Signatures of Flavorful Higgs Bosons

Stefania Gori
University of Cincinnati

Topic of the week seminar

Fermilab,
August 16th 2016

Outline

1. Introduction

- Higgs discovery & self-consistency of the Standard Model
- The Higgs and the flavor puzzle
- How to measure the coupling to 1st and 2nd generation fermions?

2. A new model for the generation of fermion masses

- A "sequestered" Two Higgs Doublet Model
- Consistency with low energy flavor measurements
- Impact on the Higgs phenomenology

3. Discovering the new Higgs states

- New production and decays of the additional Higgs bosons
- For ATLAS+CMS: are we missing any search?

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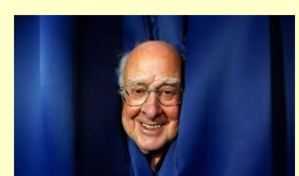
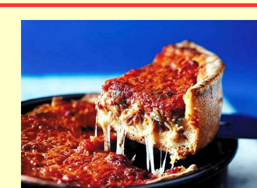
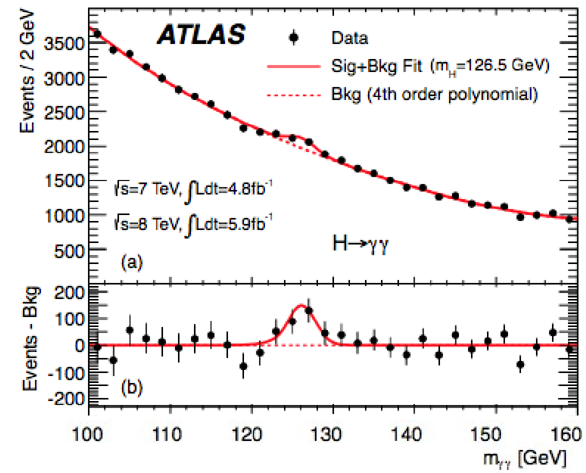
Some references

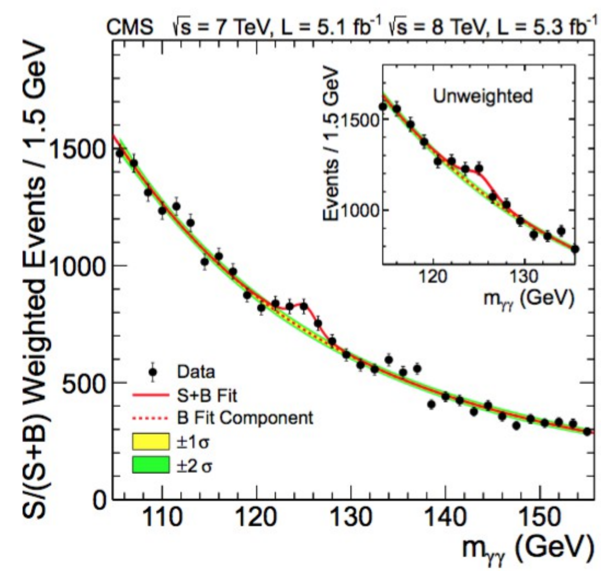
- W. Altmannshofer, SG, A. Kagan, L. Silvestrini, J. Zupan, 1507.07927 + in progress
- W. Altmannshofer, J. Eby, SG, M. Lotito, M. Martone, D. Tuckler, to appear soon

Topic of the week: **Higgs & flavor**  &  

Discovery!

The first elementary particle discovery of 21st century





CERN, July 4th 2012, ~11am

After ~30 years of experimental searches (LEP, SLC, Tevatron, LHC)

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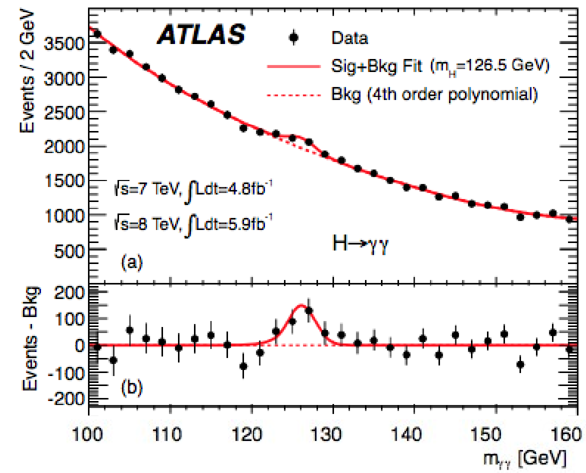

http://www.google.com/trends/

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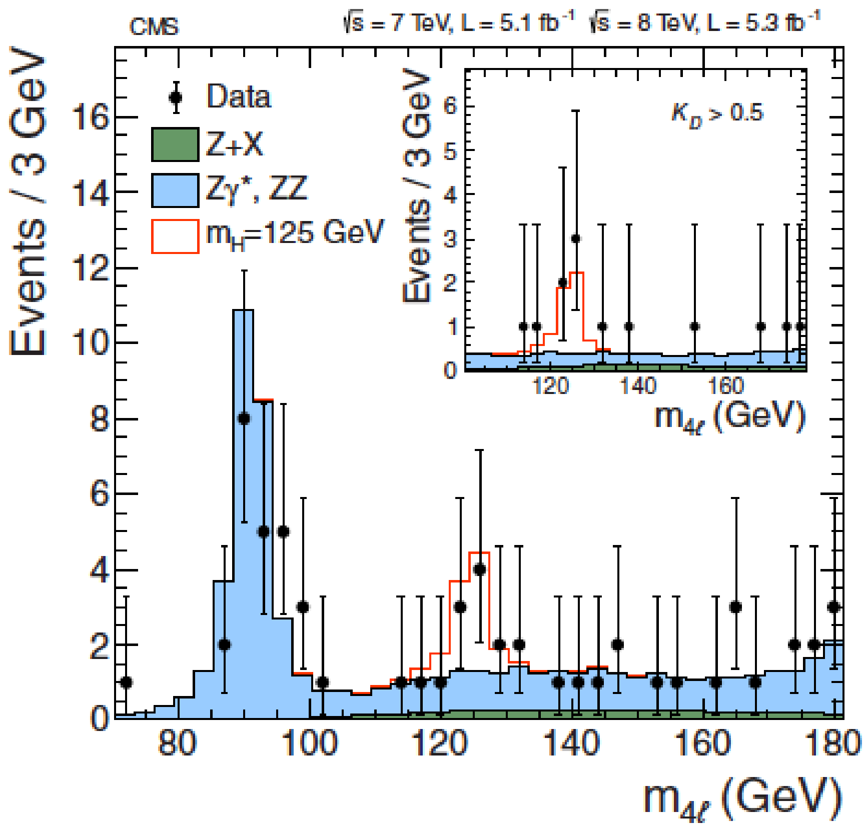
After ~30 years of experimental searches
(LEP, SLC, Tevatron, LHC)

A particle responsible for EWSB

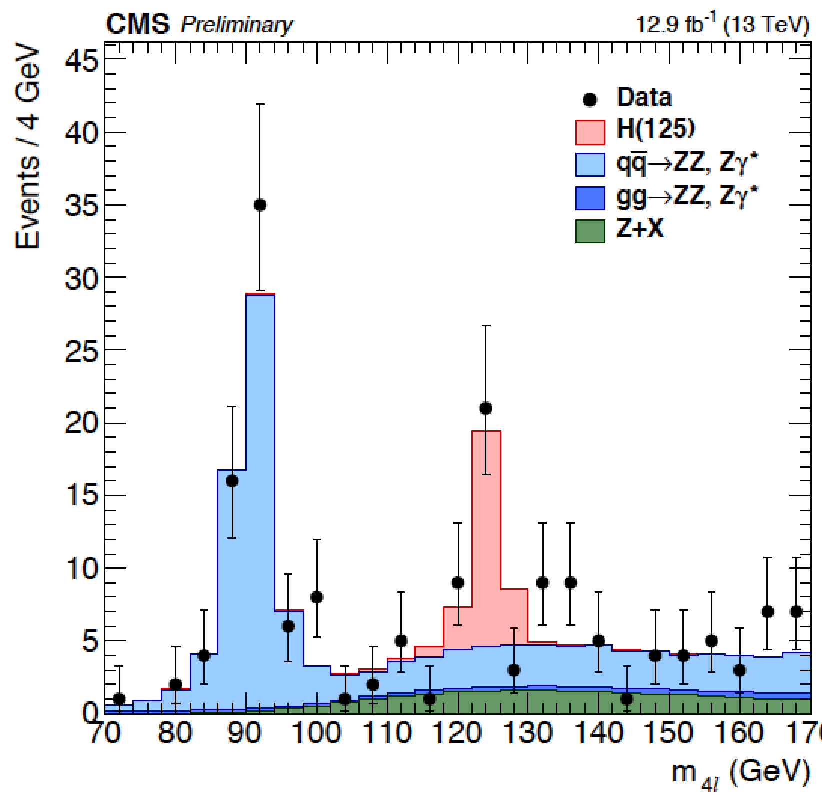
This new particle is, indeed, a Higgs boson!

It gives mass to the SM W and Z boson
(and therefore it breaks Electroweak Symmatry (EWSB))

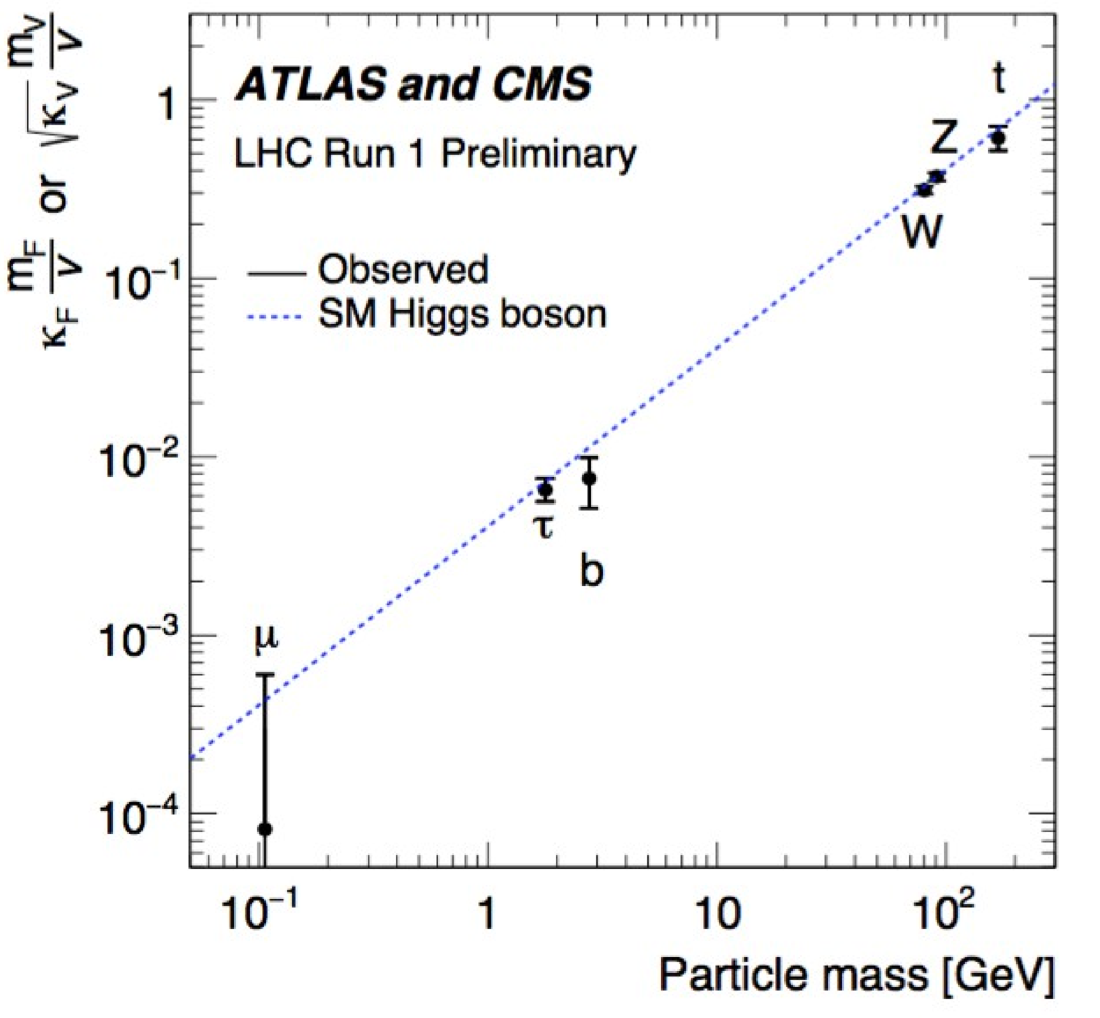
July 2012



August 2016 (after ICHEP)



Giving mass to the 3rd generation fermions



Flavor diagonal couplings to 3rd generation known with 20% - 30% uncertainty.

Substantial improvement at future LHC runs and at a ILC or FCC-ee.

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

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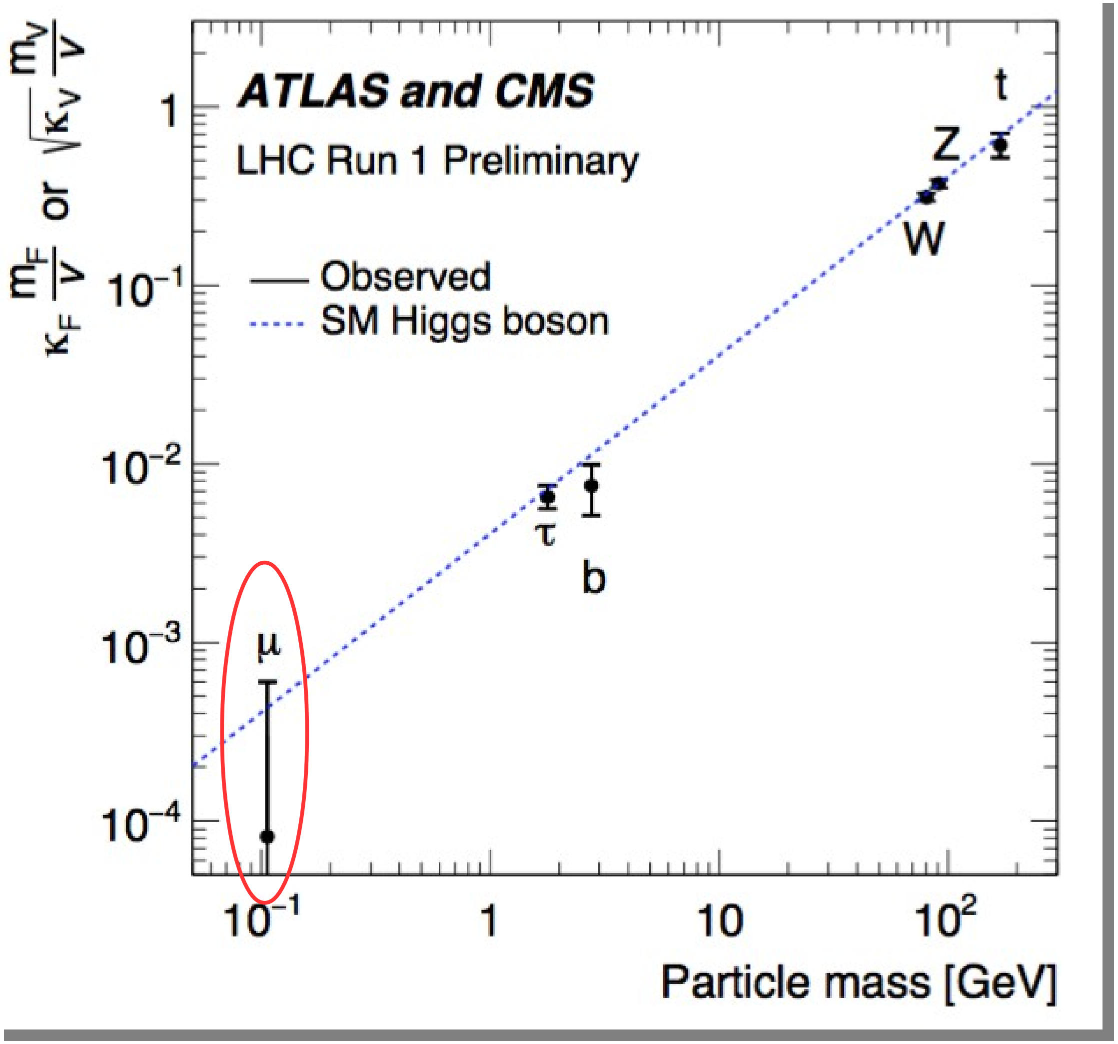

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Substantial improvement at future LHC runs and at a ILC or FCC-ee.

With large enough stats, it will be possible to get the SM muon coupling (10% accuracy with 3/ab)

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

Self-consistency of the Standard Model

Higgs mass

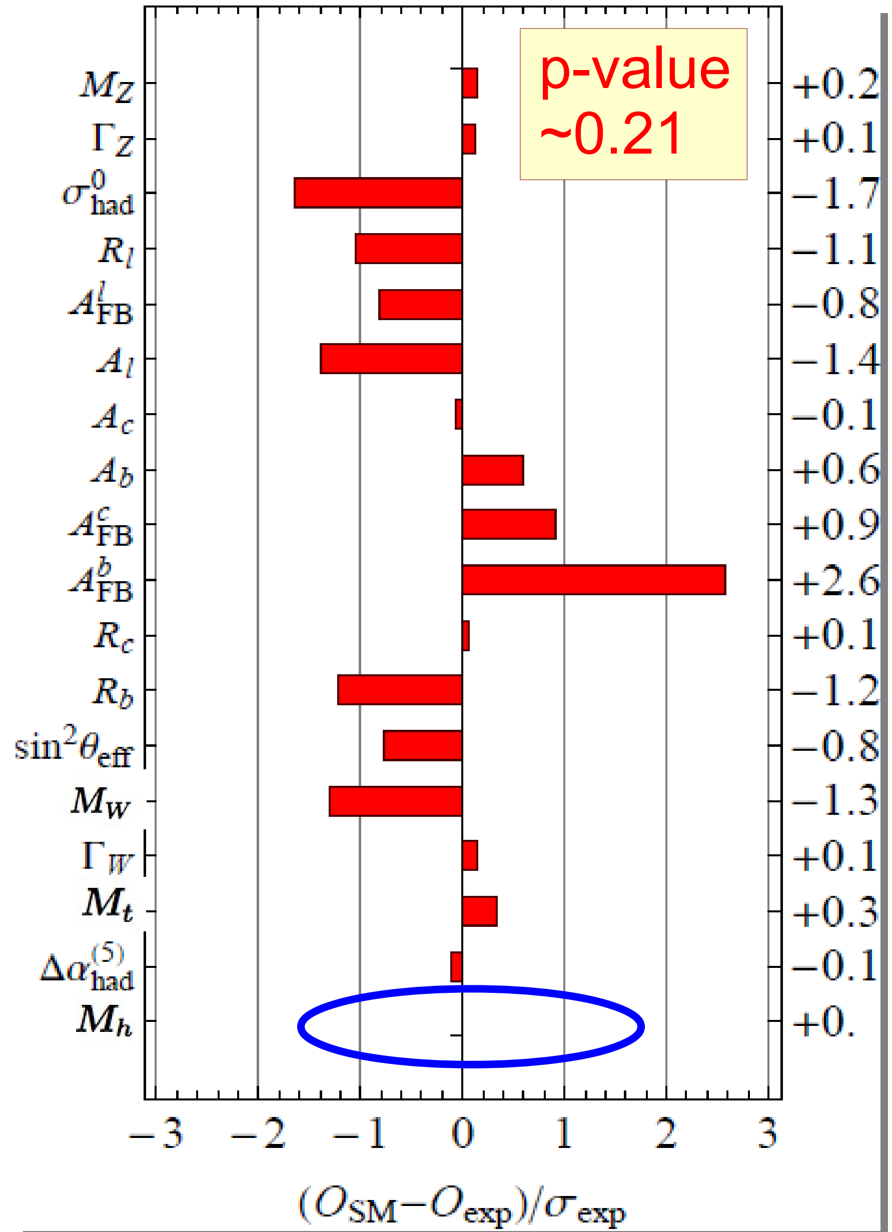
Z properties

If the Higgs is the one of the SM...

For the first time we have the measurement of a self-consistent ElectroWeak sector

Several working groups dedicated to this study: ZFITTER, Gfitter, PDG, ...

Result of many years of experimental & theory efforts



Update from Batell, SG, Wang, 1209.6382

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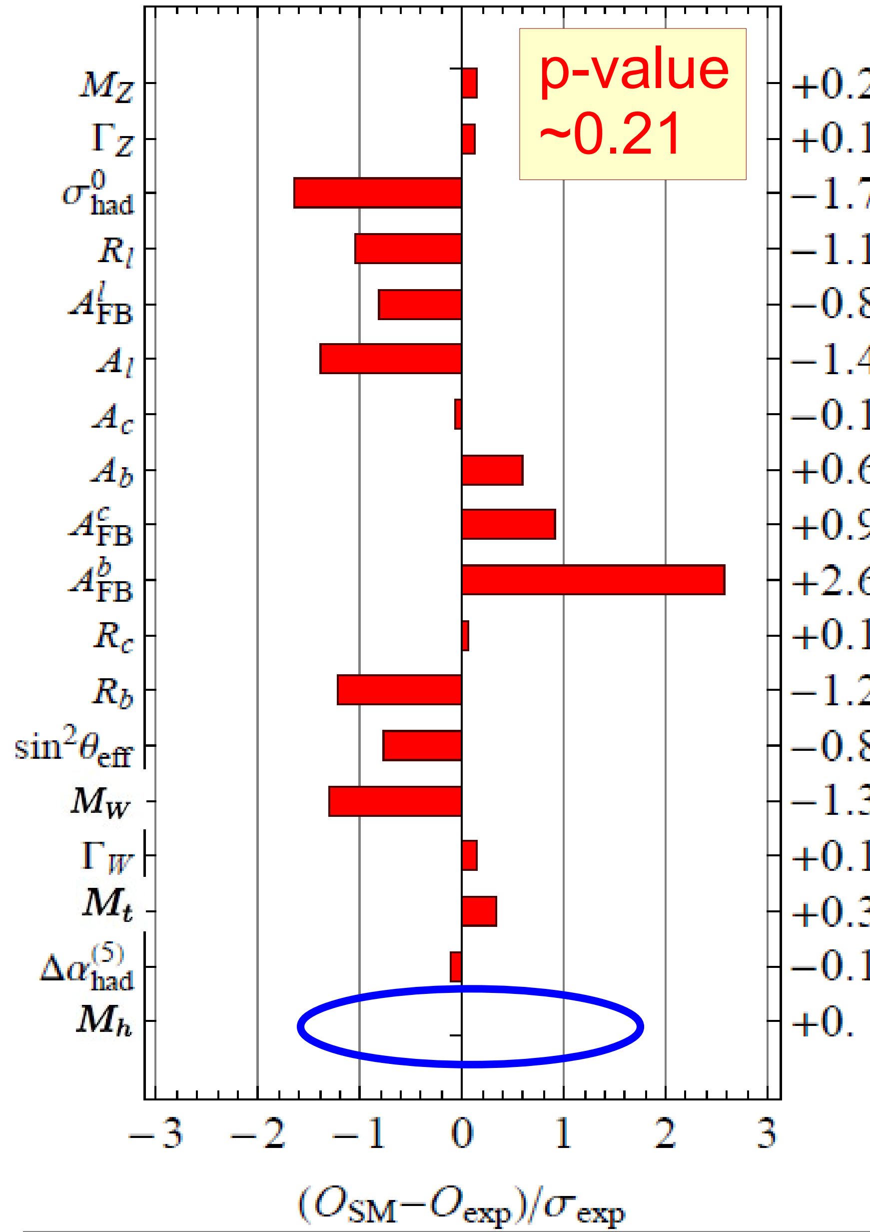
If e.g. M_h = 300 GeV → p-value ~ 3 × 10^{-5} !



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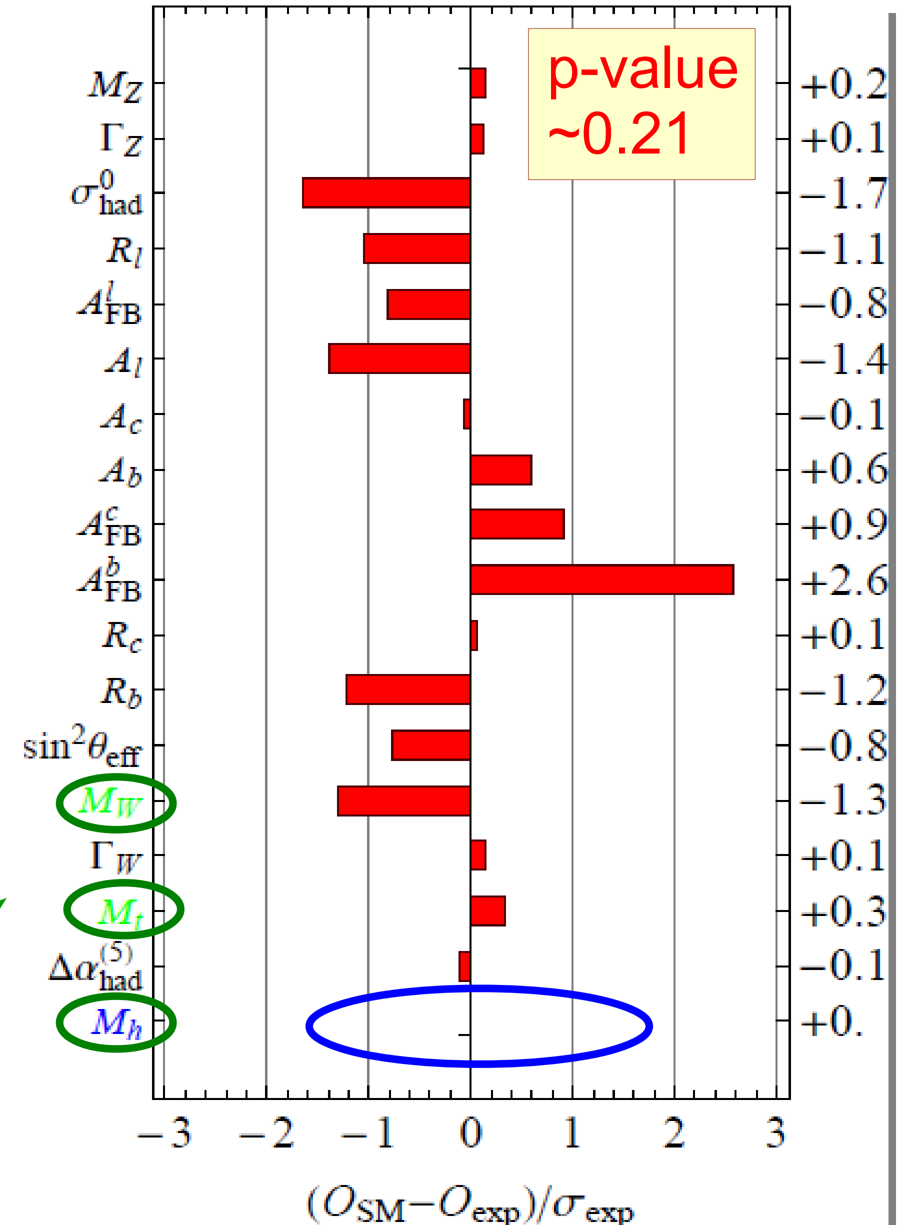
More precise measurements
in the **future of the LHC**



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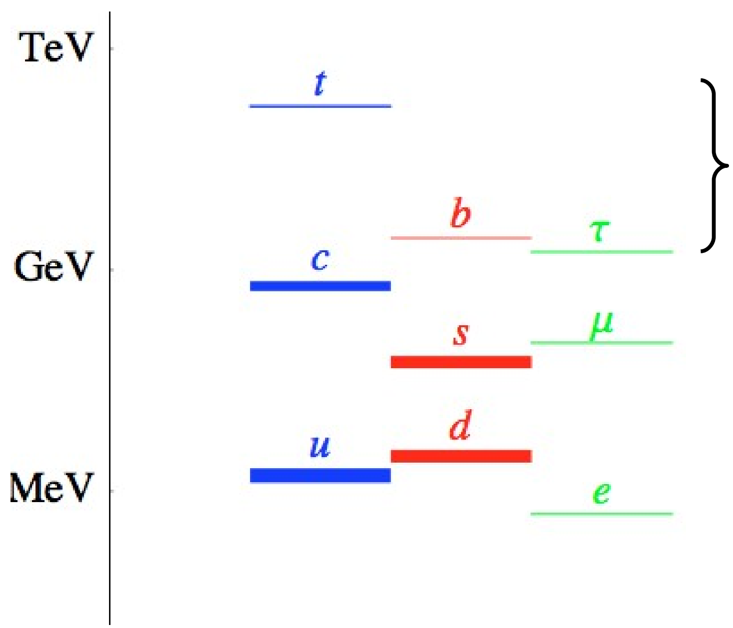
What's next? A complete picture for EWSB?

Experimentally, we do not know if the Higgs couples to

- Muons (m_μ ~ 100 MeV)
- Electrons (m_e ~ 0.5 MeV)
- Light quarks (m_c~1.3 GeV, m_s ~ 100 MeV, m_d ~ 6 MeV, m_u ~ 3 MeV)

These are very small couplings in the Standard Model (SM)



3rd generation

Huge program for precision measurements ongoing

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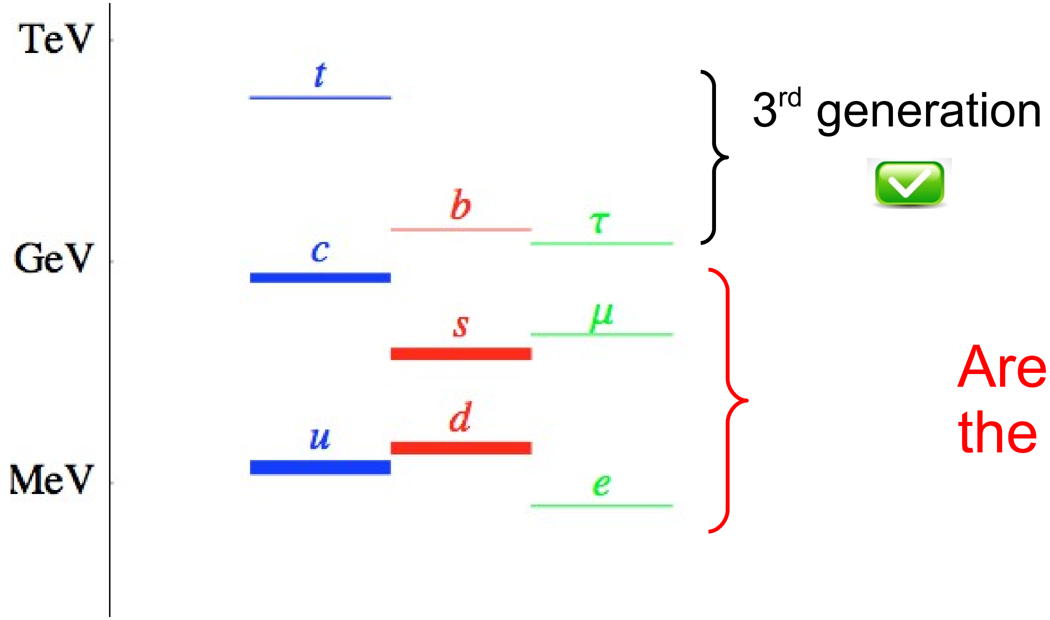

Huge program for precision measurements ongoing

Are we able to test the flavor puzzle?

Note that the consistency check for the electroweak precision observables has been done under the <u>assumption of proportionality</u> between Higgs couplings and fermion masses!

How to probe lighter Yukawas? (1)

In general, it is very challenging!

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Leptons

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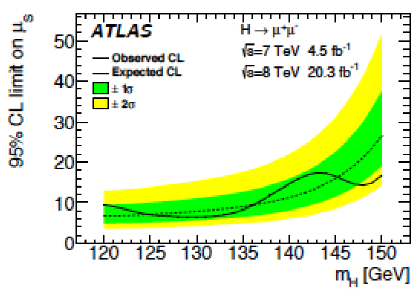
Muons:

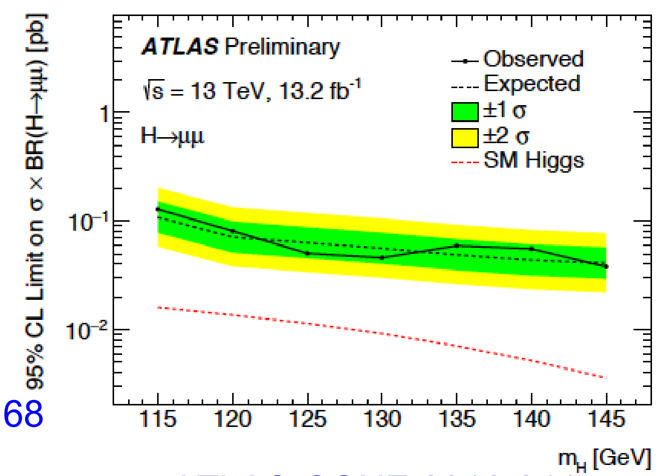
Now:

Run-1



Phys. Lett. B 738 (2014) 68

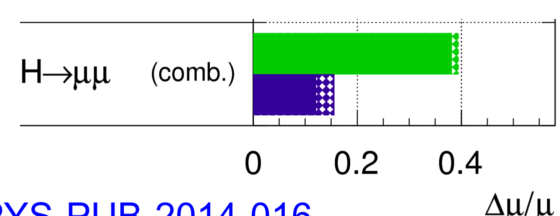
Run-2



ATLAS-CONF-2016-041

$$\mu < 3.5(\text{obs.}),\ \ 4.3(\text{exp.})$$

Future:



300 fb^{-1}
3000 fb^{-1}

ATL-PYS-PUB-2014-016

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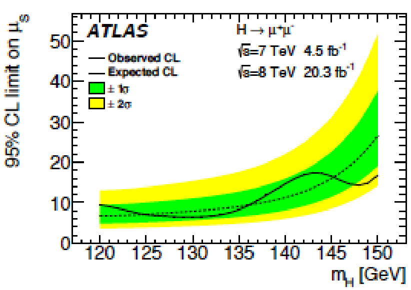

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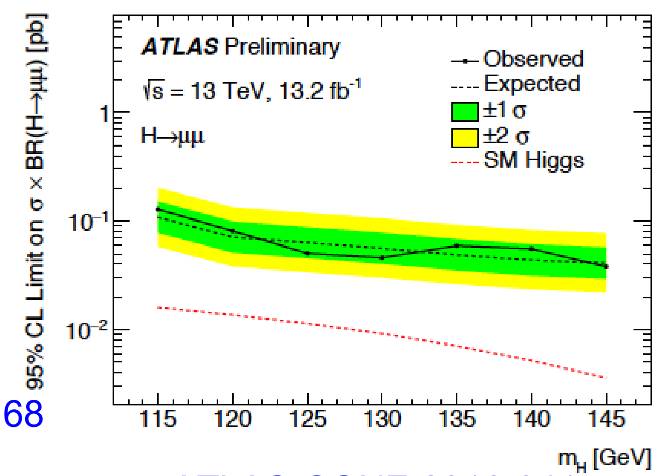
Run-2



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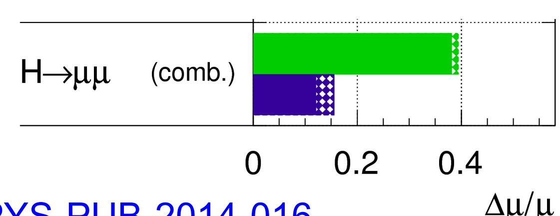


300 fb^{-1}
3000 fb^{-1}

ATL-PYS-PUB-2014-016

Electrons:

It would be easy
to measure at the LHC.
Problem = statistics

In the SM: BR(h → ee) ~ 5 × 10^{-9}

$h \to e^+e^-$	LHC8 (25/fb)	$\lvert\kappa_e\rvert \lesssim 600$	$M \gtrsim 6$ TeV
	LHC14 (300/fb)	$\lvert\kappa_e\rvert \sim 260$	$M \sim 9$ TeV
	LHC14 (3/ab)	$\lvert\kappa_e\rvert \sim 150$	$M \sim 12$ TeV
	100 TeV (3/ab)	$\lvert\kappa_e\rvert \sim 75$	$M \sim 17$ TeV
$e^+e^- \to h$	LEP II	$\lvert\kappa_e\rvert \lesssim 2000$	$M \gtrsim 3$ TeV
	TLEP (1/fb)	$\lvert\kappa_e\rvert \sim 50$	$M \sim 20$ TeV
	TLEP (100/fb)	$\lvert\kappa_e\rvert \sim 10$	$M \sim 50$ TeV

Study of FCC-ee (125):
$\kappa_e < 1.7$

Altmannshofer, Brod, Schmaltz, 1503.04830

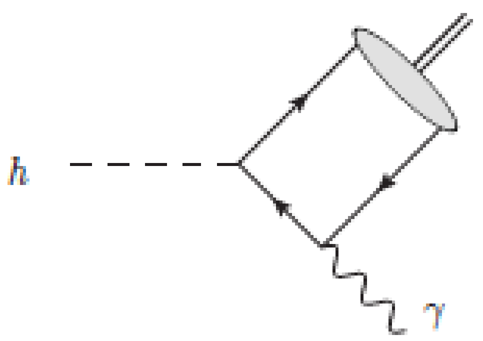
How to probe lighter Yukawas? (2)

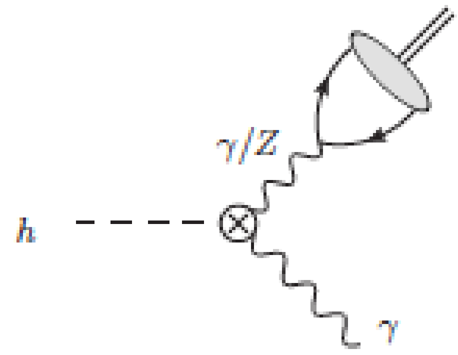
Quarks

In general, it is very challenging!

The decay of the Higgs into quarks is overwhelmed by the huge QCD background

Exclusive determinations of charm and strange Yukawas:





Example:

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

Bodwin et al. 1407.6695

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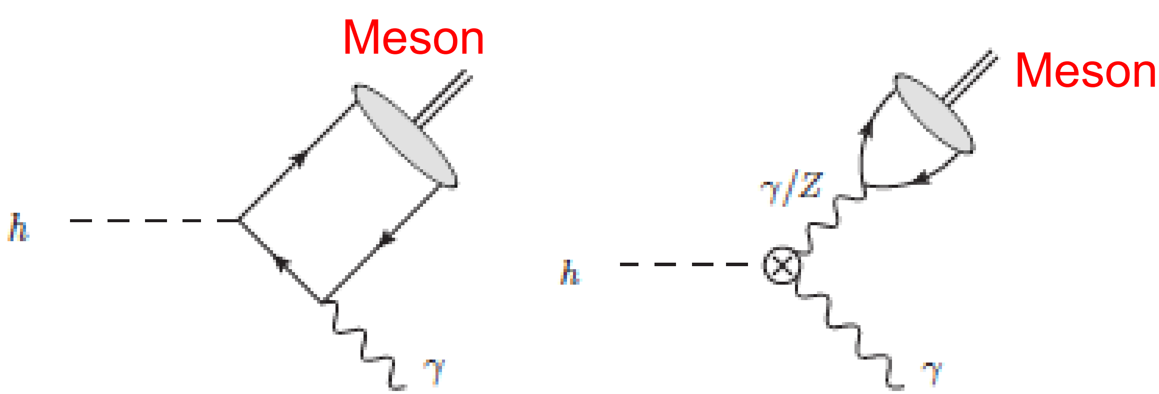

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1507.03031 (CMS), 1501.03276 (ATLAS) 20fb^{-1} @ 8 TeV
1607.03400 (ATLAS), 2.7fb^{-1} @ 13 TeV

Decay mode	Expected	Observed	SM prediction
$J/\Psi\gamma$	$1.2^{+0.6}_{-0.3} \times 10^{-3}$	1.5×10^{-3}	$\sim 3 \times 10^{-6}$
$\phi\gamma$	$1.5^{+0.7}_{-0.4} \times 10^{-3}$	1.4×10^{-3}	$\sim 2.3 \times 10^{-6}$

They correspond to

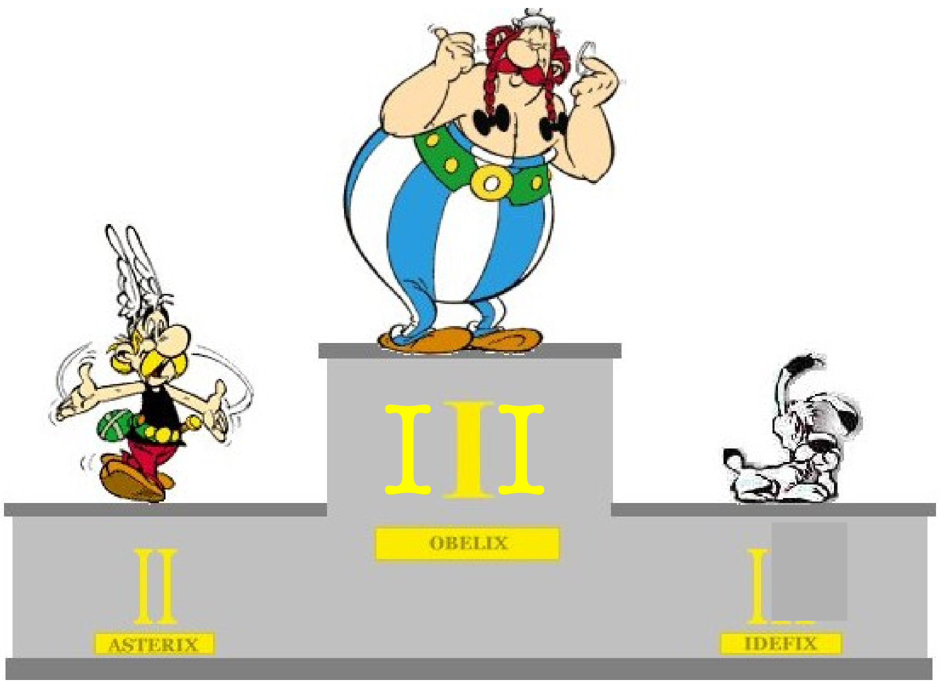
$$\kappa_c \lesssim 220, \;\; \kappa_s \lesssim 8000$$

Not yet significant, in view of the measurement of the Higgs width but they add complementarity!

Let's ask the opposite question:

What if the Higgs does not give mass to the lighter generations?

What are the implications?



Something else? | Higgs boson | Something else?

"Sequestered" fermion masses

If we have two sequestered sources of EWSB, such that

See also Ghosh et al, 1508.01501

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

- Due to the field Φ (the main component of the 125GeV Higgs)
- It gives the bulk of the 3rd generation masses

- Due to some extra source.
- It gives the bulk of the 1st and 2nd generation masses

Altmannshofer, SG, Kagan, Silvestrini, Zupan 1507.07927

This is a valid setup, given the very limited knowledge of the Higgs coupling to 1st and 2nd generation

what are the testable signatures of such a setup?

A 2HDM realization

2 Higgs doublets H and H′ with vevs v and v′ and Yukawas Y and Y′

$$\mathcal{L} = \bar{f} Y f H + \bar{f} Y' f H'$$

125 Higgs (h)   Additional Higgses (H, A, $H^{\pm}$)

Fermions receive mass from both Higgs bosons

$$\mathcal{M} = vY + v'Y'$$

$$(\mathcal{M}_0 + \Delta\mathcal{M})$$

we have one parameter, $\tan\beta = v/v'$, that can explain the hierarchy between 3rd and 2nd generation

Invoke some mechanism such that the Yukawa Y is rank 1, while the Yukawa Y' is generic (apart from 1st/2nd generation hierarchy)

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$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} m_e & \mathcal{O}(m_e) & \mathcal{O}(m_e) \\ \mathcal{O}(m_e) & m_\mu & \mathcal{O}(m_\mu) \\ \mathcal{O}(m_e) & \mathcal{O}(m_\mu) & \mathcal{O}(m_\mu) \end{pmatrix}$$

Similar structure for the up quark sector. For the down sector:

$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} m_d & \mathcal{O}(\lambda m_s) & \mathcal{O}(\lambda^3 m_b) \\ \mathcal{O}(m_d) & m_s & \mathcal{O}(\lambda^2 m_b) \\ \mathcal{O}(m_d) & \mathcal{O}(m_s) & \mathcal{O}(m_s) \end{pmatrix}$$

To generate the correct CKM matrix

Flavorful Higgs bosons

Our scenario breaks the Natural Flavor Conservation Ansatz

(up, down quarks and leptons couple to both doublets)

Natural conservation laws for neutral currents*

Sheldon L. Glashow and Steven Weinberg

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

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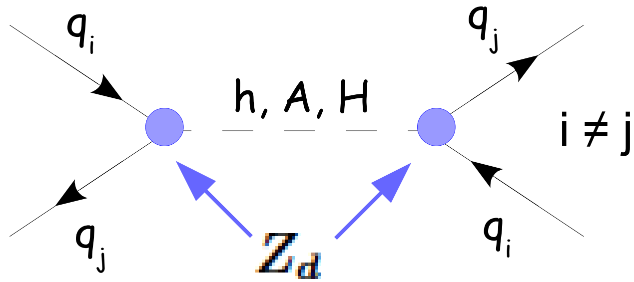
$$\begin{pmatrix} \Phi_v \\ \Phi_H \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} H' \\ H \end{pmatrix} \qquad \langle \Phi_v^\dagger \Phi_v \rangle = v^2/2,$$

$$\langle \Phi_H^\dagger \Phi_H \rangle = 0$$

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L \left[\frac{\sqrt{2}}{v} M_d \Phi_v + Z_d \Phi_H \right] D_R + \text{h.c.}$$

$$\begin{cases} Z_d = c_\beta Y - s_\beta Y' \\ M_d = \frac{v}{\sqrt{2}} (c_\beta Y' + s_\beta Y) \end{cases}$$

Tree level flavor changing neutral currents



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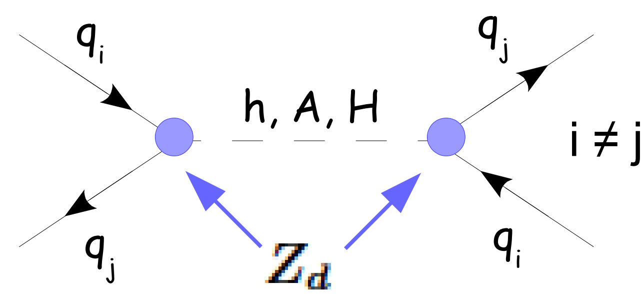

An approximate U(2) symmetry broken only by small Yukawas

Example for the lepton sector:

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Constraints from low energy flavor transitions are quite mild!

Flavor diagonal couplings of the 125 GeV h

Comparing to other extended Higgs sectors...

	W,Z κ_V	up quarks $\kappa_t,\ \kappa_c,\ \kappa_u$	down quarks $\kappa_b,\ \kappa_s,\ \kappa_d$	leptons $\kappa_\tau,\ \kappa_\mu,\ \kappa_e$
2HDM type 1				
2HDM type 2				
sequestered 2HDM				

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2HDM type 1	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
2HDM type 2	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{-s_\alpha}{c_\beta}$	$\frac{-s_\alpha}{c_\beta}$
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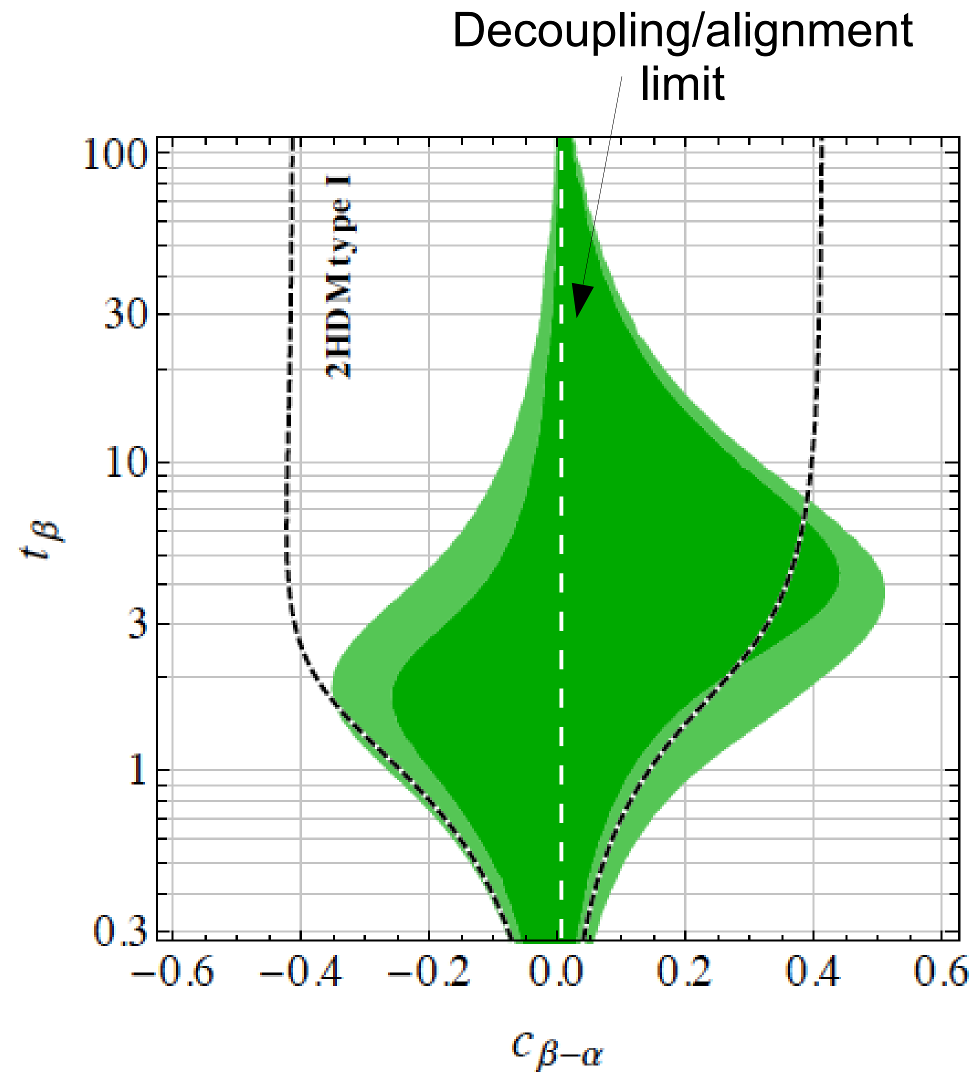
2HDM type 2	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{-s_\alpha}{c_\beta}$	$\frac{-s_\alpha}{c_\beta}$
sequestered 2HDM	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}, \frac{-s_\alpha}{c_\beta}, \frac{-s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}, \frac{-s_\alpha}{c_\beta}, \frac{-s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}, \frac{-s_\alpha}{c_\beta}, \frac{-s_\alpha}{c_\beta}$

In the sequestered 2HDM there are additional corrections to the κ's of the order of $O(m_c/m_t)$, $O(m_s/m_b)$, $O(m_\mu/m_\tau)$

Constraints from Higgs rates

Constraint in the tβ, cos(β-α) plane from the 125 GeV Higgs coupl. measurements



Constraints from Higgs rates

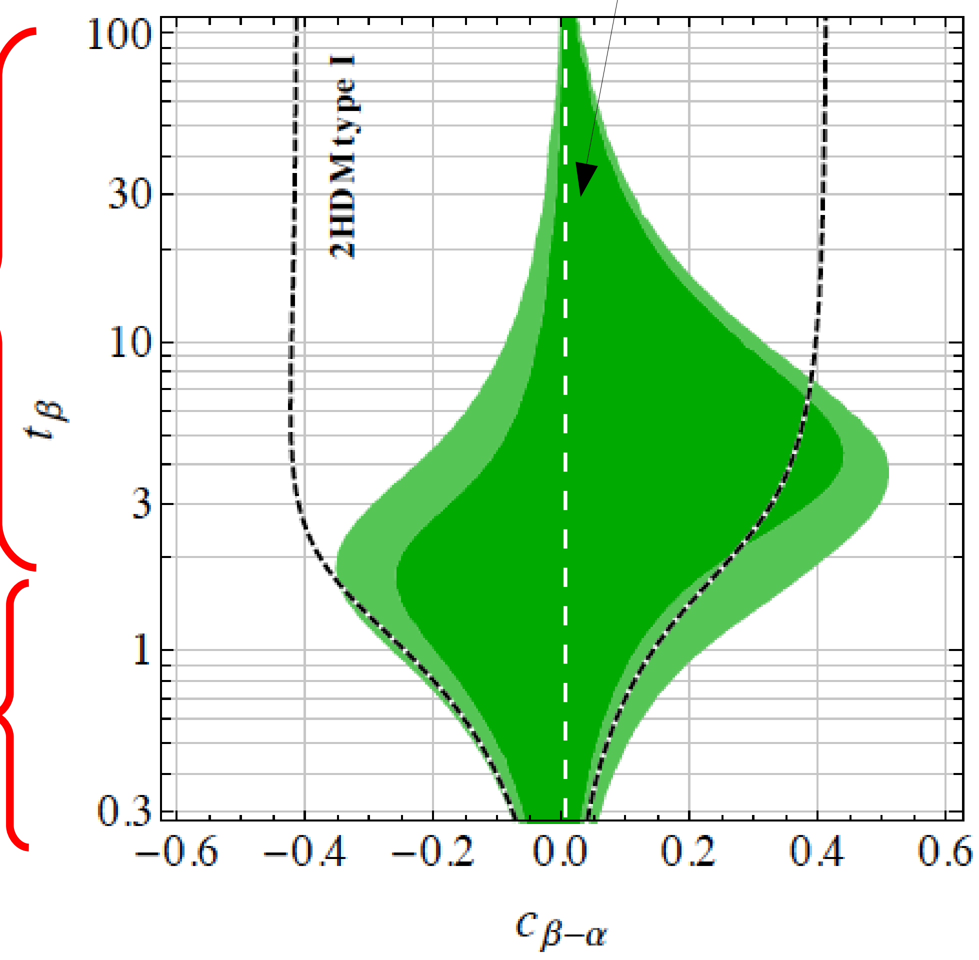
Constraint in the tβ, cos(β-α) plane from the 125 GeV Higgs coupl. measurements

1. Large enhancement of the charm Yukawa that suppresses all the other rates.

Also the muon Yukawa is large.

2. Here the constraints are similar to a type I 2HDM.
The couplings to 3[rd] generation fermions & gauge bosons drive the fit.

Decoupling/alignment limit



Flavor violating couplings of the Higgs boson

Fermion masses and the h couplings
cannot be diagonalized simultaneously

Example: $$\frac{y_{\mu\tau}}{y_\mu^{SM}} = -\frac{\Delta\mathcal{M}_{\mu\tau}}{m_\mu}\frac{\cos(\beta-\alpha)}{\sin\beta\cos\beta}$$

It becomes larger
at larger values of tanβ

Generic expectations for lepton flavor violating Higgs decays

$$\mathrm{BR}(h\to\tau\mu) \sim \frac{m_\mu^2}{3m_b^2} \sim 10^{-3}$$

$$\mathrm{BR}(h\to\tau e) \sim \frac{m_e^2}{3m_b^2} \sim 10^{-7}$$

$$\mathrm{BR}(h\to\mu e) \sim \frac{m_e^2 m_\mu^2}{3m_\tau^2 m_b^2} \sim 10^{-10}$$

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Fermion masses and the h couplings
cannot be diagonalized simultaneously

Example: $$\frac{y_{\mu\tau}}{y_\mu^{SM}} = -\frac{\Delta\mathcal{M}_{\mu\tau}}{m_\mu}\frac{\cos(\beta-\alpha)}{\sin\beta\cos\beta}$$

It becomes larger
at larger values of tanβ

Generic expectations for lepton flavor violating Higgs decays

$$\mathrm{BR}(h\to\tau\mu) \sim \frac{m_\mu^2}{3m_b^2} \sim 10^{-3}$$

Reasonable target for the LHC.

$$\mathrm{BR}(h\to\tau e) \sim \frac{m_e^2}{3m_b^2} \sim 10^{-7}$$

$$\mathrm{BR}(h\to\mu e) \sim \frac{m_e^2 m_\mu^2}{3m_\tau^2 m_b^2} \sim 10^{-10}$$

Present measurements:

CMS, 8 TeV (1502.07400)

$$\mathrm{BR}(h\to\tau\mu) < 1.51\%\ (0.75^{+0.38}_{-0.38}\%)$$

ATLAS, 8 TeV (1604.07730)

$$\mathrm{BR}(h\to\tau\mu) < 1.43\%\ (1.01^{+0.4}_{-0.29}\%)$$

CMS, 13 TeV, 2.3fb^{-1} (CMS-HIG-16-005)

$$\mathrm{BR}(h\to\tau\mu) < 1.2\%\ (1.62\%)$$

Learning from an excess...

General lesson if the LHC will discover a flavor violating $h \to \tau\mu$ decay:

There should exist a new source of EWSB

Learning from an excess...

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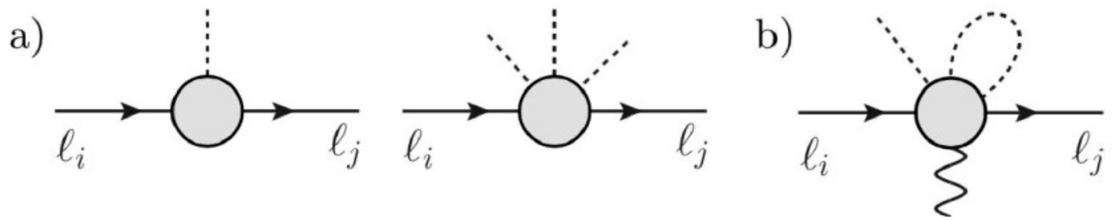
- EFT approach: $-\mathcal{L}_{\text{Yuk.}} = \lambda_{ij}(\bar{\ell}^i_L \ell^j_R)H \; + \; \frac{\lambda'_{ij}}{\Lambda^2}(\bar{\ell}^i_L \ell^j_R)H(H^\dagger H)$

See Altmannshofer, Carena, Crivellin, 1604.08221 for an exception to this principle

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

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



Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

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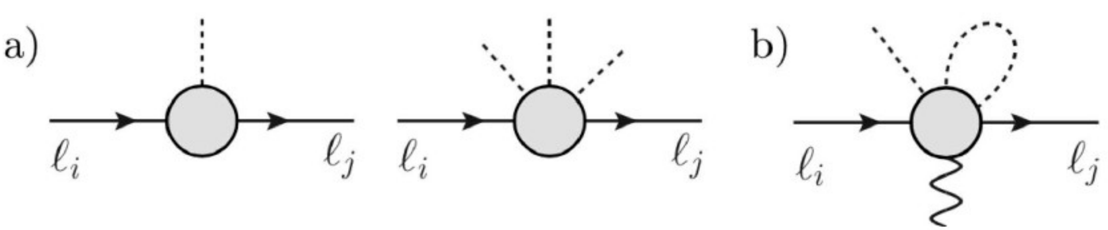

Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

B-factories:

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

BR(h → τ μ) ≤ O(10^{-6})

Learning from an excess...

General lesson if the LHC will discover a flavor violating $h \to \tau\mu$ decay:

There should exist a new source of EWSB

- EFT approach:

Let us assume there are no additional sources of EWSB,

$\Rightarrow$ BR($h \to \tau\,\mu$) $\leq$ O(10^{-6})

See Altmannshofer, Carena, Crivellin, 1604.08221 for an exception to this principle

- If we have a new source of EWSB, we can easily break this degeneracy

$$\mathcal{M}_\ell = \mathcal{M}_0 + \Delta\mathcal{M} \Rightarrow \begin{cases} Y_{\mu\tau} = c_{\rm ewk}\dfrac{\langle \mu_L|\Delta\mathcal{M}|\tau_R\rangle}{v_W} \\ c_{L,R} \sim \dfrac{\langle \mu_L|\Delta\mathcal{M}|\tau_R\rangle}{\Lambda^2}\dfrac{8\pi^2}{m_\tau} \sim 10^4\dfrac{Y_{\mu\tau}}{\Lambda^2} \end{cases}$$

O(1%) $h \to \tau\mu$ branching ratios are consistent with $\tau \to \mu\gamma$ for $\Lambda \sim$ O(10 TeV)

Additional flavor violating signatures

High energy

Flavor violating rare top decays with branching ratios as large as

$$BR(t \to ch) \sim |V_{cb}|^2 \sim 10^{-3}$$

$$BR(t \to uh) \sim |V_{ub}|^2 \sim 10^{-5}$$

Target for the future of the LHC

Present bounds:

ATLAS 8 TeV (1509.06047)
$BR(t \to ch) < 0.46\%$ (0.25%)
$BR(t \to uh) < 0.45\%$ (0.29%)

CMS 8 TeV (CMS-PAS-TOP-14-020)
$BR(t \to ch) < 1.16\%$ (0.89%)
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Low energy

Lepton flavor violating rare B meson decays with sizable branching ratios

$$\mathrm{BR}(B_s \to \tau\mu) \sim \text{few} \times 10^{-7}$$

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

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

No searches yet.

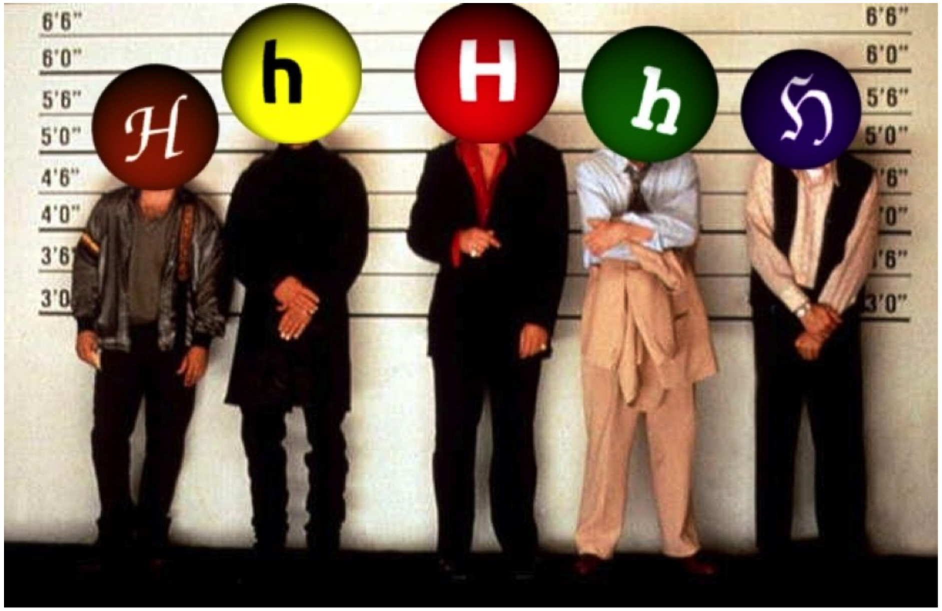
LHCb might be sensitive to the K and K* rates

$$\frac{\mathrm{BR}(\mathrm{B_s} \to \tau\mu)}{\mathrm{BR}(\mathrm{B_s} \to \mu\mu)_{\mathrm{SM}}} \propto \left(\frac{4\pi^2}{e^2}\right)^2 t_\beta^4 \frac{m_{B_s}^4}{m_A^4}$$

vs.

$$\frac{\mathrm{BR}(\mathrm{B_s} \to \mu\mu)}{\mathrm{BR}(\mathrm{B_s} \to \mu\mu)_{\mathrm{SM}}} \propto \left[1 + \frac{1}{C_{10}^{\mathrm{SM}}}\left(\frac{4\pi^2}{e^2}\right)\frac{m_{B_s}^2}{m_A^2}\left(t_\beta - \frac{m_\mu}{m_\tau}\frac{t_\beta^2+1}{t_\beta}\right)^2\right]^2$$

Phenomenology of the additional Higgs bosons



From Fermilab today, July 2012

Flavor diagonal couplings of the additional H

Comparing to other extended Higgs sectors...

	W,Z κ_V^H	up quarks $\kappa_t^H,\ \kappa_c^H,\ \kappa_u^H$	down quarks $\kappa_b^H,\ \kappa_s^H,\ \kappa_d^H$	leptons $\kappa_\tau^H,\ \kappa_\mu^H,\ \kappa_e^H$
2HDM type 1				
2HDM type 2				
sequestered 2HDM				

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2HDM type 1	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$
2HDM type 2	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$
sequestered 2HDM				

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2HDM type 1	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$
2HDM type 2	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$
sequestered 2HDM	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}, t_\beta\frac{c_\alpha}{s_\beta}, t_\beta\frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}, t_\beta\frac{c_\alpha}{s_\beta}, t_\beta\frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}, t_\beta\frac{c_\alpha}{s_\beta}, t_\beta\frac{c_\alpha}{s_\beta}$

In the sequestered 2HDM there are additional corrections to the κ's of the order of $O(m_c/m_t)$, $O(m_s/m_b)$, $O(m_\mu/m_\tau)$

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2HDM type 1				
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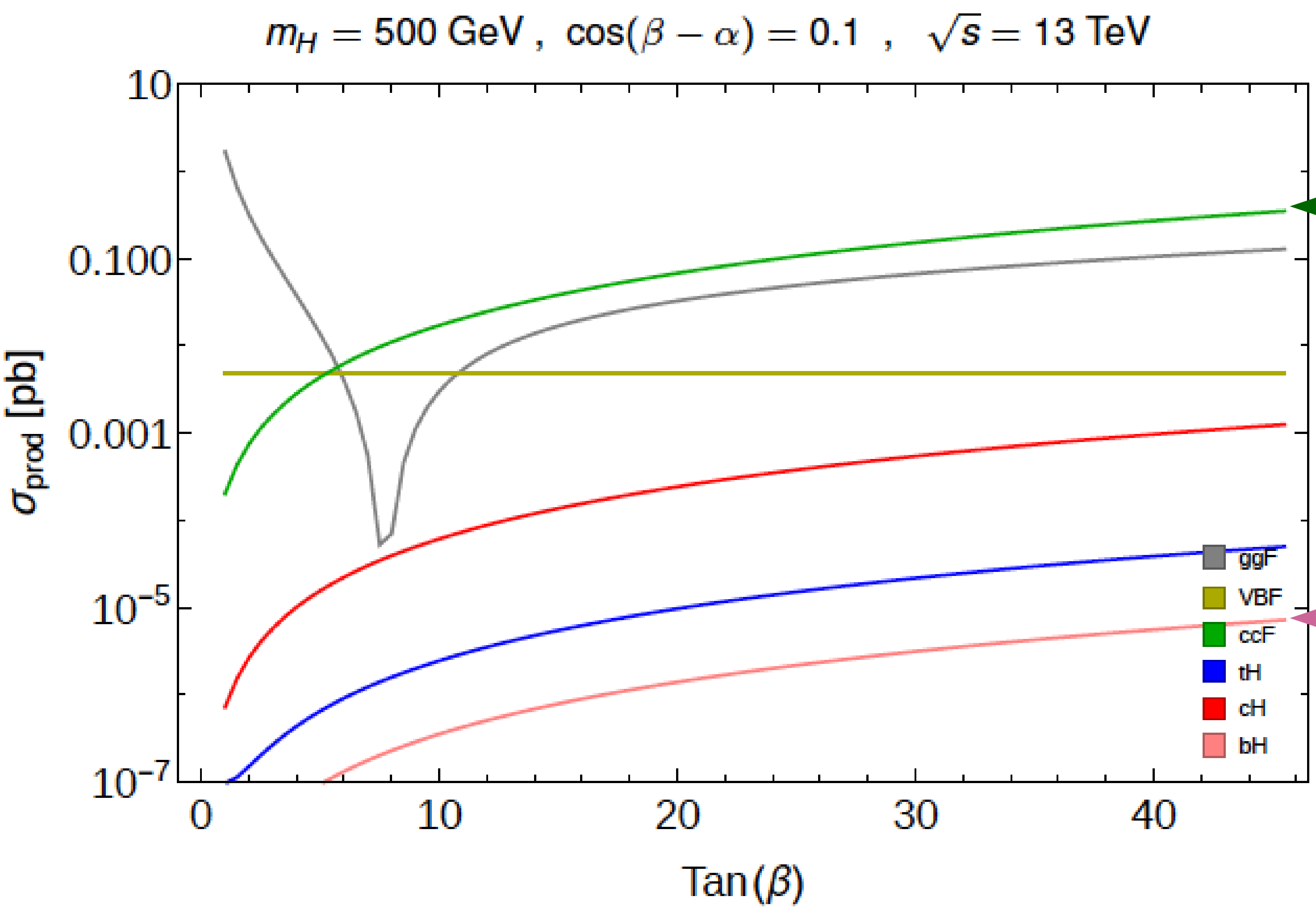
sequestered 2HDM	$c_{\beta-\alpha}$			

Quite different phenomenology, if compared to the most studied 2HDMs!
Are we missing any signature?

In the sequestered 2HDM there are additional corrections to the κ's of the order of $O(m_c/m_t)$, $O(m_s/m_b)$, $O(m_\mu/m_\tau)$

How to produce the new Higgses?

Preliminary



S-channel production becomes the most important one

Typical production in a Type II 2HDM, at large tanβ

W. Altmannshofer, J. Eby, SG, M. Lotito, M. Martone, D. Tuckler, in preparation

Different branching ratios

- In the most studied 2HDMs (Type I, II, ...)

$$\frac{\mathrm{BR}(A/H \to \mu\mu)}{\mathrm{BR}(A/H \to \tau\tau)} \simeq \frac{m_\mu^2}{m_\tau^2} \simeq 3 \times 10^{-3}$$

The $\tau\tau$ decay mode is usually the first signature we expect to discover at the LHC

- In our "sequestered" 2HDM

$$\frac{\mathrm{BR}(\mathrm{A/H} \to \mu\mu)}{\mathrm{BR}(\mathrm{A/H} \to \tau\tau)} = \begin{cases} \mathcal{O}\left(\frac{m_\mu^2}{m_\tau^2} \times \tan^4\beta\right) & \text{at moderate } \tan\beta \\ \mathcal{O}\left(\frac{m_\mu^2}{|\Delta\mathcal{M}_{\tau\tau}|^2}\right) & \text{at large } \tan\beta \end{cases}$$

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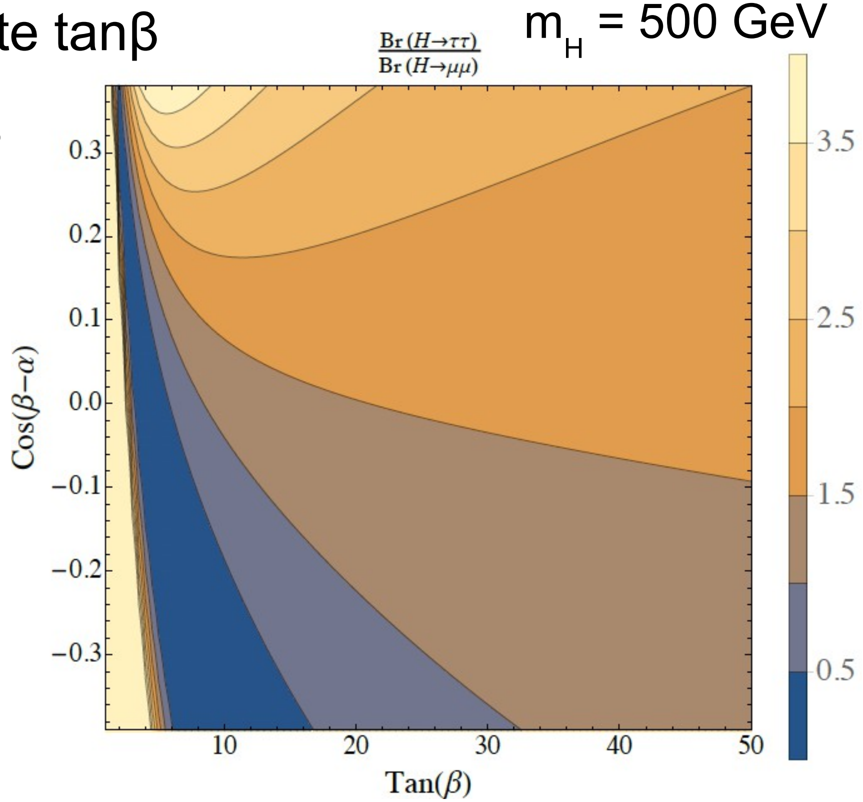
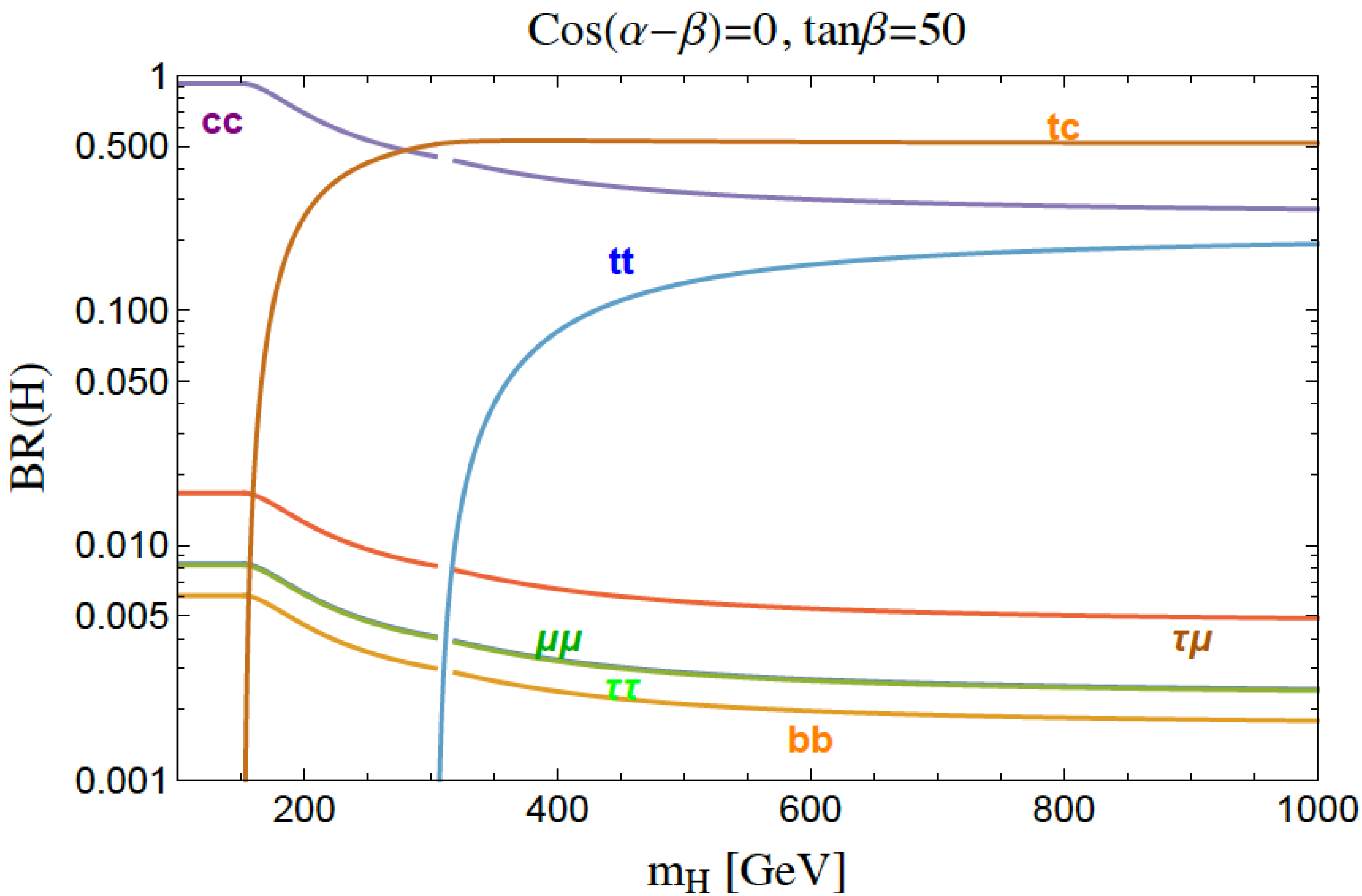
The two branching ratios are expected to be comparable



What are the signatures?



W. Altmannshofer, J. Eby, SG, M. Lotito,
M. Martone, D. Tuckler, in preparation

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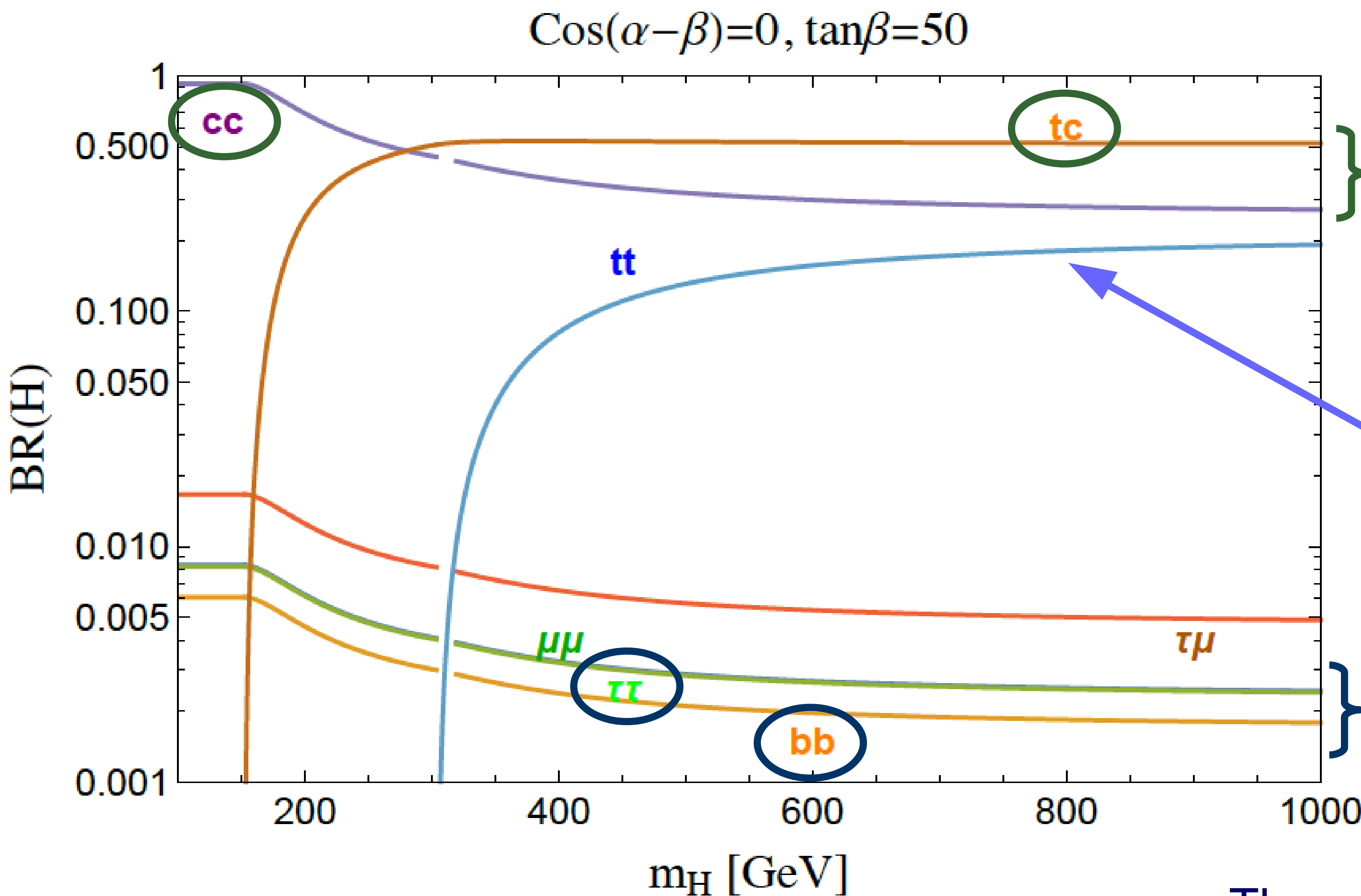


Di-jet and top-charm decay modes are the dominant ones (3)

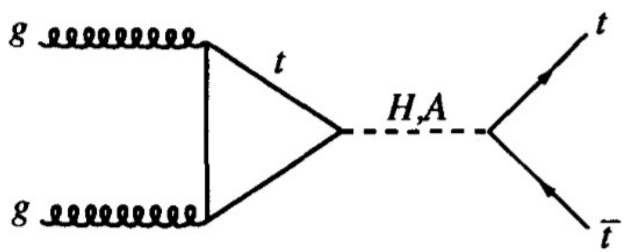
Di-top resonance... nice but difficult! (1)

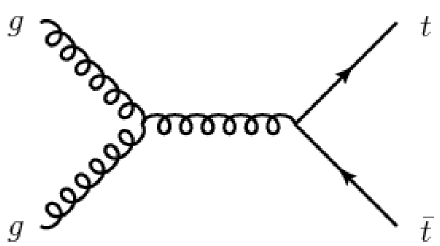
These 2 are the typical decay modes the LHC looks for ⟶ only weak constraints! (2)

W. Altmannshofer, J. Eby, SG, M. Lotito, M. Martone, D. Tuckler, in preparation

(1) Di-top resonances (1)

Large interference between

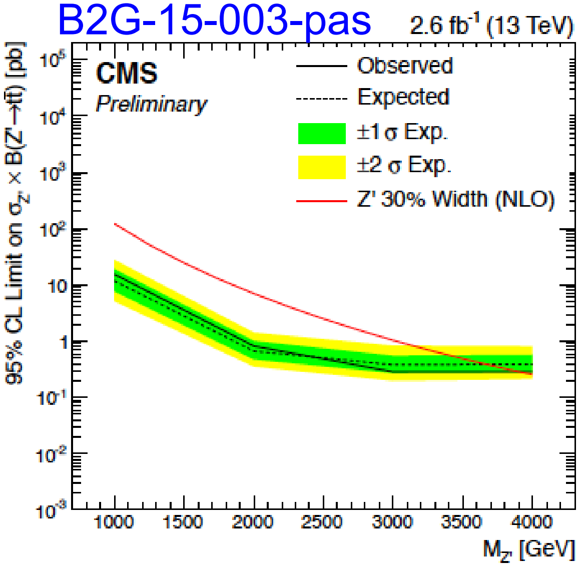




First computed by Dicus, Stange, Willenbrock '94

Not a simple rescaling of Z' di-top searches!

B2G-15-003-pas



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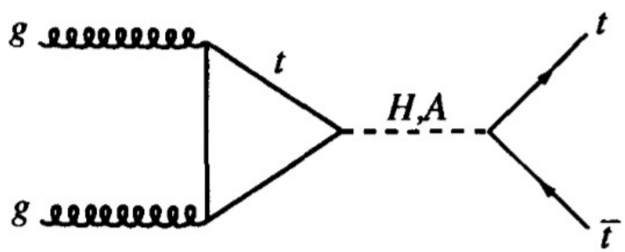

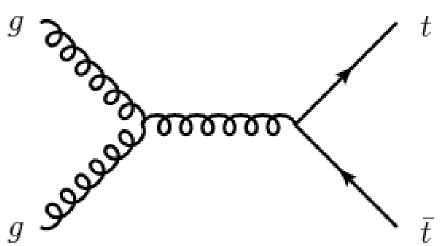

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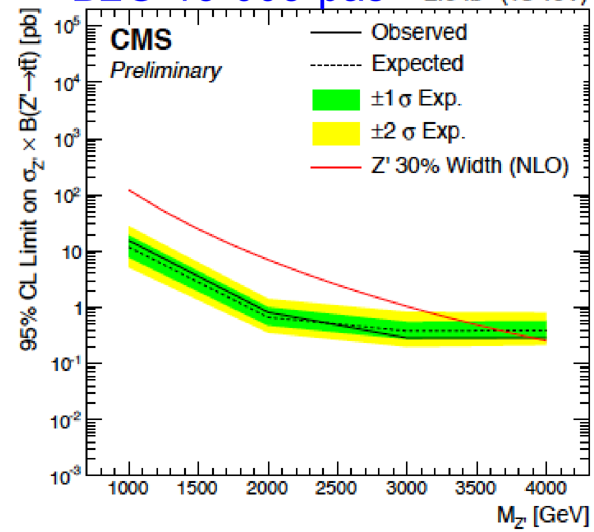
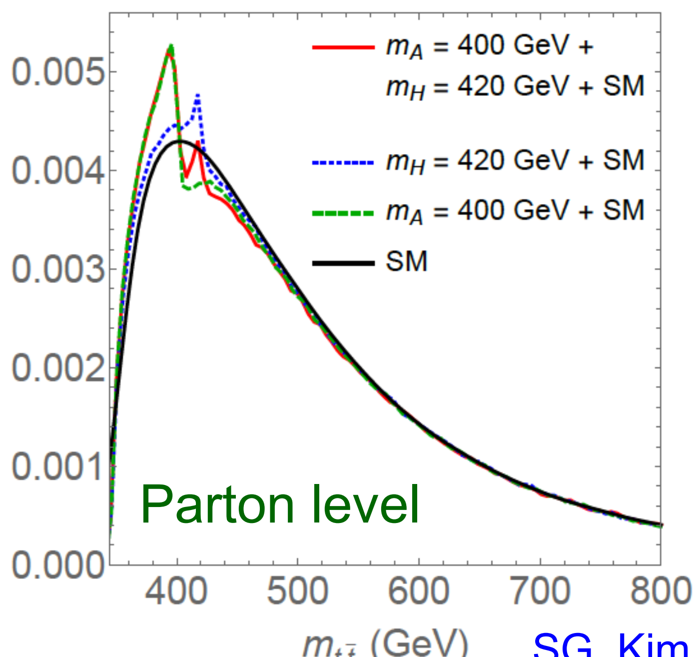
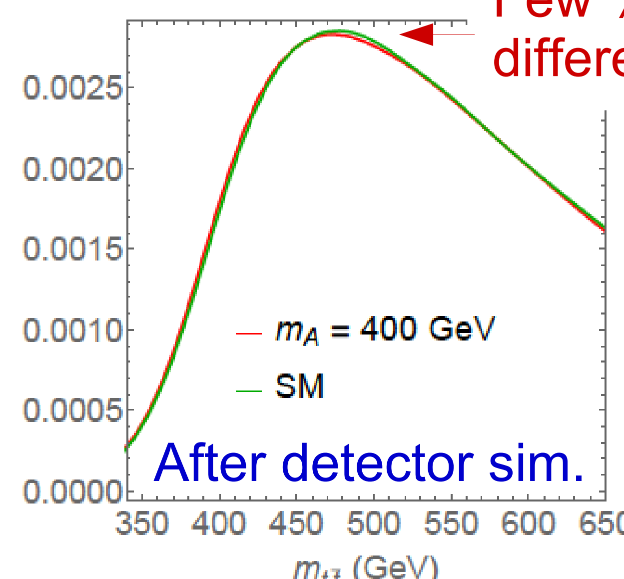


Very nice:



But



Few % difference

See also Craig et al. 1504.04630

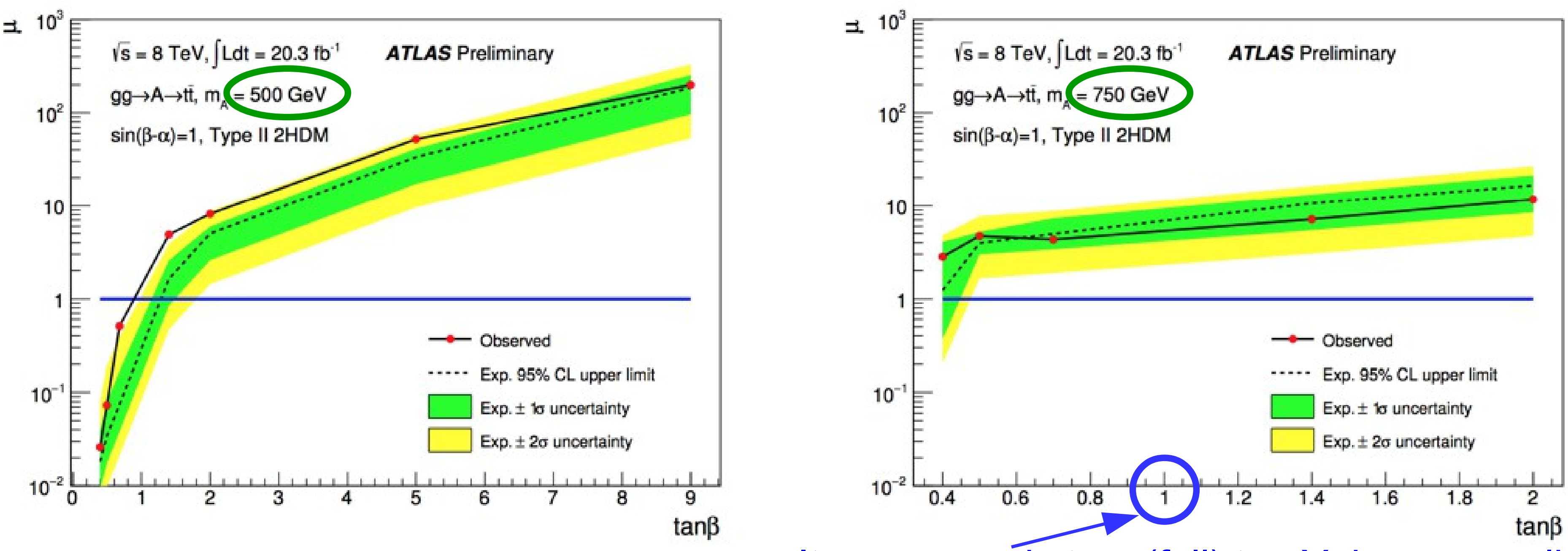
SG, Kim, Shah, Zurek, 1602.02782

(1) Di-top resonances (2)

ICHEP 2016: A first look by ATLAS

ATLAS-CONF-2016-073, 8 TeV data

Search performed for two mass points: 500 GeV and 750 GeV



It corresponds to a (full) top Yukawa coupling of the heavy Higgs with tops

Great control of systematics thanks to data driven $t\bar{t}$ measurement of sidebands

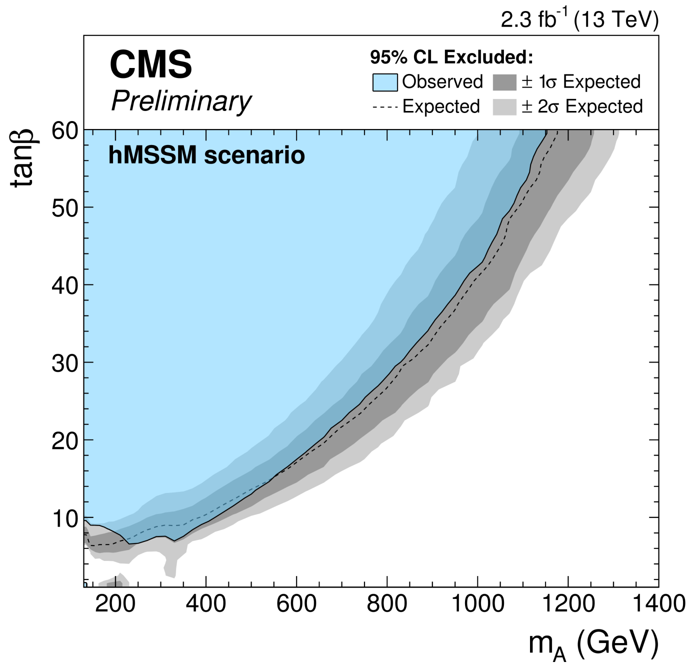
Still far from probing our scenario (factor of ~500 too small)

 S.Gori

(2) Sensitivity of current searches

Warning: this is the status pre-ICHEP

- This is the "typical" plot we are used to see for a 2HDM:



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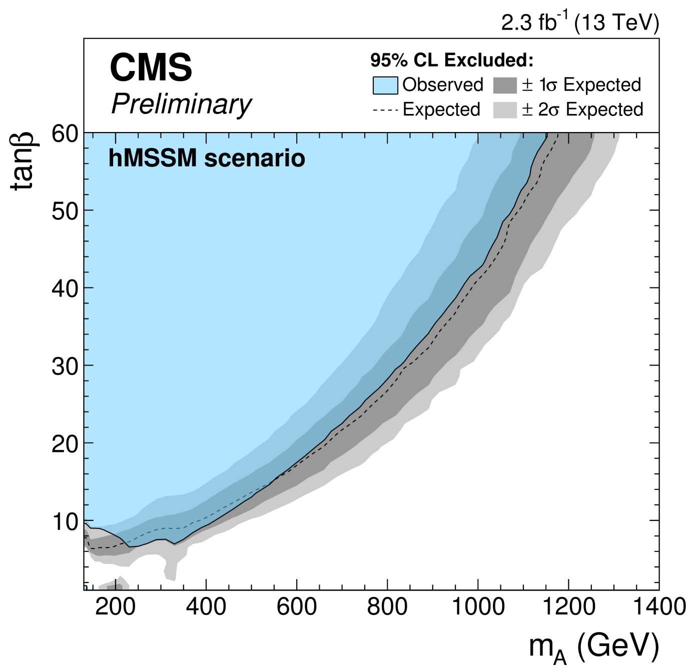
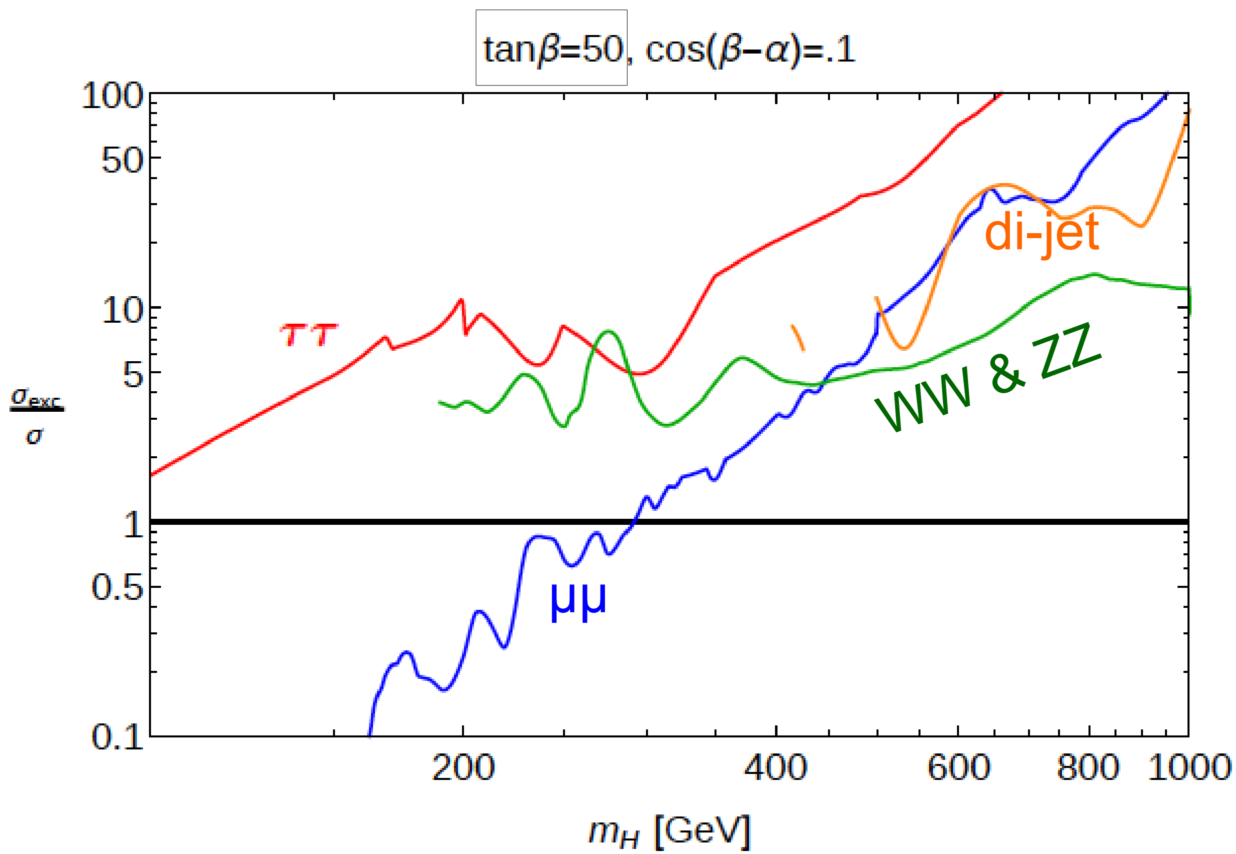


- In our model, this is **not** the most constraining signature!

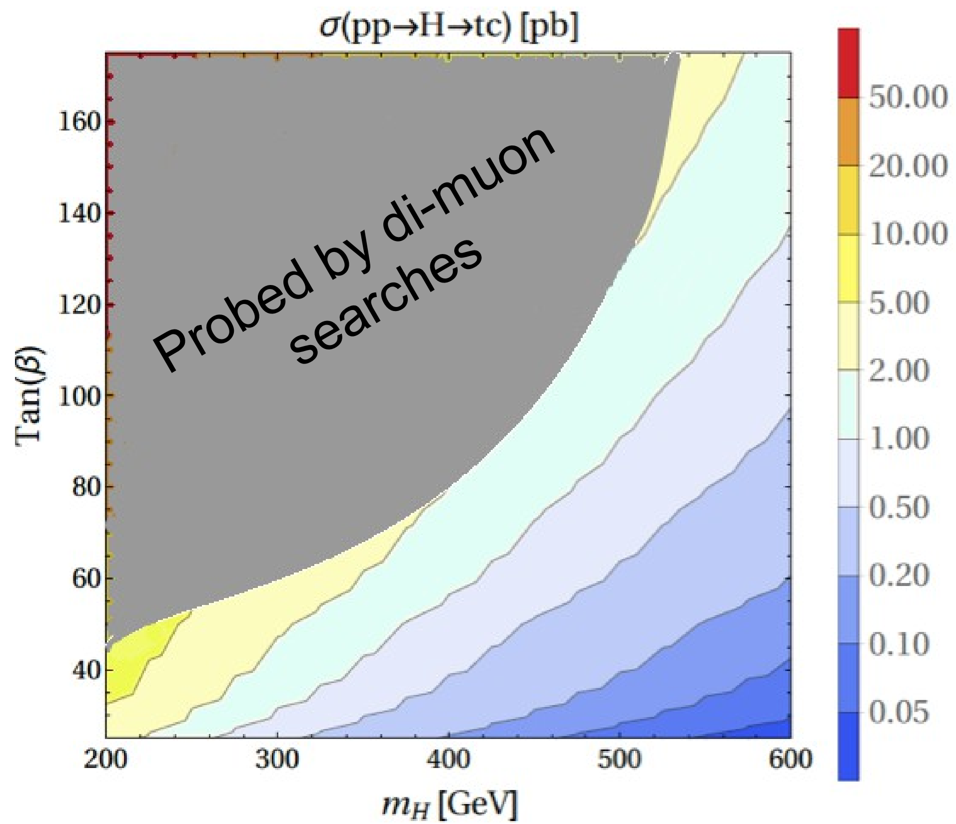


W. Altmannshofer, J. Eby, SG, M. Lotito, M. Martone, D. Tuckler, in preparation

(3) Smoking guns of the additional Higgses

New decay modes to search for:

Top-Charm



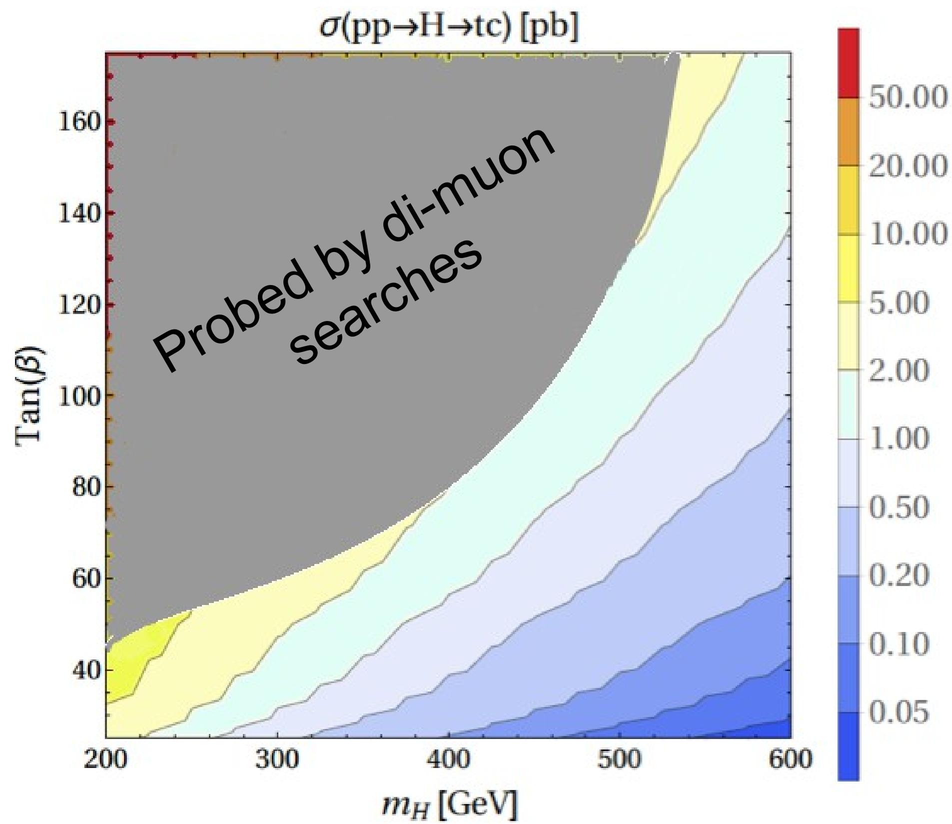
What are the LHC prospects?

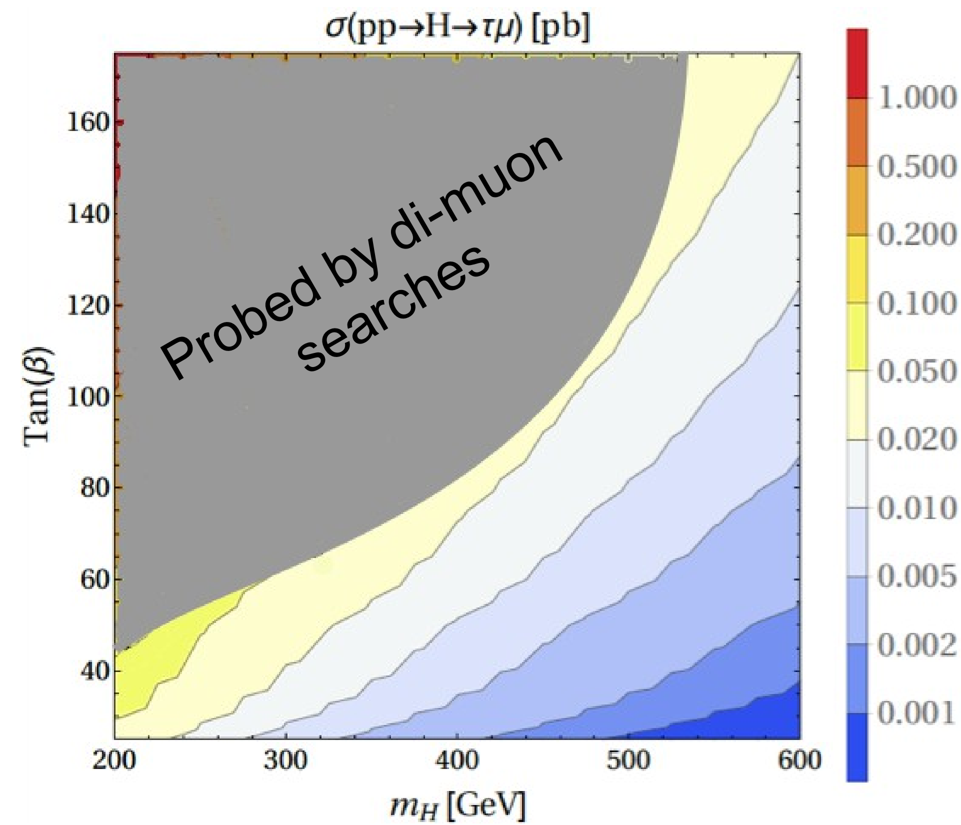
- $pp \to tH, H \to tc$ also interesting but very suppressed in our model
  see also Buschmann, Kopp, Liu, Wang, 1601.02616

(3) Smoking guns of the additional Higgses

New decay modes to search for:

Top-Charm and also: Tau-Mu





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see also Buschmann, Kopp, Liu, Wang, 1601.02616

Even if typically the μμ mode would come first.

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

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- Opportunity for testing the Higgs flavor structure:
  - Is the Higgs responsible for the mass of light quarks and leptons?

- A sequestered 2HDM with interesting new phenomenology
  - Low energy tests: rare lepton flavor violating B meson decays
  - Unique phenomenology of the additional Higgs bosons
  - <u>Smoking gun</u>: heavy Higgs flavor violating decays (top-charm!)

Does it work?

Constraints from low energy flavor observables are relatively mild

- B meson mixing observables:

Contribution to the operator $C_{4,B}(\bar{b}_R s_L)(\bar{b}_L s_R)$

$$\Delta\mathcal{M} = \begin{pmatrix} m_d & \mathcal{O}(\lambda m_s) & \mathcal{O}(\lambda^3 m_b) \\ \mathcal{O}(m_d) & m_s & \mathcal{O}(\lambda^2 m_b) \\ \mathcal{O}(m_d) & \mathcal{O}(m_s) & \mathcal{O}(m_s) \end{pmatrix}$$

$$C_{4,B} \sim \frac{\lambda^2 m_b m_s}{v^2 m_h^2} \times \frac{\cos^2(\alpha-\beta)}{\sin^2\beta\cos^2\beta}$$

This is a bit too large but in the right ballpark: $m_s \to \frac{m_s}{6} \times \frac{\sin^2\beta\cos^2\beta}{\cos^2(\alpha-\beta)}$

- Observables involving 1 ↔ 2 transitions

Kaon mixing

$$\Delta\mathcal{M} = \begin{pmatrix} m_d & \mathcal{O}(\lambda m_s) & \mathcal{O}(\lambda^3 m_b) \\ \mathcal{O}(m_d) & m_s & \mathcal{O}(\lambda^2 m_b) \\ \mathcal{O}(m_d) & \mathcal{O}(m_s) & \mathcal{O}(m_s) \end{pmatrix}$$

$$C_{4,K} \sim \frac{\lambda^3 m_s m_d}{v^2 m_h^2} \times \frac{\cos^2(\alpha-\beta)}{\sin^2\beta\cos^2\beta}$$

$$m_d \to \frac{m_d}{10} \times \frac{\sin^2\beta\cos^2\beta}{\cos^2(\alpha-\beta)}$$

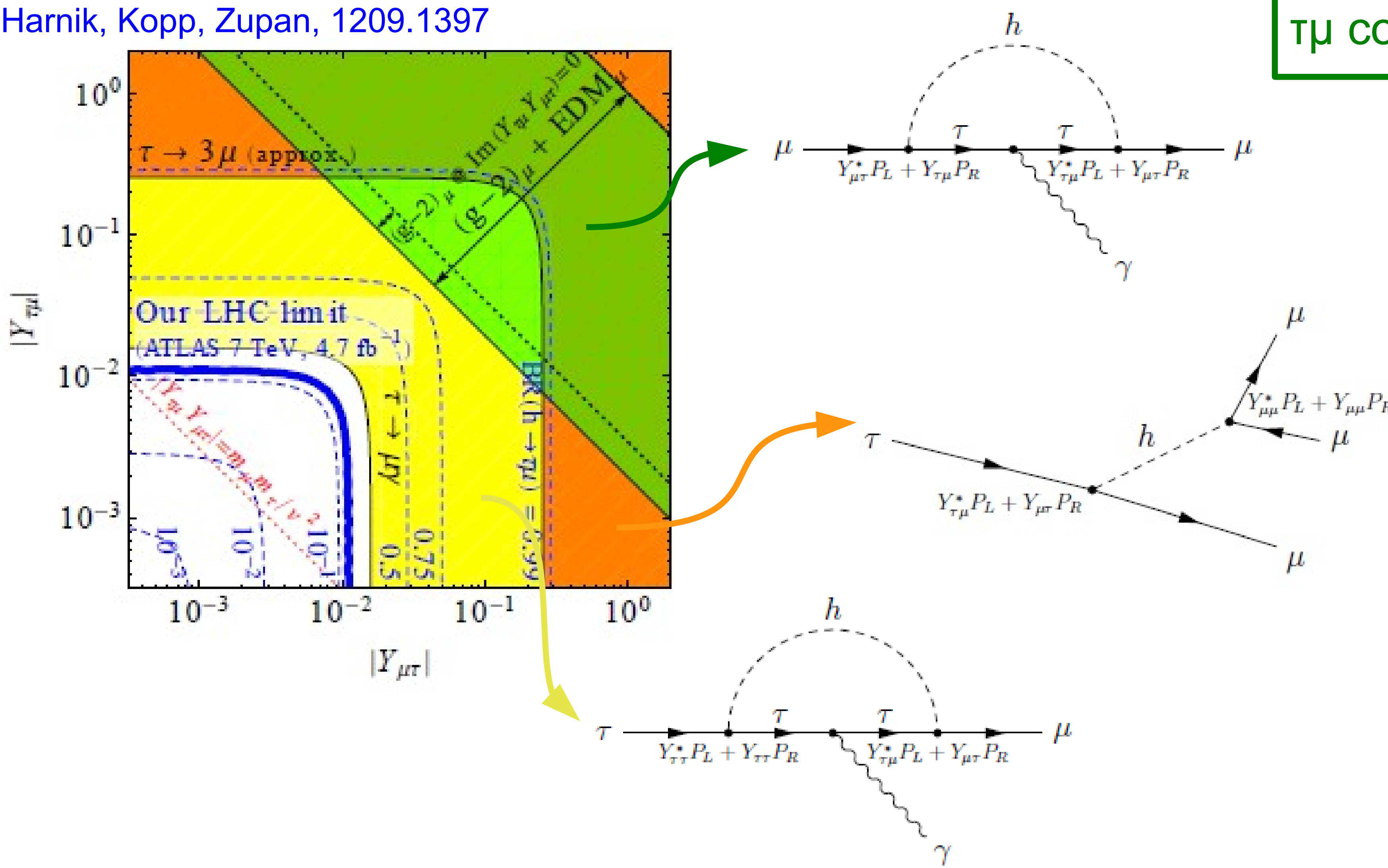
work in progress...

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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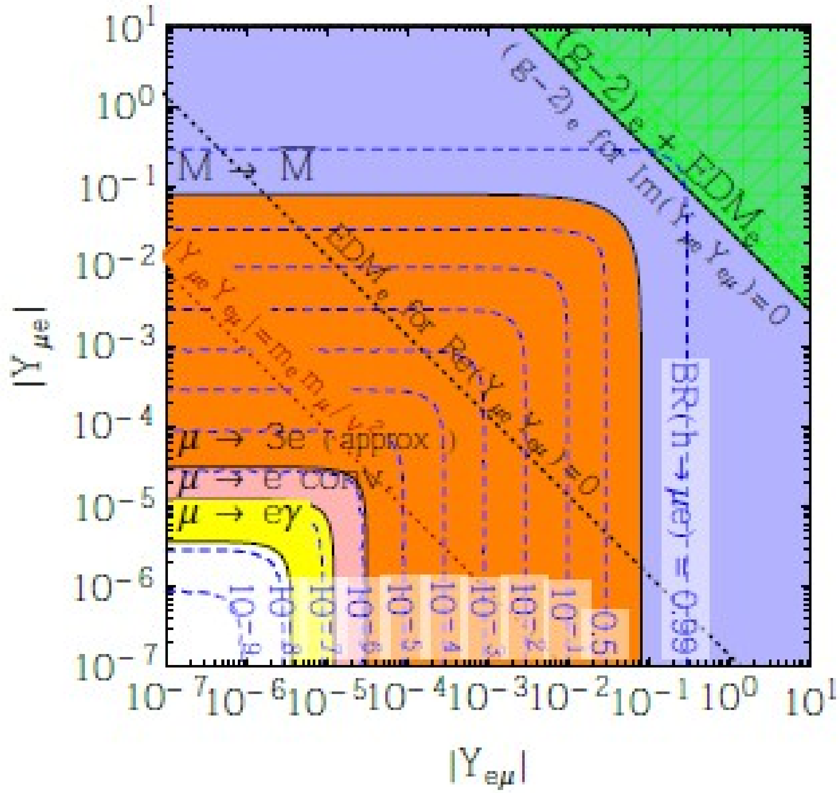
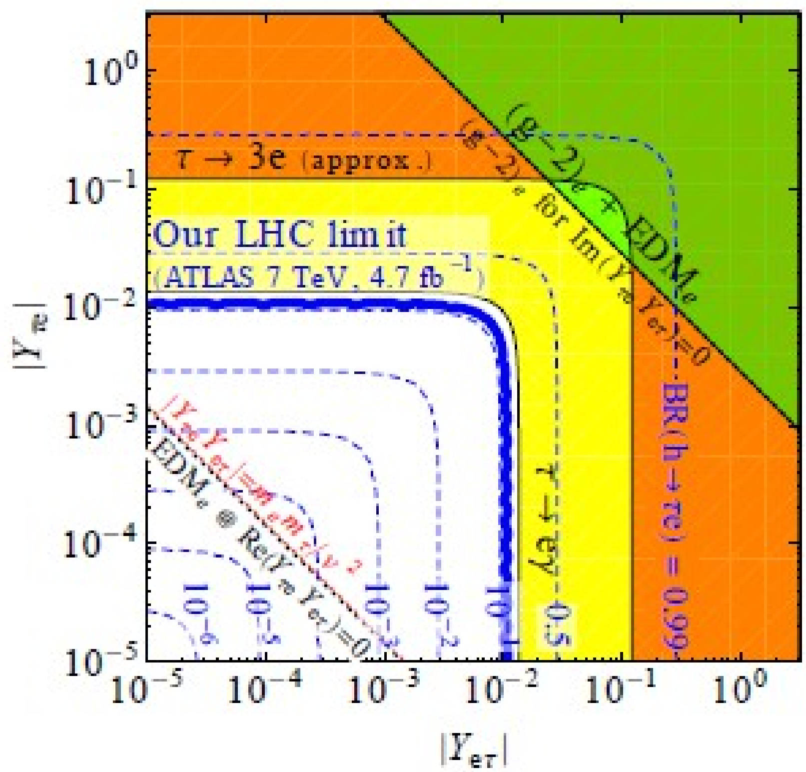
eμ, eτ couplings

Harnik, Kopp, Zupan, 1209.1397



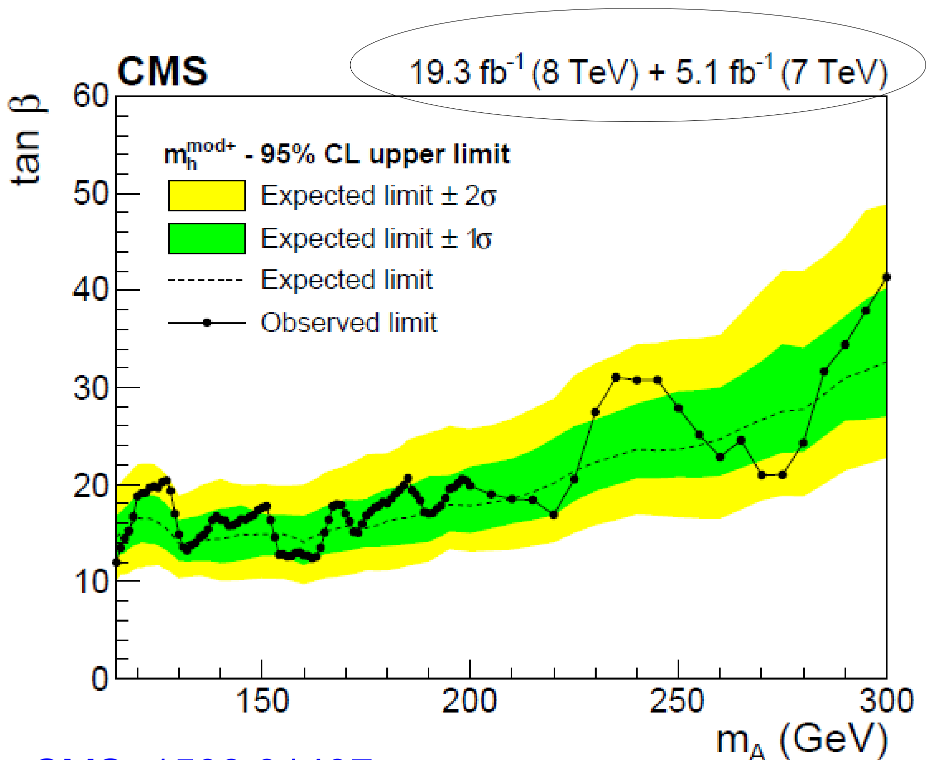


Prospects for heavy Higgs searches, μμ

$A \to \mu\mu$

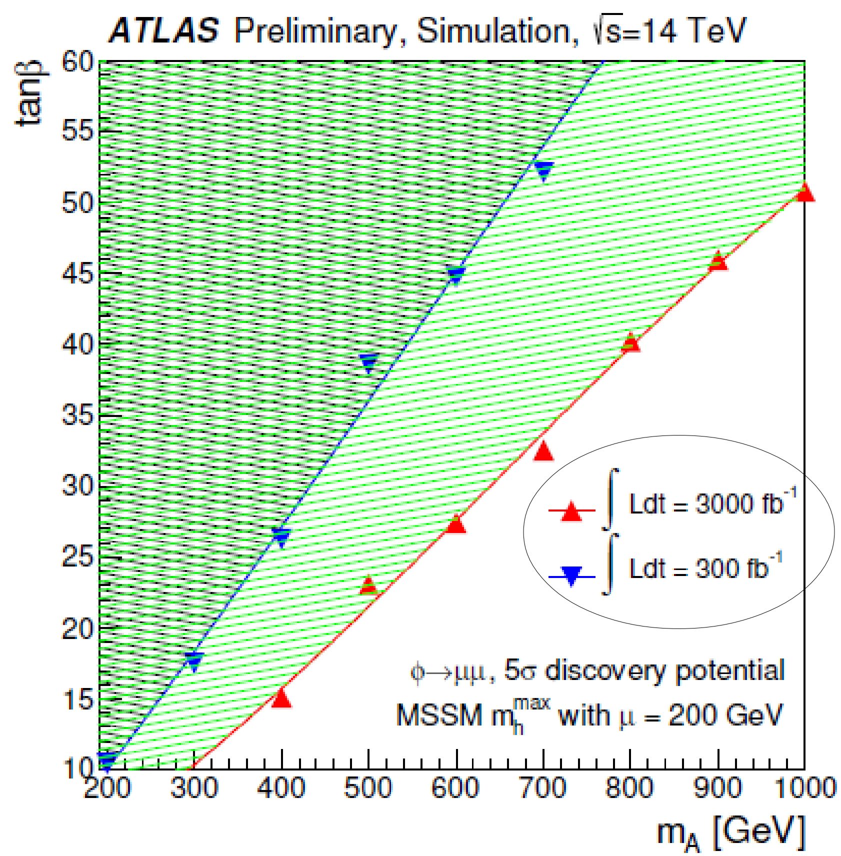
In a type II 2HDM...

Now



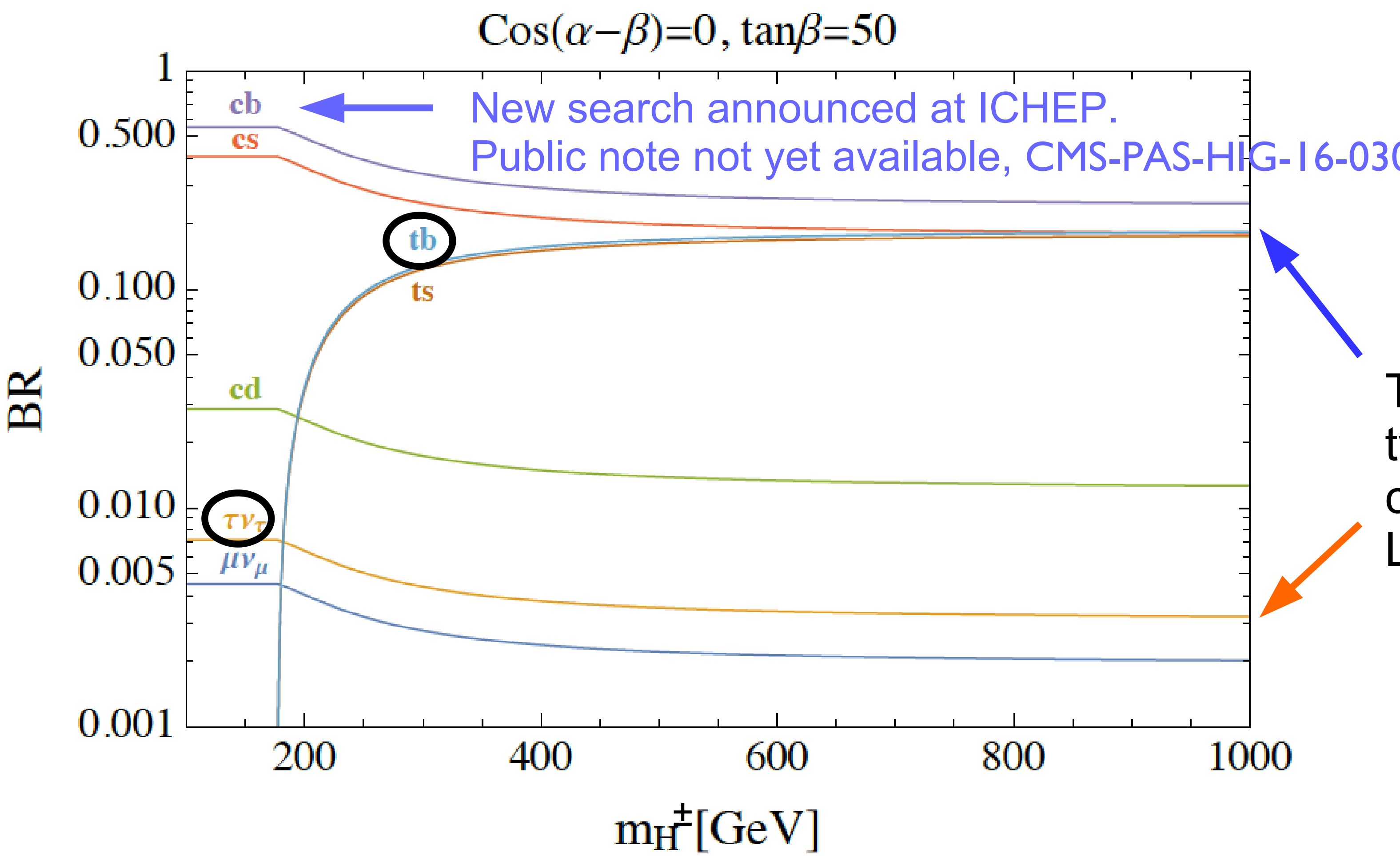
CMS, 1508.01437

Future



ATLAS-PHYS-PUB-2013-016

Signatures from the charged Higgs boson



These are the typical charged Higgs LHC searches

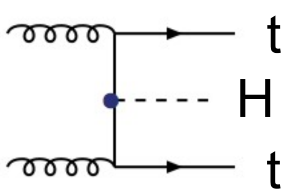
W. Altmannshofer, J. Eby, SG, M. Lotito, M. Martone, D. Tuckler, in preparation

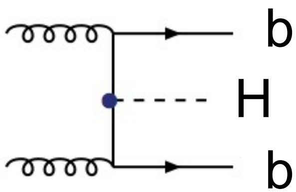
Regime of low tanβ Type II 2HDM

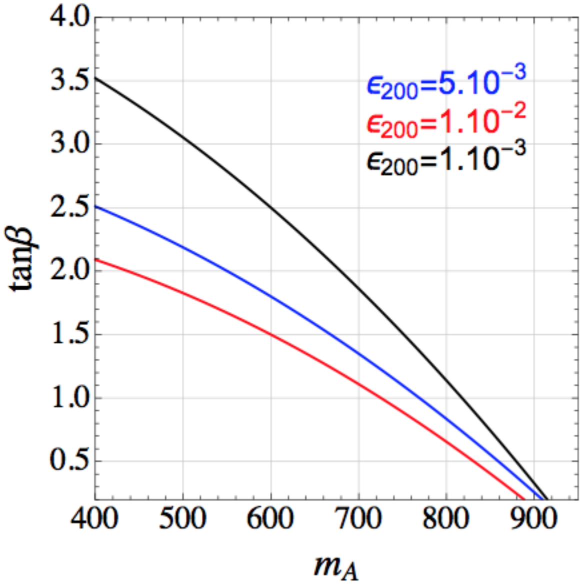
The (heavy) Higgs mainly decays into tops and EW-inos (in some specific scenarios)

SG, Kim, Shah, Zurek, 1602.02782

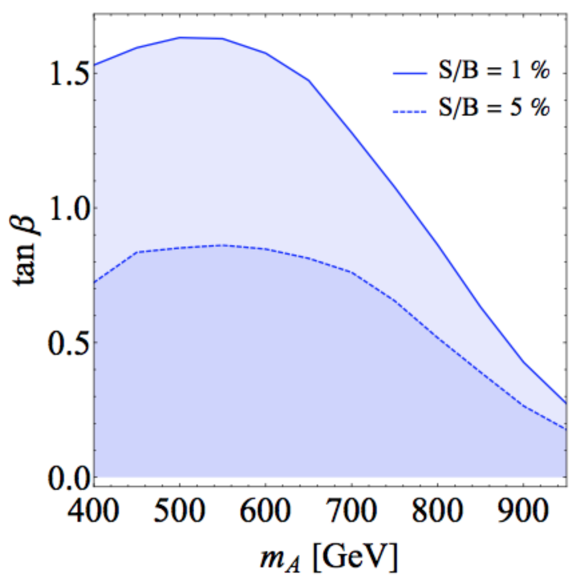
- Tops, t associated production
- Tops, b associated production



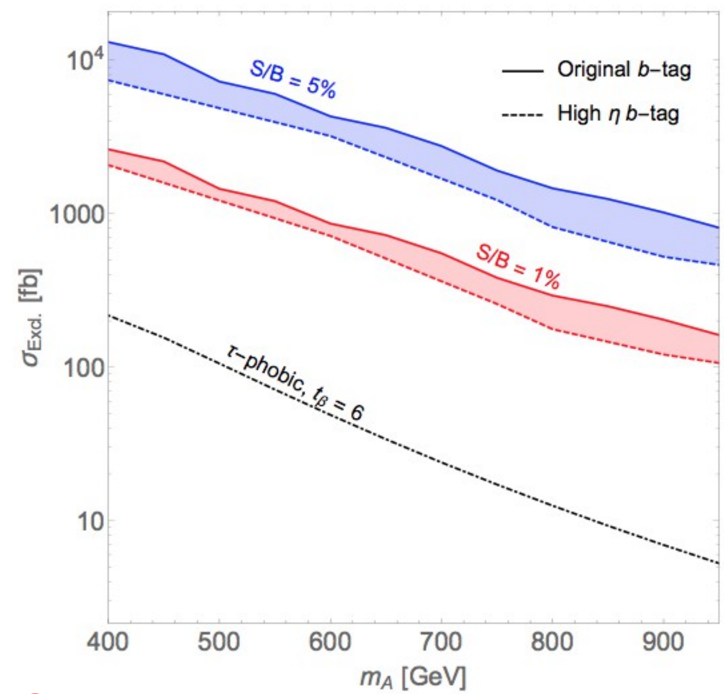




3 leptons, >1b, >2jets



1 lepton, >1b, >5jets



Better/complementary ideas?

Does the Higgs give mass to the charm?

Experimentally, we do not know if the Higgs couples to

- Muons (m_μ ~ 100 MeV)
- Electrons (m_e ~ 0.5 MeV)
- Light quarks (m_c~1.3 GeV, m_s ~ 100 MeV, m_d ~ 6 MeV, m_u ~ 3 MeV)

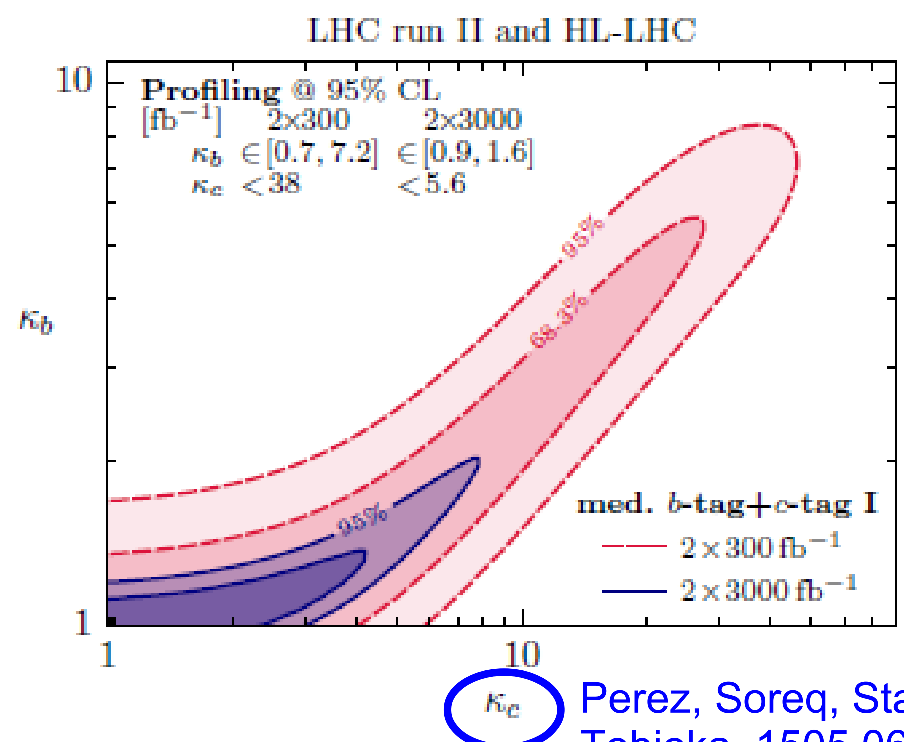
Light quarks: charm

Inclusive determination:

Signal strenght for h → bb:

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

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



Perez, Soreq, Stamou, Tobioka, 1505.06689

Difficult to measure at the LHC

For the ILC is different: expected precision at the level of (1-3)%

Fujii et al., 1506.05992

Does the Higgs give mass to the charm?

Experimentally, we do not know if the Higgs couples to

- 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)

Light quarks: charm

Summary