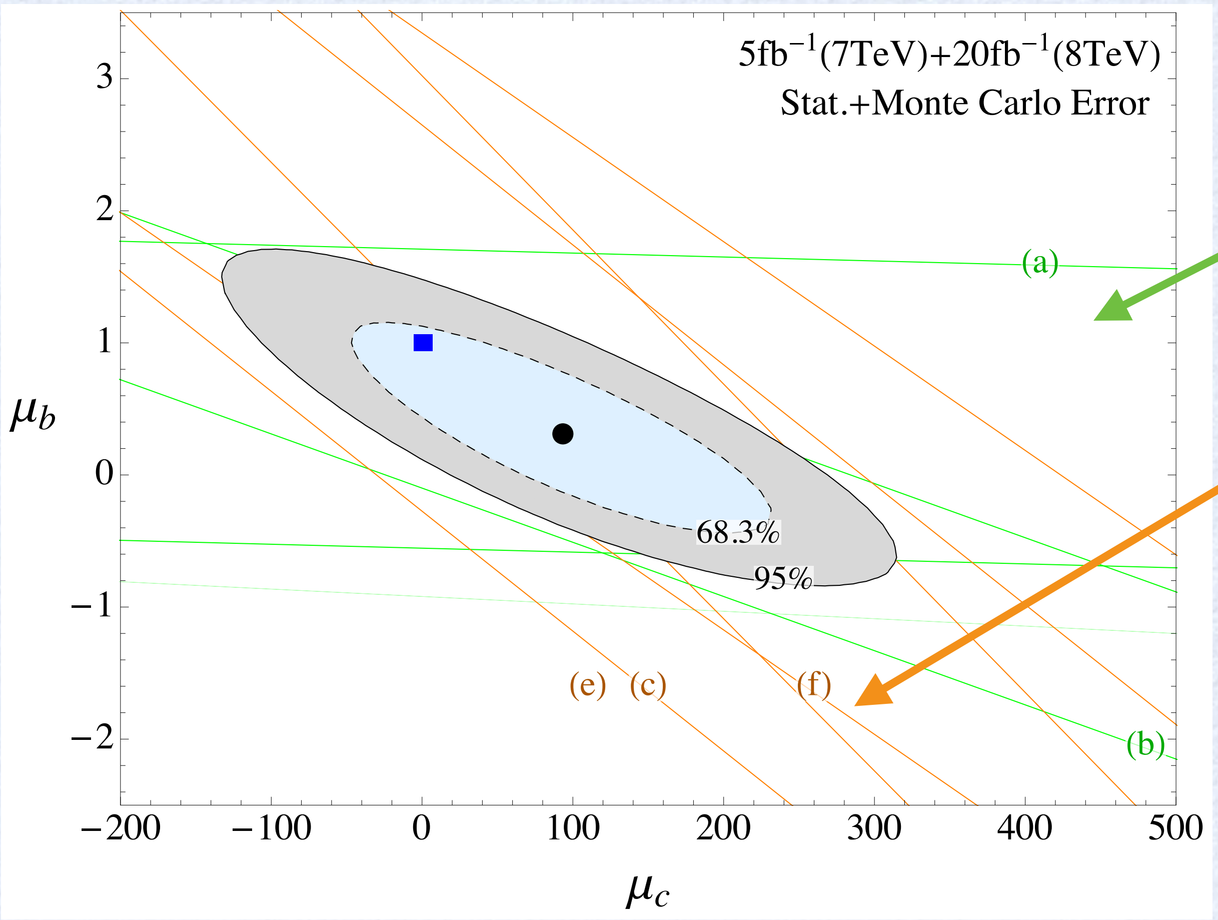

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Direct constrain the charm signal strength

estimation by using *c*-tagging on 8TeV data: $\Delta\mu_c \simeq 50\,(107)$

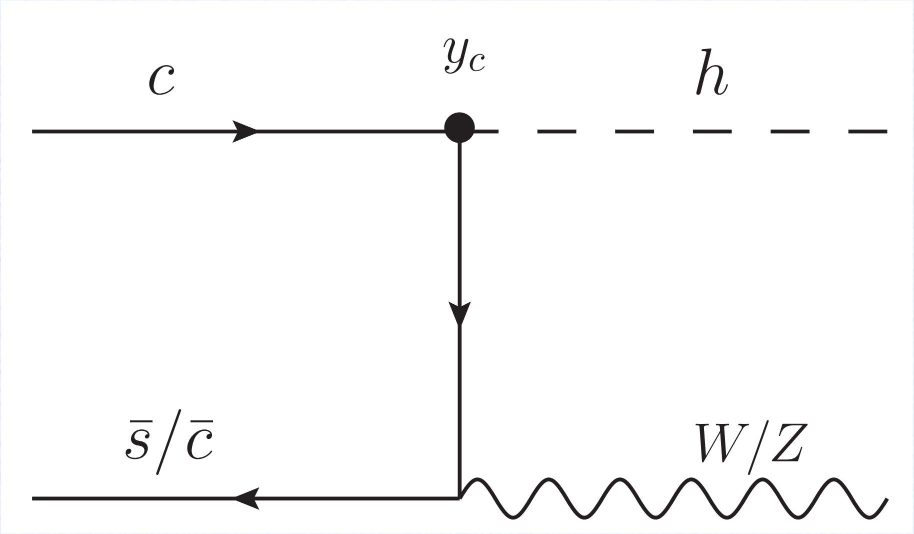
$\epsilon_b = 13\,\%$, $\epsilon_c = 19\,\%$

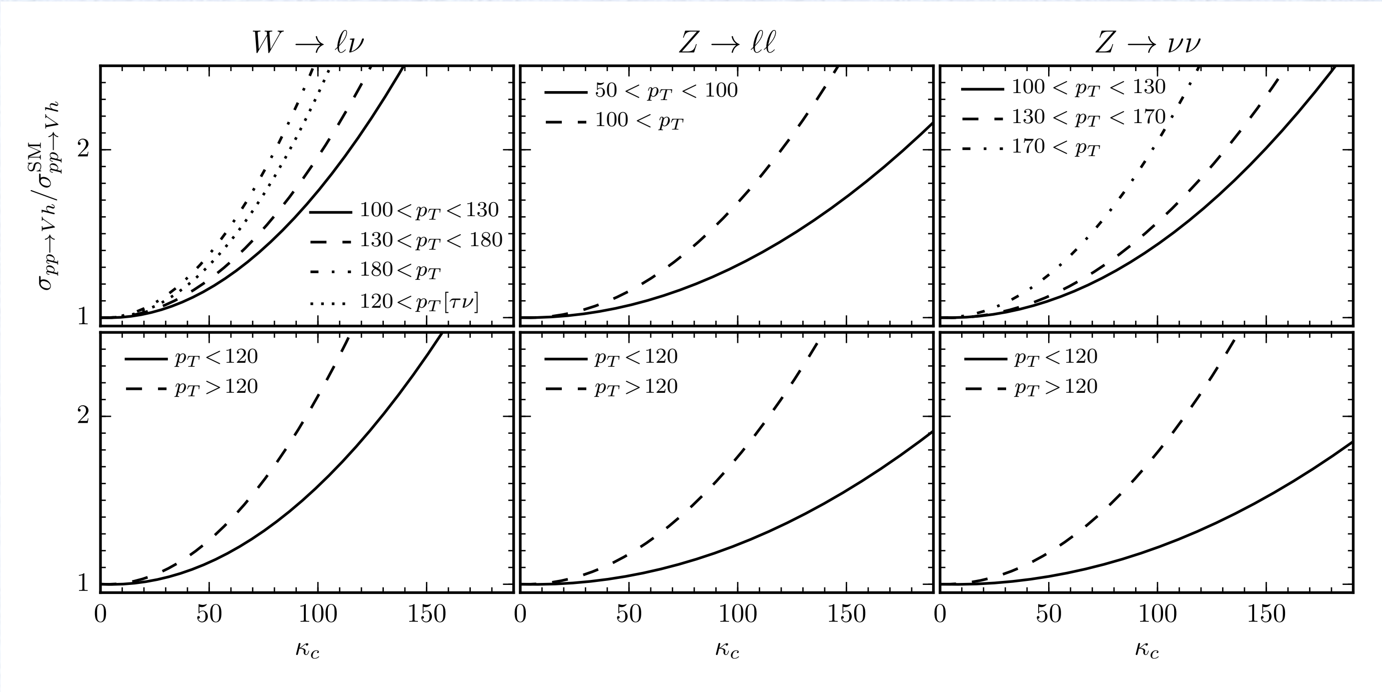
ATL-PHYS-PUB-2015-001

Recasting of $h \to bb$

assuming SM Higgs production → $\mu_c \lesssim 30$ → cannot constrain y_c

$\kappa_c = y_c / y_c^{\rm SM} \gtrsim 50$ non SM Vh production:





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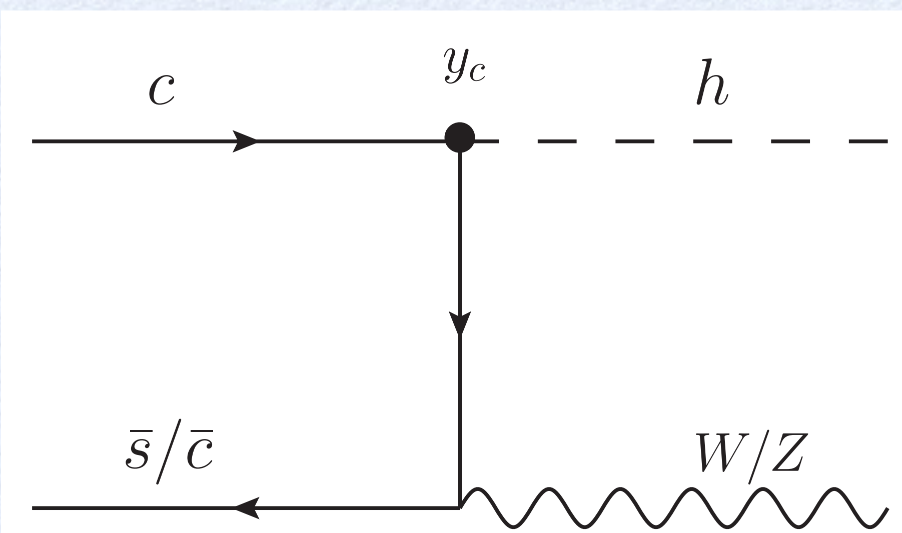
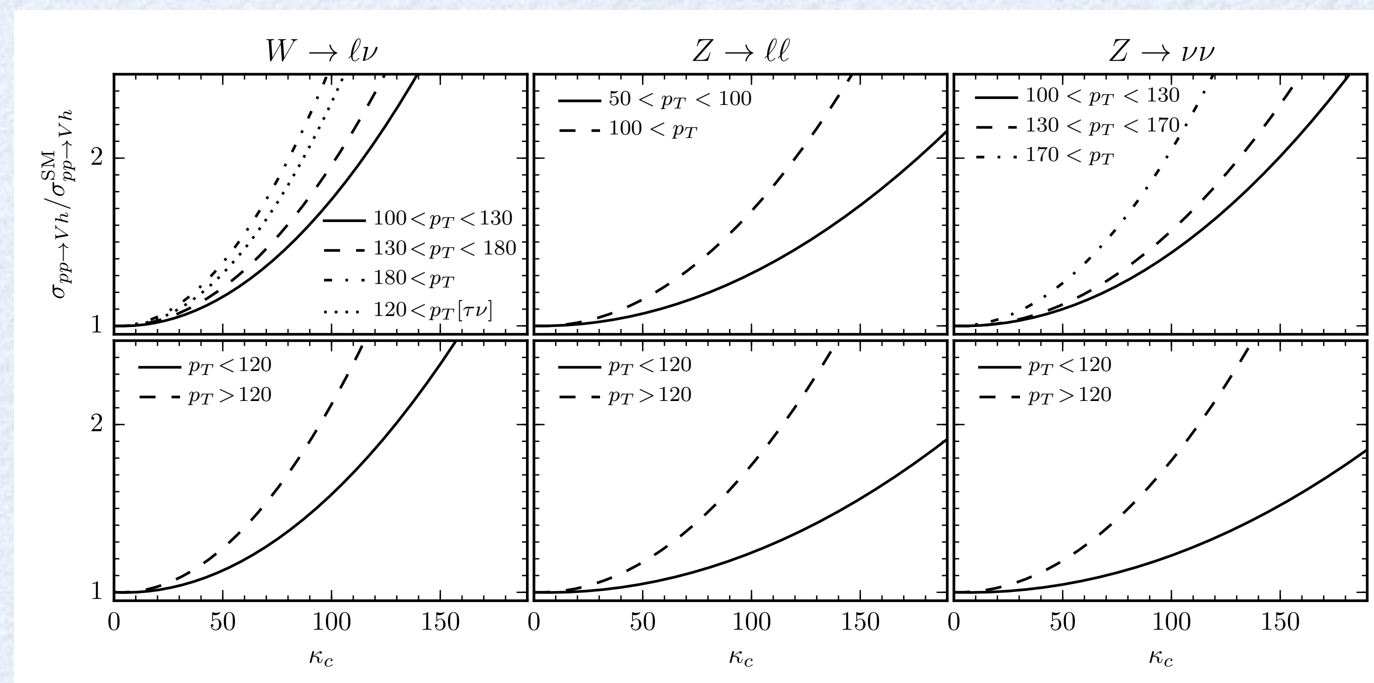
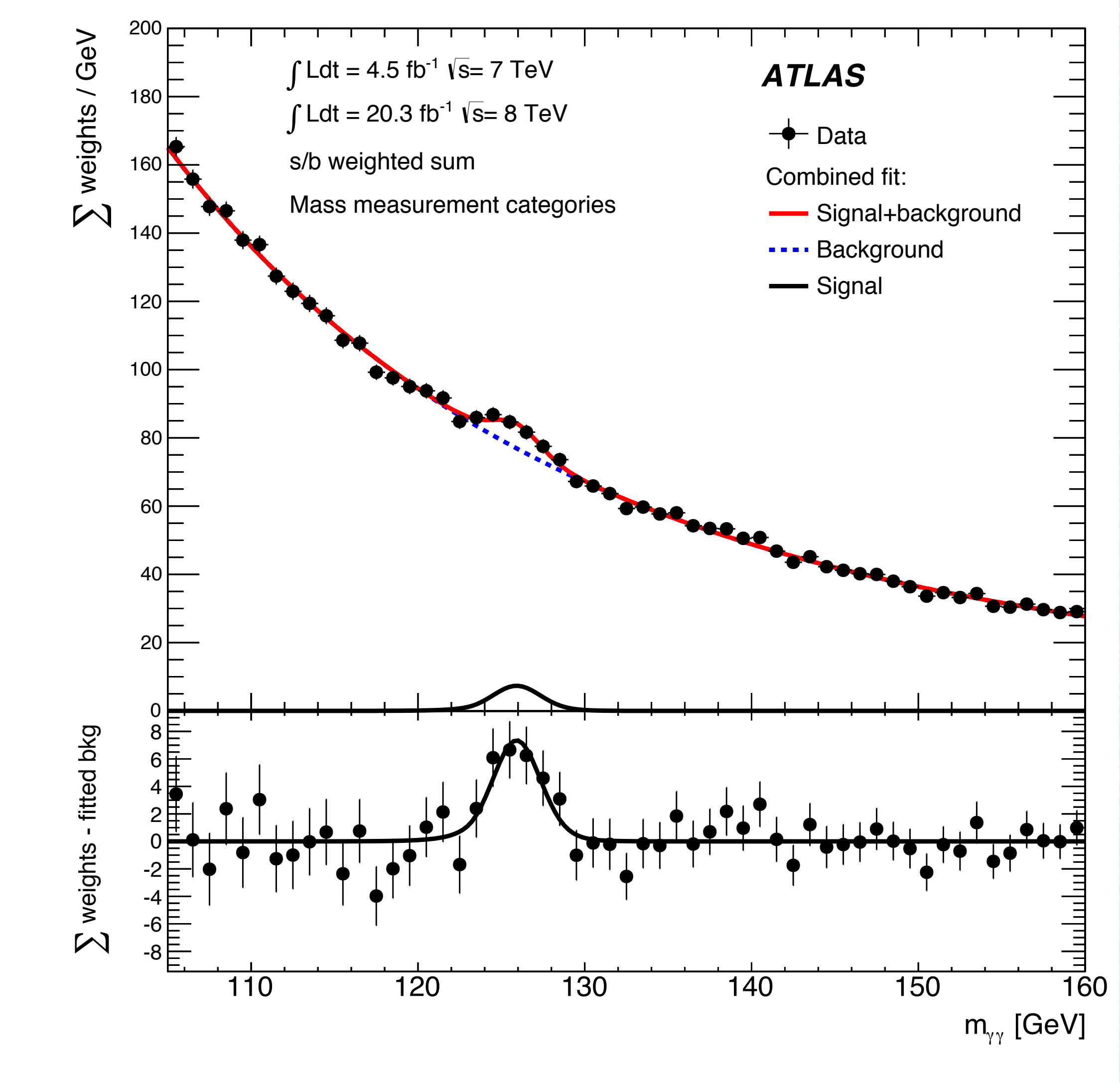




$\Rightarrow$ $\kappa_c \equiv y_c / y_c^{\rm SM} \lesssim 234$ (no runway)

Bound the total width



$$\Gamma_{\rm total} < \begin{cases} 2.4,\ 5.0\,\text{GeV}\ (\text{CMS, ATLAS}) & h \to \gamma\gamma \\ 3.4,\ 2.6\,\text{GeV}\ (\text{CMS, ATLAS}) & h \to 4\ell \\ 1.7\,\text{GeV}\ (\text{CMS}) & \text{combined } h \to \gamma\gamma,\, 4\ell \end{cases}$$

$$\Gamma^{\rm SM}_{\rm total} \simeq 4\,\text{MeV}$$

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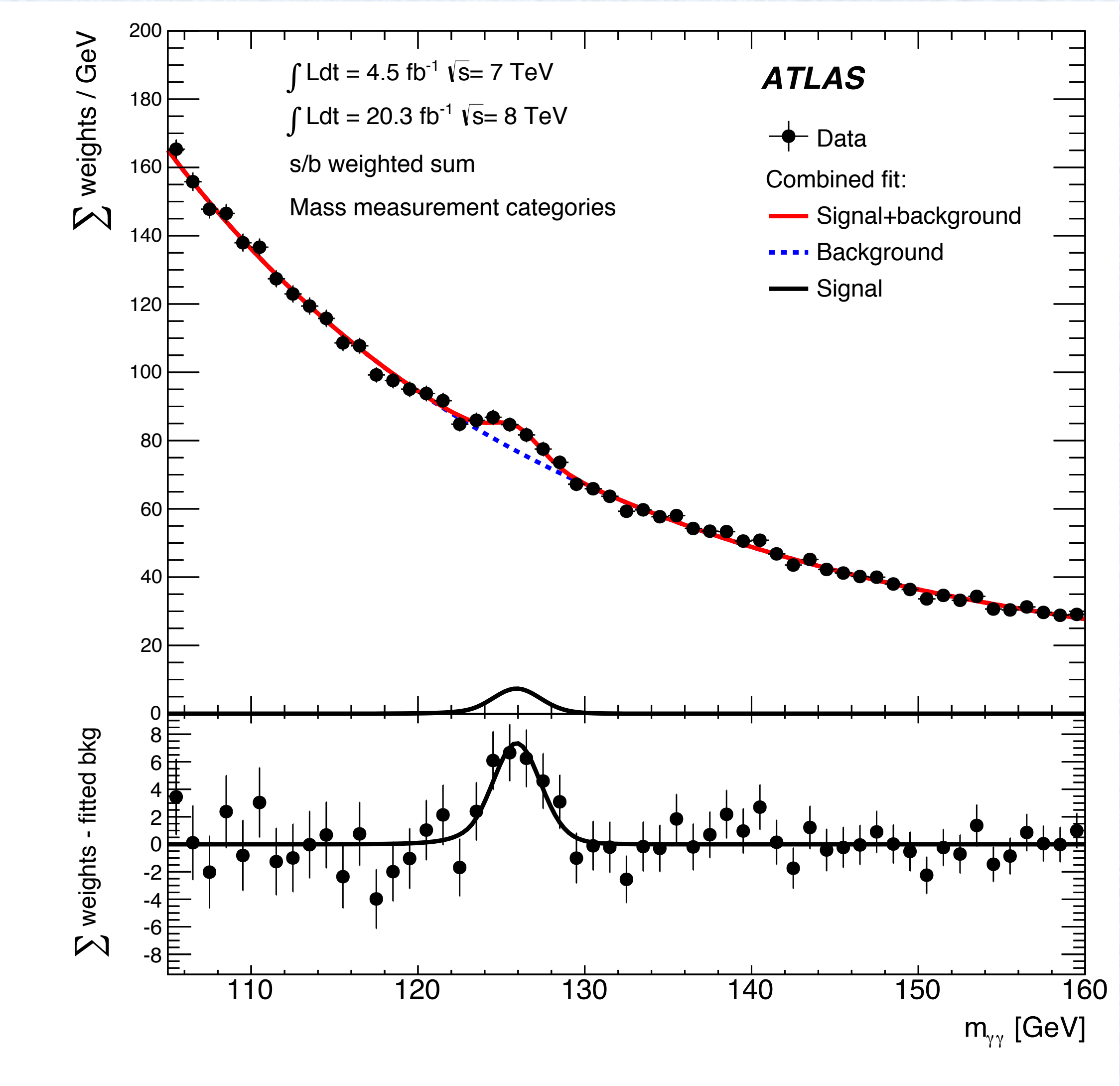

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$$\Gamma^{\rm SM}_{\rm total} \simeq 4\,{\rm MeV}$$

$$\kappa_c < 120\,,\ \ 150$$

assume that the Higgs width is saturated by $h \to cc$

Interpretation of ATLAS $h \to J/\psi\gamma$ bound

Recent ATLAS $h \to J/\psi\gamma$ (1501.03276) bound

$$\sigma(pp \to h)\mathrm{BR}_{h \to J/\psi\gamma} < 33\,\mathrm{fb}$$

The partial width: $\Gamma_{h \to J/\psi\gamma} = 1.42\,(\kappa_\gamma - 0.087\kappa_c)^2 \times 10^{-8}\,\mathrm{GeV}$

Bodwin, Peteriello, Stoynev, Velasco 1306.5770
Bodwin, Chung, Ee, Lee, Petriello 1407.6695

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Getting rid of production:

$$\mathcal{R}_{J/\psi,Z} = \frac{\sigma(pp\to h)\times \mathrm{BR}_{h\to J/\psi\gamma}}{\sigma(pp\to h)\times \mathrm{BR}_{h\to ZZ^*\to 4\ell}} = \frac{\Gamma_{h\to J/\psi\gamma}}{\Gamma_{h\to ZZ^*\to 4\ell}} = 2.79\frac{(\kappa_\gamma - 0.087\kappa_c)^2}{\kappa_V^2}\times 10^{-2}$$

$$\mathcal{R}_{J/\psi,Z} = \frac{33\,\mathrm{fb}}{\mu_{ZZ^*}\sigma^{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{h\to ZZ^*\to 4\ell}} < 9.32$$

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

LEP: $k_V = 1.08 \pm 0.07$

Falkowski, Riva 1303.1812

Constraining up-Yukawa universality

ATLAS+CMS *tth*: $\mu_{t\bar{t}h} = 2.4 \pm 0.8$

$$\kappa_t \equiv \frac{y_t}{y_t^{\rm SM}} > 0.9\sqrt{\frac{\rm BR^{SM}_{finals}}{\rm BR_{finals}}} > 0.9 \quad \text{or} \quad y_t > 250 y_c^{\rm SM}$$

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Combining with the bounds on the y_c:

$$\frac{y_c}{y_c^{\rm SM}} \lesssim 234\,,\;\; 120(150)\,,\;\; 220\,, 6.2$$

Vh(bb) recast

Higgs total width

$h \to J/\psi\gamma$

(assuming $h \to \gamma\gamma$ not much larger than SM)

global analysis

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Vh(bb) recast → 234

Higgs total width → 120(150)

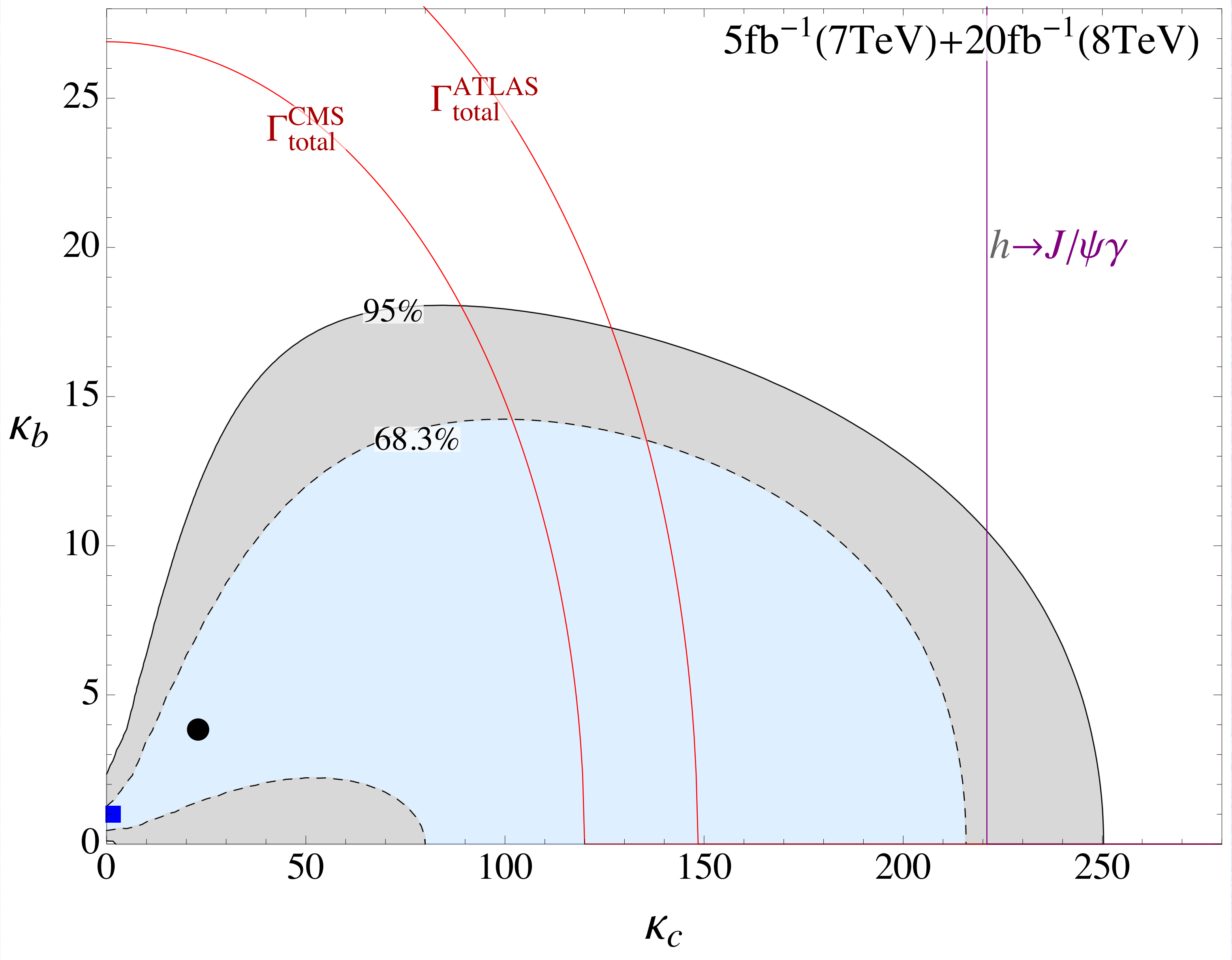
$h \to J/\psi\gamma$ → 220

global analysis → 6.2

(assuming $h \to \gamma\gamma$ not much larger than SM)

$$y_c < y_t$$

Combining all constraints

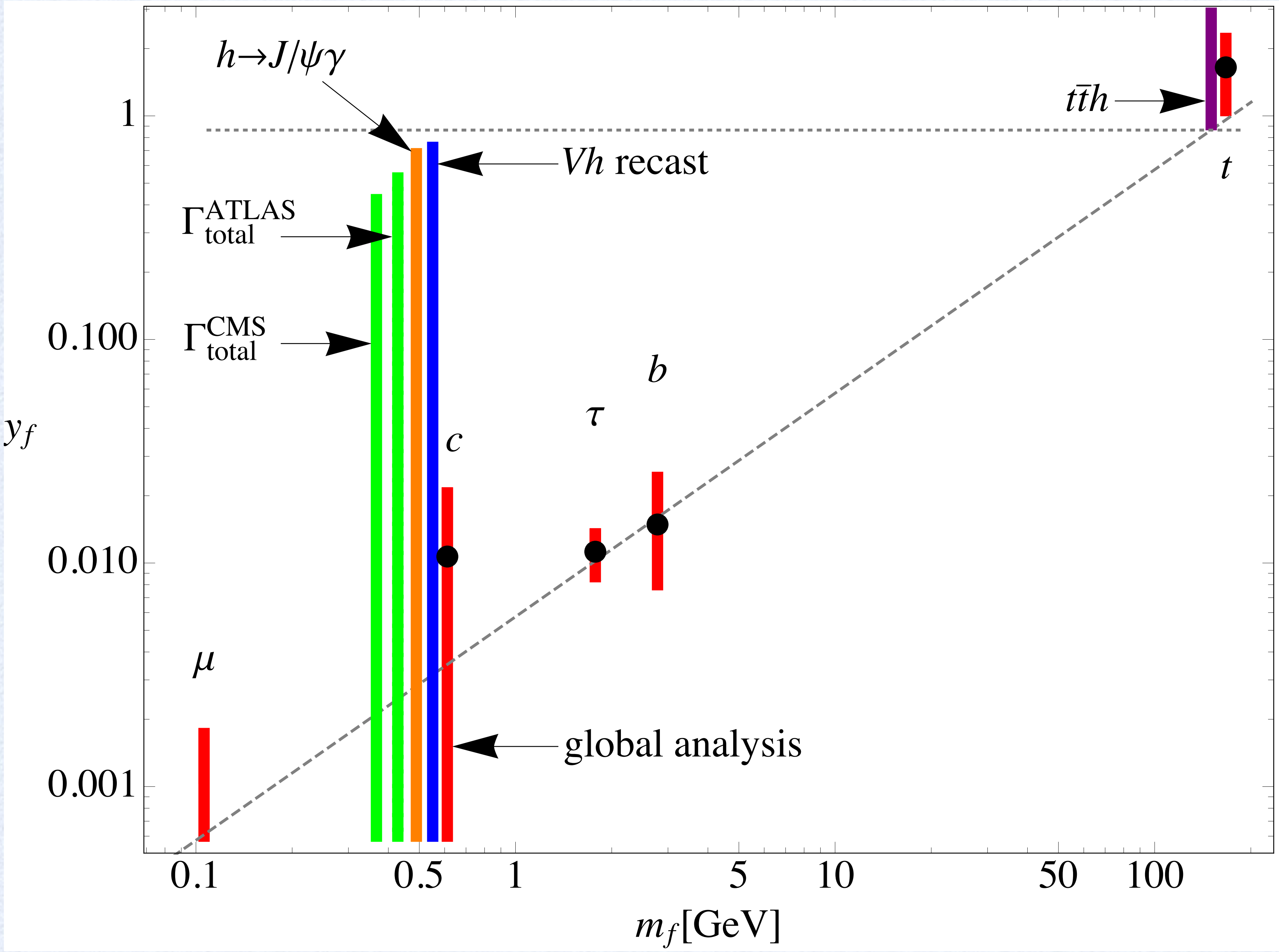


best fit point $[\kappa_b,\kappa_c]$=[0.9,2.9]

$\kappa_b(@2\boldsymbol{\sigma})$=[0.5,1.4]

$\kappa_c(@2\boldsymbol{\sigma})$=[0,6.2]

Combining all constraints



An exclusive window onto Higgs Yukawa couplings

A. Kagan, G. Perez, F. Petriello, YS, S. Stoynev and J. Zupan (1406.1722)

Bounds on light quark Yukawa

Indirect bounds on light-quarks Yukawa from current Higgs data

diagonal:

$$y_u/y_b^{\rm SM} < 1.0(1.3) \qquad y_d/y_b^{\rm SM} < 0.9(1.4)$$

$$y_s/y_b^{\rm SM} < 0.7(1.4) \qquad y_c/y_b^{\rm SM} < 0.7(1.4)$$

@ 95% CL

only the corresponding Yukawa is varied

all Higgs couplings are allowed to vary

off-diagonal: $y_{qq'}/y_b^{\rm SM} < 0.6(1) \quad q, q' \in u, d, s, c, b \quad q \neq q'$

FCNC not robust bound $y_{bs}/y_b^{\rm SM} < 8 \times 10^{-2}$

Harnik, Kopp, Zupan 1209.1397
Blankenburg, Ellis, Isidori 1202.5704

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Harnik, Kopp, Zupan 1209.1397
Blankenburg, Ellis, Isidori 1202.5704

Can even be larger than the SM bottom Yukawa!
Leads to interesting Higgs phenomenology

Exclusive decays

$$h \to MV$$

vector meson → M

γ W Z → V

W, Z → work in progress

$$h \to J/\psi\,\gamma \longrightarrow y_c$$

Bodwin, Petriello, Stoynev, Velasco, 1306.5770
Bodwin, Chung, Ee, Lee, Petriello 1407.6695
ATLAS 1501.03276

$$h \to \phi\gamma \longrightarrow y_s$$

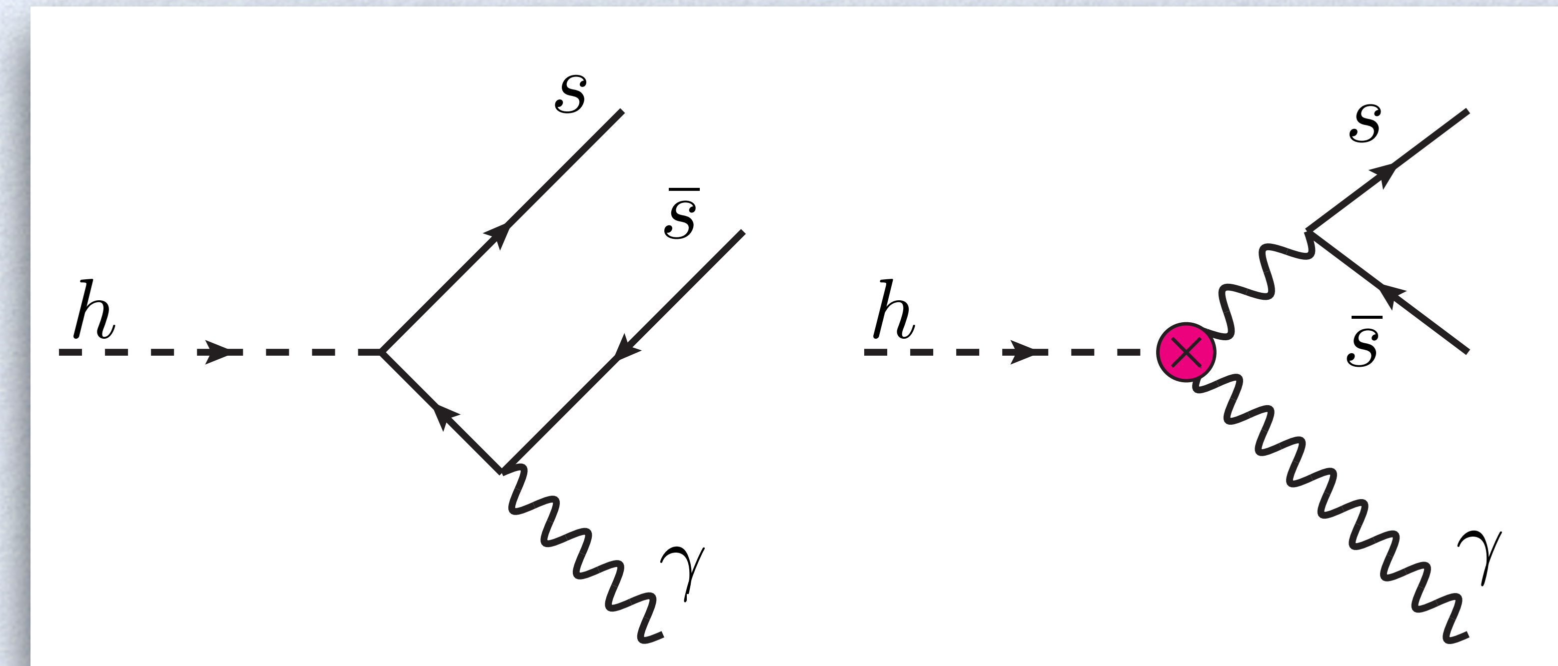
$$h \to \rho\gamma,\ \omega\gamma \longrightarrow y_d\,,\ y_u$$

Small branching ratio, BUT reduced QCD background!

Off-diagonal: $h \to \bar{B}_s^*\gamma\,,\ \bar{B}_d^*\gamma\,,\ D^*\gamma\ \ K^*\gamma$

DIAGONAL COUPLING

direct | indirect



$\propto y_s f_\perp^\phi \langle 1/u\bar{u} \rangle$

light-cone distribution amplitude (LCDA)

$\propto \dfrac{f_\phi}{m_\phi}$

photon/vector- meson mixing

$\Gamma(\phi \to e^+ e^-)$

Main sensitivity to Yukawa due to interference!

Resulting Rates

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(3.0\pm 0.3)\kappa_\gamma - 0.78\bar{\kappa}_s\right]\times 10^{-6}}{0.57\bar{\kappa}_b^2}$$

can be improved
(both theoretically and experimentally)

$\pm\mathcal{O}(20\%)$

$\bar{\kappa}_q \equiv y_q/y_b^{\mathrm{SM}}$ $\kappa_\gamma^{\mathrm{SM}} = 1$

Resulting Rates

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(3.0\pm0.3)\kappa_\gamma - 0.78\bar{\kappa}_s\right]\times 10^{-6}}{0.57\bar{\kappa}_b^2}$$

$\pm\mathcal{O}(20\%)$

can be improved
(both theoretically and experimentally)

$$\bar{\kappa}_q \equiv y_q/y_b^{\mathrm{SM}} \qquad \kappa_\gamma^{\mathrm{SM}} = 1$$

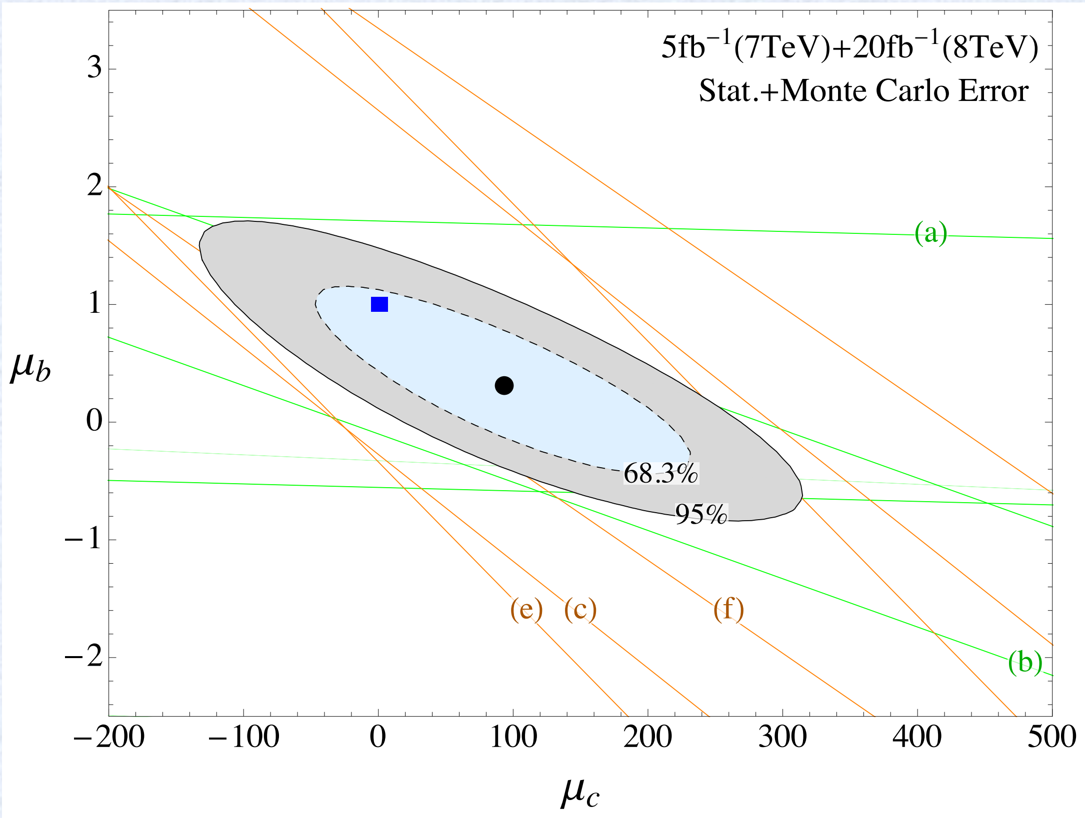
$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.2)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]\times 10^{-5}}{0.57\bar{\kappa}_b^2}$$

$$\frac{\mathrm{BR}_{h\to\omega\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.6\pm0.2)\kappa_\gamma - 0.59\bar{\kappa}_u - 0.29\bar{\kappa}_d\right]\times 10^{-6}}{0.57\bar{\kappa}_b^2}$$

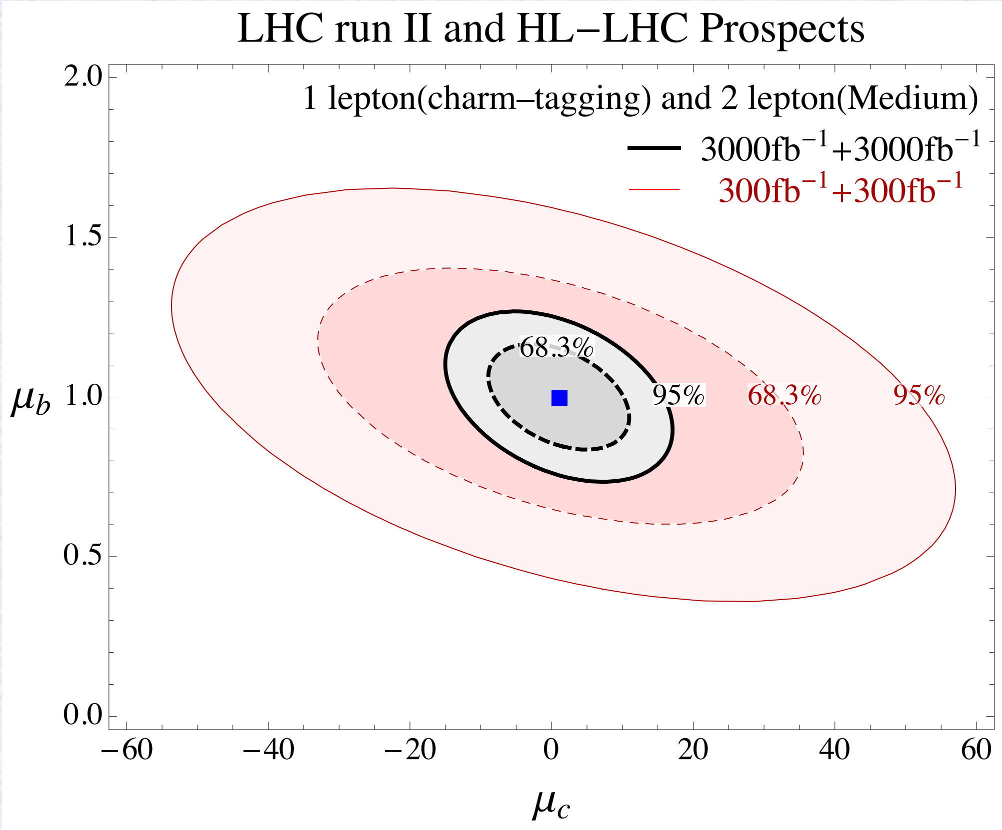
Future prospects

Future experimental prospects

from inclusive measurements:



HL-LHC



assuming working points:

$(\epsilon_b, \epsilon_c) = (0.7, 0.2)\,,\ \ (0.13, 0.19)$

$$\Delta\mu_c = \begin{cases} 23\,(45) & \text{with } 300\ \text{fb}^{-1} \\ 6.5\,(13) & \text{with } 3000\ \text{fb}^{-1} \end{cases}$$

68.3%(95%) CL

O(5%) for y_c in e^+e^- collider

Future Experimental Prospects

Hadron colliders:

- $h \to \phi \gamma$ as an example:
  - 70-75% of the ϕ decays products fall in the central region (η<2.4).
  - 3σ sensitivity with 3000 fb^{-1}:

$\sqrt{s}$ [TeV]	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\text{stat.}} > (<)$
14	$0.56\,(-1.2)$	$0.27\,(-0.81)$
33	$0.54\,(-1.2)$	$0.22\,(-0.75)$
100	$0.54\,(-1.2)$	$0.13\,(-0.63)$

factor 6 from the SM

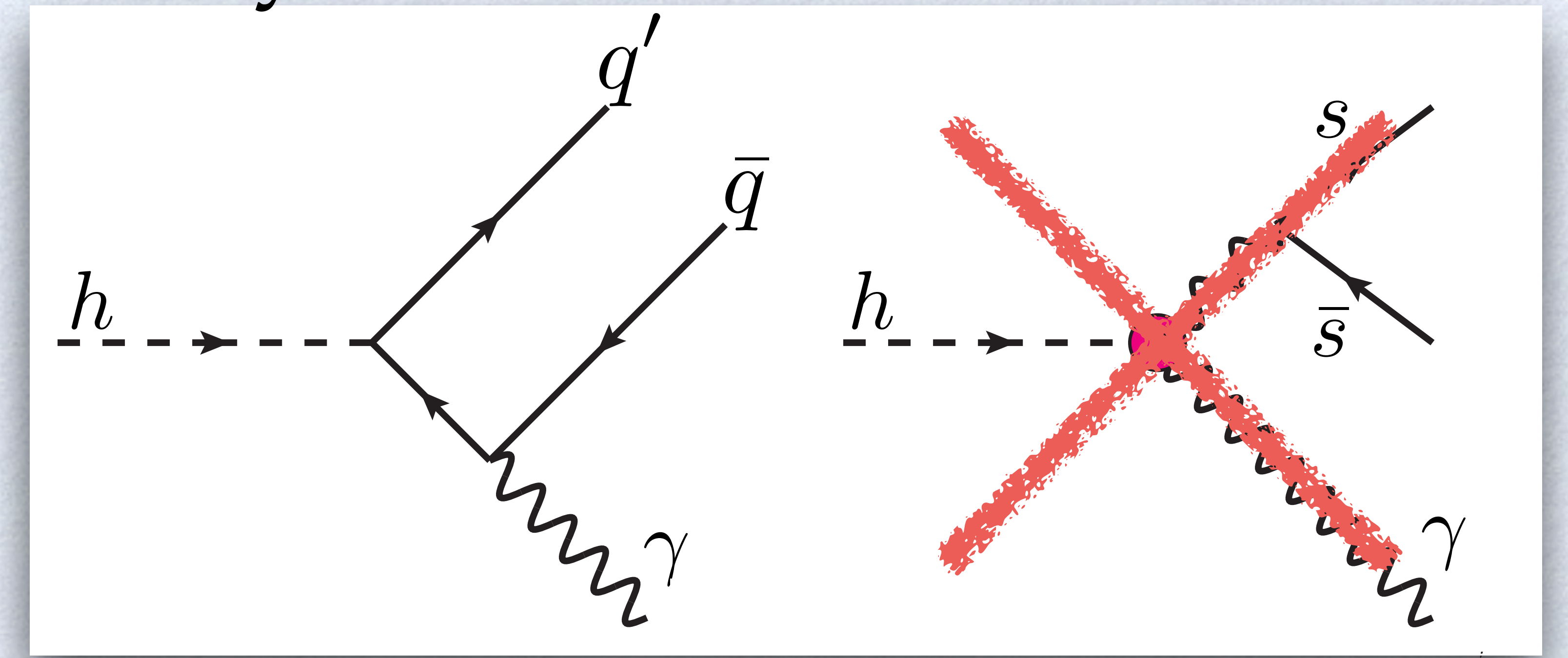
SUMMARY

- Modifications in the Higgs to light quarks coupling lead to changes in the Higgs phenomenology.
- The charm Yukawa can be probed by charm-tagging or with exclusive decay.
- The Higgs quarks non-universality is established in the up sector.
- Light quarks Yukawa can be directly probed by exclusive $h \to M\gamma$ decays. In hadron collider $h \to \phi\gamma$ is the most promising.

Backup slides

OFF-DIAGONAL COUPLING

only direct indirect



$\propto \bar{\kappa}_{bs}\ ,\ \ \bar{\kappa}_{sb}$

$$\bar{\kappa}_{qq'} = y_{qq'}/y_b^{\rm SM}$$

$$\frac{{\rm BR}_{h\to \bar{B}_s^{*0}\gamma}}{{\rm BR}_{h\to b\bar{b}}} = \frac{2.1\pm 1.0}{0.57\bar{\kappa}_b^2}\frac{|\bar{\kappa}_{bs}|^2+|\bar{\kappa}_{sb}|^2}{2}\times 10^{-7}$$

Future experimental prospects

e^+e^- colliders:

- σ~200 fb for $\sqrt{s}$= 240 GeV. 1308.6176
- For integrated luminosity of 10 (100) pb^{-1}: 2×10^6 (2×10^7) Higgses are expected. 1310.8361
- the $h\to\rho\gamma$ channel - has the largest number of events can be used to put **direct** upper bound on the first generation Yukawa couplings at the order of the SM bottom Yukawa.