(Flavor) gaps in heavy Higgs searches

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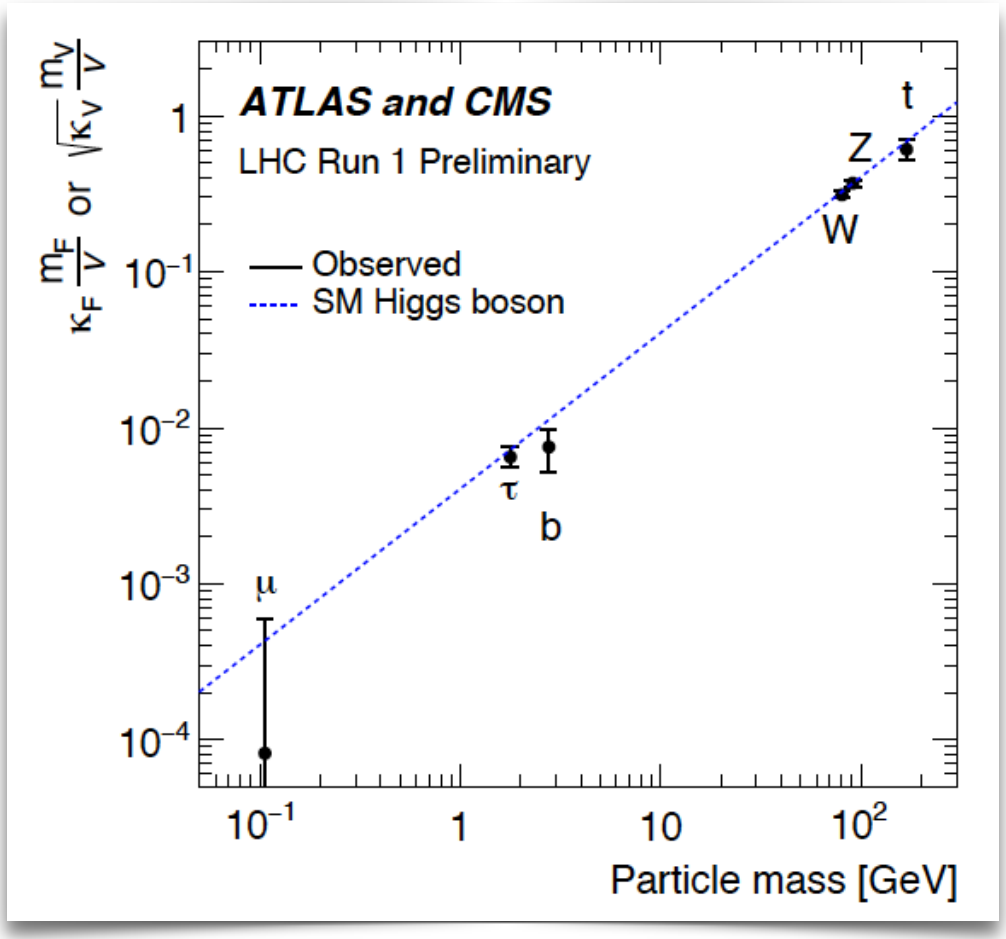
Triggering on New Physics at the HL-LHC
Princeton University

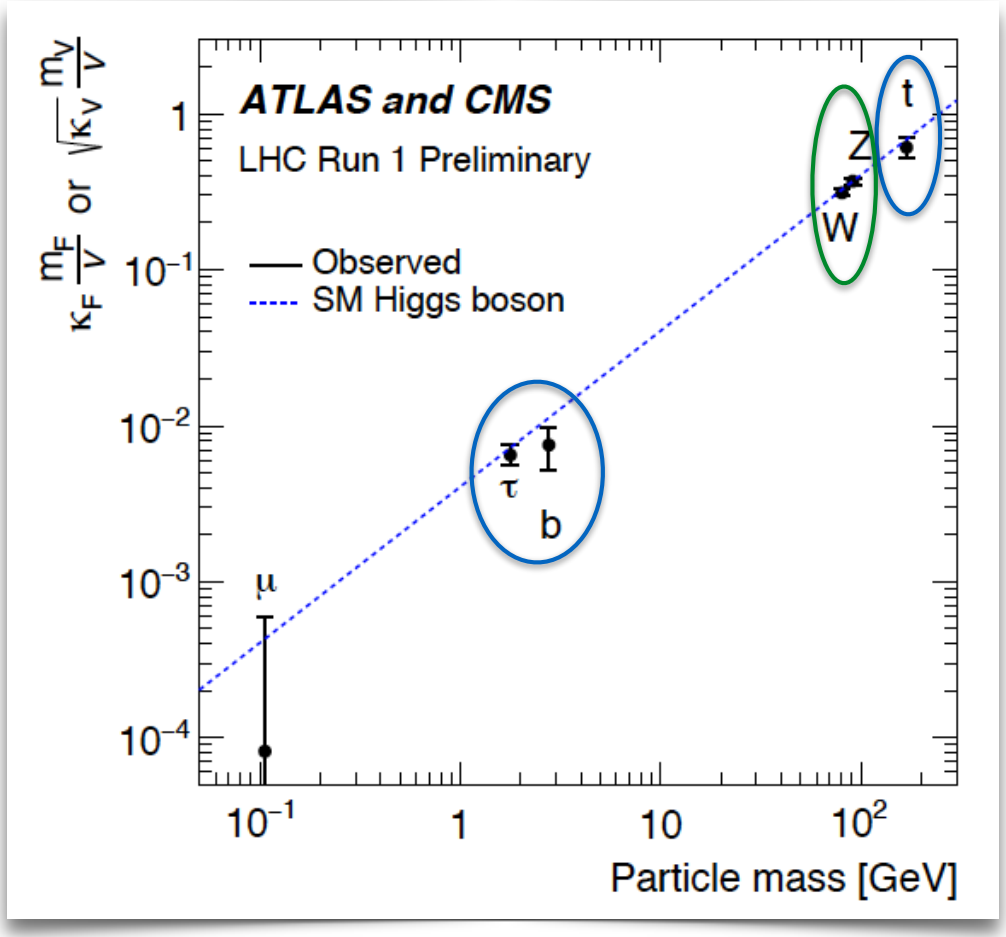
January 15, 2018

Discovery & precision



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

Discovery & precision



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

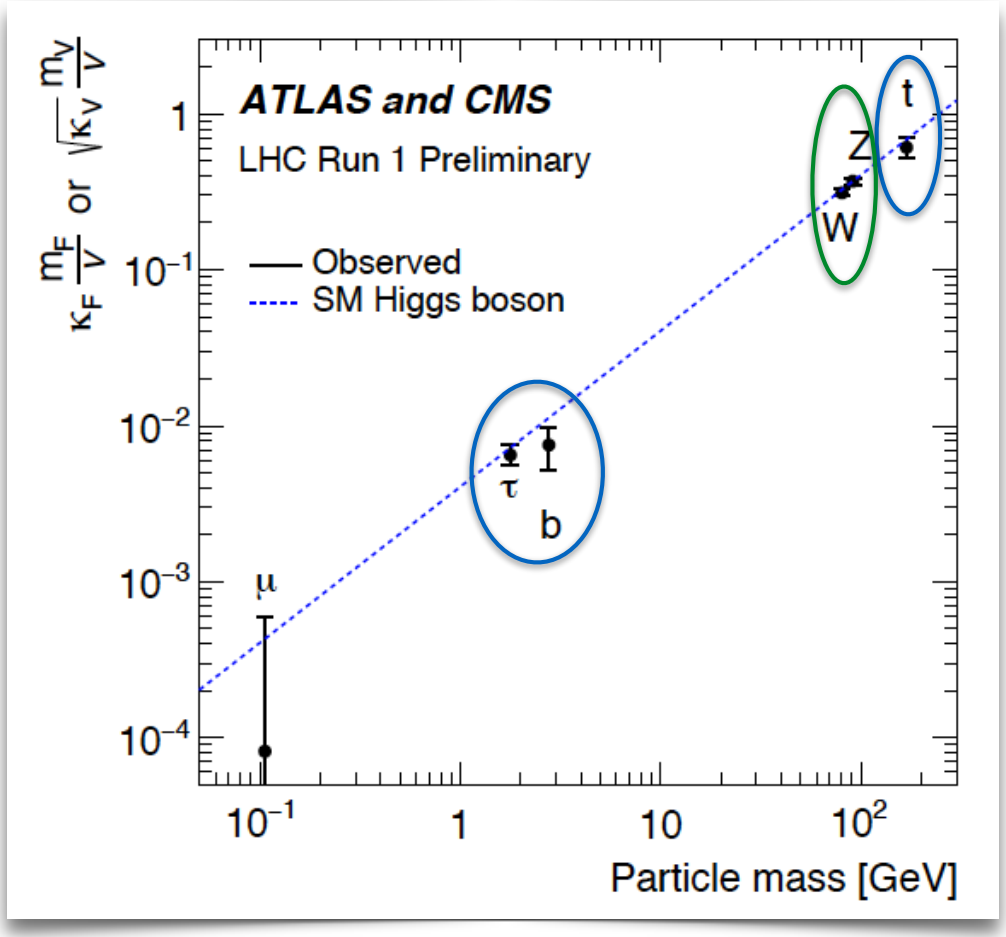
We have evidence that the Higgs gives mass to the 3rd generation fermions (and gauge bosons).

Substantial improvement in the precision of the measurements at future LHC runs.

Flavor puzzle:

The Higgs couplings to fermions are highly hierarchical.
We do not yet know if this is the case!

Discovery & precision



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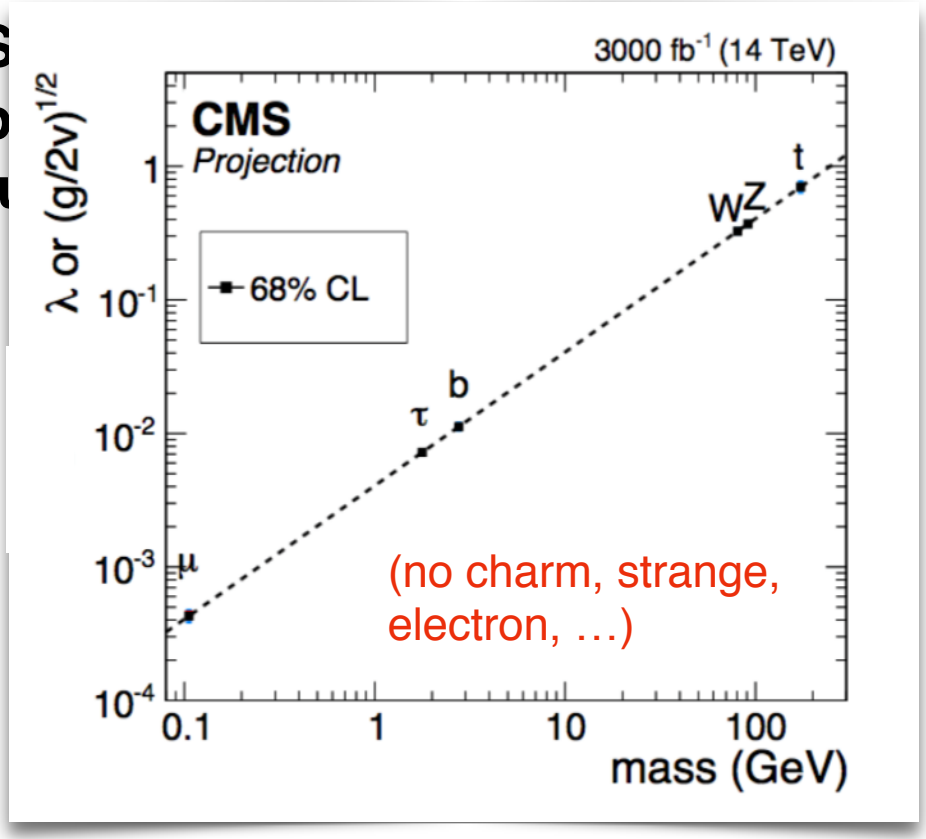


At the same time…

The Higgs sector is the “obscure” sector of the Standard Model (SM)

Most of the problems of the SM originate from the Higgs interactions!

$$\mathcal{L}_{SM} \sim \underbrace{\Lambda^4}_{\text{cc}} + \underbrace{\Lambda^2 H^2}_{\text{Naturalness}} + \underbrace{\lambda H^4}_{\text{Stability}} + \underbrace{Y H\bar{\Psi}\Psi}_{\text{Flavor}}$$

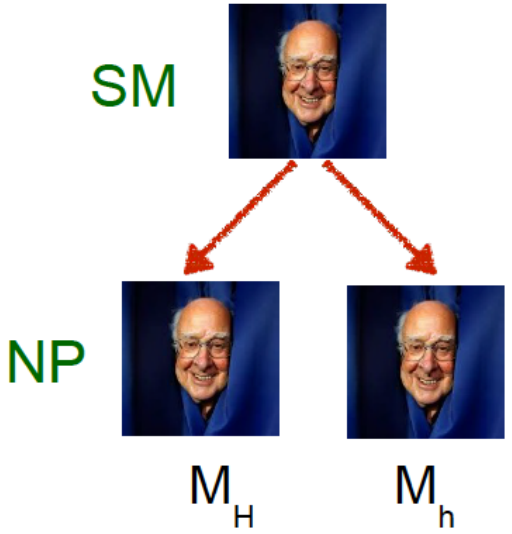
Precision measurements of the Higgs
&
Searches for new Higgs bosons

Why new Higgs bosons?

- The spin-1/2 and spin-1 sectors of our universe are rich in multiplicity. Why not also the spin-0 sector?

- Dynamical explanation of the hierarchy problem (SUSY, twin Higgs, …) → enlarged Higgs sector

- Additional Higgs bosons can be Dark Matter (inert Higgs doublet)

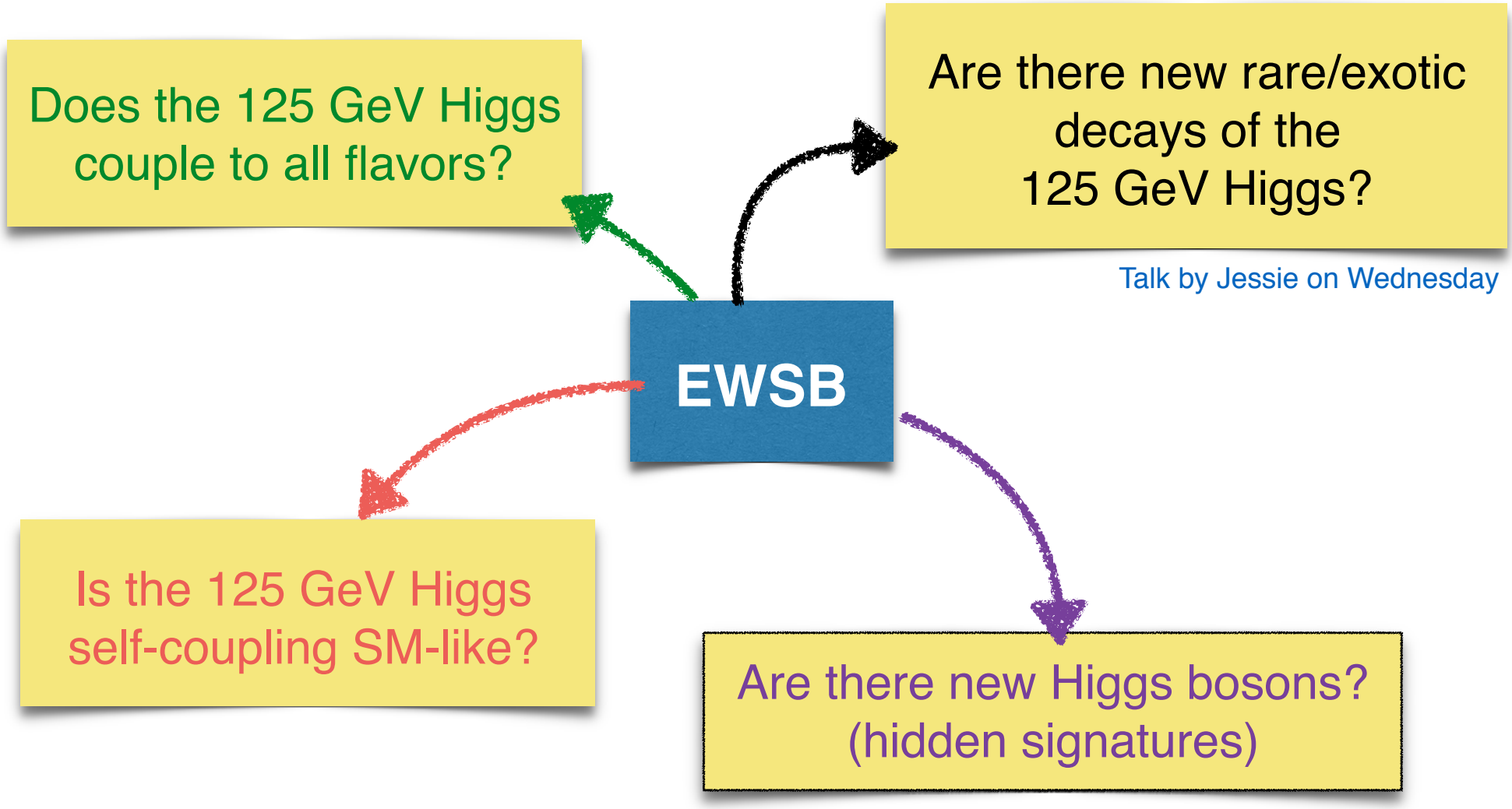


Discovery of new Higgs bosons
→ death of the anthropic principle?

(see Draper, Haber, Ruderman, 1605.03237 for exceptions)

Essential element to understand how nature deals with naturalness

Several questions for the HL-LHC



How to trigger at best to answer all these questions?
What experimental analyses to perform?

Current LHC Higgs searches

bb	ττ	μμ	γγ	hh	WW	ZZ	tt
bH	gg,bH	gg,bH		gg	all	all	gg, tt

H

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

A

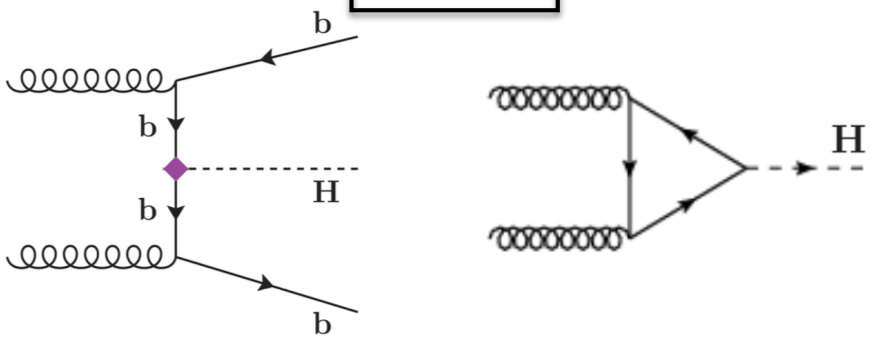
τν	tb	Wh	cs	μν	cb
(t)$H^{\pm}$ t dec	(t)$H^{\pm}$ t dec	qq fus	t decay	qq fus	t decay

$H^{\pm}$

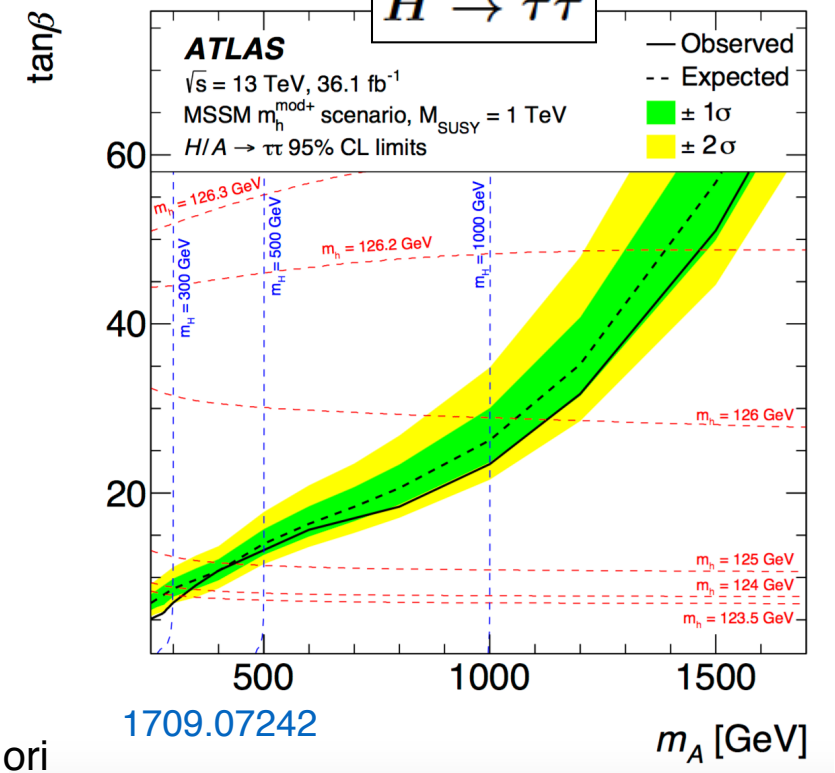
New
since ICHEP 2016

The golden channels

H/A



$H \rightarrow \tau\tau$



1709.07242

The golden channels

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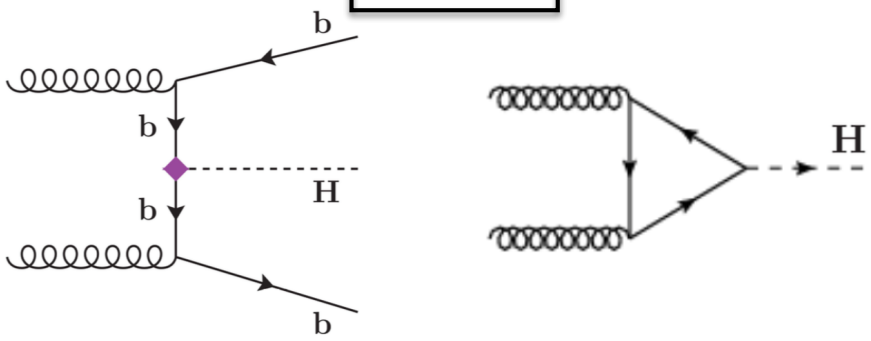
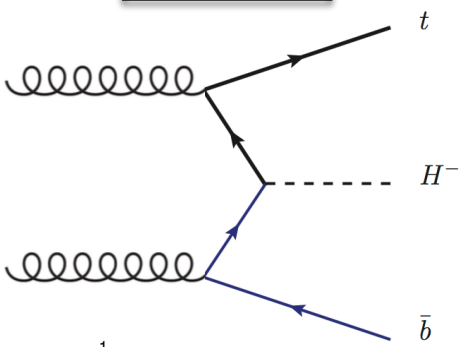


H±



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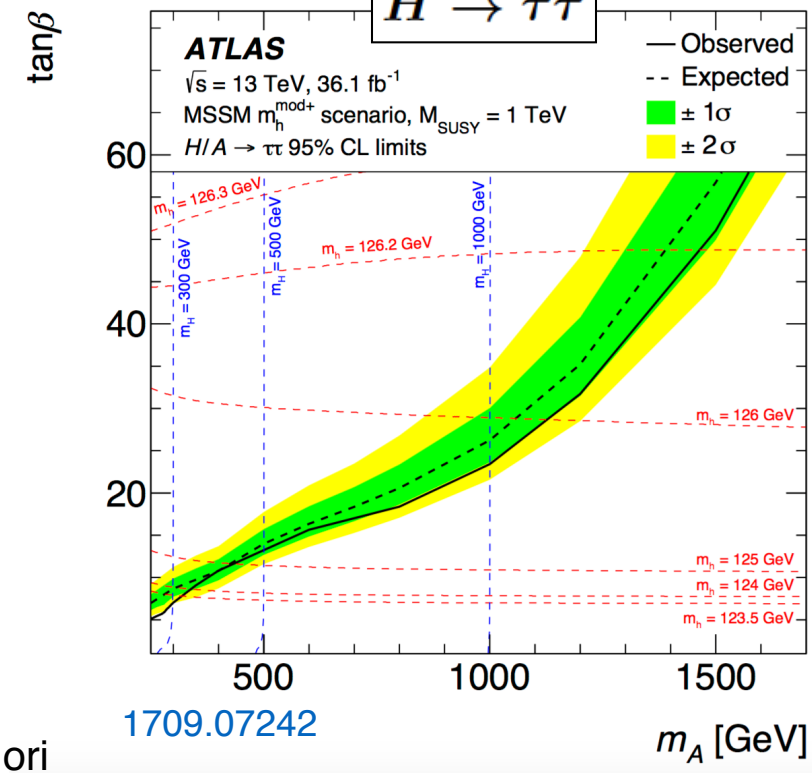

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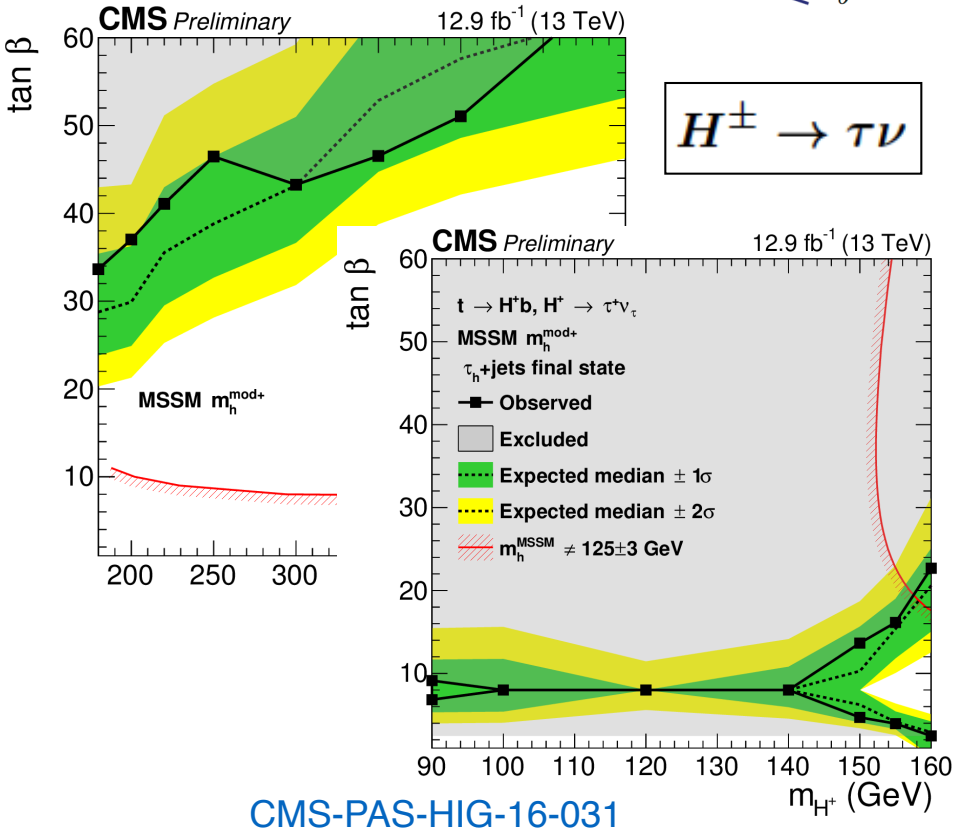
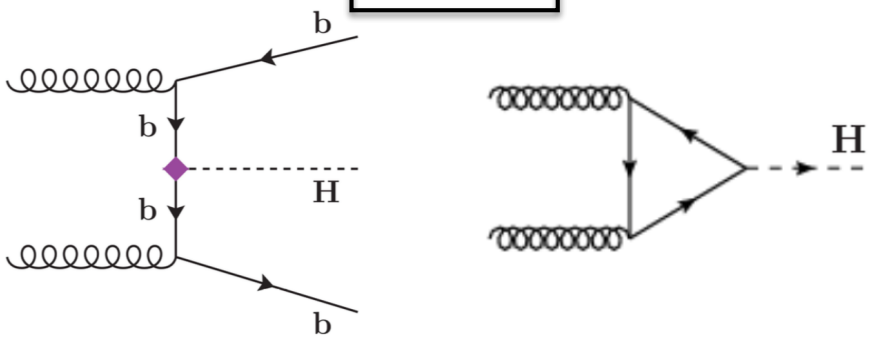


$H^{\pm} \to \tau\nu$

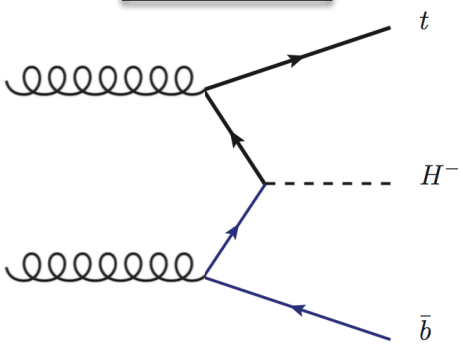
CMS-PAS-HIG-16-031

The golden channels

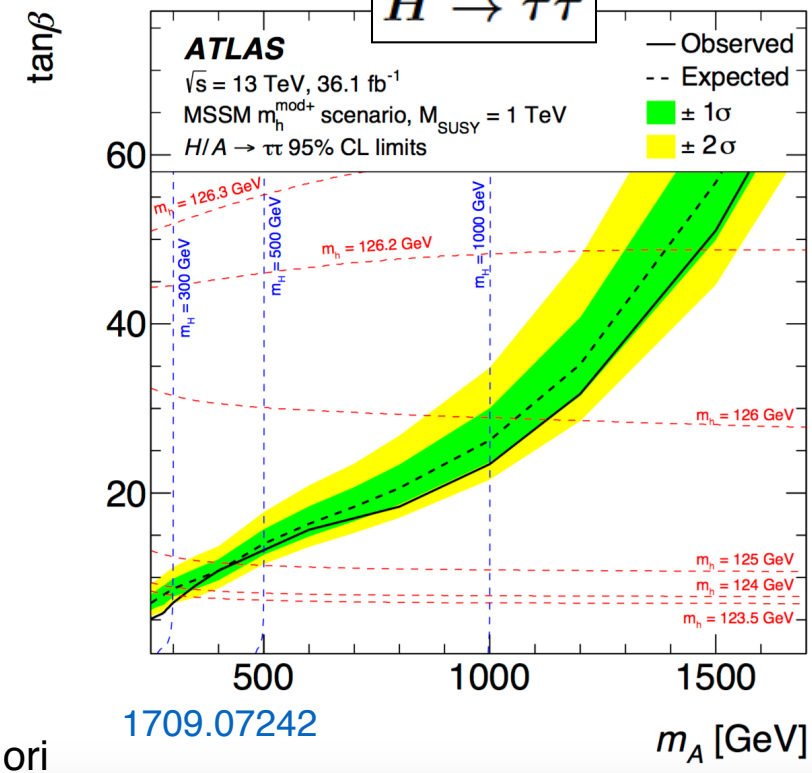
H/A



H±

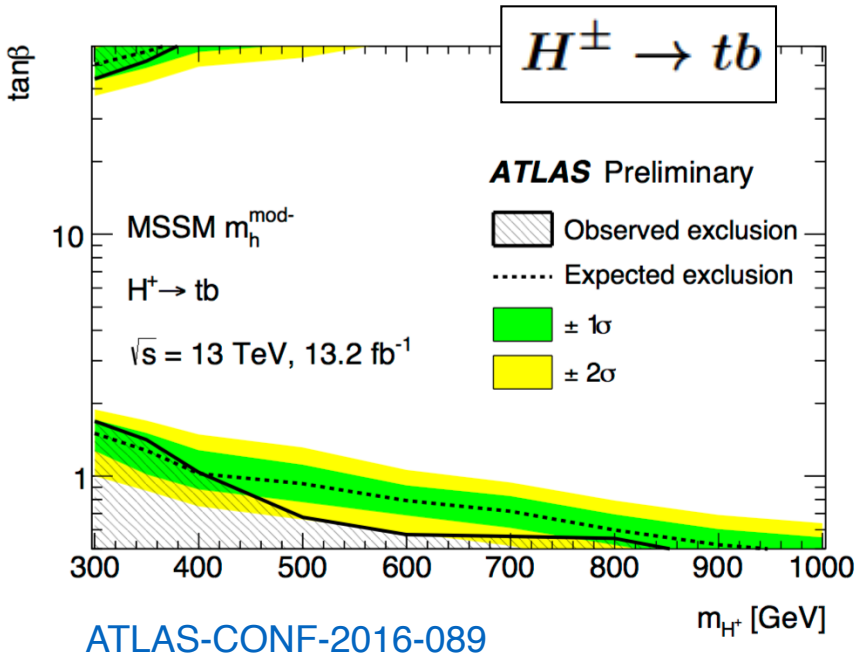


$H \to \tau\tau$



1709.07242

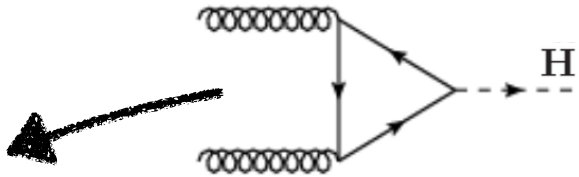
$H^{\pm} \to tb$

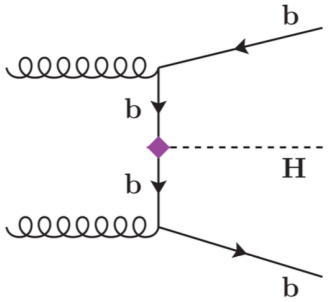


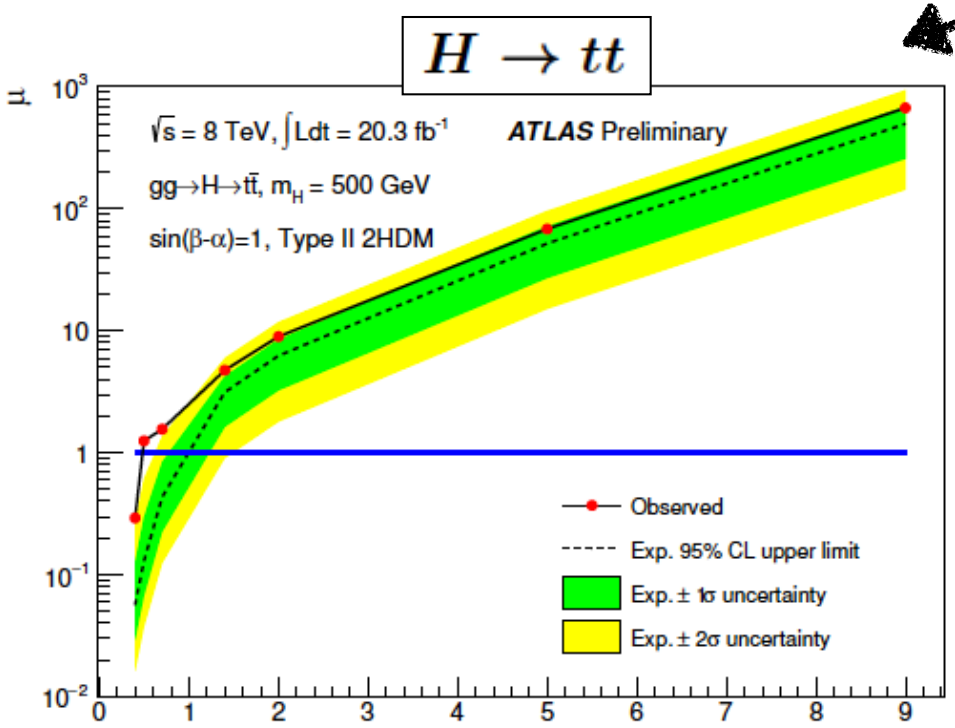
ATLAS-CONF-2016-089

Other decays to 3rd generations

More recent analysis:



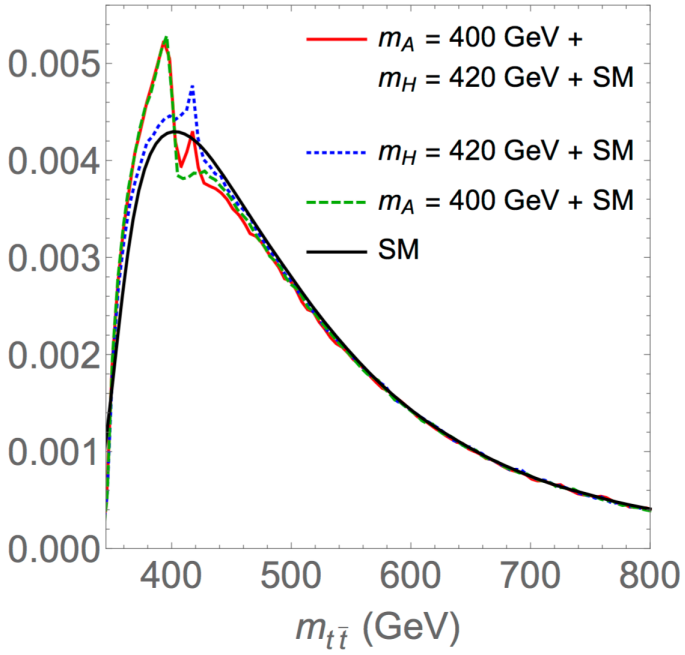




ATLAS-CONF-2016-073

- Challenge arising from the interference with the SM background
- Single lepton trigger

SG, Kim, Shah, Zurek, 1602.02782



See also Craig et al., 1504.04630

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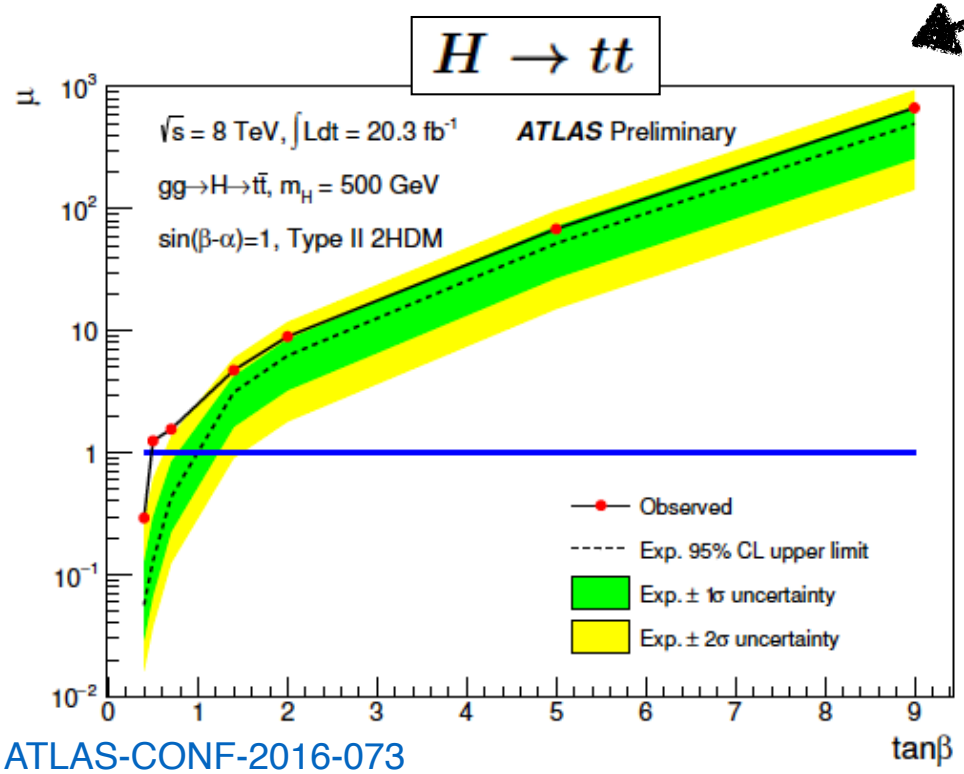

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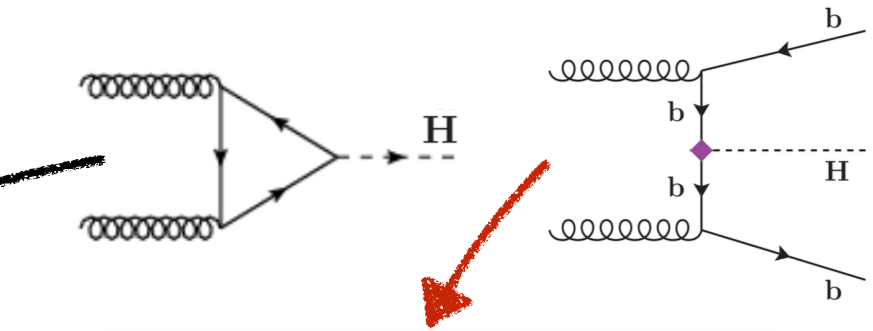

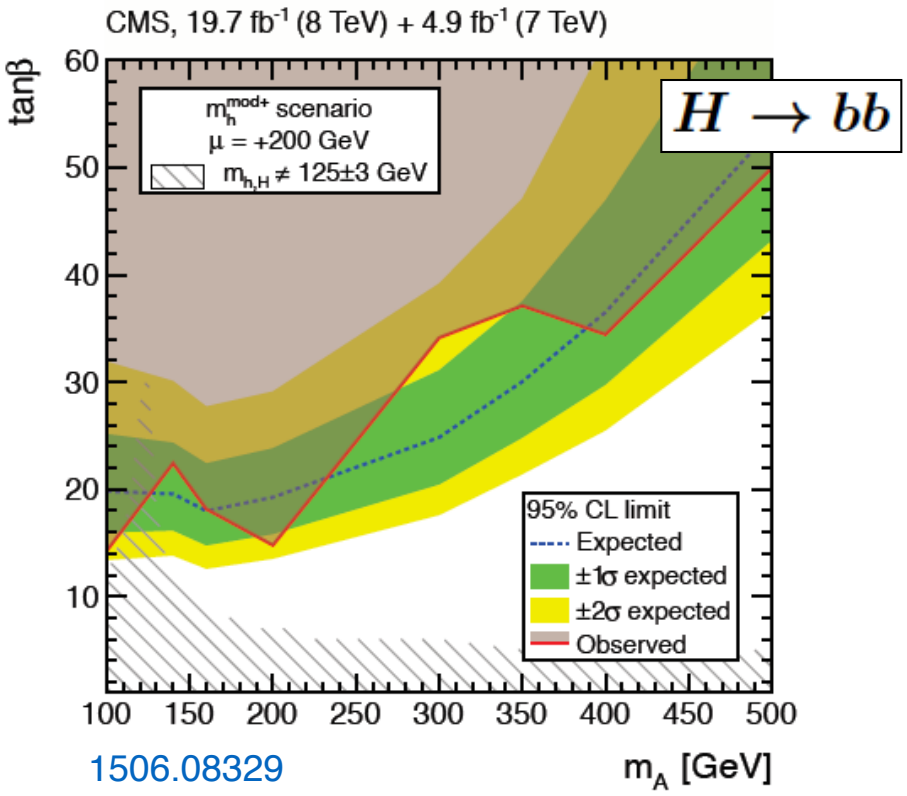

1506.08329

- Challenge arising from the interference with the SM background
- Single lepton trigger

Specialized triggers that identify b jets already at the online level.

Other decays to 3rd generations

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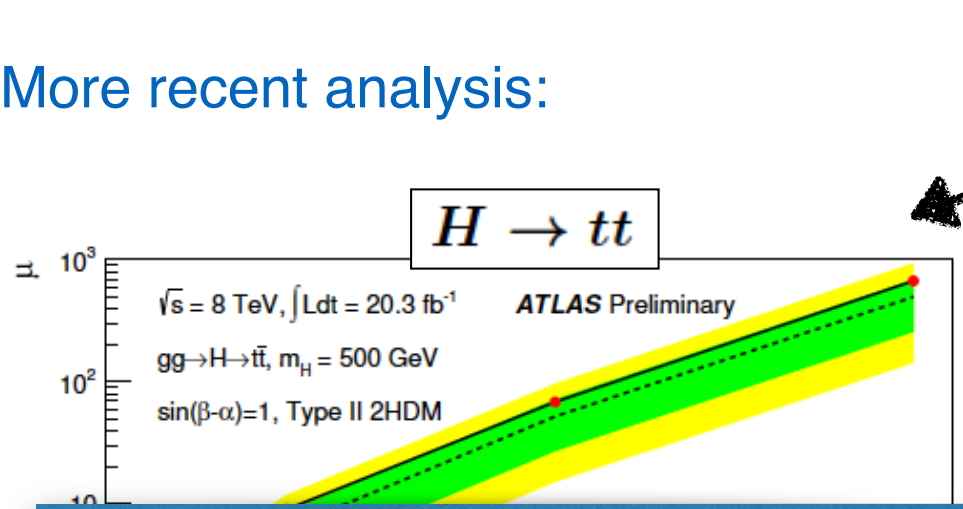

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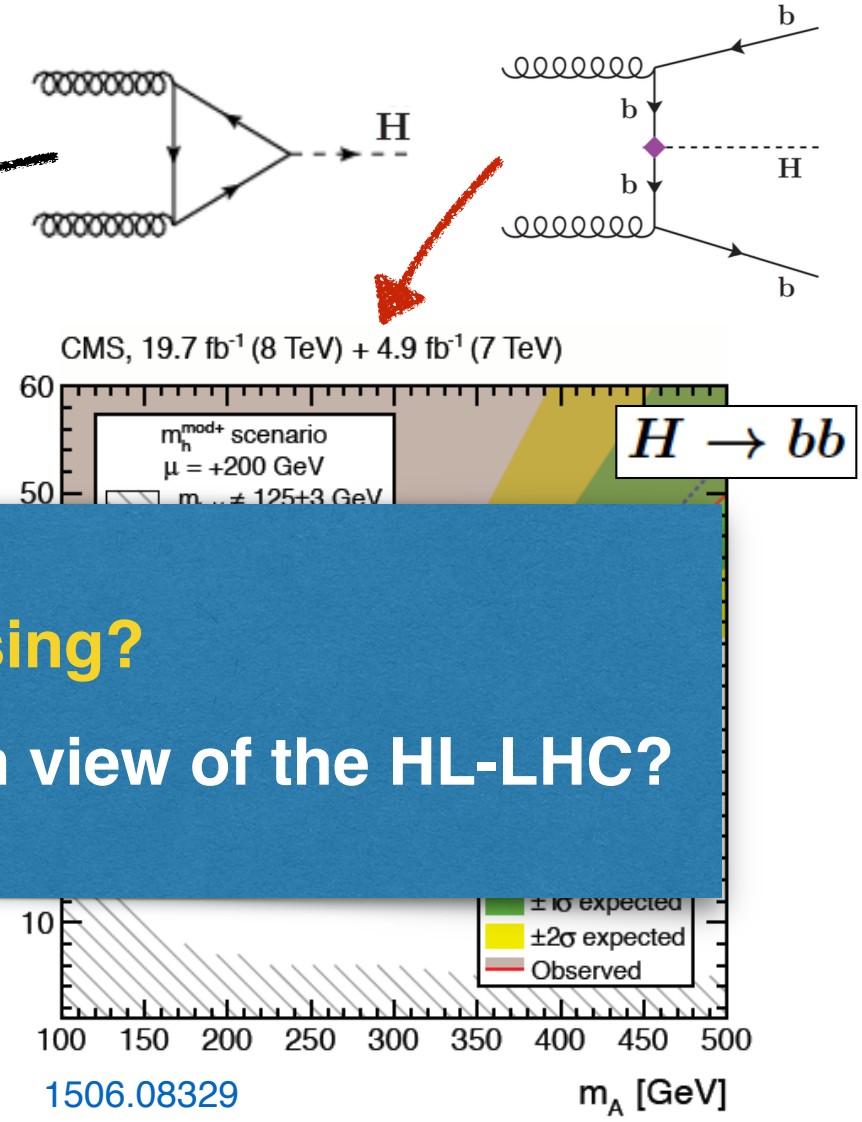


1506.08329

What is missing?

How to broaden the program in view of the HL-LHC?

- Challenge arising from the interference with the SM background
- Single lepton trigger

Specialized triggers that identify b jets already at the online level.

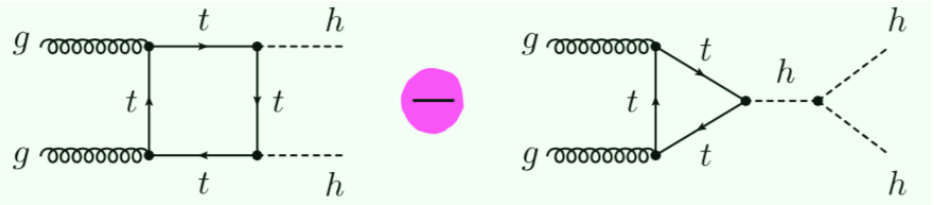
(1) “Higgs to Higgs” decays

Measurement of the h^3 term in the Higgs potential is crucial

What is the nature of the phase transition from zero to nonzero VEV?

The measurement is challenging since the di-Higgs cross section is small

→ HL-LHC will be super important!



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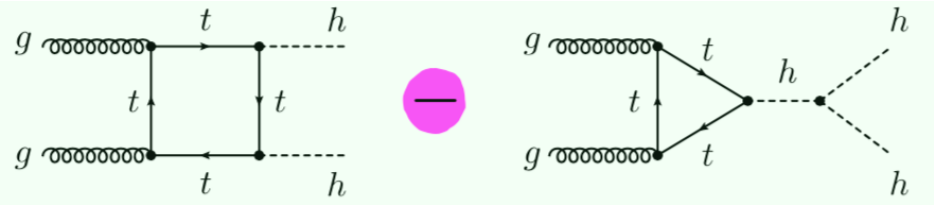

HH final state	ATLAS Significance Coupling limit (95 % C.L.)	CMS Significance
HH → bbγγ	1.05 σ $-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$	1.43 σ
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HH →bbbb	$-3.5 < \lambda_{HHH}/\lambda_{SM} < 11.0$	0.39 σ
HH →bbVV		0.45 σ
ttHH, HH-> bbbb	0.35 σ	

How to optimize the searches?
Optimized trigger strategies?
What about VBF hh production?

even sub-leading processes have a reasonable statistics

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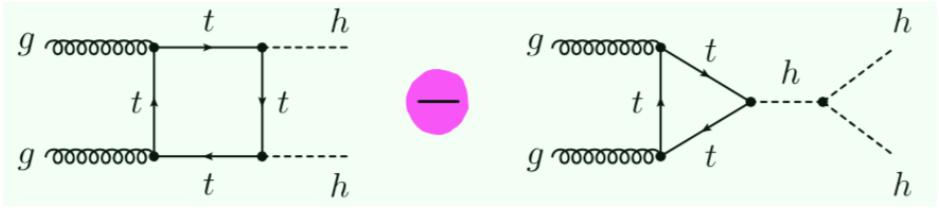

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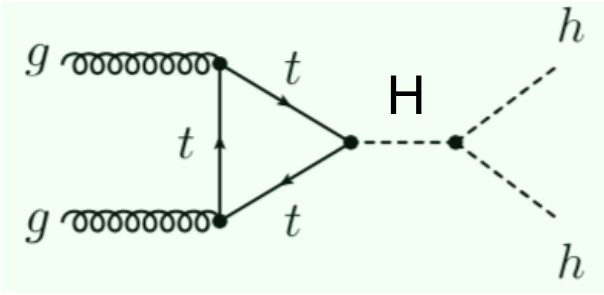
- The presence of a heavy Higgs can enhance the cross section (H → hh)



Discovery channel for a heavy Higgs?

(2) Exotic heavy Higgs decays

More discovery opportunities?

No sign (yet) of colored New Physics/SUSY at the LHC
A plausible scenario is that only electroweak (EW) particles are in kinematic reach

Heavy Higgs bosons are often a portal to electroweakinos
Reasonable cross sections and distinctive kinematics. Target for the HL-LHC!

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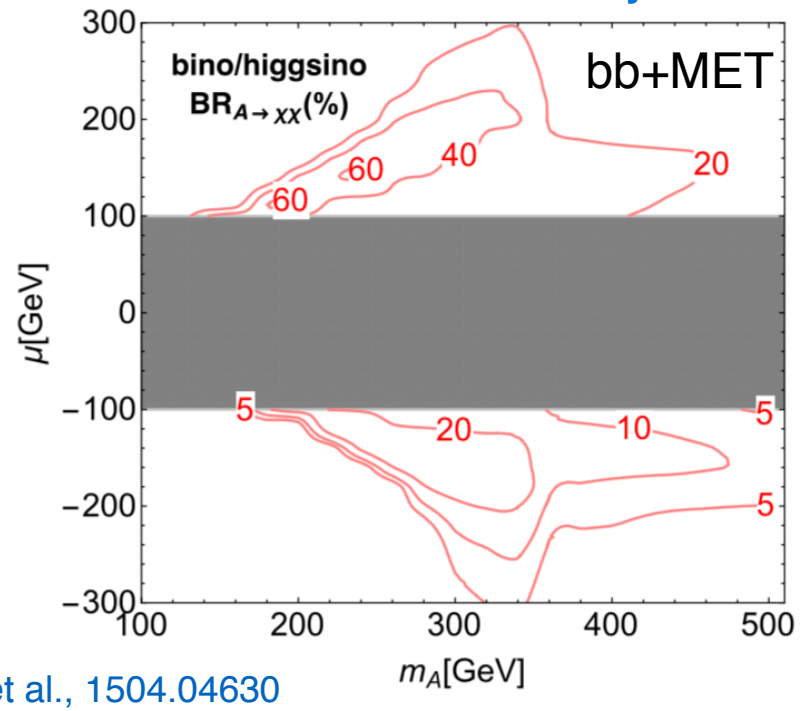
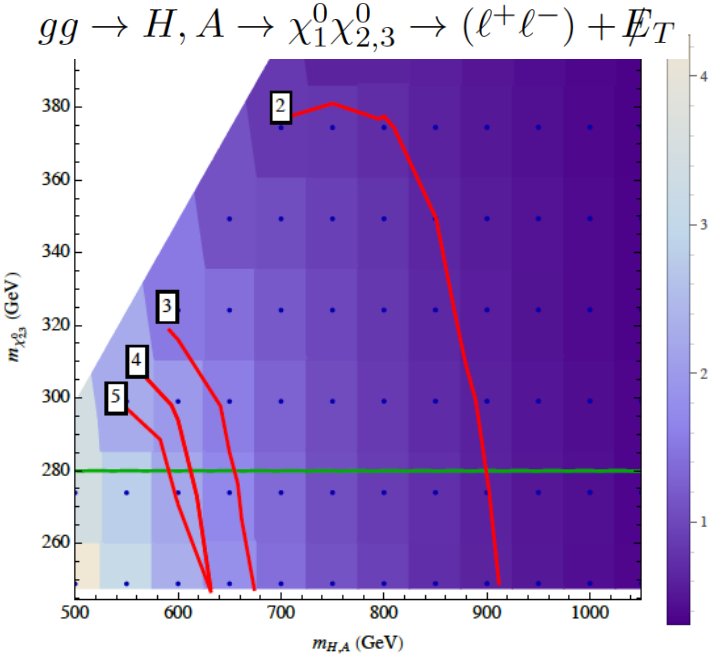
invisible decay



Craig et al., 1504.04630

"semi-visible" decay



SG, Liu, Shakya, in preparation

Complementarity with direct searches of EW particles

(3) New flavor structures

We do not know if the 125 GeV Higgs is coupled/gives mass to all flavors

Many flavor structures are allowed

Flavor constraints → 2HDMs of type I-IV

Not the full story!

Additional mechanisms to suppressed FCNCs

eg. Minimal flavor violation, flavor locking, …

D'Ambrosio et al., 0207036 Knapen, Robinson, 1507.00009

Models beyond type I-IV 2HDMs predict a distinctive pheno of the heavy Higgses, that we are missing if we only focus on type I-IV

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Example

$$\mathcal{L} = \bar{f} Y f H + \bar{f} Y' f H' \rightarrow \mathcal{M} = vY + v'Y' \quad (\mathcal{M}_0 + \Delta\mathcal{M})$$

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

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

structure obtained using flavor locking

Altmannshofer, SG, Robinson, Tuckler, 1712.01847

(analogous structure in the quark sector)

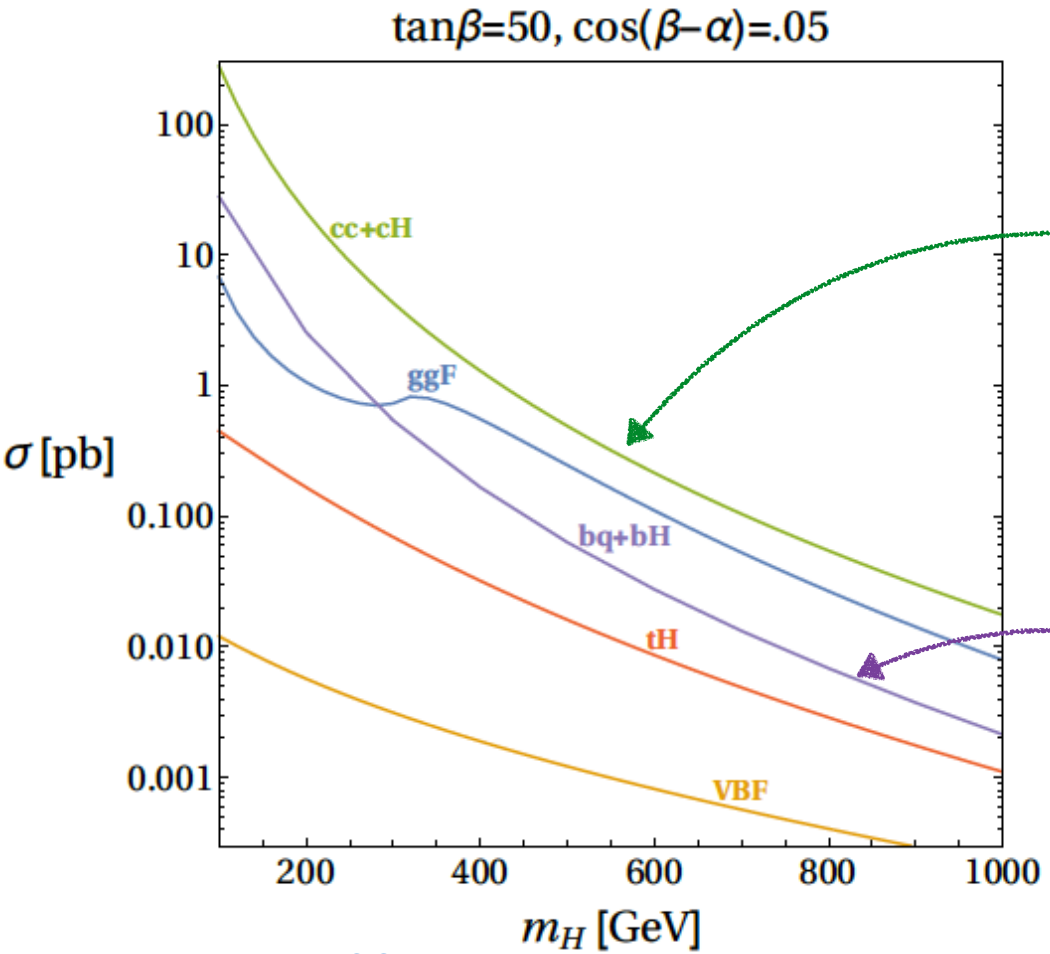
Flavor non universality

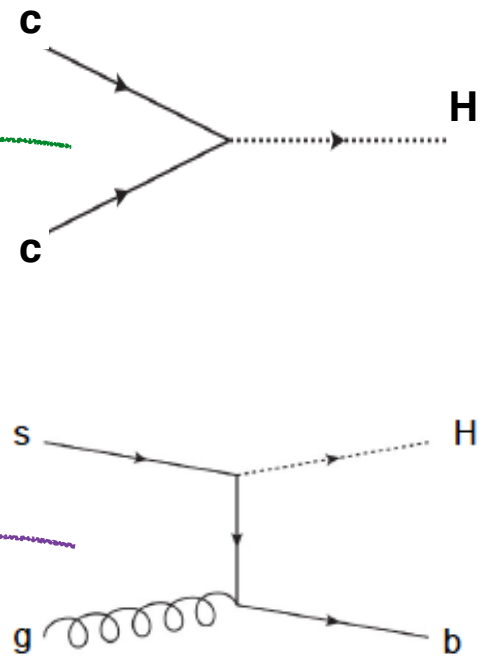
Comparing to the other flavor structures…

	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	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$
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 $O(m_c/m_t)$, $O(m_s/m_b)$, $O(m_\mu/m_\tau)$

Production & decays of the scalar H

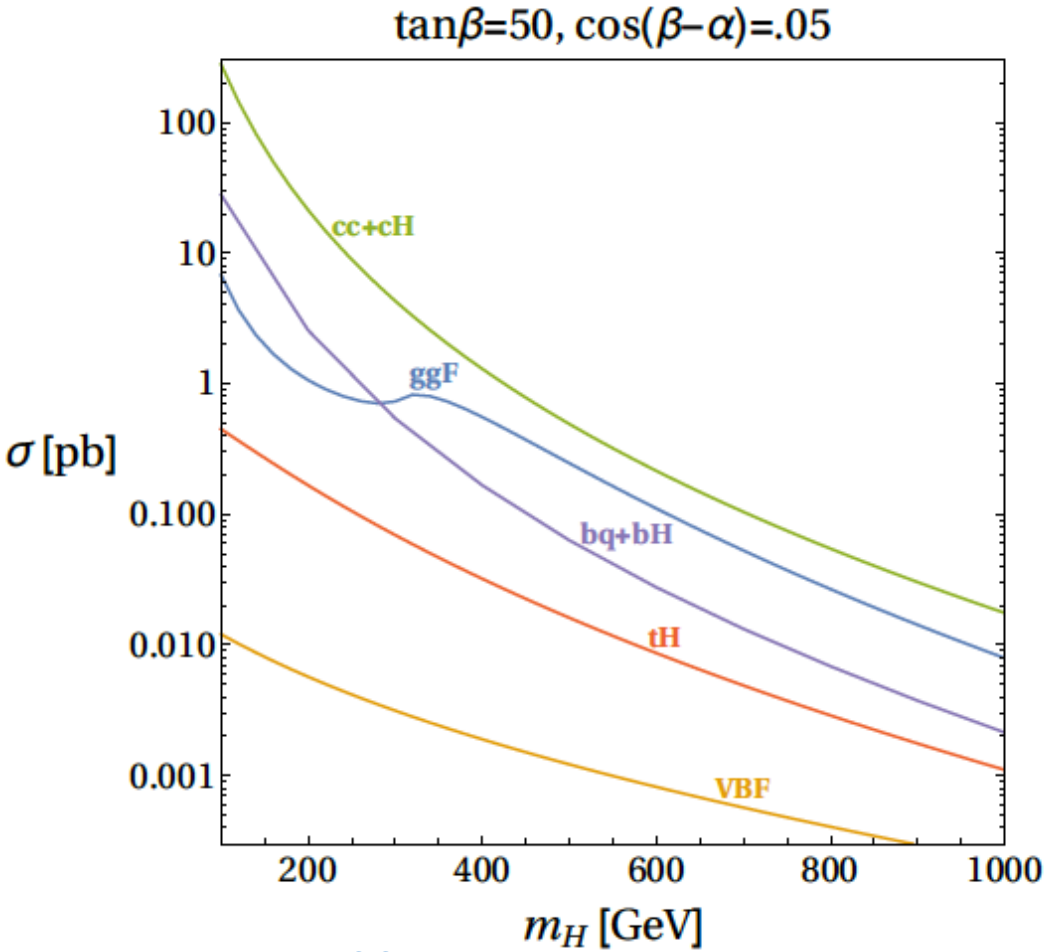




Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

bH typically suppressed, if compared to Type II 2HDMs

Production & decays of the scalar H



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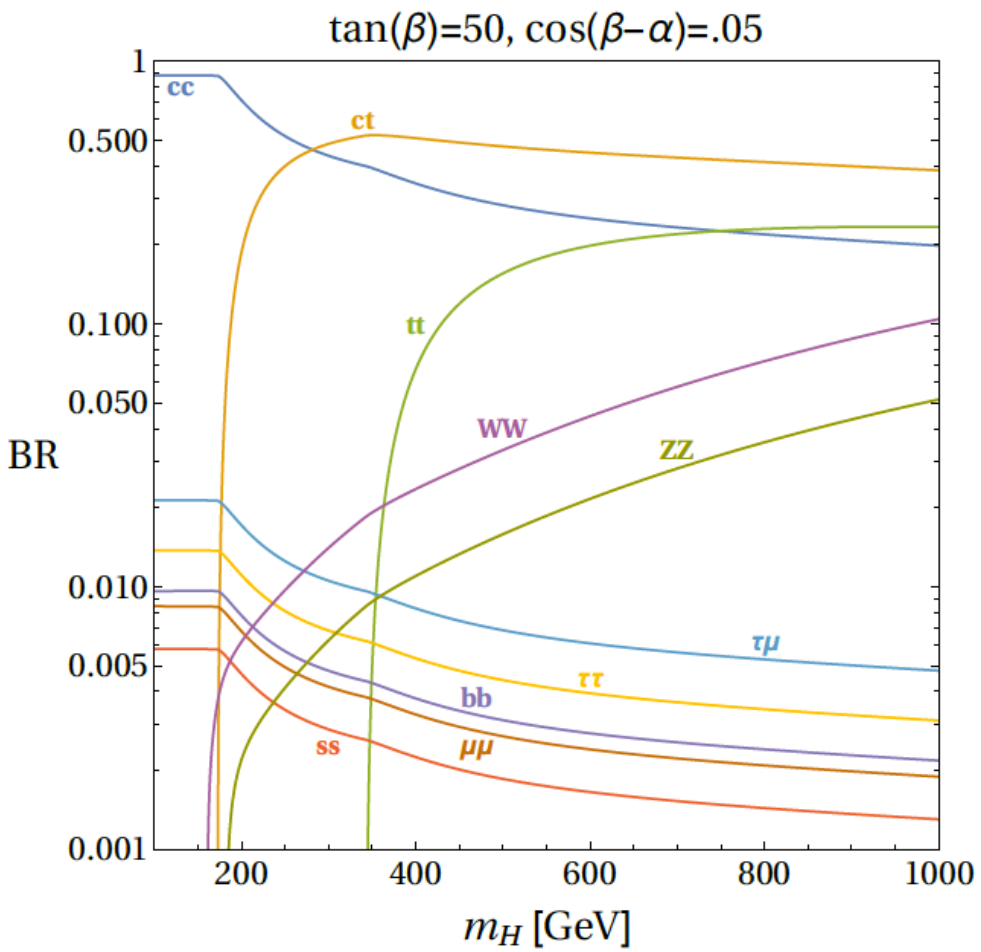
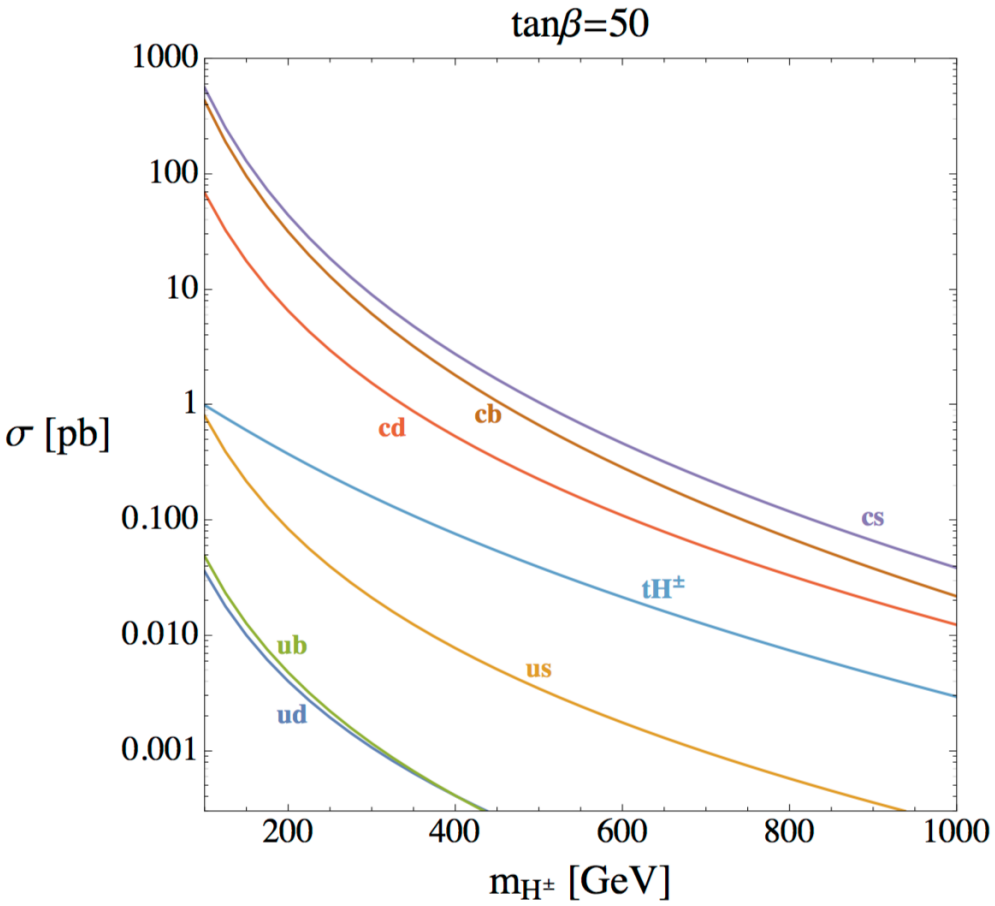
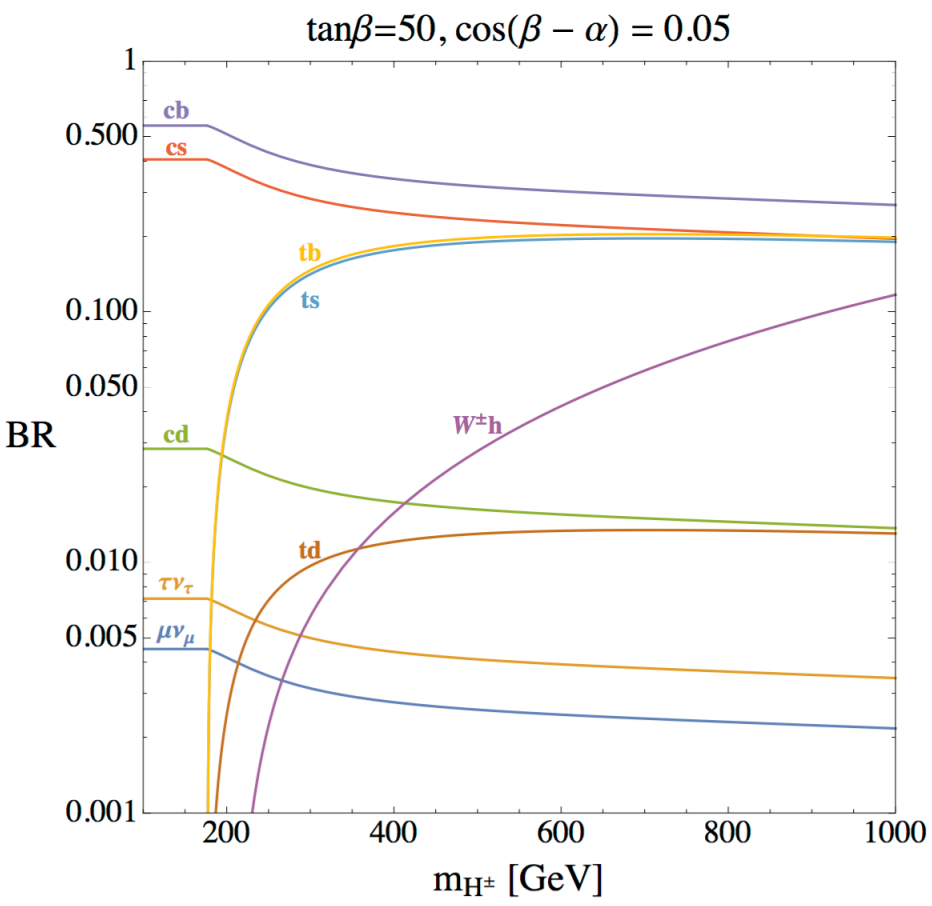


The branching ratio to the "golden" channel, τ τ, is suppressed

Production & decays of the scalar H±

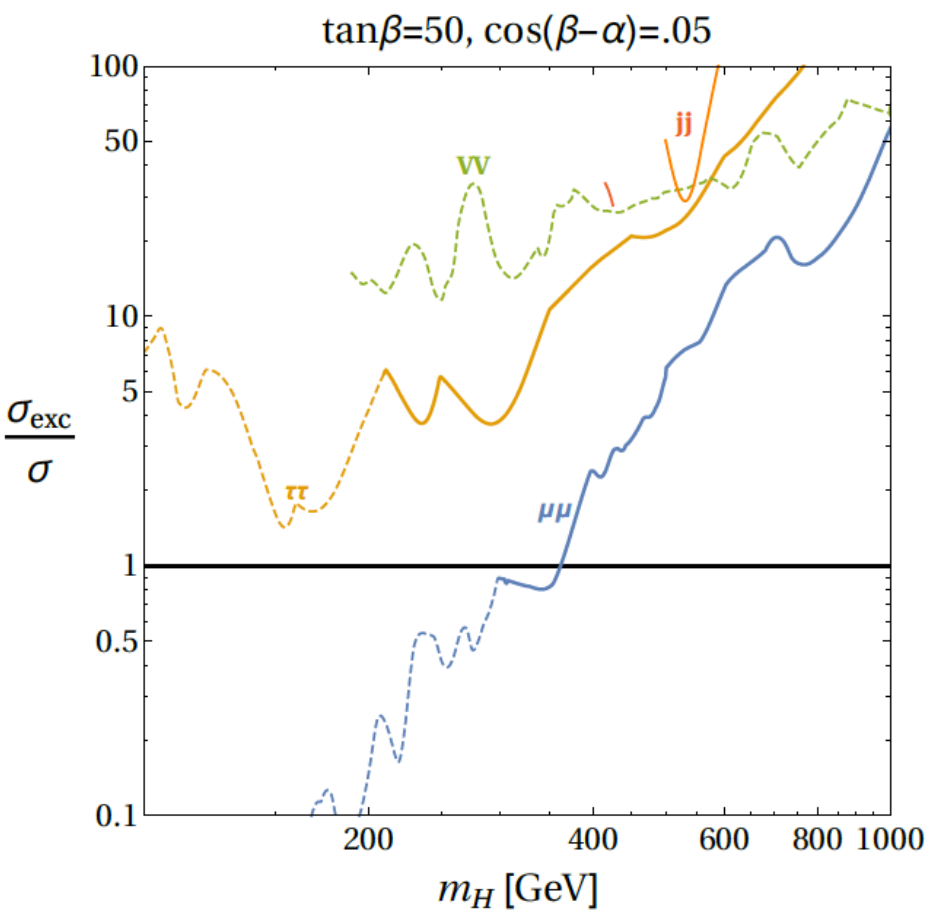




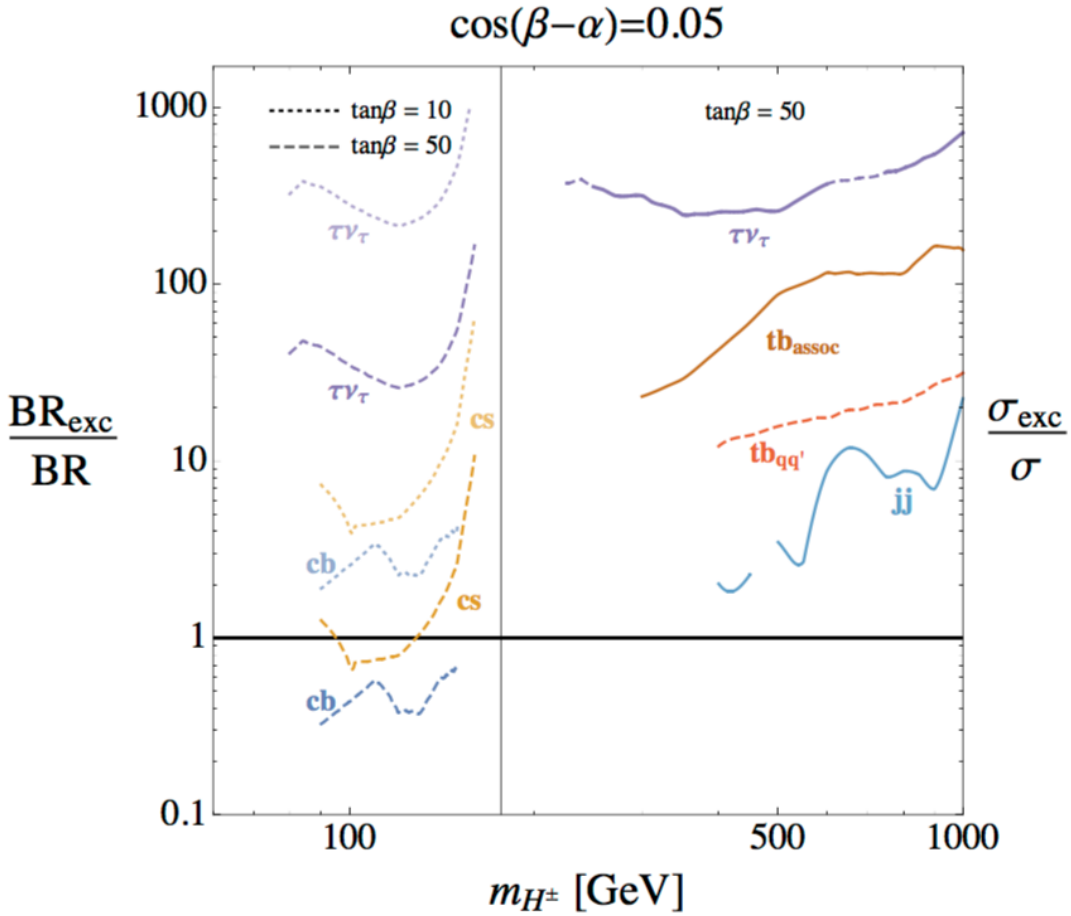
s-channel production (quark-quark fusion) is the dominant one

The branching ratio to the "golden" channels, tb, τν, are suppressed

Very weak constraints



No bound beyond LEP for tanβ ≤ 12!



No bound above the top threshold even at very high values of tanβ

What to look for at the HL-LHC? (H)

Higgs quark-quark fusion production:

Light di-jet resonances! Eventually adding charm tagging $\boxed{pp \to H \to cc}$
Data scouting, trigger-object level analysis

Top-charm resonances $\boxed{pp \to H \to tc}$
boosted regime or leptonic top to trigger on the events.
Data driven rejection of the tt background?

What to look for at the HL-LHC? (H)

Higgs quark-quark fusion production:

Light di-jet resonances! Eventually adding charm tagging $pp \to H \to cc$
Data scouting, trigger-object level analysis

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boosted regime or leptonic top to trigger on the events.
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Higgs-top (charm) associated production:

Top-charm or top-top resonances (3 or 4 tops final states)

<u>hadronic:</u> $pp \to t(c)H,\ H \to tc$
tt + (heavy) jet backgrounds with large theory uncertainties.
At the HL-LHC, search strategies exploiting large-statistics subsidiary data samples for the purpose of constraining background uncertainties.
Kinematic reconstruction of the heavy Higgs boson mass?

<u>fully leptonic:</u>
same-charge dilepton plus bottom and charm jets

Tau-mu resonances $pp \to t(c)H,\ H \to \tau\mu$

Light di-jet resonances $pp \to t(c)H,\ H \to cc$

What to look for at the HL-LHC? ($H^{\pm}$)

Targeting quark-quark fusion production!

charm-bottom resonances (also above the top threshold).
Data scouting with bottom (charm)-tagging?
charm-strange resonances (also above the top threshold).

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

Present searches focus on

$$pp \to t\bar{t} \to (Wb)(H^{\pm}b),\ H^{\pm} \to cs$$

used for triggering
(mono-lepton trigger)

For s-channel production, any other opportunity beyond data scouting?

Wh resonances (not necessarily in the boosted regime!)

$$pp \to H^{\pm} \to Wh$$

What to look for at the HL-LHC? (H±)

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Wh resonances (not necessarily in the boosted regime!)

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Charged Higgs-top associated production

charm-bottom and charm-strange resonances

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

Less challenging thanks to the additional top (that can be used for triggering)

Conclusions & Outlook

The Higgs sector as we know it looks provisional and it is the source of many problems in the SM

Need for a broad program for searches of additional Higgs bosons to test the richness of theoretical ideas

Many models even with new Higgs bosons with a mass as low as 150 GeV are hidden!

New trigger (and analysis) strategies are needed
(di-jet searches, associated production, Wh resonances, …)