Searches for an extended Higgs sector at the LHC (theory)

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University of Cincinnati

Higgs tasting workshop, 2016
Benasque, May 20th 2016

Questions for the talk

We have discovered **the** Higgs boson

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

Additional Higgs bosons?(*)

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

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a (s)

H, A, $H^{\pm}$

? —— 125 GeV —— ? ? ? —— Mass (GeV)

Representations of the SM group we focus on:

Singlet states

Doublet states

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SU(2) doublet states

A SM-like 125 GeV Higgs boson

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

$$V \supset \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \cdots + Z_6 (H_1^\dagger H_1) H_1^\dagger H_2 + h.c. + \cdots$$

The two Higgs doublets will generically mix:

$$\cos^2(\beta - \alpha) = \frac{Z_6^2 v^4}{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}$$

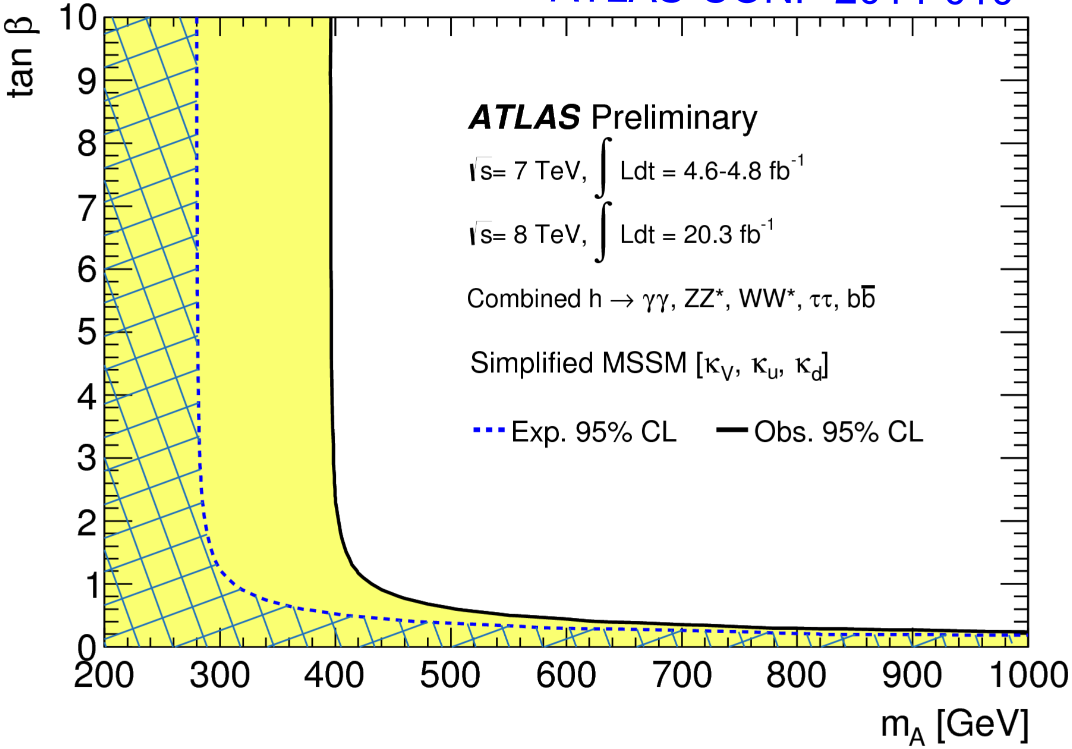
$$\Rightarrow \frac{g^2}{2} v \left[\frac{Z^2}{2\cos^2\theta} + W^2 \right] \xi_V^h h, \quad \xi_V^h = \sin(\beta - \alpha)$$

Mixing the two Higgs doublets induces a NP effect in the 125 GeV Higgs couplings

If H is heavy ⇒ Higgs with SM properties (decoupling)
If Z_6 is small ⇒ Higgs with SM properties ("alignment")

Still weak bounds

ATLAS-CONF-2014-010



Even if we do not have alignment,
we do not need much decoupling

If we have some alignment,
bounds are even weaker

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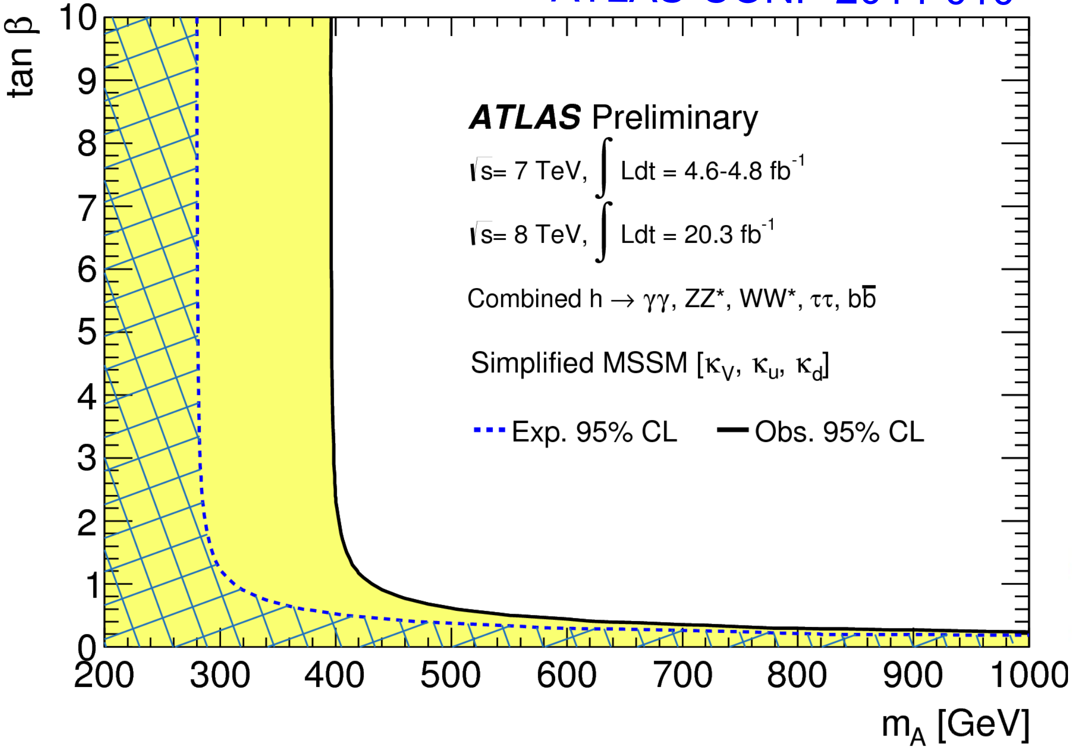

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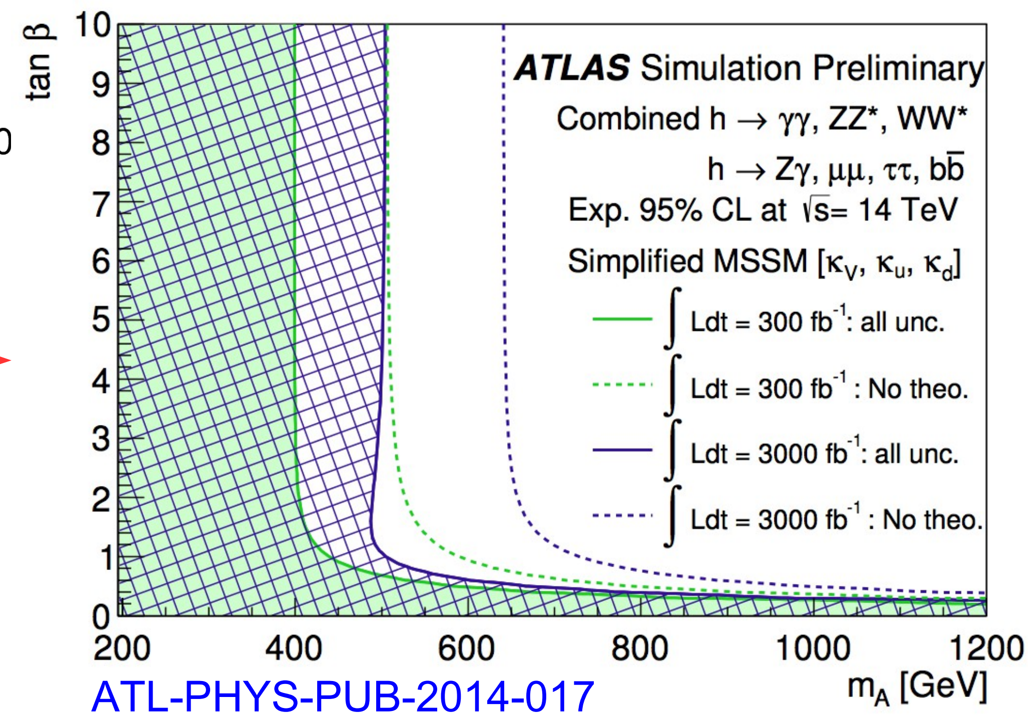
Future



ATL-PHYS-PUB-2014-017

If we focus on the alignment limit...

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

Warning: these are not the only Interesting modes!

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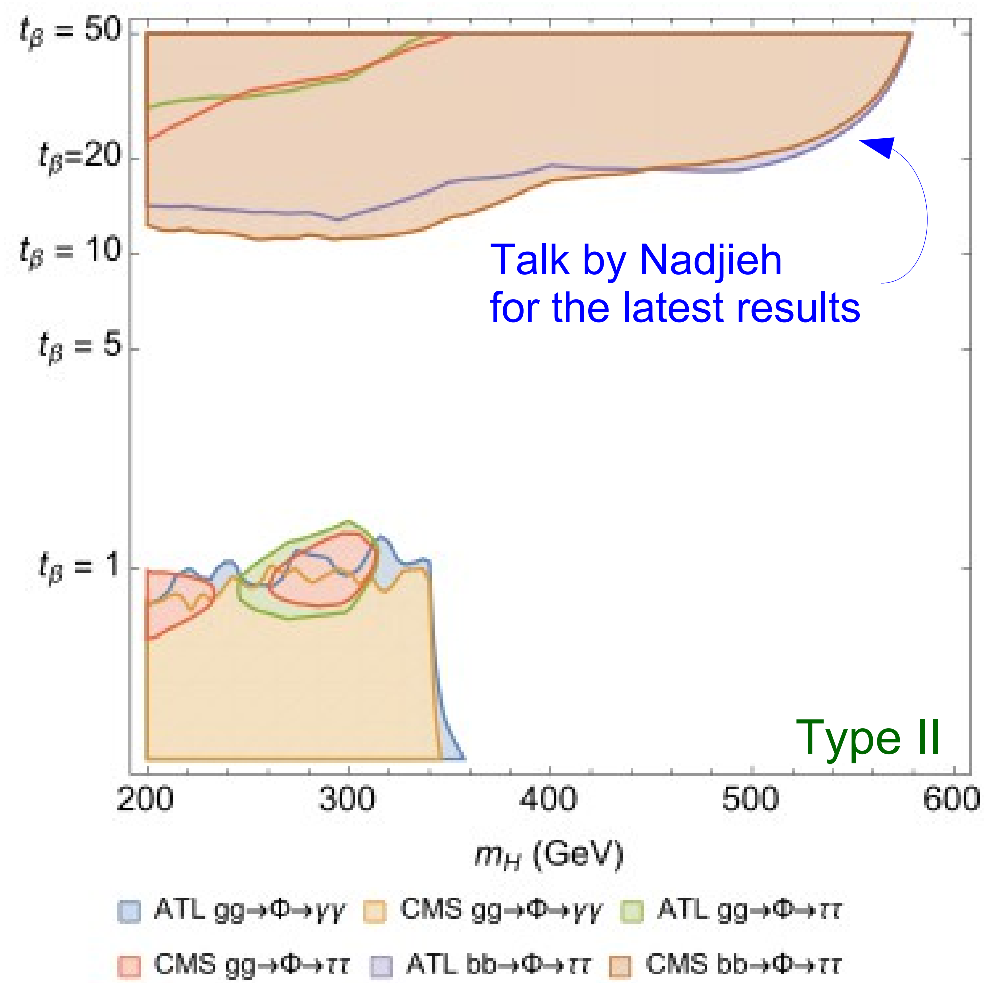
At large tanβ the heavy Higgs couplings to

- bottoms, muons and taus are enhanced
- tops are suppressed

The interpretation of the experimental searches depend on the particular type of 2HDM (e.g. Type I, II, X, Y, ...)



Craig et al. 1504.04630

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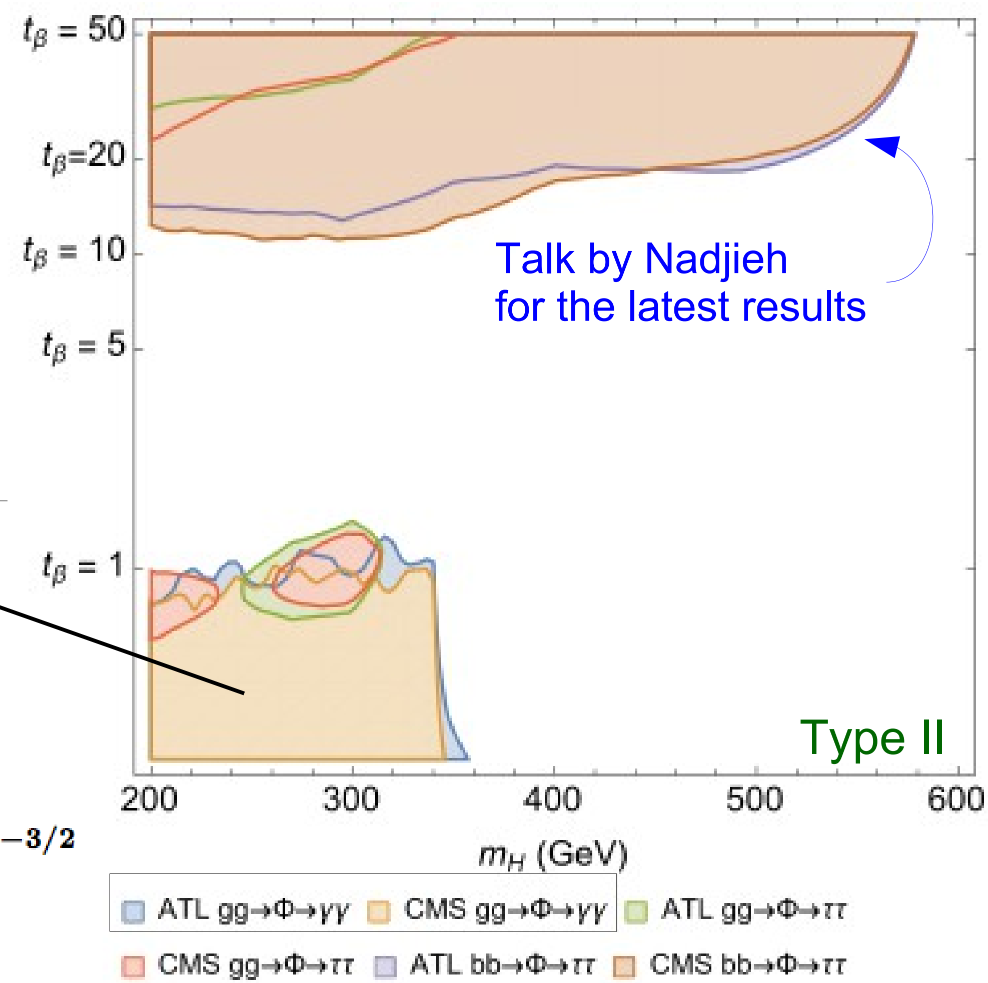

Craig et al. 1504.04630

Di-photon?

Rather weak bound from H → γγ

The bound switches off at ~2m_t since

$$\mathrm{BR}(H\to\gamma\gamma) \simeq \frac{32\alpha^2}{243\pi^2}\frac{m_A^2}{4m_t^2}|A_f|^2\left(1-\frac{4m_t^2}{m_H^2}\right)^{-3/2} \simeq 10^{-5}$$

 S.Gori

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	Wh			–
	$tb, \tau\nu$			✓
	CS			

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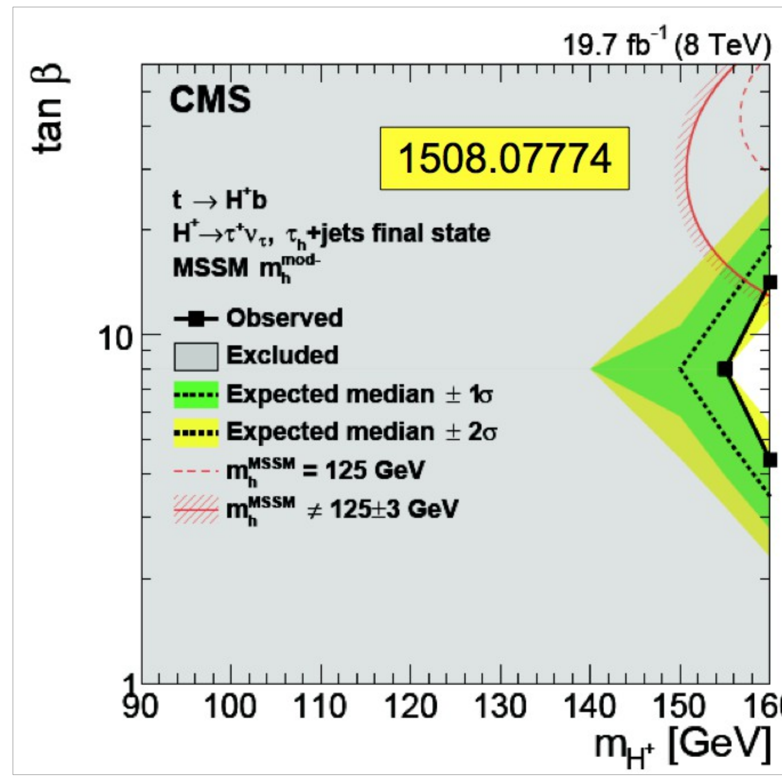
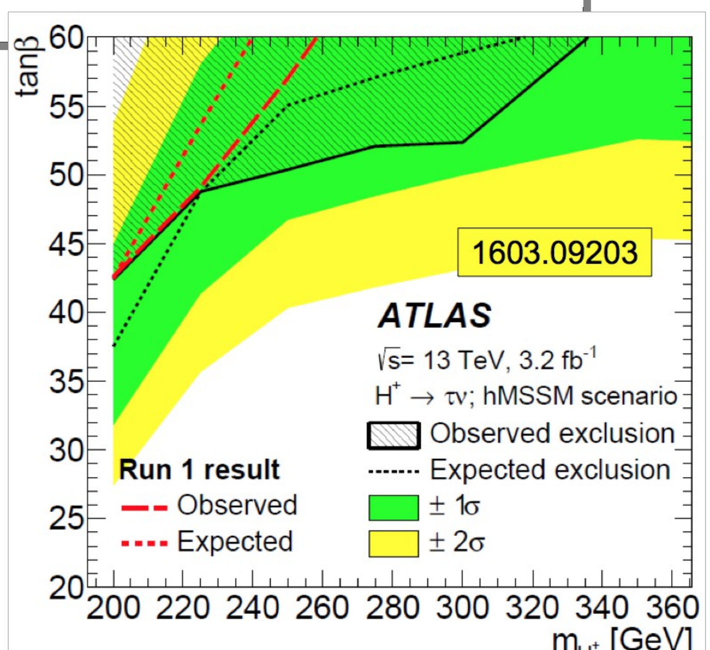
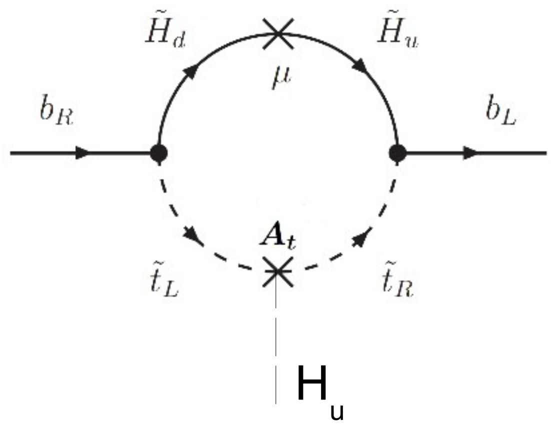




Interpretation of the experimental results

Carena et al., 1302.7033

Typically the bounds in the M_A- tanβ plane are determined using some specific MSSM scenarios (hMSSM, m_{hmod+}, m_{hmod-}, τ - phobic, …).



Results depend on the specific scenario since

- Loop corrections to the Hbb (Hττ) coupling
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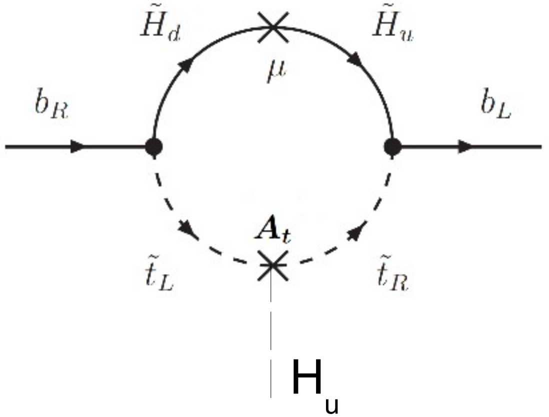

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Bounds dramatically change

if we change the flavor structure of the 2HDM:

$$\mathcal{H}_Y = \bar{Q}_L X_{d1} D_R H_1 + \bar{L}_L X_{\ell 1} e_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{L}_L X_{\ell 2} e_R H_2^c + \bar{Q}_L X_{u2} U_R H_2$$

"wrong Yukawas" (loop suppressed in the MSSM)

Generically,

- we can have flavor changing heavy Higgs decays, weakening the previous bounds. eg. H → tc
- the diagonal heavy Higgs couplings can be very different than in a Type II 2HDM

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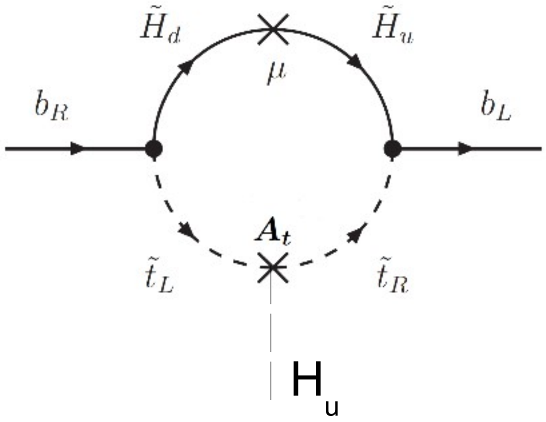

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New interesting models:
- Flavor aligned models
- Models with only third generation masses coming from the 125GeV Higgs boson

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927
See also Ghosh et al., 1508.01501

A flavor aligned 2HDM

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Pich, Tuzon, 0908.1554

$$\begin{aligned} X_{u1} &= \epsilon_t Y_u \\ X_{u2} &= Y_u \\ X_{d2} &= \epsilon_b Y_d \\ X_{d1} &= Y_d \\ X_{\ell 2} &= \epsilon_\ell Y_\ell \\ X_{\ell 1} &= Y_\ell \end{aligned}$$

Special case of
a Minimal Flavor Violating
2HDM

	Type II	Aligned
Up	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$
Down	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha+\epsilon_b\sin\alpha}{\cos\beta+\epsilon_b\sin\beta}$
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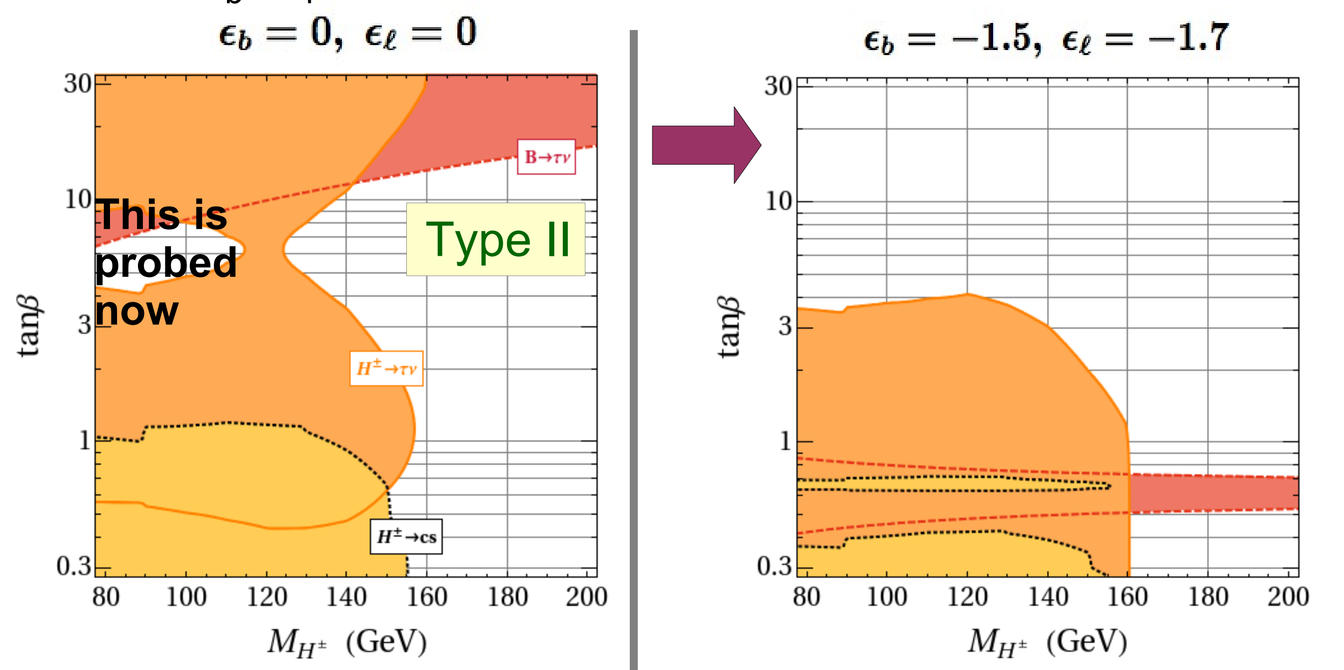
Depending on the values of ϵ_b, ϵ_τ bounds can be much weaker/stronger

Example for
the charged
H constraints:



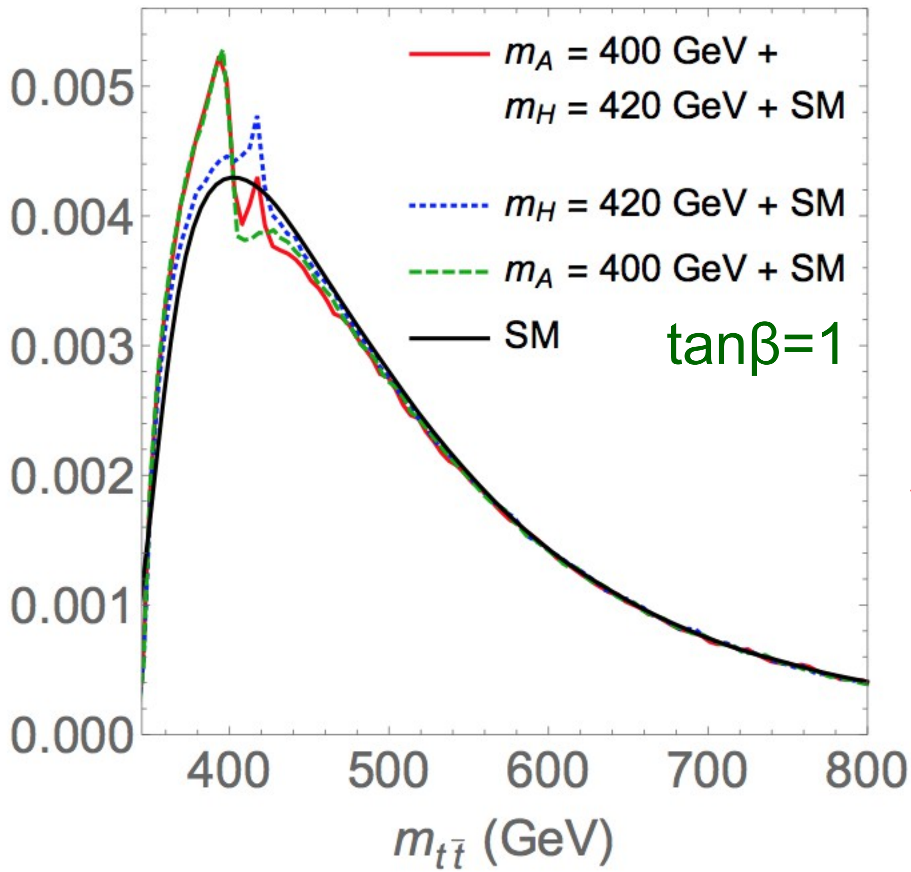
Altmannshofer, SG, Kribs,
1210.2465

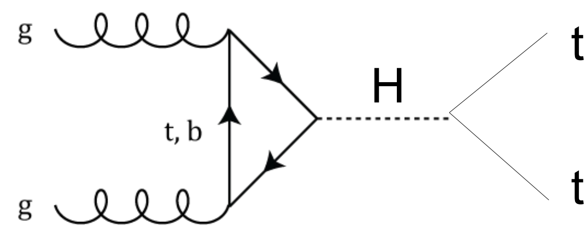
The wedge region (1)

The (heavy) Higgs mainly decays into tops at low/intermediate values of tanβ

1. What about t t resonance searches?

Parton level analysis





Gluon-initiated → Interference with the t t SM continuum

Different from a Z' → t t search

Dicus et al., 9404359

Shape analysis?
Angular correlations?

SG, IW.Kim, N.Shah, K.Zurek, 1602.02782

See also Craig et al., 1504.04630

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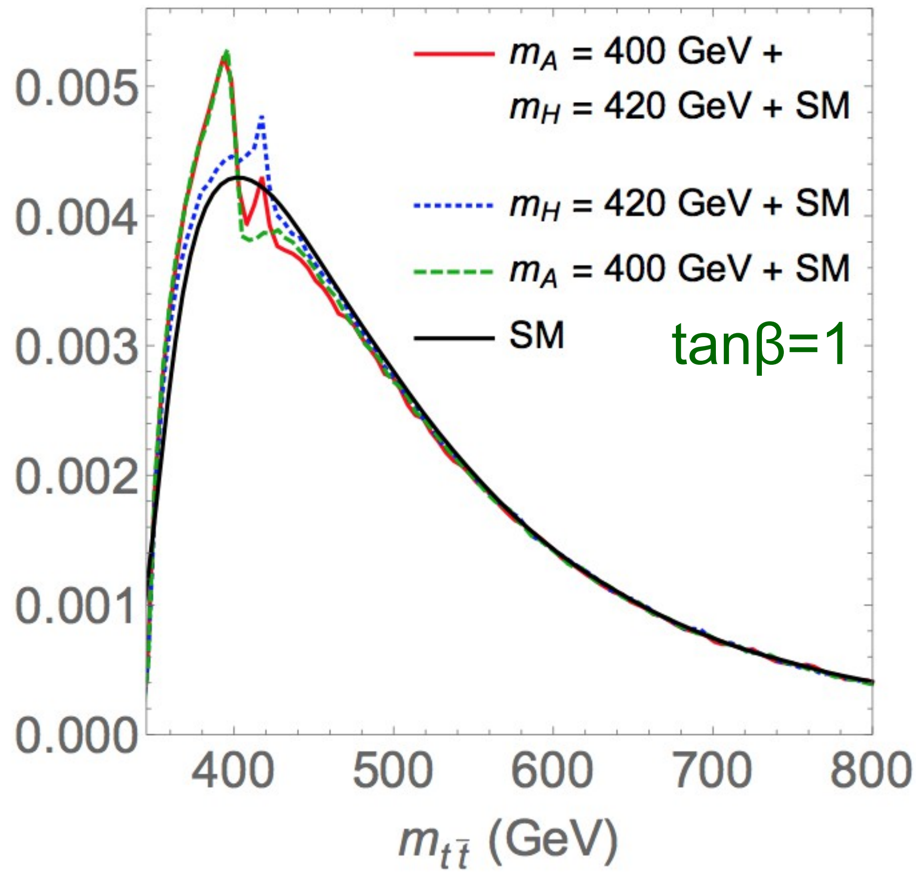

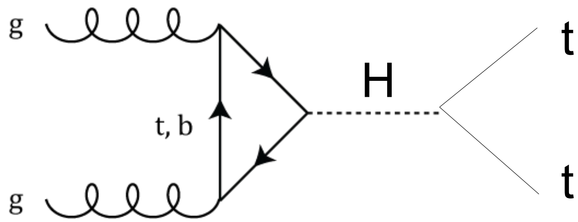

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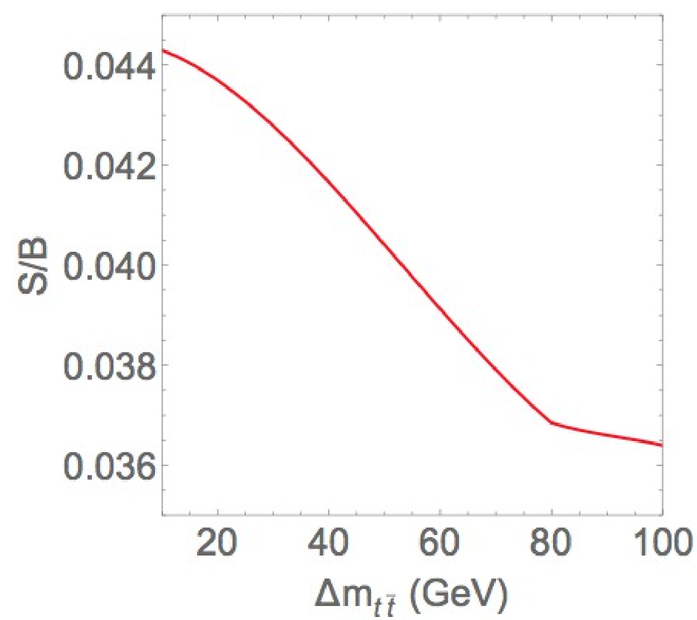
After detector effects:



SG, IW.Kim, N.Shah, K.Zurek, 1602.02782

A challenging but very important search

The wedge region (2)

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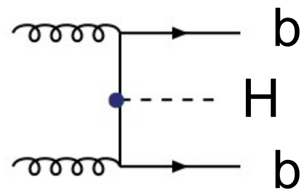
2. b associated production



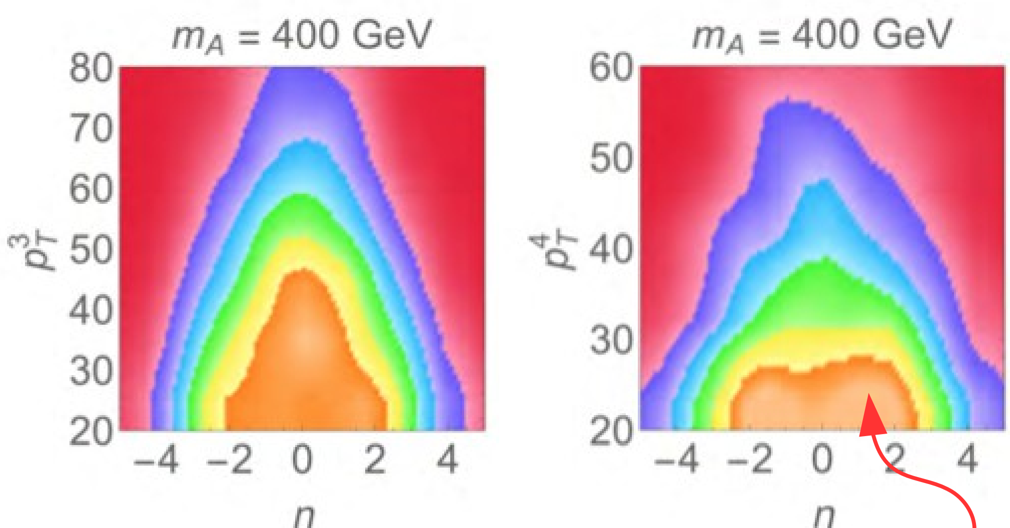
What changes?

- We do not have to worry about the interference
- the additional b quarks can be used to discriminate against the SM t t background

The challenge:

Optimize the use of this b-quarks

($S_{400,6}$ ~ 500 fb; B ~ O(1nb))



It contains ~40% of the events

SG, IW.Kim, N.Shah, K.Zurek, 1602.02782

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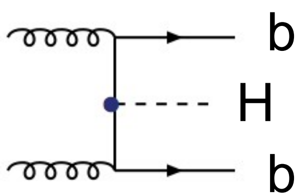

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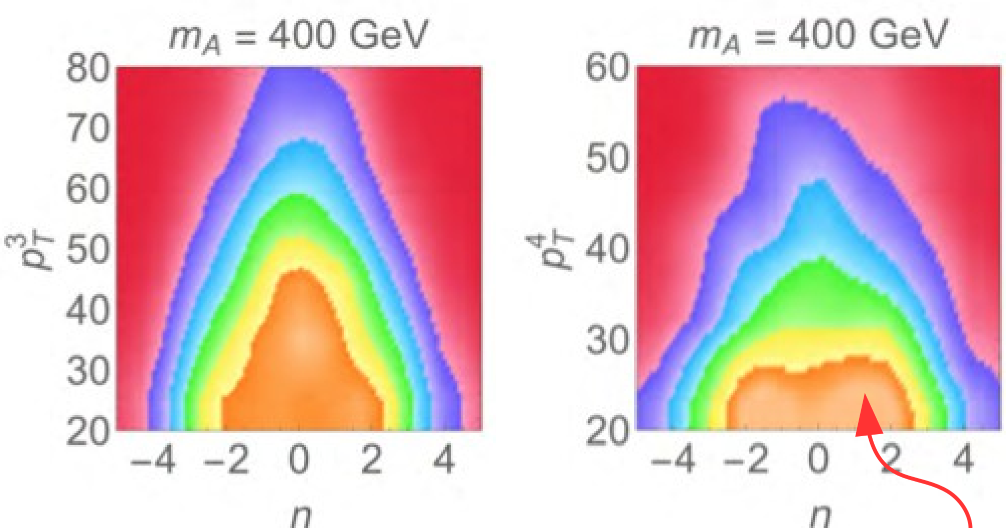

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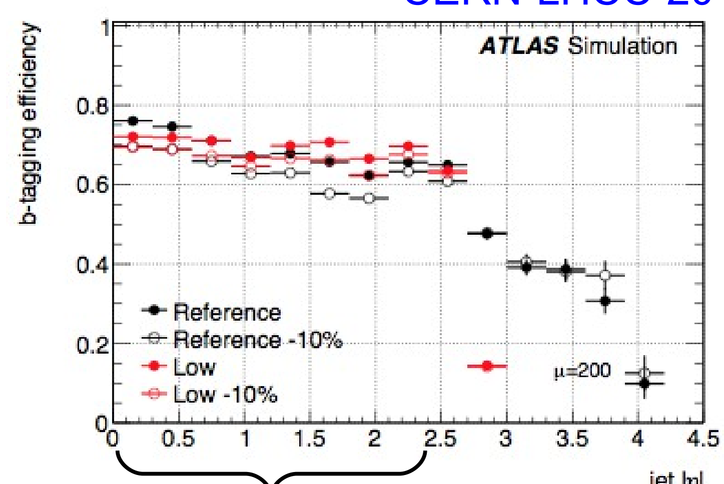
SG, IW.Kim, N.Shah, K.Zurek, 1602.02782

Opportunities:
- MVA or BDT analysis
- more forward b-tagging for the HL-LHC

See for example Hajer et al, 1504.07617

CERN-LHCC-2015-020



So far, b-tagging up to |η|

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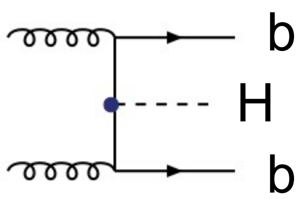

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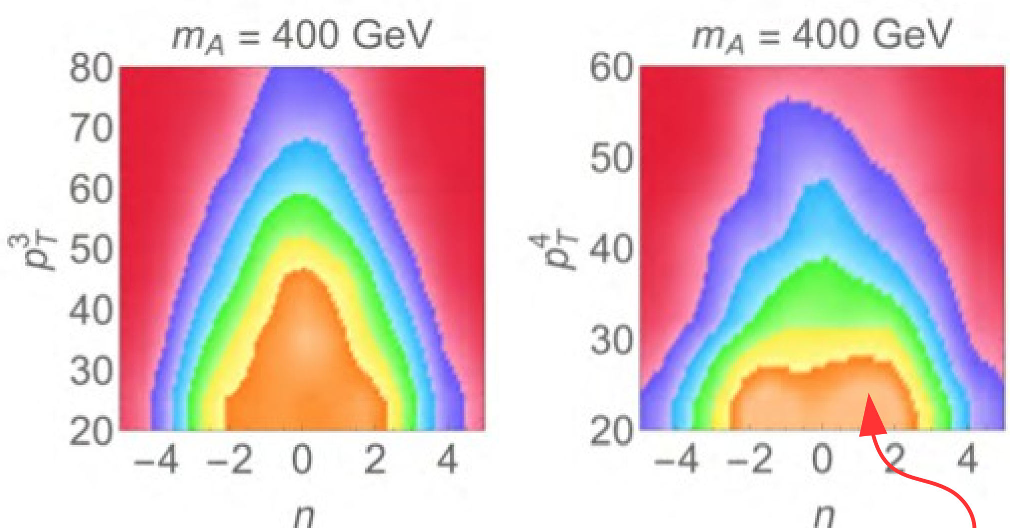

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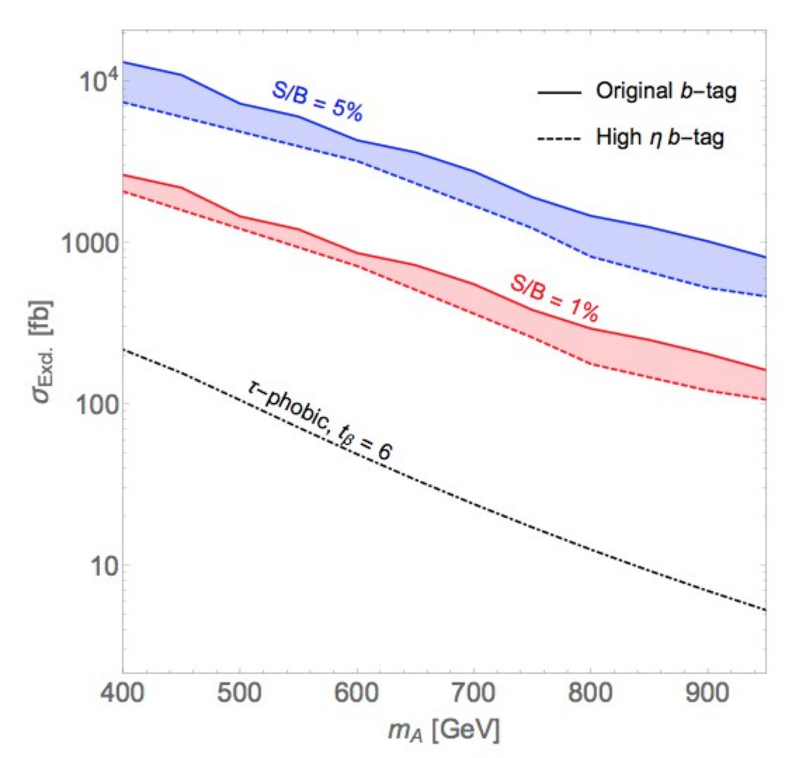

SG, IW.Kim, N.Shah, K.Zurek, 1602.02782

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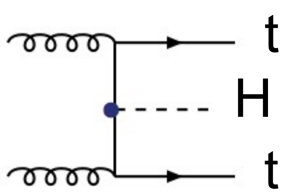
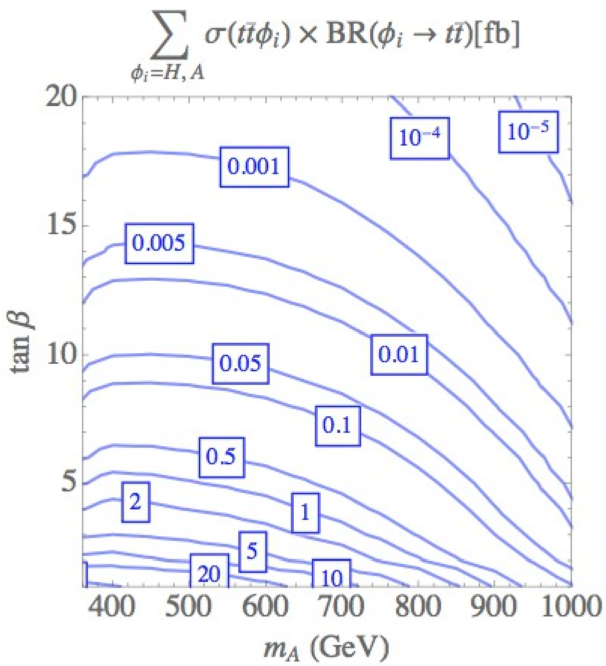


The opportunity:
We have many more objects in the signal, if compared to the t t background

The challenge:
Signal rates are much smaller



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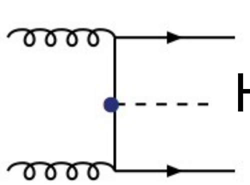

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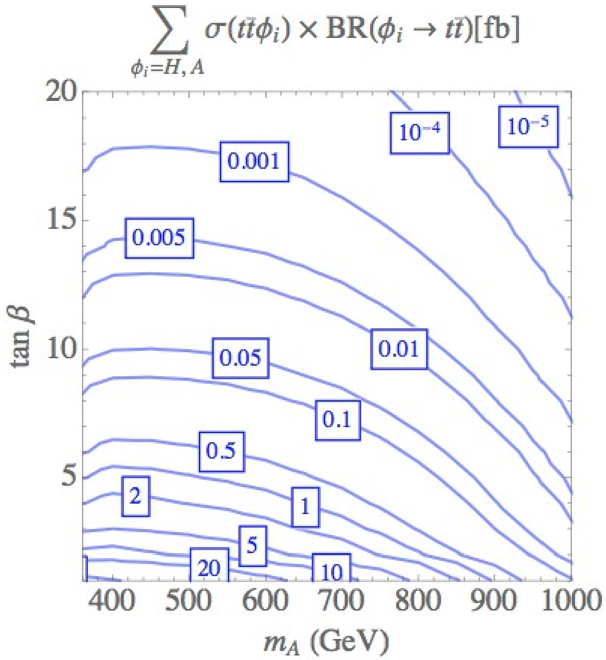

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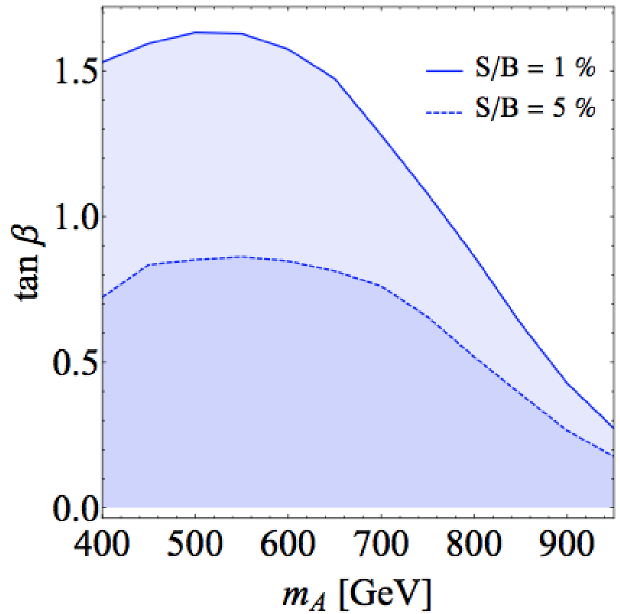

1 lepton, >1b, >5jets

 S.Gori

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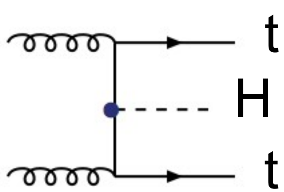

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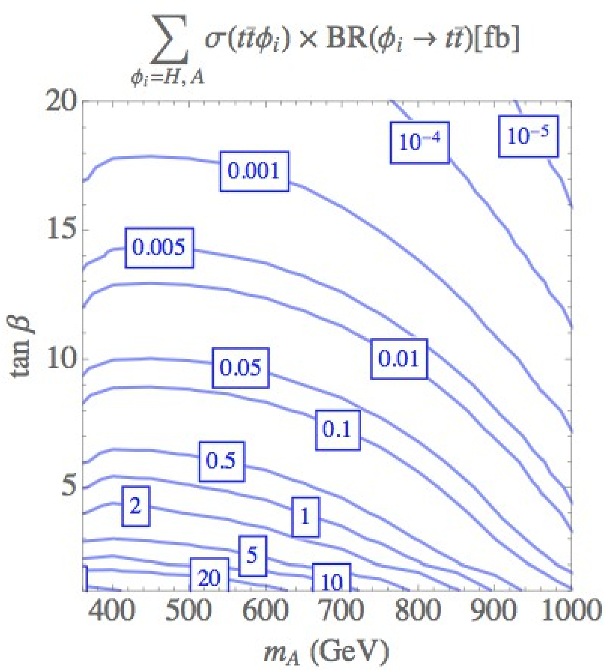

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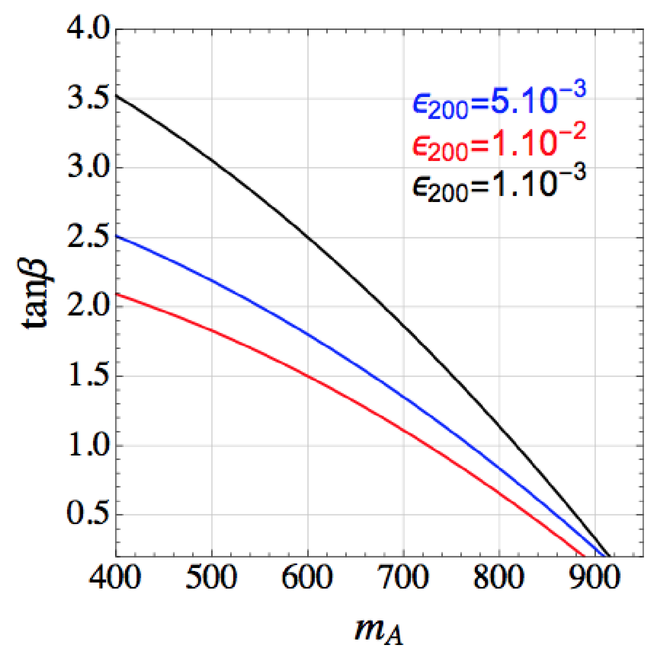

3 leptons, >1b, >2jets

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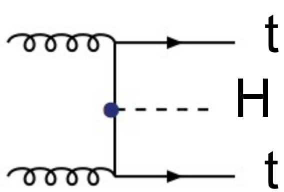

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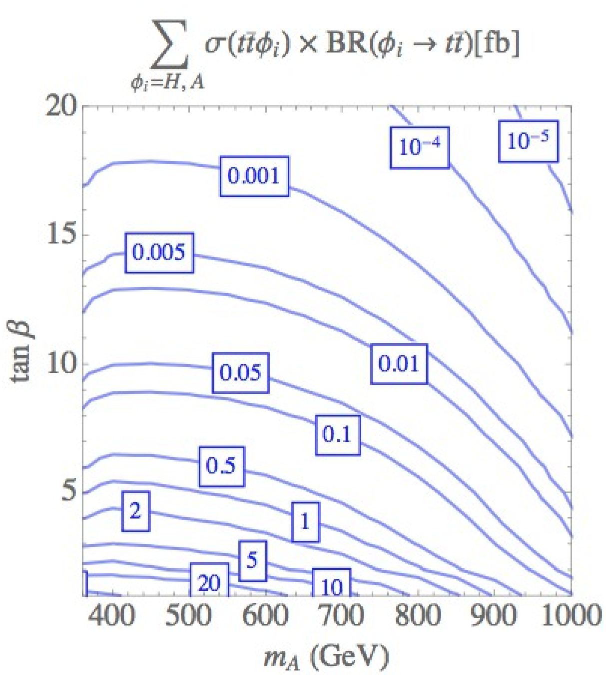

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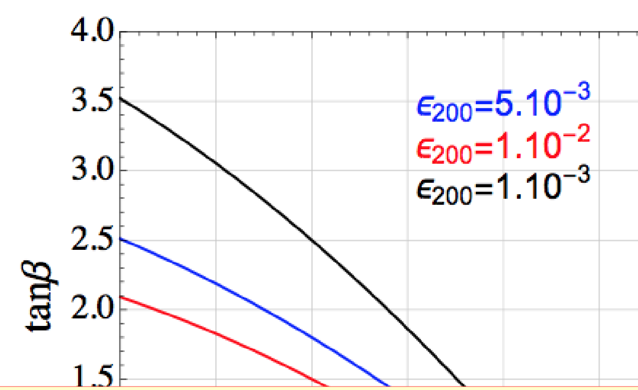


Open questions:

- what about a same sign lepton analysis?
- what about t(q) H associated production?

Scalar singlet states

Theories with light scalars

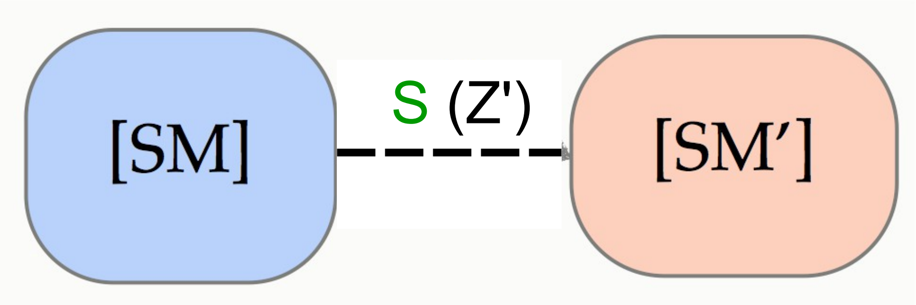
SUSY and beyond:

- 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**:

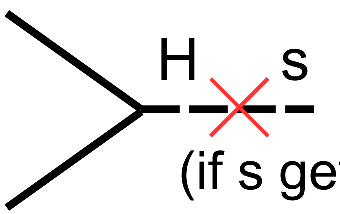
- 2HDM + scalar
- Theories for light Dark Matter with scalar mediator



How to probe these particles?

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

Direct production:



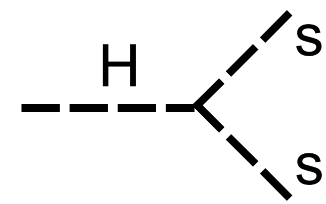
(if s gets a VEV)

(same production mechanisms as for the SM Higgs)

Higgs portal interaction

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

(125 GeV) Higgs decays:

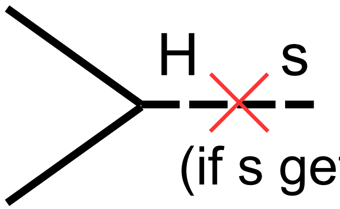


Interplay of LHC searches

How to probe these particles?

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

Direct production:



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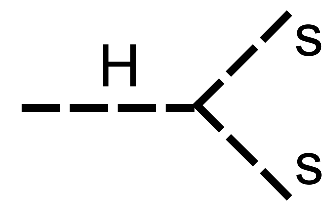
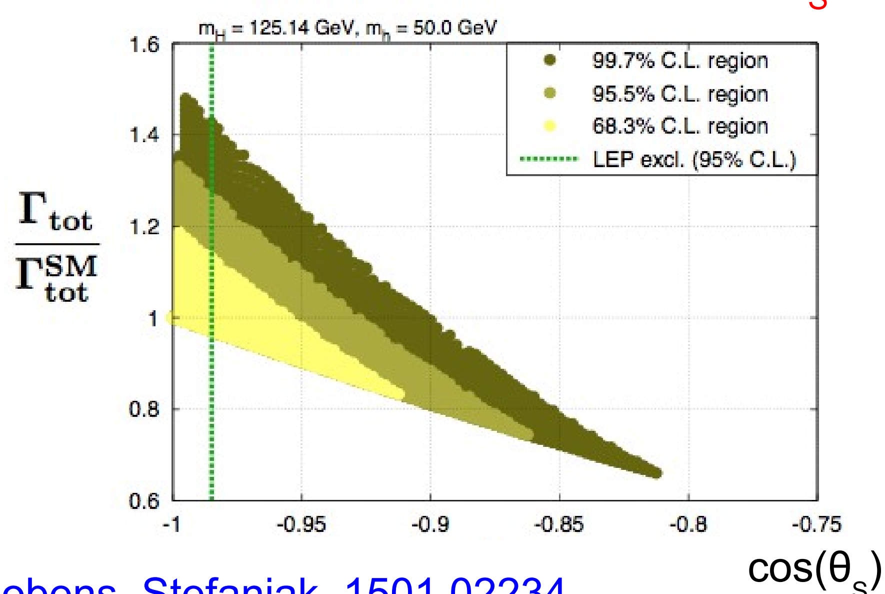
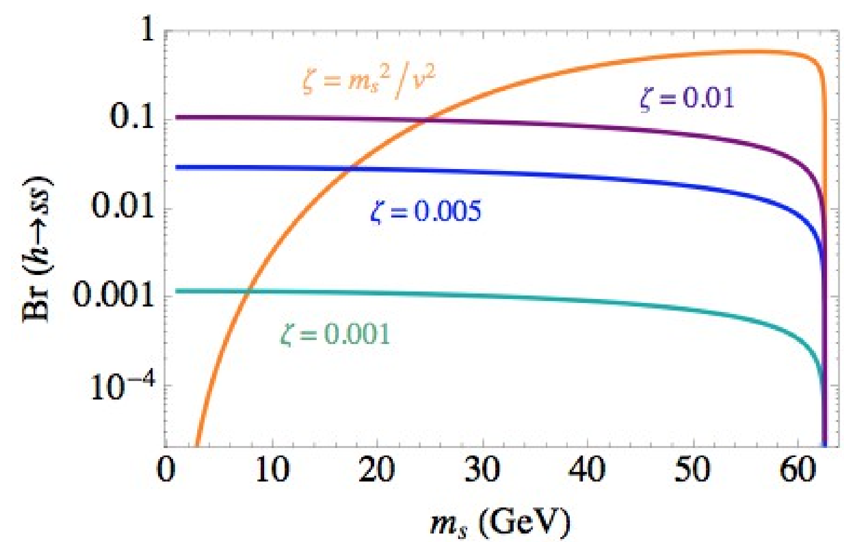


The Higgs couplings to SM particles are reduced by a factor of $\cos(\theta_s)$



Robens, Stefaniak, 1501.02234

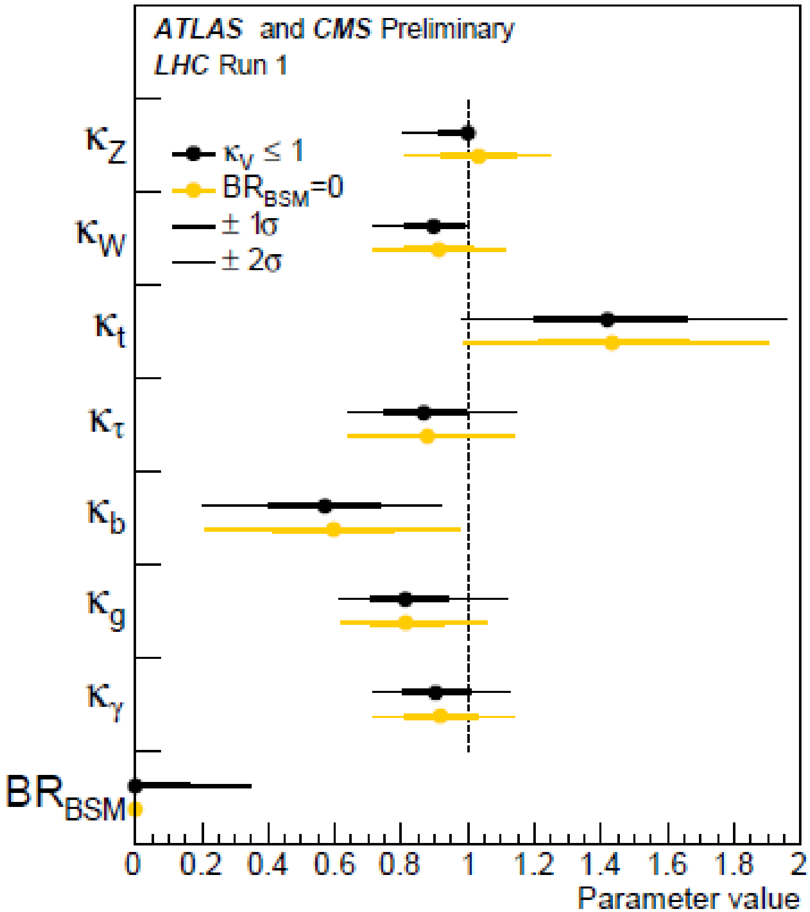
The Higgs has some "exotic" signatures



1312.4992

The exotic width of the 125 GeV Higgs

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



$BR_{BSM} < 34\%$

Prospects for the HL-LHC: ~10%

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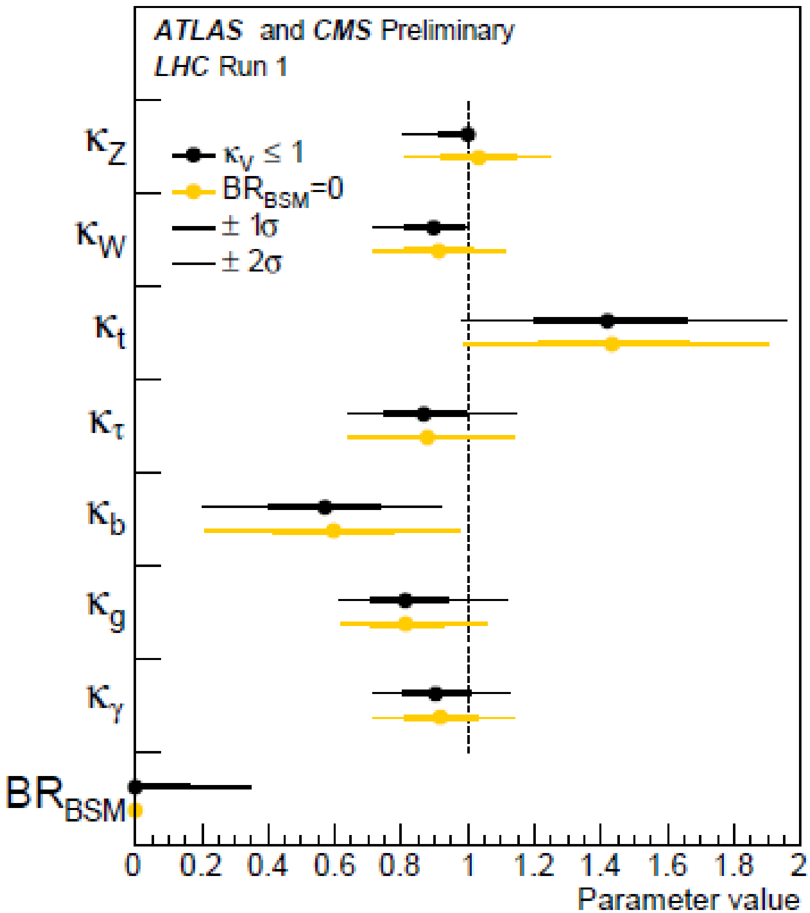
ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002



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New Higgs signatures: $h \to ss \to ?$

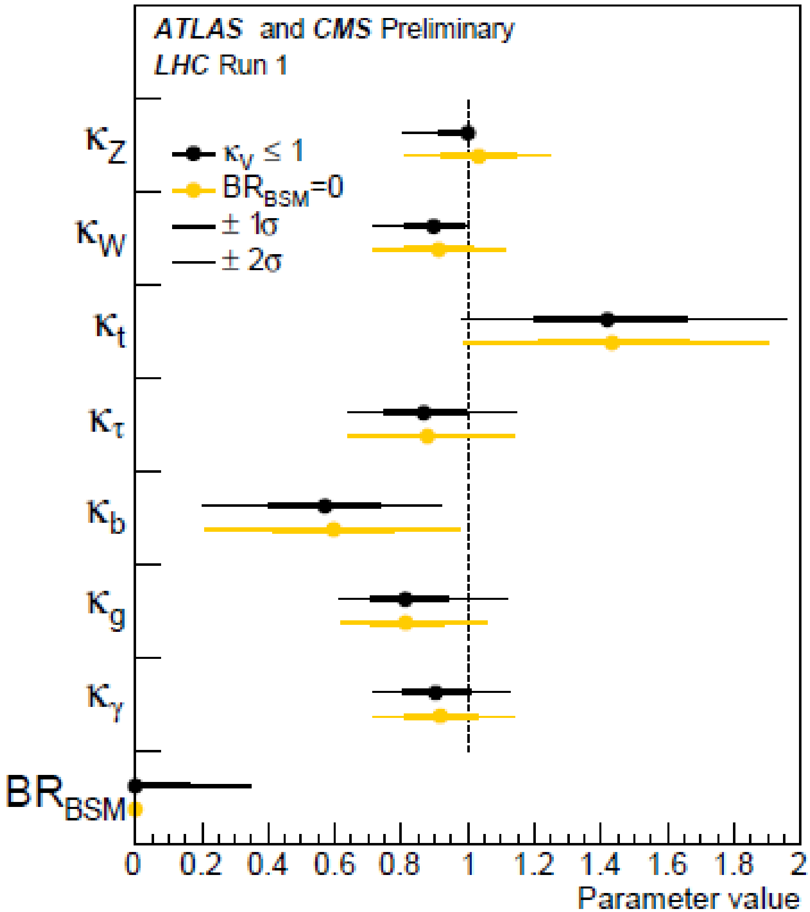
- If $\boldsymbol{\theta_s = 0}$, s is stable

  ⇒ Higgs invisible decay

Talk by Nadjieh for the latest results

The exotic width of the 125 GeV Higgs

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



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Prospects for the HL-LHC: ~10%

New Higgs signatures: $h \to ss \to$?

- If $\theta_s = 0$, s is stable

  ➡ Higgs invisible decay

  Talk by Nadjieh for the latest results

- If $\theta_s \neq 0$, s will decay to SM particles

$$\Gamma(s \to f\bar{f}) = \sin^2\theta_S \frac{N_c}{8\pi} \frac{m_s m_f^2}{v^2} \beta_f^3$$

Main BRs: bb, ττ, cc, ...

$\sin(\theta_S) \geq O(10^{-5})$	$\sin(\theta_S) \leq O(10^{-5})$
S decays promptly	S has displaced decays

Prompt Decays

From
Curtin, Essig, SG, Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992

$\mathbf{BR}(\mathcal{F}_i) \equiv \mathbf{BR}(h \to ss \to (f\bar{f})(f'\bar{f}'))$

BR(s)

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\text{BR}(\mathcal{F}_\text{i})$ 7/8 [14] TeV	Produc-tion Mode	quarks allowed $\frac{\text{BR}(\mathcal{F}_\text{i})}{\text{BR(non-SM)}}$	Limit on $\frac{\sigma}{\sigma_{\text{SM}}} \cdot \text{BR(non-SM)}$ 7/8 [14] TeV
$b\bar{b}b\bar{b}$	0.7^R $[0.2^L]$	W	0.8	0.9 [0.2]
$b\bar{b}\tau\tau$	> 1 $[0.15^L]$	V	0.1	> 1 [1]
$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4}$ $[(0.6-2)\cdot 10^{-4\ T}]$	G	3×10^{-4}	$0.6-1$ $[0.2-0.7]$
$\tau\tau\tau\tau$	$0.2-0.4^R$ [U]	G	0.005	$40-80$ [U]
$\tau\tau\mu\mu$	$(3-7)\cdot 10^{-4\ T}$ [U]	G	3×10^{-5}	$10-20$ [U]
$\mu\mu\mu\mu$	$1\cdot 10^{-4\ R}$ [U]	G	$1\cdot 10^{-7}$	1000 [U]

Extracted bound on BR(h → ss)

Prompt Decays

From
Curtin, Essig, SG, Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992

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$b\bar{b}\mu\mu$	$(2-7)\cdot 10^{-4}$ $3 \cdot 10^{-4}$	G	3×10^{-4}	$0.6 - 1$ $[0.2 - 0.7]$
$\tau\tau\tau\tau$	0.2 0.25	G	0.005	$40 - 80$ [U]
$\tau\tau\mu\mu$	$(3-7)\cdot 10^{-4}$ $4 \cdot 10^{-4}$	G	3×10^{-5}	$10 - 20$ [U]
$\mu\mu\mu\mu$	$1 \cdot 10^{-4}$ $4 \cdot 10^{-5}$	G	$1 \cdot 10^{-7}$	1000 [U]

C) HIG-14-041

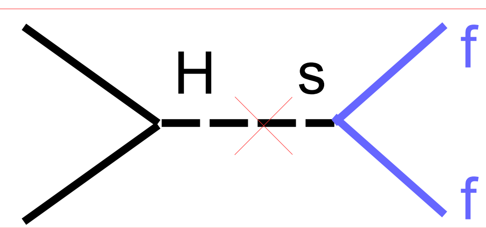
C) 1510.06534,
C) HIG-14-022

C) HIG-13-010,
A) 1505.07645

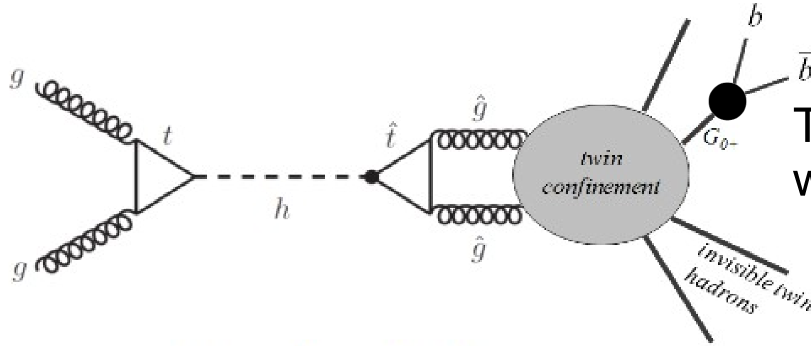
C) HIG-15-011,
A) 1505.01609

Extracted bound on BR($h \to ss$)

Wish list:
it would be great to have a similar table for the direct production of s



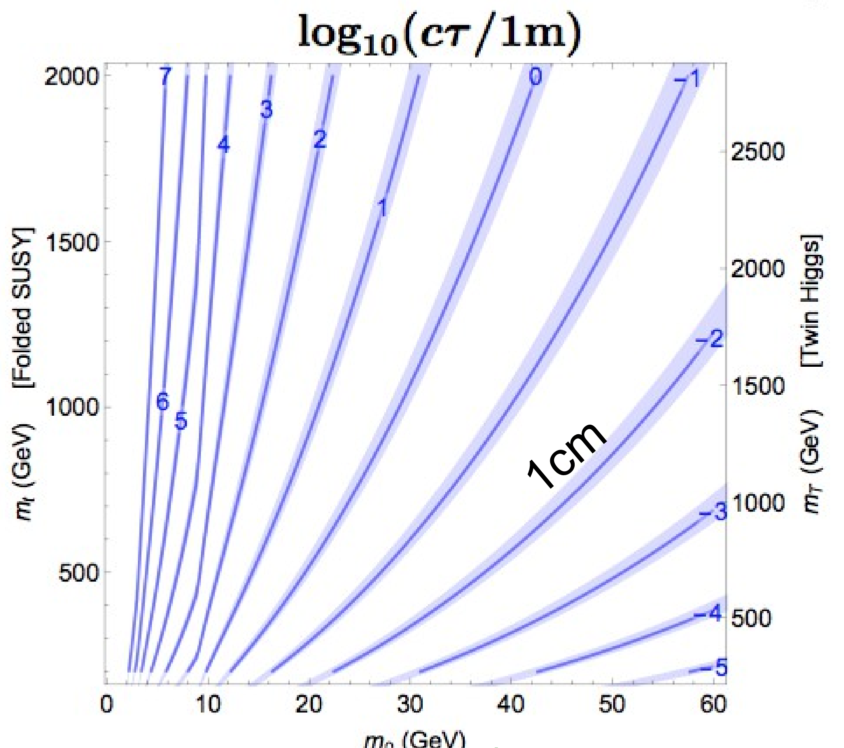
Displaced Decays



Thanks to the mixing with the Higgs

Specific example:
Glueballs in Folded SUSY or Twin Higgs models

(Top partner mass)

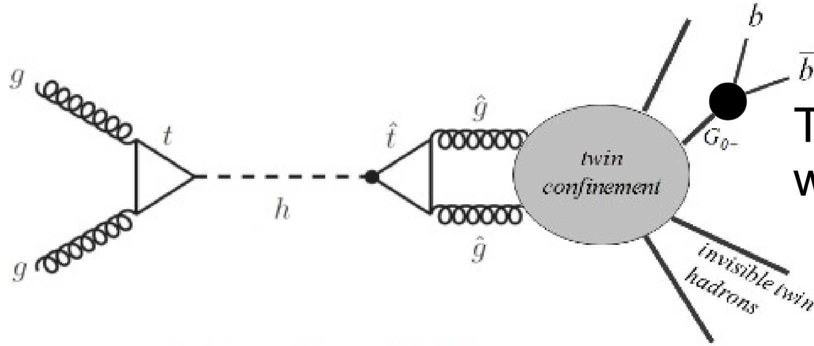


(Lightest glueball mass)

Curtin, Verhaaren, 1506.06141

$$\mathrm{BR}(h \to G_0 G_0) \;\approx\; 10^{-3}\,\kappa \left(\frac{400\mathrm{GeV}}{m_T}\right)^4 \sqrt{1 - \frac{4m_0^2}{m_h^2}}$$

Displaced Decays



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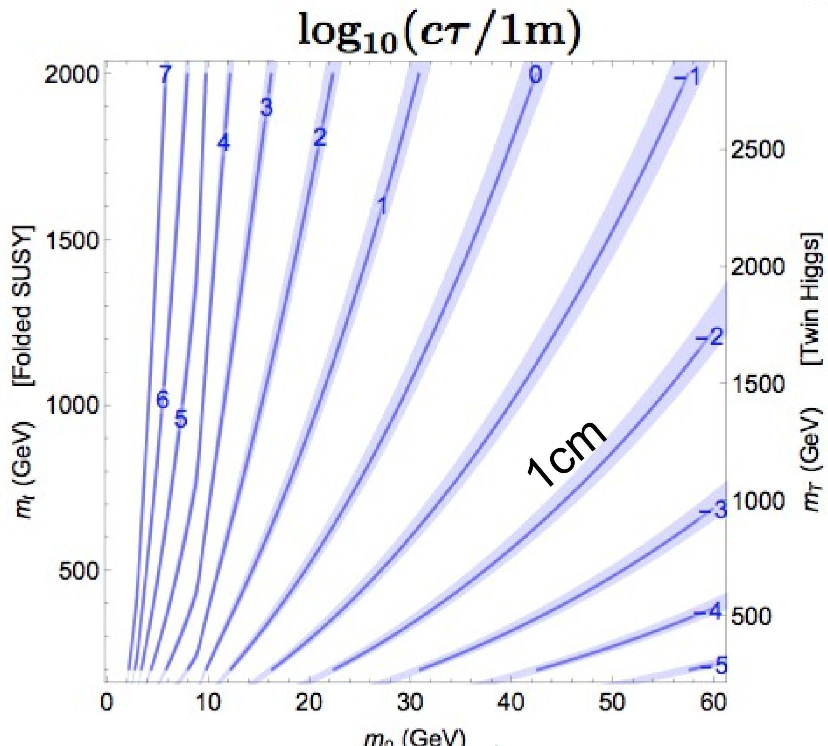

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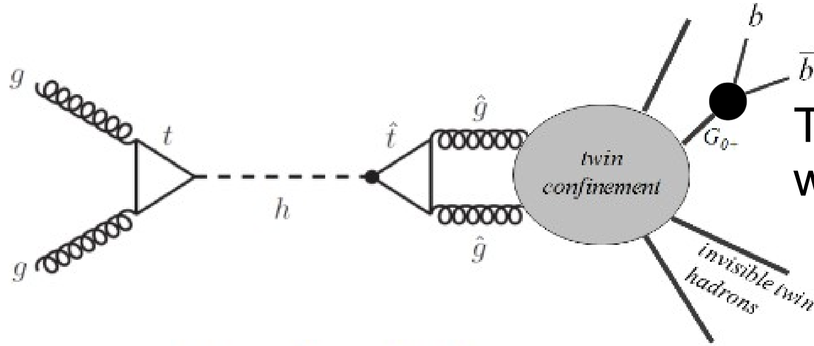
Existing displaced searches methods focus on
- 2 displaced objects or 1 displaced object & high-threshold associated object
- displacement longer than ~ 1mm - 1cm

More focused Higgs exotic displaced searches?
- only 1 displaced object + thresholds suitable for the Higgs
- very short displacements
- new dedicated displaced triggers?

Displaced Decays



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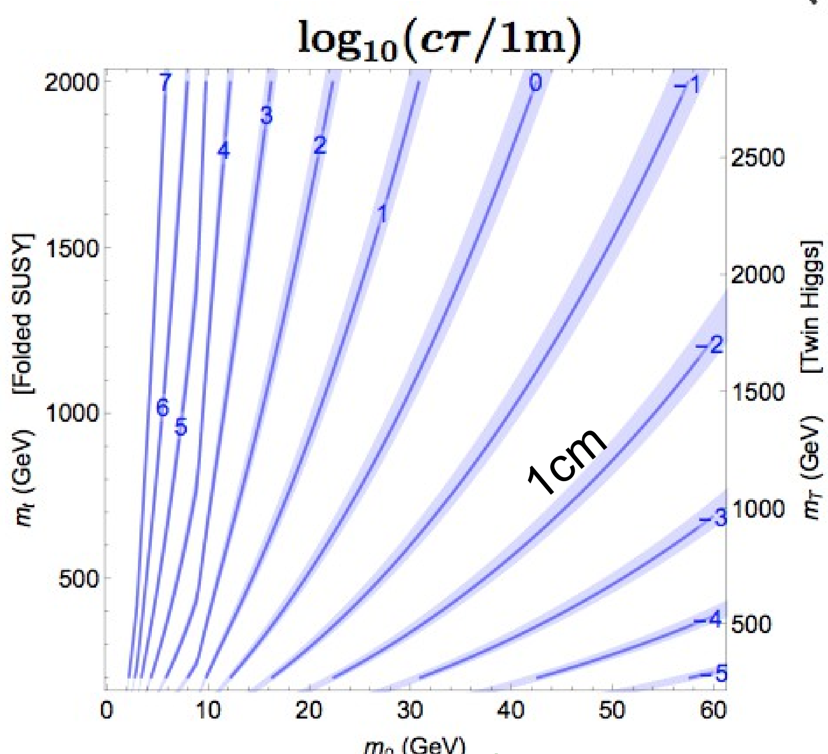

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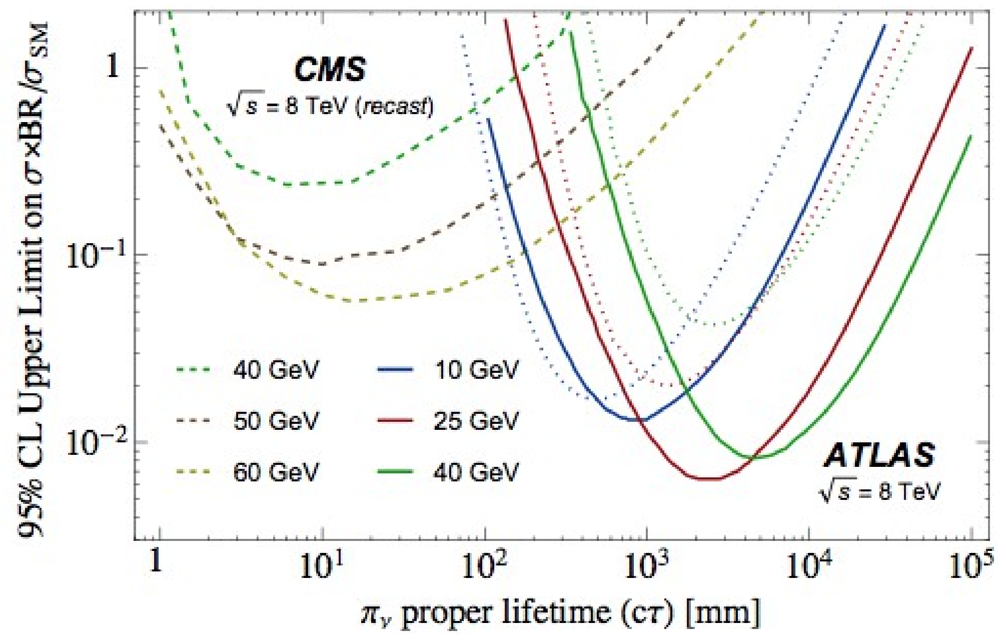
Curtin, Verhaaren, 1506.06141



Csaki, Kuflik, Lombardo, Slone, 1508.01522

$$\mathrm{BR}(h\to G_0G_0)\approx 10^{-3}\,\kappa\left(\frac{400\mathrm{GeV}}{m_T}\right)^4\sqrt{1-\frac{4m_0^2}{m_h^2}}$$

Conclusions/Take home messages

After the discovery of the 125 GeV Higgs boson,
the search for additional Higgs bosons/scalars is even more motivated

Very different search strategies for SU(2) doublet or singlet states.
Many searches are on-going

Many open questions:

- How to probe the low tanβ regime?
- How to design additional searches for light singlet scalars?
  (direct production vs. 125 GeV Higgs decays (4b, 2b2τ final states)
- Higgs decays to displaced scalars. How to test this scenario?

Complementarity with 125GeV Higgs coupling measurements

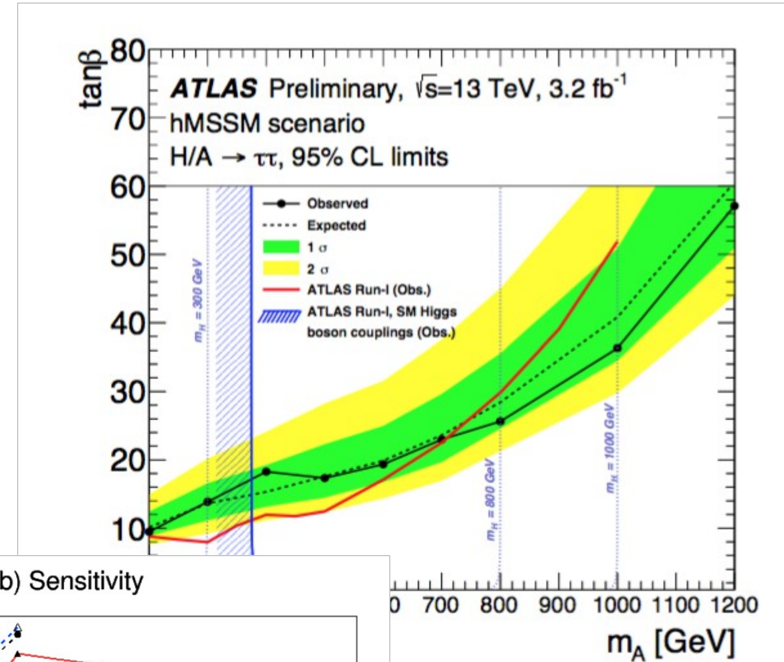
Searches for new Higgs bosons to date

In the alignment/decoupling limit:

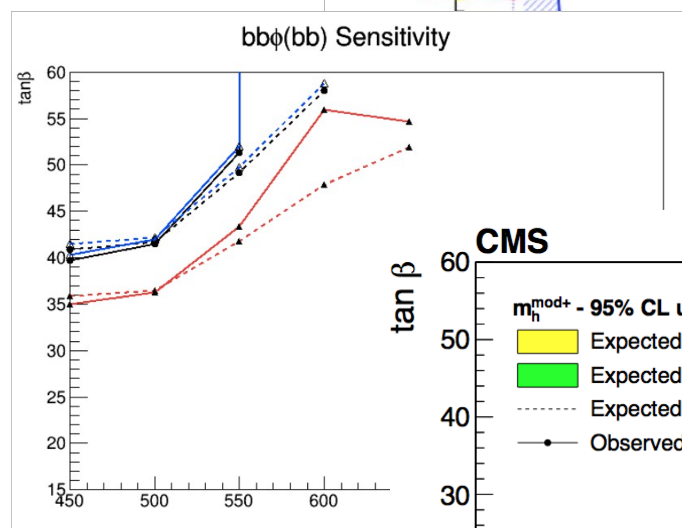
		H	A
Standard Model Decay Channels	WW, ZZ	–	
	$tt, bb, \tau\tau, \mu\mu$	✓	✓
	$\gamma\gamma$	✓	✓
	Zh		–
	hh	–	

At large tanβ the heavy Higgs couplings to

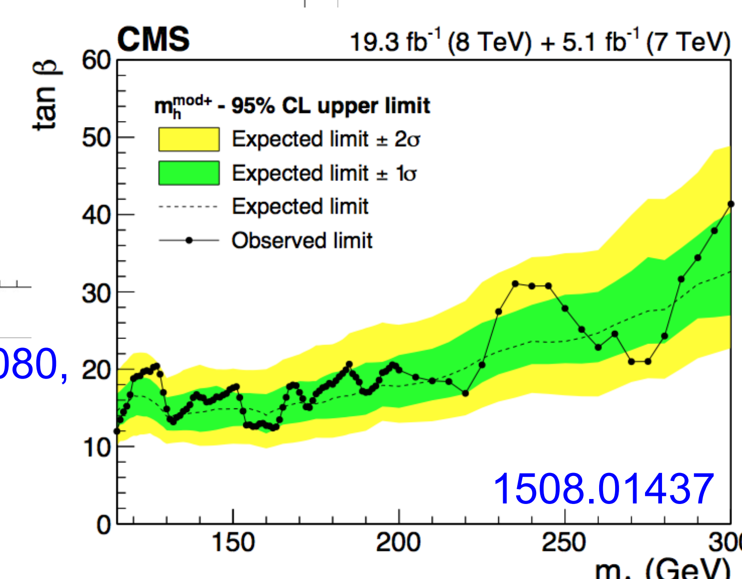
- bottoms, muons and taus are enhanced
- tops are suppressed



ATLAS-CONF-2015-061



CERN-THESIS-2015-080, Malone



1508.01437

Interpretation of the limits

Carena et al, 1302.7033

Typically the cross section limits are interpreted in the

$m_h^{\rm mod+}$
$m_h^{\rm mod-}$
$m_h^{\rm max}$
$\tau - \text{phobic}$

scenarios

$$M_1 = \frac{5}{3}\frac{s_{\rm w}^2}{c_{\rm w}^2} M_2$$

$$\begin{aligned} m_t &= 173.2\ \text{GeV}, \\ M_{\rm SUSY} &= 1000\ \text{GeV}, \\ \mu &= 200\ \text{GeV}, \\ M_2 &= 200\ \text{GeV}, \\ X_t^{\rm OS} &= 1.5\, M_{\rm SUSY}\ \text{(FD calculation)}, \\ X_t^{\overline{\rm MS}} &= 1.6\, M_{\rm SUSY}\ \text{(RG calculation)}, \\ A_b &= A_\tau = A_t, \\ m_{\tilde g} &= 1500\ \text{GeV}, \\ M_{\tilde l_3} &= 1000\ \text{GeV}\ . \end{aligned}$$

$$\begin{aligned} m_t &= 173.2\ \text{GeV}, \\ M_{\rm SUSY} &= 1000\ \text{GeV}, \\ \mu &= 200\ \text{GeV}, \\ M_2 &= 200\ \text{GeV}, \\ X_t^{\rm OS} &= -1.9\, M_{\rm SUSY}\ \text{(FD calculation)}, \\ X_t^{\overline{\rm MS}} &= -2.2\, M_{\rm SUSY}\ \text{(RG calculation)}, \\ A_b &= A_\tau = A_t, \\ m_{\tilde g} &= 1500\ \text{GeV}, \\ M_{\tilde l_3} &= 1000\ \text{GeV}\ . \end{aligned}$$

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

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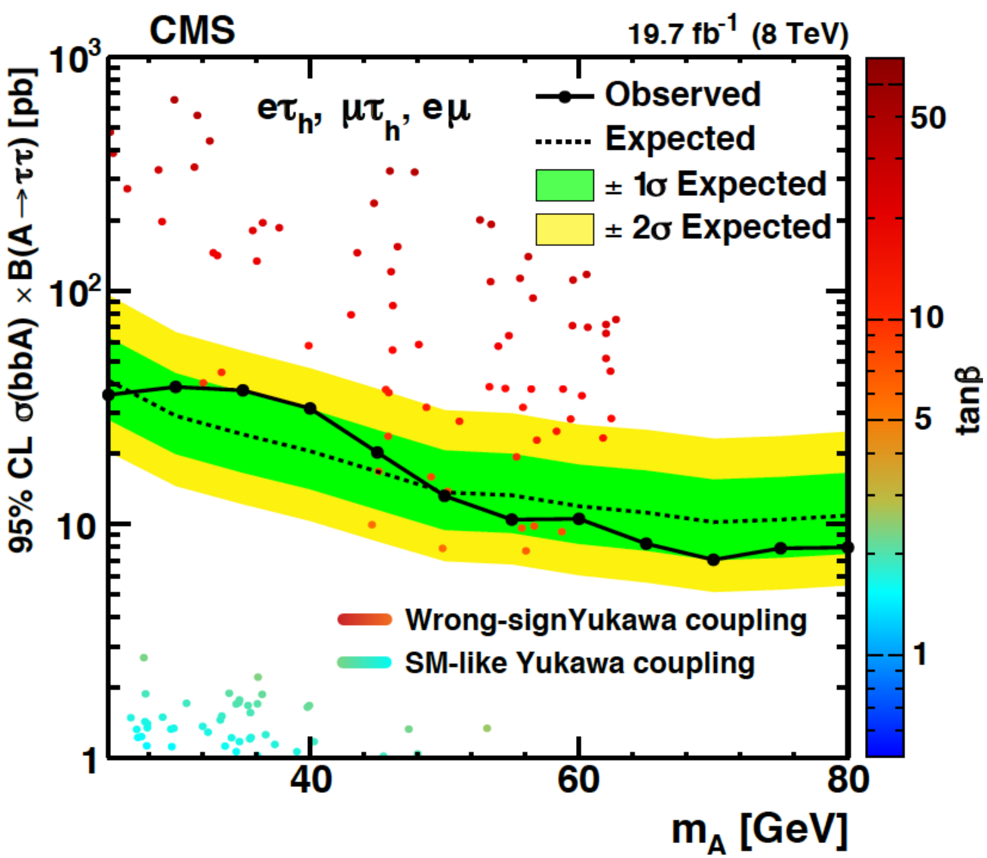
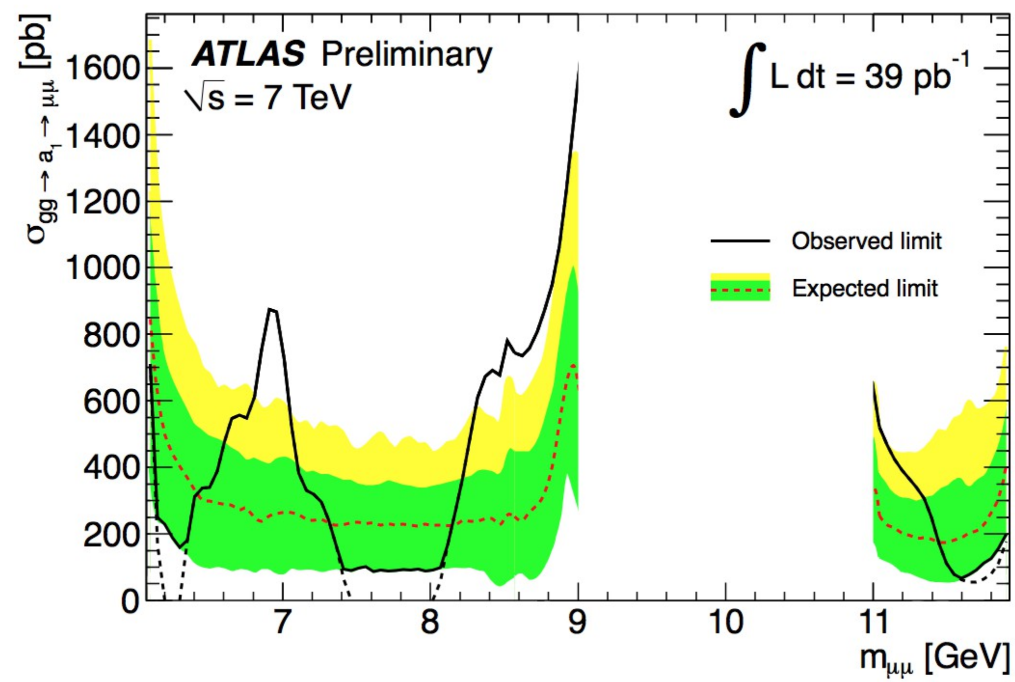
Direct searches for singlet states

CMS-HIG-14-033



pp → (bb)s, s → ττ

ATLAS-CONF-2011-020



pp → s, s → μμ