מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

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 (in progress)

INTRODUCTION

Higgs in the Standard Model (SM)

induce electroweak (EW) gauge boson masses and unitarization

was tested in a quantitative way:
(1) direct: measuring $h \to WW,ZZ$
(2) indirect: EW precision

induce the fermions masses and unitarization

much less known:
mainly on 3rd generation

significant progress can be made

OUTLINE

- Introduction
- Probing Higgs to light quarks couplings
- Establish quark Higgs non-universality couplings from the current data
- 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

INTRODUCTION

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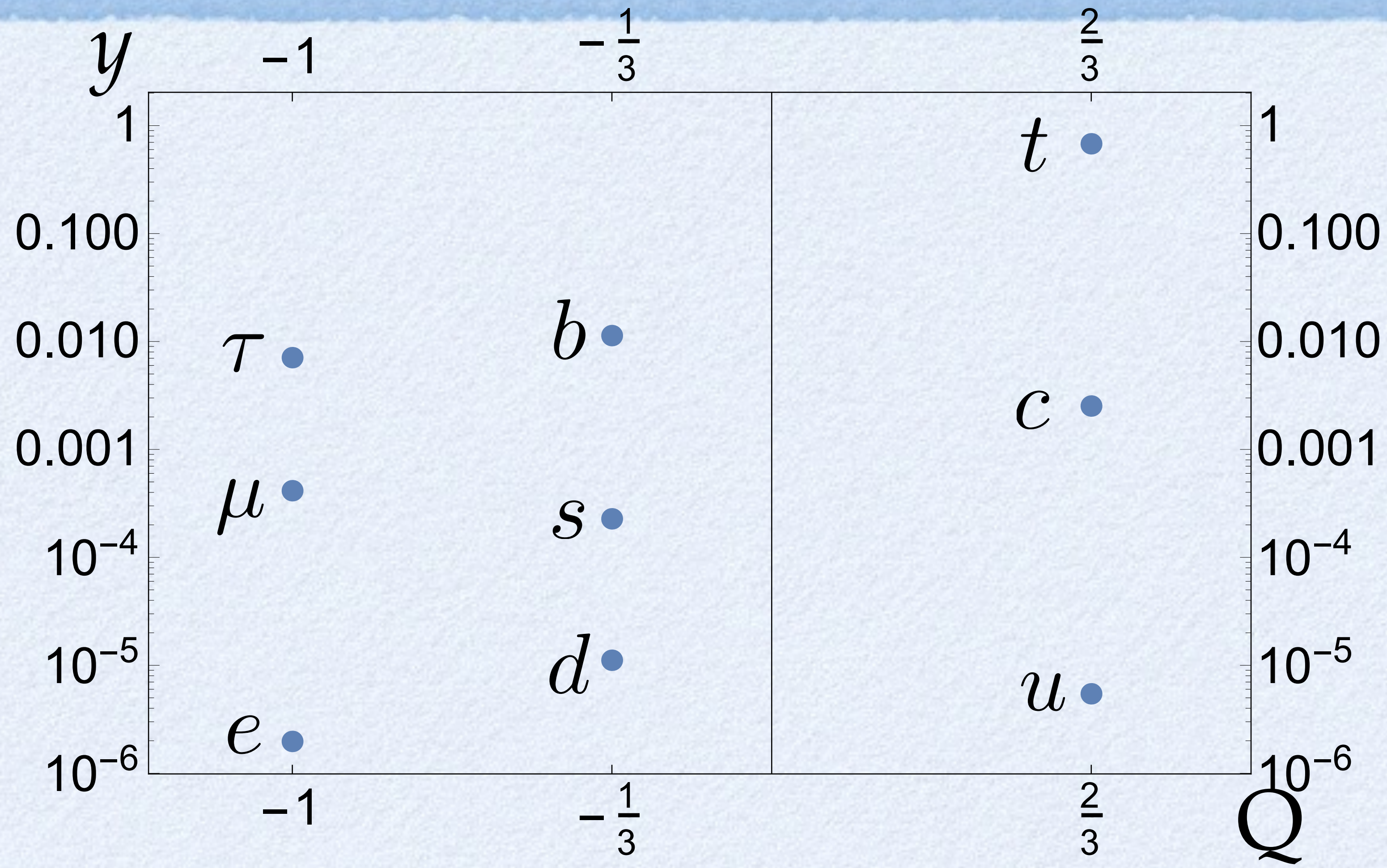
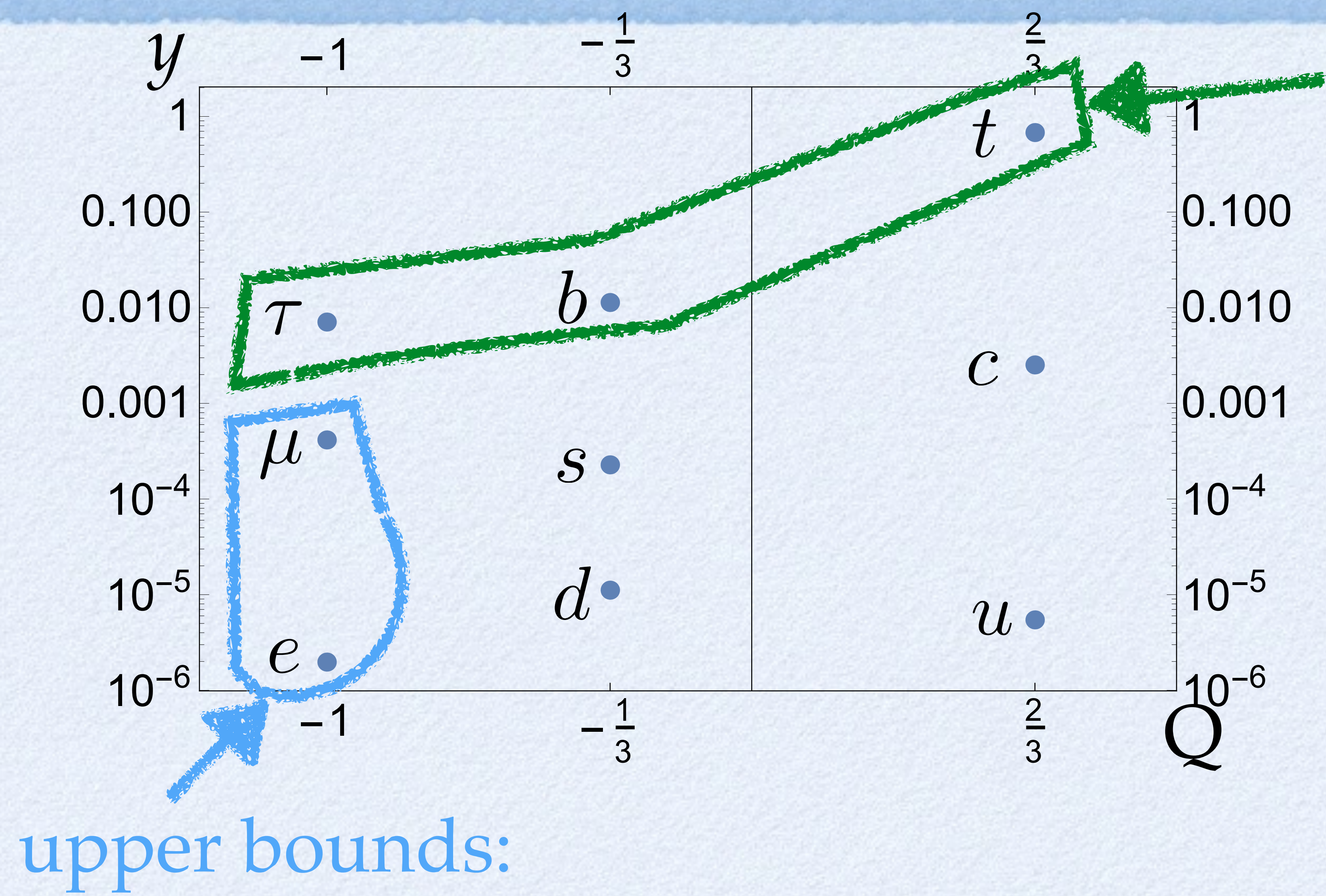
- non-universal and hierarchical
- diagonal

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

INTRODUCTION



INTRODUCTION



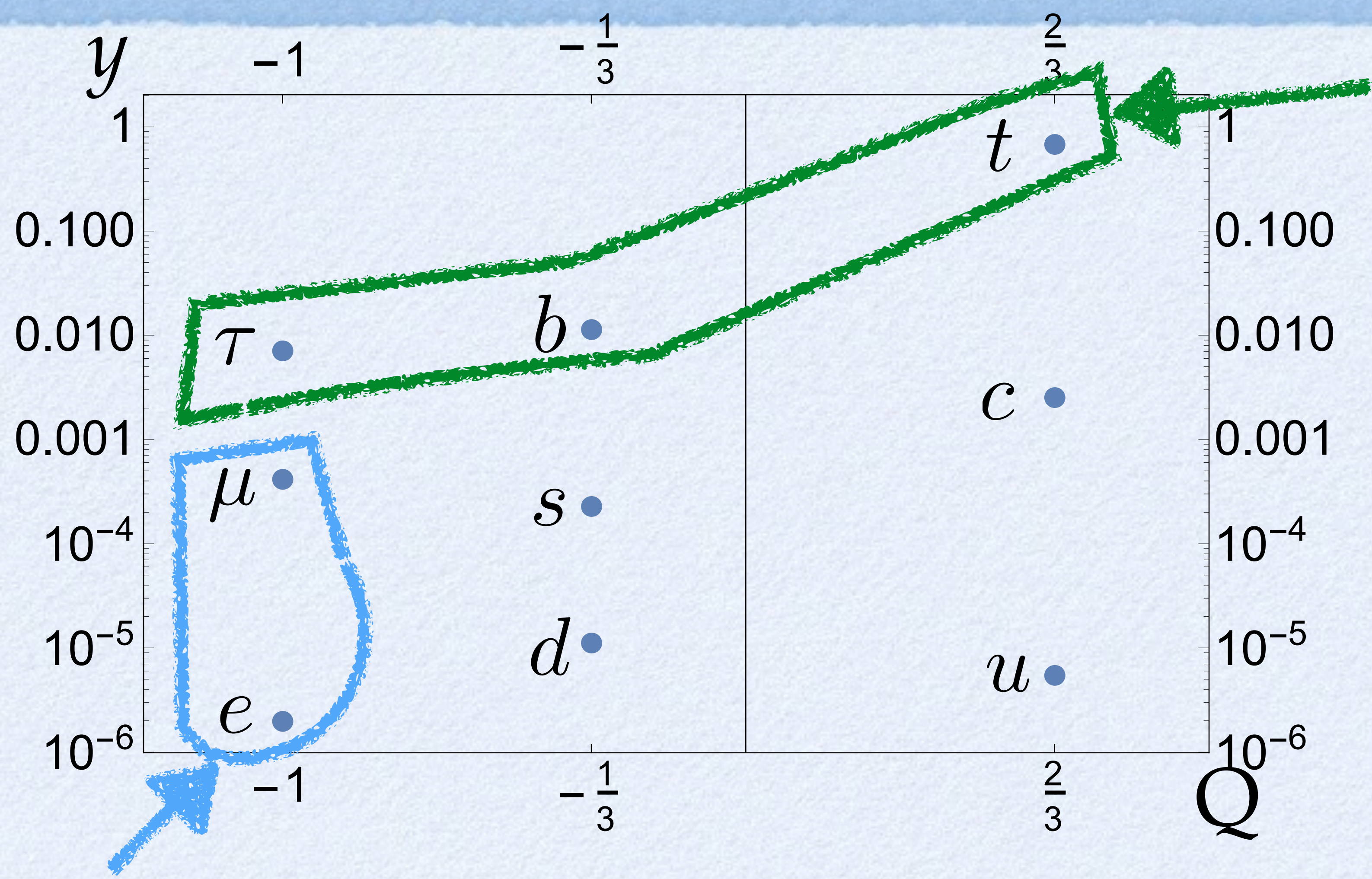
$\mu_\tau = 0.98 \pm 0.22$

$\mu_b = 0.71 \pm 0.31$

$\mu_{t\bar{t}h} = 2.41 \pm 0.81$

CMS $\mu_\mu < 7.4$

INTRODUCTION



current measurements

(ATLAS+CMS)

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

$$\mu_b = 0.71 \pm 0.31$$

$$\mu_{t\bar{t}h} = 2.41 \pm 0.81$$

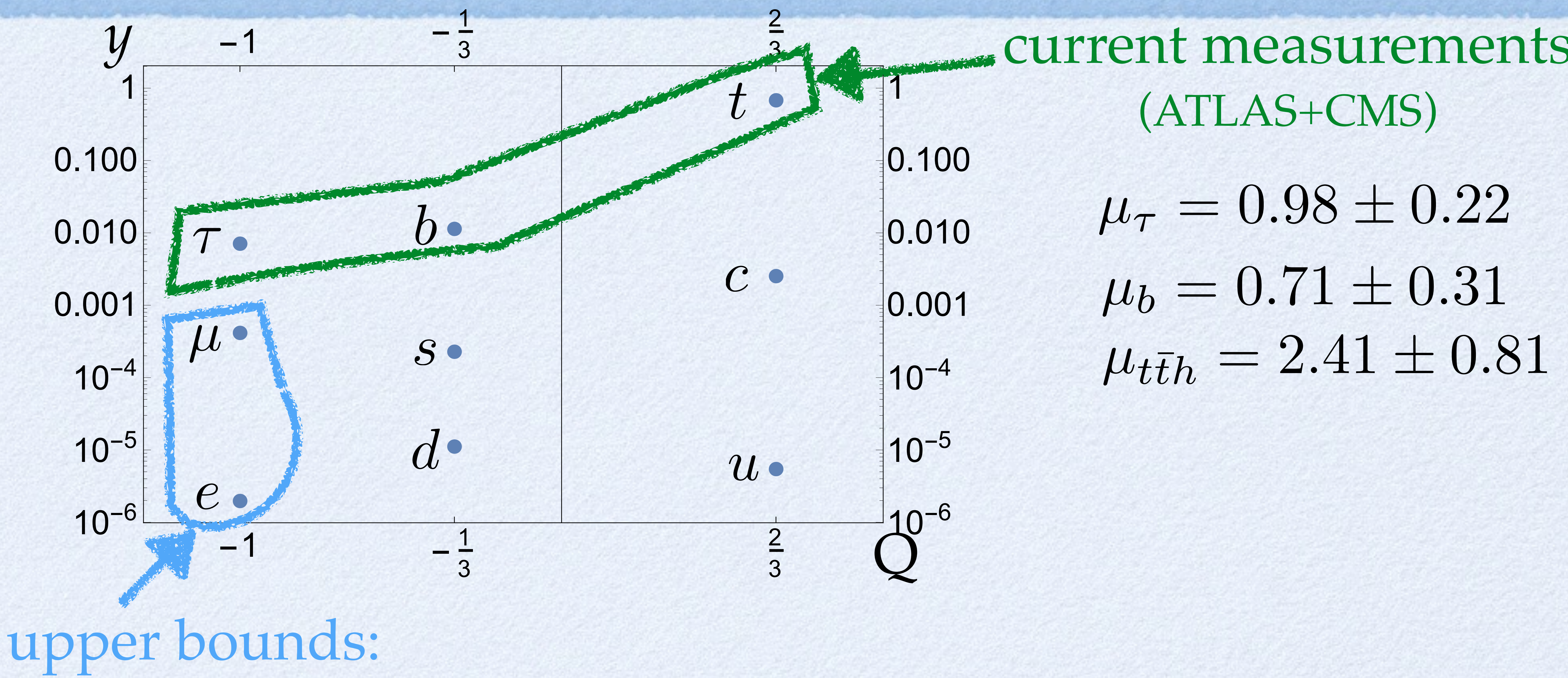
upper bounds:

CMS $\mu_\mu < 7.4$

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

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

INTRODUCTION



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Does the Higgs couple like the mass to light quarks?

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.

Probing Light Quarks

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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 (in progress)
ATLAS-CONF-2013-068
ATLAS-CONF-2014-063

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 (in progress)
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)

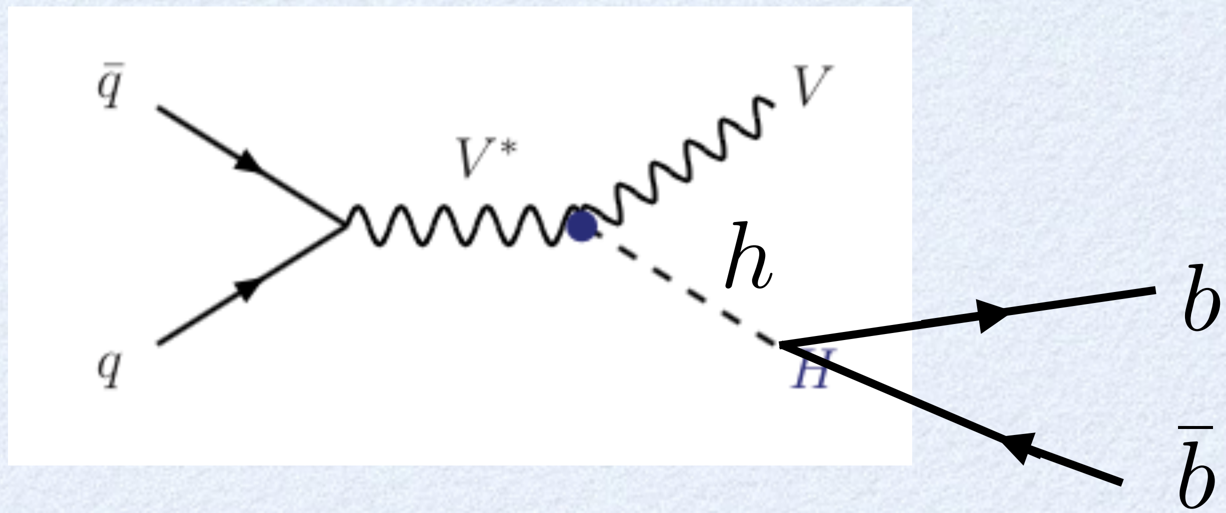
G. Perez, YS, E. Stamou and K. Tobioka (in progress)

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→bb

Vh(bb) search:



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

$$\mu_b = \frac{\sigma \mathrm{BR}_b}{[\sigma \mathrm{BR}_b]^{\mathrm{SM}}} \to \mu_b + \left(\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\right)\frac{\mathrm{BR}_c^{\mathrm{SM}}}{\mathrm{BR}_b^{\mathrm{SM}}}\mu_c$$

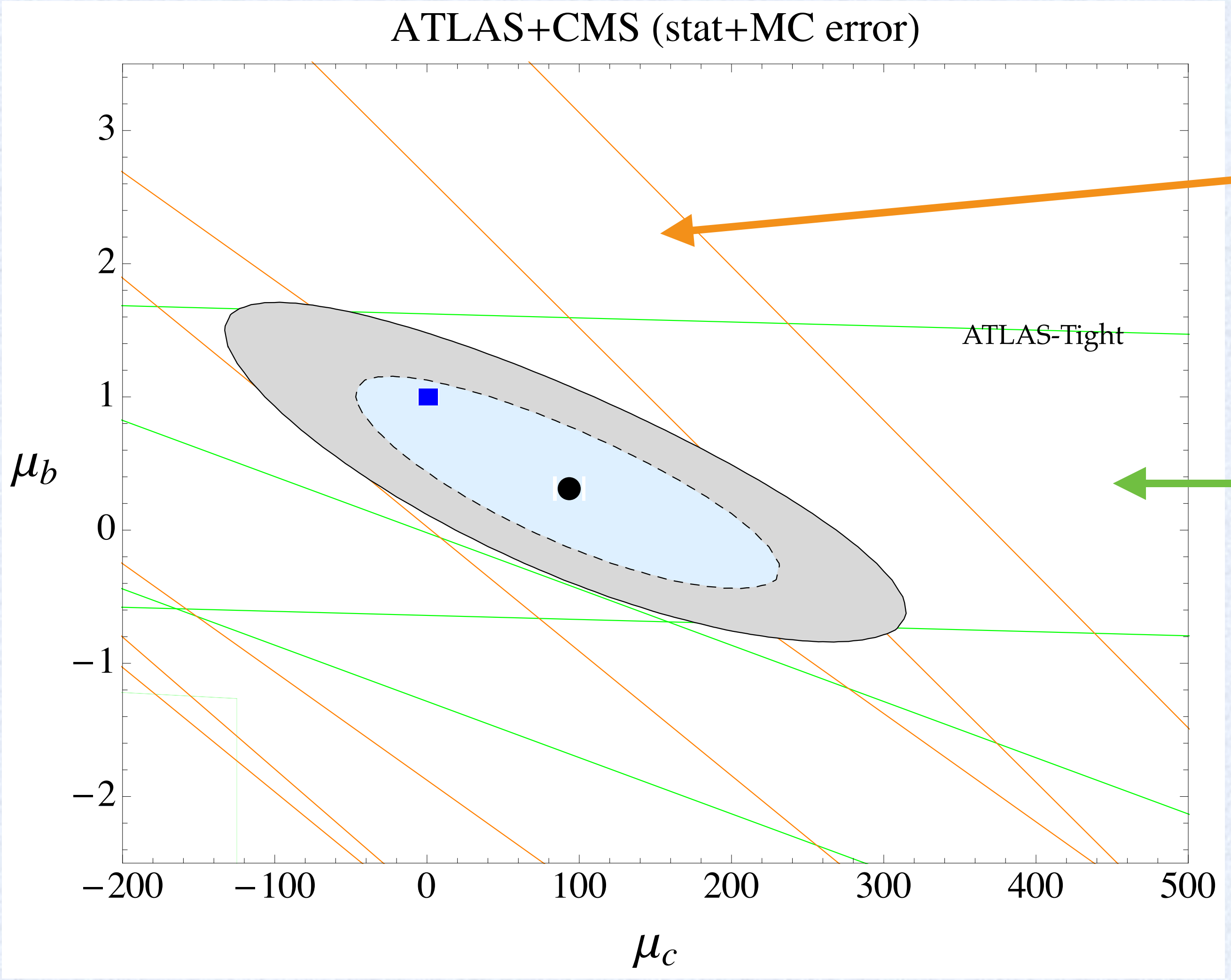
tagging efficiencies

Use several "charm-tagging" working points (of ATLAS and CMS)

Direct constrain the charm signal strength

Recasting of $H \to bb$

$$\mu_b = \frac{\sigma \mathrm{BR}_b}{[\sigma \mathrm{BR}_b]^{\mathrm{SM}}} \to \mu_b + \left(\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\right)\frac{\mathrm{BR}_c^{\mathrm{SM}}}{\mathrm{BR}_b^{\mathrm{SM}}}\,\mu_c$$



CMS	Loose	Med1	Med2	Med3
ϵ_b	88%	82%	78%	71%
ϵ_c	47%	34%	27%	21%

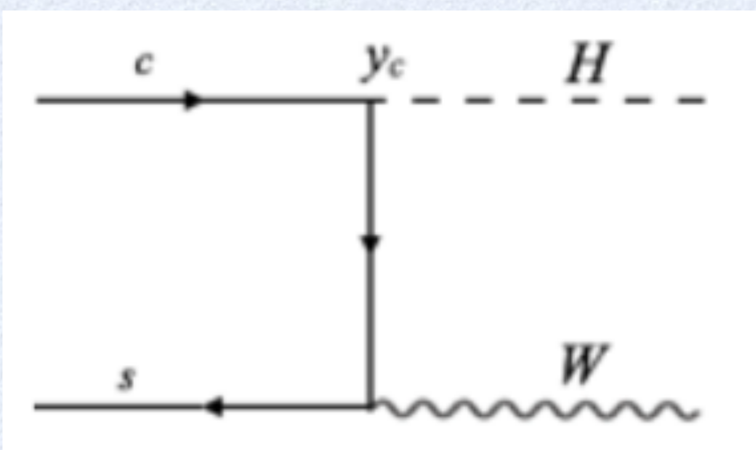
ATLAS	Med	Tight
ϵ_b	70%	50%
ϵ_c	20%	3.8%

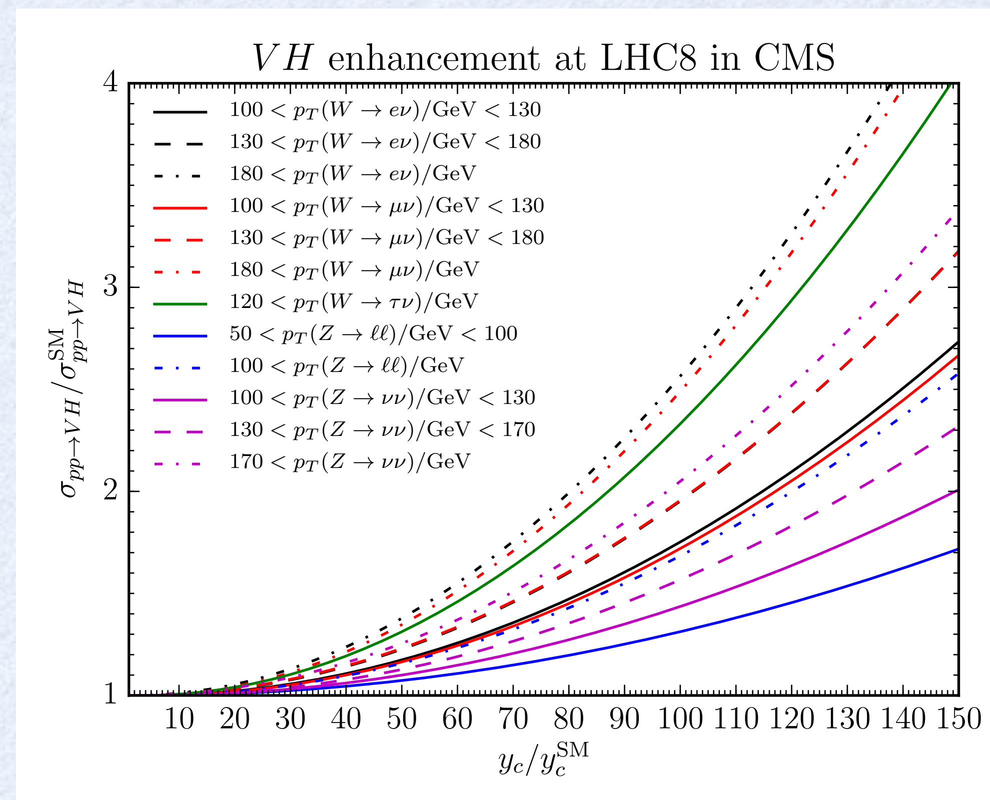
Direct constrain the charm signal strength (can be improved by dedicated *c*-tagging)

Recasting of H→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:





→ $\kappa_c = y_c/y_c^{\rm SM} < 250$ (no runway)

Bounds from Higgs to J/ψ and the total width

Interpretation of ATLAS recent $h\to J/\psi+\gamma$ (1501.03276):

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

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

Getting rid of production:

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

$$\mathcal{R}_{J/\psi,Z} = \frac{33\,\mathrm{fb}}{\mu_{ZZ^*}\sigma^{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{h\to ZZ^*\to 4\ell}} < 9.32 \quad \Rightarrow \quad \kappa_c < 210\kappa_V + 11\kappa_\gamma$$

LEP: $k_V = 1.08 \pm 0.07$

Falkowski, Riva 1303.1812

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Falkowski, Riva 1303.1812

Higgs total width bound: $\Gamma_h < 2.6\,\mathrm{GeV}$ ALTAS, $\Gamma_h < 1.7\,\mathrm{GeV}$ CMS $\Rightarrow$ $\kappa_c < 150\,,\;\; 120$

Constraining up-Yukawa universality

ATLAS+CMS *tth*:

$$\mu_{t\bar{t}h} = 2.41 \pm 0.81 \Rightarrow |\kappa_t| = \left|\frac{y_t}{y_t^{\rm SM}}\right| > 0.9\sqrt{\frac{{\rm BR}^{\rm SM}_{h\to \rm relevant\ modes}}{{\rm BR}_{h\to \rm relevant\ modes}}} > 0.9$$

or $\quad y_t > 250 y_c^{\rm SM}$

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$$\text{or} \quad y_t > 250 y_c^{\rm SM}$$

Combining with the bounds on the y_c:

Recast *Vh(bb)*: $y_c < 250 y_c^{\rm SM}$

From $h\to J/\psi+\gamma$: $y_c < 230 y_c^{\rm SM}$

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

Higgs total width: $y_c < 150 y_c^{\rm SM}\,,\ 120 y_c^{\rm SM}$

$\Rightarrow$ $y_c < y_t$

Global Higgs data analysis

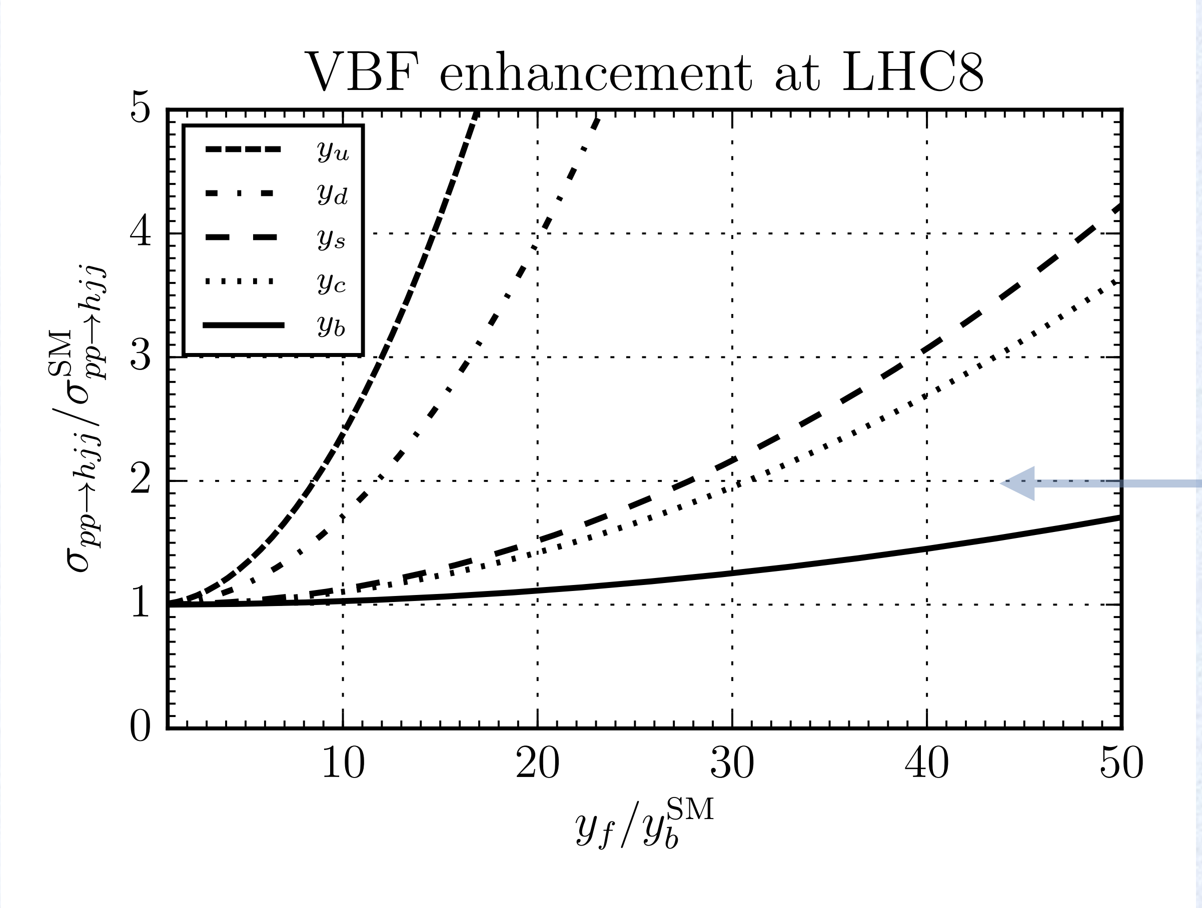
The conventional way of doing the fit leads to $\kappa_c \lesssim 6$

It is equivalence to the untagged Higgs decays bound, driven by VBF

$$\mu_{\mathrm{VBF}\to h\to WW^*} = 1.27^{+0.53}_{-0.45}$$

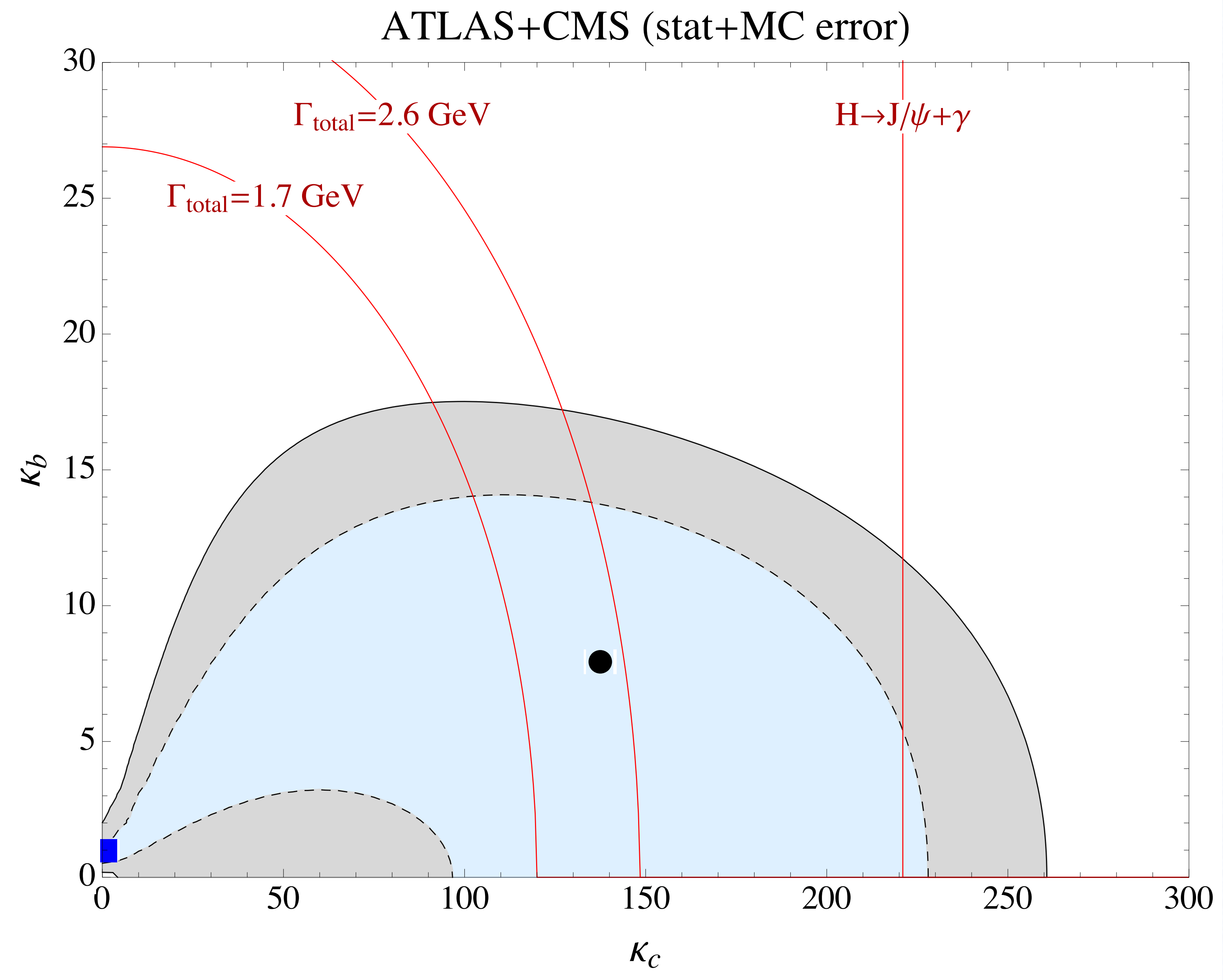
$$\mu_{\mathrm{VBF}\to h\to WW^*} = \left(\kappa_V^2 + \bar{\sigma}_{\mathrm{VBF}}^{\mathrm{non-SM}}\right)\frac{\kappa_V^2}{\Gamma_h/\Gamma_h^{\mathrm{SM}}}$$

always set to zero



currently, small effect but important for the interplay with other collider

Combining all constraints

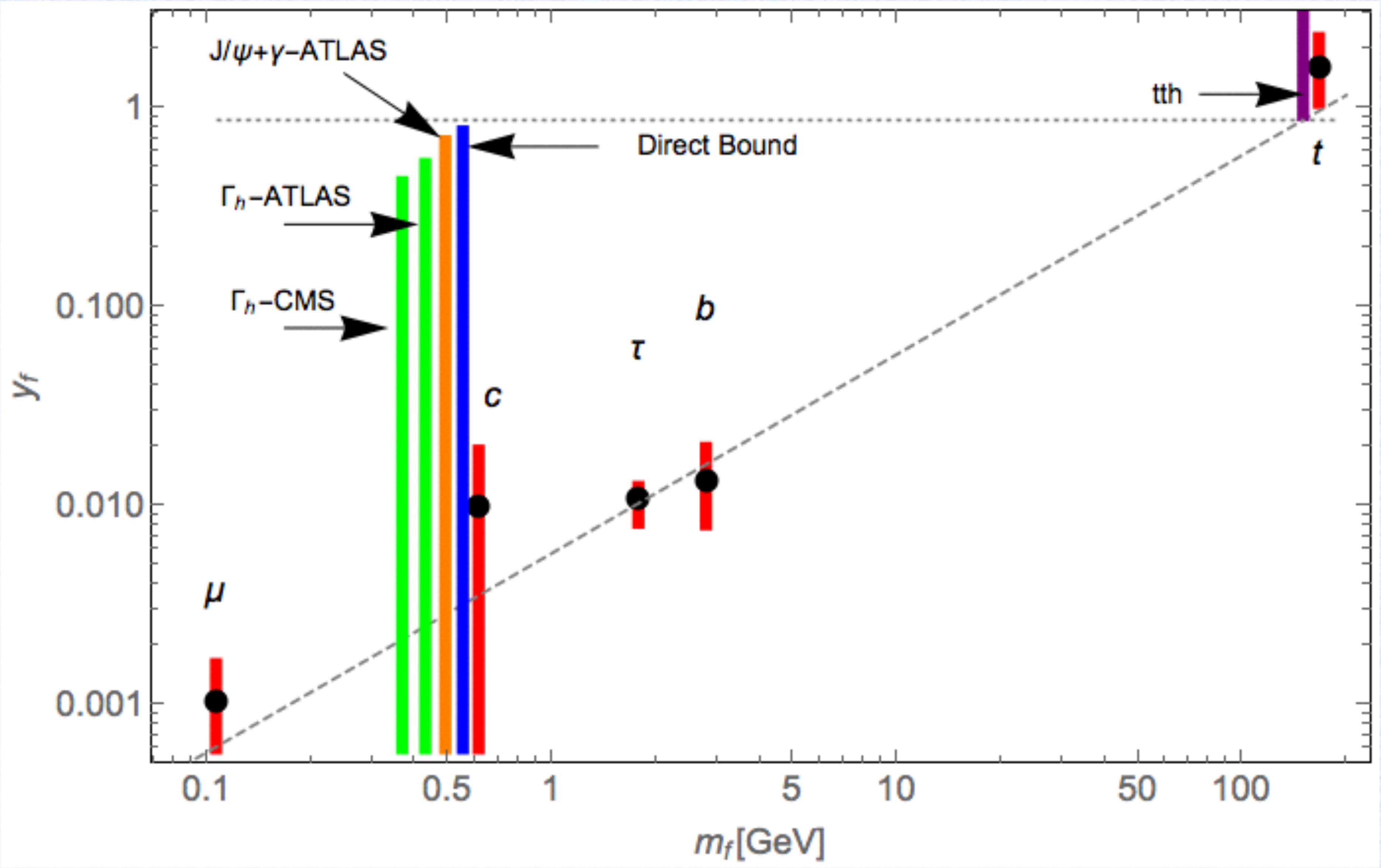


best fit point $[\kappa_b, \kappa_c]$=[0.9,2.9]

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

κ_c(@2$\boldsymbol{\sigma}$)=[0,6]

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

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 — γ 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

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

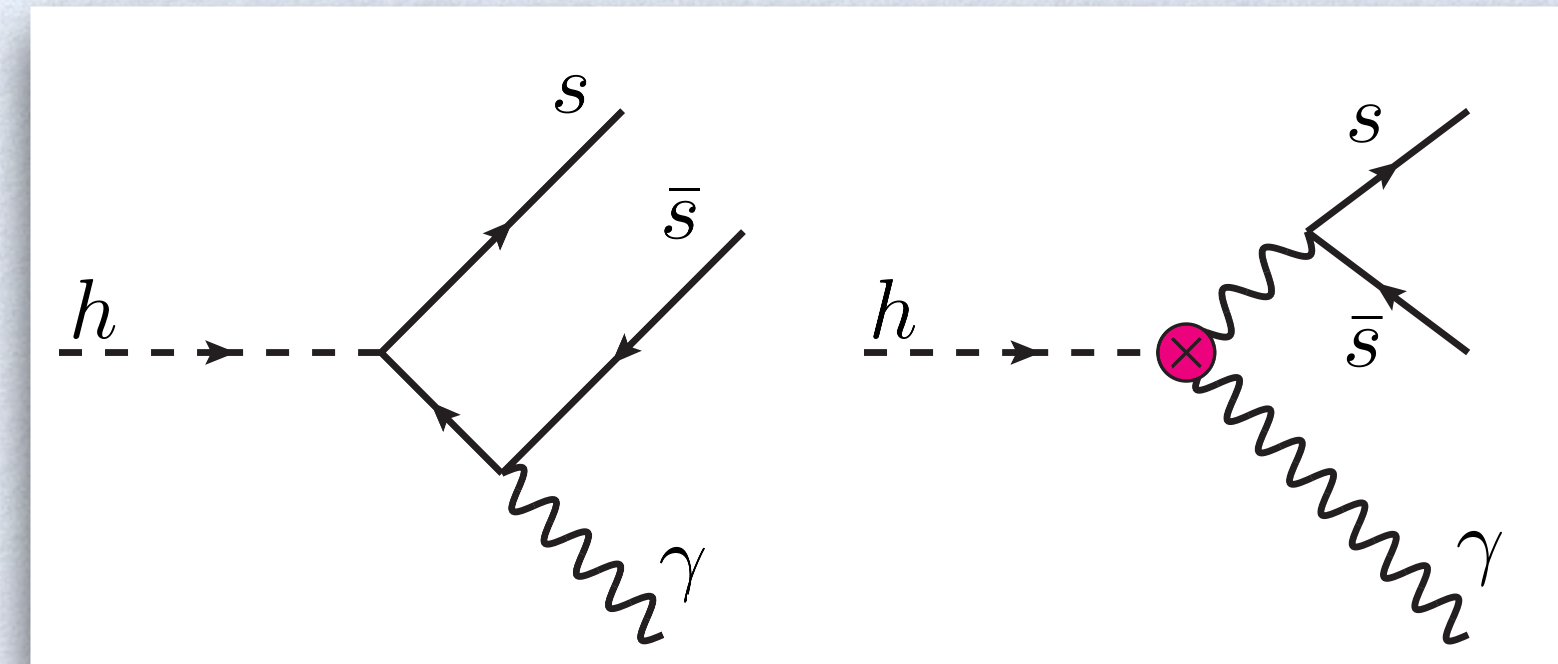
$$h \to \rho\gamma,\ \omega\gamma \longrightarrow y_d\,,\ y_u$$

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)

$\propto \frac{f_\phi}{m_\phi}$ 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)

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

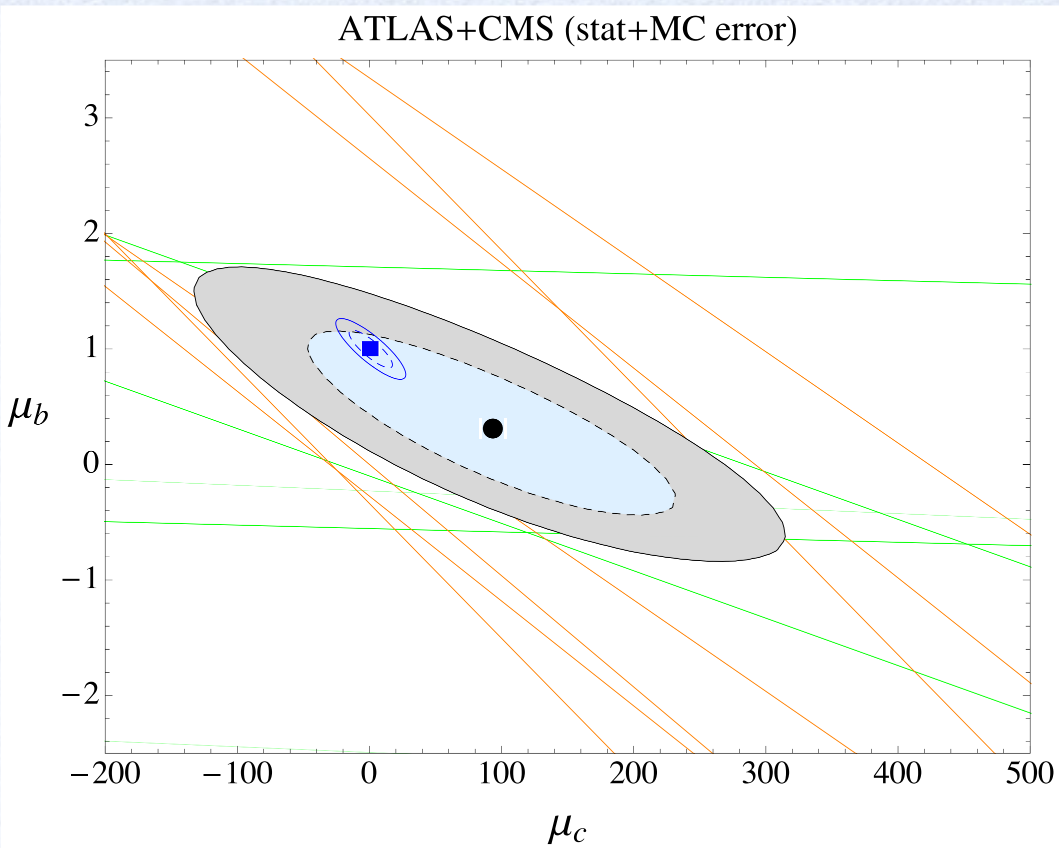
$$\bar{\kappa}_q \equiv y_q/y_b^{\mathrm{SM}} \qquad \kappa_\gamma^{\mathrm{SM}} = 1$$

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm 0.2)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]\times 10^{-5}}{0.57\bar{\kappa}_b^2}$$

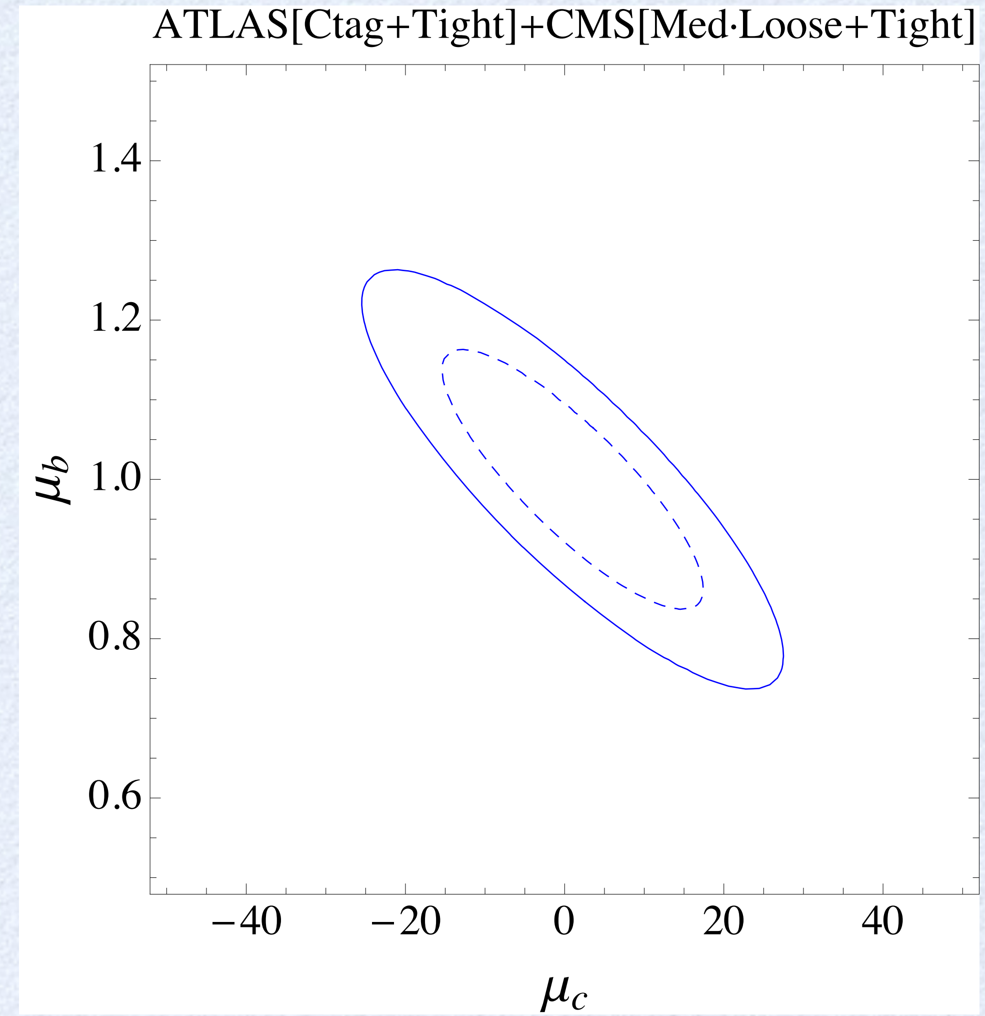
$$\frac{\mathrm{BR}_{h\to\omega\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.6\pm 0.2)\kappa_\gamma - 0.59\bar{\kappa}_u - 0.29\bar{\kappa}_d\right]\times 10^{-6}}{0.57\bar{\kappa}_b^2}$$

Future prospects

from inclusive measurements:



HL-LHC



Assuming working points:

ATLAS: $(\epsilon_b\,, \epsilon_c) = (0.5\,, 0.038), (0.12\,,\ 0.19)$

CMS: $(\epsilon_b\,, \epsilon_c) = (0.88/0.82\,, 0.47/0.34), (0.5\,,\ 0.04)$

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]	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\rm stat.} > (<)$
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

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 $h\rightarrow\boldsymbol{\rho}\gamma$ 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.

Future experimental prospects

$$h \to \rho\gamma$$

# of Higgses	$\bar{\kappa}_u > (<)$	$\bar{\kappa}_u^{\text{stat.}} > (<)$	$\bar{\kappa}_d > (<)$	$\bar{\kappa}_d^{\text{stat.}} > (<)$
2×10^6	$1.1(-1.5)$	$1.4(-2.8)$	$1.2(-1.4)$	$0.96(-1.1)$
2×10^7	$0.80(-1.1)$	$0.42(-0.69)$	$0.87(-1.0)$	$0.48(-0.61)$

$$h \to \omega\gamma$$

# of Higgses	$\bar{\kappa}_u > (<)$	$\bar{\kappa}_u^{\text{stat.}} > (<)$	$\bar{\kappa}_d > (<)$	$\bar{\kappa}_d^{\text{stat.}} > (<)$
2×10^6	$1.6(-4.1)$	$1.5(-3.7)$	$2.0(-3.2)$	$1.9(-3.0)$
2×10^7	$0.84(-1.9)$	$0.69(-1.6)$	$1.0(-1.5)$	$0.85(-1.3)$

$$h \to \phi\gamma$$

# of Higgses	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\text{stat.}} > (<)$
2×10^6	$1.5(-3.1)$	$1.4(-2.8)$
2×10^7	$0.81(-1.6)$	$0.64(-1.3)$

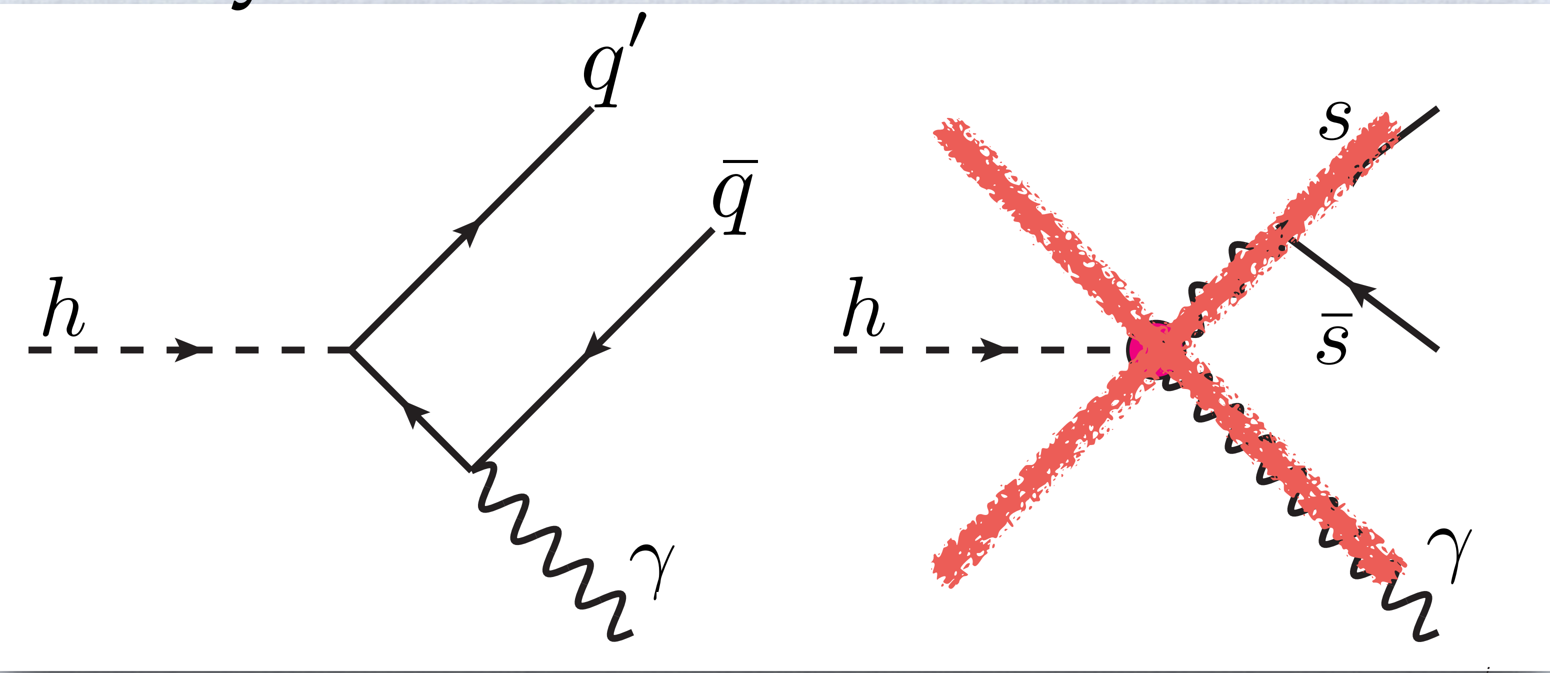
Summary

- 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 $h \to V\gamma$ decays. In hadron collider $h \to \phi\gamma$ is the most promising, in e^+e^- collider $h \to \rho\gamma$ is the most promising.

Backup slides

OFF-DIAGONAL COUPLING

only direct indirect



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

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

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