New signals from the Higgs boson(s)

Stefania Gori
University of Cincinnati

The 13th Workshop of the LHC Higgs Cross Section Working Group
CERN, July 13th 2016

Higgs signatures for the LHC

We have discovered **the** Higgs boson

Is it the full story for ElectroWeak Symmetry Breaking (EWSB)?

Additional Higgs bosons?(*) **Any missed signature?**

Novel production modes

(3) a (s)

(1)

(2) H, A, $H^{\pm}$

? 125 GeV ? ? ? Mass (GeV)

Novel decay modes

(Higgs exotic decays, Jessie's talk)

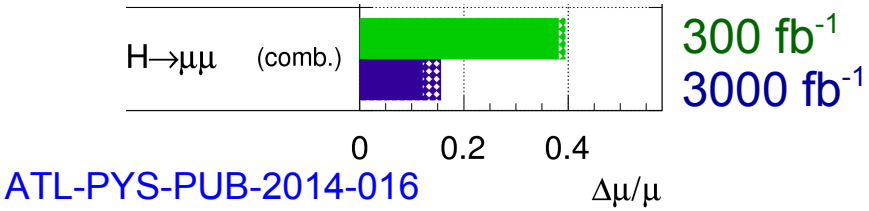
(*) Disclaimer: I will also discuss new scalars not participating to EWSB

Higgs coupling to light generations (1)

General challenge:

measure the 125 GeV Higgs couplings to 1st and 2nd generations

The Higgs coupling to muons will be measured:



ATL-PYS-PUB-2014-016

What about 2nd generation quarks?

Several ways to determine/ set bounds on the Higgs-charm Yukawa (J/Ψ γ decay, …)

Study of **Higgs production?**

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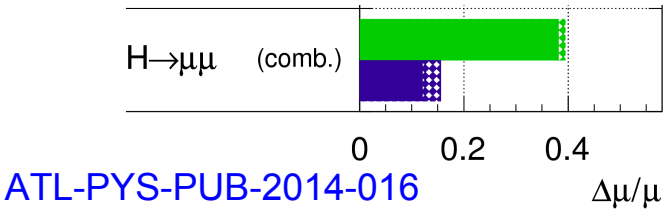

300 fb^{-1}
3000 fb^{-1}

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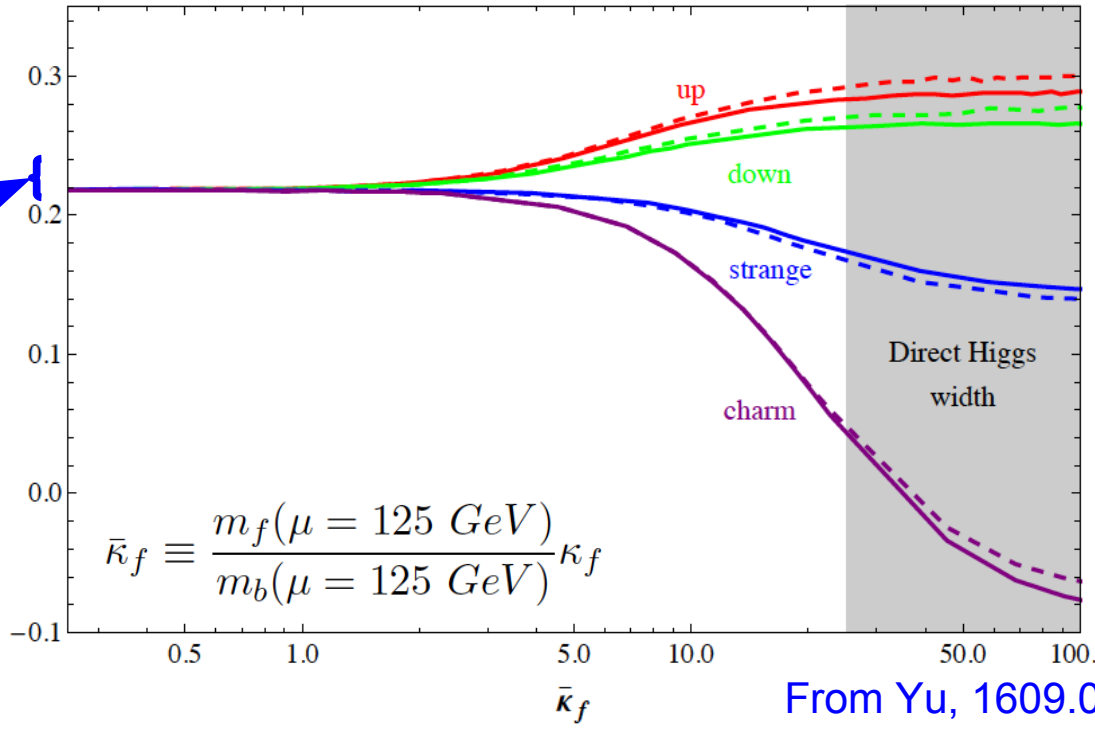
What about
2nd generation quarks?

Several ways to determine/
set bounds on the Higgs-charm
Yukawa (J/Ψ γ decay, …)

Focusing on new signatures/
interpretation of data:

$$\mathcal{A} = \frac{\sigma(W^+h) - \sigma(W^-h)}{\sigma(W^+h) + \sigma(W^-h)}$$

0.4% is the estimated
uncertainty at the HL-LHC



From Yu, 1609.06592

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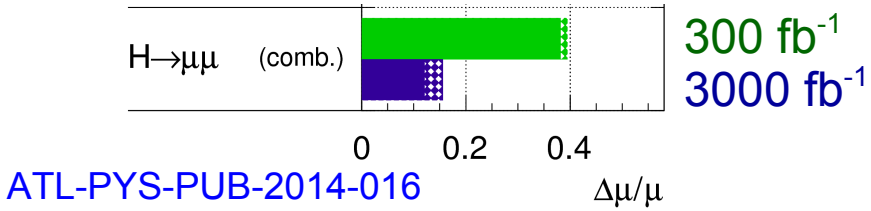

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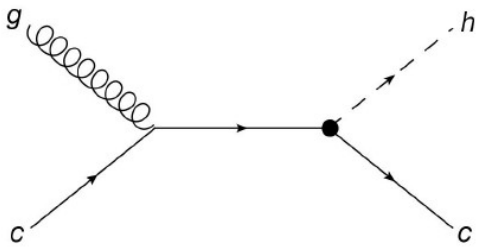
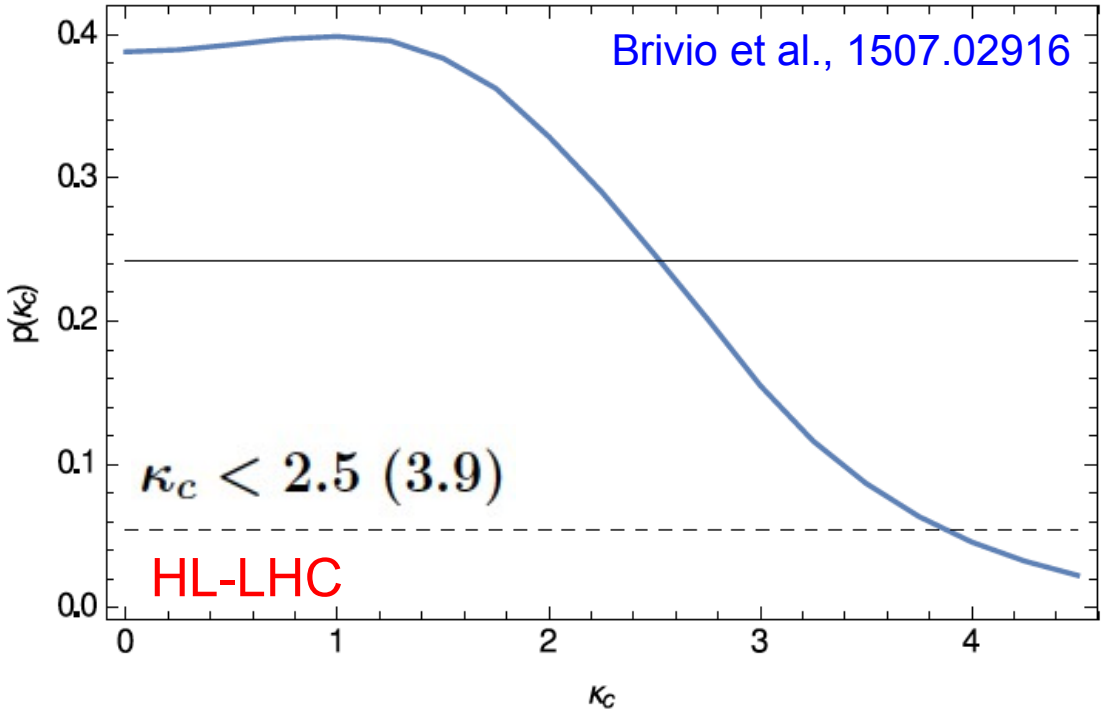
Study of Higgs-charm production



κ_c	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2
S	874	877	885	899	917	941	973	1008	1052



Current LHC heavy Higgs searches (2)

bb	ττ	μμ	γγ	Zγ	hh	WW	ZZ	tt
bH	gg,bH	gg,bH		gg	gg	gg, VFB	gg, VFB	gg, tt,bb

H

bb	ττ	μμ	γγ	Zγ	Zh	tt
bH	gg,bA	gg,bA		gg	gg,bA	gg tt,bb

A

New since ICHEP 2016

τν	tb	Wh	cs	μν	cb
(t)$H^{\pm}$ t dec	(t)$H^{\pm}$ t dec	qq fus	t decay	qq fus	t decay

$H^{\pm}$

see also talk by Cecile this morning

Current LHC heavy Higgs searches (2)

bb	ττ	μμ	γγ	Zγ	hh	WW	ZZ	tt
bH	gg,bH	gg,bH		gg	gg	gg, VFB	gg, VFB	gg, tt,bb

H

bb	ττ	μμ	γγ	Zγ	Zh	tt
bH	gg,bA	gg,bA		gg	gg,bA	gg tt,bb

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$H^{\pm}$

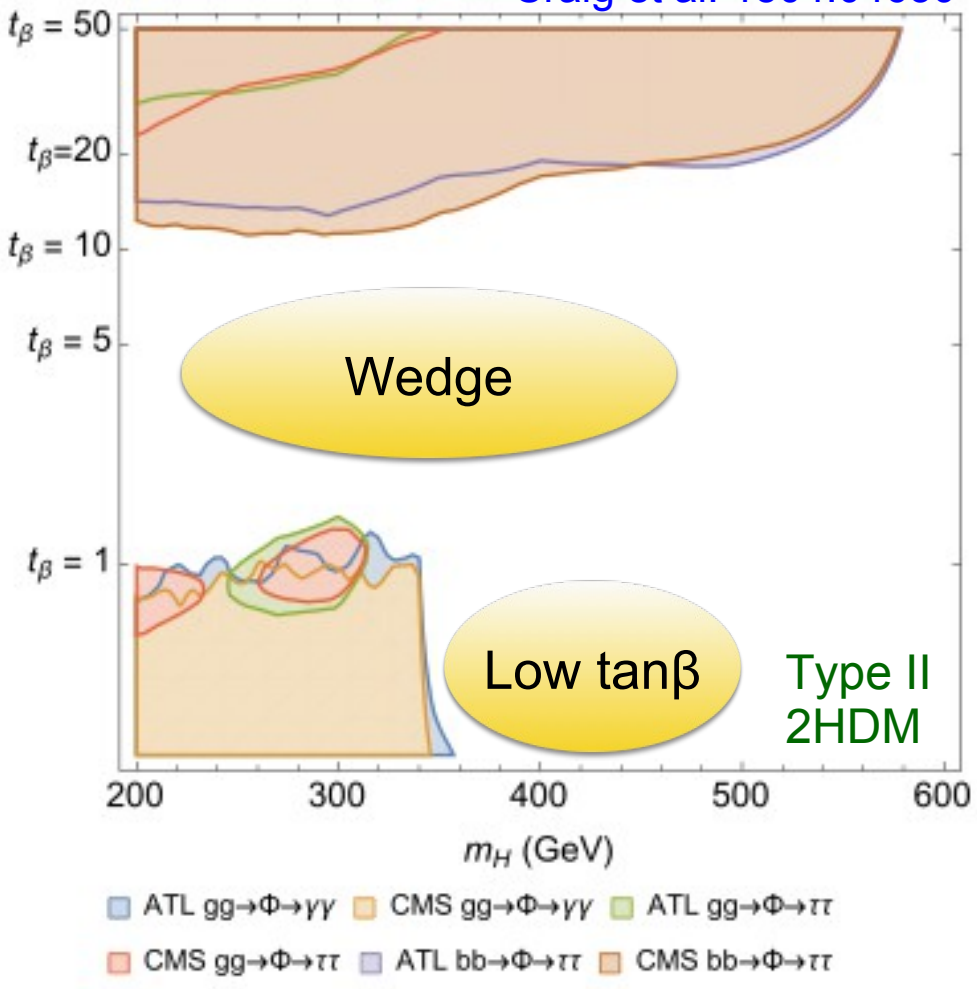
New since ICHEP 2016

Not targeted at a new Higgs

see also talk by Cecile this morning

The "famous" gaps in heavy H searches (2)

Craig et al. 1504.04630



(status for aligned models)

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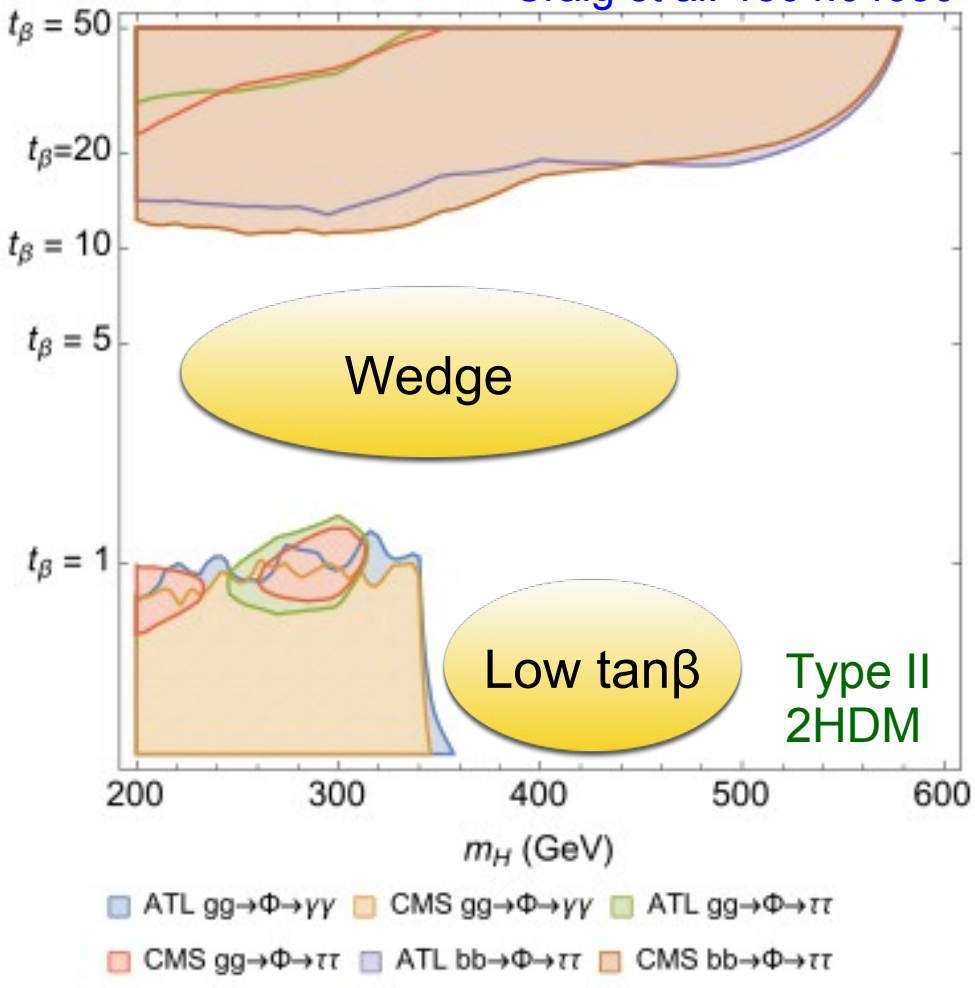


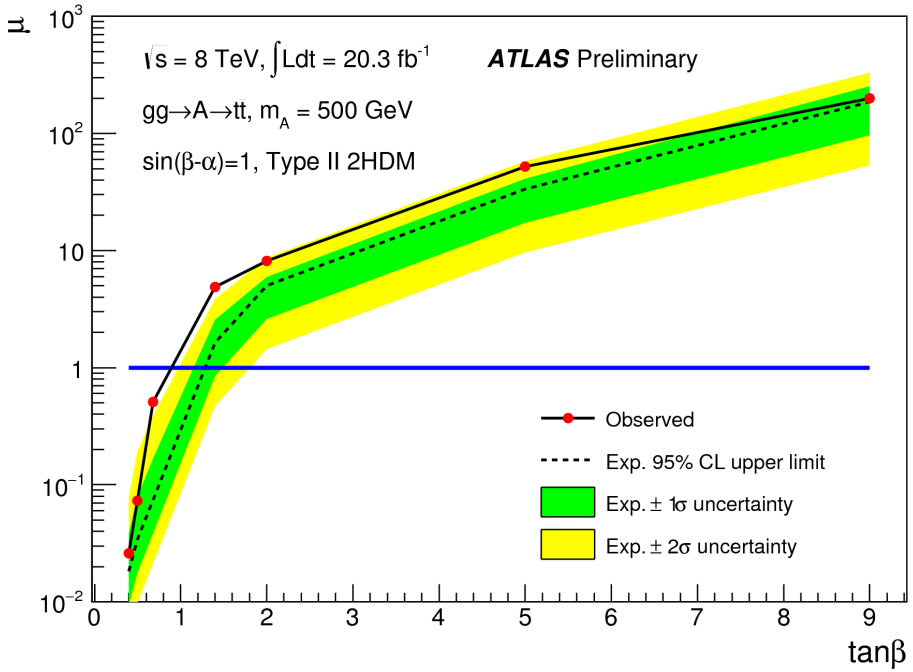
(status for aligned models)

Several new searches can probe these regions

1. $pp \rightarrow H/A \rightarrow t\bar{t}$,
2. $pp \rightarrow b\bar{b}H/A,\ H/A \rightarrow t\bar{t}$,
3. $pp \rightarrow t\bar{t}H/A,\ H/A \rightarrow t\bar{t}$

1. Done

ATLAS-CONF-2016-073



Heavy quark associated productions (2)

2. & 3.

Recently, ATLAS and CMS have performed similar searches, even if not targeted on heavy Higgses:

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2. $pp \to b\bar{b}H/A,\ H/A \to t\bar{t}$,
3. $pp \to t\bar{t}H/A,\ H/A \to t\bar{t}$

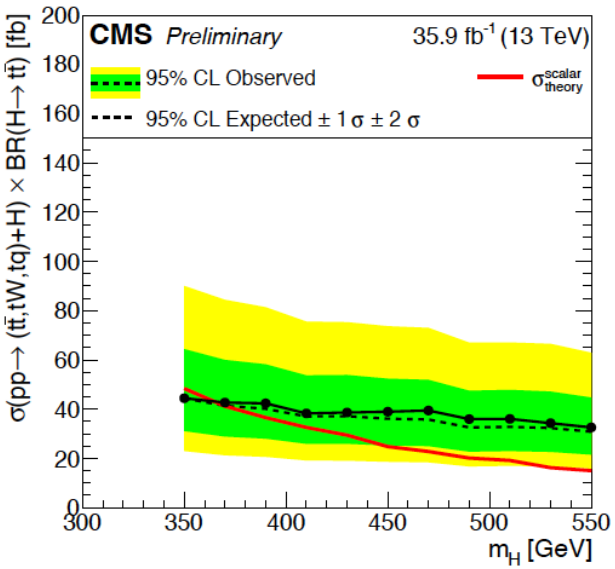
Search for beyond the standard model physics in events with two leptons of the same sign, missing transverse momentum, and jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

$pp \to \tilde{g}\tilde{g},\ \tilde{g} \to t\bar{t}\chi_1$ CMS-PAS-SUS-16-035

Search for new phenomena in $t\bar{t}$ final states with additional heavy-flavour jets in 13.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

ATLAS-CONF-2016-104

$pp \to T\bar{T},\ T \to tH, Wb$



Important especially for HL-LHC

How can we use the info that we have a new resonance?
What about 3 lepton signatures?

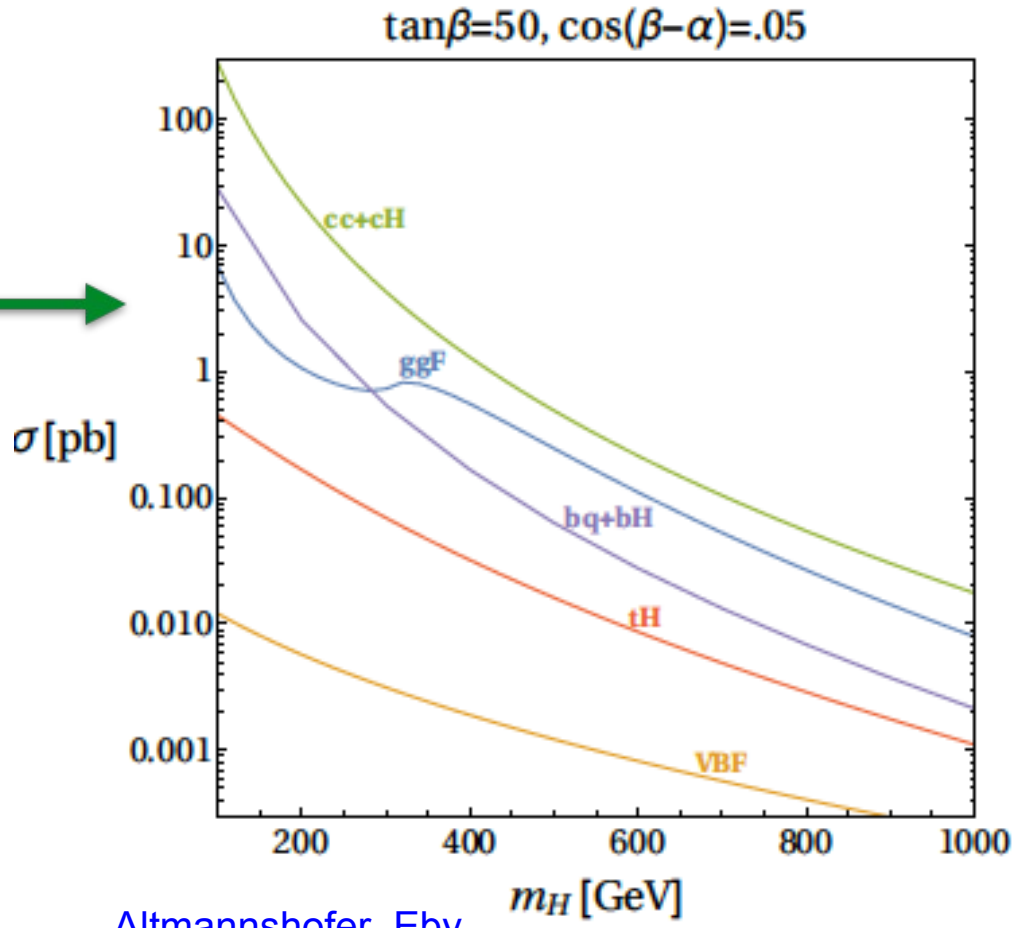
Charm associated production (2)

Important effort of the working group in making recommandations for Hbb production in 2HDMs/MSSM scenarios

What about Hcc production? (cross sections + distributions)

WHY is this important?

- Several flavor models for multi-Higgs theories predict sizable cross sections (example: flavorful 2HDM)
- The recommandations could be used for the SM Higgs boson, as well



Email exchange with Stefano Frixione, Fabio Maltoni, and Marius Wiesemann

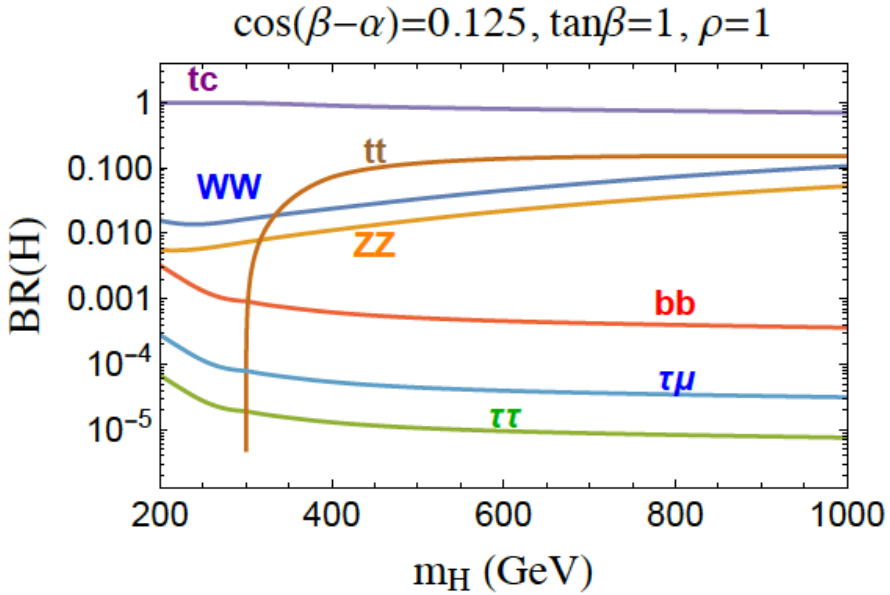
Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

New flavored heavy Higgs signatures (2)

Flavor violating heavy Higgs decays easily arise in flavor models

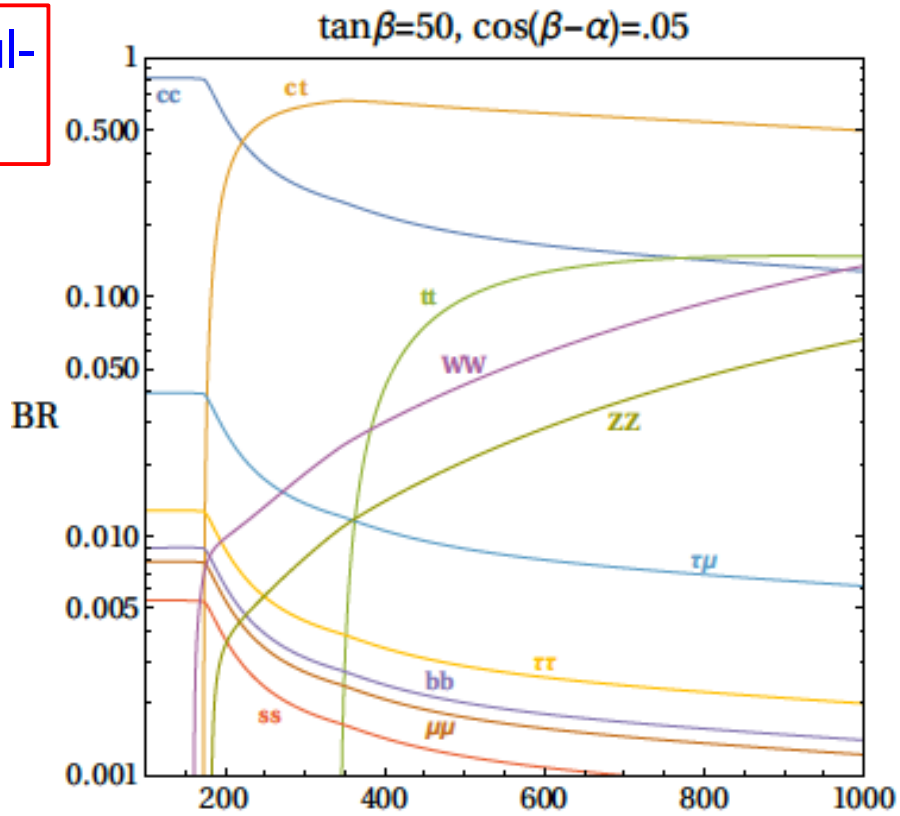
2 benchmark models:

PQ-2HDM



SG, Grojean, Juste, Paul, appearing soon

Flavorful-2HDM



Altmannshofer, Eby,
SG, Lotito, Martone, Tuckler, 1610.02398

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3Flavorful2HDM

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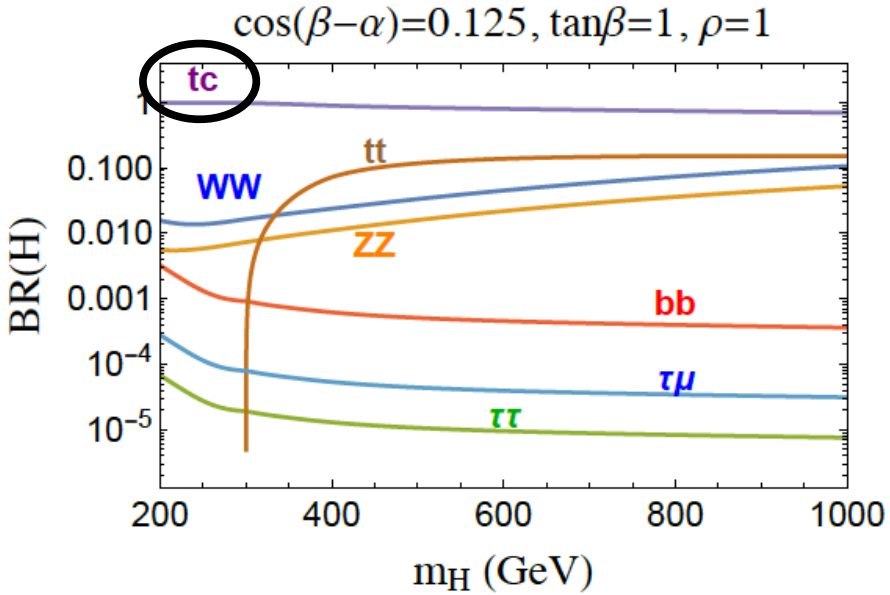

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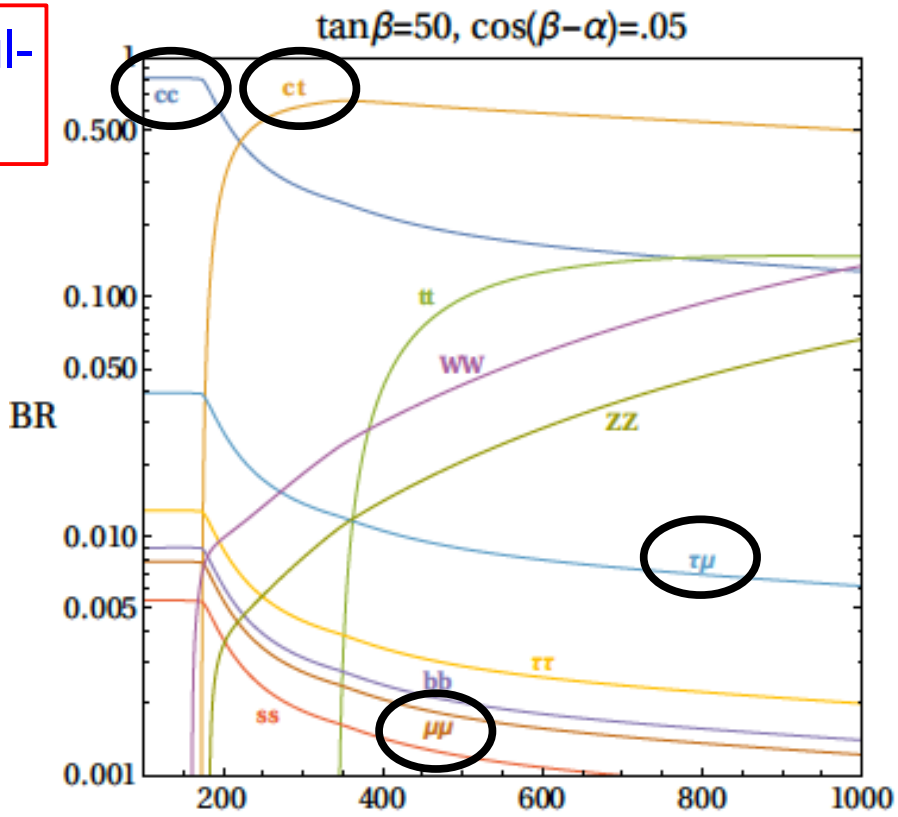


Altmannshofer, Eby,
SG, Lotito, Martone, Tuckler, 1610.02398

New opportunities for ATLAS/CMS searches:

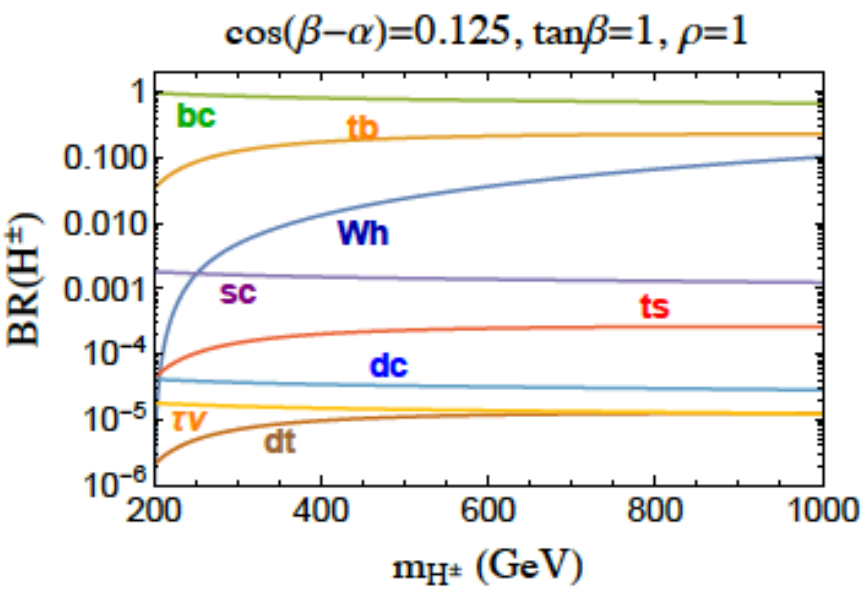
$$pp \to H/A \to tc, \quad pp \to t(c)H/A, H/A \to tc, \quad pp \to t(c)H/A, H/A \to tt$$
$$pp \to H/A \to \tau\mu \quad pp \to t(c)H/A, H/A \to \tau\mu, \quad pp \to c(c)H/A \to \mu\mu, \cdots$$

New flavored charged Higgs signatures (2)

Also the phenomenology of $H^{\pm}$ changes dramatically

One can use the two benchmark models of last slide for interpretation.

PQ-2HDM



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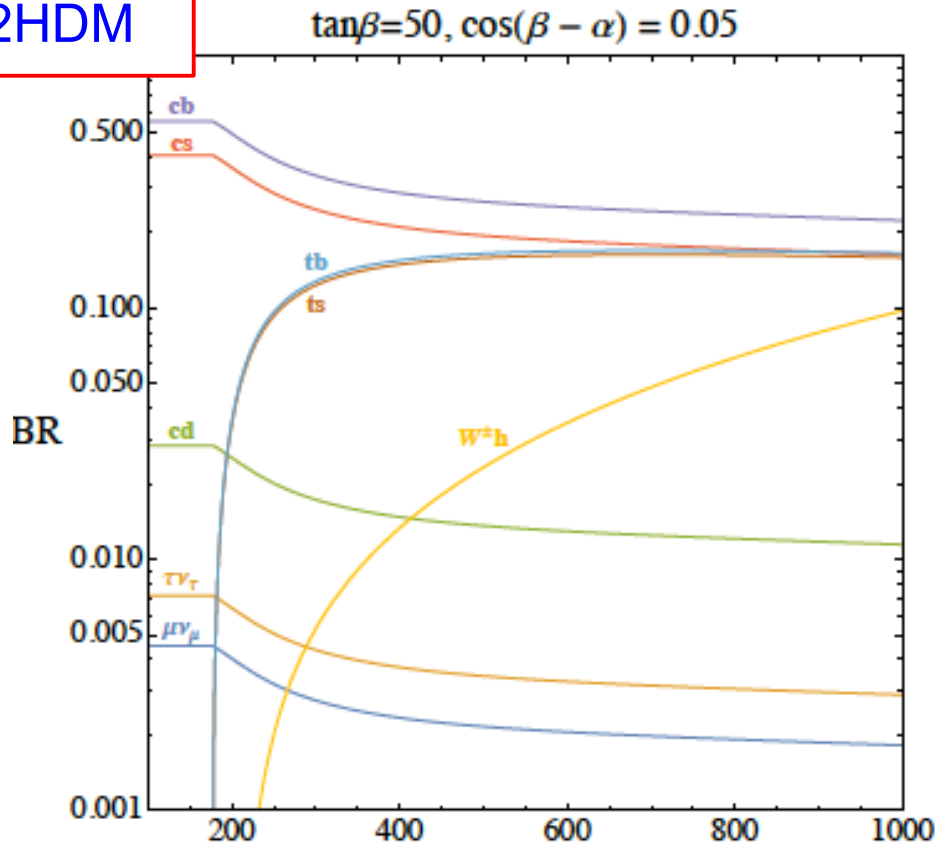

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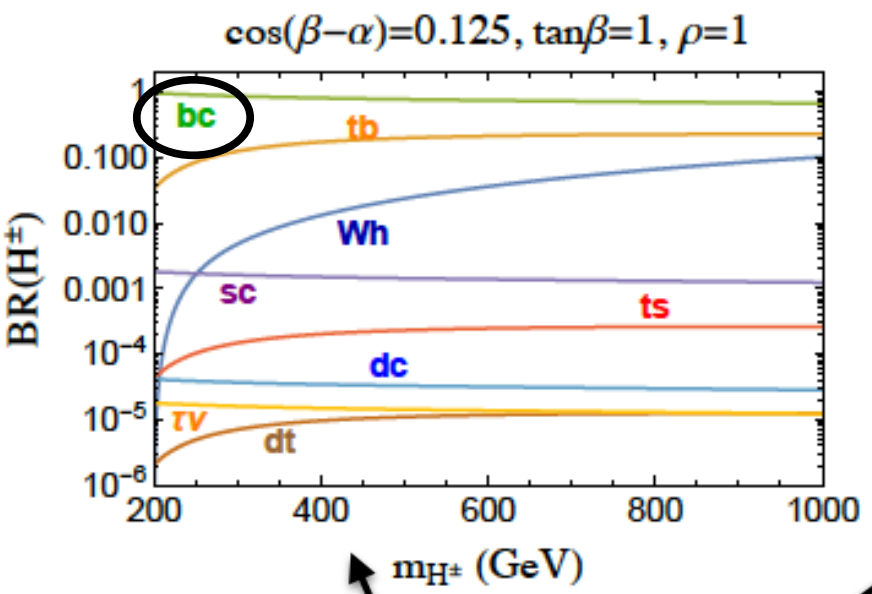

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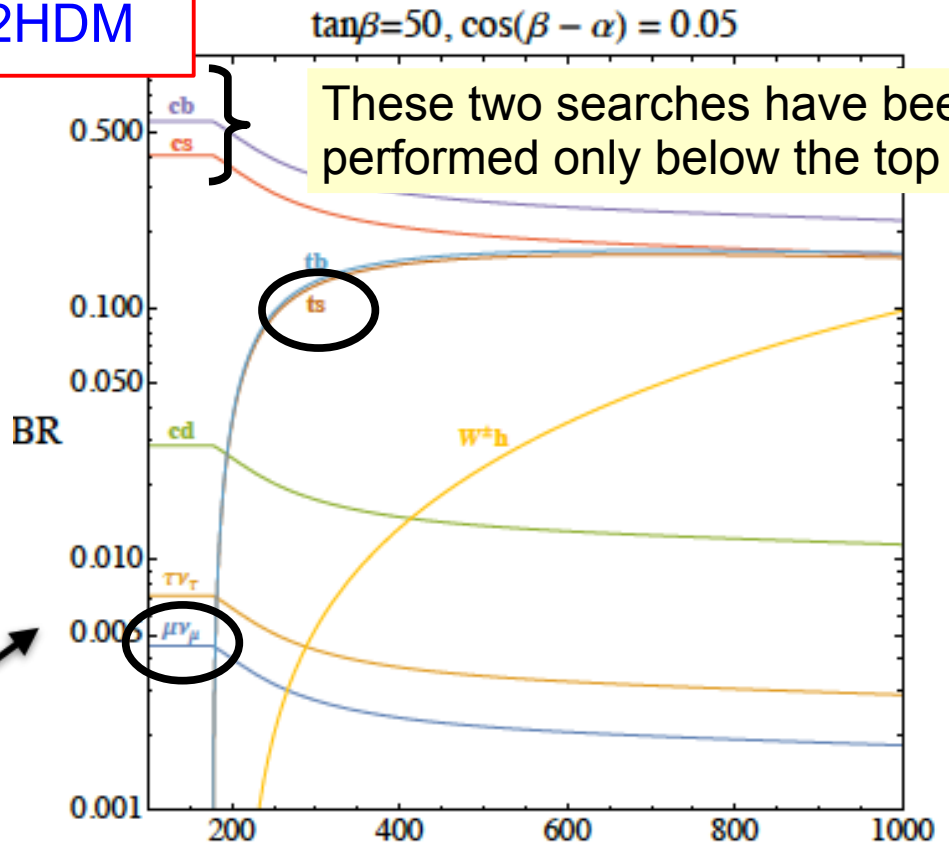
- qq fusion
- t associated production

Flavorful-2HDM



These two searches have been performed only below the top mass!

Altmannshofer, Eby,
SG, Lotito, Martone, Tuckler, 1610.02398

Decay modes with NP particles (2)

Organization principles for heavy Higgs searches

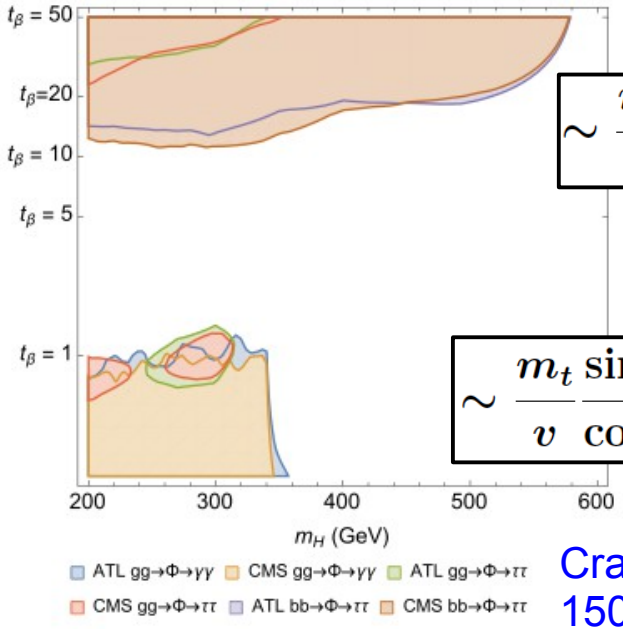
Not too far away from the alignment limit

(and therefore not too large couplings to massive gauge bosons)

$$|\cos(\alpha-\beta)| \lesssim \text{few} \cdot \mathcal{O}(0.1)$$

		H	A
Standard Model	WW, ZZ	–	
Decay Channels	$tt, bb, \tau\tau, \mu\mu$	✓	✓
	$\gamma\gamma$	✓	✓
	Zh		–
	hh	–	

Going back to our wedge region...



$$\sim \frac{m_b}{v}\frac{\cos\alpha}{\sin\beta}\tan\beta \sim \frac{m_b}{v}\tan\beta$$

$$\sim \frac{m_t}{v}\frac{\sin\alpha}{\cos\beta}\frac{1}{\tan\beta} \sim \frac{m_t}{v}\frac{1}{\tan\beta}$$

Craig et al.
1504.04630

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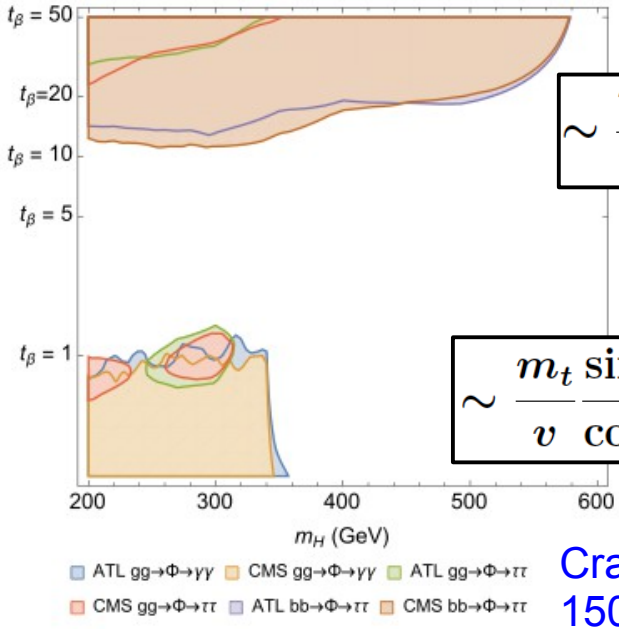

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Craig et al.
1504.04630

In the regime of not too large values of tanβ, the heavy Higgs width is relatively small

Motivation for looking for
H → NP particles
(not too large couplings with NP are needed to have a sizable BR)

Example of heavy Higgs decays to NP (2)

Several benchmarks proposed in the YR4, with heavy Higgses with new decay modes to NP particles

A few examples:

- "Higgs to Higgs" decays (2HDM $BP1_E$)

  long cascades

  Proposed by Haber, Stal, 1507.04281

$$H^{\pm} \to W^{\pm} A, \quad A \to ZH$$

- Higgs decays involving charginos or LSPs

  NMSSM "BP7_2" scenario

$$gg \to H \to \tilde{\chi}\tilde{\chi},$$
$$\tilde{\chi}_1^0\tilde{\chi}_1^0 : 391 \text{ fb}, \ \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm} : 337 \text{ fb}$$

See also talks by Ulrich & Stefan earlier today

To perform searches with the same final states as those done for the 125 GeV Higgs?
(larger room for kinematics, typically less challenging analyses)

Additional signatures arising in
- SUSY theories
- Twin Higgs models?

Theories with light scalars (3)

SUSY and beyond:

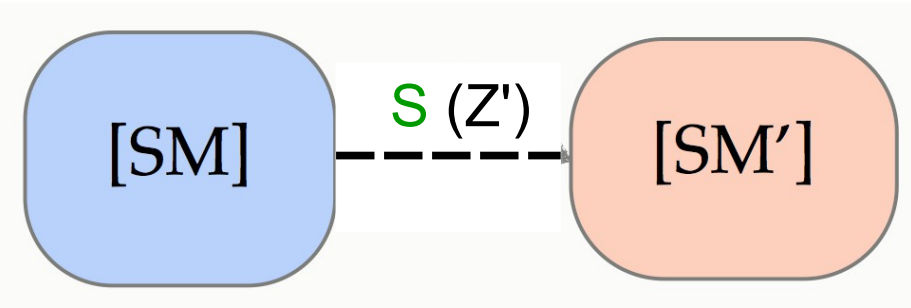
- NMSSM
  - (approximate) R-symmetric limit: light pseudoscalar (a).
  - (approximate) PQ-symmetric limit: light pseudoscalar (a), scalar (s), singlino (χ_1).

- Folded SUSY, Twin Higgs models, fraternal twin Higgs model:
  - light glueballs

Burdman et al, 0609152,
Chacko et al, 0506256,
Craig et al, 1501.05310

More generically, in **Simplified models**:

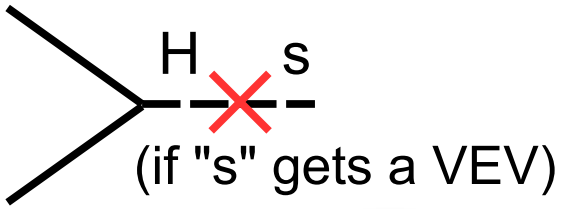
- 2HDM + scalar
- Theories for light Dark Matter with scalar mediator



Production of light scalars at the LHC (3)

Since they are not charged under the SM symmetries...

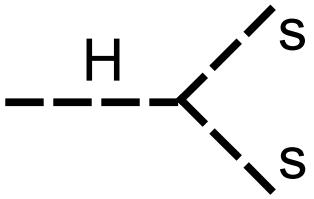
Direct production:



Higgs portal interaction

$$\frac{\xi}{2}|H|^2 s^2$$

(125 GeV) Higgs decays:



The Higgs couplings to SM particles are reduced by a factor of $\cos(\theta_s)$

The Higgs has some "exotic" signatures

Dependence on two different parameters

$$\tan(\theta_S) \simeq \frac{\xi v_h v_S}{m_h^2 - m_S^2}$$

ξ

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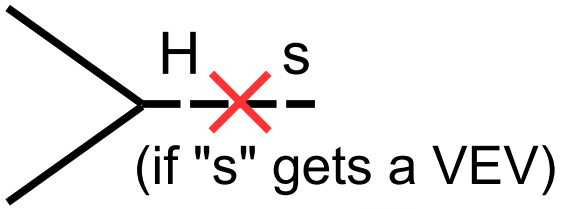

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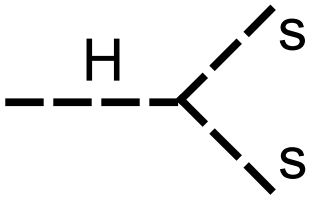

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$$\tan(\theta_S) \simeq \frac{\xi v_h v_S}{m_h^2 - m_S^2} \quad \longleftrightarrow \quad \xi$$

Complementarity

Direct production of a single scalar

Higgs exotic decays

Production of light scalars at the LHC (3)

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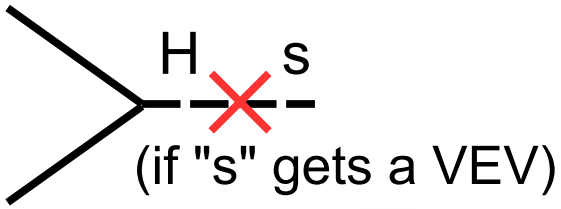

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Dependence c

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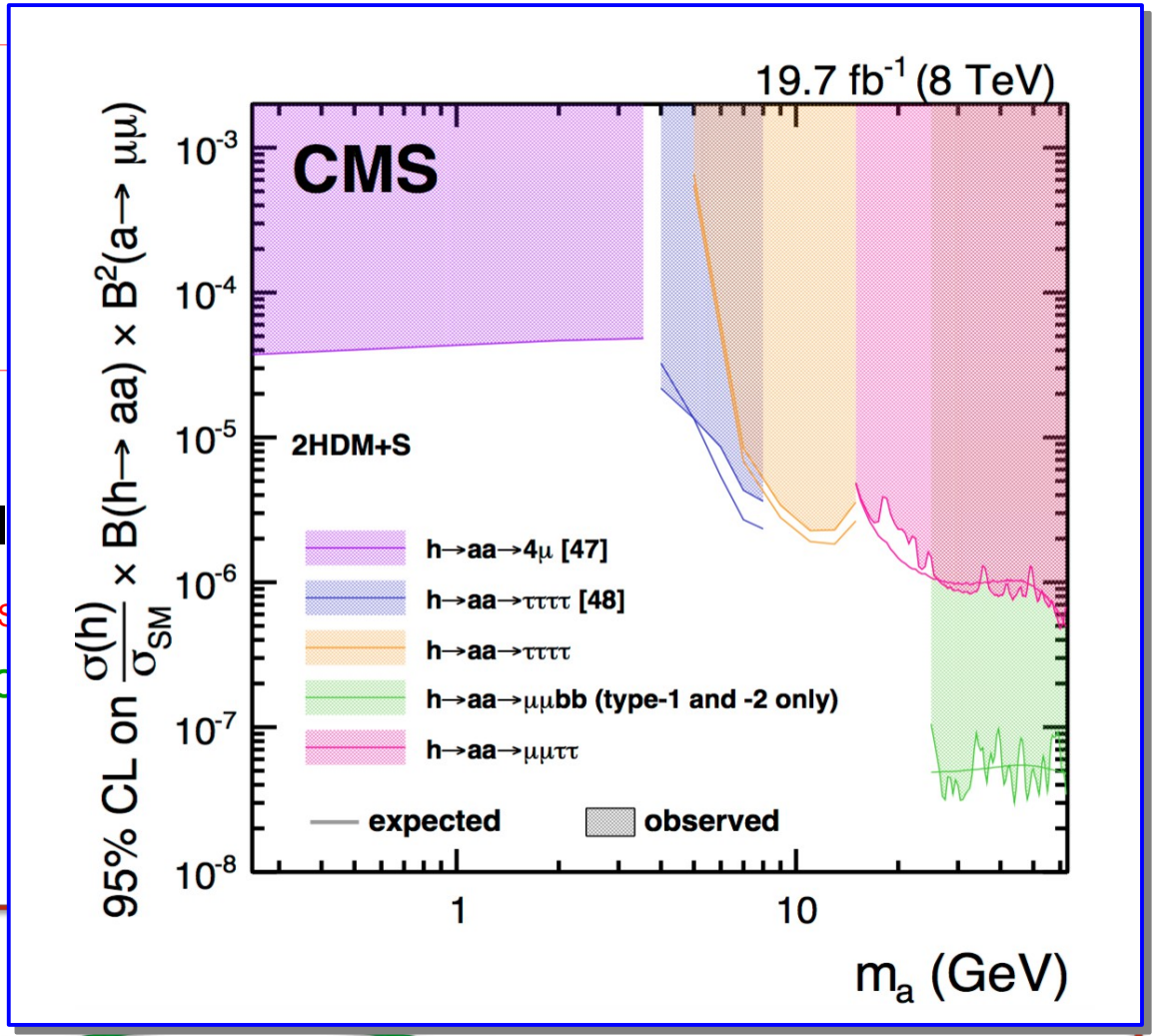
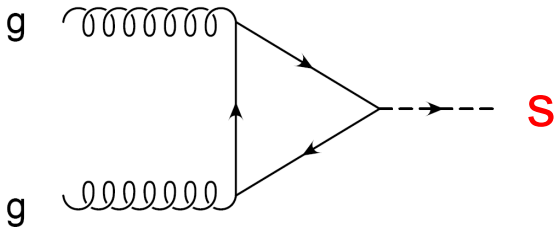


Direct production of a single scalar

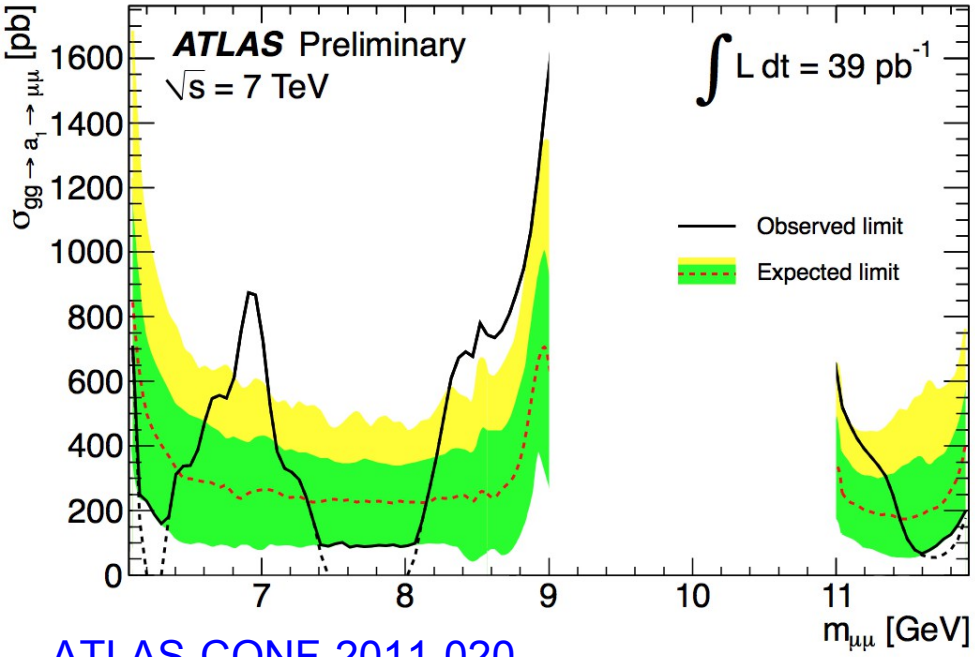
Higgs exotic decays

Direct production of a single light scalar (3)



Searches for a light scalar can be challenging for ATLAS and CMS due to trigger thresholds, softeness of the decay products, backgrounds, ...

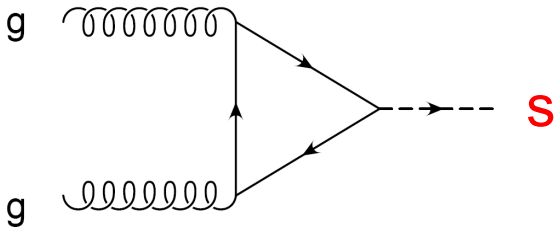
One of the very few searches:
di-muon resonances $pp \to s,\ s \to \mu\mu$



ATLAS-CONF-2011-020

Haisch, Kamenik, 1601.05110
for the LHCb prospects

Direct production of a single light scalar (3)



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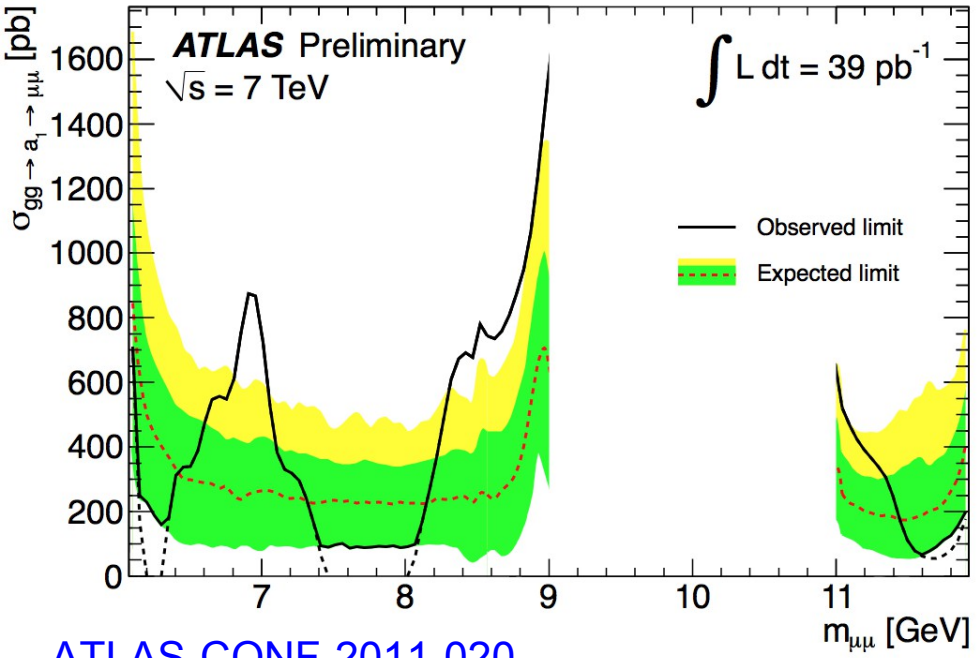

ATLAS-CONF-2011-020

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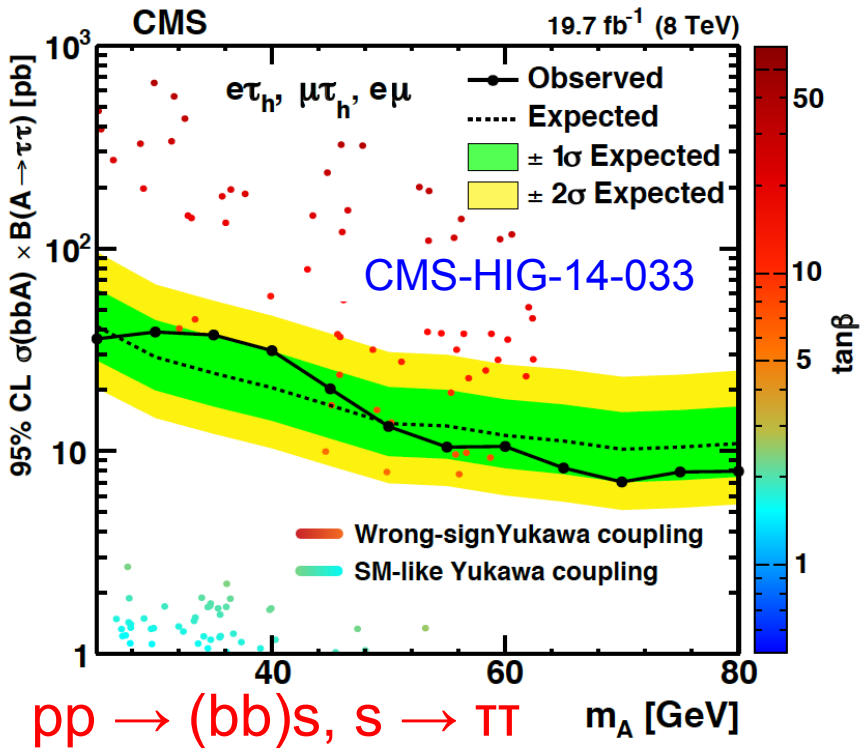
for the LHCb prospects

Unique opportunity to test these scalars using associated production

Very few searches!

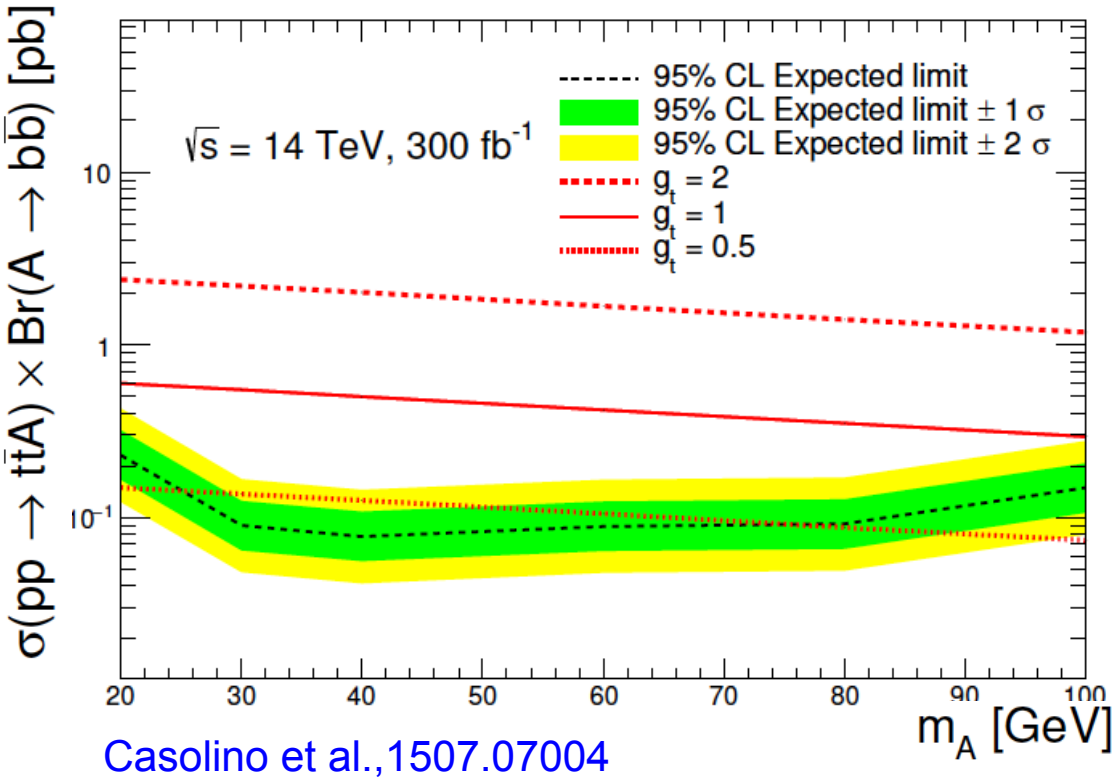


pp → (bb)s, s → ττ

A large set of new searches can be done! (3)

A phenomenological analysis (P):

$pp \rightarrow (tt)s,\ s \rightarrow bb$



Casolino et al.,1507.07004

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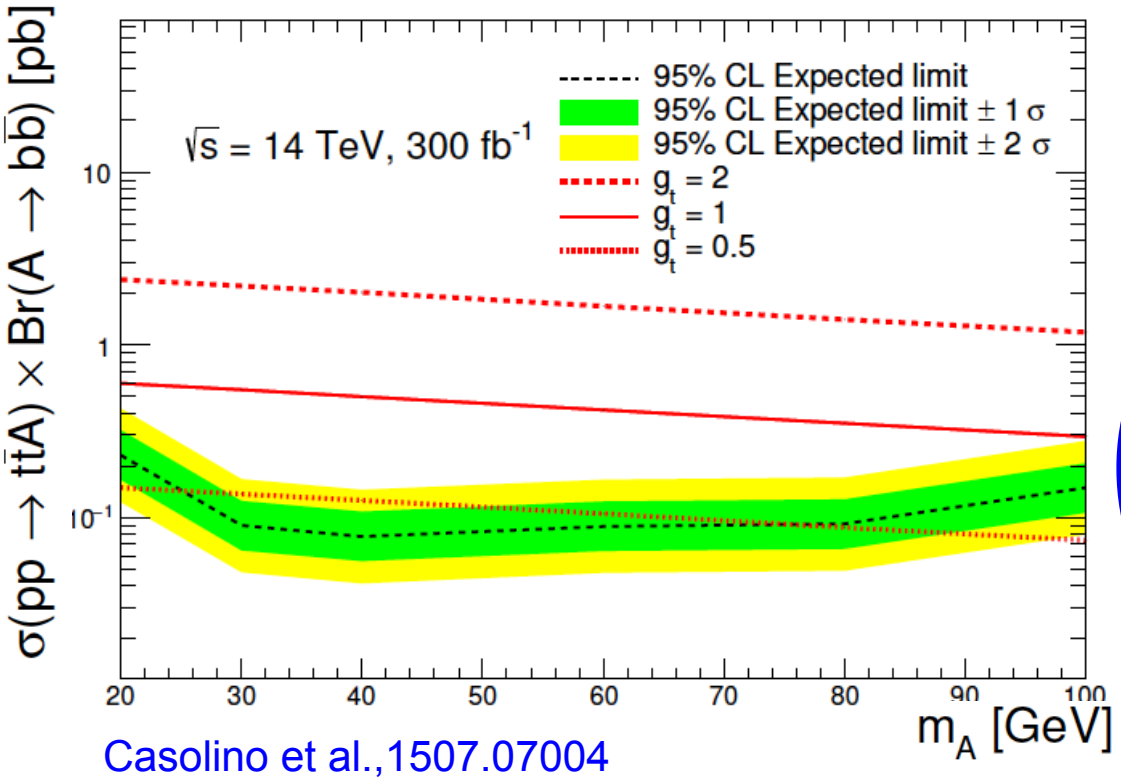


Casolino et al.,1507.07004

What about:

	$A \to \tau\tau$	$A \to \gamma\gamma$	$A \to bb$
bbA	CMS		
ttA			P
VBF A			
Z/W A			
jA			
γA			

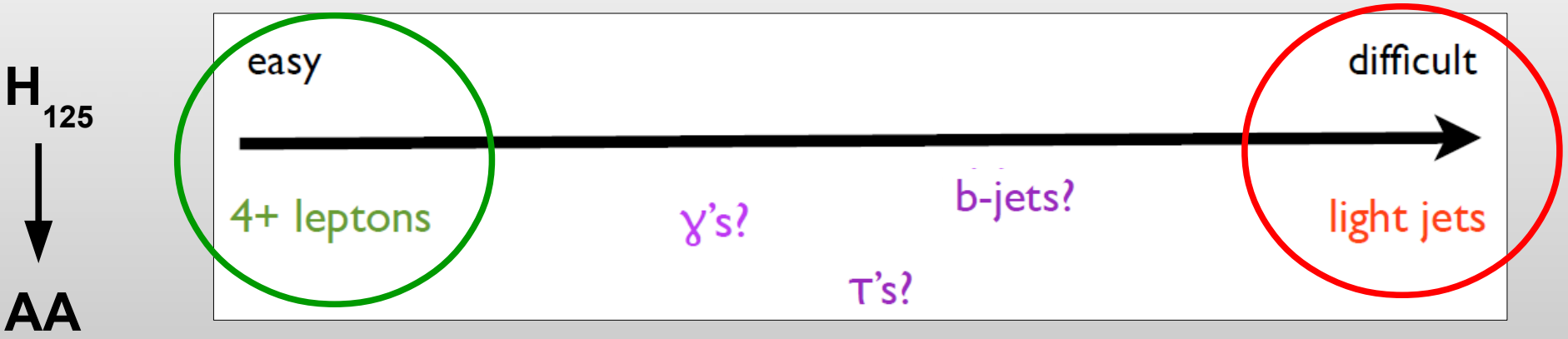
Possible combined trigger 1 jet\photon + soft object(s) to catch this type of signatures (also usefull for compressed NP scenarios)?

Very important complementarity with Babar searches and with LHCb prospects! (see talk by Lorenzo)

The future goal for light scalars

The LHC is going to be a SM Higgs factory

$O(10^8)$ Higgs bosons will be produced with $3000fb^{-1}$ data



Higgs produced in gluon fusion

Subleading production Modes of the 125 GeV Higgs (Wh, Zh, tth, ...)

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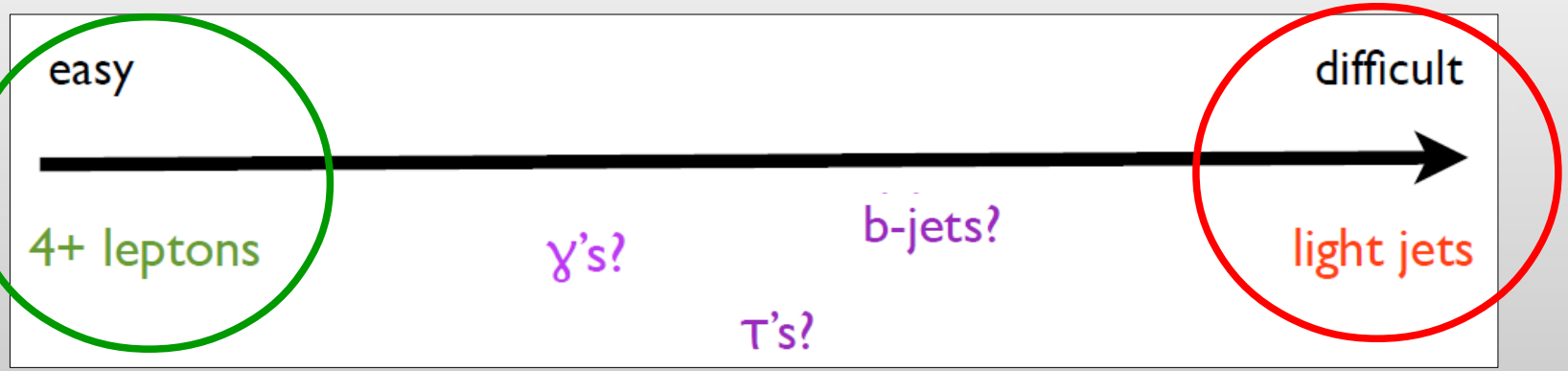
H_{125} → AA



Higgs produced in gluon fusion

Subleading production Modes of the 125 GeV Higgs (Wh, Zh, tth, ...)

pp → A

	$A \to \tau\tau$	$A \to \gamma\gamma$	$A \to bb$
bbA	CMS		
ttA			
VBF A	To fill out		To fill out
Z/W A			
jA			
γA			

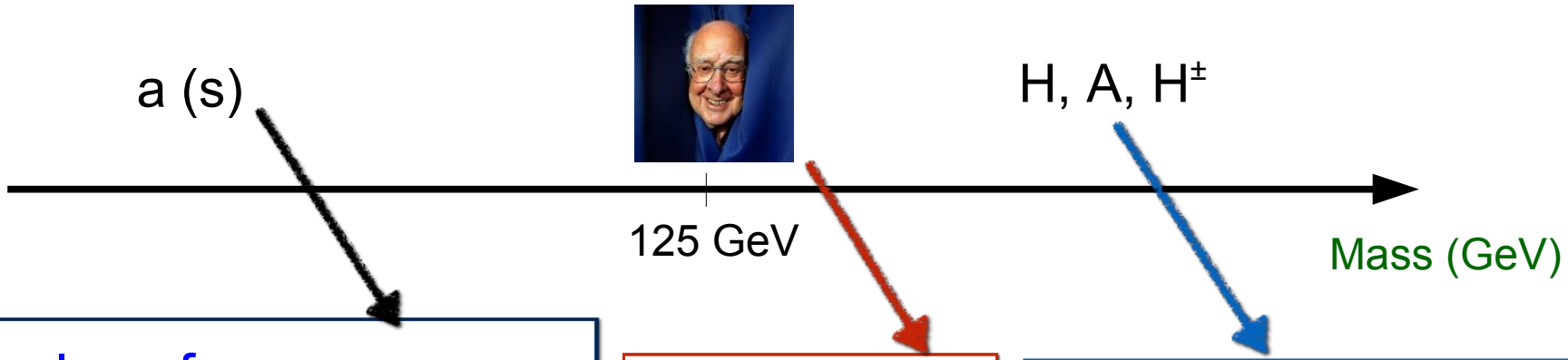
+ di-muon & di-electron searches

Complementarity with LHCb

Summary

One or more Higgs bosons?

Thinking about missing signatures...



Interplay of

- Single direct production
- 125GeV Higgs exotic decays

Soft Triggers!

Production & light Yukawas

- Flavorful signatures
- New decay modes to NP particles

Going beyond MFV: flavorful U(2)

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

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, tanβ = 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)

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

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

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

It also generates the correct CKM matrix

Flavor diagonal couplings of the heavy H

Comparing to other extended Higgs sectors...

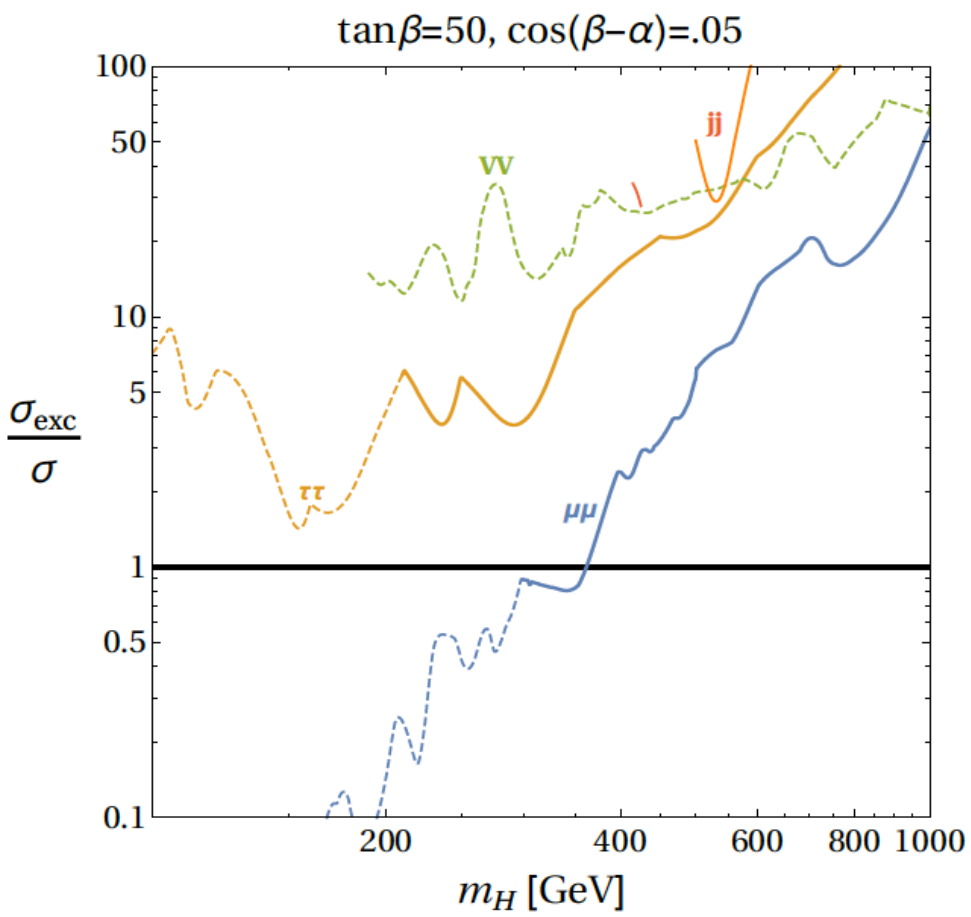
	W,Z κ_V^H	up quarks κ_t^H, κ_c^H, κ_u^H	down quarks κ_b^H, κ_s^H, κ_d^H	leptons κ_τ^H, κ_μ^H, κ_e^H
2HDM type 1	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$
2HDM type 2	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$
Flavorful 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 flavorful 2HDM there are additional corrections to the κ's of the order of $O(m_c/m_t)$, $O(m_s/m_b)$, $O(m_\mu/m_\tau)$

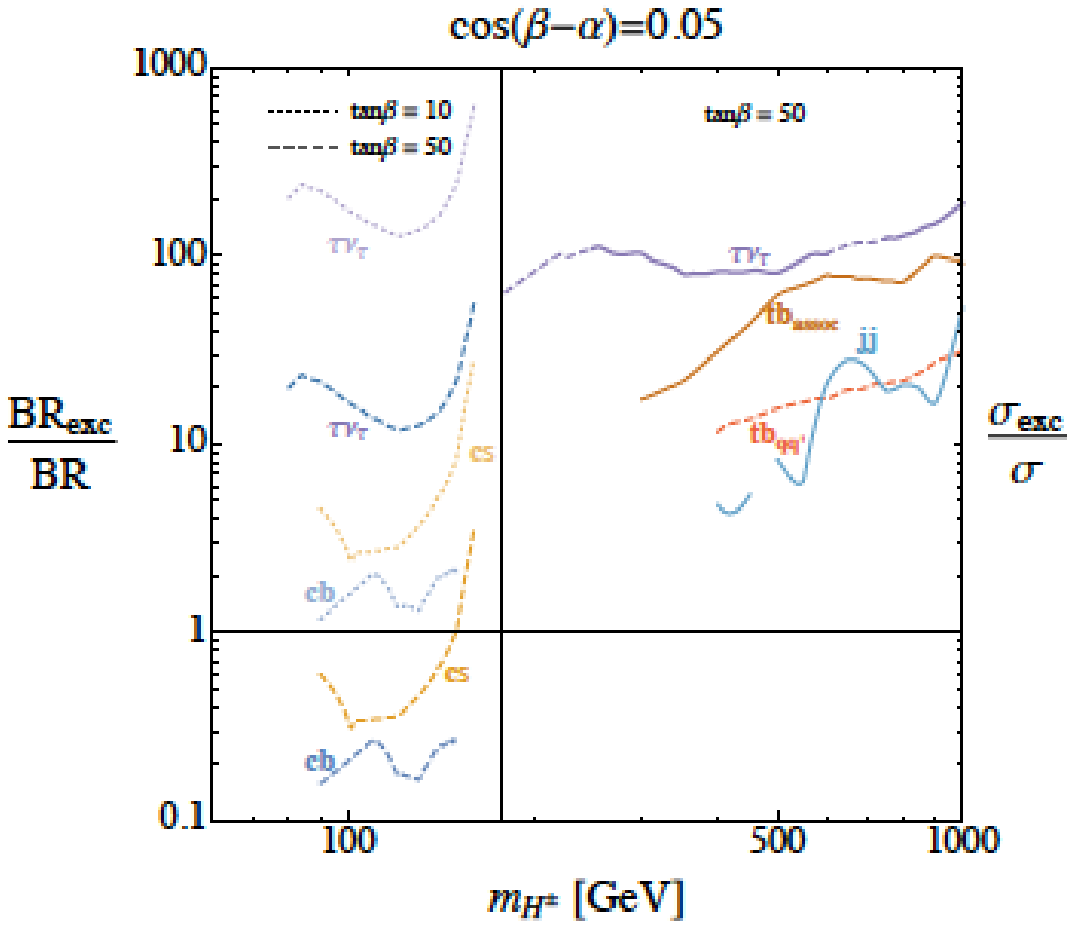
Weak bounds on the flavorful 2HDM

Even at very large values of tanβ:

Altmannshofer, Eby, SG,
Lotito, Martone, Tuckler, 1610.02398



Neutral Higgs



Charged Higgs