What do we learn on the new H bosons? (1)

So far we have considered the couplings of the 125 GeV Higgs boson

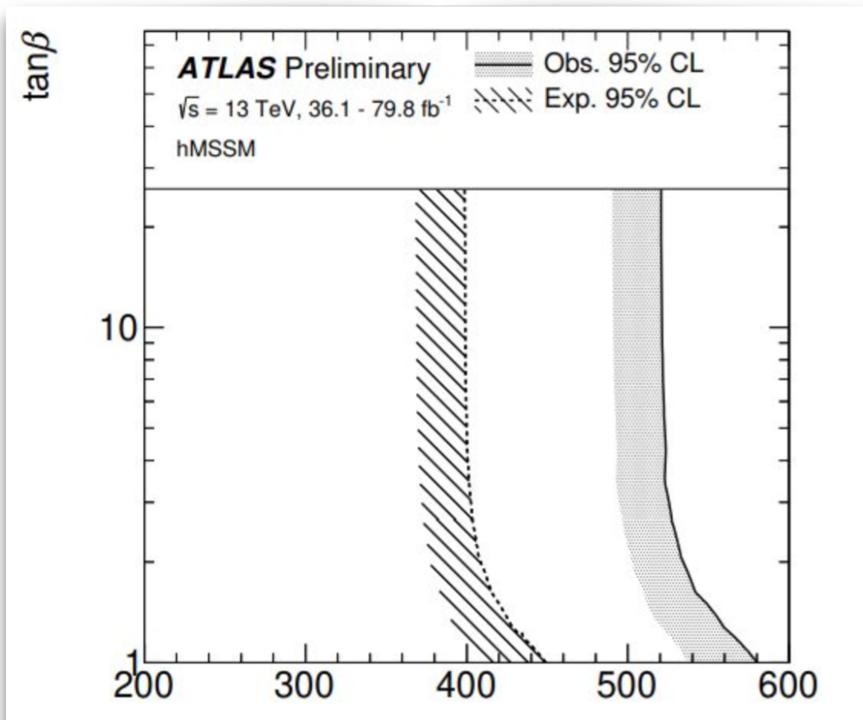
$$\kappa_V = \sin(\beta - \alpha)$$

The couplings of the heavy Higgs bosons are related:

Upper bound on the coupling of the heavy Higgses with gauge bosons:

$$\kappa_V^H = \cos(\alpha - \beta) \simeq x$$

Furthermore, (very) generically we obtain a lower bound on the heavy Higgs mass



ATLAS-CONF-2018-031

$$\alpha = \beta - \pi/2 + \underbrace{O(\lambda_i v^2/M_A^2)}_{x}$$

What do we learn on the new H bosons? (1)

So far we have considered the couplings of the 125 GeV Higgs boson

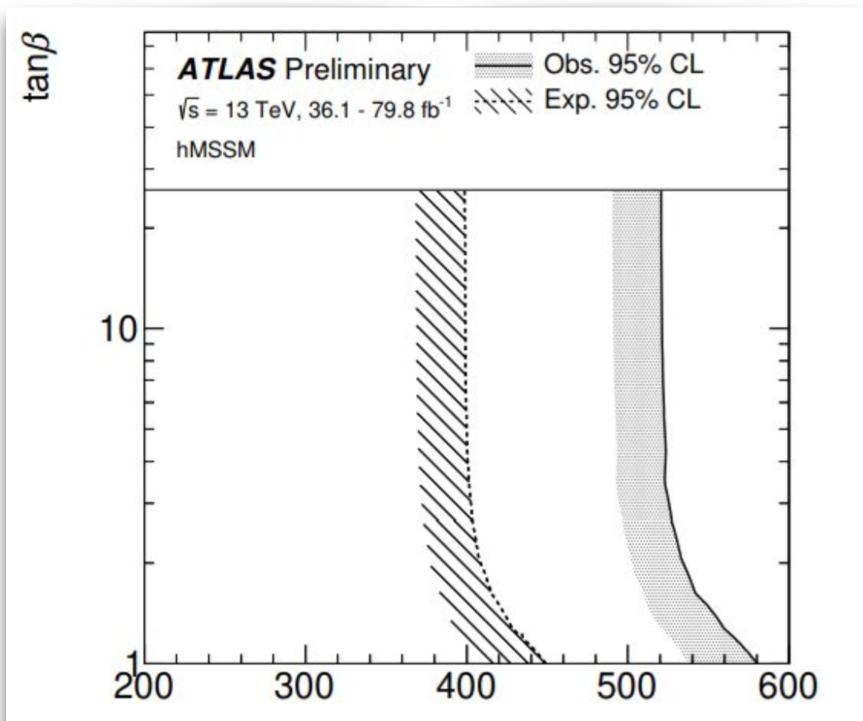
$$\kappa_V = \sin(\beta - \alpha)$$

The couplings of the heavy Higgs bosons are related:

Upper bound on the coupling of the heavy Higgses with gauge bosons:

$$\kappa_V^H = \cos(\alpha - \beta) \simeq x$$

Furthermore, (very) generically we obtain a lower bound on the heavy Higgs mass



$$\alpha = \beta - \pi/2 + \underbrace{O(\lambda_i v^2/M_A^2)}_{x}$$

We measure the 125 GeV Higgs & we learn about new Higgs bosons (couplings and mass)!

ATLAS-CONF-2018-031

Heavy Higgs boson couplings

A bound on x gives also information about the heavy Higgs couplings with fermions

	$y_{\mathrm{2HDM}}/y_{\mathrm{SM}}$	Type-II K
125 GeV Higgs	hVV	$s_{\beta-\alpha}$
	hQu	$s_{\beta-\alpha} + c_{\beta-\alpha}/t_\beta$
	hQd	$s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$
	hLe	$s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$
Heavy scalar	HVV	$c_{\beta-\alpha}$
	HQu	$c_{\beta-\alpha} - s_{\beta-\alpha}/t_\beta$
	HQd	$c_{\beta-\alpha} + t_\beta s_{\beta-\alpha}$
	HLe	$c_{\beta-\alpha} + t_\beta s_{\beta-\alpha}$
Heavy pseudo-scalar	AVV	0
	AQu	$1/t_\beta$
	AQd	t_β
	ALe	t_β

Note the flavor universality!

$$y_{Q^i} = \boldsymbol{K} \times m_{Q^i}/v$$

independent on i

Heavy Higgs boson couplings

A bound on x gives also information about the heavy Higgs couplings with fermions

	$y_{\mathrm{2HDM}}/y_{\mathrm{SM}}$	Type-II K	Alignment limit:
125 GeV Higgs	hVV	$s_{\beta-\alpha}$	1
	hQu	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	1
	hQd	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$	1
	hLe	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$	1
Heavy scalar	HVV	$c_{\beta-\alpha}$	0
	HQu	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$1/t_\beta$
	HQd	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$	t_β
	HLe	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$	t_β
Heavy pseudo-scalar	AVV	0	0
	AQu	$1/t_\beta$	$1/t_\beta$
	AQd	t_β	t_β
	ALe	t_β	t_β

Note the flavor universality!

$$y_{Q^i} = K \times m_{Q^i}/v$$

independent on i

Heavy Higgs boson couplings

A bound on x gives also information about the heavy Higgs couplings with fermions

	$y_{\rm 2HDM}/y_{\rm SM}$	Type-II K	Alignment limit:
125 GeV Higgs	hVV	$s_{\beta-\alpha}$	1
	hQu	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	1
	hQd	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$	1
	hLe	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$	1
Heavy scalar	HVV	$c_{\beta-\alpha}$	0
	HQu	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$1/t_\beta$
	HQd	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$	t_β
	HLe	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$	t_β
Heavy pseudo-scalar	AVV	0	0
	AQu	$1/t_\beta$	$1/t_\beta$
	AQd	t_β	t_β
	ALe	t_β	t_β

Note the flavor universality!

$$y_{Q^i} = K \times m_{Q^i}/v$$

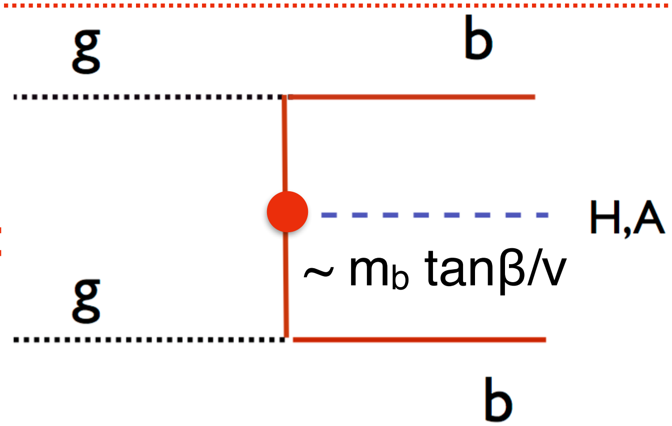
independent on i

The pheno of the additional Higgs is determined by β and their mass

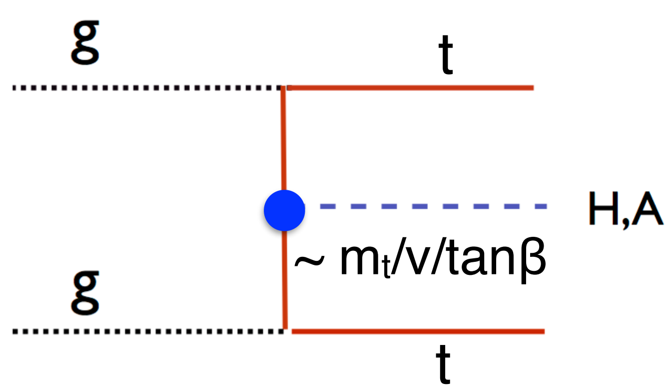
How to produce these H bosons at the LHC?

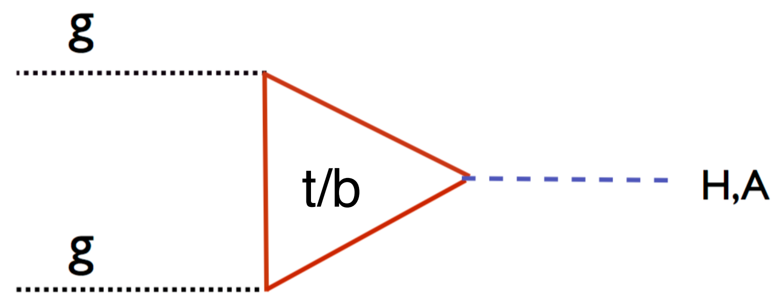
* Neutral Higgs bosons (H,A)

Dominant
at large tanβ:

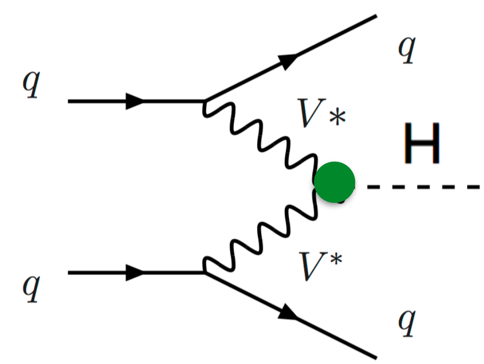


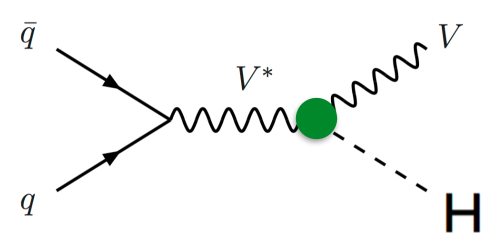
Dominant
at small tanβ:





Suppressed in
the alignment limit:

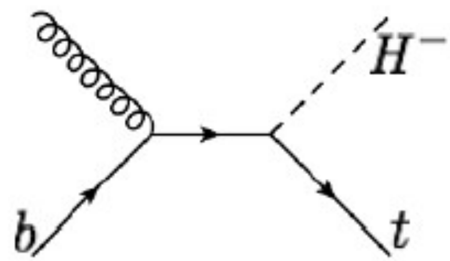




How to produce these H bosons at the LHC?

* Charged Higgs bosons ($H^\pm$)

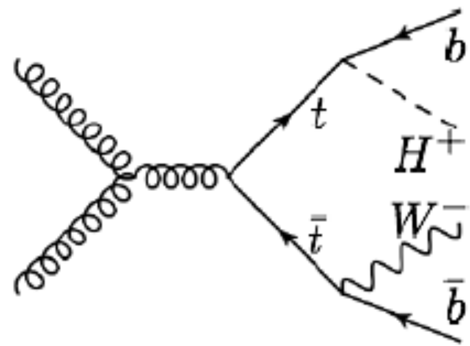
Above the top mass:



$H^\pm\, b_R\, t_L \sim m_b \tan\beta / v$

$H^\pm\, t_R\, b_L \sim m_t / \tan\beta / v$

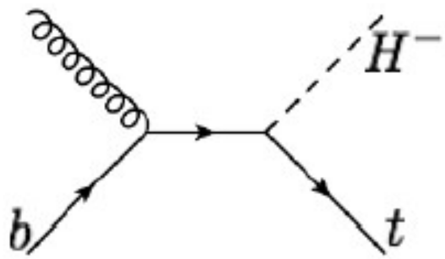
Below the top mass:



How to produce these H bosons at the LHC?

* Charged Higgs bosons ($H^\pm$)

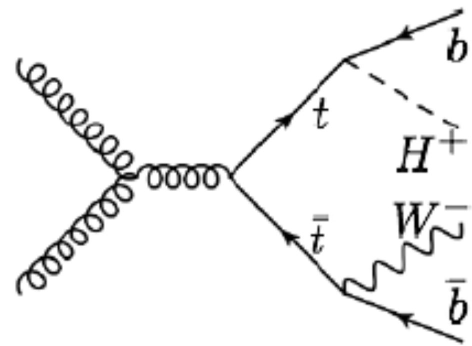
Above the top mass:

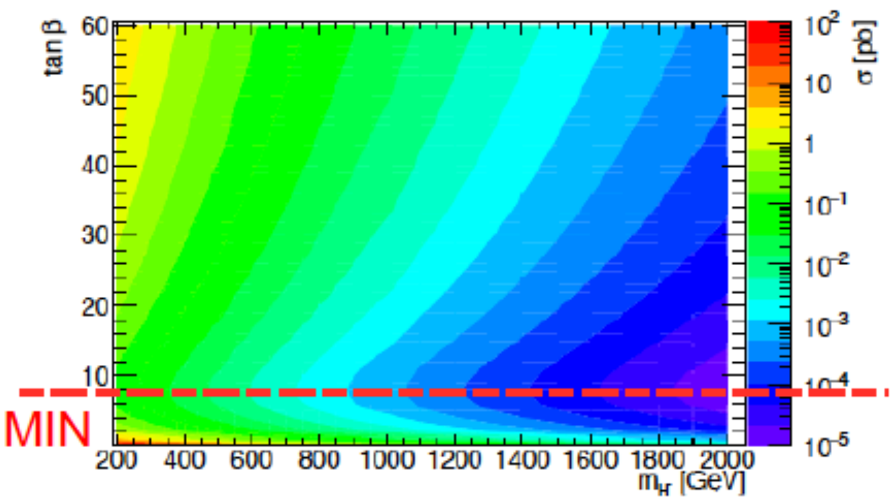


$H^\pm \, b_R \, t_L \sim m_b \tan\beta / v$

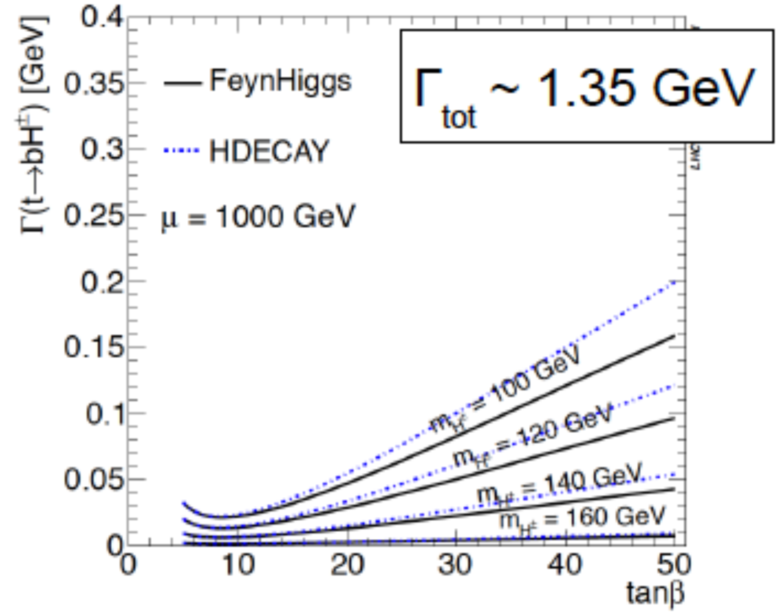
$H^\pm \, t_R \, b_L \sim m_t / \tan\beta / v$

Below the top mass:





From the LHCHXSWG YR4, 1610.07922



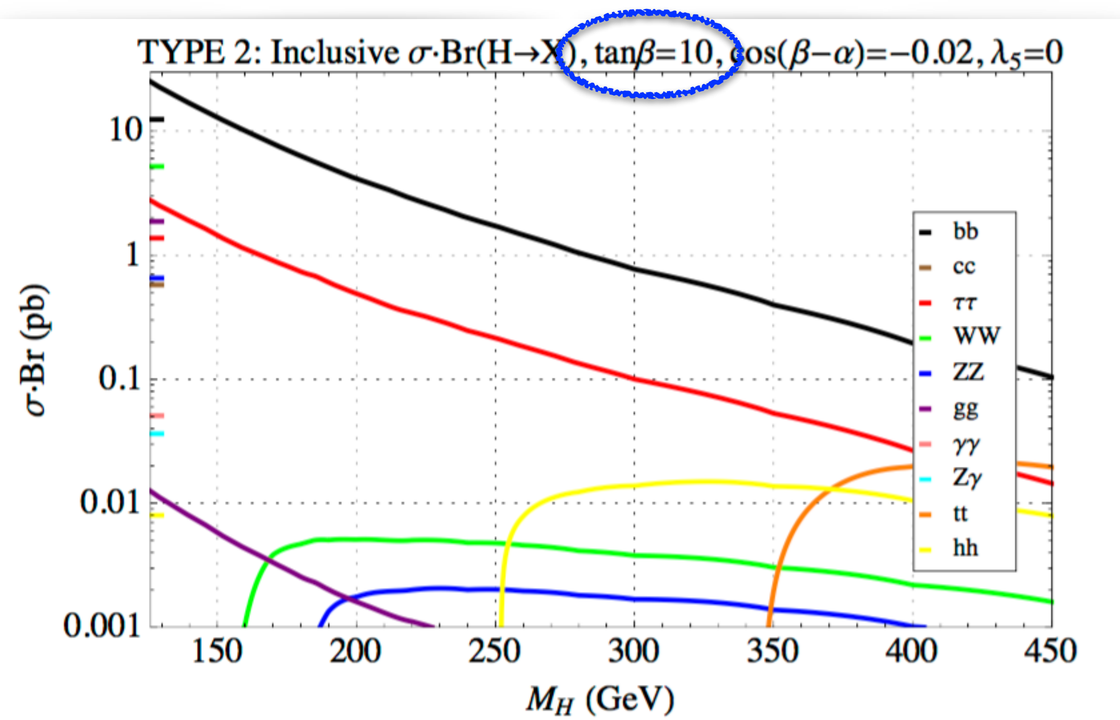
From the LHCHXSWG YR2, 1201.3084

What are the signatures?

* Neutral Higgs bosons

Large tanβ:
enhanced couplings with bb, tautau

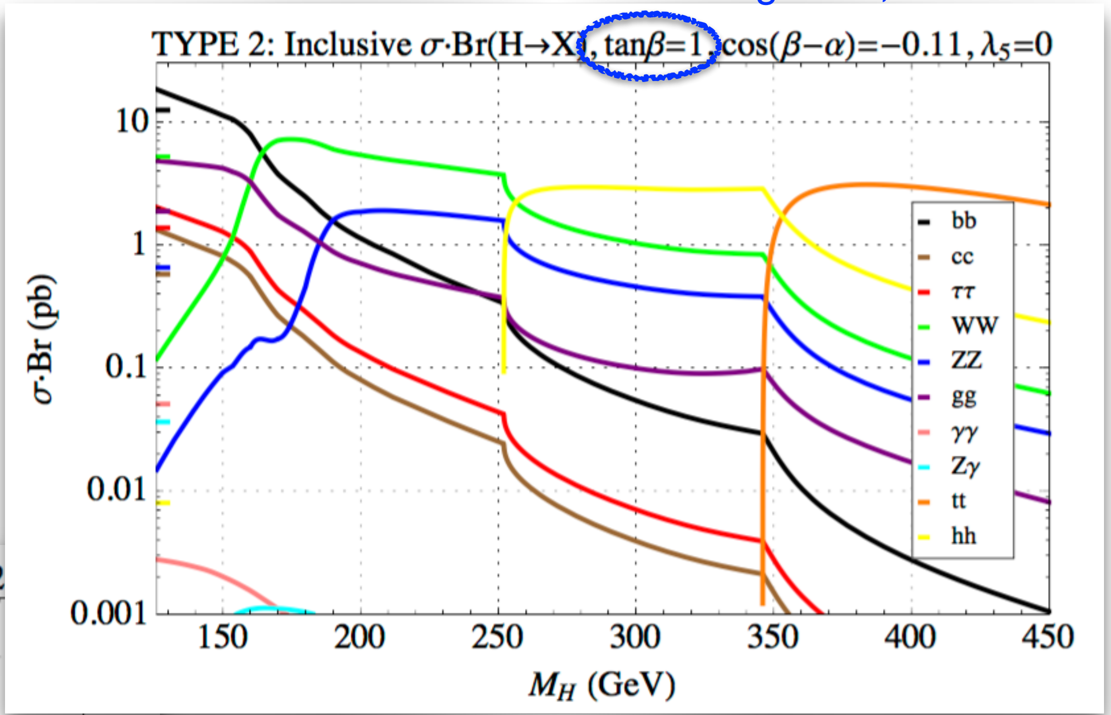
Alignment limit:
suppressed couplings with hh, WW, ZZ



What are the signatures?

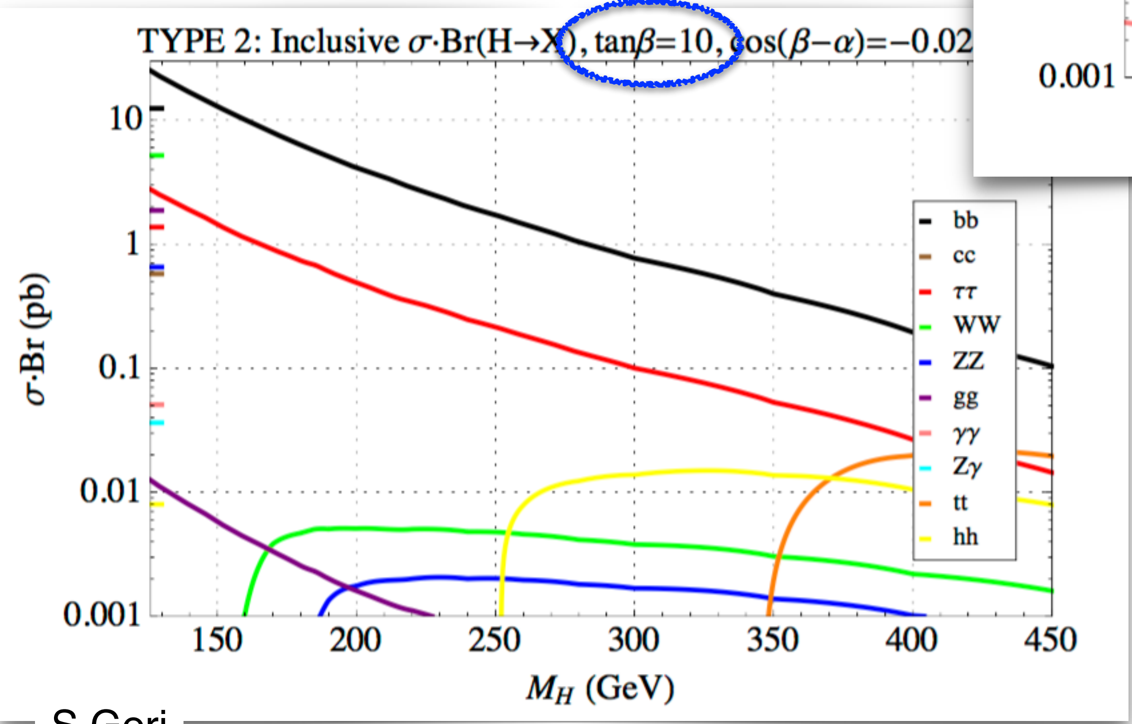
Craig et al., 1305.2424

* Neutral Higgs bosons



Large tanβ:
enhanced couplings with bb, tautau

Alignment limit:
suppressed couplings with hh, WW, ZZ

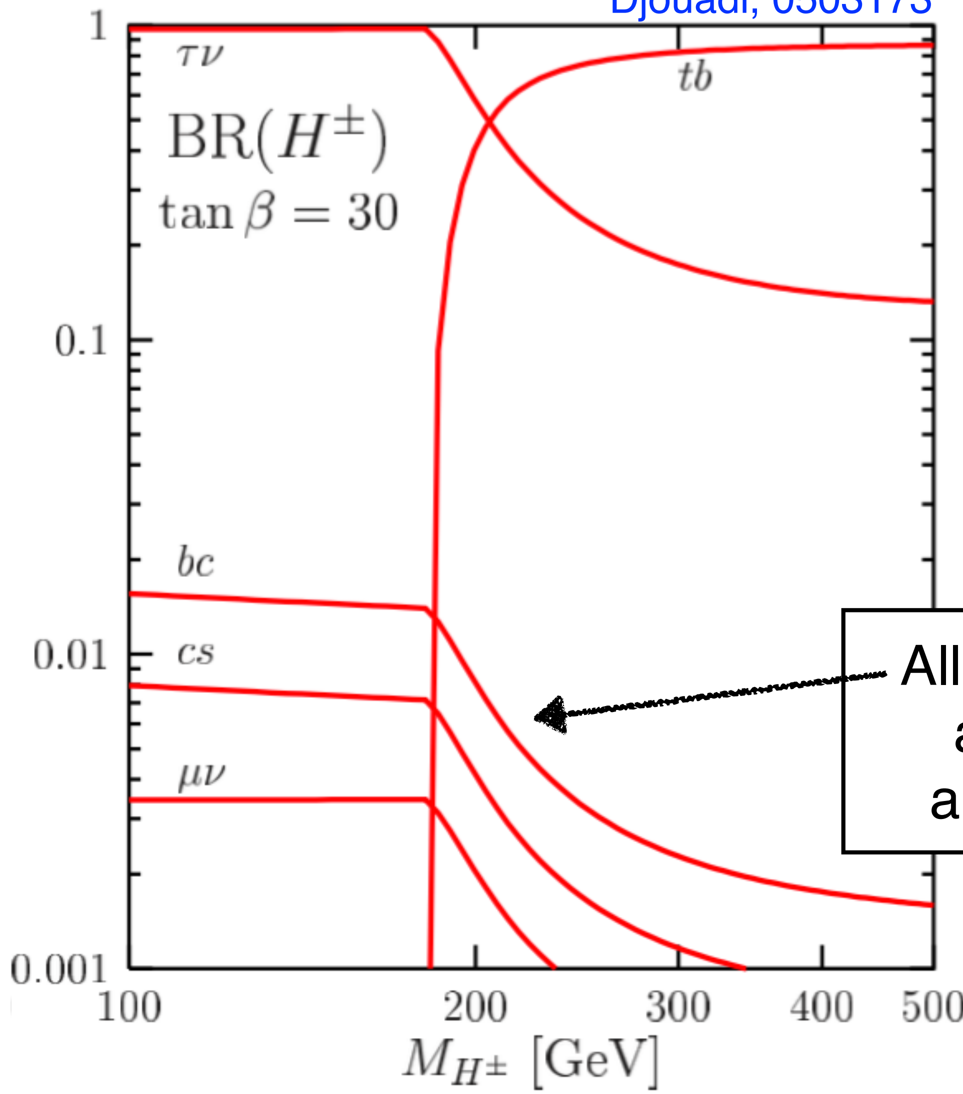


Small tanβ:
enhanced couplings with tt

What are the signatures?

* Charged Higgs bosons

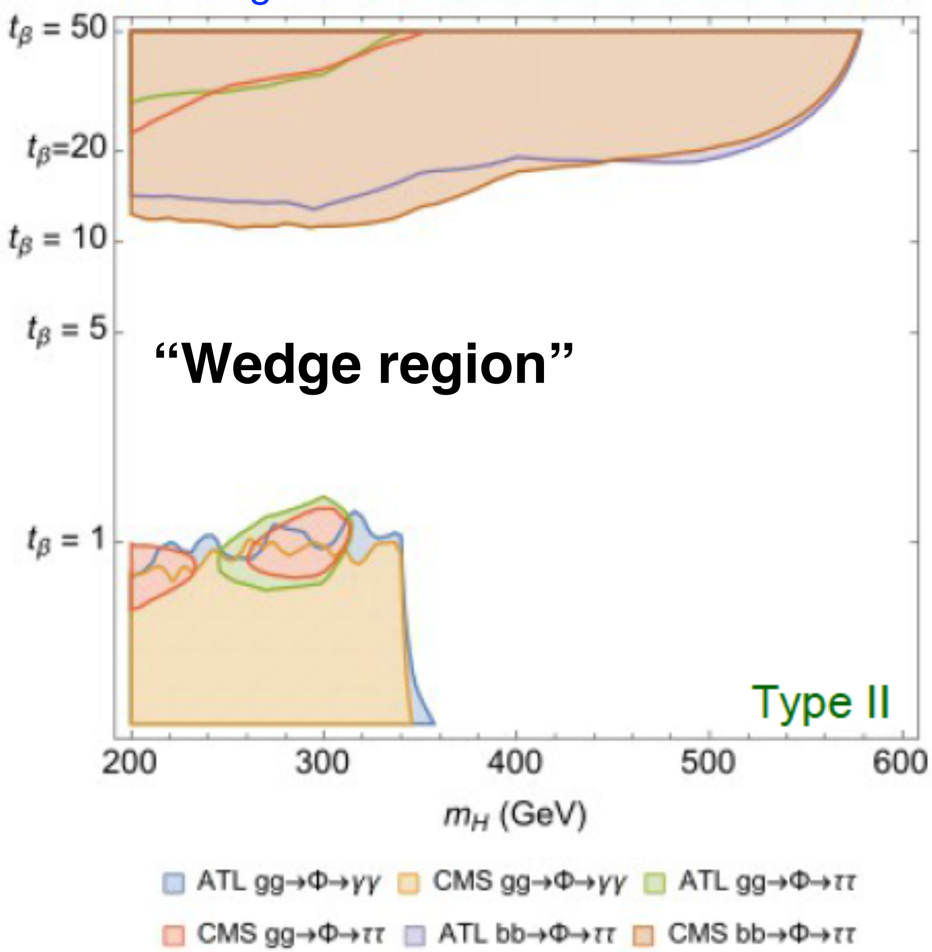
Djouadi, 0503173



All the other decay modes are pretty suppressed above the top threshold

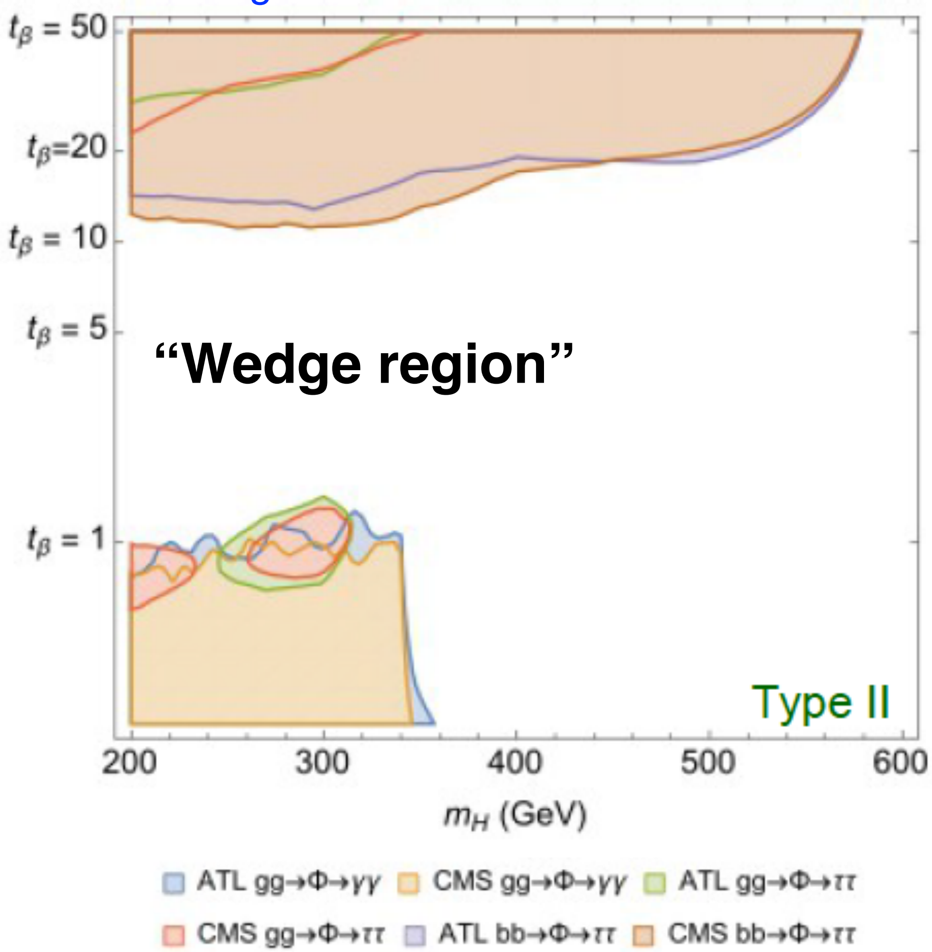
Understanding the LHC bounds

Craig et al. 1504.04630

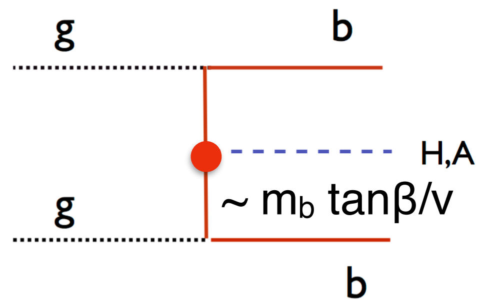


Understanding the LHC bounds

Craig et al. 1504.04630



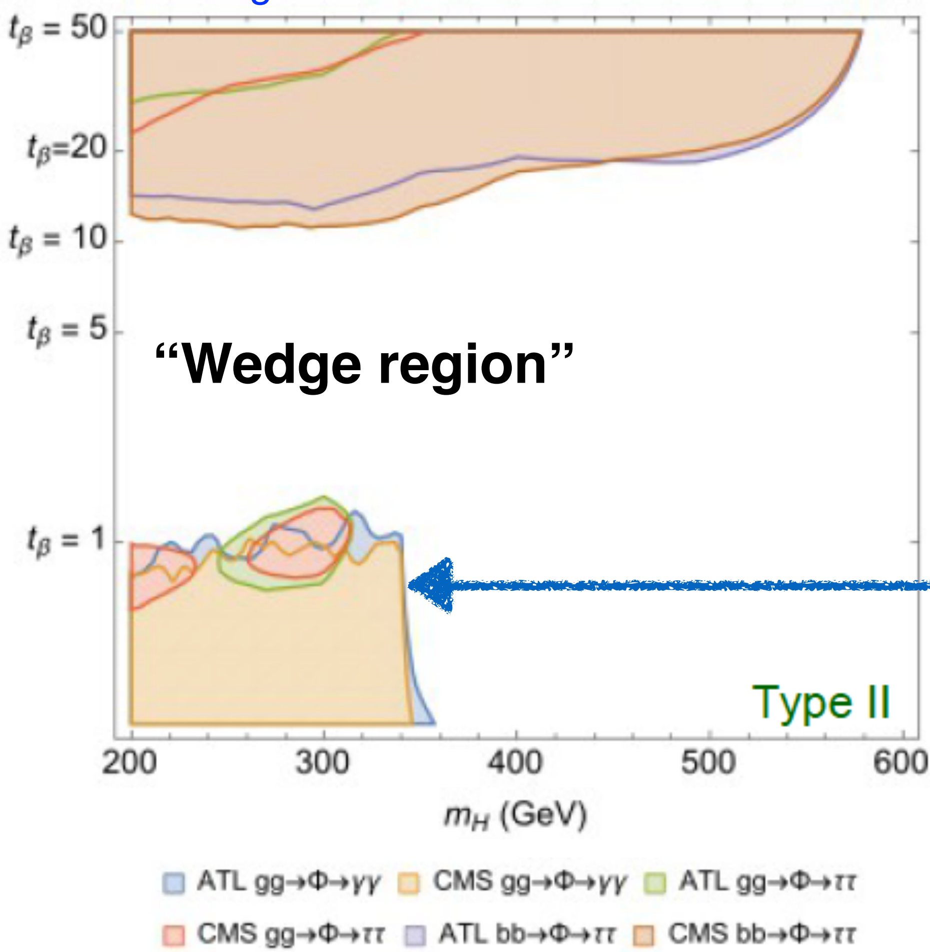
In this direction, the production rate becomes larger and larger:



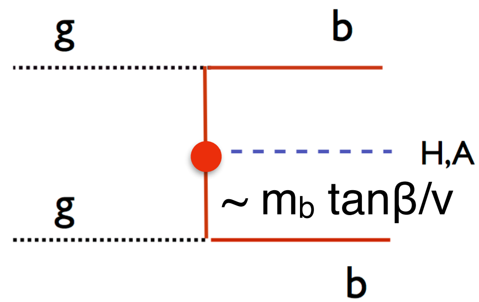
The decay into taus is the golden channel

Understanding the LHC bounds

Craig et al. 1504.04630



In this direction, the production rate becomes larger and larger:

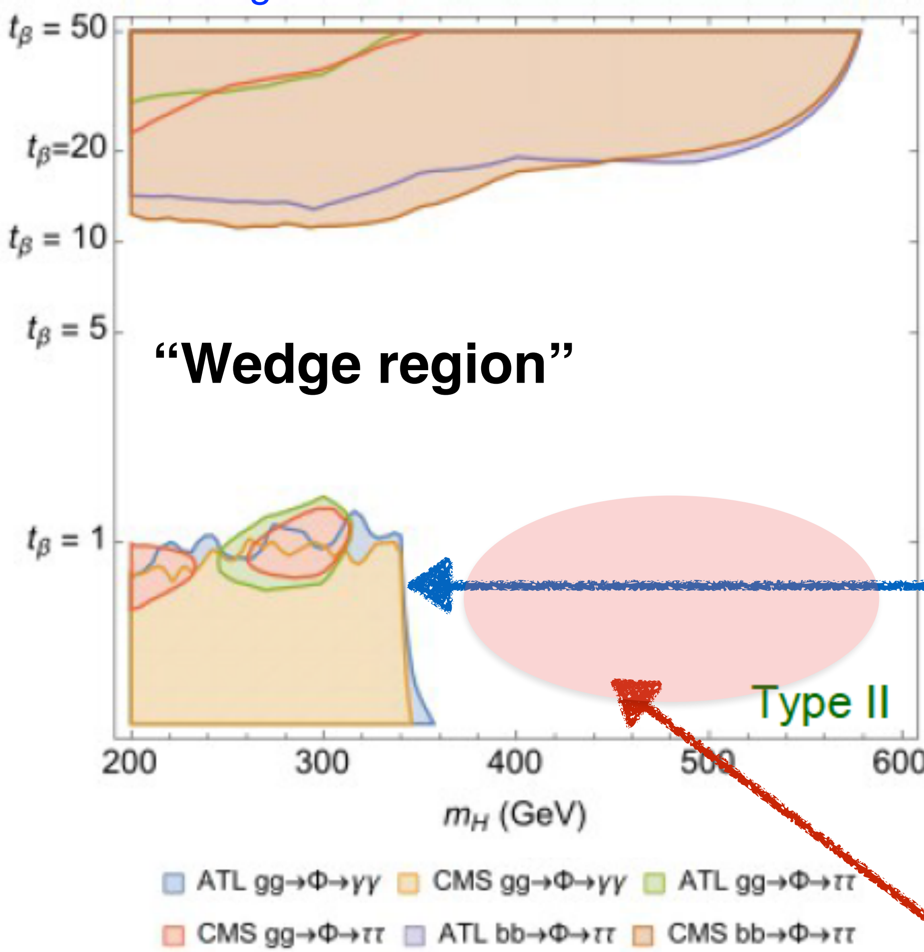


The decay into taus is the golden channel

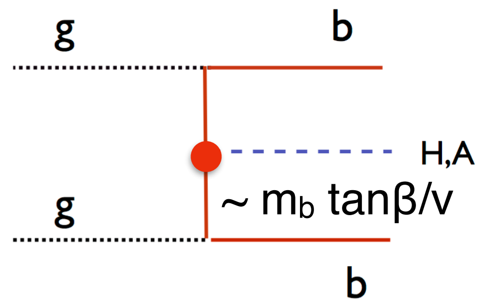
Large gluon fusion cross section (top loop).
Main decay modes:
WW, ZZ, hh (suppressed in the alignment limit), γγ

Understanding the LHC bounds

Craig et al. 1504.04630



In this direction, the production rate becomes larger and larger:



The decay into taus is the golden channel

Large gluon fusion cross section (top loop).
Main decay modes:
WW, ZZ, hh (suppressed in the alignment limit), γγ

What about here?

The challenging low tanβ regime

(above the top threshold)

In this region, the new Higgs bosons mainly decay to top quarks

Are the $Z' \to tt$ effective to set bounds?

The challenging low tanβ regime

(above the top threshold)

In this region, the new Higgs bosons mainly decay to top quarks

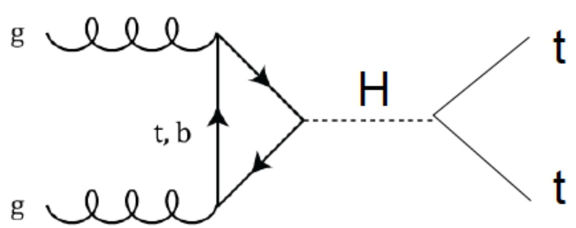
Are the Z'→tt effective to set bounds? **NO**

The challenging low tanβ regime
(above the top threshold)

In this region, the new Higgs bosons mainly decay to top quarks

Are the Z'→tt effective to set bounds? **NO**

Differently from the Z',
the Higgs process is gluon-initiated:



Interference with the
t t SM continuum

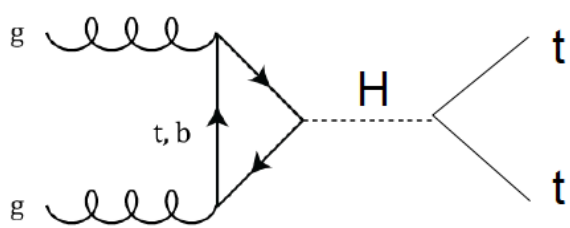
Dicus et al., 9404359

The challenging low tanβ regime
(above the top threshold)

In this region, the new Higgs bosons mainly decay to top quarks

Are the Z’→tt effective to set bounds? **NO**

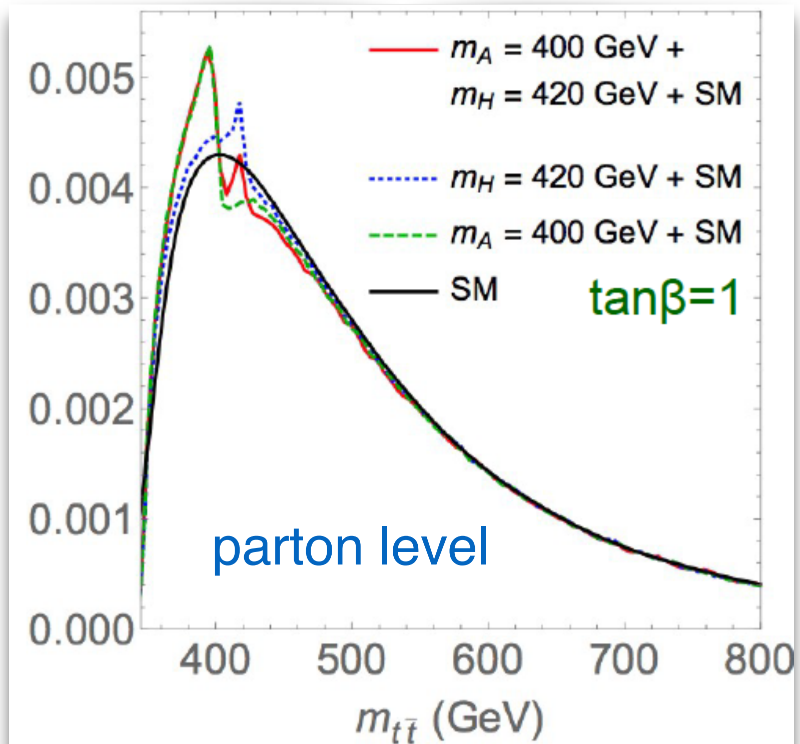
Differently from the Z’,
the Higgs process is gluon-initiated:



Interference with the
t t SM continuum

Dicus et al., 9404359

SG, Kim, Shah, Zurek, 1602.02782



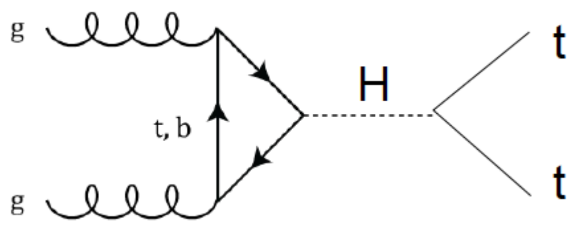
Shape analysis?
Angular correlations?

The challenging low tanβ regime
(above the top threshold)

In this region, the new Higgs bosons mainly decay to top quarks

Are the Z’→tt effective to set bounds? **NO**

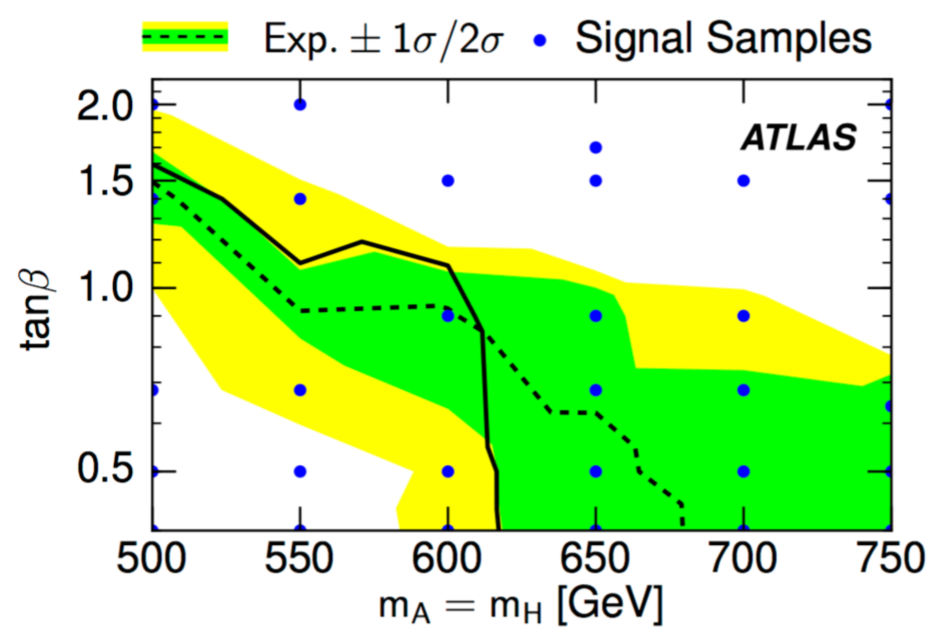
Differently from the Z’,
the Higgs process is gluon-initiated:



Interference with the
t t SM continuum

Dicus et al., 9404359

The ATLAS search is
now available!

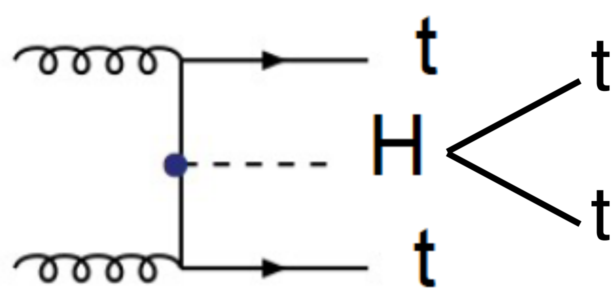


1707.06025

The challenging low tanβ regime
(above the top threshold)

In this region, the new Higgs bosons mainly decay to top quarks

What about exploiting ttH associated production?

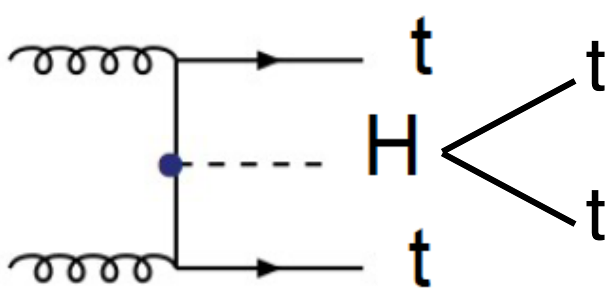


4 top signature

The challenging low tanβ regime
(above the top threshold)

In this region, the new Higgs bosons mainly decay to top quarks

What about exploiting ttH associated production?

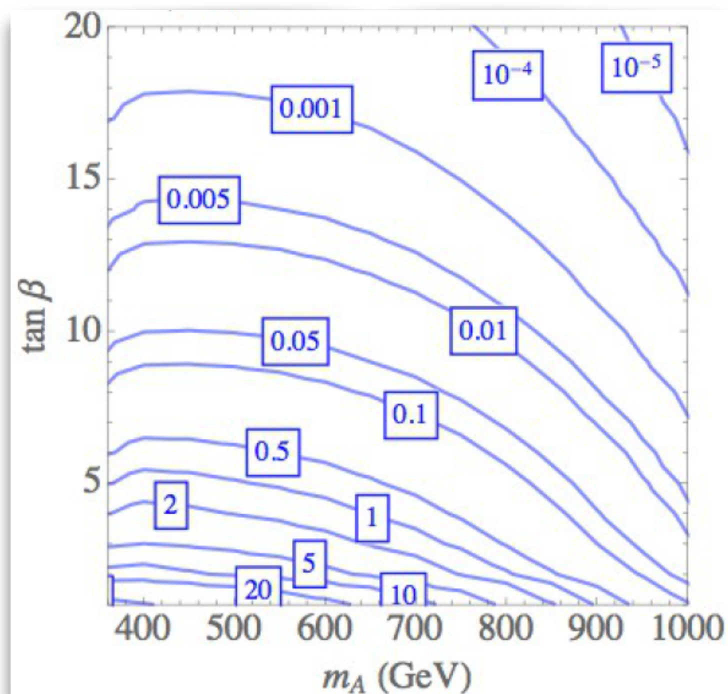


4 top signature

The challenge:

Signal rates are much smaller

Cross section in fb

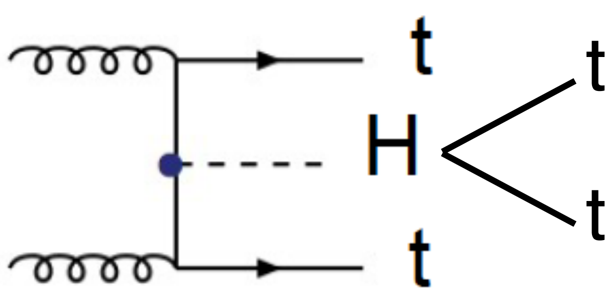


SG, Kim, Shah, Zurek, 1602.02782

The challenging low tanβ regime
(above the top threshold)

In this region, the new Higgs bosons mainly decay to top quarks

What about exploiting ttH associated production?



4 top signature

The opportunity:

We have many more objects in the signal,
if compared to the t t background

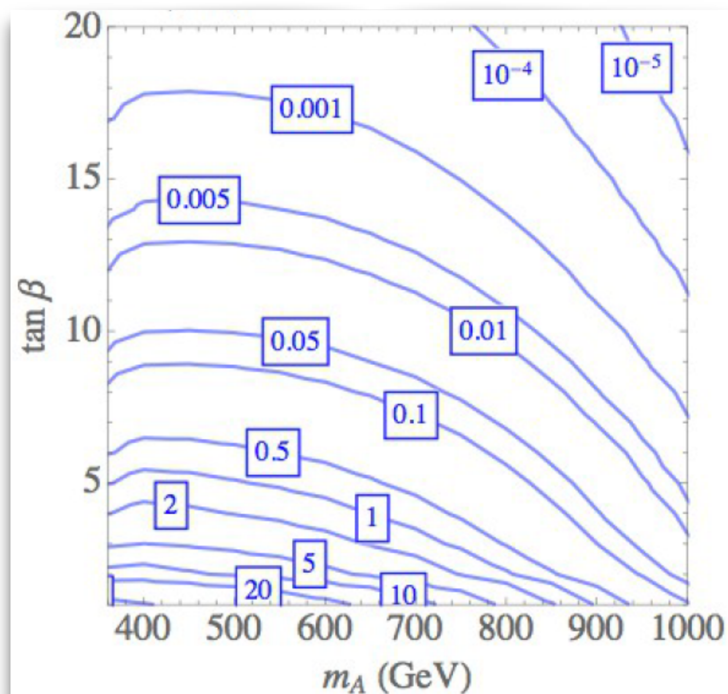
Two possible strategies:

- many (b) jets + at least 1 lepton
- multi-leptons + (b) jets

The challenge:

Signal rates are much smaller

Cross section in fb

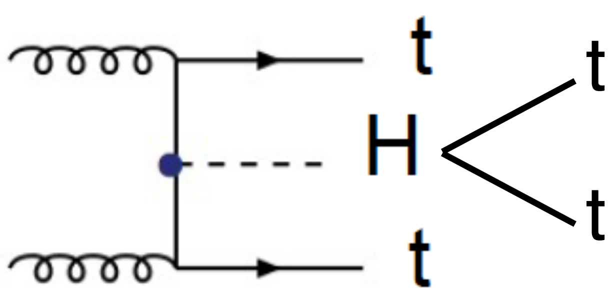


SG, Kim, Shah, Zurek, 1602.02782

The challenging low tanβ regime
(above the top threshold)

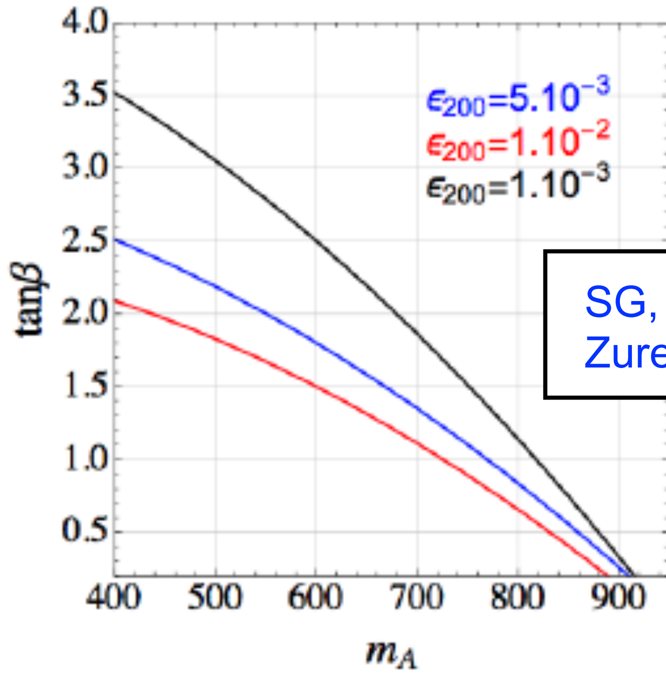
In this region, the new Higgs bosons mainly decay to top quarks

What about exploiting ttH associated production?



4 top signature

Counting experiment:



SG, Kim, Shah, Zurek, 1602.02782

The opportunity:

We have many more objects in the signal, if compared to the t t background

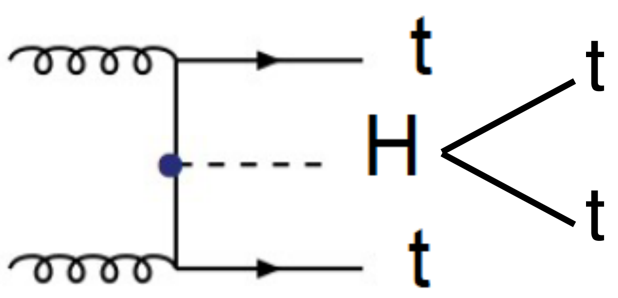
Two possible strategies:

- many (b) jets + at least 1 lepton
- multi-leptons + (b) jets

The challenging low tanβ regime
(above the top threshold)

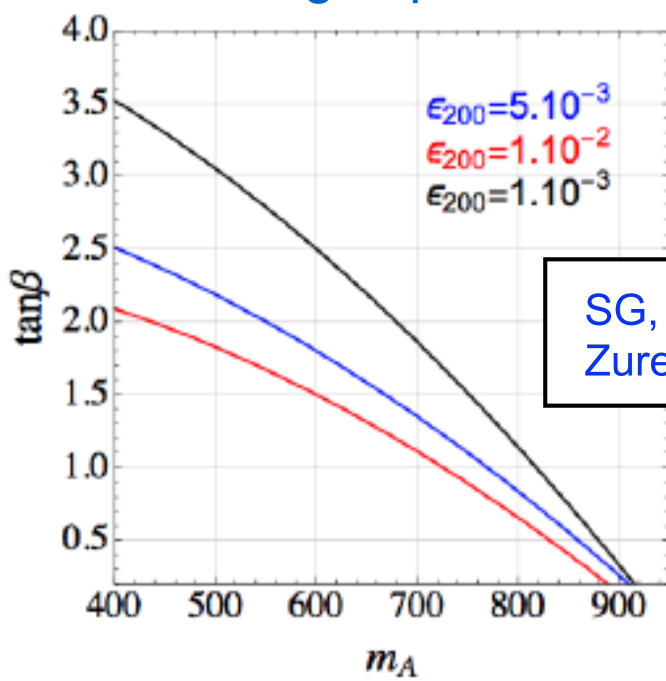
In this region, the new Higgs bosons mainly decay to top quarks

What about exploiting ttH associated production?



4 top signature

Counting experiment:



SG, Kim, Shah, Zurek, 1602.02782

The opportunity:

We have many more objects in the signal, if compared to the t t background

Two possible strategies:

- many (b) jets + at least 1 lepton
- multi-leptons + (b) jets

Open questions:

* any possibility to have some reconstruction?
* boosted regime?
* tHj production?

A broad LHC search program

H

bb	$\tau\tau$	$\mu\mu$	$\gamma\gamma$	hh	WW	ZZ	tt
bH	gg,bH	gg,bH		gg	all	all	gg, tt

A

bb	$\tau\tau$	$\mu\mu$	$\gamma\gamma$	Zh	tt
bH	gg,bA	gg,bA		gg,bA	gg, tt

$H^{\pm}$

$\tau\nu$	tb	Wh	cs	$\mu\nu$	cb
(t)$H^{\pm}$ t dec	(t)$H^{\pm}$ t dec	qq fus	t decay	qq fus	t decay

Still many questions to be answered & many new searches to be performed…

Chapter 2

Beyond type-II
2HDMs

New flavor structures

2. Beyond type I-IV 2HDMs

(20 slides ago) we learned that low energy flavor measurements constrain the flavor structure of models with more than one Higgs doublet

Question: are type I-IV 2HDMs the only possibility to address this issue? **NO**

2. Beyond type I-IV 2HDMs

(20 slides ago) we learned that low energy flavor measurements constrain the flavor structure of models with more than one Higgs doublet

Question: are type I-IV 2HDMs the only possibility to address this issue? **NO**

Let us discuss two of examples:

1. Flavor aligned 2HDMs Pich, Tuzon, 0908.1554
2. Flavorful 2HDMs Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

2. Beyond type I-IV 2HDMs (alignment)

(20 slides ago) we learned that low energy flavor measurements constrain the flavor structure of models with more than one Higgs doublet

Question: are type I-IV 2HDMs the only possibility to address this issue? **NO**

Let us discuss two of examples:

1. **Flavor aligned 2HDMs** Pich, Tuzon, 0908.1554
2. Flavorful 2HDMs Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

$$\begin{cases} X_{u1} = a_u X_{u2} \\ X_{d2} = a_d X_{d1} \\ \text{+ corresponding one in the lepton sector} \end{cases}$$

2. Beyond type I-IV 2HDMs (alignment)

(20 slides ago) we learned that low energy flavor measurements constrain the flavor structure of models with more than one Higgs doublet

Question: are type I-IV 2HDMs the only possibility to address this issue? **NO**

Let us discuss two of examples:

1. **Flavor aligned 2HDMs** Pich, Tuzon, 0908.1554
2. Flavorful 2HDMs Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

$$\begin{cases} X_{u1} = a_u X_{u2} \\ X_{d2} = a_d X_{d1} \\ \text{+ corresponding one in the lepton sector} \end{cases}$$

This structure leads to NO FCNCs at the tree-level

<u>Note for the experts:</u>
this structure is not stable under RGEs.
The most general stable structure is the Minimal Flavor Violating one

2. Beyond type I-IV 2HDMs (alignment)

(20 slides ago) we learned that low energy flavor measurements constrain the flavor structure of models with more than one Higgs doublet

Question: are type I-IV 2HDMs the only possibility to address this issue? **NO**

Let us discuss two of examples:

1. **Flavor aligned 2HDMs** Pich, Tuzon, 0908.1554
2. Flavorful 2HDMs Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

$$\begin{cases} X_{u1} = a_u X_{u2} \\ X_{d2} = a_d X_{d1} \\ \text{+ corresponding one in the lepton sector} \end{cases}$$

This structure leads to NO FCNCs at the tree-level

Reduced couplings of the heavy Higgs:

$$\xi_\ell^H = \frac{\cos\alpha + a_\ell \sin\alpha}{\cos\beta + a_\ell \sin\beta}$$

$$\xi_d^H = \frac{\cos\alpha + a_d \sin\alpha}{\cos\beta + a_d \sin\beta}$$

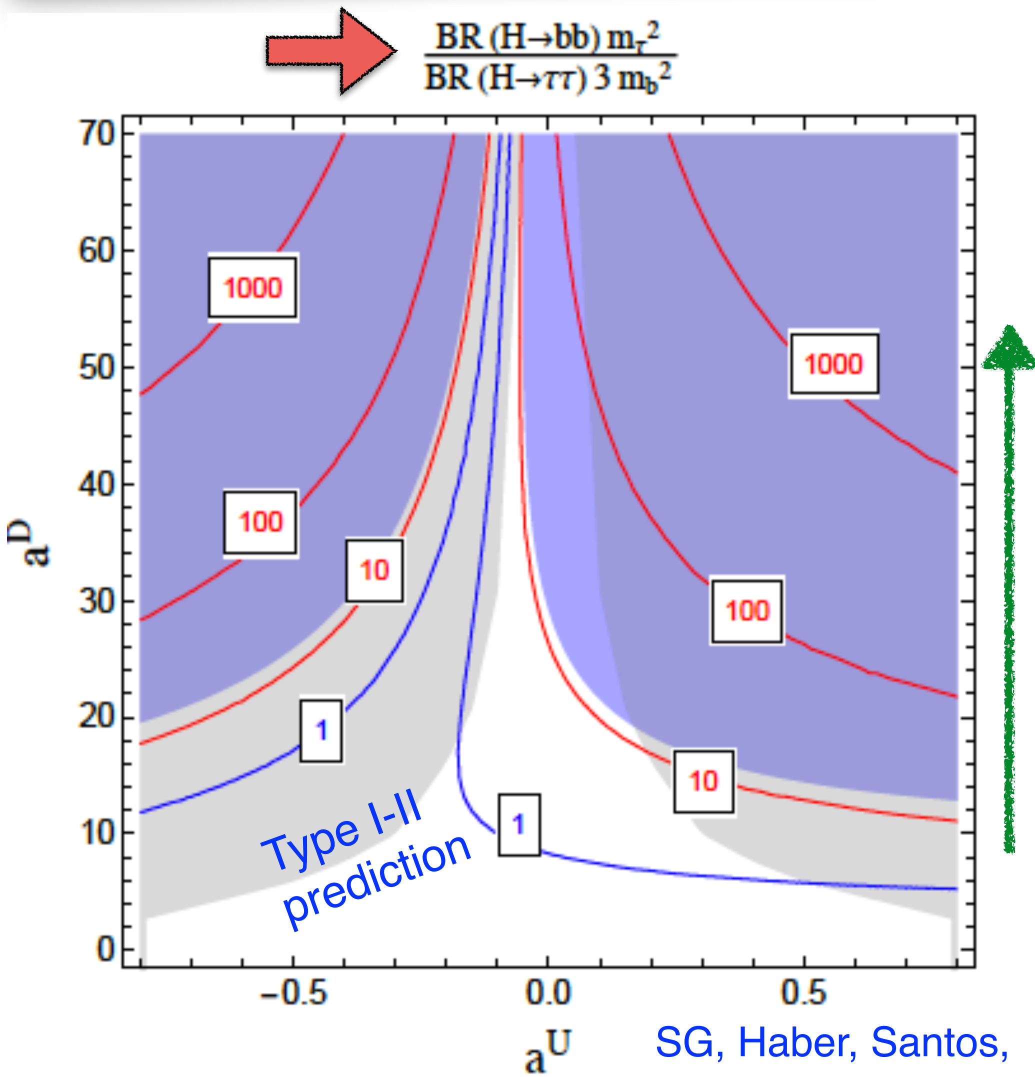
Note for the experts:
this structure is not stable under RGEs.
The most general stable structure is
the Minimal Flavor Violating one

Pheno highlights of the aligned 2HDM

Branching ratios and production cross sections of the heavy Higgs bosons can be very much altered, if compared to a type-II 2HDM

Pheno highlights of the aligned 2HDM

Branching ratios and production cross sections of the heavy Higgs bosons can be very much altered, if compared to a type-II 2HDM



Exclusion from b(b)H, H → bb

The tau tau mode does not lead to a constraint in this plane for this choice of parameters

In this region, the H → bb searches have a better sensitivity than in a Type I-II 2HDM

SG, Haber, Santos, 1703.05873

2. Beyond type I-IV 2HDMs (flavorful)

(20 slides ago) we learned that low energy flavor measurements constrain the flavor structure of models with more than one Higgs doublet

Question: are type I-IV 2HDMs the only possibility to address this issue? **NO**

Let us discuss two of examples:

1. Flavor aligned 2HDMs   Pich, Tuzon, 0908.1554
2. **Flavorful 2HDMs**   Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L \underline{X_{d1}} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L \underline{X_{d2}} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

$$X_{d1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

$$X_{d2} = \begin{pmatrix} m_e & \mathcal{O}(m_e) & \mathcal{O}(m_e) \\ \mathcal{O}(m_e) & m_\mu & \mathcal{O}(m_\mu) \\ \mathcal{O}(m_e) & \mathcal{O}(m_\mu) & \mathcal{O}(m_\mu) \end{pmatrix}$$

2. Beyond type I-IV 2HDMs (flavorful)

(20 slides ago) we learned that low energy flavor measurements constrain the flavor structure of models with more than one Higgs doublet

Question: are type I-IV 2HDMs the only possibility to address this issue? **NO**

Let us discuss two of examples:

1. Flavor aligned 2HDMs Pich, Tuzon, 0908.1554
2. **Flavorful 2HDMs** Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L \underline{X_{d1}} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L \underline{X_{d2}} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

$$X_{d1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

$$X_{d2} = \begin{pmatrix} m_e & \mathcal{O}(m_e) & \mathcal{O}(m_e) \\ \mathcal{O}(m_e) & m_\mu & \mathcal{O}(m_\mu) \\ \mathcal{O}(m_e) & \mathcal{O}(m_\mu) & \mathcal{O}(m_\mu) \end{pmatrix}$$

breaking of the flavor universality!

The couplings of the heavy Higgs are flavor specific!

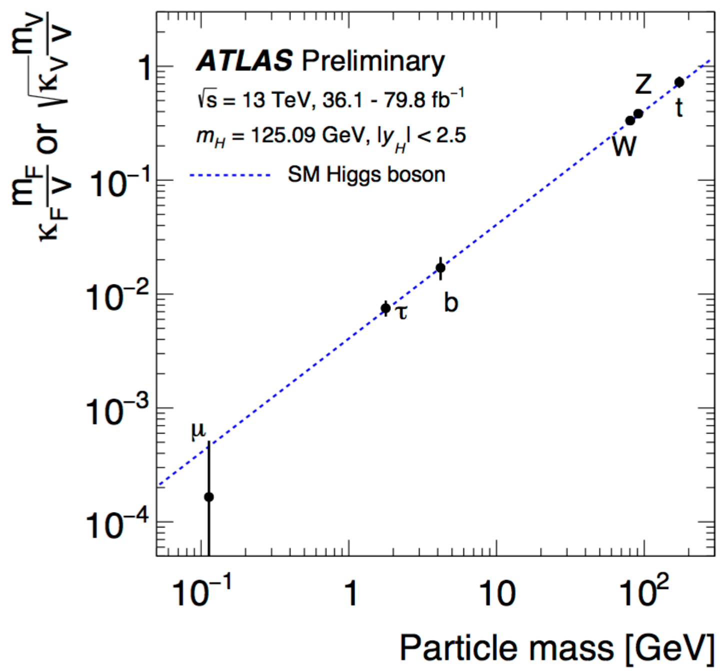
$$\xi_t^H = \frac{1}{\tan\beta}\frac{\sin\alpha}{\cos\beta}$$

$$\xi_c^H = \tan\beta\frac{\cos\alpha}{\sin\beta}$$

Flavor universality

How much do we know about it?

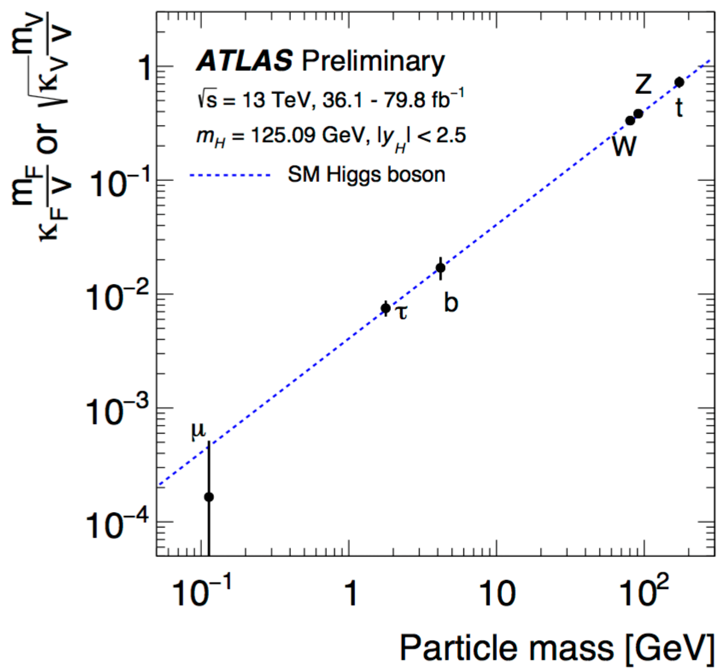
From the Higgs perspective:



Flavor universality

How much do we know about it?

From the Higgs perspective:



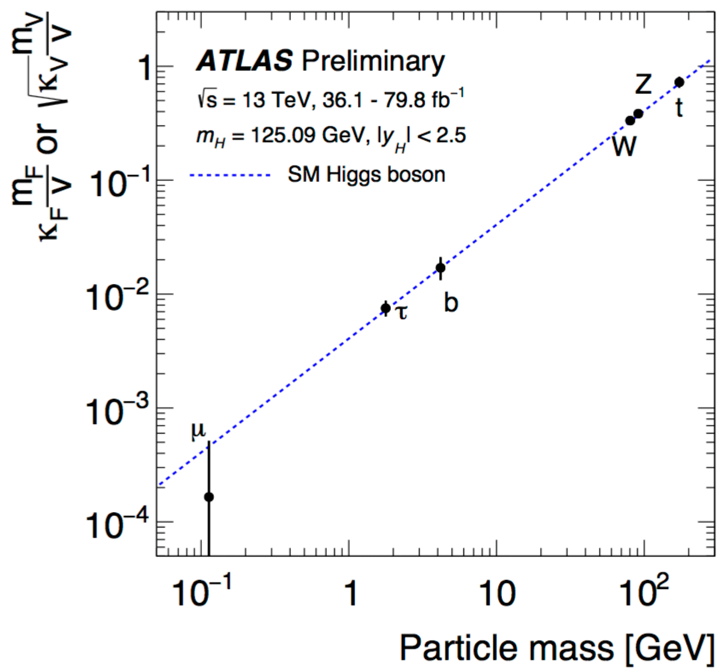
The coupling with muons is different from the coupling with taus.

Not much additional info. Is the Higgs coupling to 1st and 2nd generations?

Flavor universality

How much do we know about it?

From the Higgs perspective:



The coupling with muons is different from the coupling with taus.

Not much additional info. Is the Higgs coupling to 1st and 2nd generations?

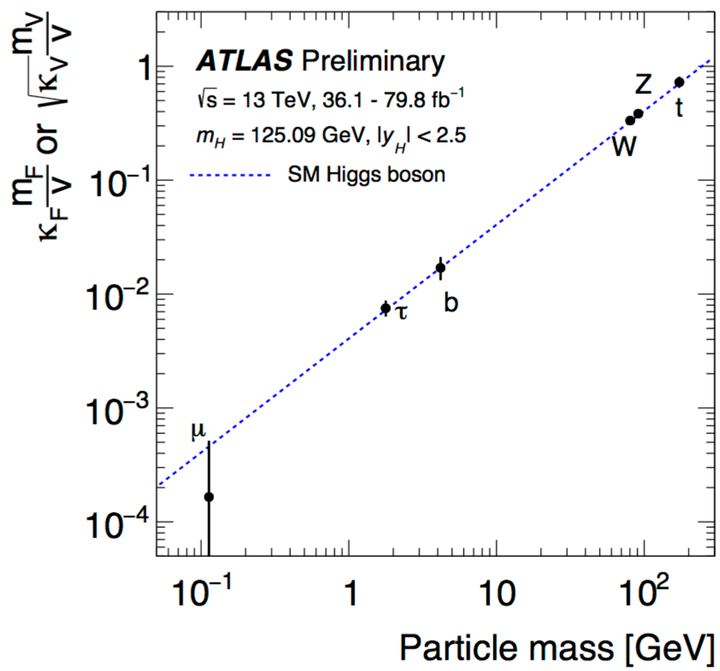
From the low energy flavor physics perspective:

Recently, several flavor anomalies are pointing towards the breaking of lepton flavor universality.

Flavor universality

How much do we know about it?

From the Higgs perspective:



The coupling with muons is different from the coupling with taus.

Not much additional info. Is the Higgs coupling to 1st and 2nd generations?

From the low energy flavor physics perspective:

Recently, several flavor anomalies are pointing towards the breaking of lepton flavor universality.

Examples are the
R_K, R_{K^*}, R_D, R_{D^*} anomalies

$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)}$$

$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$

SM: $R_K^{[1,6]} = 1.00 \pm 0.01$

at the LHCb: $R_K^{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$

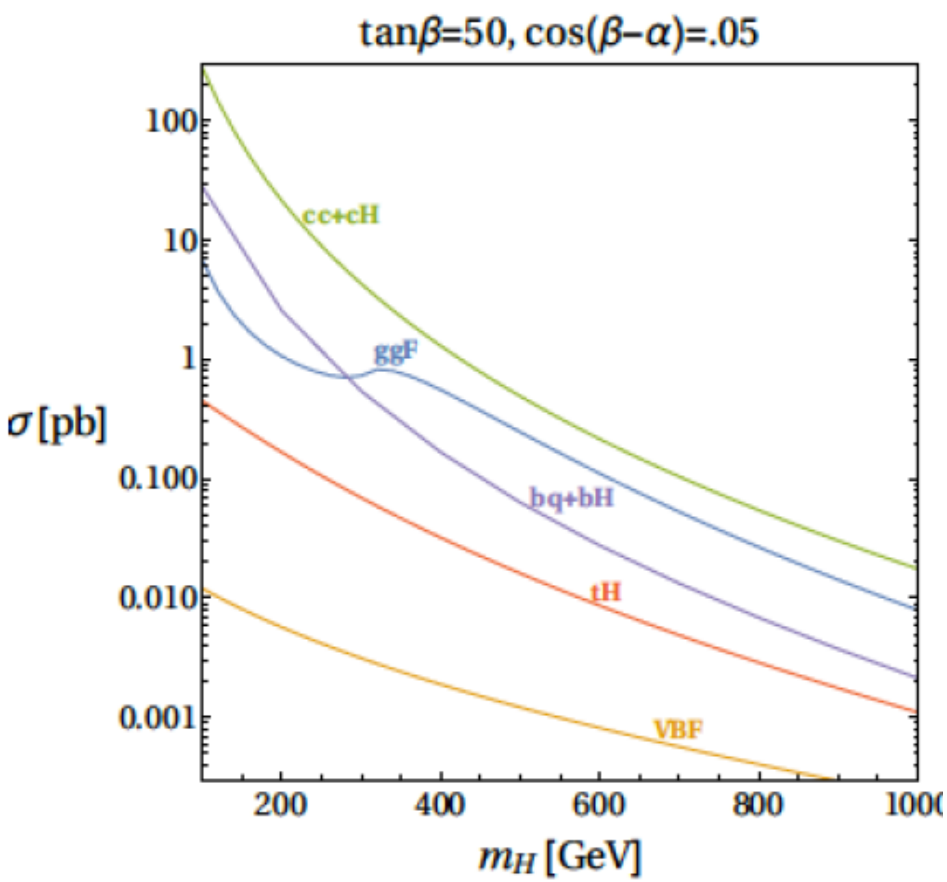
Pheno highlights of the flavorful 2HDM

Branching ratios and production cross sections of the heavy Higgs bosons can be very much altered, if compared to a type-II 2HDM
Additional signatures arise!

Pheno highlights of the flavorful 2HDM

Branching ratios and production cross sections of the heavy Higgs bosons can be very much altered, if compared to a type-II 2HDM
Additional signatures arise!

Production

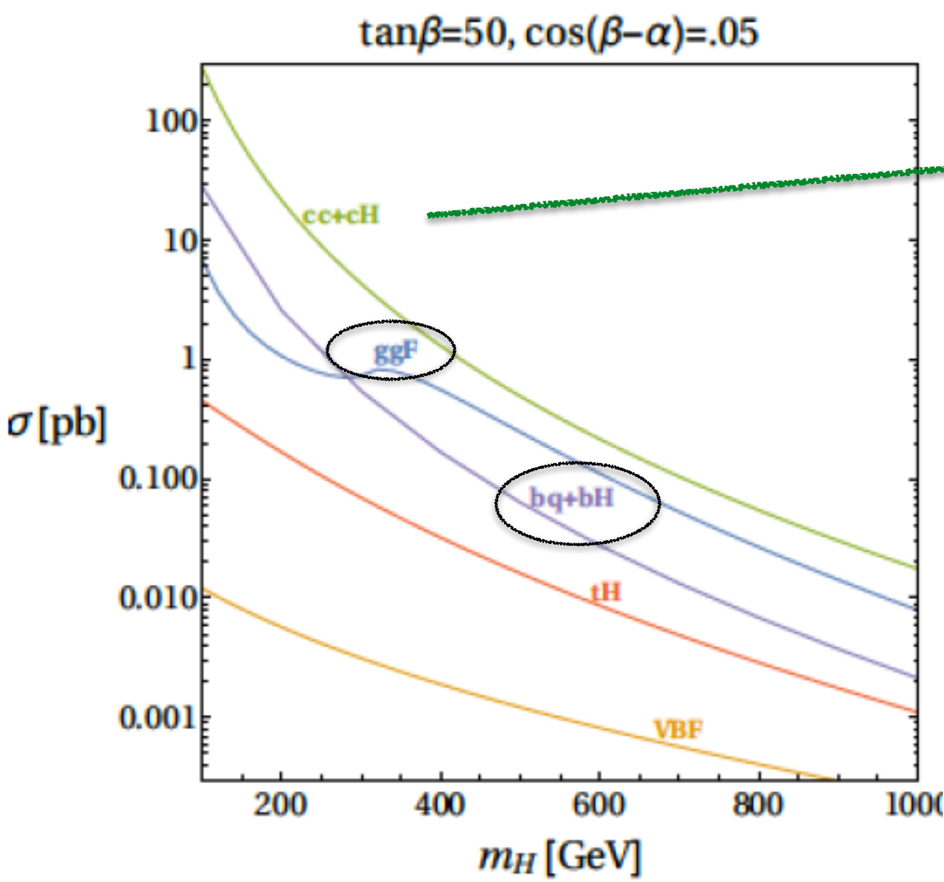


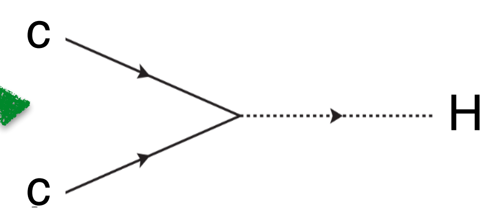
Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

Pheno highlights of the flavorful 2HDM

Branching ratios and production cross sections of the heavy Higgs bosons can be very much altered, if compared to a type-II 2HDM
Additional signatures arise!

Production



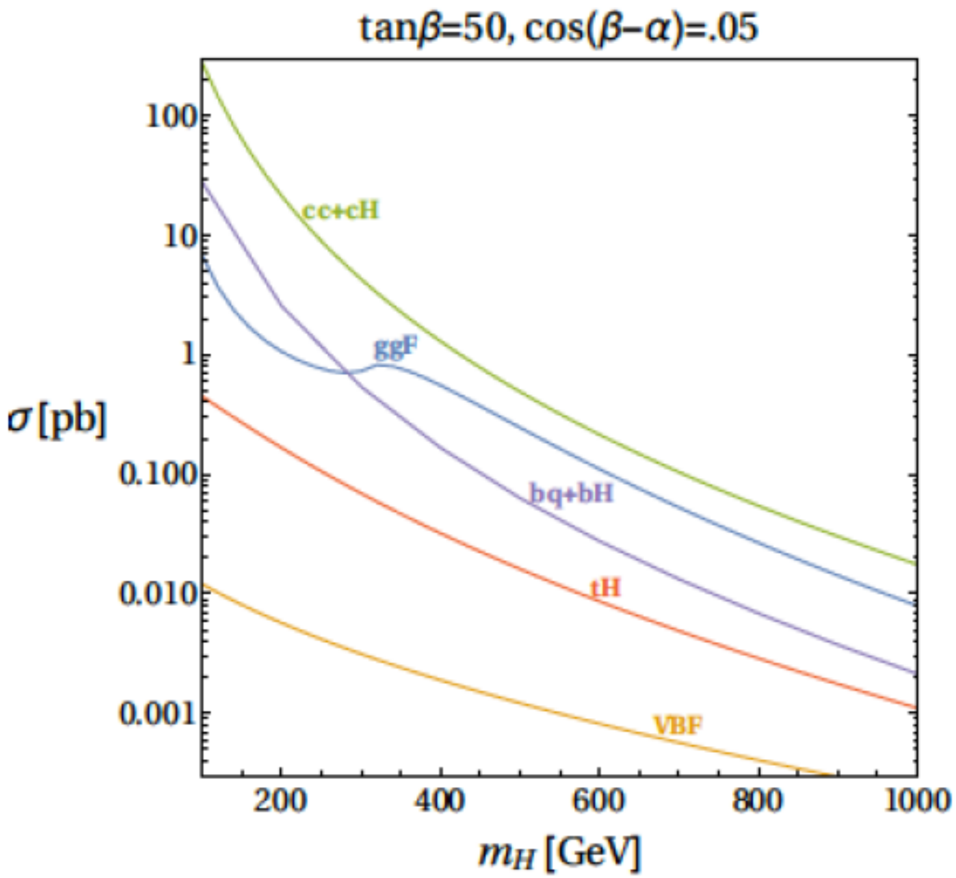


Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

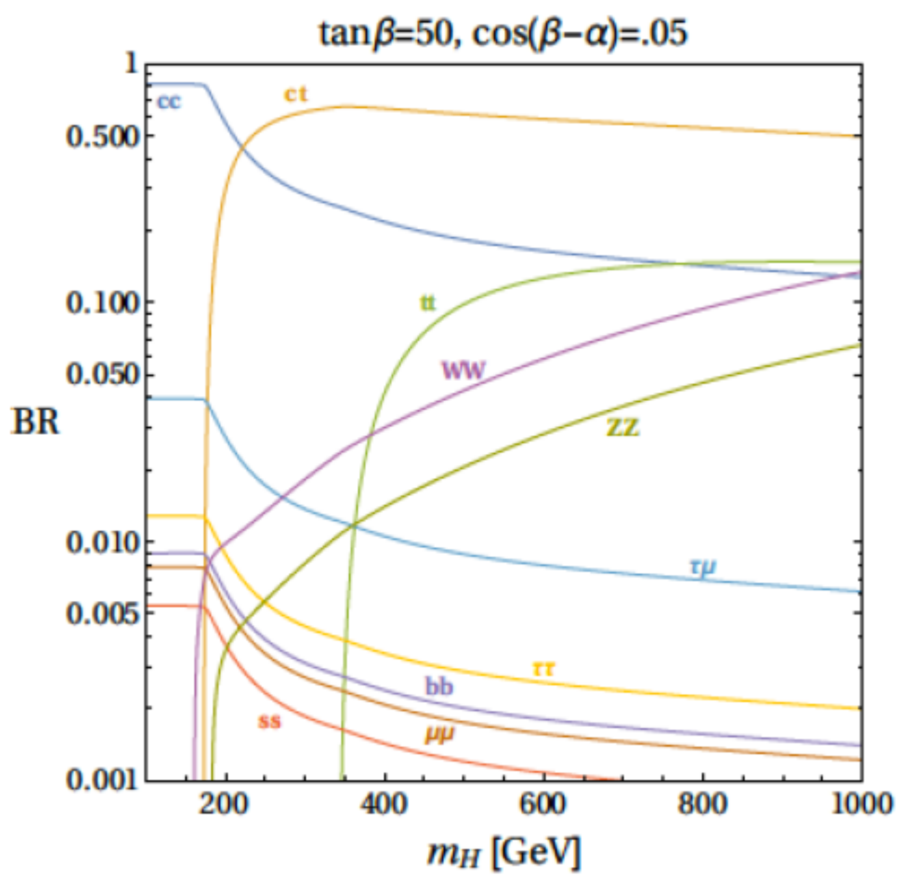
Pheno highlights of the flavorful 2HDM

Branching ratios and production cross sections of the heavy Higgs bosons can be very much altered, if compared to a type-II 2HDM
Additional signatures arise!

Production



Decay

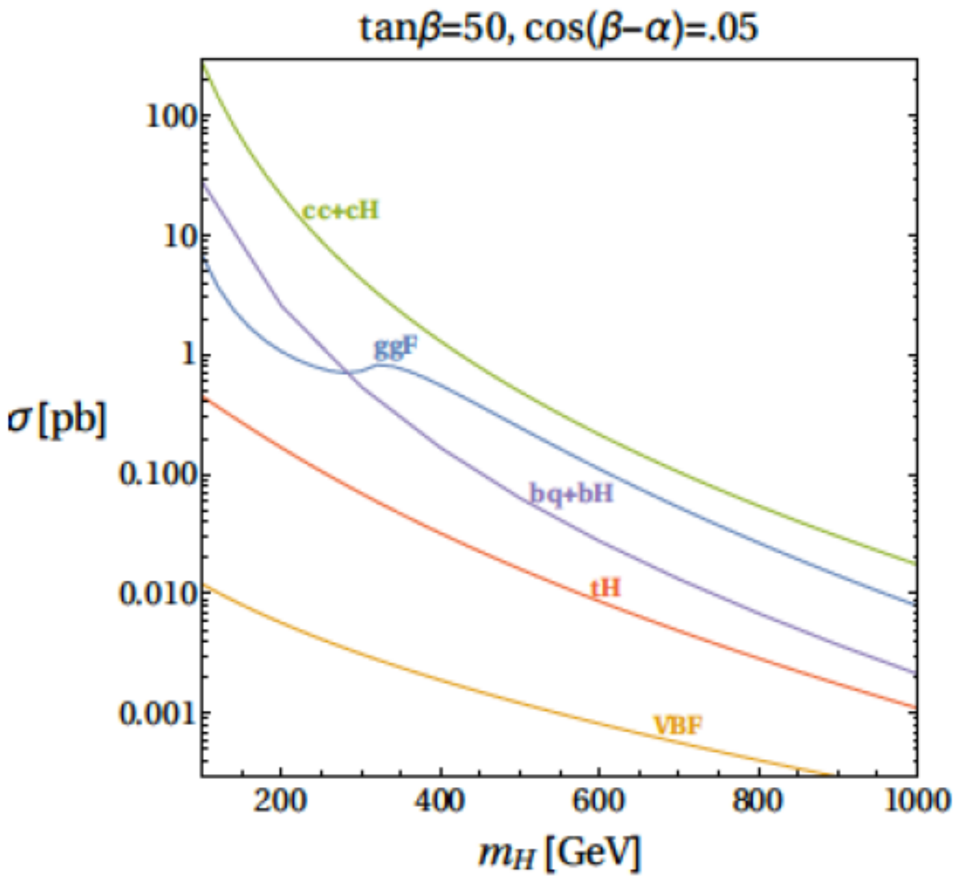


Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

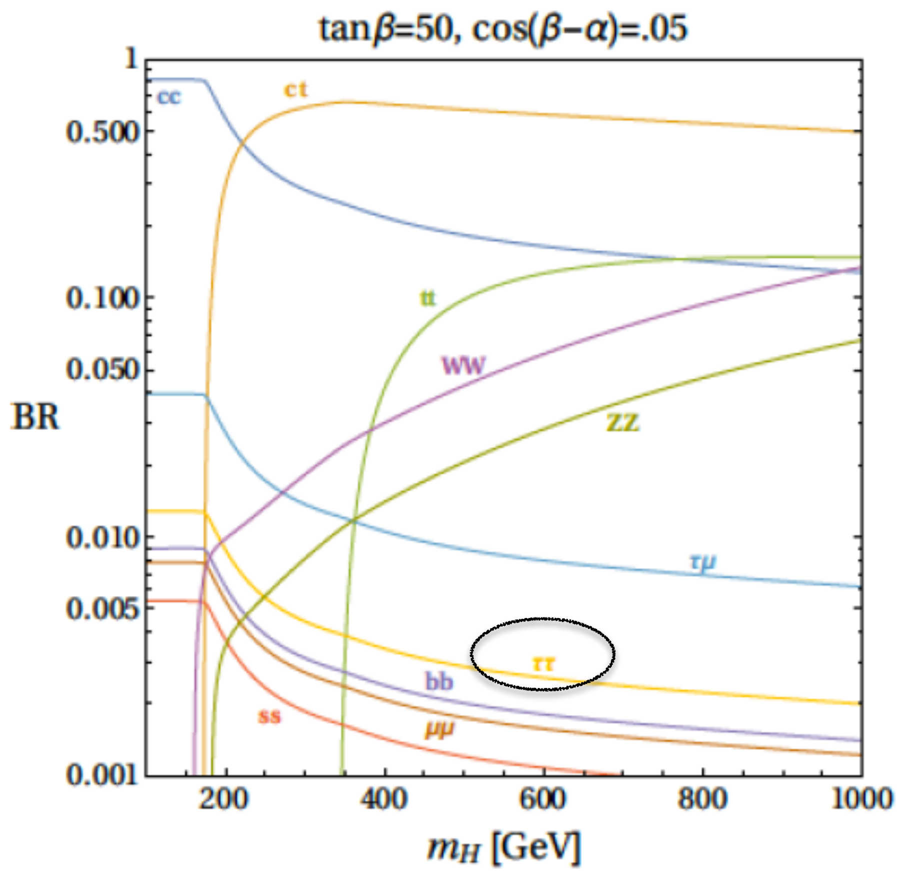
Pheno highlights of the flavorful 2HDM

Branching ratios and production cross sections of the heavy Higgs bosons can be very much altered, if compared to a type-II 2HDM
Additional signatures arise!

Production



Decay

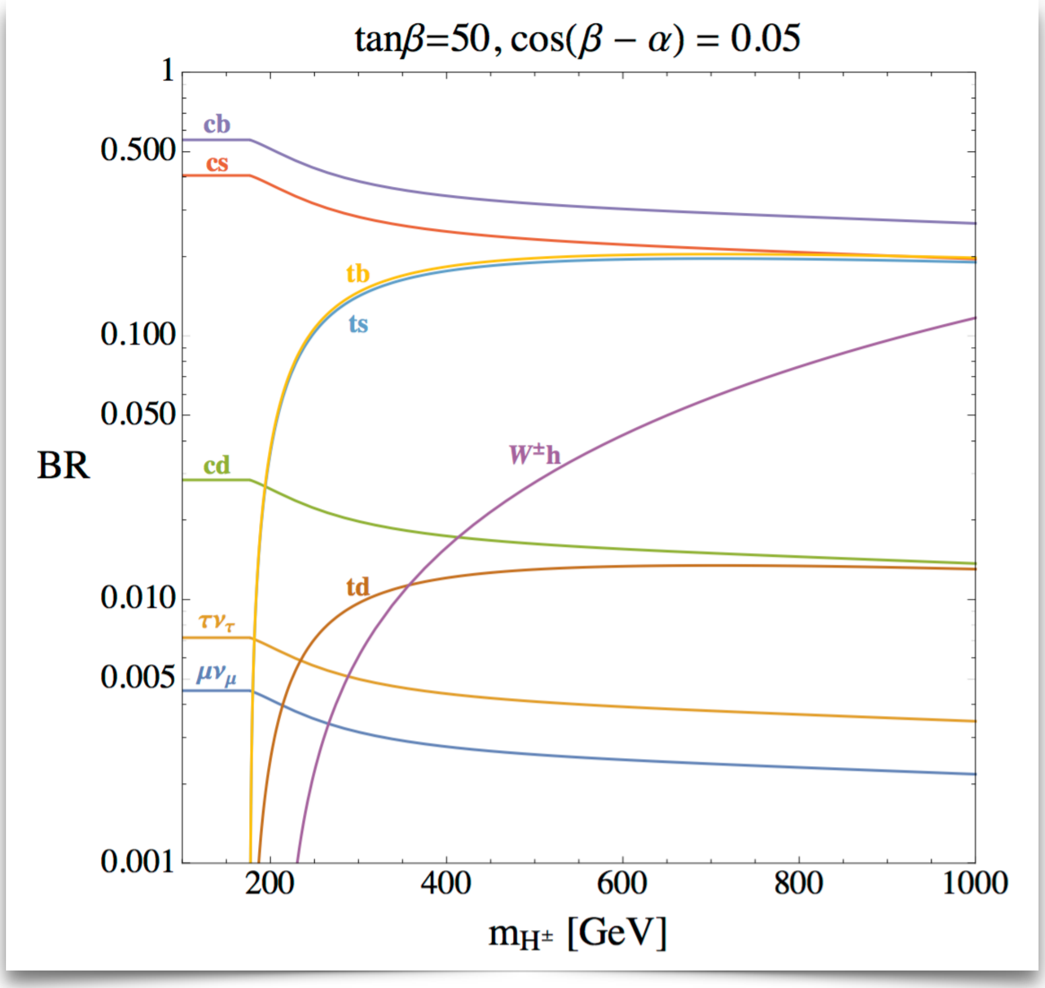


Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

Pheno highlights of the flavorful 2HDM

Branching ratios and production cross sections of the heavy Higgs bosons can be very much altered, if compared to a type-II 2HDM
Additional signatures arise!

Interesting charged Higgs phenomenology, as well:

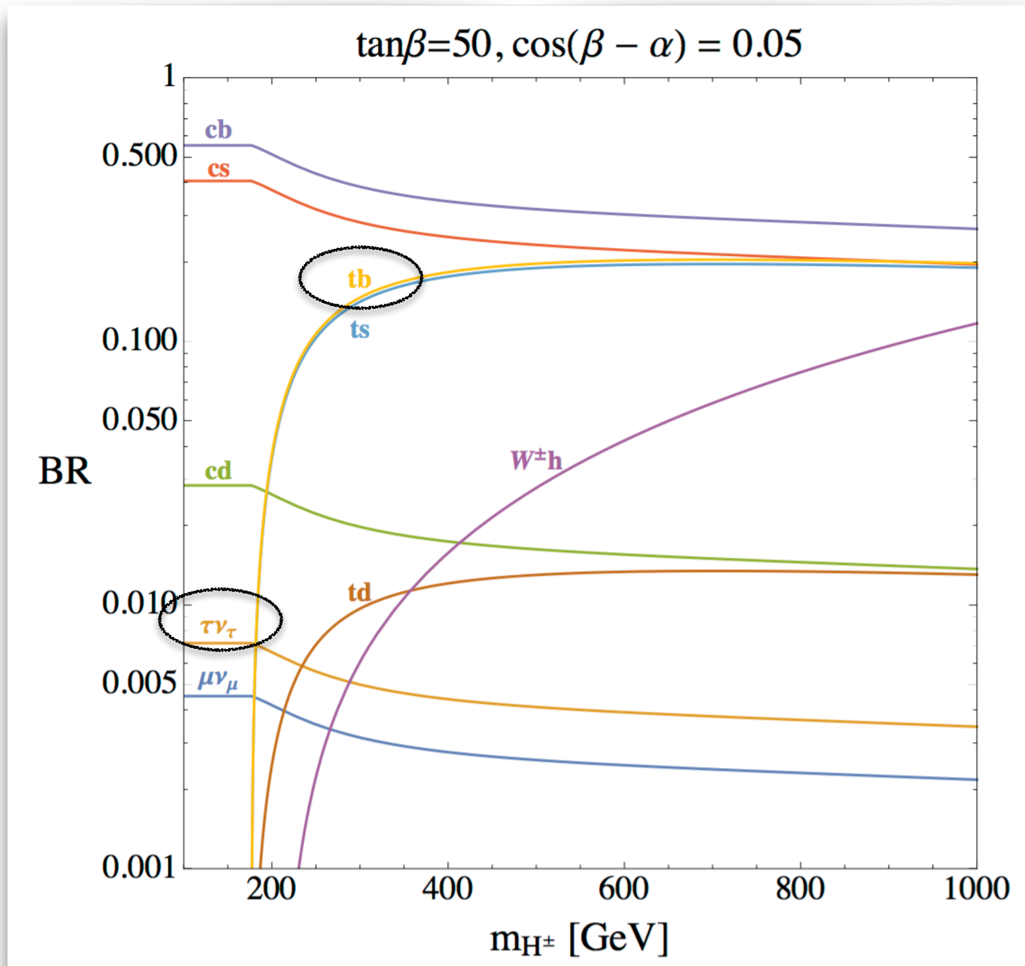


Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

Pheno highlights of the flavorful 2HDM

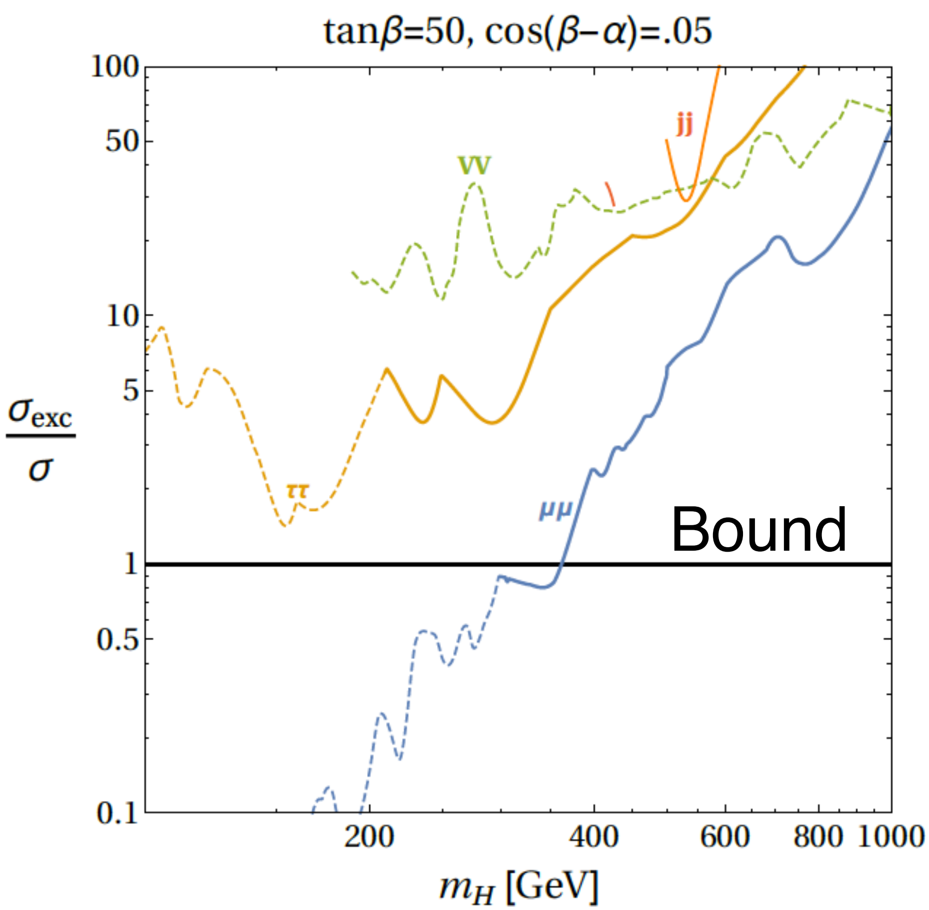
Branching ratios and production cross sections of the heavy Higgs bosons can be very much altered, if compared to a type-II 2HDM
Additional signatures arise!

Interesting charged Higgs phenomenology, as well:



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

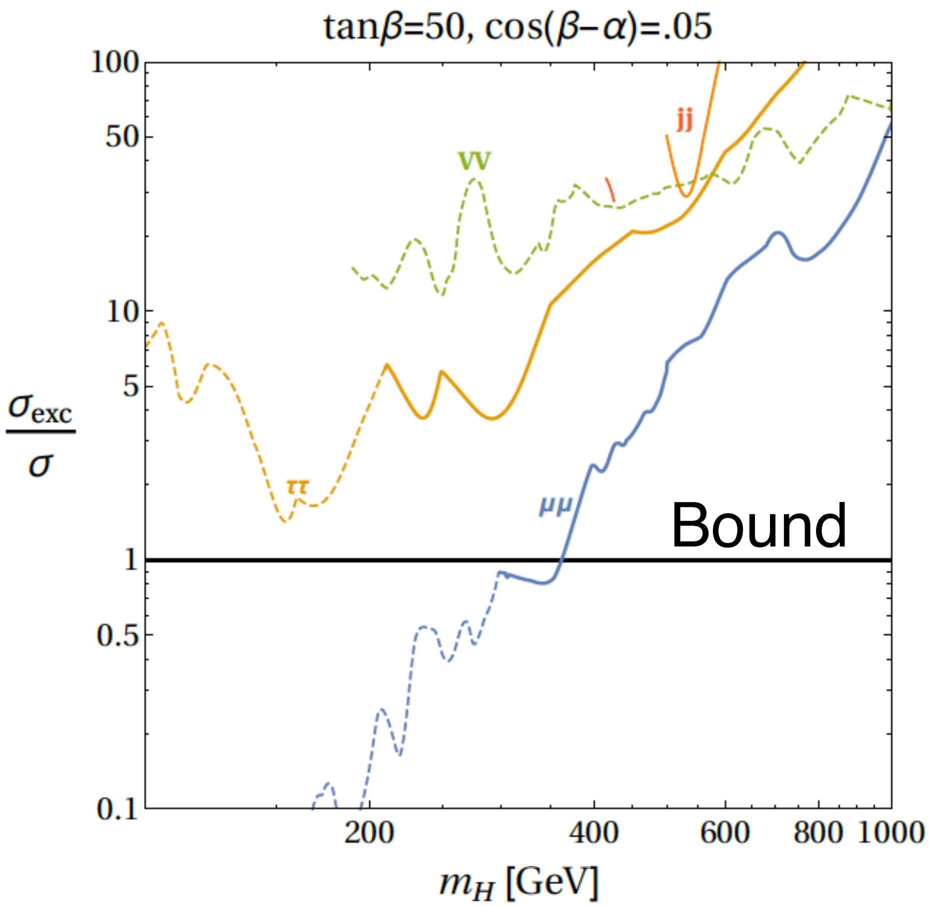
Very weak constraints & long wish-list



Bounds at ~ 400GeV for very large tanβ (= 50)

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

Very weak constraints & long wish-list



Bounds at ~ 400GeV for very large tanβ (= 50)

Wish-list:

Targeting quark-quark fusion production!

$\boxed{pp \to H \to tc}$

$\boxed{pp \to H \to \tau\mu}$

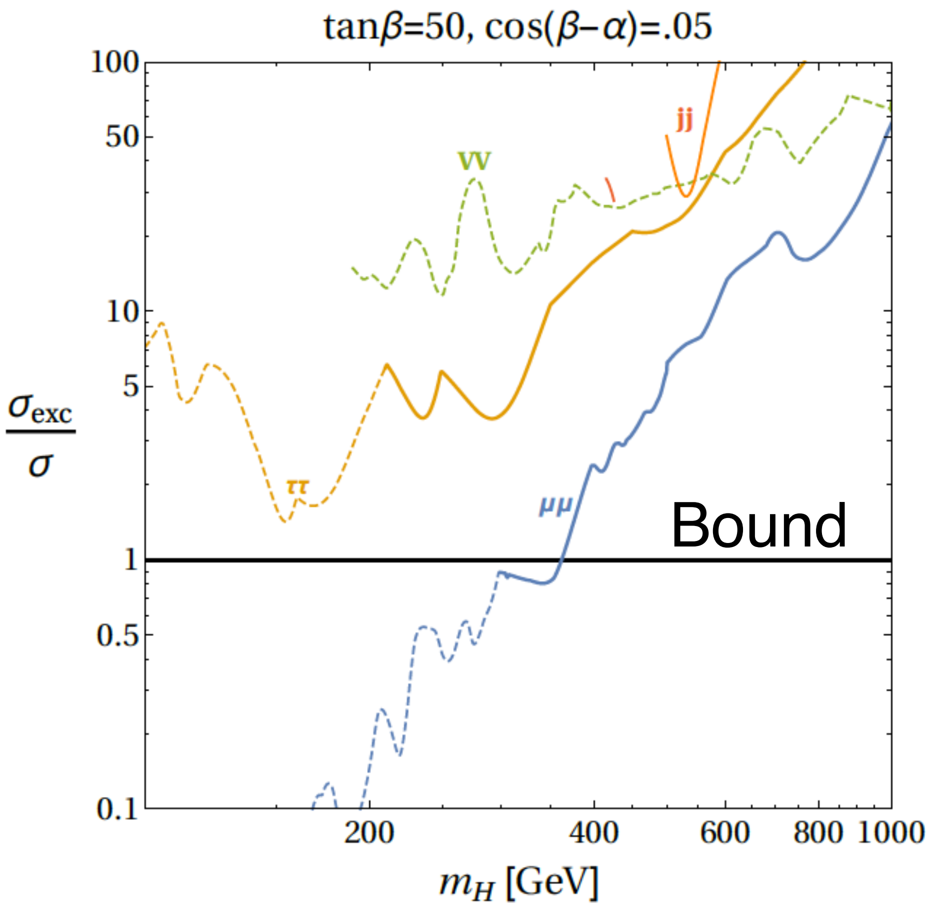
$\boxed{pp \to H \to cc}$

$\boxed{pp \to H^{\pm} \to cs,\ cb}$

Challenging and very interesting possible new searches

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

Very weak constraints & long wish-list



Bounds at ~ 400GeV for very large tanβ (= 50)

Wish-list:

Targeting quark-quark fusion production!

$\boxed{pp \to H \to tc}$

$\boxed{pp \to H \to \tau\mu}$

$\boxed{pp \to H \to cc}$

$\boxed{pp \to H^\pm \to cs,\ cb}$

Top associated production:

$\boxed{pp \to t(c)H,\ H \to tc}$

$\boxed{pp \to t(c)H,\ H \to \tau\mu}$

$\boxed{pp \to t(c)H,\ H \to cc}$

Challenging and very interesting possible new searches

?

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

Take home message

Several novel flavor structures are allowed by the measurements of low energy flavor transitions

Novel flavor structures imply a different phenomenology of the additional Higgs bosons.

→ The present LHC searches are typically not as powerful

Novel possible searches to be performed!

More comments on exotic signatures

More complete models containing two (or more) Higgs doublets can lead to sizable branching ratios of the new Higgs bosons into New Physics particles.

One example is the MSSM:

Many scenarios lead to the decay of the heavy Higgs into SUSY particles

More comments on exotic signatures

More complete models containing two (or more) Higgs doublets can lead to sizable branching ratios of the new Higgs bosons into New Physics particles.

One example is the MSSM:

Many scenarios lead to the decay of the heavy Higgs into SUSY particles

"m_h^{max}"

Carena et al, 1302.7033

$$m_t = 173.2 \text{ GeV},$$
$$M_{\text{SUSY}} = 1000 \text{ GeV},$$
$$\boxed{\begin{aligned}\mu &= 200 \text{ GeV},\\ M_2 &= 200 \text{ GeV},\end{aligned}}$$
$$X_t^{\text{OS}} = 2\, M_{\text{SUSY}}$$
$$X_t^{\overline{\text{MS}}} = \sqrt{6}\, M_{\text{SUSY}}$$
$$A_b = A_\tau = A_t,$$
$$m_{\tilde{g}} = 1500 \text{ GeV},$$
$$M_{\tilde{l}_3} = 1000 \text{ GeV}$$

super-partners of the Higgs & the W boson

Tanβ = 5, m_H = 500GeV

$$\mathrm{BR}(H \to \chi_1^\pm \chi_1^\pm,\ \chi_1^\pm \chi_2^\pm,\ \chi_1^0 \chi_1^0) \sim 0.15,\ 0.35,\ 3 \times 10^{-2}$$

More comments on exotic signatures

More complete models containing two (or more) Higgs doublets can lead to sizable branching ratios of the new Higgs bosons into New Physics particles.

One example is the MSSM:

Many scenarios lead to the decay of the heavy Higgs into SUSY particles

"m_h^{max}"

Carena et al, 1302.7033

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 2\, M_{\rm SUSY} \\
X_t^{\overline{\rm MS}} &= \sqrt{6}\, M_{\rm SUSY} \\
A_b = A_\tau &= A_t, \\
m_{\tilde g} &= 1500 \text{ GeV}, \\
M_{\tilde l_3} &= 1000 \text{ GeV}
\end{aligned}
$$

super-partners of the Higgs & the W boson

Tanβ = 5, m_H = 500GeV

$$\mathbf{BR}(H \to \chi_1^\pm\chi_1^\pm,\ \chi_1^\pm\chi_2^\pm,\ \chi_1^0\chi_1^0) \sim \mathbf{0.15,\ 0.35, 3\times 10^{-2}}$$

"tau-phobic"

Carena et al, 1302.7033

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\rm SUSY} &= 1500 \text{ GeV}, \\
\mu &= 2000 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 2.45\, M_{\rm SUSY} \\
X_t^{\overline{\rm MS}} &= 2.9\, M_{\rm SUSY} \\
A_b = A_\tau &= A_t\ , \\
m_{\tilde g} &= 1500 \text{ GeV}, \\
M_{\tilde l_3} &= 500 \text{ GeV}
\end{aligned}
$$

super-partner of the SM taus

Tanβ = 20, m_H = 900GeV

$$\mathbf{BR}(H \to \tilde\tau_1\tilde\tau_1) \sim \mathbf{0.25}$$

More comments on exotic signatures

More complete models containing two (or more) Higgs doublets can lead to sizable branching ratios of the new Higgs bosons into New Physics particles.

One example is the MSSM:

Many scenarios lead to the decay of the heavy Higgs into SUSY particles

"m_h^{max}" Carena et al, 1302.7033

$$m_t = 173.2 \text{ GeV},$$
$$M_{\rm SUSY} = 1000 \text{ GeV},$$
$$\boxed{\mu = 200 \text{ GeV}, \quad M_2 = 200 \text{ GeV},}$$
$$X_t^{\rm OS} = 2\, M_{\rm SUSY}$$

super-partners of the Higgs & the W boson

Tanβ = 5, m_H = 500GeV

$$\mathrm{BR}(H \to \chi_1^{\pm}\chi_1^{\pm},\ \chi_1^{\pm}\chi_2^{\pm},\ \chi_1^0\chi_1^0) \sim 0.15,\ 0.35,\ 3\times10^{-2}$$

"tau-phobic" Carena et al, 1302.7033

$$m_t = 173.2 \text{ GeV},$$
$$M_{\rm SUSY} = 1500 \text{ GeV},$$
$$\mu = 2000 \text{ GeV},$$
$$M_2 = 200 \text{ GeV},$$
$$X_t^{\rm OS} = 2.45\, M_{\rm SUSY}$$

-partner of the SM taus

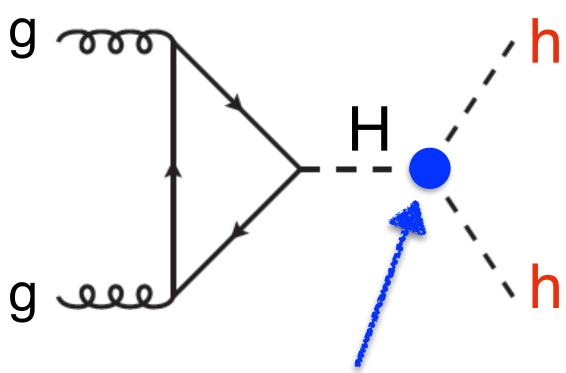
Tanβ = 20, m_H = 900GeV

$$\mathrm{BR}(H \to \tilde{\tau}_1\tilde{\tau}_1) \sim 0.25$$

Opportunity to look for SUSY particles produced from heavy Higgs decays? ?

A note on "Higgs to Higgs decays"

The heavy Higgs bosons can decay sizably into two 125 GeV Higgs bosons



this coupling is non-0
away from the alignment limit

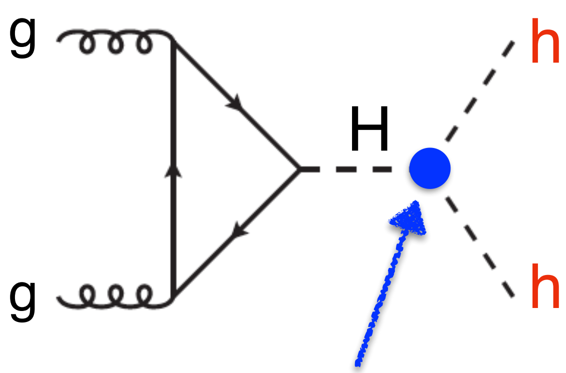
Keeping into account the present (125 GeV) Higgs data, one can show that BR(H $\rightarrow$hh) can be at the ~ 50% level!

Correspondingly, the "standard" heavy Higgs decay modes will be suppressed

see eg. Baggio et al. 1403.1264

A note on “Higgs to Higgs decays”

The heavy Higgs bosons can decay sizably into two 125 GeV Higgs bosons

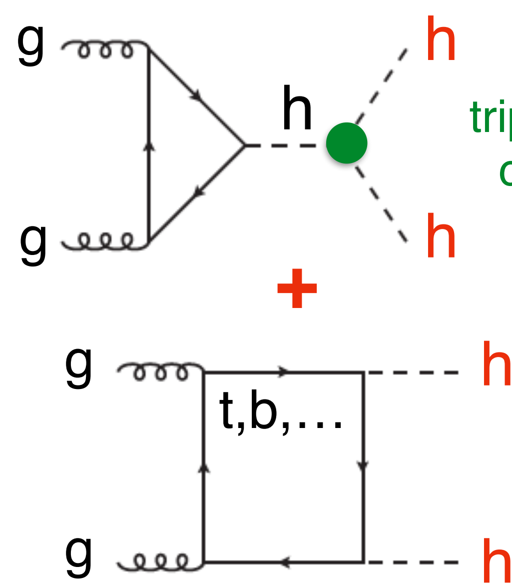


this coupling is non-0
away from the alignment limit

Keeping into account the present (125 GeV) Higgs data, one can show that BR(H $\to$hh) can be at the ~ 50% level!

Correspondingly, the “standard” heavy Higgs decay modes will be suppressed

The (125GeV) di-Higgs production cross section will be different than the one of the SM



triple Higgs coupling

The cross section can be enhanced by a factor of O(10)

see eg. Baggio et al. 1403.1264

Challenges & opportunities in hh production

The cross section is rather small in the SM: ~ 40fb
(as opposed to the ~ 50 pb for gluon fusion single-Higgs production)

The most abundant signature is hh → 4b
Present bounds on the cross section at around ~13 times the SM

challenging!

Challenges & opportunities in hh production

The cross section is rather small in the SM: ~ 40fb
(as opposed to the ~ 50 pb for gluon fusion single-Higgs production)

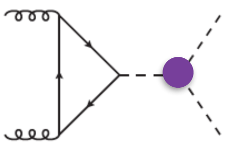
The most abundant signature is hh → 4b
Present bounds on the cross section at around ~13 times the SM

challenging!

This measurement is very important because it gives info on the shape of the Higgs potential. In the SM:

$$V = V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4$$

This coefficient
is fully determined



very important measurement

Challenges & opportunities in hh production

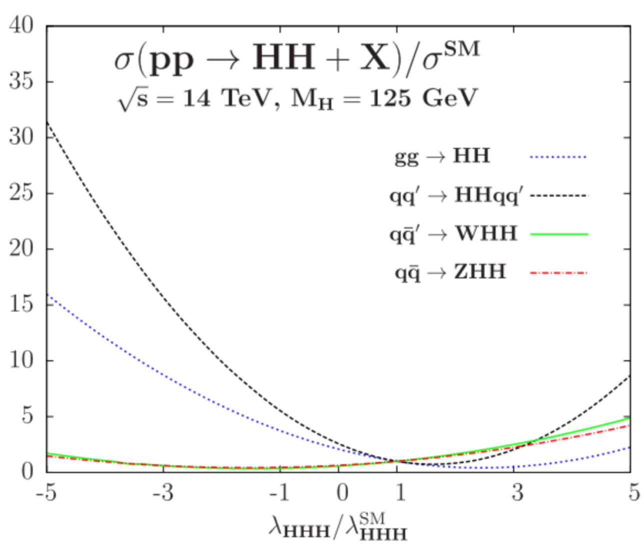
The cross section is rather small in the SM: ~ 40fb
(as opposed to the ~ 50 pb for gluon fusion single-Higgs production)

The most abundant signature is hh → 4b
Present bounds on the cross section at around ~13 times the SM

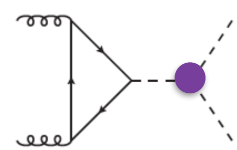
challenging!

This measurement is very important because it gives info on the shape of the Higgs potential. In the SM:

$$V = V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4$$



This coefficient is fully determined



very important measurement

Challenges & opportunities in hh production

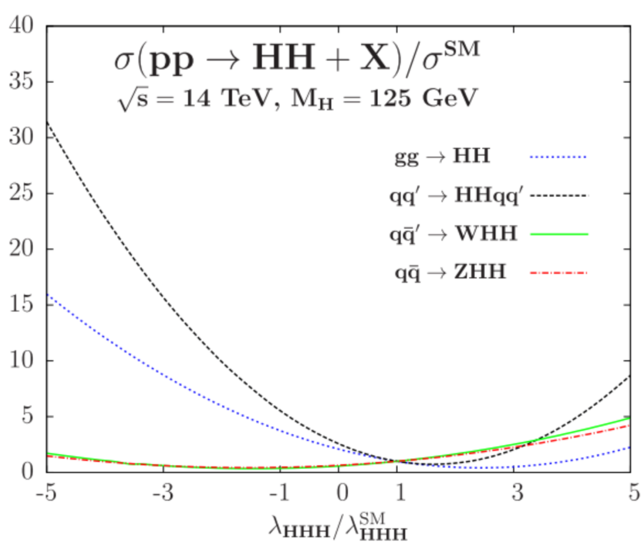
The cross section is rather small in the SM: ~ 40fb
(as opposed to the ~ 50 pb for gluon fusion single-Higgs production)

The most abundant signature is hh → 4b
Present bounds on the cross section at around ~13 times the SM

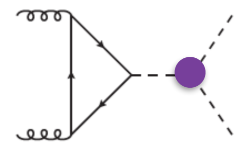
challenging!

This measurement is very important because it gives info on the shape of the Higgs potential. In the SM:

$$V = V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$



This coefficient
is fully determined



Implications for theories for electro-weak baryogenesis?

Prospects for the High-Luminosity LHC?

very important measurement

Future prospects in di-Higgs production

At the high-luminosity LHC (3000 fb^{-1}):

Channel	CMS	ATLAS
$HH \to bbbb$	$Z(\sigma_{HH}(SM))=0.39\ \sigma$ CMS PAS FTR-16-002	$-4.1 < \lambda_{HHH}/\lambda_{SM} < 8.7$ @95 % C.L. ATLAS-TDR-030
$HH \to bb\tau\tau$	1.6 xSM CMS-TDR-019	$0.6\ \sigma$ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ @95 % C.L. ATL-PHYS-PUB-2015-046
$HH \to bb\gamma\gamma$	$1.43\ \sigma$ CMS PAS FTR-16-002	$1.5\ \sigma$ $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ @95 % C.L. (stat only) ATLAS-TDR-030
$HH \to WWbb$	$0.45\ \sigma$ CMS PAS FTR-16-002	
$tt(HH \to bbbb)$		$0.35\ \sigma$ ATL-PHYS-PUB-2016-023

Most results will be updated for the Yellow Report of the high-luminosity / high-energy LHC

Chapter 3

(Light) singlet scalars (pseudoscalars)

Looking for light (< 125 GeV)
particles at the LHC

Models with singlet scalars

- Many well motivated theories beyond the SM contain new scalars that are not charged under the SM gauge symmetries:

  the Next to Minimal Supersymmetric Standard Model (NMSSM),
  models of neutral naturalness (twin Higgs, …),
  models for EW baryogenesis,
  models for Dark Matter (DM) with scalar mediators, …

Models with singlet scalars

* Many well motivated theories beyond the SM contain new scalars that are not charged under the SM gauge symmetries:

  the Next to Minimal Supersymmetric Standard Model (NMSSM),
  models of neutral naturalness (twin Higgs, …),
  models for EW baryogenesis,
  models for Dark Matter (DM) with scalar mediators, …

* More freedom from LEP.

LEP bounds are typically weak, as opposed to bounds on EW charged particles
(…the ~100GeV rule of thumb for electrically charged particles)

* It is interesting to study what searches can be done at the LHC for light (< 125 GeV) scalars. Different experimental strategies?

Models with singlet scalars

* Many well motivated theories beyond the SM contain new scalars that are not charged under the SM gauge symmetries:

  the Next to Minimal Supersymmetric Standard Model (NMSSM),
  models of neutral naturalness (twin Higgs, …),
  models for EW baryogenesis,
  models for Dark Matter (DM) with scalar mediators, …

* More freedom from LEP.

LEP bounds are typically weak, as opposed to bounds on EW charged particles
(…the ~100GeV rule of thumb for electrically charged particles)

* It is interesting to study what searches can be done at the LHC for light (< 125 GeV) scalars. Different experimental strategies?

* Theoretically: why light?

- symmetries protecting their mass.

Examples are the R-symmetry & the Peccei-Quinn symmetry in the NMSSM

- Models of DM that require a light scalar

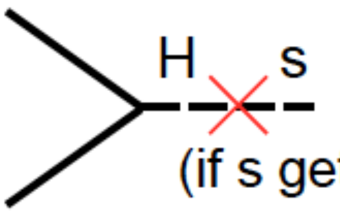
How to probe light (< 125 GeV) scalars?

Higgs portal interaction

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

How to probe light (< 125 GeV) scalars?

1. Direct production:



(if s gets a VEV)

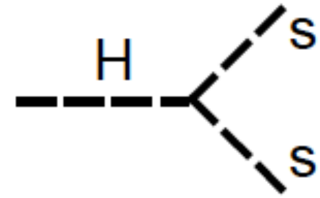
(same production mechanisms as for the SM Higgs)

Higgs portal interaction

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

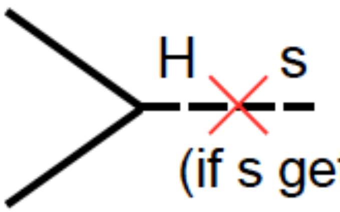
Interplay of LHC searches

3. (125 GeV) Higgs decays:



How to probe light (< 125 GeV) scalars?

1. Direct production:

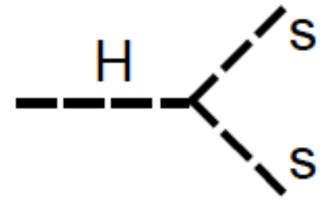


(if s gets a VEV)

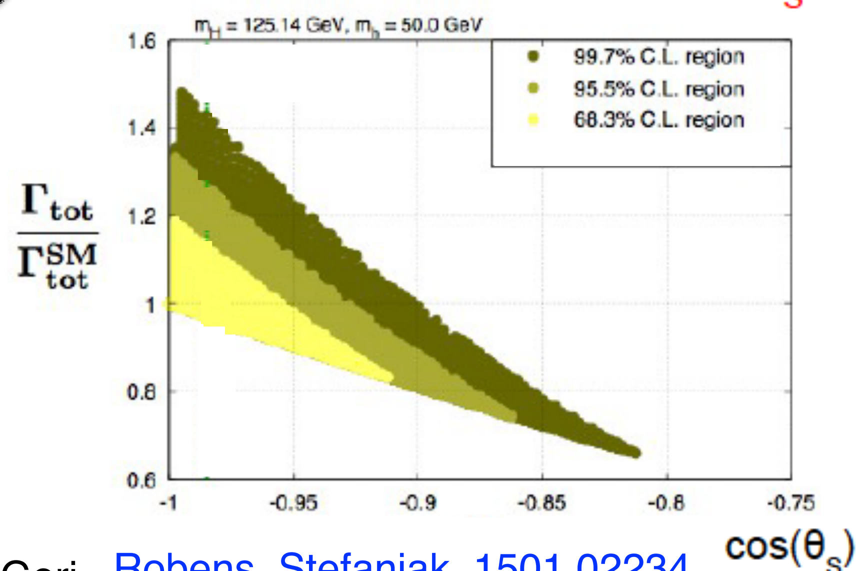
Higgs portal interaction

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

3. (125 GeV) Higgs decays:



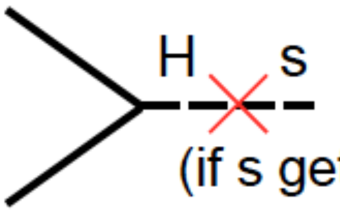
2. The Higgs couplings to SM particles are reduced by a factor of $\cos(\theta_S)$



 Robens, Stefaniak, 1501.02234

How to probe light (< 125 GeV) scalars?

1. Direct production:

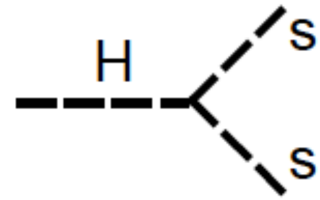


(if s gets a VEV)

Higgs portal interaction

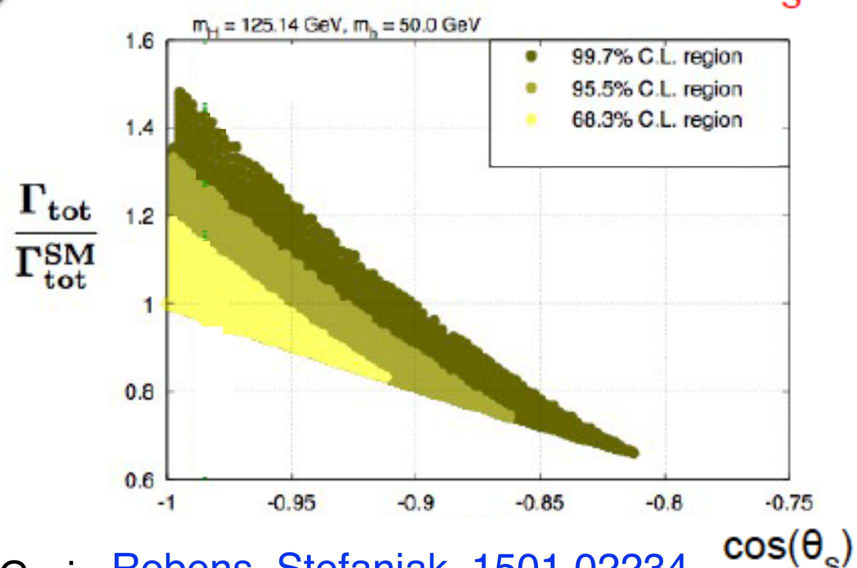
$$\frac{\xi}{2}|H|^2 s^2$$

3. (125 GeV) Higgs decays:



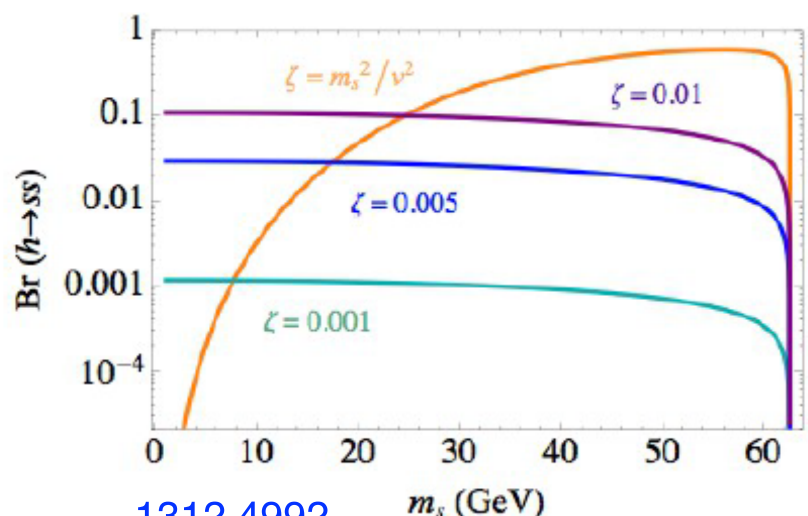
It does not depend on the mixing, θ_S

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



Robens, Stefaniak, 1501.02234

The Higgs has some "exotic" signatures



1312.4992

1.

Direct production of a new scalar

The production cross section$_{_s}$ = production$_{_\text{SM Higgs}}$*$\sin^2(\theta_S)$
Same production modes as for the SM Higgs

Only a few LHC searches have been performed.

Examples are bbA, A →μμ
ggA, A →μμ, (also searched for by LHCb)
ggA, A →γγ
bbA, A →tautau