Higgs and flavor and the LHC

Stefania Gori
Perimeter Institute for Theoretical Physics

GGI workshop: Gearing up for LHC13

Florence,
September 25th 2015

Scope of the talk

Higgs & Flavor

- Give an overview of the status/future prospects for the measurement of the "difficult" Higgs couplings: flavor universal and flavor violating

  Several analyses +
  LHCHXWG Yellow report 4, Exotic chapter, in preparation

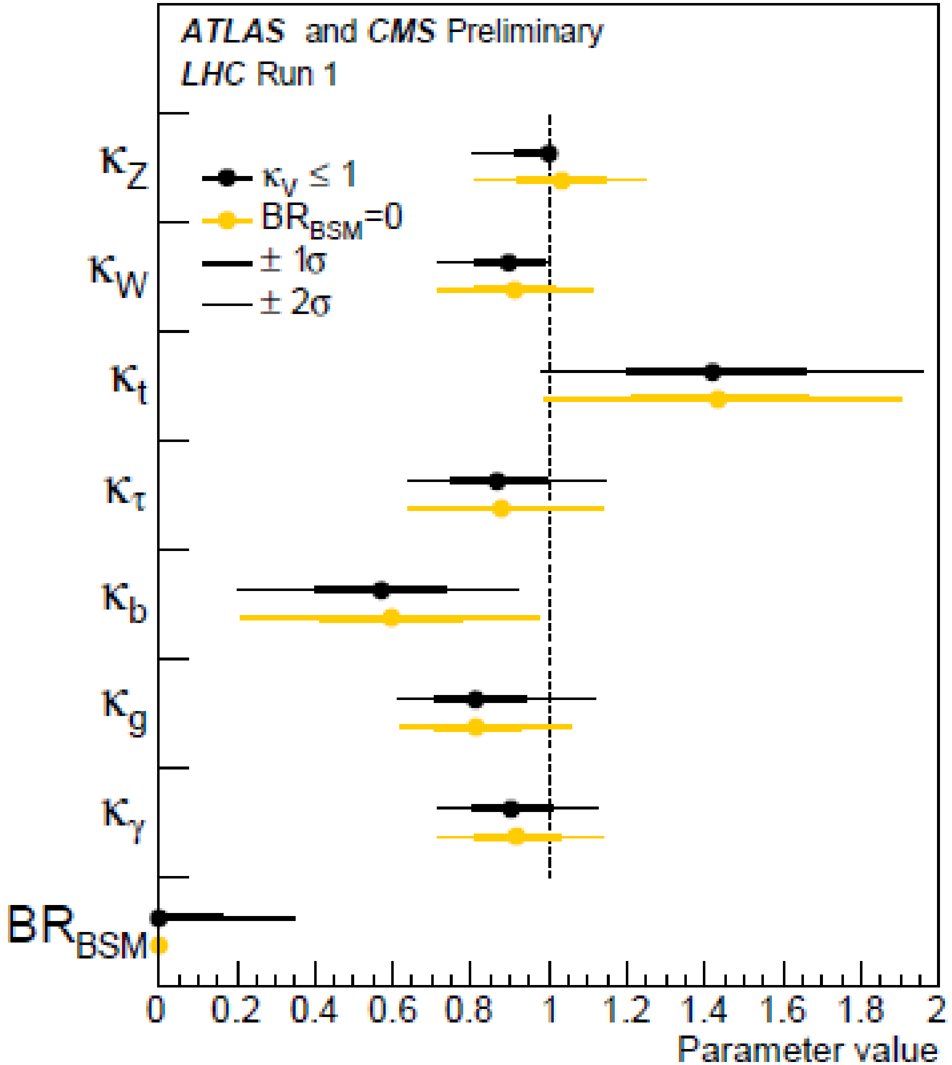
- Discuss what we learn if, in the future, we discover a non-zero Higgs flavor violating coupling (focus on the lepton sector).
  Connection with the flavor puzzle?

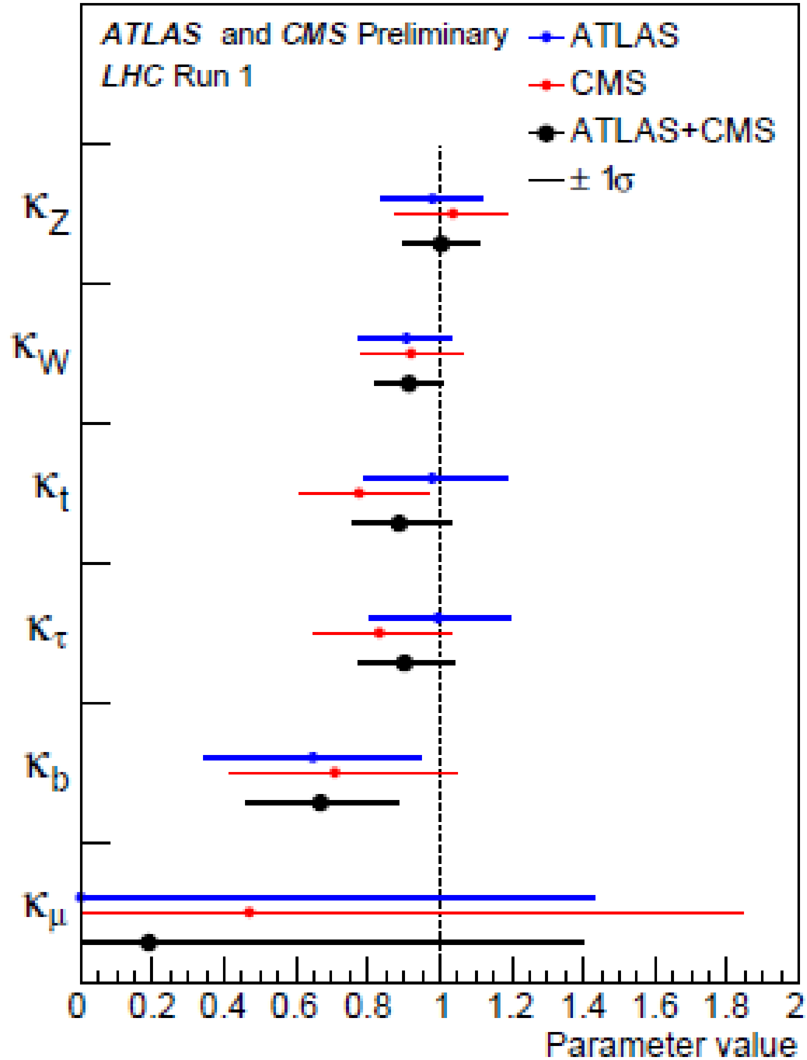
  Wolfgang Altmannshofer, SG, Alex Kagan,
  Luca Silvestrini, Jure Zupan, 1507.07927 + work in progress

Testing Higgs couplings @ LHC Run I

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

New





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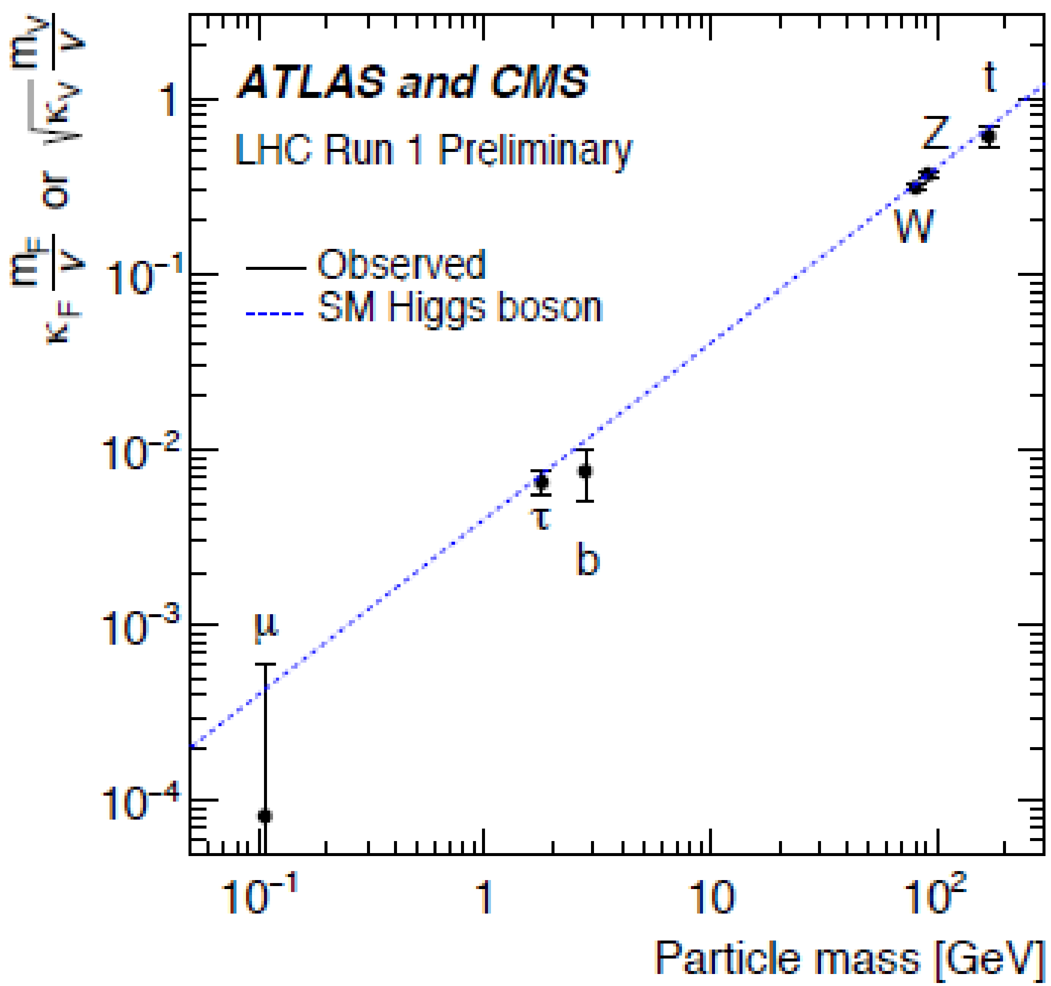

We are starting to test the SM flavor puzzle

Evidence for breaking

$$\frac{\mathrm{BR}(h \to \tau\tau)}{\mathrm{BR}(h \to \mu\mu)} \neq 1$$

We have basically no info...

On the couplings with

- Muons ($m_\mu \sim 100$ MeV)
- Electrons ($m_e \sim 0.5$ MeV)
- Light quarks ($m_c \sim 1.3$ GeV, $m_s \sim 100$ MeV, $m_d \sim 6$ MeV, $m_u \sim 3$ MeV)

Question:
Can we get to know if the Higgs gives mass to these particles?

We have basically no info...muons

On the couplings with

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Muons:

In the SM: BR($h \longrightarrow \mu\mu$) ~ 2.2×10^{-4}

Now: $\kappa_\mu = 0.2^{+1.2}_{-0.2}$

Future:

ATLAS-PHYS-PUB-2013-014

$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \mu\mu$ (comb.)	0.39	0.38	0.15	0.12
(incl.)	0.47	0.45	0.19	0.15
(ttH-like)	0.73	0.72	0.26	0.23

Warning: these are rates, not couplings!

We have basically no info...electrons

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Electrons:

$h \to e^+e^-$	LHC8 (25/fb)	$\lvert\kappa_e\rvert \lesssim 600$
	LHC14 (300/fb)	$\lvert\kappa_e\rvert \sim 260$
	LHC14 (3/ab)	$\lvert\kappa_e\rvert \sim 150$
	100 TeV (3/ab)	$\lvert\kappa_e\rvert \sim 75$
$e^+e^- \to h$	LEP II	$\lvert\kappa_e\rvert \lesssim 2000$
	TLEP (1/fb)	$\lvert\kappa_e\rvert \sim 50$
	TLEP (100/fb)	$\lvert\kappa_e\rvert \sim 10$
d_e	current	$\mathrm{Im}\,\kappa_e \lesssim 0.017$
	future	$\mathrm{Im}\,\kappa_e \sim 0.0001$
$(g-2)_e$	current	$\mathrm{Re}\,\kappa_e \lesssim 3000$
	future	$\mathrm{Re}\,\kappa_e \sim 300$

In the SM:
$\mathrm{BR}(h \longrightarrow ee) \sim 5 \times 10^{-9}$

Altmannshofer, Brod, Schmaltz, 1503.04830

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Can we get to know if the Higgs gives mass to these particles?

Light quarks: charm

1. Inclusive determination:

Signal strenght for h⟶bb:

$$\frac{\sigma_h \mathrm{BR}_{b\bar{b}} \epsilon_{b_1} \epsilon_{b_2} + \sigma_h \mathrm{BR}_{c\bar{c}} \epsilon_{c_1} \epsilon_{c_2}}{\sigma_h^{\mathrm{SM}} \mathrm{BR}_{b\bar{b}}^{\mathrm{SM}} \epsilon_{b_1} \epsilon_{b_2} + \sigma_h^{\mathrm{SM}} \mathrm{BR}_{c\bar{c}}^{\mathrm{SM}} \epsilon_{c_1} \epsilon_{c_2}} =$$

$$\left(\mu_b + \frac{\mathrm{BR}_{c\bar{c}}^{\mathrm{SM}}}{\mathrm{BR}_{b\bar{b}}^{\mathrm{SM}}} \frac{\epsilon_{c_1} \epsilon_{c_2}}{\epsilon_{b_1} \epsilon_{b_2}} \mu_c\right) \Big/ \left(1 + \frac{\mathrm{BR}_{c\bar{c}}^{\mathrm{SM}}}{\mathrm{BR}_{b\bar{b}}^{\mathrm{SM}}} \frac{\epsilon_{c_1} \epsilon_{c_2}}{\epsilon_{b_1} \epsilon_{b_2}}\right)$$

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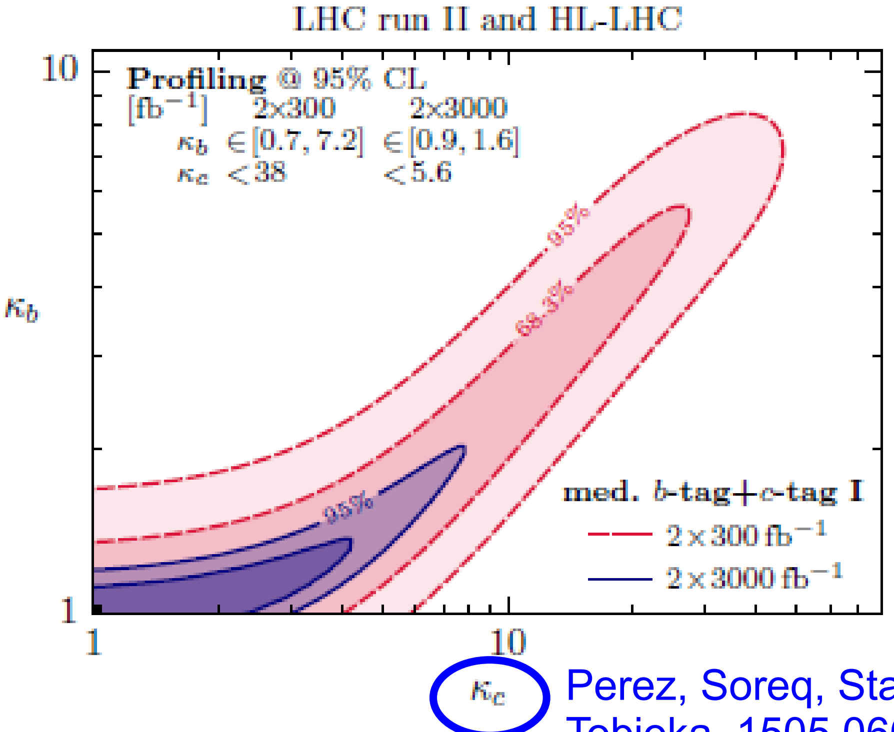

Perez, Soreq, Stamou, Tobioka, 1505.06689

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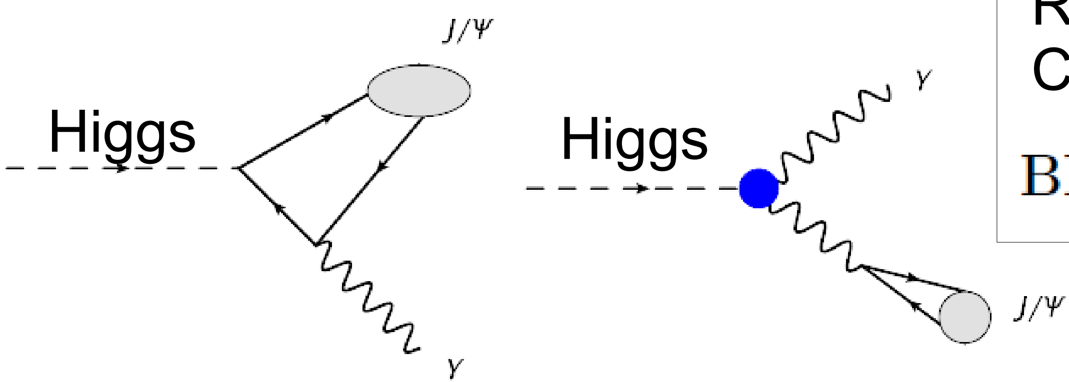
2. Exclusive determination:
Quarkonium interferometry



Recent ATLAS (1501.03276) and CMS (1507.03031) searches:

$$\mathrm{BR}(h \to J/\Psi + \gamma) \leq 1.5 \times 10^{-3}$$

$$\mathrm{BR}(h \to J/\Psi + \gamma) = 3.4 \times 10^{-6} (\kappa_\gamma - 8.7 \cdot 10^{-2} \kappa_c)^2$$

Bodwin et al. 1407.6695

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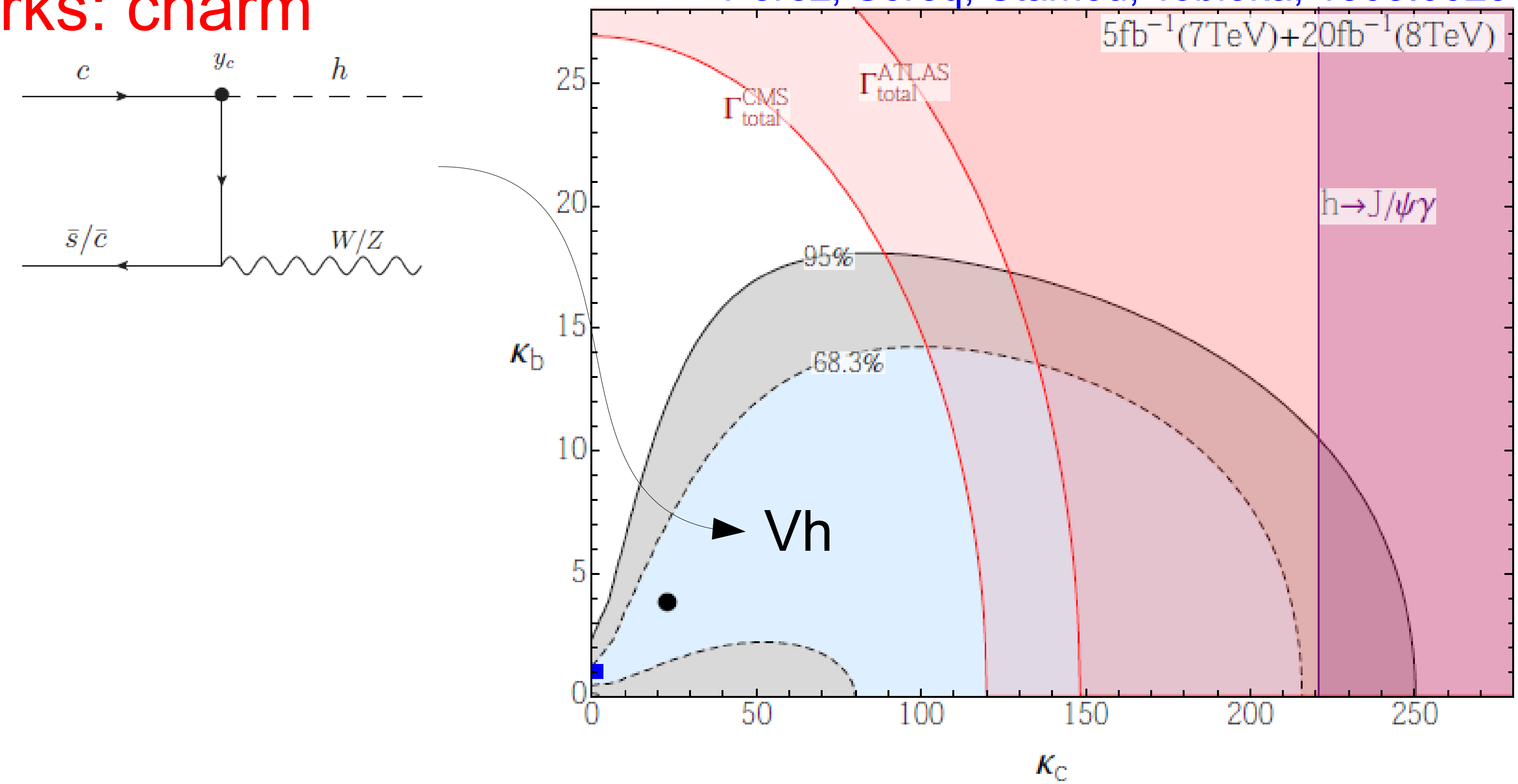
Summary

Perez, Soreq, Stamou, Tobioka, 1503.00290



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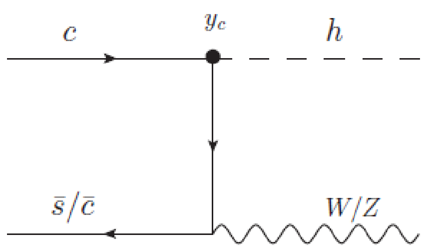
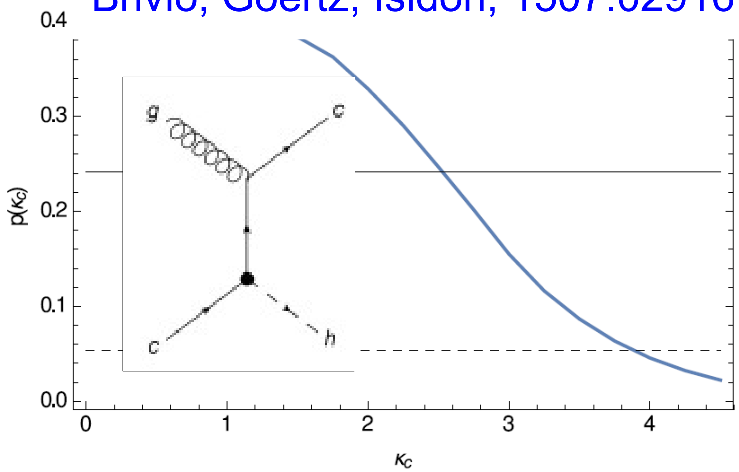


Brivio, Goertz, Isidori, 1507.02916



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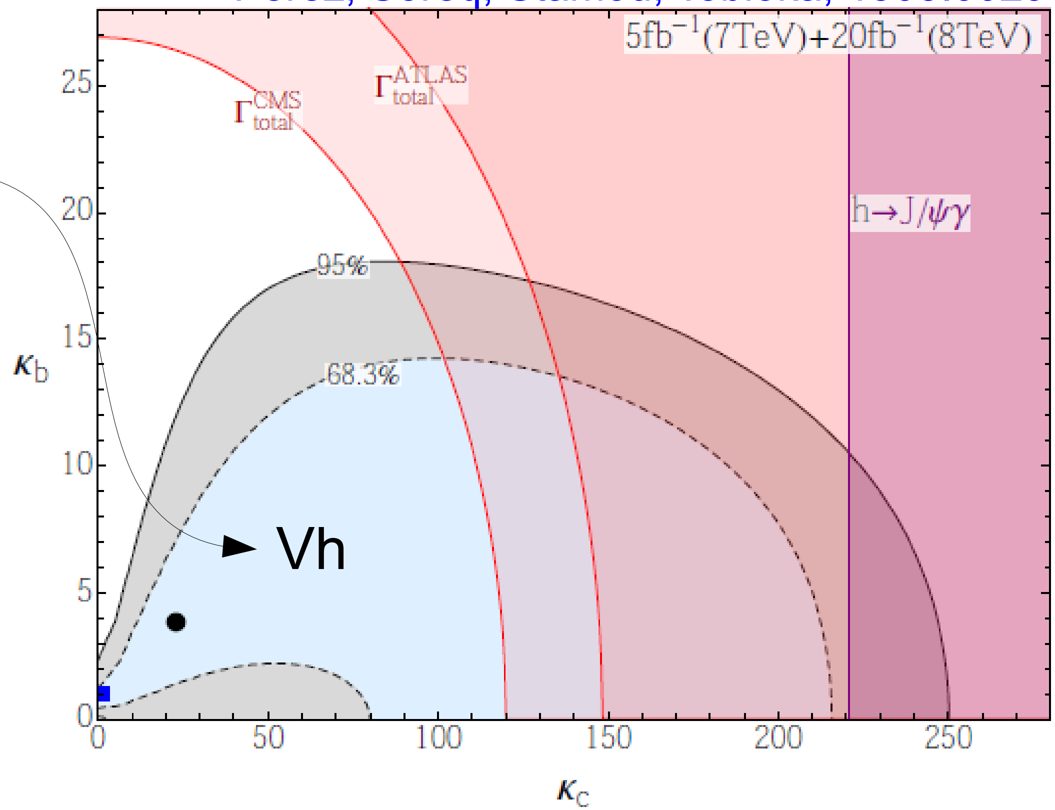

We have basically no info...strange

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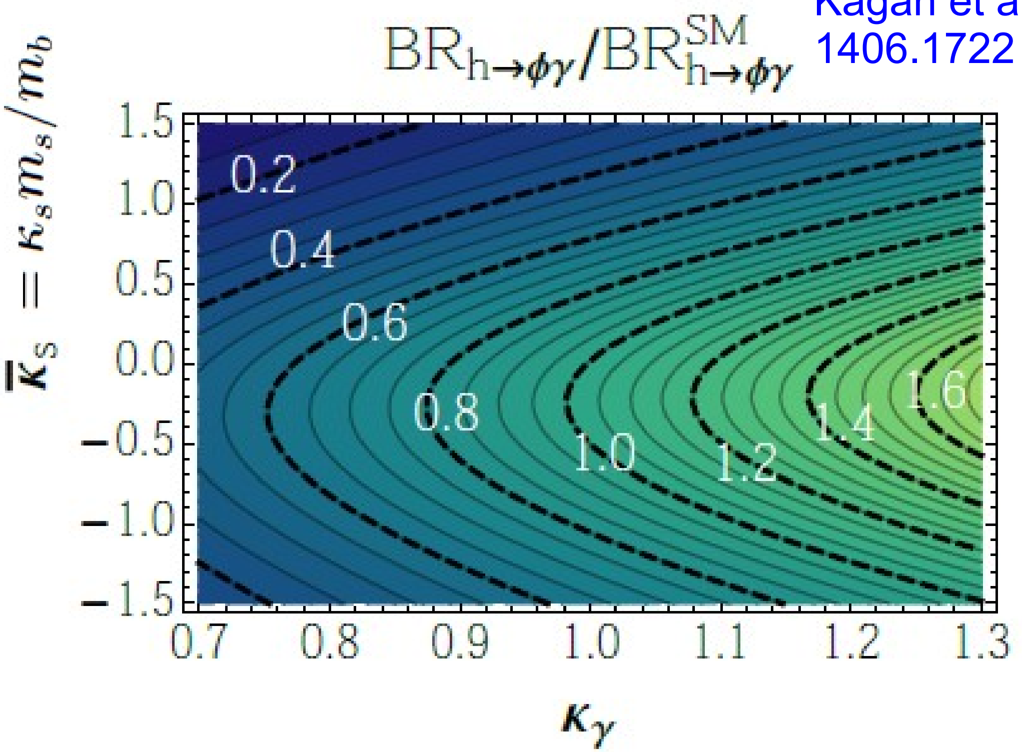
Light quarks: strange

$$\mathrm{BR}(h \to \phi\gamma) = 2.9 \times 10^{-6}(\kappa_\gamma - 2.6 \cdot 10^{-3}\kappa_s)^2$$

Kagan et al. 1406.1722



Very hard!

This is the only idea so far on how to directly measure this coupling

Experimental prospects?
YR4 of LHC HXSWG, in progress

Flavor violating Higgs couplings

In the SM, the Higgs flavor violating couplings are ~ 0.

➡ Great chance to discover New Physics

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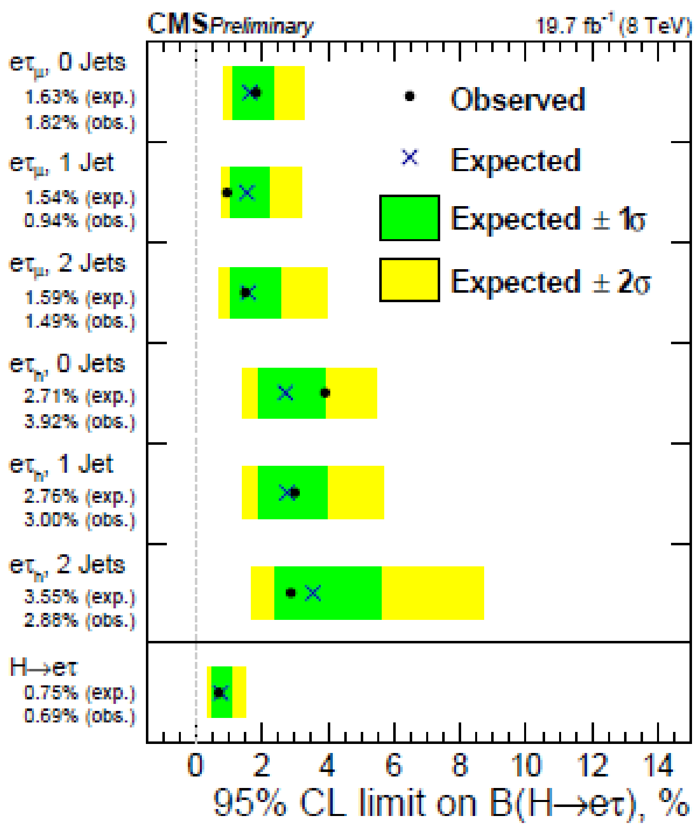
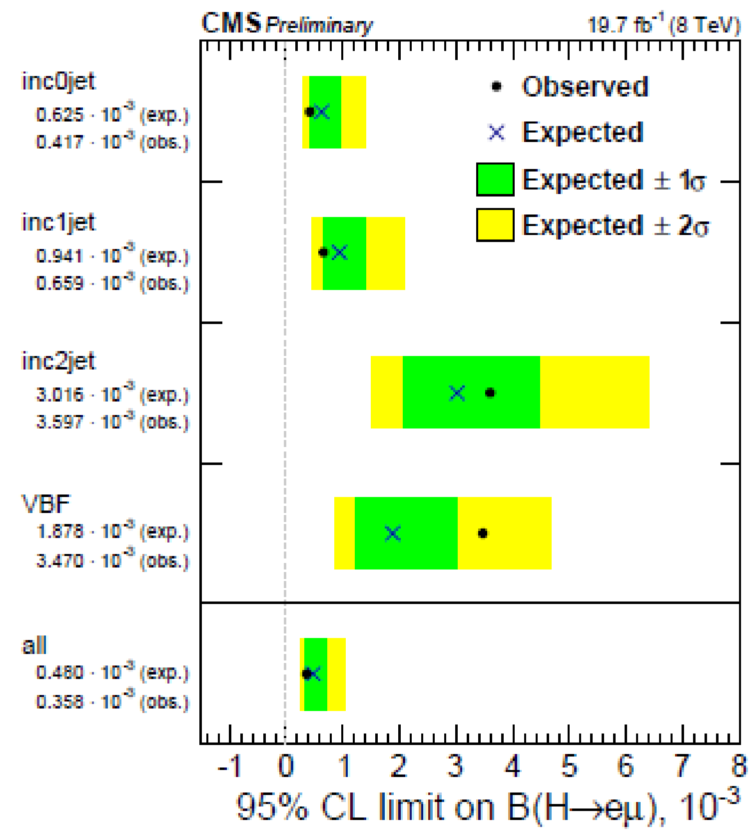
A few recent ATLAS and CMS searches:

eμ, eτ couplings:

New

CMS PAS HIG-14-040





$$\begin{aligned} BR(h \to e\tau) &< 0.7\% \\ BR(h \to e\mu) &< 0.036\% \end{aligned}$$

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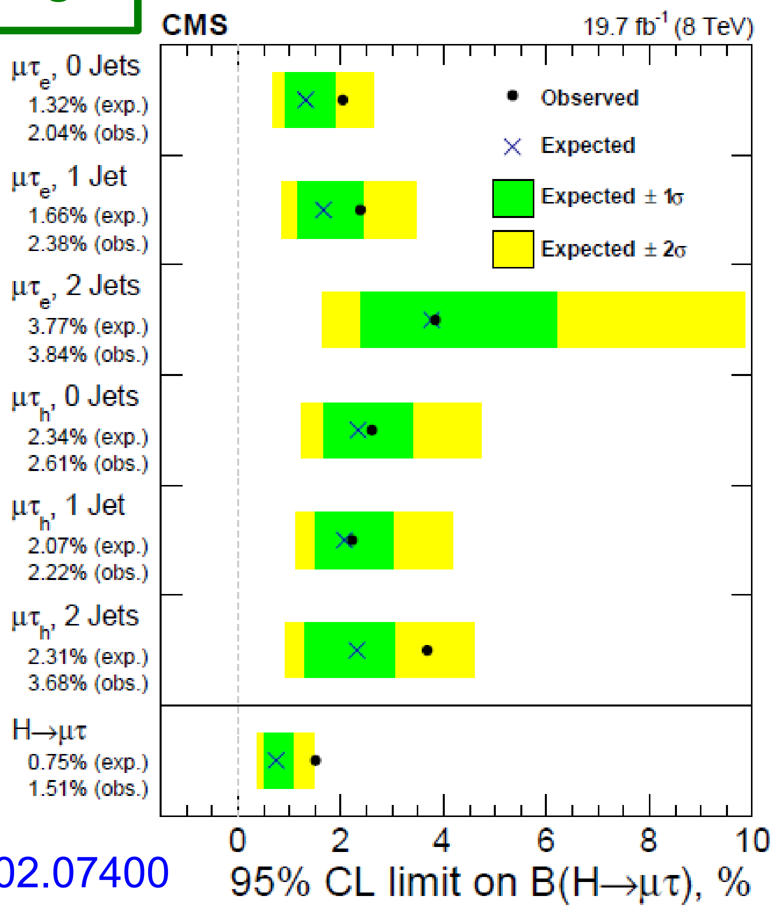
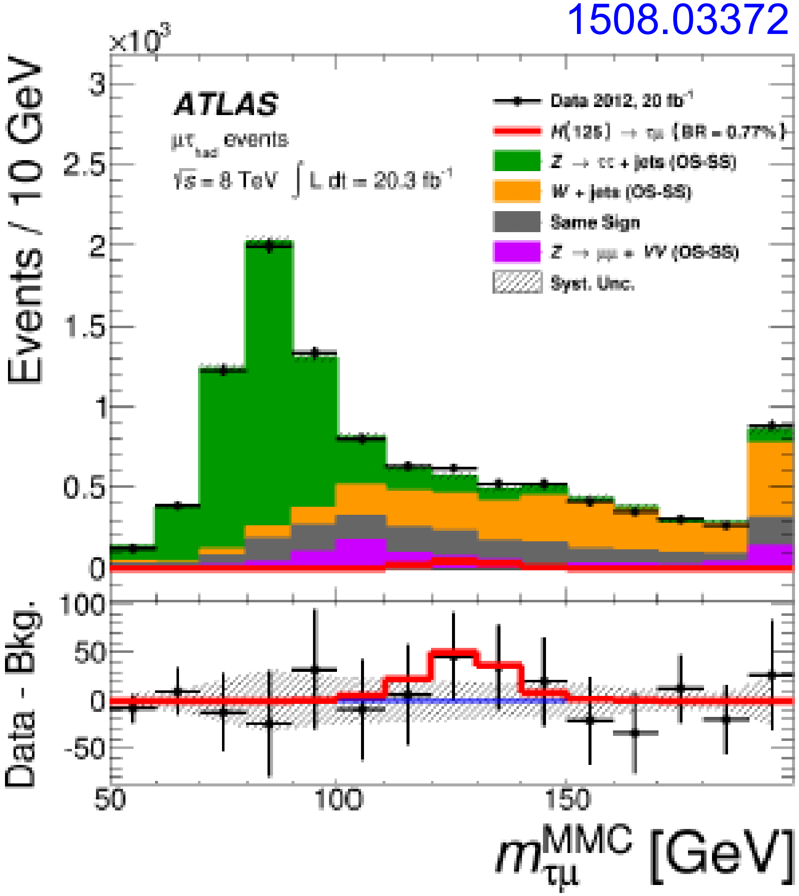


1502.07400

1508.03372



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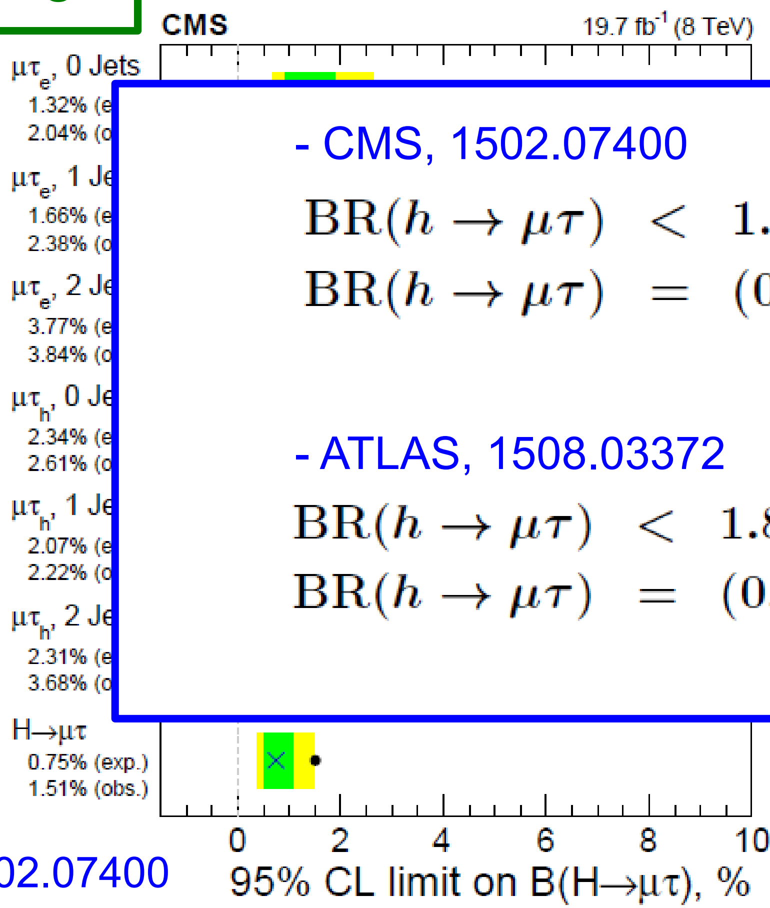

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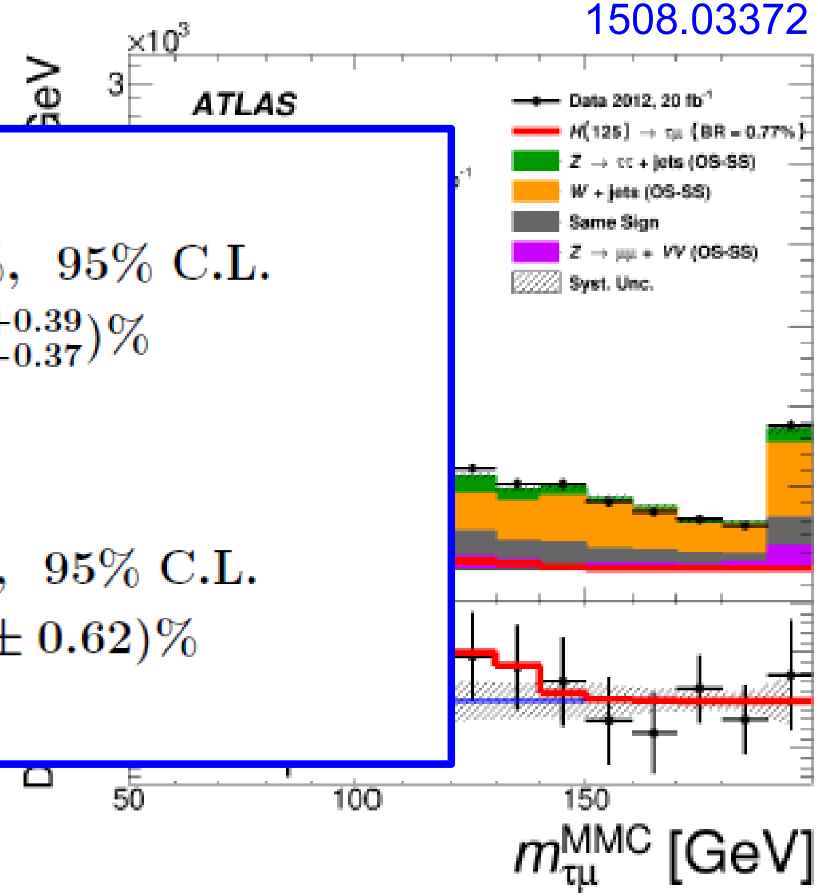


- CMS, 1502.07400

$$\mathrm{BR}(h \to \mu\tau) \ < \ 1.51\%, \ \ 95\%\ \mathrm{C.L.}$$
$$\mathrm{BR}(h \to \mu\tau) \ = \ (0.84^{+0.39}_{-0.37})\%$$

- ATLAS, 1508.03372

$$\mathrm{BR}(h \to \mu\tau) \ < \ 1.85\%, \ \ 95\%\ \mathrm{C.L.}$$
$$\mathrm{BR}(h \to \mu\tau) \ = \ (0.77 \pm 0.62)\%$$

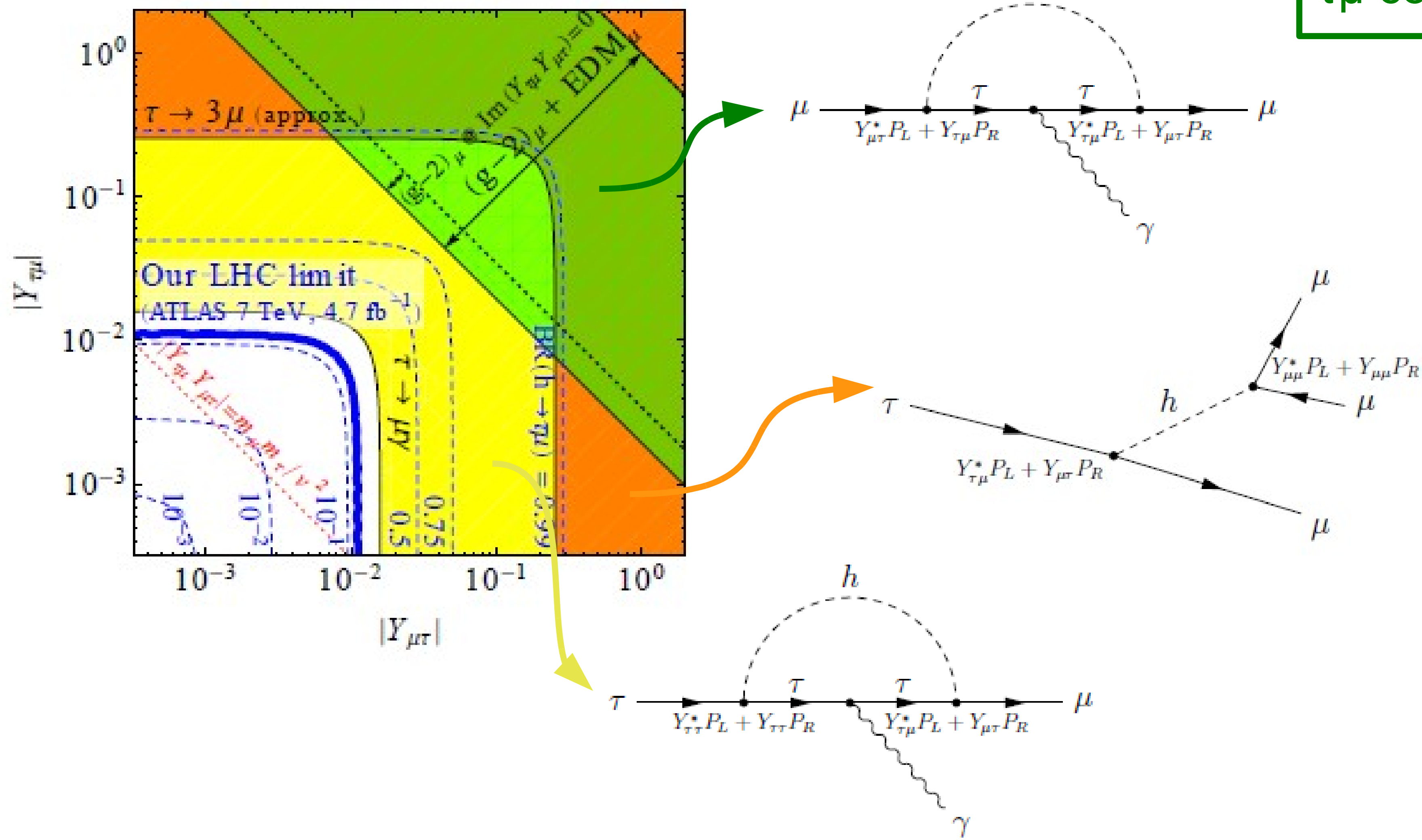
Only hadronic tau

Some "theory" constraints

If the Higgs has sizable flavor changing couplings,
it will affect several low energy flavor observables...

Harnik, Kopp, Zupan, 1209.1397

τμ couplings



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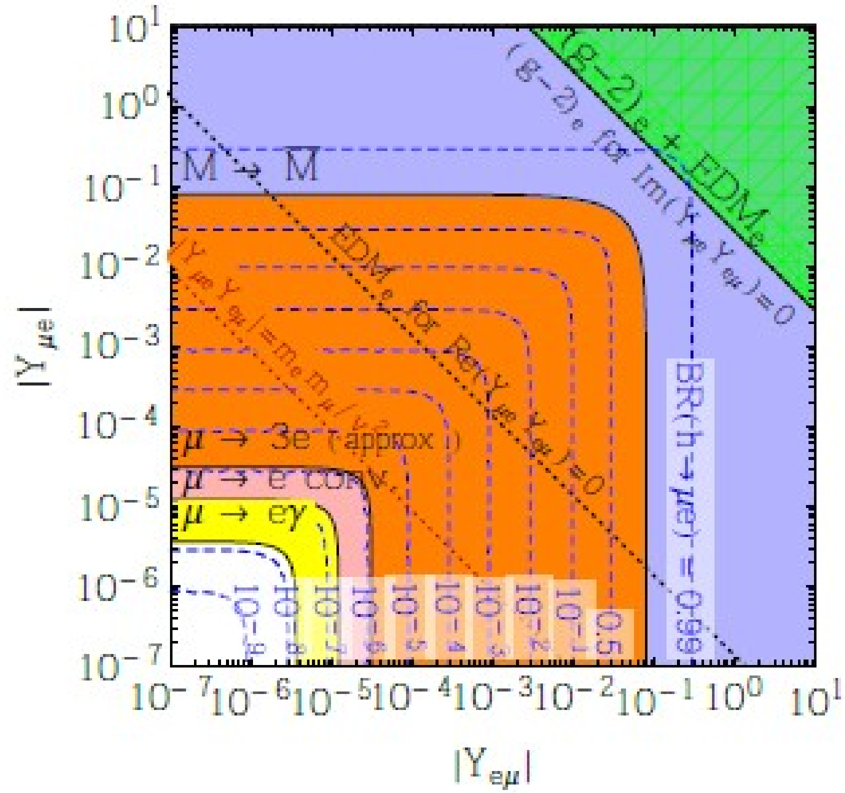
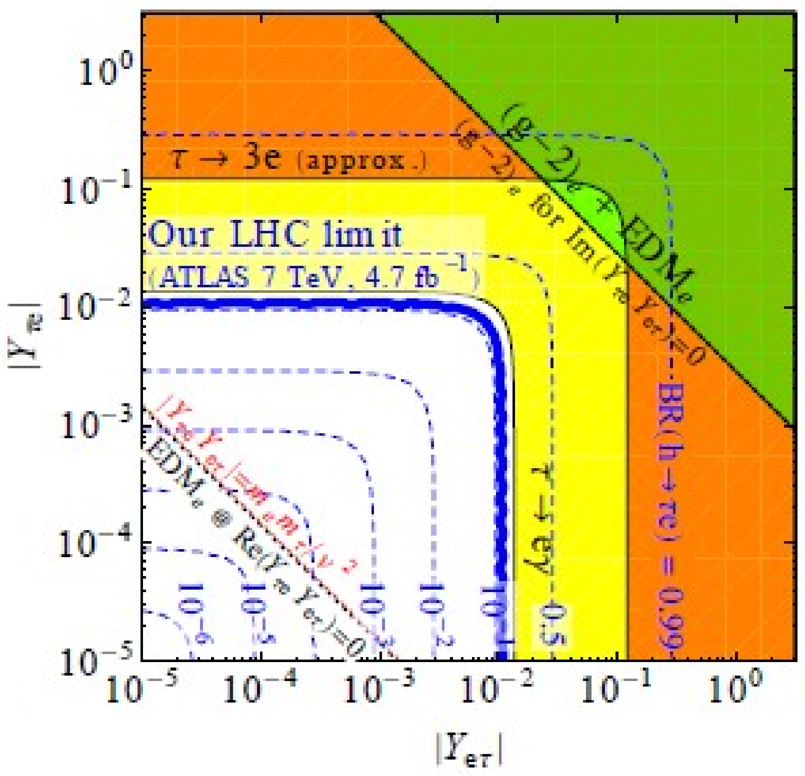




EFTs for Higgs flavor violation (1)

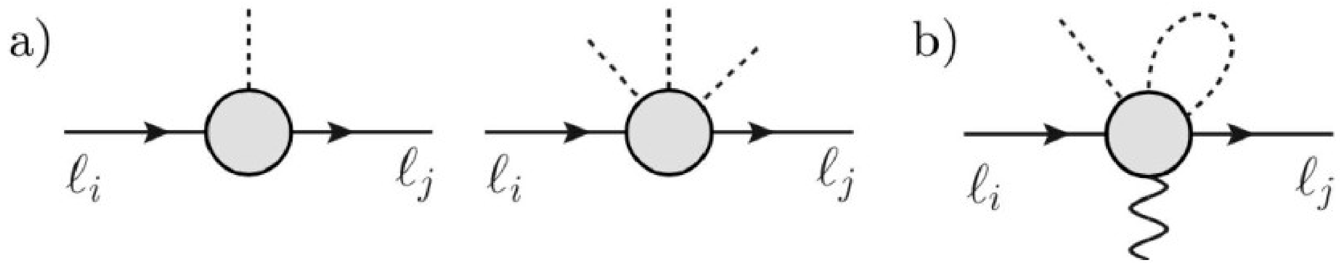
What do we learn from a possible non zero flavor changing Higgs coupling?

EFT approach: integrating out the new physics at scale Λ:

$$-\mathcal{L}_{\text{Yuk.}} = \lambda_{ij}(\bar{\ell}^i_L \ell^j_R)H \; + \; \frac{\lambda'_{ij}}{\Lambda^2}(\bar{\ell}^i_L \ell^j_R)H(H^\dagger H) + \ldots.$$

Let us assume there are no additional sources of EWSB,
then the "blobs" have to contain charged fields:

$$L_{\text{eff}} = c_{L,R}\, m_\tau \frac{e}{8\pi^2}(\bar{\mu}_{R,L}\sigma^{\mu\nu}\tau_{L,R})F_{\mu\nu}, \qquad c_{L,R} \sim \frac{v^2}{\Lambda^2}\frac{1}{m_\tau v}\langle \tau_L|\lambda'|\mu_R\rangle \sim \frac{Y_{\tau\mu}}{m_\tau v}$$



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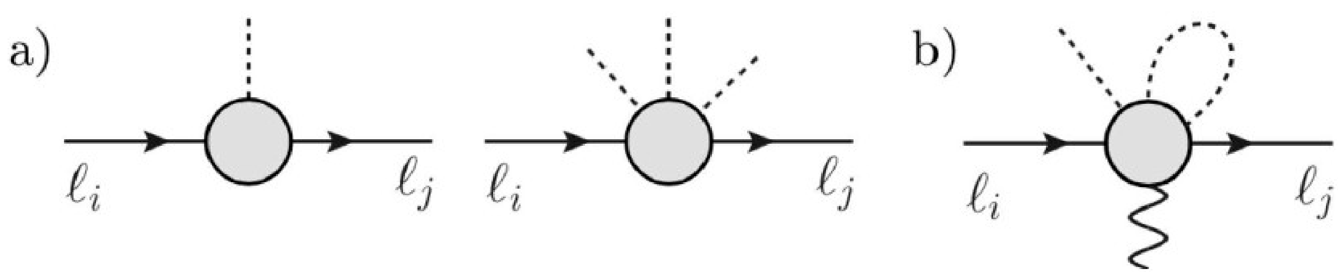

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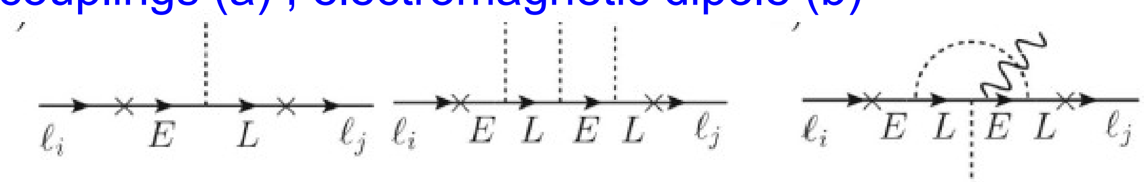
Example for a realization:



EFTs for Higgs flavor violation (2)

We have strong constraints from Babar searches of τ ⟶ μ γ:

$$\mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}\ (90\%\ \mathrm{CL}) \ \Rightarrow\ \sqrt{|c_L|^2 + c_R|^2} < \frac{1}{(3.8\mathrm{TeV})^2}$$

This bound can be read in terms of a bound on BR(h ⟶ τ μ):

BR(h ⟶ τ μ) ≤ 10^{-6}

To be compared with the ATLAS

$$\begin{aligned} \mathrm{BR}(h \to \mu\tau) &< 1.85\%,\ \ 95\%\ \mathrm{C.L.} \\ \mathrm{BR}(h \to \mu\tau) &= (0.77 \pm 0.62)\% \end{aligned}$$

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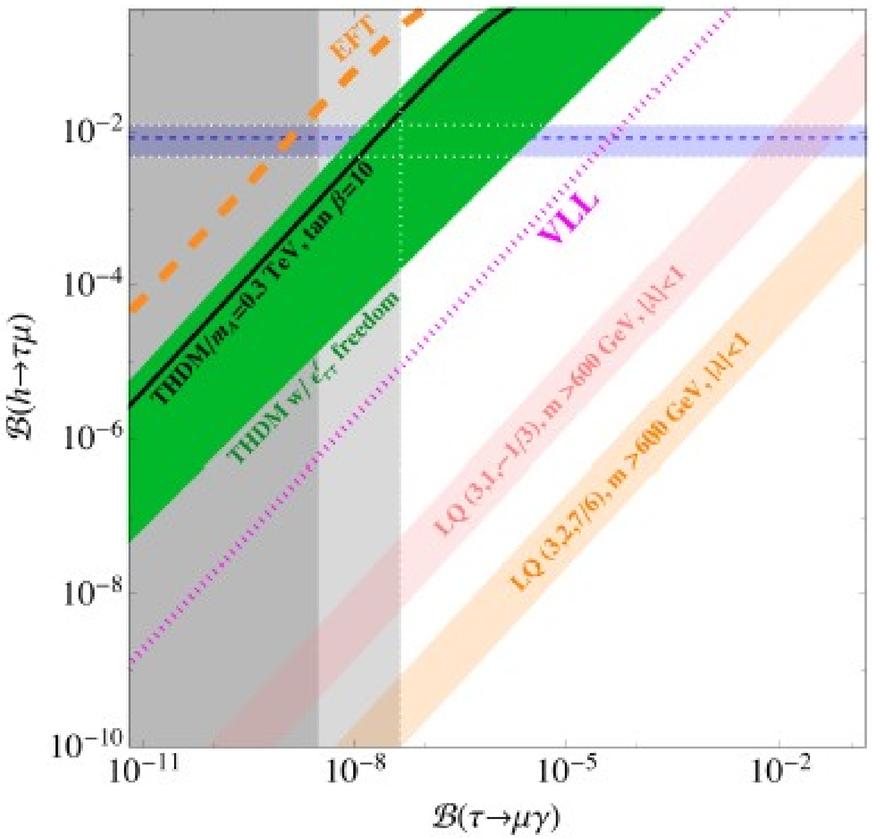
Beyond EFT:



Dorsner et al, 1502.07784

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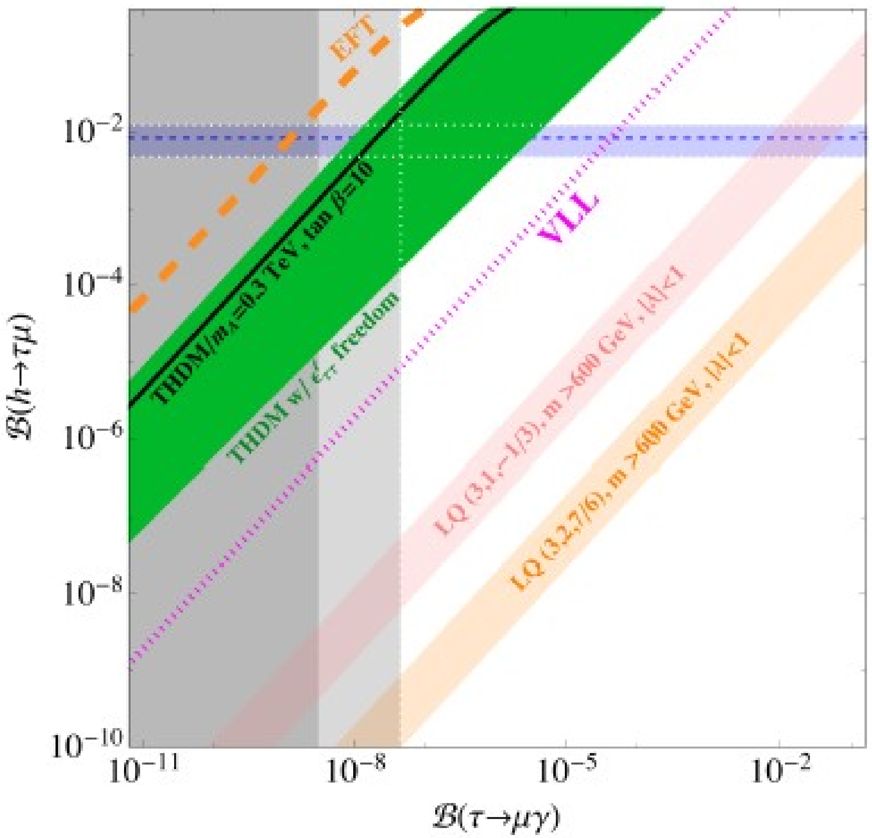

Dorsner et al, 1502.07784

Conclusion: if we do not have any additional source of EWSB, τ ⟶ μ γ rules out the possibility of having a sizable BR(h ⟶ τ μ)

Of course, one can always fine tune...

Additional sources of EWSB

If we have some additional source of EWSB, such that

See also Ghosh et al, 1508.01501

$$\mathcal{M}_\ell = \mathcal{M}_0 + \Delta\mathcal{M}$$

Due to Φ (the main component of the 125GeV Higgs)

It gives the bulk of m_τ

Due to some extra source.

It gives the bulk of m_μ and the flavor violating part

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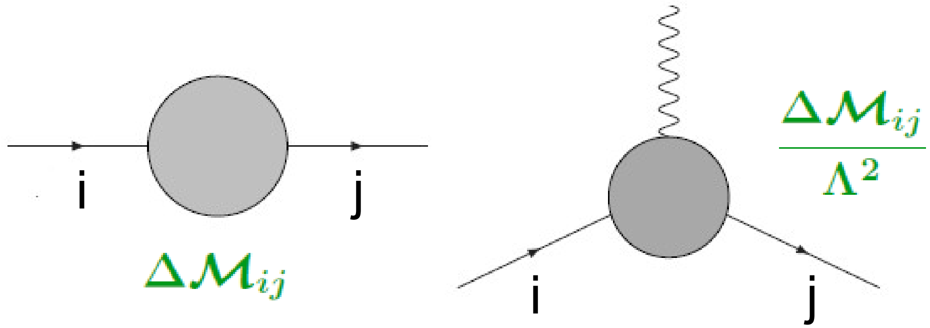
$$Y_{\mu\tau} = c_{\rm ewk}\frac{\langle\mu_L|\Delta\mathcal{M}|\tau_R\rangle}{v_W},$$

$$c_{L,R} \sim \frac{\langle\mu_L|\Delta\mathcal{M}|\tau_R\rangle}{\Lambda^2}\frac{8\pi^2}{m_\tau} \sim 10^4\frac{Y_{\tau\mu}}{\Lambda^2}$$

(c_{ewk} depends on the particular EWSB sector)

NP scale at which $\Delta\mathcal{M}$ is generated

The ATLAS central value is consistent with $\tau \longrightarrow \mu\gamma$ for $\Lambda \geq O(10\text{ TeV})$



Two realizations

- Consider two Higgs doublets ϕ and ϕ' with the same quantum numbers, with vev's v and v' ($\tan\beta = v/v'$)

It carries the most part of EWSB

(we have one parameter, $\tan\beta$, that can explain $m_\tau \gg m_\mu$)

Two realizations

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(we have one parameter, tanβ, that can explain $m_\tau \gg m_\mu$)

1. Z_3 symmetry based 2HDM:

$$-\mathcal{L}_Y = \lambda^e_{33}\bar{\ell}_3\phi e_3 + \lambda^e_{23}\bar{\ell}_2\phi' e_3 + \lambda^e_{32}\bar{\ell}_3\phi' e_2 + H.c.$$

$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 \\ 0 & m_{33} = \lambda^e_{33}\frac{v}{\sqrt{2}} \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} 0 & m_{23} = \lambda^e_{23}\frac{v'}{\sqrt{2}} \\ m_{32} = \lambda^e_{32}\frac{v'}{\sqrt{2}} & 0 \end{pmatrix}$$

We would like: $|m_{32}/m_{23}| < \text{few}$

"Horizontal model"

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1. Z_3 symmetry based 2HDM:

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$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 \\ 0 & m_{33} = \lambda^e_{33}\frac{v}{\sqrt{2}} \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} 0 & m_{23} = \lambda^e_{23}\frac{v'}{\sqrt{2}} \\ m_{32} = \lambda^e_{32}\frac{v'}{\sqrt{2}} & 0 \end{pmatrix}$$

We would like: $|m_{32}/m_{23}| < \text{few}$

"Horizontal model"

2. 2HDM with a generation mirror vector-like (VL) leptons:

$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 \\ 0 & m_{33} = \lambda^e_{33}\frac{v}{\sqrt{2}} \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} m'_{22} = \lambda^e_{23}\frac{v'}{\sqrt{2}} & m'_{23} = \lambda^e_{23}\frac{v'}{\sqrt{2}} \\ m'_{32} = \lambda^e_{32}\frac{v'}{\sqrt{2}} & m'_{33} = \lambda^e_{33}\frac{v'}{\sqrt{2}} \end{pmatrix}$$

VL leptons induce a rank-1 structure

We would like: $m'_{ij} \sim \mathcal{O}(m_\mu)$

"General model"

Some parametrics

- In these 2HDMs, the mixing between ϕ and ϕ' leads to flavor changing Higgs couplings. In particular:

$$y^h_{\mu\tau} = -\frac{\langle \mu_L | \Delta\mathcal{M} | \tau_R \rangle}{v_W} R_{\alpha\beta}, \qquad R_{\alpha\beta} = 2\,\frac{\cos(\alpha-\beta)}{\sin 2\beta}$$

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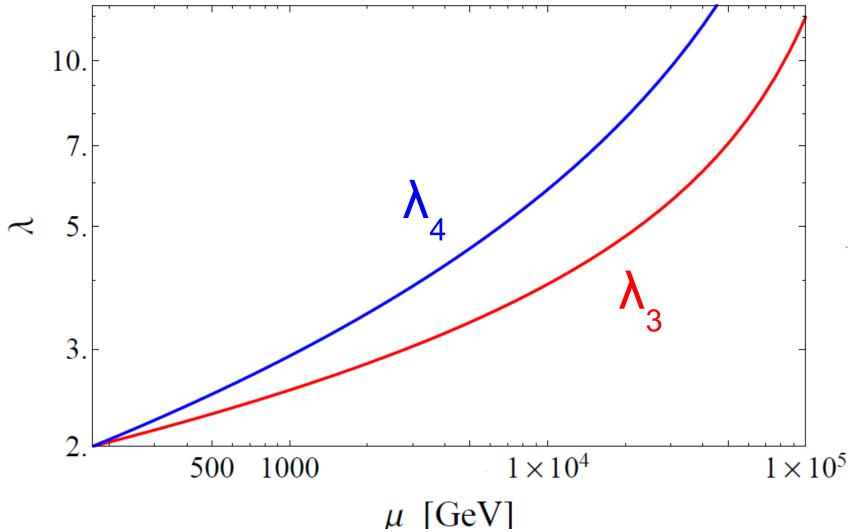
$$V = m^2\phi^\dagger\phi + m'^2\phi'^\dagger\phi' - \mu^2(\phi^\dagger\phi' + \phi'^\dagger\phi) + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(\phi'^\dagger\phi')^2 + \lambda_3(\phi^\dagger\phi)(\phi'^\dagger\phi') + \lambda_4(\phi^\dagger\phi')(\phi'^\dagger\phi)$$

$$R_{\alpha\beta} = \frac{v_W^2}{m_A^2}\left(-2\lambda_1 + \lambda_{34} + (2\lambda_2 - \lambda_{34})\frac{1}{\tan^2\beta}\right)$$

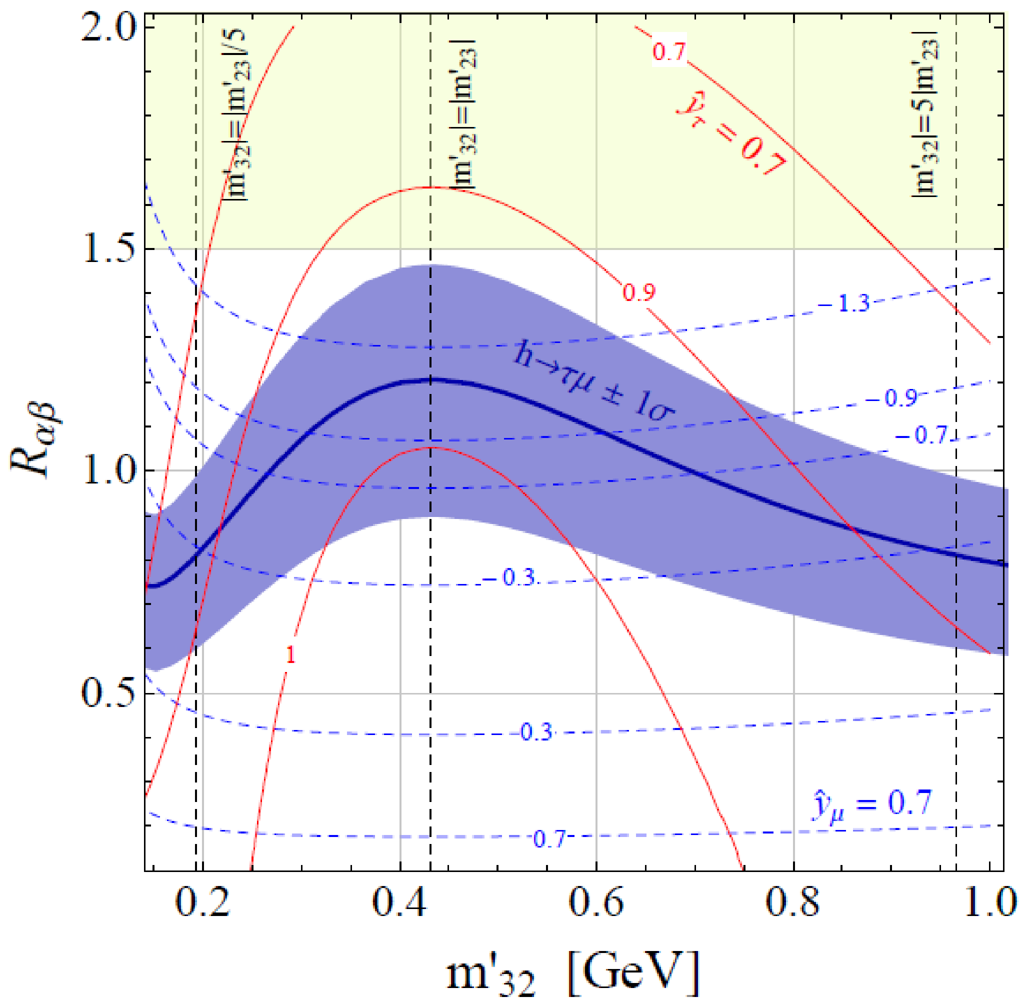
Large $\lambda_3+\lambda_4$ is required to have a BR(h⟶ τ μ) ~ 1%.



Higgs lepton couplings: horizontal

Wolfgang Altmannshofer, SG, Alex Kagan, Luca Silvestrini, Jure Zupan, 1507.07927

Not too hierarchical mass matrix



Constraint from the measurement of the HZZ coupling

Region favored by the CMS h ⟶ τ μ analysis

Breaking of universality:

$$\hat{y}_\mu \simeq \frac{c_\alpha}{s_\beta} - \frac{(\Delta\mathcal{M})_{\mu\mu}}{m_\mu}\frac{c_{\beta-\alpha}}{s_\beta c_\beta}$$

$$\hat{y}_\tau \simeq \frac{c_\alpha}{s_\beta}$$

Higgs lepton couplings: horizontal/generic

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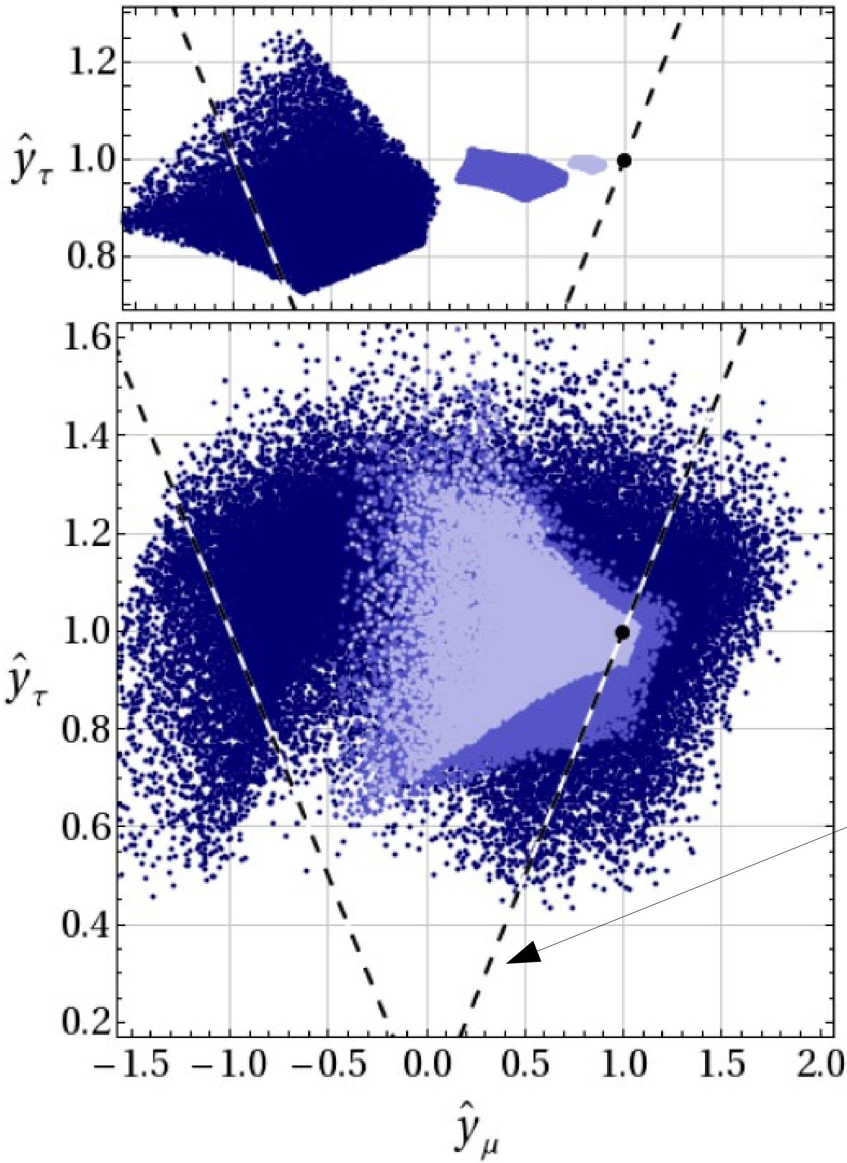

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Universality relation

CMS measurement
1/3 CMS measurement
1/10 CMS measurement

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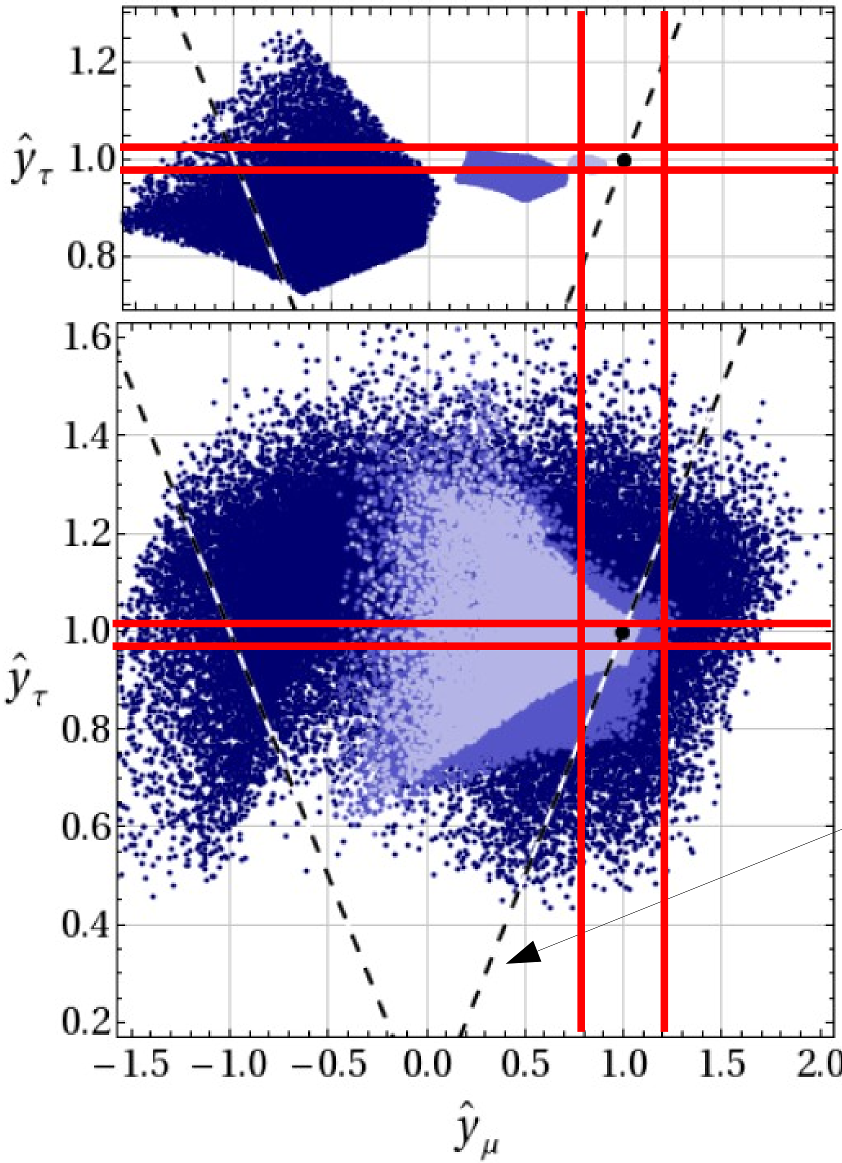

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Extension to the quark sector

- At present, no hint for a non-zero Higgs quark flavor changing coupling
- It is interesting to study/test models with breaking of universality
- Maybe our Higgs is not giving mass to the light quark generations...

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$$\mathcal{M}_0 \sim \begin{pmatrix} 0 & 0 \\ 0 & m_b \end{pmatrix}, \quad \Delta\mathcal{M} \sim \begin{pmatrix} m_s & m_s \\ m_s & m_s \end{pmatrix}$$ Down sector

A structure like this can also reproduce the 2-3 block of the CKM matrix since $m_s \sim V_{cb} m_b$

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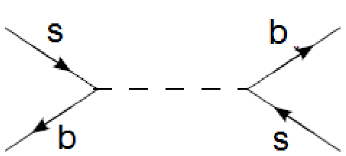


Some bounds arise from B meson low energy observables:

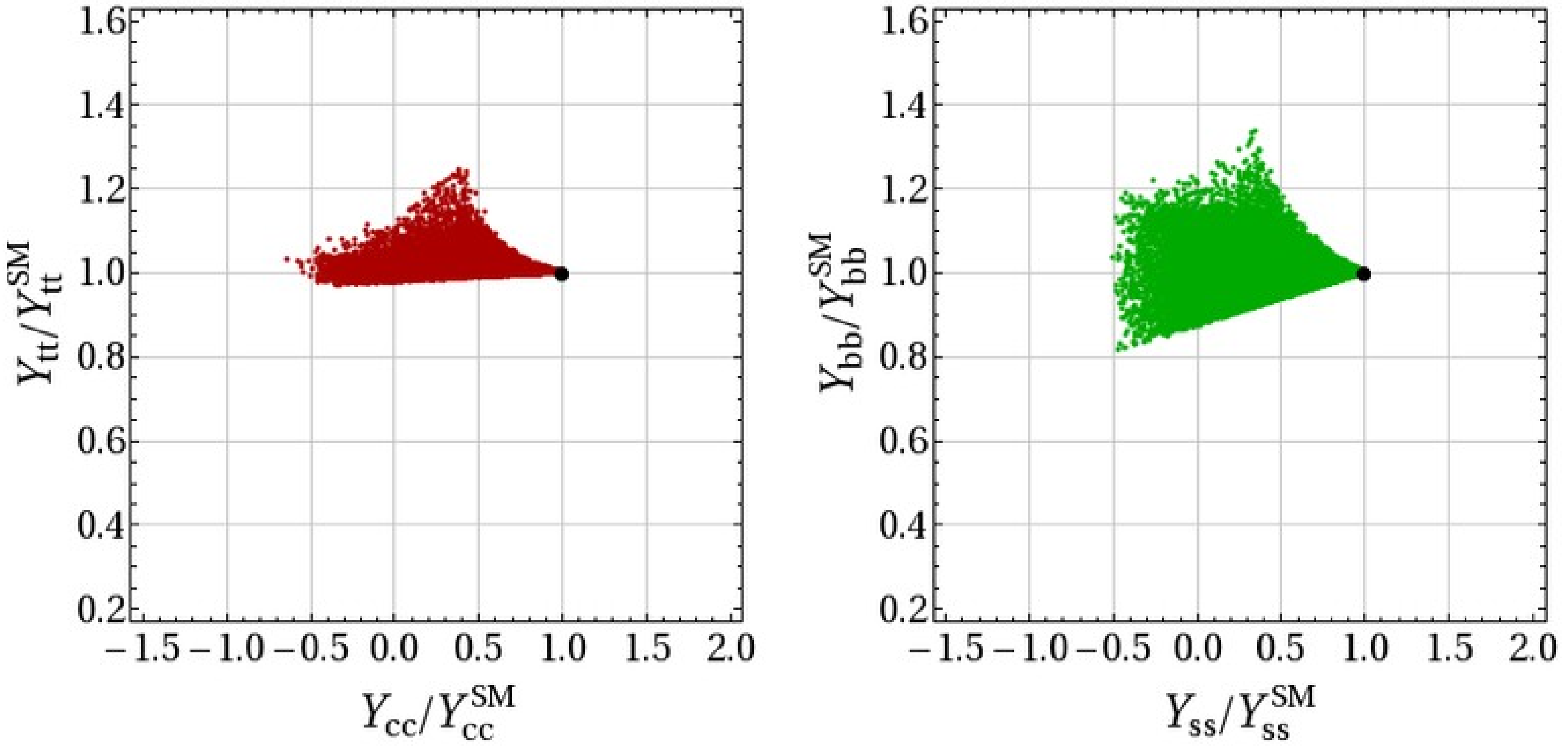
B meson mixing: contribution to the operator $C_4(\bar{b}_R s_L)(\bar{b}_L s_R)$, $C_4 \sim \frac{V_{cb}^2 m_b^2}{v_W^2 m_h^2} R_{\alpha\beta}^2$

This is a bit too large, but we are in the right ballpark: $m_s \sim V_{cb} m_b \to \frac{V_{cb} m_b}{6 R_{\alpha\beta}}$

 S.Gori

Non universal quark Higgs couplings

Wolfgang Altmannshofer, SG, Alex Kagan,
Luca Silvestrini, Jure Zupan, in progress



3 generations quarks and leptons

Does a construction like that work for 3 generations?

$$\mathcal{M}_0 \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_t \end{pmatrix}, \quad \Delta\mathcal{M} \sim \begin{pmatrix} m_u & m_u & m_u \\ m_u & m_c & m_c \\ m_u & m_c & m_c \end{pmatrix}$$

Up sector

$$\mathcal{M}_0 \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix}, \quad \Delta\mathcal{M} \sim \begin{pmatrix} m_d & m_d & m_d \\ m_d & m_s & m_s \\ m_d & m_s & m_s \end{pmatrix}$$

Down sector

- Also the CKM matrix can be generated by this structure since

$$V_{ub} m_b \sim \text{few} \times m_d, \; V_{us} m_s \sim \text{few} \times m_d$$

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- Also the CKM matrix can be generated by this structure since $V_{ub} m_b \sim \text{few} \times m_d,\ V_{us} m_s \sim \text{few} \times m_d$

- A nice approximate U(2) flavor symmetry for the first two families

Rotating to the mass eigenstate basis:

$s \leftrightarrow d : V_{td} m_s \sim \lambda^3 m_s$ instead of the naive λ m_s ~ few m_d

Still a little too large: $m_d \to \frac{m_d}{10 R^2_{\alpha\beta}}$

Similarly for the lepton sector: $e \leftrightarrow \mu : \frac{m_e m_\mu}{m_\tau}$ instead of the naive m_e

Pheno consequences+open questions

- This framework can be relatively easily in agreement with low energy flavor transitions, in addition to produce the correct pattern for quark and lepton masses and mixing angles.

- Interesting new signatures arise:

  - Sizable BR($B_s \longrightarrow \tau\,\mu$) Not clear if LHCb can do this

  In particular, at large values of tanβ, we can obtain

$$\frac{\mathrm{BR}(B_s \to \tau\mu)}{\mathrm{BR}(B_s \to \mu\mu)_{\mathrm{SM}}} \sim 200$$

Together with a small NP effect in $B_s \longrightarrow \mu\,\mu$

$$\frac{\mathrm{BR}(B_s \to \tau\mu)}{\mathrm{BR}(B_s \to \mu\mu)_{\mathrm{SM}}} \propto \left(\frac{4\pi^2}{e^2}\right)^2 \tan^4\beta \frac{m_{B_s}^4}{m_A^4} \left(\frac{|(\Delta\mathcal{M})_{\mu\tau}|^2 + (|\Delta\mathcal{M})_{\tau\mu}|^2}{m_\mu^2}\right)$$

  - In the same region of parameter space, sizable BR($B \longrightarrow K^{(*)}\tau\mu$)

$$\mathrm{BR}(B \to K^{(*)}\tau\mu) \sim 10^{-7}$$

GOAL for the LHCb

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GOAL for the LHCb

- Questions:
  - Can a "horizontal" model (based on discrete symmetries) work for three generation quarks and leptons?
  - Correlated pheno of the additional Higgs bosons

Wolfgang Altmannshofer, SG, Alex Kagan, Luca Silvestrini, Jure Zupan, in progress

Conclusions

- With Run I LHC, we got to know the first features of the Higgs boson: we know that
  - It is the (main) responsible of EWSB
  - It gives (some) mass to the third generation quarks and leptons

- We have almost no idea of many couplings of the Higgs:
  - Higgs couplings to light quarks and leptons (flavor conserving)
  - Higgs flavor violating couplings

- Opportunity of testing the Higgs flavor structure:
  - Is the Higgs responsible for the mass of light quarks and leptons?
  - Connection between flavor violating Higgs couplings and the SM flavor puzzle?